# Office of High Energy Physics Accelerator R&D Task Force Report

## Appendix 3

**William Barletta,**

**Accelerator Education in America**

# Accelerator Education in America*

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*January 10, 2012*

Accelerators are essential to discoveries in fundamental physics, biology, and chemistry. Particle beam-based instruments in medicine, industry and national security form a multi-billion dollar per year industry. More than 55,000 peer-reviewed papers with accelerator as a keyword are available on the Web. Yet only a tiny fraction of U.S. universities offer any formal graduate program in accelerator science and its core technologies despite some efforts by national accelerator laboratories to expand that presence in major research universities. Several reasons can be cited: 1) The science and technology of particle beams and other non-neutral plasmas cuts across traditional academic disciplines. 2) Electrical engineering departments have evolved toward micro- and nano-technology and computing science. 3) Nuclear engineering departments have atrophied at many major universities. 4) With few exceptions, student interest at individual universities is not extensive enough to support a strong faculty line. 5) Funding agency support of university-based accelerator research infrastructure is insufficient to support the development of new faculty lines.

What universities are at the core of training in accelerator science in the United States? The determining characteristic of a healthy university program is the presence of viable faculty lines with a minimum of two tenure-track faculty combined with regular core offerings. The field becomes slightly broader if one includes those physics and engineering faculties that have individual members with specialized interests in the field such as plasma-based accelerators. In addition some departments have nuclear and particle physics faculty who successfully place their students in national laboratories to do thesis research in accelerator physics and technology.

Group I, the major research universities in the United States with structured programs including graduate and undergraduate courses that are producing PhD level physicists are the following (in alphabetical order):

Cornell University
Indiana University
Michigan State University
Stanford University
University of California at Los Angeles
University of Maryland (College Park)

Also initiating structured Ph.D. programs in accelerator science are

Massachusetts Institute of Technology,
Old Dominion University (in affiliation with Jefferson Lab), and

* This report is a work in progress and will be part of a longer invited paper to be published in Reviews of Accelerator Science and Technology.

[1] For a history of the USPAS sessions, see http://uspas.fnal.gov/

Stony Brook University (in affiliation with Brookhaven Lab).

To this list one may add Group II, universities with a single faculty member (either tenured or research faculty) whose primary research activity is accelerator science or multiple faculty with narrowly focused research activities:

Colorado State University
Duke University
Illinois Institute of Technology
Texas A&M
Northern Illinois University
University of California at Berkeley
University of Chicago
University of Hawaii
University of Southern California
University of Texas at Austin
Vanderbilt University

Some universities such as the University of Michigan and Columbia had produced some accelerator PhD's but now have none in the pipeline as the single faculty advisor has left or is no longer accepting students. A single interested faculty member has at best great difficulty sustaining a university program. An historical look[2] at the principal producers of PhD level accelerator scientists is given in figure 1. Rather surprisingly the number of students (MS and PhD) is a large fraction of (but in most cases is consistent with) the total historical production.

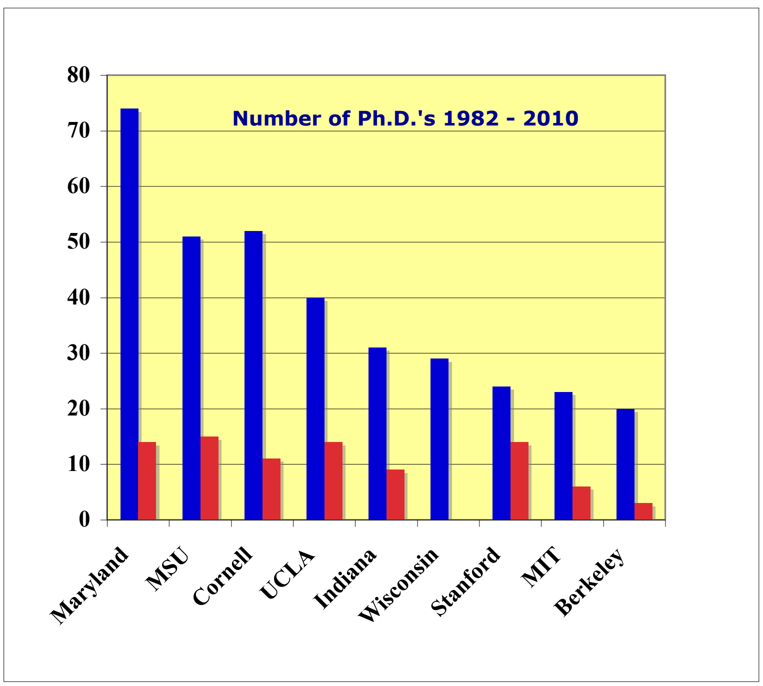



*Figure 1: PhD's in accelerator science (blue) and present graduate students (red)*

[2] Both sets of data have been provided to the author by the universities cited. Note that the expected number of PhDs produced annually is roughly 20% of the present level of students.

Even Group I universities offer only two or three regular courses in accelerator physics and technology. Some examples are given in the Appendix. The listed courses are generally an undergraduate and a graduate course in accelerator physics plus a regularly offered seminar style course in special topics. Therefore, all the universities in both Group I and Group II must rely heavily on the US Particle Accelerator School to provide the specialized academic coursework for their students. For this reason the USPAS rubric of for-credit courses hosted by major research universities is an essential aspect of formal accelerator education in America.

Students may register for one full course (≥ 45 contact hours) or choose two half-courses (≥23 contact hours each) where each half-course is one week in duration. By successfully completing the course requirements that include lectures, daily problem solving and examinations, students can earn university credit. A full-course earns the equivalent[3] of 3 semester hours of host university credit; each half-course earns the equivalent of 1.5 semester hours of credit. All courses run in parallel so students can take one full course, or two half-courses, or they may opt for only one half-course during either week of the program if the hosting university allows half credits. The percentage of students who take our classes for credit remains high, averaging 63%. In recent years the USPAS has had about 150 students (of all levels) per session.

The host universities generally require that course descriptions and instructor CVs be submitted roughly one year in advance of the session, to be vetted by their faculty. In addition, all USPAS courses are vetted and co-listed at Indiana University; Old Dominion is preparing to do the same. MIT students who take the undergraduate USPAS course receive MIT credit for course 8.277 and graduate students receive credit for 8.790.

Figure 2 combines USPAS attendance for the past decade with the data of Figure 1. Universities producing many PhDs make heavy use of the USPAS courses.

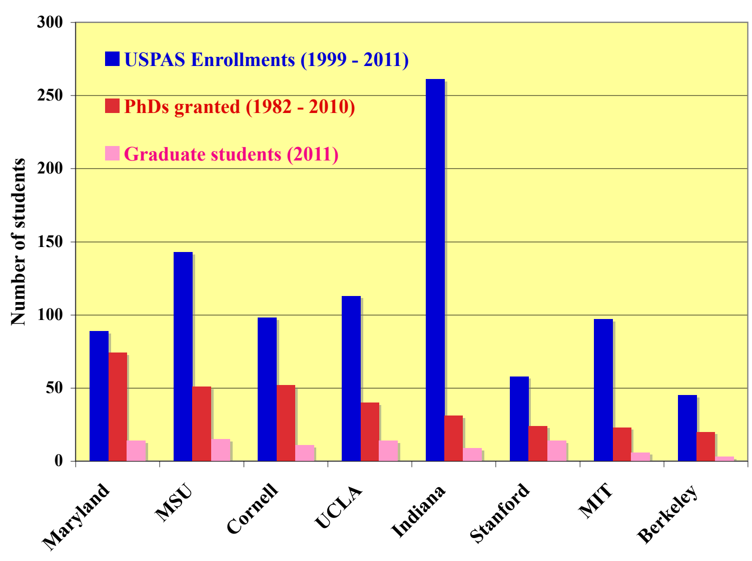



*Figure 2: Student attendance at USPAS from the primary U.S. universities that produce PhDs in accelerator science*

[3] Some of our hosts are on the quarter system; in that case an equivalent quarter credit is awarded.

USPAS offers a highly varied, responsive, and balanced curriculum of science, engineering, computational and hands-on courses. These offerings, distributed as shown in Figure 3 include:

Physics courses:

- General principles of accelerator physics, design of storage rings and synchrotrons, linacs, intense beam accelerators, beam optics, spin dynamics
- Synchrotron radiation sources, free electron lasers, strong field radiation,
- Beam theory, non-linear dynamics, collective effects, beam instabilities,
- Computational methods in beam dynamics, beam optics and electromagnetism,
- Radiation physics and accelerator safety, radiation effects,

Engineering and technology

- Experimental techniques, microwave measurement and beam instrumentation labs, accelerator vacuum labs, beam manipulation techniques
- RF systems, magnetic systems, superconducting magnets, superconducting RF, superconducting materials, beam sources
- Use of lasers in accelerators, optics-based diagnostics, optical-based timing systems
- High power electronics, pulsed-power electronics, high power rf-sources
- Shielding and accelerator safety systems,

Applications and management

- Accelerator applications in medicine, discovery science, and industry,
- Management of scientific research facilities
- Project management

Each year the USPAS offers one or more hands-on laboratory courses in which students learn to use sophisticated instrumentation such as network analyzers, fiber lasers, etc. Full, 2-week experimental courses in beam physics at operating accelerators are offered roughly every two years. The most recent of these offerings used the ERL-based free electron laser at Jefferson Lab. The next such hands-on offering will be at Duke in the Winter 2013. Unfortunately, due to practical considerations only a dozen students can be handled in such courses.

Whether at USPAS sessions or at universities, the lack of hands-on experience with running accelerators is a notable deficiency in the U.S. as compared with Europe, where there are several small accelerators at universities. This lack could be ameliorated with the development of optical-analog, beam-physics experiments[4] or small cyclotrons[5], including electron-model machines. The

[4] An optical analog pepper-pot emittance measurement experiment was developed for the S2009 USPAS course, "Accelerator and Beam Diagnostics" taught by Willem Blokland, Tom Shea and Alexander Zhukov, Oak Ridge National Lab; John Byrd, Lawrence Berkeley National Lab and Uli Raich, CERN http://uspas.fnal.gov/programs2/2009/UNM/courses/BeamDiagn.shtml

[5] A notable example is the 12-inch cyclotron plus instructional physics program built at Rutgers by Timothy Koeth and his student team. (http://www.physics.rutgers.edu/cyclotron/ ). This machine and program are briefly described in Appendix 2.

later could do cutting edge research in space charge dynamics at a machine cost of less than $500k while a student training model might cost less than one-half of that amount. Small synchrotrons using small, industry made magnets are also quite feasible and not all that expensive, but no one has looked seriously at them except Michigan State which built and operated a very small, four quadrant, electron synchrotron for studying beam physics at transition.

Typical class enrollment (see figure 3) ranges from 40 in our undergraduate class to several in highly specialized classes. This latter number explains why single universities cannot afford to offer specialty courses even if appropriate resident or guest faculty are available to teach.

As is common at most U.S. universities, at the completion of each course the students provide an evaluation of the course content selected by our faculty and of the quality of the instruction. These data provide feedback to the USPAS Director, Curriculum Advisory Committee, and USPAS Board of Governors as well as to the individual instructors.

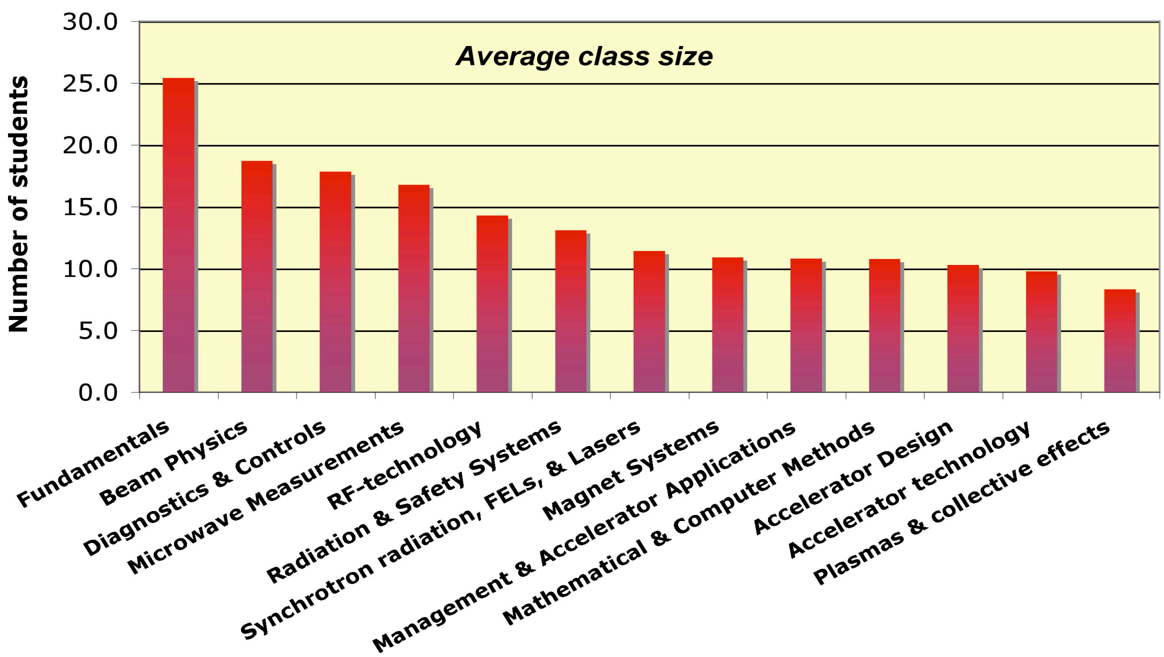



*Figure 3: Average enrollment in USPAS courses by type*

The USPAS also provides an unparalleled source of continuing education for accelerator physicists, technologists, and engineers from our national consortium members. Attendees from the national laboratories and partner universities remain our core constituency. Figure 4 shows the breakdown of attendees from our sponsoring institutions over the past twenty-four years. The institutions that historically have had largest accelerator operations (and operating budgets) send the largest numbers of participants. Normalizing MSU and Cornell by their respective operating budgets, one sees a participation level equivalent to Fermilab and SLAC.

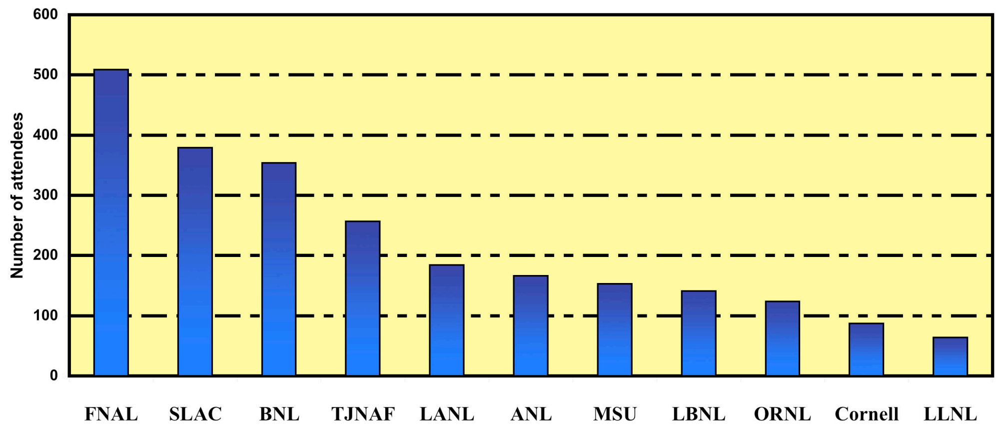



*Figure 4. Attendance at USPAS sessions from sponsoring institutions from 1987 - 2011*

With respect to overall interest in accelerator education from both degree-seeking students and those from the national laboratories and industry, the trend has been markedly upward in the past few years (Figure 5). Average attendance per session has risen less 130 to nearly 150.

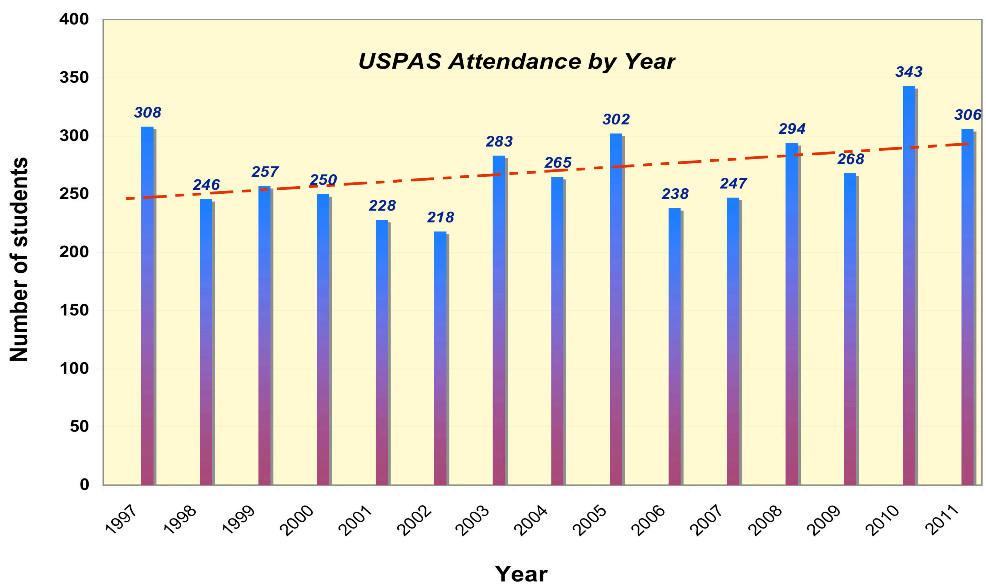



*Figure 5. Student attendance at the past 28 sessions of the US Particle Accelerator School. The dashed line is a linear regression trend line.*

The US Particle Accelerator School together with Indiana University offers the opportunity to earn a Master of Science Degree in Beam Physics and Technology. Students earn credit toward the Indiana University diploma at USPAS/university-sponsored courses by selecting their USPAS course for Indiana University credit instead of the host university credit. For each program, USPAS instructors are given visiting professor appointments and USPAS courses are added to the Indiana University curriculum. Award of a Master of Science Degree requires 30 hours of credit with a grade point average of B or above; a maximum of 8 credit hours may be transferred; some credits earned at previous USPAS courses may be eligible for transfer. There is a strict five-year limit to obtain the Master of Science degree. Generally, students may complete the Master's degree program within 3 years. At this time, we are unable to accept international students into the IU/USPAS Master's Degree Program. To date, IU/USPAS Master's Degrees have been awarded to seven students. Presently we have seven active students in the Master's program

A crucial part of any student's training is the opportunity to participate in cutting edge accelerator research programs. Given top-quality faculty supervision, students can do accelerator research in areas that are central to an institution's accelerator development program. An outstanding example of such work is the optimization of superconducting rf-cavity structures as part of Cornell's ERL research program. At MSU a large number of students play a strong active role in the NSCL program. NSCL graduate research topics include SRF cavity design, modeling, and measurement techniques, SRF-related material science, high-intensity ion-source development, large dynamic range beam instrumentation. At UCLA, the extensive, world-class experimental program in plasma accelerators, both in the Physics and Electrical Engineering Departments has produce a new generation of intellectual leaders in advanced acceleration techniques. At the University of Maryland, the novel electron-model storage ring (UMER) has played a vital role in advancing the understanding of the transport of space charge-dominated beams and has produced a substantial fraction of the PhD in accelerator physics and engineering from U.S. universities. DOE investment in a few more small research machines at universities would pay large dividends to the large accelerator-based science programs of the Office of Science.

It must be emphasized that many breakthroughs in accelerator science and technologies have been pioneered at universities with on-campus machines. A few examples are superconducting rf-accelerators (at Stanford and Cornell), superconducting compact cyclotrons (MSU), and pretzel orbits for high-luminosity collider operation (Cornell). Of course, such innovations require top-notch faculty lines[6] as well as highly talented students.

Of course increasing opportunities for PhD-level education will not be fruitful if talented undergraduates in physics and engineering are uniformed of and not attracted to them. As a first step to attract high quality students, the USPAS, Fermilab and Argonne National Laboratory instituted the Lee Teng Internships[7] in FY 2008. Teng Interns[8] should have just completed their junior year (or for exceptionally talented students, their sophomore year) prior to the summer of the internship. The interns take the USPAS course, "Fundamentals of Accelerator Physics," and then complete an eight-week research project at FNAL or ANL under the supervision of a mentor. The mentors remain available to guide the student through graduate school application

[6] When a university commits to a faculty line, it makes a commitment of a few million dollars. That means that universities must expect faculty in the hard science and engineering to be able to secure research grants of ~$300 to 500 k per year. Without sufficient opportunities from Office of Science program offices, one cannot expect a sufficient cadre of world-class accelerator faculty in US universities.

[7] http://www.illinoisacceleratorinstitute.org/

[8] Ten Lee Teng Interns are selected each year. The selection committee not only chooses the awardees but also matches them with the mentors at each laboratory. The author has been pleased to teach the Lee Teng interns each summer at the USPAS session.

and / or a senior thesis. Moreover, according to the Office of Workforce Development for Teachers and Scientists[9], participating in a summer research internship substantially raises the chances of a student's being selected for a DOE Office of Science Fellowship. The USPAS intends to propose to expand this program to the other Office of Science national laboratories plus four major research universities.[10] The cost for an expanded internship program would be approximately $300k per year.

The DOE national laboratories must and do play an essential active role in the education and training of accelerator scientists and engineers. Summer Undergraduate Laboratory Internships Student (SULI programs) are one way; providing instructors and financial support for USPAS session is another; providing research opportunities for thesis projects is a third.

Figure 6 shows an estimate of the average contribution that the consortium laboratories make from their own budgets each year to the annual USPAS educational program. This long-term funding commitment that the laboratories make to the annual USPAS budget is an exceedingly strong, public statement about the importance that they attach to the contributions of USPAS to the U.S. accelerator physics and engineering effort.

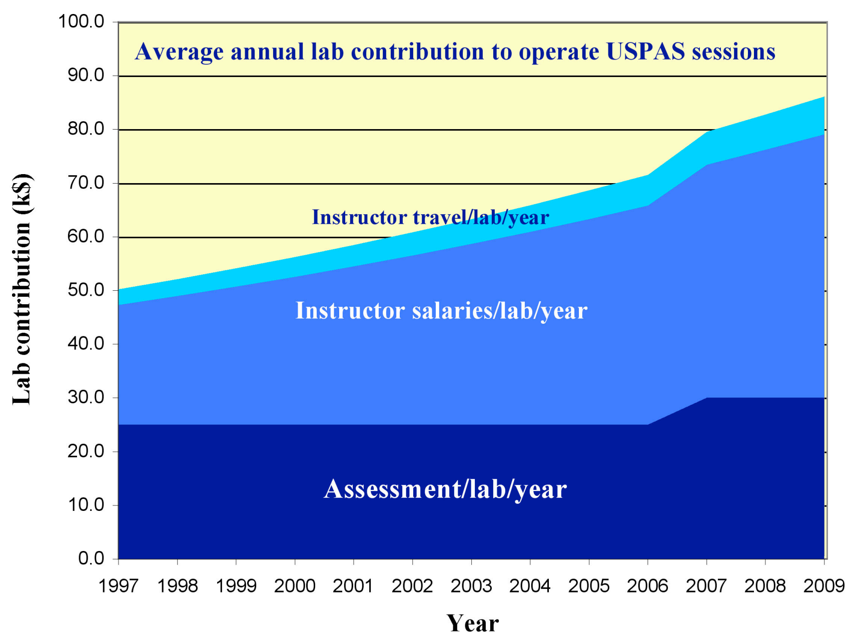


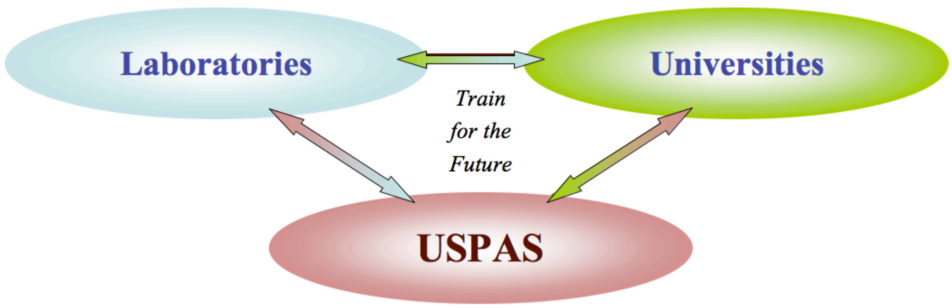

*Figure 6. The monetized average annual contribution by Office of Science laboratories and USPAS consortium universities to operate the USPAS academic sessions.*

However, it would be a conceit to imagine that the laboratory system could supplant the principal role of major research universities with on-campus facilities. The Office of Science laboratories must attract top undergraduate talent to graduate study of accelerator physics and technology as well as to graduate study of accelerator-based science. A necessary condition is that

[9] Private communication, Dennis Kovar, 2010.
[10] An expanded internship program in industry or with the Department of Defense could be developed on a cost-sharing basis.

undergraduates must be made aware of the intellectual challenge and excitement of accelerators. However, the best undergraduates expect to study at a great research university. For the best graduate education, students should spend a large fraction of time on campus; an education at a great laboratory is not an education at a great university. Therefore the national laboratories must seek to enrich the intellectual life on campuses by creating new opportunities for significant accelerator research to be done on-campus.

Educating the next generation of scientists and engineers to build and pilot the engines of discovery for accelerator-based science, medicine, and industrial production must remain a strong three-way partnership. Each partner has an essential role that must be continually nurtured. The USPAS is proud of its role in the U.S. educational enterprise.




*Summary recommendations*

Over the past twenty-five years, U.S. education in accelerator science and technology has been carried out in a close, successful partnership among universities, national accelerator laboratories and the USPAS. Over that same period the accelerator-relevant infrastructure has atrophied considerably. Therefore, an important aspect of an accelerator stewardship program should be directed toward strengthening this partnership with the addition of more structured programs and hands-on training opportunities in research universities. Several universities have recently expressed new or renewed interest in developing advanced degree programs in accelerator physics, but new funding is going to have to be available from the DOE or NSF to support these new programs. At a few universities there is also interest expressed by electrical engineering and nuclear engineering departments. The latter are important for training students in areas such as high-power electronics or techniques of high-power thermal and radiation load design.

Judging from the attendance at USPAS sessions over the past five years, student interest has never been higher. Taking advantage of the opportunity these students represent will require an expanded investment in university-based accelerator research and in a new generation of hands-on training instruments. An accompanying expanded program of student internships would attract some of our most talented undergraduate physics and engineering students into graduate study in accelerator science and technology. The Unites States Particle Accelerator School has historically played a strong, central and institutionally neutral coordinating role in the education of accelerator physicists in the U.S. and looks forward to continuing that role as a vital part of the new stewardship program.

# APPENDIX 1

## Examples of Accelerator Science Courses in Accelerator Physics

**Cornell courses**

*Undergraduate:*

Physics 4456: Introduction to Accelerator Physics and Technology

Physics 4488: Advanced Topics in Accelerator Physics

*Graduate:*

Physics 7656: Introduction to Accelerator Physics and Technology

Physics 7688: Advanced Topics in Accelerator Physics

<u>Course Recommendations Beyond the Core Subjects : Strongly Recommended:</u>

PHYS 656 (7656) Introduction to Accelerator Physics and Technology
PHYS 657 (7657) The Storage Ring as a Source of Synchrotron Radiation
PHYS 688 (7688) Advanced Topics in Accelerator Technology

Cornell has always had a strong connection with the U.S. Particle Accelerator School (USPAS) and is a member of the USPAS consortium. Cornell faculty members have regularly been instructors for the USPAS since the accelerator school's inception. Cornell hosted USPAS sessions in 1988 and 2005.

**MSU courses**

PHY 861 -- Beam Physics

PHY 961 -- Non-Linear Beam Dynamics

PHY 962 -- Particle Accelerators

PHY 963 -- U.S. Particle Accelerator School

PHY 964 -- Seminar in Beam Physics Research

PHY 905 -- Special Problems (*recent offerings*)

RF Linear Accelerators, 2009

The Accelerator Physics of FRIB, 2011

MSU has provided distance-learning, on-line courses in beam physics through its VUBeam program for the past 20 years. A unique feature of VUBeam, which is jointly supported by OHEP and MSU, is that many, if not all, of the lectures are done live and fully interactive with the watching students communicating via some software originally developed by Cornell. MSU is an active member of USPAS consortium, and has offered several specialty courses in accelerator physics at NSCL in recent years. Most importantly, MSU has provided hands-on training to many accelerator physics graduate students who have made significant contributions in several areas.

MSU hosted the USPAS in 2007 and will repeat as host in 2012. By enrolling in PHY963, MSU students can enroll in USPAS course work and automatically earn graduate credit at MSU, regardless of where the USPAS course is held. One MSU faculty member has developed four separate courses for the USPAS and holds the record for the most courses and the number of student hours taught at the School.

**MIT courses**

*Undergraduate*

8.277 (6.608) Fundamentals of Accelerators, Lecture, three hours. Principles of charged-particle acceleration, principles of linacs, synchrotrons and storage rings, beam characterization, synchrotron light sources, medical accelerators, and free electron lasers.

MIT has hosted USPAS sessions in 1997 and 2010.

**Stanford**

*Undergraduate*

APPPHYS 324 Introduction to Accelerator Physics

Physics of particle beams in linear and circular accelerators. Transverse beam dynamics, acceleration, longitudinal beam dynamics, synchrotron radiation, free electron lasers, collective instabilities and nonlinear effects. Topics of current research in accelerator physics. Selected laboratory measurements at SLAC to augment the lecture material. Terms: alternate years, given next year | Units: 3 | Grading: Letter or Credit/No Credit

Stanford has hosted USPAS sessions in 1992 and 1998.

**UCLA courses**

*Undergraduate*

150. Physics of Charged-Particle and Laser Beams (4)

Lecture, three hours; discussion, one hour. Requisites: courses 1A, 1B, and 1C (or 1AH, 1BH, and 1CH), 110A, 110B, 115A, 115B. Physics of charged-particle and laser beams presented as a unified subject. Basic physics of charged-particle beams, covering relativistic particle motion in electromagnetic fields, transverse focusing, acceleration mechanisms, linear and circular accelerators, and advanced topics. Some fundamentals of laser physics, including gain and broadening mechanisms, linear light optics, laser resonators, and advanced topics and applications. P/NP or letter grading.

*Graduate*

250. Introduction to Acceleration of Charged Particles (4)

Lecture, three hours. Requisites: courses 210A, 210B, 215A. Principles of charged-particle acceleration, including principles of synchrotrons and storage rings, beam parameter determination, statistical behavior of beams and beam cooling techniques, synchrotron light sources, colliding beam storage rings, medical accelerators, and free electron lasers.

269C. Seminar: Accelerator Physics (2 to 4)

Seminar, three hours. Physics principles governing design and performance analysis of particle accelerators, using existing accelerators as examples and emphasizing interplay among design goals, component performance, and operational experience. S/U grading.

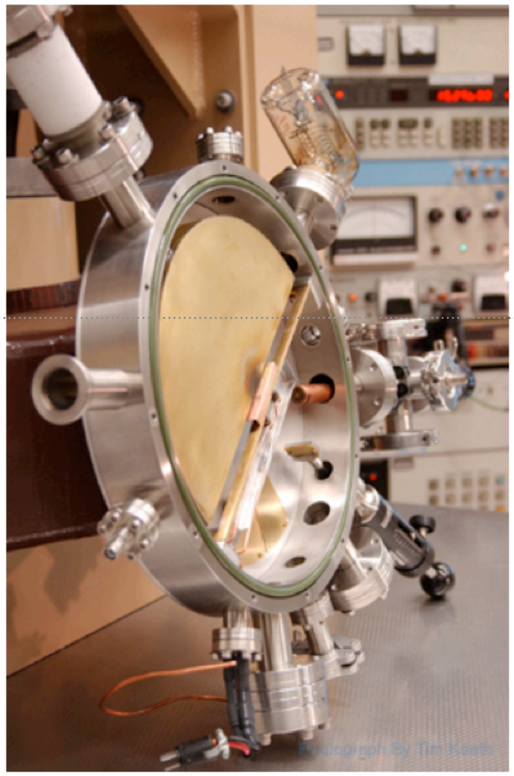
294. Research Tutorial: Accelerator Physics (2 to 4)

Lecture, one hour; discussion, two hours. Required of each graduate student doing research in this field. Seminar and discussion by faculty, postdoctoral fellows, and graduate students on topics of current interest in accelerator physics. May be repeated for credit. S/U grading.

UCLA has hosted USPAS sessions in 1994 and 2002.

# APPENDIX 2

The 12-inch Rutgers Cyclotron is a research-grade accelerator capable of producing 1 million electron volt (1 MeV) protons that is used as a dedicated teaching tool employed in the Modern Physics Lab (MPL) courses at Rutgers University to give students a working introduction to accelerator physics.



It was designed and built by undergraduate students at a cost less than $100,000. Under the guidance of Dr. Timothy Koeth. The continuous evolution of this cyclotron, spanning more than a decade, is carried out by new generations of students, while project continuity is provided by dedicated volunteer faculty and staff. Because of the sophisticated level of the work, one or two students are chosen from the MPL class body and are committed to the cyclotron for an entire semester.

At the end of the semester, the cyclotron students compose one joint report as well as present their work to classmates in an oral session. Thanks to the labors of their predecessors, incoming students can now generate and manipulate beams under differing conditions, compare with simulations, and perform beam orbit analysis, all providing a comfortable introduction to the theory and practices of today's state-of-the-art accelerators. Because of their Rutgers Cyclotron experiences, five of the fourteen cyclotron students have altered their academic course to pursue accelerator science.

By their research with this machine the students have produced eight "white papers" of sophisticated experiments completed: Operation of a 9-Inch Cyclotron, Ion Source Studies: Parts I & II, 12-Inch Cyclotron DEE Voltage Studies, Observation of Betatron Motion, 12-Inch Cyclotron Magnet Studies, Electrostatic Deflector Energy Measurements, and Azimuthally Varying Field vs. Weak Focusing Pole Tips.

# Office of High Energy Physics Accelerator R&D Task Force Report

## Appendix 4
## More university courses on accelerator-related fields

**Editor's note: At the end of Appendix 3, Accelerator Education in America by William Barletta, is a list of university courses on topics in accelerator science. The courses listed below, not included in Barletta's list, are also university offerings on accelerator-related topics.**

**Colorado State**
ECE/ENGR580 - Accelerator Engineering
Course description:
This course will introduce the student to particle beam accelerator technology and engineering - a multidisciplinary and broad field. A description of the historical development of accelerators and storage rings and the present uses of the various genres of machines will be provided. The basic principles and the important features of the action of electric and magnetic fields used in accelerators to bend, focus and accelerate charged particles will be presented. Special attention will be given to the technology, the design and the workings of accelerator components and peripherals systems including the magnets and the radio-frequency systems. The basic principles and the important features of the action of electric and magnetic fields used in accelerators to bend, focus and accelerate charged particles will be presented. Finally a glimpse into the accelerators of the future will be discussed. This course is suitable for third or fourth year undergraduate students and graduate students with a background in electrical engineering, physics, or applied physics.

ECE/ENGR581 - Microwave and Beam Instrumentation Lab
Course description:
This course will introduce the student to particle beam instrumentation, microwave measurements, and magnetic measurements used in the design and diagnosis of charged particle beam accelerator systems. Modern accelerators rely on beam manipulation, measurement and control using electromagnetic fields at microwave frequencies as well as through the use of magnetic fields to produce and control the beam in the desired manner. This course will consist of lectures introducing topics in beam instrumentation, microwave, and magnetic measurements that will then be performed in the laboratory environment by the students. This course is suitable for third or fourth year undergraduate students and graduate students with a background in electrical engineering, physics, or applied physics.

Colorado State is planned to host USPAS in summer 2013

**Naval Postgraduate School**

*Graduate*

PH4055 Free Electron Laser Physics

The physical principles describing free electron lasers are explained with applications to

ship defense from sea-skimming missiles, and to new radiation sources for scientific research. Theory is applied to experimental facilities around the world. Topics include optical resonator design, general laser concepts, laser beam propagation, relativistic electron dynamics, phase-space analysis, and
numerical simulation. Prerequisites: PH4353, E&M.

PH4056 Radiofrequency Weapons, High Power Microwaves, and Ultrawide Band Systems
The physical principles describing free electron lasers are explained with applications to ship defense from sea-skimming missiles, and to new radiation sources for scientific research. Theory is applied to experimental facilities around the world. Topics include optical resonator design, general laser concepts, laser beam propagation, relativistic electron dynamics, phase-space analysis, and
numerical simulation. Prerequisites: PH4353, E&M.

PH4353 Topics in Advanced Electricity and Magnetism (4-0) As Required
Topics selected from: Electromagnetic radiation, including radiation from antennas and accelerating particles, and radiation scattering from charged particles. Additional topics may include Cerenkov radiation, free electron lasers, and the relativistic formulation of electrodynamics. Prerequisites: PH3152, PH3352 and PH3991.

PH3360 Electromagnetic Wave Propagation (4-1) Summer/Winter
Introduction to vector fields and the physical basis of Maxwell's equations. Wave propagation in a vacuum, in dielectrics and conductors, and in the ionosphere. Reflection and refraction at the interface between media. Guided waves. Radiation from a dipole. Prerequisites: MA2121 and a course in basic electricity and magnetism.

**University of Maryland**

*Graduate*

ENEE 686. Charged Particle Dynamics, Electron and Ion Beams (3)
General principles of single-particle dynamics; mapping of the electric and magnetic fields; equation of motion and methods of solution; production and control of charge particle beams; electron optics; Liouville’s theorem; space charge effects in high current beams; design principles of special electron and ion beam devices.

# Office of High Energy Physics Accelerator R&D Task Force Report

## Appendix 5

## Testimony of Jere Glover,
## Executive Director of the Small Business Technology Council

**Editor's note: The following is a brief summary taken from the testimony of Jere Glover, Executive Director of the Small Business Technology Council, at recent Congressional hearings on HR1540, showing the documented success of the SBIR program.**

**Small Business Technology Council of the National Small Business Association**
**1156 15th Street NW, Suite 1100, Washington, DC 20005**

**The SBIR Program – It Is Working!**

The SBIR program is now 28 years old, with tens of thousands of awards and many studies. What are the conclusions? How is it being used by the SBIR agencies? Is it successful in the commercialization of advanced technology? Is it being copied anywhere else in the world? Is it relevant in today's economy?

· The most recent and most intensive study was a six-year analysis by the prestigious National Research Council of the National Academies published in 2008 by National Academies Press,[i] which concluded:

> "By strengthening the SBIR program, the Committee believes that the capacity of the United States to develop innovative solutions to government needs and promising products for the commercial market will be enhanced." (Paragraph 1.6, page 53)

· SBIR companies have produced approximately 25% of key innovations in the past 10 years– with only 2.5% of the Federal R&D extra-mural budget.[ii] The 11 agencies participating in the SBIR program have adapted the SBIR program to their particular missions with considerable success. (A Google search of "SBIR Success Stories" provides over 30,000 returns.) See SBIR Success Stories at www.sbtc.org.

· The commercialization success of the SBIR program is unparalleled in Federal R&D programs with its focus on the Phase III production outcome. According to the NAP study, "… approximately 30-40 percent of projects generate products that do reach the marketplace." (Page 129) This is further exemplified by the very high rate of patents generated by SBIR firms compared to universities and large businesses – 38% of U.S. patents for small business (with < 4% of the Federal R&D budget); 3% for universities (with 28% of the budget); and 55% for large businesses (with 36% of the budget).[iii] For universities, it is "publish or perish." For small businesses, it is "patent and produce products or perish." These commercialization efforts produce products, jobs and tax revenue to help pay for our universities.

· The NAP study also found that the following countries have adopted an SBIR-type program – Sweden, Russia, The United Kingdom, The Netherlands, Japan, Korea, Taiwan and other Asia countries (Page 54). A European Union policy paper has a goal of 15% of EU R&D funding to SMEs.[iv]

· Further, the NAP study found that the SBIR program builds meaningful bridges to universities:

> ". . . about a third of all NRC Phase II and Firm Survey respondents indicated that there had been involvement by university faculty, graduate students, and/or a university itself in developed technologies. (Page 64) . . . These data underscore the significant

> level of involvement by universities in the program and highlight the program's contribution to the transition of university research to the marketplace." (Page 65)

· SBTC believes that this partnership between universities and small business is an important economic multiplier that is unique to the U.S. innovation strategy. We have always strongly supported this partnership throughout the entire 28-year history of the program.[v] We see the important successes that these strong university/small business partnerships have created in Silicon Valley, Route 128, San Diego, Research Triangle Park, Ann Arbor, and others across the country. The U.S. needs more such programs.

· The importance of these partnerships is reinforced by the NAP study of 2002, wherein they state:

> "Public-private partnerships, involving cooperative research and development activities among industry, government laboratories, and universities, can play an instrumental role in accelerating the development of new technologies from idea to market."[vi]

· U.S. universities have produced 119 Nobel Laureates in the past 25 years, and they graduate the brilliant scientists and engineers that our innovative companies need. Small companies introduce the innovative products to the marketplace that keeps the U.S. in the forefront of technology. We need this partnership.

[i] *An Assessment of the Small Business Innovation Research Program*, National Research Council, National Academies Press; Charles W. Wessner, *Editor*, Committee on Capitalizing on Science, Technology, and Innovation; 2008; http://www.nap.edu/catalog.php?record_id=11989

[ii] *Where Do Innovations Come From? Transformations in the U.S. National Innovation System*, 1970-2006, published by THE INFORMATION TECHNOLOGY & INNOVATION FOUNDATION, Washington, DC July 2008.

[iii] *A New View of Government, University, and Industry Partnerships,* This paper was submitted by Jere Glover, Chief Counsel of the Office of Advocacy, at the Senate Committee on Small Business Roundtable Discussion on the SBIR program on August 4, 1999.

[iv] http://cordis.europa.eu/fp7/home_en.html

[v] *A New View of Government, University, and Industry Partnerships,* op. cit.

[vi] *Government-Industry Partnerships for the Development of New Technologies*, National Research Council, National Academies Press: Charles W. Wessner, Editor; 2002**,** page 23; http://www.nap.edu/catalog/10584.html

## Office of High Energy Physics Accelerator R&D Task Force Report

## Appendix 6

## AES –
## Examples of Lab and Industry Collaboration Funded by Government

**Editor's note: The following is a copy of a statement from Alan Todd, Vice President, Advanced Energy Systems, Inc.**

Recent UK government funding has facilitated the implementation of a unique accelerator test facility which can provide enabling infrastructures targeted for the development and testing of novel and compact accelerator technologies, specifically through partnership with industry and aimed at addressing applications for medicine, health, security, energy and industrial processing. The infrastructure provision on the Daresbury Science and Innovation Campus (DSIC) will permit research into areas of accelerator technologies which have the potential to revolutionise the cost, compactness and efficiency of such systems. The main element of the infrastructure will be a high performance and flexible electron beam injector facility, feeding customised state-of-the-art testing enclosures and associated support infrastructure. The facility operating parameters and implementation status will be described, along with primary areas of commercialised technology development opportunities.

**Office of High Energy Physics Accelerator R&D Task Force Report**

# Appendix 7

## Meyer Tool, Inc. –
## Prioritizing the Advancement of Basic Science and Research

January 31, 2012

Sandra Biedron
Colorado State University

Sandra:

Thanks for contacting me to provide input for your report to for the Department of Energy that in turn will go to Congress. Prioritizing the advancement of basic science and research, and maintaining the facilities to support this endeavor, is critical for America to stay at the forefront of innovation and early commercialization that will support our nation's long-term growth and prosperity. History has proven that future technological advancement in all the areas addressed in the study, while unknown in detail what is to come, definitely exists. America needs to identify avenues to speed the process while minimizing cost. This will promote opportunities for America to be "first to market" with the outcomes.

Being from industry, our suggestions and concerns stem from the marketability view and how to increase build-speed and minimize cost.

1. Enhance technology transfer initiatives. Look for ways to utilize lab/industry partnerships as early on in the process as possible to ultimately lower costs and increase speed of completion, therefore speed to market.
   a. Partner with industry from inception to garner input in every phase. We applaud the effort being made to include industry in developing a strategy.
   b. Allow best value industry to participate in Engineering Studies during the design phase. Partner with Industry fabrication specialists who can help scientists/physicists who know what they want/need the project to do, with people who have built similar or earlier generation designs. Fabrication specialists/shops can provide input on design build-ability. This can happen throughout the design process. For example, while determining the cost/benefit of various strategies, industry can be enlisted to provide practical industry knowledge of build costs. When a strategy is chosen, we can help streamline effective design before drawings are set in stone or to go out for competitive quote, enhancing the probability that the finished project will perform to expectations while lowering total cost and increasing speed to completion. When detailing designs that have never been built before, there are bound to be fabrication questions. Costly risks such as "extras" in the form of redesign or fabrication rework during the build phase are minimized through early industrial collaboration.
   c. When going out to competitive bid, request best value proposals, not lowest cost. Be sure that bids are awarded to industrial partners with the capability to execute in a timely fashion for lowest **total** cost, vs. initial low cost. Best value companies may offer best value strategies in their proposal. Best value suppliers are capable partners who mitigate cost

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through the life of the project. Initial low cost providers may lack the ability or capacity to perform obligations in a cost effective, timely manner. They may be unable to offer appropriate fabrication suggestions to the inevitable questions that arise during the life of the projects. All of the above can hinder a project timeline, adding dramatic cost including rework and increased cost of money. Develop criteria to evaluate suppliers so only those capable are considered for award and low-cost, yet technically weak suppliers are weeded out.

3. Address the skills gap/shortage in science/technology fields. Rebuilding U.S. manufacturing and the continued growth of high-technology industries are dependent on the availability of high-quality personnel, especially in the scientific and technical disciplines. The idea of U.S. laboratories partnering with educational institutions to use our research facilities as a training ground for next generation scientists and engineers, such as that suggested by the Illinois Accelerator Research Center (IARC) at Fermilab, is incredibly important for providing employable candidates with relevant experience and useful, next-generation skills that will be required to compete in the global market of the future. This will be of critical importance to support both a strong national industrial base and continuing research objectives which ultimately support economic growth and job creation. U.S. long-term ability to compete internationally depends on it.

4. Level the playing field for U.S. companies involved in U.S. taxpayer funded science projects. The U.S. allows foreign completion for these projects while European countries do not. In addition, European countries remove the effect of the Value Added Tax (VAT) levies (17-19%) for these bids, meaning that European companies are inadvertently favored in the U.S. bid process, reducing the effectiveness of "Buy American". Introduce policy to support American businesses as competitive partners. Eliminate the competitive advantage that the VAT tax reduction provides to European partners, resulting in a hindrance to American growth. U.S. industry does not have the same support internationally as we provide to our foreign competition when they bid on projects here at home. I've enclosed a summary of the VAT tax issue along with suggested action items for your reference.

5. Protect intellectual property. Do not trade American intellectual property to foreign competing governments for their "in-kind" contributions such as free labor. When the US or their national labs enter into these agreements, the result is trading a short-term advancement for our future. Other governments are willing to financially support these agreements because they are taking the long-term view. Gaining access to innovation and technological skills that they currently do not possess is the key to national competitiveness and future growth and prosperity. As the National Association of Manufacturers (NAM) states in their Technology Policy:

"Innovation is one of our greatest strengths and a major contributor to economic growth and industrial competitiveness. For this reason, it is important for policymakers both to nurture the creation and application of technology and vigorously protect intellectual property, as the creation of technology *is* the creation of intellectual property. Without strong protection, the incentives for future innovation-directed R&D will be inhibited.

The NAM supports a coordinated policy that strengthens the protection of intellectual property rights afforded by both domestic laws and international agreements and includes strong coordination and oversight by the governmental agencies tasked with protecting our nation's intellectual property. U.S. policy should reflect the vital importance of intellectual property rights for U.S. industrial competitiveness and made a priority item on the national agenda."

Please do not allow government labs to engage in agreements that trade our future away.

6. Initiate consistent and long-term funding policies that support a continued and competitive investment in basic science, research and long-term economic growth. Inconsistent year-to-year funding and/or national funding at levels inferior to our international peers, reduces our ability to achieve goals that will foster US ability to be "first to market" with innovation and technological advances.

Thank you for asking Meyer Tool & Mfg., Inc. to contribute. It is an honor and part of our personal mission.

Sincerely,

Eileen Cunningham
President

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**Specialists in cryogenic, vacuum and pressure technology**

## Office of High Energy Physics Accelerator R&D Task Force Report

# Appendix 8

# Niowave, Inc. –
# DOE's Role in Commercialization of Particle Accelerators:
# An Industry Perspective

# DOE's Role in Commercialization of Particle Accelerators: An Industry Perspective

Terry Grimm and Jerry Hollister
Niowave, Inc.
Lansing MI

*February 2012*

The DOE's Office of Science has led the development of particle accelerators for basic research in the physical sciences. The advances made on accelerators at the DOE have opened a large array of high tech applications in defense, biomedical and industrial applications. Efficient transfer of this know-how to US industry has the potential to foster a robust high tech industry that dominates its international competitors [1].

The DOE laboratories' core mission is basic research, and from their founding days in the Manhattan Project have had a self-reliant culture that has tended to exclude industry involvement in research and development. Industry has been dealt with as a vendor and kept at "arm's length" to avoid the perception of a conflict of interest. In addition, the DOE labs have been operated as limited liability corporations that protect their intellectual property from industry and each other. Both of these policies limit tech transfer.

Because of the increasingly competitive international economy, we believe part of DOE's core mission should be the commercialization of their breakthroughs and know-how so that the US continues to prosper and lead the world. Therefore, we recommend that DOE pursue the following:

· **Private industry participate in DOE basic research and take a lead role when capable.**
This would likely increase DOE's budget to carry out the basic research, but lead to overall savings for the US government due to the value added to the US economy. Defense contractors are an example of partnerships between the government and industry where industry leads the R&D.

· **DOE participate in industrial research.**
DOE's contribution will add value to the US economy, and would compel industrial investment and effectively leverage the government's investment in basic research.

· **Intellectual property at the DOE laboratories should be freely distributed amongst other DOE laboratories and to US industry.**
This would reduce costs in the IP department of each DOE lab, and greatly enhance tech transfer and commercialization.

Finally, we believe the formation of DOE funded commercialization facilities at the DOE laboratories is unnecessary. Such commercialization facilities would be expensive to set up and operate, exacerbate the current "arm's length" culture, and add a layer of bureaucracy. Rather, we believe implementing our recommendations above will more efficiently develop strong public-private ventures that will lead the world in this important industry.

[1] Accelerators for America's Future, US DOE, June 2010, http://www.acceleratorsamerica.org/

**Office of High Energy Physics Accelerator R&D Task Force Report**

# Appendix 9

## Lawrence Berkeley National Laboratory –
## Ion Beam Technology

Ernest Orlando Lawrence Berkeley National Laboratory

1) **Ion Sources and Injectors for Next Generation Accelerators**

Ion sources and injectors are critical components for the success of next generation accelerators for discovery science. Examples are the proposed Project X facility which will brake open the intensity frontier and a broad range of applications from spallation neutron source scaling (e. g. SNS upgrades), future transmutation of nuclear waste, accelerator driven reactors and fusion plasma heating (e. g. at ITER). Strategic investments into ion source and injector R&D can promises to deliver enabling technology with >10-fold improved performance in critical categories. Key ion source and injector requirements are:

- high brightness, i. e. high beam currents (pulsed and/or cw) and small emittance (<0.2 mm mrad) for negative hydrogen, protons and heavy ions
- high current for high power beams, e. g. multi-MW beams for fusion plasma heating by neutral beam injection, proton drivers for transmutation of nuclear waste, fusion fission hybrids, formation of secondary beams (muon, kaon, neutrino, …)
- ion source lifetime (i. e. the source operation time between service) and robustness
- efficient and reliable Low Energy Beam Transport (LEBT), including implementation of ion beam time structures on a ~10 ns time scale

Ion source development has an over 70 year old history. But recent advances in nanotechnology and advanced computing have not been folded into ion source design and operation concepts. With a commitment to focused R&D efforts, drastic enhancements in ion source performance could be achieved that could enable exciting science at the intensity frontier and advanced nuclear and fusion energy concepts and many spin-offs into industrial applications can be anticipated.

References:
- http://projectx.fnal.gov/
- http://www-ibt.lbl.gov/index.html (Ion Beam Technology group at LBNL)

**2) Advanced accelerator technology for neutron and gamma generators**

Neutron and gamma generators use nuclear reactions to generate useful yields of n- and γ-radiation. They are widely used for a broad range of applications of strategic importance in national security (e. g., active interrogation techniques for detection of nuclear material, nuclear non-proliferation and safeguards), industry (e. g. well logging and materials metrology) and in emerging medical applications (e. g., Boron Neutron Capture Therapy). In particular, the replacement of radiological sources (urgent to minimize the risk of their malevolent use in dirty bombs) and global needs for nuclear safeguards and non-proliferation verification in an environment of expanding nuclear industries require transformational increases in operational capabilities by orders of magnitude in critical metrics including
- system compactness
- output yields (e. g., $>10^{11}$ n or gamma/s)

• operational flexibility (e. g., cw and nano-second pulsed operation)
• and lifetime (e. g., >20,000 h to replace Americium-Beryllium and Californium sources)

A sustained and focused R&D effort is urgently needed to develop the scientific and technological underpinnings of advanced neutron and gamma generators with game changing capabilities that enable their wide spread field use in highly strategic areas of national security, industry and materials science.

References:
-O. Waldmann and B. A. Ludewigt, “A permanent-magnet microwave ion source for a compact high-yield neutron generator”, AIP Conference Proceedings, 1336, 479 (2011)
-A. Persaud, et al., “Development of a compact neutron source based on field ionization processes”, J. Vac. Sci. Tech. B 29, 02B107 (2011)
- Q. Brian, et al., “Nuclear resonance Fluorescence for materials assays”, IEEE Trans. Nucl. Sci. 58, 400 (2011)
-“Radiation Source Use and Replacement”, National Research Council, 2008, ISBN: 0-309-11015-7, http://www.nap.edu/catalog/11976.html

**3) Ultimate Ion Nano-beams**

Ion nano-beams, with energies ranging from sub-keV to MeV, can enable exciting new science and technology developments in broad areas including disruptive concepts for computer and sensor technology, surface and materials structuring and analysis, and quantitative bio-nanotechnology e. g. through in vivo cell engineering.

Currently, ion nano-beams are available only for gallium and helium ions and there exists no solution for the reliable formation of ion beams with single digit nanometer dimensions and flexible energy. But if we were able to form beams of e. g. nitrogen or phosphorus ions focused to a spot size of 1 nm and a tunable energy (~0.1 to 5 keV), then we could create arrays of precisely placed dopant atoms and color centers in silicon and diamond and implement disruptive sensing and information processing techniques, including quantum computing ideas. These disruptive capabilities can be developed with a focused effort in applied accelerator R&D, requiring breakthroughs in ion formation, cooling, transport and detection.

References:
-T. Schenkel, et al., "A spin quantum bit architecture with coupled donors and quantum dots in silicon", http://arxiv.org/abs/1110.2228
-J. J. L. Morton, et al., Embracing the quantum limit in silicon computing, Nature 479, 345 (2011)
-A. M. Tyryshkin, et al., Electron spin coherence exceeding seconds in high-purity silicon, Nat. Mat. 11, 143 (2012)
-G. Fuchs, et al., Excited-state spin coherence of a single nitrogen-vacancy centre in diamond, Nat. Phys. 6, 668 (2010)

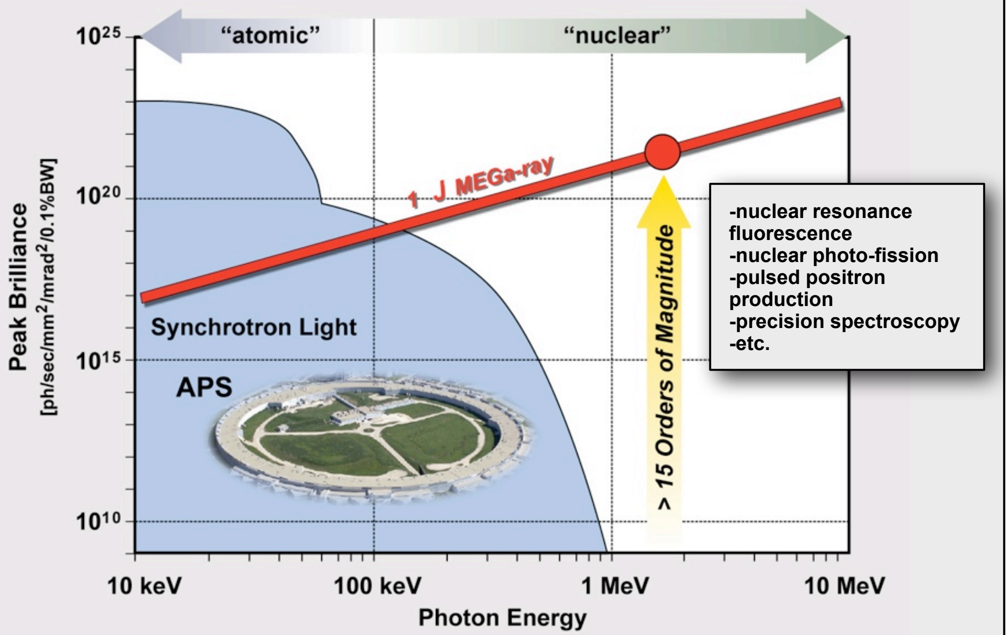
## Office of High Energy Physics Accelerator R&D Task Force Report

## Appendix 10

## Lawrence Livermore National Laboratory – MEGa-ray Technology

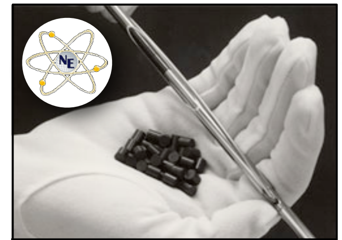
# LLNL's Mono-energetic Gamma-ray (MEGa-ray) Technology is Transformational

## MEGa-rays are a Revolutionary Leap in Light Source Capability




## New Solutions to National Missions are Enabled by MEGa-rays

**HEU Grand Challenge**
*detection of shielded material*

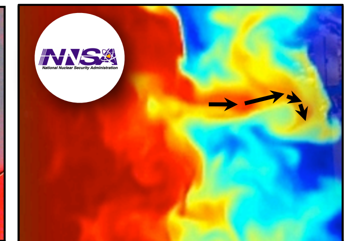


**Nuclear Fuel Assay**
*100 parts/million accuracy*

**Waste Imaging/Assay**
*hands-free content certification*

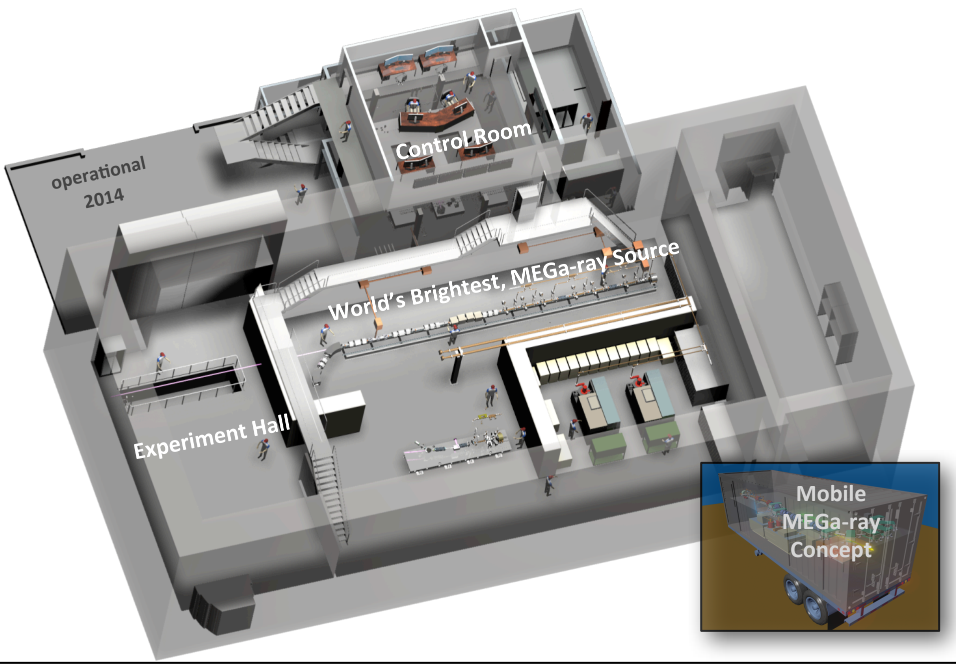
**Stockpile Surveillance**
*micron-scale & isotope specific*

**Medical Imaging**
*low density & isotope specific*



**Dense Plasma Science**
*isotope distribution & velocity*

## LLNL's Nuclear Photonics Facility




## LLNL's MEGa-ray technologies and facilities will provide:

- A world-leading, tunable, mono-energetic, ultrahigh brightness & flux gamma-ray user capability
- A unique, isotope-specific ability to rapidly detect, assay and image the contents of thick objects (LLNL patent)
- A testbed for development of fundamentally new solutions to a wide array of nuclear and materials issues that span multiple agencies and organizations
- A platform for the development of compact, mobile and field deployable MEGa-ray sources
- A catalyst for a renaissance in nuclear science and studies of fundamental nuclear physics with photon beams, i.e. Nuclear Photonics

**Office of High Energy Physics Accelerator R&D Task Force Report**

# Appendix 11

# Los Alamos National Laboratory – National Security and Defense

**Editor's note: This document is from Los Alamos National Laboratory**

## National Security and Defense

### Section 1: National Security Applications

National Security driven research in accelerator technology has tended to focus mainly on very high-peak or average-power systems or light-weight, very compact systems. This research has led to the development of new, innovative technologies, such as advanced control software (EPICS), megawatt RF tubes, and photoinjectors and has significantly advanced the state of the art in existing technologies, such as intense-beam physics codes and their experimental validation, superconducting technology, megawatt-class RF and accelerator components, RFQ's, and induction accelerators. Spin-offs of these efforts have made and will continue to make significant contributions to other Office of Science departments. The rest of this section gives a subset of the wide-range of National Security accelerator related mission space and then covers a few of the successful defense national laboratory/industrial partnerships.

*Nuclear Stockpile Stewardship*

Future certification of the US nuclear weapons stockpile will require a predictive understanding of dynamic materials response through simulations of full-scale weapons systems. These simulations will rely on accurate constitutive models of material dynamics at the component level including understanding the effects of kinetics in delaying dynamic phase transitions, developing models for explosives safety, understanding materials casting processes, and the dynamic behavior of nuclear materials. Development, testing, and validation of these constitutive models is needed as weapons systems materials age and are modified to meet future stockpile needs, or new processes are discovered to be important in nuclear weapons performance. The validation of new models for nuclear weapons performance, as well as for new high performance materials, will require state-of-the-art imaging of reduced scale up to full-scale systems. To do so requires relying on techniques such as multi-time electron or proton radiography, or coherent-imaging techniques using high-energy photon beams (XFELs) generated by accelerator drivers.

*Active Interrogation Systems*

Active interrogation (AI) systems are needed to detect the illicit transportation of nuclear and radiological materials. Production of the interrogation particles, either protons, neutrons, gammas, or muons, require innovative developments in accelerator technology. The highest priority AI systems are either compact, short range or long stand-off. The compact short-range systems must be very compact and transportable. The long stand-off systems will rely on very high-energy, 100's of MeV to GeV, particles. High energy proton and muons can be transported kilometers with an acceptable loss. Muons are uniquely suited to probe phenomena of interest to national security that are not well addressed by electrons, photons, or protons. In many cases, muons provide unique and unambiguous material signatures. The use of muons for homeland security applications creates a new window of need and opportunity to exploit accelerated muons in a wide range of homeland security applications – as well as the more obvious basic science and industrial applications.

*Directed Energy Applications*

The need for speed-of- light weapons came to prominence during the Strategic Defense Initiative. Although the need for ballistic missile defense has a lessened priority, the need for cruise missile defense has gained prominence given the likely spread of this weaponry to aggressor nations. The Navy has identified a CW, MW-class, IR FEL as a future weapons system for ship defense. It provides naval platforms with a highly effective and affordable point defense capability against surface and air threats, future anti-ship cruise missiles or swarms of small boats. The advantages of an FEL are that it provides an unlimited magazine with speed-of-light delivery. The Navy states that the FEL is a revolutionary weapon that will transform how the Navy fights future battles. The Office of Naval Research is currently funding an Innovative Naval Prototype (INP) program for FEL technology which will demonstrate scalability of the necessary FEL physics and engineering for an eventual MW-class device.

*High Power RF Applications*

Electronic equipment is susceptible to attack through electro-magnetic pulse (EMP) and high-power microwave (HPM). EMP and HPM are closely related, with EMP being the ultra-wideband limit of HPM. Damage to electronics and electrical components from an EMP induced by a nuclear explosion was observed even at the first nuclear test in 1945. HPM source requirements are similar to high-power microwave tube requirements for driving accelerators and are used for defense applications such as vehicle stopping at checkpoints to thwart suicide bombers, induced IED pre-detonation for road clearing, and command and communication disablement through HPM payloads on missiles or unmanned aircraft. Additionally, there is an anti-personnel application (discrimination) using millimeter waves in the 90-100 GHz regime, as alternative non-lethal option.. The development of high-power microwave tubes needed for such applications requires the ability to produce and control intense electron beams at comparatively low energy, and this effort has driven the development of intense beam modeling tools, along with high power components of use throughout the accelerator field.

*Spallation Neutron Sources*

Spallation neutron sources are used to measure nuclear cross sections, to develop single event upset (SEU) resistant electronics, and provide neutrons for weapons program isotope production. Precise cross-sections for fission in nuclear materials, as well as cross-sections for capture on actinides are key to understanding nuclear weapons performance. Accelerator-based capabilities exist to measure these at both low and high neutron energies. The “overlap” neutron energy range from 1 keV to 2 MeV is important for weapons radiochemical measurements, but is a very difficult region to probe experimentally.

*X-Ray Bremsstrahlung Sources*

NNSA has determined that Bremsstrahlung sources are part of its roadmap for SNM movement detection program, and similar programs are part of DTRA’s portfolio. For NNSA, the Nuclear Emergency Response Team (NEST) responds to nuclear emergencies. One of its teams, the Accident Response Group (ARG), is responsible for damaged US weapons, and other, the Joint Technical Operations Team (JTOT), would respond to a terrorist weapon. Both teams need portable radiography capabilities. Other applications include field certifying integrated circuits (such as for DAPRA’s TRUST program) and deployed radiography of suspected SNM contraband.

*Nuclear Assay for Counter Proliferation*

Spent nuclear fuel from commercial and research reactors has plutonium and enriched uranium that must be safeguarded to avoid diversion for military or other applications. Techniques are being developed to quantify the amount and type of fissile material in spent fuel rods removed from reactors. One technique uses an electron or proton accelerator to produce neutrons within a lead slowing down spectrometer (LSDS). A spent fuel rod placed in this environment will emit time-dependent fast neutron spectrum from nuclear fission that can be detected to measure the amount of fissile isotopes in the rod.

*Nuclear Weapons Neutron Effects Testing*

The DOE has need to test the susceptibility of electronic device performance to short bursts of high-dose neutrons. Historically these tests were conducted at the Sandia Pulse Reactor, but this reactor was shut down several years ago. This type of testing could be performed at an accelerator-driven neutron source, where a neutron spallation target is neutronically coupled to a subcritical assembly. A short burst of protons delivered by an accelerator or storage ring can produce an intense, short burst of neutrons for component testing. This application is best served by a large proton accelerator facility located at a national laboratory.

*Government/Industrial Partnerships*

National Security research has also led to successful government/industrial partnerships and with a resulting transfer of technology from the government to the private sector. The following are significant examples of technology transfer.

*Dynapower and General Electric*

For the Spallation Neutron Source (SNS) accelerator, Los Alamos developed a compact modulator technology that directly pulsed the cathode of the vacuum tube amplifiers. This technology is able to deliver long pulses (approximately 1 msec) at peak and average power levels of 10 MW and 1 MW respectively. Subsequent to the SNS development, has this technology was transferred to Dynapower Corporation, the world's leading independent manufacturer of custom power conversion equipment, and is actively supporting Dynapower corporation in the development of four modulator systems for the Proton Engineering Frontier Project for a 100 MeV, 1.6 ma proton accelerator supported by the Korea Atomic Energy Research Institute.

One of the innovations behind the development of the compact modulator technology for SNS was the development of high power, nanocrystalline transformer cores. Based on the SNS development, Los Alamos has teamed with GE to apply this core technology for the development of compact transformer systems in support of DARPA initiatives. The size and weight advantages of this design are driving interest from the Navy for the proposed All Electric Ship.

*Carnegie Mellon, Spang Industries, University of Pittsburgh*

Los Alamos has teamed with Carnegie Mellon, Spang Industries, and the University of Pittsburgh to develop advanced solar power conditioning equipment. This project is funded by the ARPA-E and draws on previous government laboratory expertise to develop high efficiency polyphase resonant inverters using advanced magnetics. The polyphase resonant topology was originally developed for SNS converter modulator. The ARPA-E designs will push performance parameters to achieve the program goal of a 100 kW inverter weighing 25 kG. To achieve this Carnegie Mellon and Spang will develop a more advanced cobalt based nanocrystalline alloy that will be used for the power magnetics. From the magnetic material developed by Carnegie Mellon and Spang, Los Alamos will develop the appropriate power circuitry and transformer designs. The University of Pittsburgh will develop the economic models to implement the solar equipment in the U.S. market place.

*Communications and Power Industries (CPI)*

DOE has been supporting the development of high power IOT technology since the late 1980's. This technology combines the attributes of both klystrons and gridded tubes and promises large size and weight savings relative to conventional klystron technology. IOT technology has widespread commercial application in the TV broadcast arena where these power amplifiers provide approximately 12 kW of average power and up to 50 kW of peak power. As a result of this development, a 250 kW average power IOT was successfully delivered and operated on an accelerator. Also, LANL funded the development of a 750 kW peak power IOT at CPI in support of space based applications and the development of a 1 MW average power IOT. While these applications were all driven by accelerators, they represent the only R&D investments geared towards extending the power of IOT technology. As a result of these investments, IOTs have advanced to where they deliver up to 160kW of average power and are in service for high consequence military applications. They are also considered one of the enabling technologies for the Navy FEL program.

*The Boeing Co. and Advanced Energy Systems*

The Boeing Co. is the lead to develop the Free Electron Laser Innovative Naval Prototype (FEL INP) for the Office of Naval Research. Boeing has been successful at tapping the expertise that currently exists at the DOE laboratories to design this high-power FEL prototype. This expertise includes high-average-power accelerators, both normal conducting and superconducting, energy recovery linac as well as a myriad of supporting technologies such as high-power RF, controls, etc. Boeing's success at teaming with the national laboratories such as LANL, Jefferson Lab and Argonne on the FEL INP bodes well for the transfer of accelerator technologies from the DOE labs to industry.

Advanced Energy System (AES) and LANL collaborated on a challenging task of designing, fabricating and assembling the high-average-current normal-conducting radio-frequency (NCRF) gun. This project involved successful technology transfer from LANL to AES on both the design and manufacturing of this NCRF gun. The sophisticated cooling channels were designed by AES in full coordination and real time with the physics design effort at LANL. This well-coordinated design effort is the reason why the NCRF gun works exceedingly well at the end of the fabrication and assembly phase.

## Section 2: Technology Gaps

*High Brightness Beams*

A broad range of new materials are needed for military applications that can be enabled by the combined high resolution probes from particle and photon beams.  Examples of such materials include high explosives and high strength armor where typically an understanding and control of micron-scale features is critical to the material performance. Energetic proton and electron beams that can penetrate thick samples are used for high resolution radiography, augmented by FEL-produced coherent photons, to yield ultra high-resolution, images of the internal characteristics of the materials under dynamic conditions. Such a beam facility would lead to the development of materials tailored at the microscopic scale for specific applications. The broad-based need for such material development has driven a need for high brightness particle beams and very short wavelength x-ray Free Electron Lasers.

The development of new accelerator and beam technologies are key to cost-effectively enhancing existing systems and significantly improving present performance by delivering high-energy, high-charge, low-emittance proton and electron beams. In addition to more conventional accelerator technologies, an alternative technology relies on laser-driven acceleration as a source of primary beams for radiography and to create secondary probe beams to study physical processes such as warm dense matter (WDM) and measurements of equation of state (EOS), both of interest to the nuclear weapons, plasma physics, and fusion communities.

*High Average Power Beams*

The production of high average-power beams using electrons, the FEL, or protons, Neutral Particle Beam or Accelerator Production of Tritium, has been driven by national security missions. High average power ion beams are also needed for weapons-related isotope production. Research leading to the demonstration of a high-average-current superconducting RF electron gun will have significant impact on the design of the next-generation high-power FEL. The injector technology gap includes delivering a robust long lifetime photocathode with reasonable (> 1%) quantum efficiency capable of delivering amperes of current. Electron beams having peak currents in the several thousand ampere range are needed as drivers for full-scale radiography of weapons components. The generation and propagation of such beams requires the development of components that can handle megawatts of power and transport the resultant beams with very low loss.

The energy recovery linac and beam transport designs require higher fidelity numerical simulations, particularly for beam halo production and coherent synchrotron radiation (CSR) effects. There are additional technology gaps for diagnostics, particularly for non-intercepting diagnostics for high-current beams and for halo measurements. In the highest intensity particle beams generated to date, the evolution and confinement of a diffuse particle halo actually determines the beam intensity limit due to losses which in turn can lead to radiation and activation of the beam hardware. High average power beams are particularly vulnerable in that even a halo that may be many orders of magnitude smaller than the beam core is sufficient to limit beam operation. The understanding of the mechanisms that generate halo is lacking at the level of dynamic range required to control the phenomenon.

*New Accelerator Systems for Active Interrogation*

The active interrogation (AI) mission requires the development of two types of systems: compact, mobile proton and other ion accelerators, and high energy proton or muon beams. The compact systems are typically lower energy, less than 50 MeV and at modest currents, less than 10 mA, but need to be light enough to be carried by a few people and small enough to be transported by pick-up truck. The high energy systems are typically greater than 500 MeV. To enable the use of muon interrogation requires significant advances in the efficient capturing, cooling and then acceleration of muons, and advances in high-gradient, efficient accelerator technology.

Laser-plasma accelerators offer the potential for a significant reduction in size for high-energy beam production. The simulated electric fields for these accelerators are PetaV/m for protons and ~ GeV/m for heavier ions. Success in high-energy laser proton acceleration rests on a new paradigm, and volumetric interaction with relativistically transparent, over-dense targets. Significant progress has been achieved in accelerating both protons and heavy ions based on these novel processes.

*High-Power RF Sources*

New high-power, efficient and compact microwave sources are required to cover the range from 0.1 GHz to the Terrahertz regime.

*Bremsstrahlung Sources*

Currently, commercial systems exists at both low X-ray energies for imaging electronics systems and higher X-ray energies for radiography of denser nuclear material, but these systems are too heavy to be man-portable (for example, the 6-MeV Varian Linatron M6 which produces 800R/min weighs about a ton). The state-of-the-art in lightweight commercial systems at these X-ray energies is the JME PXB6 betatron, capable of producing doses > 3R/min at 1 m, but still weighs over 300 lbs. Technology gaps needed for NNSA and DTRA programs include lighter weight systems that are tunable, and may include an integrated RF and linac as well as advances in lightweight pulse power.

*Modeling and Simulations*

Modeling and simulation capabilities have played a significant role in enabling accelerator advances for defense applications. These capabilities have been applied to understanding fundamental beam physics, as design tools including evaluating the expected performance, and for evaluating performance of operating systems. Advances in computational speed, reductions in cost of computer memory, and on-going developments in software and computer architectures have all contributed to ever-increasing more realistic accelerator simulation capabilities. Recent developments in multi-processor computing including the move towards exascale computing and the development of inexpensive, yet very-high-performance desk-top systems such as those based on GPU technology should be exploited. Development of these systems will allow routine multi-particle beam simulations with realistic numbers of particles per bunch, allowing exploration of beam physics dominated effects at a level not yet explored. The understanding and mitigation of beam loss and beam-halo effects in high-average-power ion accelerators, where details at the one part in $10^8$-level or better is required, would immediately benefit.

Advances in fast, inexpensive computing also enable needed improvements in near-real-time accelerator modeling and control optimization that will improve operation of existing systems as well as enable the successful deployment of evermore complex accelerator-based interrogation and weapons systems. The use of real-time accelerator control system and diagnostics information to drive high-performance modeling and simulation capabilities coupled with fast, intelligent controls optimization algorithms has not yet been exploited.

*Reliability, Availability, and Maintainability, and Inspectability (RAMI)*

Large complex accelerator systems and compact systems that need to be deployed in the field can benefit from system engineering approaches such as Reliability, Availability, Maintainability and Inspectability (RAMI) analysis to ensure dependable and reproducible performance. Through a well-integrated design approach, RAMI modeling capability along with world-wide accelerator system RAMI data can be exploited to improve end-product performance and reliability. Such tools were previously developed for the NNSA-funded Accelerator Production of Tritium (APT) project in collaboration with industry (Grumman/Advanced Energy Systems) and were used to validate the design. There has been a resurgence of interest in using this approach for the design of the European Spallation Neutron Source (ESS) and potentially to improve the design of accelerator-driven systems for energy production that must maintain very low numbers of beam interruptions to minimize target/reactor stresses and reliable electrical power to customers. Investments could be used to develop a standardized, modern RAMI modeling approach that would potentially benefit most new projects.

*Spallation Sources*

The application of innovative accelerator and beam transport technology has the potential to enable continuous coverage of the neutron energy range from a single source from 10’s of eV to several MeV with significantly increased neutron intensity and improved energy resolution. Realization of such a source also has relevance to other national security mission areas including nonproliferation, criticality safety, energy security, and for basic nuclear physics and astrophysics.

*Beam Diagnostics*

As the current state of beam brightness and power has been increased to unprecedented levels, diagnostics which are capable of measuring the beam phase space have become increasingly challenging. At present there are no techniques that can precisely determine the beam phase space density for the brightest beams, e.g. for the current generation of X-ray Free Electron Lasers. The further development of this field will be greatly aided by the development of beam diagnostics which can be used to facilitate the complex phase space manipulations that are required.

**Section 3: Research to Address Gaps**

*Very High-Brightness Electron Beams*

The next generation of XFELs will require an order of magnitude higher brightness electron beams than have been achieved to date. Coherent synchrotron emission (CSR) is a significant brightness limiting mechanism for the very high brightness electron beams required for XFELs. Modeling and measurements on existing machines is required to fully quantify the limitations imposed by CSR.

New methods are required to measure the beam phase space volume, or emittance, of the brightest beams, namely those in the current and proposed generation of X-ray Free Electron lasers. Diagnostics must to built that can measure the ultra small emittance values of 0.1 mm-mrad and the temporal length of the ultra short bunch pulses that are anticipated in these devices. Both concept development and experimental demonstration are required.

XFELs and active muon interrogation will benefit from emittance partitioning or exchange schemes, in which excess transverse emittance can be relocated into the longitudinal dimension.

*High Power Systems*

The demonstration of high-power, high-gradient superconducting components is required, such as > 50 MV/m superconducting cells or alternative accelerating structures that operate at > 4 K, MW-class power couplers, high-efficiency MW IOT RF tubes. MW class beams requires research directed toward the generation and the understanding of beam halo generation during the propagation of ampere beams so the beam intensities can be pushed to the required ever-higher levels.

Ion and electron beam systems have benefited significantly in recent years by the application of superconducting cavity technology, which has helped improve both the beam performance of these systems and the operating efficiency. The development of high efficiency, higher-gradient superconducting systems is essential since operating cost and maintenance are significant issues of any high-power system. Advanced photocathode concepts are also required. Alternative superconducting materials, such as magnesium diboride ($MgB_2$), suggest that the critical field limit can be exceeded and that accelerating gradients as high as 100 MV/m may be achievable. Cavity shape optimization and eliminating seams through new fabrication techniques may also help in reaching higher gradients.

Electron systems that deliver high average power today primarily rely on induction linear accelerator technology using pulsed-diode cathodes to generate the high peak-current beam. Innovation in induction cell technology to reach higher fields and longer pulses is needed. Significant improvements are needed for pulsed cathodes capable of reliably producing high current densities at lower diode voltages (high efficiency) are needed to generate high-quality (low emittance), high-current beams for electron radiography.

At the present time, high-power RF sources are limited by beam dynamics and power density issues to given power limits that generally decrease with increasing frequency. Research is needed in the physics of intense, low-energy beams to determine how to extend the present limits and improve efficiency.

Both large-scale numerical models are needed along with large dynamic range experimental verification.

*Exascale Computing*

Particle simulations are now at the level of modeling every particle within a beam, though the calculations are not yet comprehensive; typically the collective effects that often limit the beam intensities are not computed fully self-consistently. Taking such models to the next generation of parallelism and speed, the so called exascale, should enable a much higher quality and fully self-consistent model of a given beam application. The most important physics that is not now being modeled correctly is 3-D space-charge in photoinjectors, wakefields, and CSR. Modeling CSR correctly is the most difficult of these problems, and limitations to 1-D approaches have now been identified. Noise that seeds the microbunch instability (MBI) and the MBI gain itself both require energy-dependent CSR models.

*Applied System Engineering*

Fielded systems in critical applications must have a high expectation for full functionality. New technologies need to be developed that is focused on improving the reliability and ease of maintenance for accelerator systems.

*Fast Kickers*

Through a process dubbed “pulse stacking,” the number of protons per pulse in a storage ring can be enhanced significantly while allowing variable pulse time structure to optimize time-of-flight measurements to improve experimental signal-to-noise ratios. Conceptual studies to realize this capability have been done but there are several technology challenges. Several new techniques and devices need to be developed including rapidly-tuned RF cavities and their control, fast-rise extraction kickers, multi-frequency resonance control, beam stability, and multiplexed beam transport. Results of these advances will be of great interest to the accelerator-technology community.

*RF Sources*

HPM systems require the development of systems with the ability to provide short (10 to 30 nsec) pulses at high repetition rates to increase the likelihood of significant effect, at powers of 100s of MW to 1 GW. Target frequency susceptibility tends to be ~ 10%, so narrowband RF sources need to be frequency swept for longer pulses.

Technology gaps needed for NNSA and DTRA programs include lighter weight systems that are tunable, and may include an integrated RF and linac as well as advances in lightweight pulse power. R&D is required for: air-core transformers, compact diode-directed solid-state Marx technology, higher energy storage capacitors, integrated pulse power and linac technology, development of compact higher frequency (W-band) sources and linacs to further reduce size and weight, electron diode systems that have optimized beam focusing over wide voltage ranges (one-half to several MeV).

*Alternative Particle-Accelerators*

New compact proton superconducting cyclotrons based on advanced design and construction techniques have several applications. One application requires a compact cyclotron that operates up to 20 MeV but weighs less than 500 lbs. Another application requires a transportable GeV cyclotron.

Laser-driven sources have designs for a range of self-consistent laser parameters (energy, intensity, and pulse length) that could provide a specified proton beam. However, the optimal laser for this application does not exist so we can simply test that design point. The codes need to be validated with experiments in relevant broad regions of laser performance parameter space.

The practical implementation of muon interrogation requires further development of the collection and acceleration of muons.

**Goes to the Energy Group:**

The campaign of ignition experiments has begun at the National Ignition Facility (NIF). These experiments are stimulating a resurgence of interest in inertial fusion energy systems, including Heavy Ion Fusion (HIF). Although much progress was made in the past, there has been no recent significant funding to support accelerator technology develop for HIF. There are now new opportunities for experimental collaboration on beam physics and accelerator research focused on developing the needed integrated systems for reliable cost-effective energy production using HIF. Recent advances in accelerator science that can be leveraged and have a potential impact on HIF include: long-term operation of large heavy-ion accelerator facilities with high availability and high reliability; higher fields have been demonstrated in superconducting magnets(the operating range has doubled); developments in control systems and diagnostics for high-intensity accelerators; the ability to simulate complex beam and target systems has improved dramatically – simulation codes have been validated on a range of accelerators and basic science experiments; driver-scale ion sources with adequate beam parameters have been demonstrated for single beams, including high charge state ions. To move closer to the realization of HIF as a potential energy source will require new advances in both induction and RF accelerator technologies, including hybrid systems and acceleration of multiple beams. Major challenges also exist in better understanding limitations due to space charge, emittance growth, beam-gas and beam-plasma interactions that all must be sufficiently controlled throughout the HIF driver accelerator.

US energy policy should also support other alternative methods of producing energy including the development of sub-critical accelerator-driven energy systems (ADS). Long-term energy security and greenhouse gas reduction has motivated a return to nuclear energy. Recent events in Fukushima highlight the danger of nuclear waste in spent fuel rods that are temporarily stored at nuclear reactors around the world. Solving the nuclear waste problem requires burning long-lived transuranic actinides (neptunium, plutonium, americium and curium) that exist in spent fuel. There is significant recent progress in the development and prototyping of technology, as well as integrated demonstration capability in both Europe and Asia. The US is lagging, although much of the early technology was developed through US DOE/NNSA funding.

Most activities world-wide are focused on proton-driven systems, however other alternatives such as high-average-current electron accelerators can also produce the necessary fast-spectrum neutrons for transmuting these long-lived actinides. One of the major advantages of this approach is that it does not require a large facility (such as proton-based ADS) and it can be designed into a compact subcritical assembly that offers neutron multiplication to compensate for the relatively low neutron production rate from the (gamma,n) process. A subcritical ADS has the advantage over critical reactors in that it can operate with fertile-free fuel, thus reducing reprocessing costs and waste streams, and may be a "game-changer" in the utilization of a subcritical burner.

A US ADS test bed or demonstration facility should be pursued. A natural location for such a facility would be a US National laboratory where infrastructure for high-power beam operations, an appropriate-category nuclear facility could be supported, and existing centers of technical excellence in accelerator technology already exist. Advances are needed in several key accelerator technology areas including SC technology (higher gradients and lower operating temps) and improvements in reliability through advanced controls applications, state-of-the art simulations, and beam diagnostics.

**Goes to the Medical Group:**

*Note that this is not only a medical issue but a National Security issue*

Molybdenum-99 Production

Technetium-99m is a metastable nuclear isomer used in ~ 20M diagnostic medical procedures per year (accounting for roughly 85% of all nuclear imaging procedures). Currently, technetium-99m is generated by the decay of molybdenum-99 (Mo-99), which has a half-life of about 66 hours. Mo-99 is typically produced in the core of a nuclear reactor, most of which use highly enriched uranium (HEU), which is a proliferation risk acknowledged by NNSA. This has lead NNSA to fund the development of alternative technologies through the Global Threat Reduction Initiative, which includes research on reactor-based technologies using low-enriched uranium (LEU) and accelerator technologies. Both proton-driven and electron-driven production of Mo-99 have already been demonstrated through this program.

Technology gaps exist that require accelerator development for producing the large quantities of medical 99mTc required in the US. Advances in these areas will benefit not only Mo-99 production, but production of other medical radioisotopes as well. R&D is required for

- Higher average current cavities
- More efficient accelerators
- Reduced cost accelerators
- Advances in high power target design to minimize the required amount of expensive target material.

• Advanced beam diagnostics, both intercepting and non intercepting. A particularly important diagnostic is simultaneous measurement of IR and OTR on the beam window.

• Characterization of the branching ratio between the metastable and ground states for high spin deficit photonuclear reactions for optimizing design (94Mo(γ,n)93Mo vs 93mMo and 206Pb(γ,2n)204Pb vs 204mPb are examples). These branching ratios are extremely difficult to measure and are not well described by theory. These reactions are difficult to measure in these particular reactions because the ground state is either very long lived in the case of 93Mo, or stable in the case of 204Pb.

# Office of High Energy Physics Accelerator R&D Task Force Report

## Appendix 12

## Sandia National Laboratories –
## SPARC Proposal

**Editor's note: This document from Sandia National Laboratories is on their proposal to build SPARC.**

Sandia National Laboratories is proposing to build a Short-Pulse Accelerator Research Center (SPARC). SPARC will include two pulsed-power accelerators in a single campus hosted by Sandia's Albuquerque, New Mexico site. The two accelerators, named SPARC-E and SPARC-Z, have been designed to meet the nation's long-term needs in radiation effects science (RES) and high energy density physics (HEDP), respectively. The pulsed-power architecture for both accelerators will be based on scaled versions of new linear transformer driver (LTD) technology being tested today. The LTD architecture employed by SPARC is a new approach to creating high-current or high-voltage power devices. The most significant advance in pulsed-power energy storage since the invention of the Marx generator in 1924, LTDs are a scalable approach to pulsed power in which simple components are assembled into larger modules. The modules can be combined in different ways to produce electrical currents that are not only higher than present pulsed-power approaches, but also reduce accelerator operations stress nearly 50-fold.

While the specific parameters of the two accelerators differ, their engineering design, manufacturing, testing, and environmental safety and health requirements have significant overlap, thereby reducing the overall project cost and timeline. There is also significant overlap in the scientific and engineering expertise required to build, maintain, operate, and diagnose the two machines.

SPARC-E is a high-voltage short-pulse (130 ns) electron-beam accelerator. It will produce radiation environments needed to certify future stockpile components for hostile environments.

SPARC-Z is a high-current variable-pulse (130-1000 ns) accelerator capable of coupling to a variety of target loads for both RES and HEDP applications. It will be capable of producing megajoules of 1-10 keV x rays. This far exceeds that which is currently available today in the laboratory. Similarly, the facility will be able to achieve controlled energy densities in large volumes many times in excess of what are possible today. Large samples (i.e., with diameters on the order of a centimeter) of critical nuclear materials will be compressed isentropically to pressures and temperatures of interest, reducing the amount of uncertainty that results from extrapolating from what we can presently measure. Finally, higher-risk and less-mature ideas being studied in fusion and radiation science have the potential to further enhance the usefulness of SPARC-Z beyond what we can confidently predict with existing codes.

SPARC-E and SPARC-Z will anchor a world-class campus that will bring together the nation's best scientists and engineers to work on RES and HEDP. The SPARC accelerators will be the world's largest and most powerful pulsed-power accelerators, which will use a next-generation LTD architecture that will help the United States maintain its leadership in pulsed power. Moreover, the unprecedented laboratory pressures and yields will enable these accelerators to not only meet the certification and science-based stockpile-stewardship needs of the country, they will also create opportunities for new science and engineering discoveries. The resulting collaborations between researchers at the weapons laboratories and universities to harvest the fruits of this project will ensure a steady stream of talented scientists eager to work at our national laboratories and knowledgeable independent reviewers of our work. For this reason, we believe SPARC will surely benefit our nation in additional ways that we may not fully envision today, just as "a mighty flame follows a little spark." (Dante Alighieri)

Pulsed power accelerators have a long history of providing the means for certifying and testing the stockpile that goes back over 50 years. The high efficiency of energy transfer from storage capacitors to a target load makes them a relatively inexpensive means for producing high x-ray yields and driving large samples to high pressures.

The high energy density science community has developed many *high-current* pulsed power accelerators over the past 50 years. [We define a high-current accelerator to be one that delivers in excess of 1,000,000 amperes (1 MA) to a physics target load.] The prime-power source of a *conventional* high-current machine consists of one or more Marx generators. A Marx is an array of n capacitors that are charged in parallel to the same voltage V, and discharged in series (using switches) to create a total voltage equal to n*V.

The refurbished Z facility at Sandia is presently the world's largest and most powerful pulsed-power accelerator, and represents the state-of-the-art of conventional Marx-based technology. The accelerator is 33 meters in diameter, stores 20 MJ of electrical energy, and delivers 85 terawatts (TW) of electrical power (5-7 MJ) to its vacuum chamber. Depending on the inductance of the target load, the electrical power results in as much as 27 MA of current flowing through the load. By comparison, the National Ignition Facility, the world's largest laser facility, delivers up to 1.8 MJ of green laser light into its vacuum target chamber out of an initial stored energy in its capacitors of 400 MJ. It is for this reason that pulsed-power technology is preferable for applications requiring large energies or doses.

The refurbished Z includes 36 pulsed power modules. The prime power source of each module is a Marx generator, and the energy from each Marx is passed through four stages of pulse compression before it reaches the target load at the center of the machine. These stages compress the energy in both space and time and increase the energy density (equivalent to pressure) of the electrical power from $2x10^5$ J/m$^3$ ($2x10^{-6}$ Mbar) to ~$10^{13}$ J/m$^3$ (100 Mbar). This large pressure is used to drive experiments to high energy density conditions (>1 Mbar).

A Marx generator is, in essence, an LC circuit, i.e., a circuit that consists of an inductor (with inductance L) connected to a capacitor (with capacitance C). The characteristic discharge time of the current pulse produced by such a circuit is approximately $2(LC)^{1/2}$. The width of the current pulse produced by a Z Marx is 1.5 µs. Experiments conducted on Z require that a linear combination of 130-ns-wide current pulses, one generated by each of Z's 36 modules, be delivered to the load. To produce a 130-ns pulse, each module uses four stages of pulse compression to shorten the pulse produced by its Marx generator.

The pulse-compression hardware includes four pulse-forming transmission lines, a laser-triggered gas switch, and two sets of self-closing water switches. To achieve the highest peak currents, the 36 modules are triggered simultaneously so that their energy is combined into a single, 130-ns-wide current pulse. For shockless dynamic materials experiments, the discharge from each of the 36 modules are staggered in time to produce a specific current pulse shape that increases the drive pressure on the sample without creating a shock in the material. Creating the exact current pulse shape needed for each experiment requires precise timing of each module, achieved through a combination of two independent Marx trigger systems and 36 independently timed laser-triggered gas switches. In this way, current pulses of approximately 1 µs in duration have been produced to support experiments.

However, the pulse-compression stages significantly decrease the efficiency of the refurbished Z accelerator. The stages also increase the effort required to maintain the machine, and make it more difficult to perform an accurate and predictive circuit simulation of an accelerator shot. Furthermore, the design of Z also includes a number of impedance mismatches, which create reflections of the power pulse within the accelerator. Such internal reflections also decrease accelerator efficiency, damage the accelerator (after the primary power pulse has been delivered to the load), and make it more challenging to simulate an accelerator shot. For these reasons, scaling conventional accelerator architecture to current and/or voltage levels beyond that of the refurbished Z is not the optimum path forward.

The SPARC-E and SPARC-Z accelerators will be based on a *next-generation* architecture that improves upon existing conventional pulsed-power accelerators. While a number of architectures have been proposed for the design of future high-current pulsed power machines, we believe the most attractive approach is based on the new LTD architecture. The architecture uses two simple design concepts: single-stage pulse compression and impedance matching.

Like a Marx generator, an LTD is also, in essence, an LC circuit. In conventional pulsed-power accelerators, the pulse width $2(LC)^{1/2}$ of the Marx generators is long (e.g., 1.5 μs in the case of Z), and shorter pulses are obtained through multiple pulse-compression stages. In the proposed SPARC LTD architecture, the pulse width $2(LC)^{1/2}$ is an order of magnitude less, approximately 130 ns, hence no additional pulse compression stages are needed. This approach eliminates the inefficiencies and most of the other difficulties associated with the pulse-compression stages typically employed by conventional pulsed power machines. The shorter LC time constant is obtained by reducing both the inductance (L) and capacitance (C) of each circuit. The power pulse produced by the accelerator's LTDs is transported to the physics-package load by a system of impedance-matched transmission lines, to minimize reflections of the power pulse within the accelerator.

## SPARC-E will be an 84-TW 1.5-MA electron-beam accelerator.

$P$ = 84 TW

$E$ = 14 MJ

$V_{e\text{-beam}}$ = 56 MV

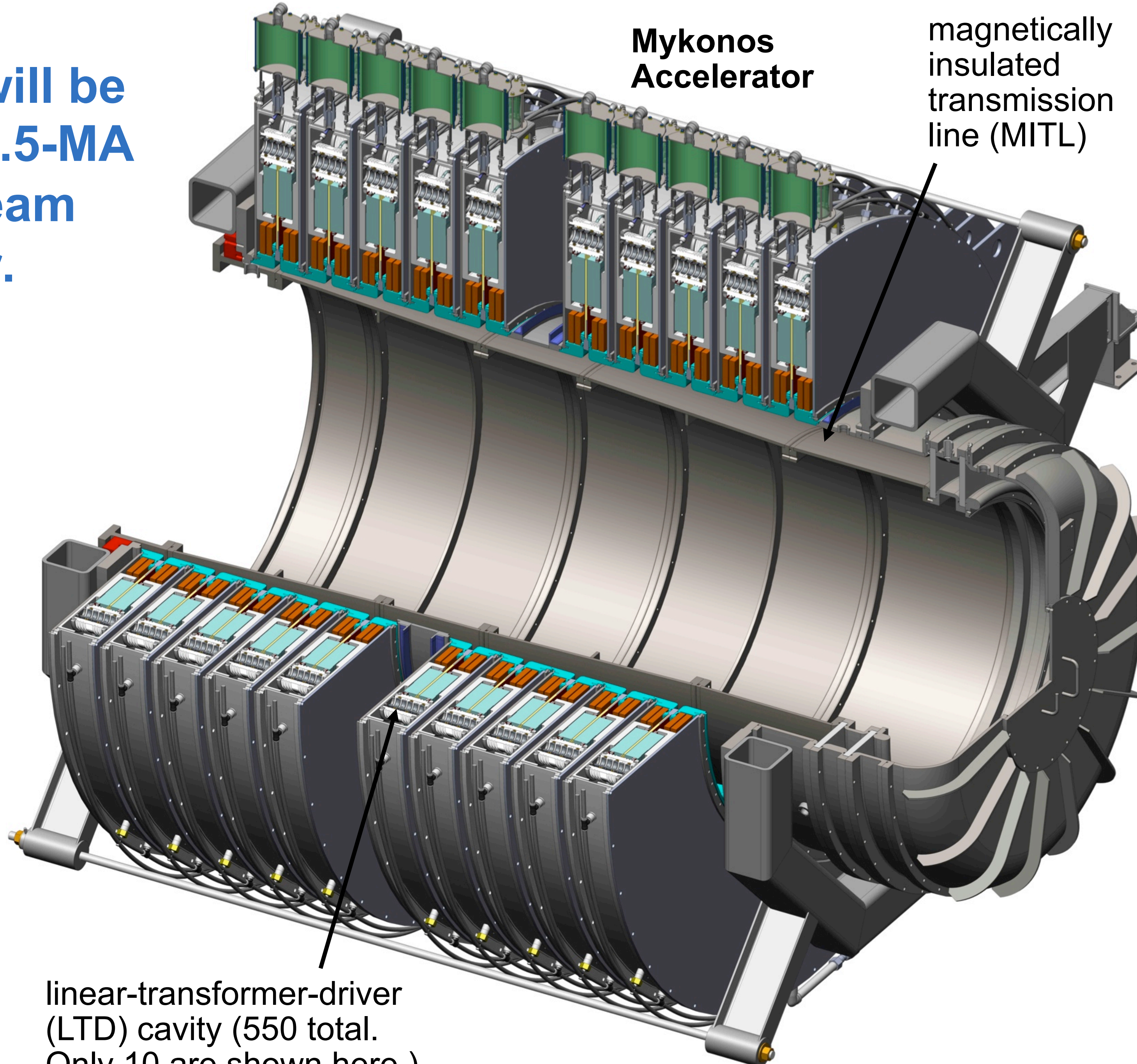
$I_{e\text{-beam}}$ = 1.5 MA

$\tau_{FWHM}$ = 170 ns

width = 3 m

length = 120 m

$\eta_{e\text{-beam}}$ = 75%



# SPARC-Z will be an 800-TW 63-MA pulsed-power accelerator.

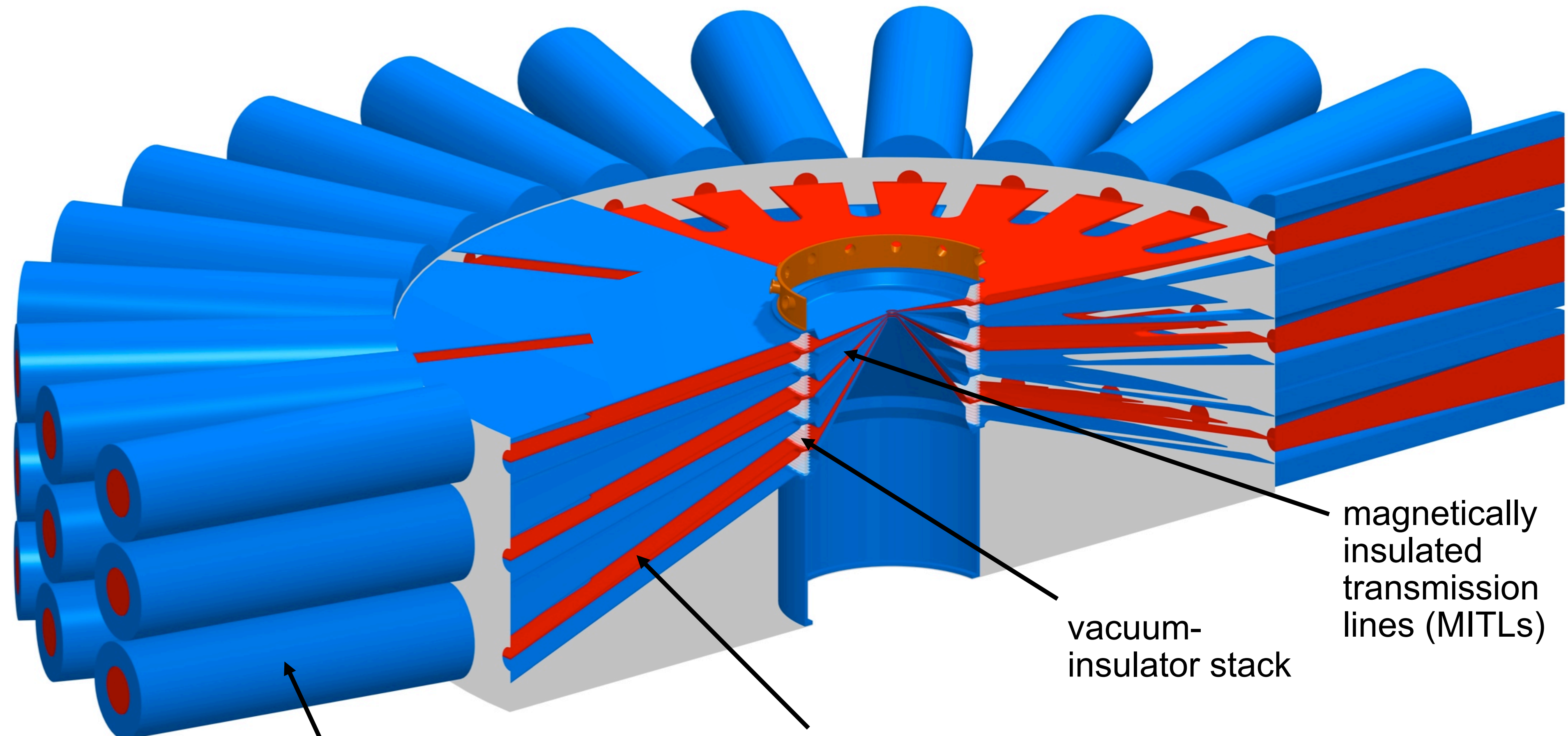
$P = 830$ TW
$E = 130$ MJ

$V_{stack} = 16$ MV
$L_{vacuum} = 20$ nH

$I_{load} = 63$ MA
$\tau_{implosion} = 110$ ns

$E_{radiated} = 20$ MJ
diameter = 50 m

$\eta_{x-ray} = 15\%$



Office of High Energy Physics Accelerator R&D Task Force Report

## Appendix 14

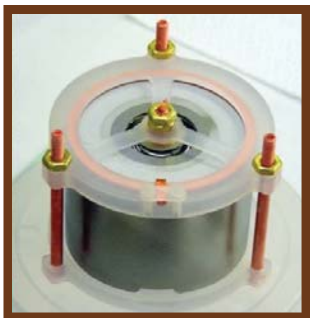
## National Nuclear Security Administration – Radiation Sensors and Sources Roadmap

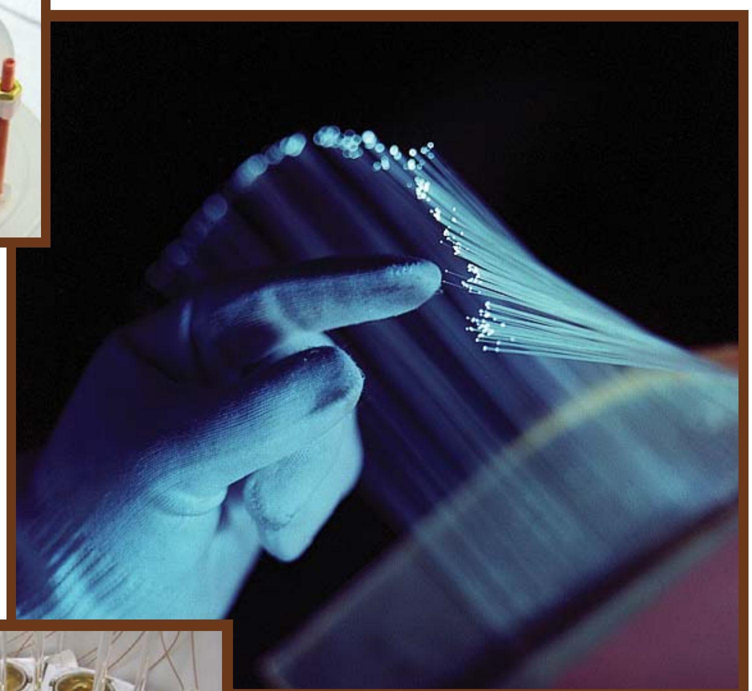
National Nuclear Security Administration

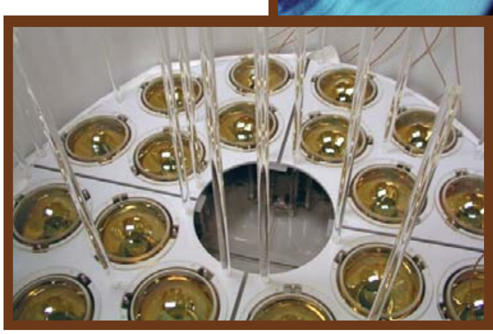
NA22-OPD-01-2010

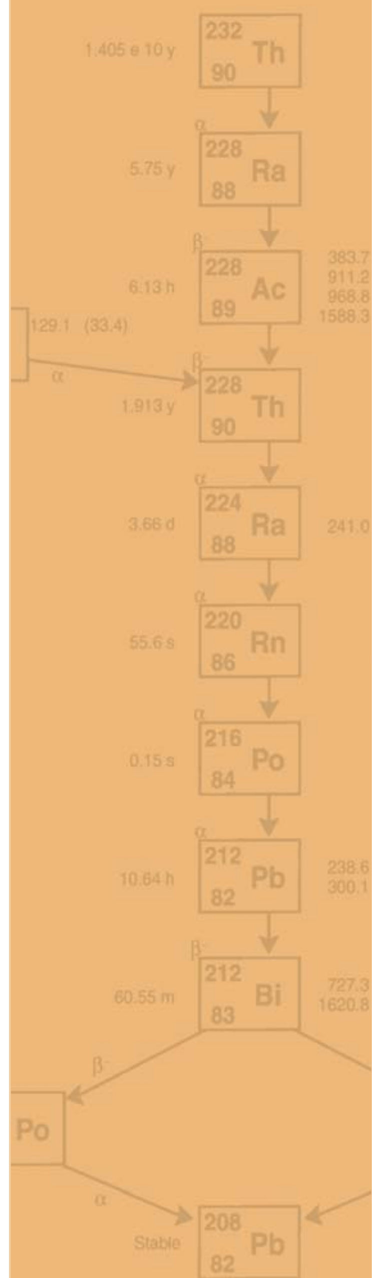
# Special Nuclear Materials Movement Detection Program

## *Radiation Sensors and Sources Roadmap*










**October 2009**

**Office of Nonproliferation and Verification Research and Development (NA-22)**

## On the Cover

Top:
High-purity germanium is a mature technology for high-resolution measurements of special nuclear materials.

Middle:
Lithium-doped scintillating glass optical fibers are a viable medium for large-area, solid-state, thermal neutron sensors.

Bottom:
Water Cerenkov detectors doped with trace quantities of $^{10}B$ and $^{157}Gd$ rely on photo-detection of Cerenkov radiation created by gamma-ray emissions from neutron capture agents held in a water solution.

Comments and inquiries regarding this document should be directed to Dr. Edward Watkins, NNSA/NA-22 at 202-586-6609 or Dr. Robert Runkle, NNSA/NA-22 at 202-586-5118.


## Acknowledgements

### *Working Group Members*

To better focus the research and development efforts of the Special Nuclear Material (SNM) Movement Detection Program within NA-22, an expert working group was assembled to establish a technical roadmap for this program. This working group consisted of technical and programmatic representatives from across the Department of Energy complex. The working group contributed to all phases of this document's development by contributing and editing text, leading workshops, and providing technical and programmatic input to NA-22. The members of the working group are:

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Jim White, Oak Ridge National Laboratory
Quang Jen Wu, Lawrence Livermore National Laboratory

### *Subject Matter Experts*

Critical to the development of this document was the solicitation of input from subject matter experts across a variety of disciplines. This input formed the basis of this document, the *Radiation Sensors and Sources Roadmap*. The group convened in early 2008 for a three-day meeting to gather input, which primarily consisted of the identification of research and development investment options. The group consisted of subject matter experts from across the Department of Energy complex and academia. These subject matter experts, listed by section, are:

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Q1010

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**Office of Nonproliferation and Verification Research and Development (NA-22) Publication Release Form**

*Special Nuclear Materials Movement Detection Program—Radiation Sensors and Sources Roadmap*

My signature indicates that I have reviewed and approved for unlimited release within the nonproliferation community the *Special Nuclear Materials Movement Detection Program—Radiation Sensors and Sources Roadmap*, NA22-OPD-01-2010.

This document prioritizes specific investment options for achieving the requirements outlined in the *Special Nuclear Materials Movement Detection Portfolio—Technology Roadmap*, NA22-PDP-02-2007.

Dr. T. Jan Cerveny
Assistant Deputy Administrator
Office of Nonproliferation and Verification Research and Development

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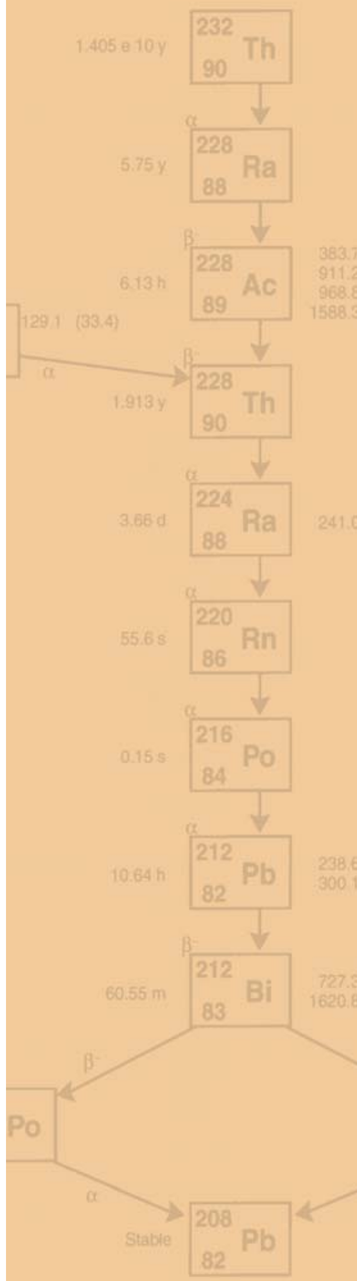
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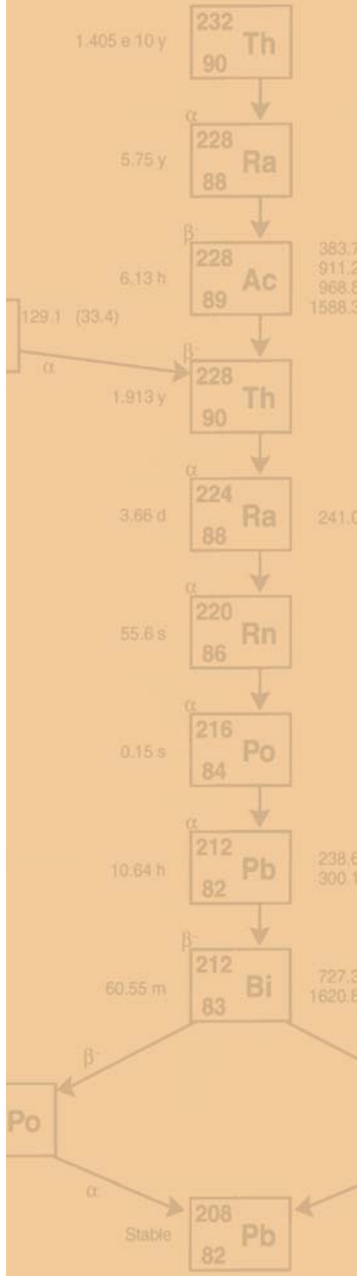



# Executive Summary

The Office of Proliferation Detection (NA-221) within the National Nuclear Security Administration's (NNSA) Office of Nonproliferation and Verification Research and Development (NA-22) has established a multi-year strategy in the form of program plans and roadmaps to conduct the research and development (R&D) necessary to demonstrate next-generation special nuclear materials (SNM) movement detection technologies. This strategy sets an ambitious schedule to plan, execute, and demonstrate mission-relevant components and technologies for SNM detection. As established in the 2006 strategic document, *SNM Movement Detection Portfolio—Goals, Objectives, and Requirements*, the high-level program requirements are:

- Detect shielded highly enriched uranium (HEU)
- Detect SNM at standoff distances
- Detect shielded weapon-grade plutonium

These requirements directly target the development of high-impact technologies for nuclear material detection that are applicable to nuclear nonproliferation applications including material monitoring, interdiction, and verification, as well as counterproliferation and counterterrorism, where synergies exist.

The SNM Movement Detection Program then created a technical roadmap, the *SNM Movement Detection Portfolio—Technology Roadmap* in 2007 that identified and prioritized high-level technology classes for R&D. That document articulated the priorities of the SNM Movement Detection Program to other agencies internal and external to the Department of Energy. This document, the *Radiation Sensors and Sources Roadmap*, further defines and prioritizes investments in specific R&D topics that support NA-22's needs in the areas of radiation sensors and sources. It portends to facilitate communication with the national laboratory, academic, and small-business communities that have been tasked to perform long-term R&D.

The SNM Movement Detection Program assembled an expert technical and programmatic working group consisting of subject matter experts (SMEs) from across the Department of Energy's national laboratory complex. Their task was to define the state-of-the-art and important new directions for research necessary to ensure progress toward the program requirements. Additionally, this working group leveraged input and recommendations from over 50 scientists and engineers from the Department of Energy national laboratories and academia. With this input, the working group and NA-22 staff developed a methodology to organize and analyze the collected data. This methodology prioritizes relevant R&D options within five technical areas:

- Photon detection systems
- Neutron detection systems
- Imaging methods
- Photon sources
- Neutron sources

## *Executive Summary*

The SNM Movement Detection Program developed the following criteria to guide its investments. Options within each technical area were chosen based on their ability to: (a) emphasize revolutionary over evolutionary approaches, (b) give greater importance to lower-maturity R&D areas that are likely to produce greater advances in detection capability with long-term investments, and (c) assign greater importance to R&D areas that provide the most impact across all three program requirements. The program prioritized investment options first according to the priority of the associated technical class from the *SNM Movement Detection Portfolio—Technology Roadmap,* and then by their anticipated impact. The prioritization, listed in **Table ES-1**, is the result of this effort. Only those investment options that received a high priority rating or those with a medium priority but high impact rating are listed. Many other investment options were considered during the roadmap process.

**Table ES-1. Long-term investment option priorities chosen to support the R&D priorities established in the *SNM Movement Detection Portfolio—Technology Roadmap*.**

| Priority | Impact | Topic Area | Investment Option |
|---|---|---|---|
| High | High | Photon detection systems | Alternate radiation detection and readout concepts |
| | | | Spectroscopy algorithms for signal-starved spectra |
| | | Neutron detection systems | Large-area, thermal neutron detection systems |
| | | | Algorithm development for exploitation of time-correlation observables |
| | | | Large-area, fission neutron detection systems |
| | | Photon sources | Next-generation accelerator concepts |
| | | | Low-energy, monoenergetic, tunable sources |
| | | | Development of compact, mobile photon sources |
| | | Neutron sources | Next-generation ion sources |
| | | | Robust, human-portable systems |
| | | | Directional beams of high-energy neutrons |
| | Medium | Photon detection systems | Assess deployment feasibility of proven non-traditional radiation detectors |
| | | | New strategies for charge collection in semiconductors |
| | | | Stable, solid-state readout technology for scintillators |
| | | | Detection limit mapping |
| | | Neutron detection systems | Measurements and phenomenological modeling of SNM fission signatures |
| | | | Measurements and phenomenological modeling of cosmic-ray induced neutron backgrounds |
| | | Photon sources | Development of high-energy, quasi-monoenergetic sources |
| | | | High-repetition-rate LINACs |
| | | Neutron sources | Transportable, high-flux sources |
| | | | Scenario definition for standoff applications |
| | | | Advances in time-tagged neutron sources |
| Medium | High | Photon detection systems | Algorithms for active interrogation signatures exploitation |
| | | Neutron detection systems | Solid-state thermal neutron detection systems |
| | | Imaging methods | Imaging systems not reliant on segmentation/modulation |
| | | | Scatter cameras that track secondary particle production |
| | | | Simultaneous gamma-ray and neutron imaging |
| | | | Single-crystal, high-energy neutron imaging systems |

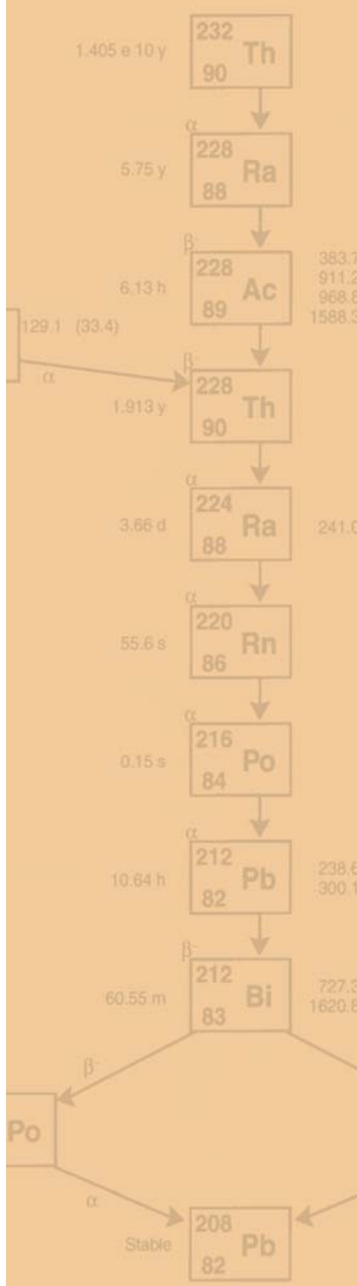
# Introduction

The Office of Proliferation Detection (NA-221) has established a multi-year strategy in the form of program plans and roadmaps to conduct the research and development (R&D) necessary to demonstrate next-generation nuclear nonproliferation technical capabilities and component technologies. These strategies set an ambitious schedule to plan, execute, and evaluate the R&D necessary to demonstrate new capabilities.

This effort represents the culmination of a process that began in 2006 with the collection of capability requirements from users across the nonproliferation community. User input was an integral part of the goals, objectives, and requirements documents developed for the NA-221 mission programs, including Special Nuclear Material (SNM) Movement Detection, U-235 Production Detection, and Pu Production Detection. Following the completion of the *SNM Movement Detection Portfolio—Goals, Objectives, and Requirements* document (NA-22-PDP-03-2006), the SNM Movement Detection Program then created a technical roadmap, *SNM Movement Detection Portfolio—Technology Roadmap* in 2007, which identified and prioritized technology classes in need of R&D. This document—the *Radiation Sensors and Sources Roadmap*—further defines and prioritizes investments in specific R&D topics that support NA-22's needs in the areas of radiation sensors and sources. The goal of this document is to facilitate communication by clearly stating NA-22's specific R&D priorities with the national laboratory, university, and small-business communities.

## Overview

The Office of Proliferation Detection consists of eleven R&D programs that are grouped by mission areas, enabling technologies, and signatures and observables, as illustrated in **Figure 1**. It applies the unique skills and capabilities of the NNSA and Department of Energy national laboratories and facilities to meet the R&D needs to close technology gaps identified through close interaction with other U.S. Government agencies and in support of U.S. Government policy. It also draws upon the talents and strengths of the academic community and industry to complement the national laboratories, where appropriate, and develops the tools, technologies, techniques, and expertise to address the most challenging problems related to detection, localization, and analysis of the global proliferation of weapons of mass destruction, with special emphasis on nuclear weapon technology and SNM diversion. Additionally, NA-221 funds limited research that supports counterproliferation and counterterrorism where there is synergy with the nonproliferation mission.



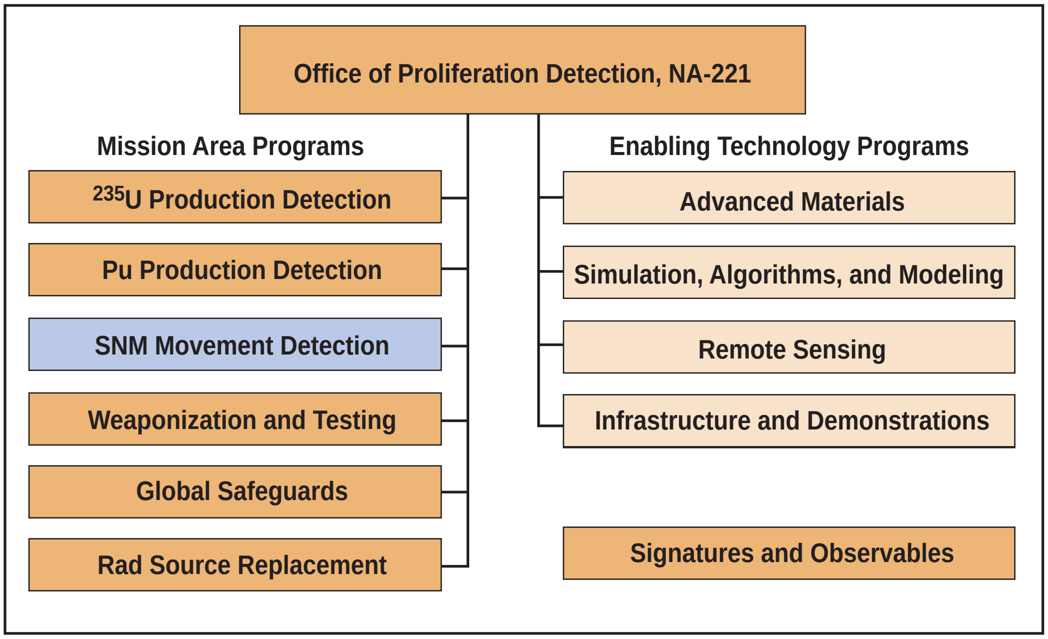



Figure 1. NA-221 Office of Proliferation Detection organization.

NA-221 plays a key role in filling the critical middle ground between fundamental research and near-term systems development by using the unique capabilities of the national laboratories to conduct basic and applied research and technology integration. Through the extensive relationships that national laboratories maintain with universities, basic science from academia and federal research programs are brought together to develop real-world system solutions based on insights into national security problems. NA-221 delivers technical know-how that has been developed and validated to U.S. Government acquisition programs and the U.S. industrial base to support national security missions. Technical advances, new proven methodologies, and improvements to capabilities are transferred to operational programs through technical partnerships, including development of special demonstration apparatus to assist major acquisition efforts.

NA-221 provides long-term emphasis and support for a broad spectrum of technology areas predominantly considered to be at the applied research and advanced applied research levels of development. In the characterization of technical maturity defined by the Department of Defense (DoD) Research, Development, Test, and Evaluation (RDT&E) or Technology Readiness Levels (TRLs), this program focuses upon technologies at the RDT&E Level 6.1 and 6.2 or TRL 1–5. These levels of technical maturity correspond to developing a concept, performing basic research, and performing research to demonstrate the proof of principle. In some rare instances, and only after consultation with a specific end-user, a technology development project may be taken through a formal demonstration stage of development (TRL 6–7). NA-22 may occasionally provide for field-testing a particular technology, but developing a fieldable demonstration prototype is in partnership with a specific end-user.

The purpose of the SNM Movement Detection Program is to conduct early stage R&D that supports the broad missions of NA-22, including SNM monitoring, interdiction, and verification. The SNM Movement Detection Program funds R&D to improve the spatial, energy, and time resolution of both gamma-ray and neutron detection methods applicable to nuclear nonproliferation problems. Typical investments in this program focus on improving electronics and other components necessary to efficiently readout the detectors, developing novel detection techniques, and improving existing techniques. R&D conducted in this program will have broad applicability to the radiation detection community at large, but requirements are derived its requirements from the mission programs of the NA-22 office.

## Scope

The *Radiation Sensors and Sources Roadmap* is the third document in a series that establishes the SNM Movement Detection Program's goals and milestones, which are listed in **Table 1**. In 2006, an expert working group developed the first document, entitled *Special Nuclear Materials Movement Detection Portfolio—Goals, Objectives, and Requirements*, NA-22-PDP-03-2006, which defined the requirements for the SNM Movement Detection Program as:

- Detect shielded highly enriched uranium (HEU)
- Detect SNM at standoff distances
- Detect shielded weapon-grade plutonium

These high-level requirements form the basis for this long-term proliferation detection R&D program within NA-22. The second document, the *SNM Movement Detection Portfolio—Technology Roadmap*, NA22-PDP-02-2007, identified and prioritized technology classes in need of R&D to meet the aforementioned requirements. **Table 2** lists these technology classes and their priority levels. The *SNM Movement Detection Program—Technology Roadmap* articulated priorities of the SNM Movement Detection Program to other agencies internal and external to the Department of Energy.

**Table 1. Program Assessment Rating Tool (PART) requirements for the SNM Movement Detection Program.**

| Year | PART Requirement for SNM Movement Detection |
|---|---|
| 2006 | Complete general goals, objectives, and requirements |
| 2007 | Complete SNM movement detection roadmap |
| 2009 | Complete initial technical feasibility studies for alternative technology approaches |
| 2010 | Complete external expert/user review and ranking |
| 2011 | Complete ranking of alternative approaches and down-selection process |
| 2012 | Complete research phase on selected approaches |
| 2013 | Demonstrate developed technologies and methods |

**Table 2. R&D priorities established in the *SNM Movement Detection Portfolio—Technology Roadmap*.**

| Topic Area | R&D Technology Class | Priority Level |
|---|---|---|
| Photon detection systems | High-resolution gamma-ray detectors | High |
| | Gamma detection—timing, multiplicity, signatures | High |
| | Algorithms for ID in active systems | Medium |
| Neutron detection systems | Neutron detection—timing, multiplicity, signatures | High |
| | Large-area detectors—high-energy | High |
| | Solid-state neutron detectors | Medium |
| | Large-area detectors—thermal | Low |
| Imaging methods | 3-D neutron tracking detector | Medium |
| | Electronically collimated systems | Medium |
| | Mechanically collimated systems | Low |
| | Neutron imaging detectors | Low |
| Photon sources | Broad spectrum | High |
| | Monoenergetic | High |
| Neutron sources | Accelerator based | High |
| | Radioactive source based | Low |

The *Radiation Sensors and Sources Roadmap* identifies and prioritizes specific R&D investment options within the context of past and ongoing work. The roadmap process and its product (this document) seek to define a set of investments to address the gaps identified in the current state of the art, leading the program closer to meeting its long-term R&D goals. This roadmap is thus a technical guide to the Radiation Sensors and Sources Program and can be used to identify topics for yearly proposal solicitations, guide the selection of proposals, and establish priorities for program budgets by:

- Comparing technology development pathways, as identified in this document, with currently supported R&D efforts in order to develop a program investment strategy.
- Identifying shortfalls or technology gaps in pathways that can be used as the basis for future R&D.
- Defining the guiding principles of a program investment plan for meeting program requirements by 2013 and beyond.
- Serving as a communication tool between NA-22 and the national laboratory, academic, and small-business R&D communities.

The dynamic international proliferation environment and the potential for the rapid emergence of new technical challenges and technological developments may subject this document to regular revision, for example in the case of anticipated treaty verification requirements. The intent is to periodically convene a working group to review the continued relevance of this document and, where necessary, make recommendations for modification.

This document is the culmination of significant effort on the part of a number of contributors including a working group augmented by a subject matter expert group that supplied technical input and advice. The formulation followed the general outline set forth in the *SNM Movement Detection Portfolio—Technology Roadmap*. Beginning with the prioritized technology classes defined in Table 2, this document divides technology development space into five broad topic areas—Photon Detection Systems, Neutron Detection Systems, Imaging Methods, Photon Sources, and Neutron Sources.

Data for the development of this roadmap were collected by the working group during an intensive three-day workshop with the SMEs. The layout of this document follows the data collection process that was structured as follows:

- **Technology Requirements.** Each group validated the prioritized technology classes for their technology area and identified any additional needs for R&D that would be required to meet the program goals. The groups discussed how the results from the *SNM Movement Detection Portfolio—Goals, Objectives, and Requirements* applied to their technical area. This discussion set the scope for each group and their subsequent efforts.
- **Survey of Field.** The SMEs described the current state of the art for their technical area including a broad survey of ongoing R&D. This survey sets a starting point for any future investments in R&D in each respective field.
- **Identification of Shortfalls.** The SMEs then identified gaps between the program's requirements (goals) and the current state of the art (starting point). These shortfalls take the form of specific R&D scope necessary to meet the program's requirements.
- **Investment Options.** The SMEs then identified R&D options that, if successful, would fill the identified technology shortfalls. For each potential solution, the group provided the relative impact, current maturity, risk of failure, cost to complete, and time necessary to complete the R&D needed to realize the solution. The impact was characterized as high—will significantly advance the state of the art toward the goal; medium—will provide moderate advances in the state of the art toward the goal; or low—will provide minimal advancement toward the goal.

Following completion of the workshop, NA-22 evaluated the technology requirements, current state of the art, shortfalls, and potential investment options. Based on the prioritized technology classes established in the roadmap and anticipated impact levels for each investment option, NA-22 independently prioritized the list of investment options to form a program plan. This document summarizes that plan.

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# Photon Detection Systems

## Technology Requirements

Application of photon detection systems to SNM movement detection spans many methods from compact, mobile, low-power passive systems to large-scale, fixed-site, active-interrogation systems. This expansive application space imposes a wide and varying range of requirements on the photon detection components of the various overall detection systems. For example, some applications require fast detectors to exploit time coincidence measurements, while others require high precision in the determination of the incident gamma-ray energy; in essentially all applications, the role of photon detection systems is to further four generic goals:

- *Detection*—The simplest form of photon measurement is the use of a detector to count gamma rays. Gross counting can flag the presence of radioactive material, which could be SNM. Gamma-ray spectroscopy can exploit more sophisticated signatures to provide higher detection performance.
- *Location*–Photon detection systems can provide location information via either proximity search, where a non-directional detector is moved through space, or via systems specifically designed to provide directional information. These systems will be addressed separately in the *Imaging Methods* section.
- *Identification*—Gamma-ray spectroscopy provides the capability to identify constituent isotopes in an energy spectrum if sufficient fidelity is provided. This creates the capability to differentiate SNM from other radioactive materials, as well as determining the detailed isotopic composition of the SNM itself. In some applications, it is desirable to distinguish between enrichment levels or between weapon-grade and reactor-grade materials.
- *Characterization*—Photon detection can be used to determine attributes of the radioactive material such as mass and activity. Analysis of the full-energy spectrum of medium- and high-resolution data can be used to estimate the density and atomic number of intervening material between the source and the detector, as well as self shielding from the SNM itself. The nature of the fission process allows for the possibility of exploiting correlations between gamma rays, gamma rays and neutrons, and gamma rays and interrogating particles to further characterize fissionable material, including mass and neutron multiplication.

No one set of requirements can be specified to achieve all these goals within the entire application space, and there is likely no application that imposes all of them, but the following qualitative requirements broadly capture the overall needs.

Absolute collection efficiency is often the dominant figure of merit of a photon detector, and the interrelation between absolute detection efficiency, material size, and cost must be part of any design trade-off. Detectors with high energy resolution tend to be expensive per unit volume and thus have limited absolute collection efficiency for a given cost. Even a material with a low intrinsic efficiency can have large absolute collection efficiency if it is inexpensive to manufacture in large volumes. Minimum useful detector sizes are typically of *O*(1,000–10,000 $cm^3$)* for applications ranging from handheld instruments to portal monitors.

If a detector can meet absolute collection efficiency requirements, then energy resolution, which describes the precision with which the energy deposition of the incident photon can be determined, often becomes the relevant figure of merit. High-resolution gamma-ray detectors, whose development is a first-priority item in the *SNM Movement Detection Portfolio—Technology Roadmap*, enable each of the goals above. Energy resolution is crucial in distinguishing threatening and benign materials, reconstructing directionality from scattering events, mitigating interferences of adjacent peaks when identifying isotopes, and reducing background under full-energy peaks in detector response functions so that the magnitude of emitted fluxes can be precisely calculated. All next-generation photon detectors of interest to this roadmap must provide a high degree of spectroscopic capability. A reasonable target energy resolution for detection systems is 1 percent at 662 keV.

In analogy to energy resolution, time resolution describes the precision with which the arrival time of a measured photon can be determined, and time resolution determines the maximum count rate at which photons can be individually distinguished. These parameters are generally determined by the rise and fall times of detector pulses. For the majority of applications that examine uncorrelated, weak signals, count-rate limits in the thousands of counts per second range are acceptable. Time-correlation measurements, whose application to SNM detection is a first-priority item in the *SNM Movement Detection Portfolio—Technology Roadmap*, impose different measurement constraints. Time-correlation applications can make use of nanosecond resolution, although it is not yet clear what resolution will be required in any particular application. Active interrogation systems present the largest challenges to time resolution due to the massive event rates expected in some cases. Especially in systems using pulsed sources, there may be a need to handle instantaneous rates exceeding one million counts per second.

Essentially all nonproliferation applications require detection systems to be robust, mobile, and field-deployable. Photon detection systems that are suitable and effective for laboratory use may not be usable in field situations where infrastructure and personnel capabilities are limited. The most prominent example is that of high-purity germanium (HPGe), which has seen limited field deployment despite significant advances in cryostat design and mechanical cooling technology. Fielded systems must operate under a wide range of factors including temperature variation, shock, and vibration. Many applications require operation under battery power, and this roadmap document is particularly interested in the development of high-resolution photon detectors that do not consume significant electrical power.

Algorithms play a key role in converting detector-response data into actionable information. Advanced algorithms are required for identification of SNM in field applications where there is a large amount of background “clutter.” Specifically,

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* This document uses the notation “…of *O*” to denote “on the order of.” For example, “an external electric field of *O*(100–1,000 V/m)” means “an external electric field on the order of 100–1,000 V/m.”

algorithms must distinguish SNM from naturally occurring radioactive material, commercial sources, and medical isotopes in both active and passive applications. The algorithms must perform this identification in real time without the assistance of an analyst. This identification must be possible using energy calibrations attainable in the field and must be possible for spectra with a low number of counts. Algorithms operating in active interrogation settings must overcome new challenges associated with the introduction of artifacts from high-event-rate operation. Given the development of active interrogation, the development of algorithms for isotope identification in active interrogation systems was a second-priority item in the *SNM Movement Detection Portfolio—Technology Roadmap*.

## Survey of Field

Following discovery and growth of advanced materials, detection media must be converted into detection systems, and this section discusses the methods and tools developed to convert a given material into a photon detection system. The process of integrating radiation-sensitive materials into radiation detection systems can be conceptually divided into three steps. First, the detector material, which may consist of a scintillator, semiconductor, or gas, must be packaged in a manner to meet the competing requirements of detection efficiency, energy resolution, etc. Second, readout technology converts the inherent signal, e.g., scintillation light, into a form suitable for data processing. Third, data analysis algorithms process the readout and translate it into actionable information consistent with the goals of detect, identify, locate, and characterize. Each of these steps may overlap, such as in the case of pulse-shape analysis, which may be integrated into readout technology.

### *Integration of Materials into Radiation Detectors*

*Solid Scintillators*—Perhaps the most ubiquitous detection materials deployed en masse today are plastic scintillators [Kou05]. Since plastic scintillators are manufactured via dissolution of an organic scintillator into a formable polymer, they have the advantages of procurement in large volumes and many shapes, room-temperature operation, high durability, and low cost. Disadvantages result from their poor energy resolution and general lack of full-energy depositions, sensitivity to neutrons and poor pulse-shape discrimination, reduced light collection when formed into large panels, and low intrinsic efficiency.

The other large scintillator category consists of inorganic crystals. Slow inorganics such as NaI are mature technologies with medium resolution (6–10%), moderate cost, and moderate size. They can be somewhat fragile, crack under rapid temperature changes, and usually require shock-mounting. Modest temperature changes routinely encountered in field operation result in gain shifts large enough to require frequent energy calibration [She97]. Some systems contain small embedded sources or light pulsers to continuously measure or control gain shifts associated with the photo-cathode response [Sau05].

The newer lanthanum halides are fast inorganic scintillators with better energy resolution than NaI, in the range of 2–4 percent at 662 keV, but they are still expensive and not yet available in large sizes. Their performance improvement over NaI is limited by non-proportionality effects that are significant at lower energies [Bal05][Dor04]. There may also be a limitation for use in large detectors because of self activity due to the intrinsic natural activity of $^{138}La$ [Ker06].

Scintillation crystals that are hygroscopic, such as NaI and $LaBr_3$, must be encapsulated. They are typically sealed in a metallic can, coated on the inside with a diffuse reflector, and sealed with a window, which is transparent to scintillation light. Those that are not hygroscopic, such as $CdWO_4$, can be used immediately after polishing. In either case, a reflective coating is usually applied to all surfaces not in contact with the photo sensor.

*Liquid Scintillators*—Detectors realized in the liquid phase are mostly scintillators that are based on organic phosphors dissolved in hydrocarbon solvents. Organic liquid scintillators share the common requirements of containment and maintenance of an oxygen- and water-free head space in the containment vessel. In the case of hydrocarbon-based scintillators, containment is often an issue because the solvents dissolve or otherwise damage the plastics that might be used for the vessel, necessitating the use of stainless steel, glass, or fused quartz. A glass or quartz window is required for the interface between the vessel and the scintillator, although in some cases it is possible to use a photomultiplier tube's face plate as the interface.

Liquid organic scintillators can be made into large detectors, operate at room temperature, and are less expensive than crystalline scintillators, but still cost more than plastics. Further, they can be used with pulse-shape discrimination techniques, but these show poor performance for neutron energies less than 500 keV [Bel81]. The disadvantages are poor energy resolution (15–30%), large nonlinearities, and a low full-energy-peak fraction. The biggest disadvantages of field use of liquid scintillators are that the typical solvents are toxic and/or flammable and the coefficient of thermal expansion is not negligible. Their primary potential at this time rests in applications where the possibility of detecting gamma rays and neutrons in one detector outweighs fieldability difficulties.

Detectors using liquefied noble gases, which are either refrigerated or at high pressure, have been demonstrated [Kno00]. The detectors are fabricated from ultra-pure gas that is contained in stainless steel or titanium vessels. These devices behave like ionization chambers and offer resolution similar to that obtained with CZT and $LaBr_3$. Their main drawbacks are the need for refrigeration and/or high pressure and the relatively low density of liquefied gas.

*Semiconductors*—High-purity germanium (HPGe), shown in **Figure 2**, is a mature technology that serves as the "gold standard" for high-resolution measurements of SNM with its energy resolution of ~0.3 percent at 662 keV and highly linear response. While expensive and of limited size, the primary limitation on field deployment is its need for low-temperature operation. Progress has been made on mechanically cooled systems but, it has come at the expense of energy resolution, although recent work

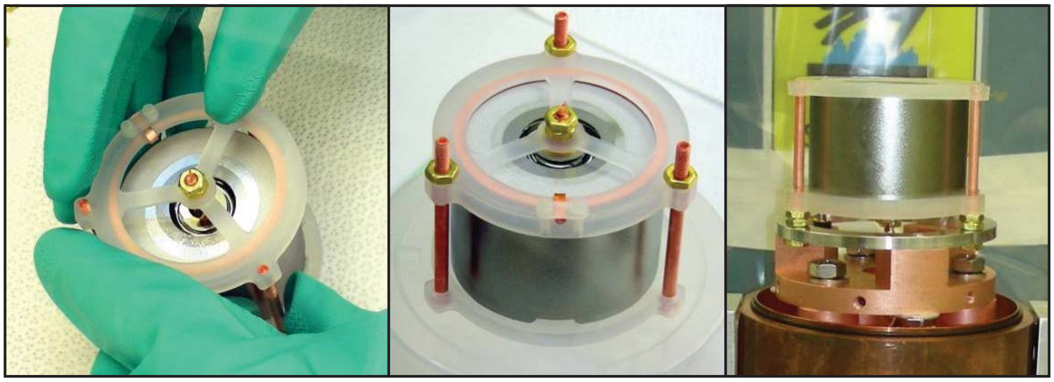


Figure 2. Photographs of high-purity germanium crystal assembly including insulator (clear plastic), high-voltage contacts (copper ring and center wire), and cold plate (bottom of right-hand photograph). Figure courtesy of Jim Fast, Pacific Northwest National Laboratory.

reports a resolution of ~0.4 percent at 662 keV in the latest systems [Can09]. For either mechanically or liquid-cooled systems, the required infrastructure, system size, and system mass pose problems for field use. HPGe has seen limited use as a secondary screening tool for a more detailed evaluation of a suspect item flagged by other systems.

The only room-temperature semiconductor at present is CZT with a typical energy resolution of 1 to 2 percent and a highly linear response (e.g., see [Che08][Fen04][Yon08]). Due to its small crystal size, the absolute collection efficiency required for many applications can be achieved only by integrating crystals into an array (e.g., see [Yon08][Mat06]).

*Gaseous Detectors*—Proportional and ionization chambers consist of a vessel containing high-purity gas and a readout system, e.g., set of electrodes consisting of a thin central wire. When ionizing radiation passes through the gas volume, atoms or molecules are ionized, and the charge is collected on the electrodes. In proportional chambers, the electric field is sufficiently high that collisions between drifting electrons and neutral gas atoms cause additional ionization near the anode wire; the signal is then proportional to the energy deposited in the gas.

Gases can also be used as scintillators. An incoming photon in a gas, such as high-pressure xenon, will excite xenon atoms to states from which they fluoresce. The xenon detector has sufficient energy resolution (2%) and good proportionality [Kno00]. In principle, xenon detectors could be unlimited in size, but the response slows as the size increases. Significant drawbacks are the packaging and transportation requirements placed on high-pressure gases. In addition, performance is limited by unresolved issues with microphonics and electromagnetic pickup.

The most significant drawback of all gas detectors for ionizing electromagnetic radiation is the low density of the sensitive volume. For example, even in the case of xenon with its relatively high atomic number, its density is ~0.6 g/cm$^3$ (when pressurized). By contrast, CsI, which has the same probability of interaction on a per-atom basis, has a density of 4.5 g/cm$^3$—making it about 7 times more efficient per unit volume than a xenon gas chamber.

## Photon Detection Systems

*Bolometers*—Bolometers are unconventional detectors that consist of a superconductor, insulator, and semiconductor cooled to the point that the detecting element's heat capacity is approximately 1 MeV/mK [Net95][Ens05][Irw06]. Absorption of a photon results in an increase of temperature, which results in the creation of phonons. The number of phonons created per deposited unit energy is 2 to 3 orders of magnitude greater than phonons in germanium under the same conditions. The fundamental advantage of cryogenic sensors is ultra-low noise due to low operating temperature (typically 0.1 to 10 K), which can be exploited for extremely high-precision measurement of particle energy, interaction time, or incident power. This translates into ultra-high resolutions [Ull05][Ali08][Dor08], for example 50 eV at 60 keV. **Figure 3** shows the effect of this resolution in the 100-keV range where various lines from uranium and plutonium reside. Multiplexed microcalorimeter gamma-ray detector arrays are now in development and have revealed unprecedented spectral detail of SNM [Dor07].

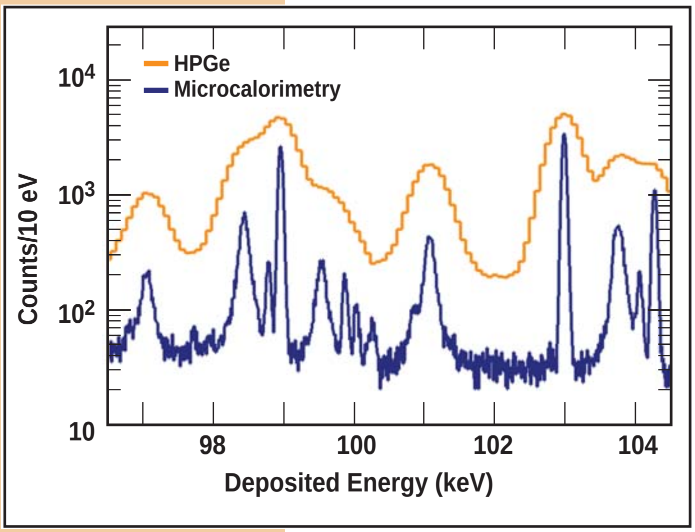



Figure 3. Plot of counts versus deposited energy acquired using microcalorimetry as compared to that of HPGe. This figure demonstrates the separation of various low-energy peaks in Pu not achievable with HPGe. Figure courtesy of Michael Rabin, Los Alamos National Laboratory.

Several key scientific obstacles must be overcome to set the stage for the transition from R&D to development and engineering. To date, this technology has been demonstrated with only a few materials and is limited to approximately 10 events per second. Because the size of the detecting element must be relatively small, the absolute detection efficiency for gamma-ray detection is low. Gamma-ray detector arrays with large format (>100 pixels) have been fabricated and assembled but have not yet shown simultaneous operation of all sensors with high resolution. A combination of improved pixel design and signal processing will be needed to make microcalorimeter speed (event counting rate) comparable to that of HPGe spectrometers while retaining the improved resolution. Improvements in absorber materials will be required to extend the applicable energy range from ~200 keV to several hundred keV; these improvements will also increase per-pixel speed. In-depth understanding will be required to determine both the practical and in-principle limits of uncertainty for quantitative materials analysis (isotopic and elemental ratios) determined from microcalorimeter spectra. For nuclear materials analysis through x- and gamma-ray spectroscopy, microcalorimeter detectors hold the greatest promise for those applications where long measurement times are tolerable and spectral resolution has especially large benefits.

### Readout Technology

*Photomultiplier Tubes*—Photomultiplier tubes (PMTs) convert scintillation photons into electrical signals. The first part of a PMT is a photo-sensitive layer (photocathode) that emits electrons when struck by a photon. The number of electrons is proportional to the photon energy, ideally in a very linear way. The electrons then pass through an amplifying cascade ending with enough charge to be integrated with precision. PMTs offer high gains, large collection areas, and high linearity. The disadvantages of PMTs include temperature sensitivity, high-voltage operation, relative fragility, and relative bulk. While a mature technology, new PMTs have been developed with quantum efficiency up to about 45% at 380 nanometers (nm) [Pan08][Vaq08]. An important factor in the performance of a scintillation system is the spectral overlap between the scintillation wavelength and the sensitivity of the photocathode. The various bialkali photocathodes used in most PMTs have good sensitivity in the ultraviolet and a peak response around 400 nm. The response falls to zero near 600 nm where the photoelectrons no longer have sufficient energy to escape the surface of the photocathode. Most common plastic scintillators have emission wavelengths in the 370 to 580 nm range that are well matched to the photocathode sensitivity. Liquid scintillators have a maximum emission wavelength of 425 nm. Inorganic scintillators span a similar range to plastics (e.g., the peak emission wavelength for NaI is 415 nm), except for some of the fast unactivated inorganics that emit at wavelengths as short as 220 nm.

*Photodiodes*—Photodiodes also convert scintillation light into electrical signals, but, in contrast to PMTs, photodiodes offer high quantum efficiencies (up to 80% in the infrared, but less in the blue and ultraviolet) in smaller and sturdier configurations with less power consumption. Photodiodes operate on principles similar to PMTs but within semiconducting materials rather than a series of layers and electrodes in a vacuum. Photodiodes have spectral sensitivities that span a much wider range than photocathodes, peaking in the near infrared around 900 nm. The major problem with photodiodes is electronic noise due to capacitance and leakage current, which become worse as the active area becomes larger. Dark current also rises rapidly above room temperature, limiting use at elevated temperatures. This noise can significantly reduce the energy resolution of the detector system. Because of these limitations, PMTs remain the current choice for fielded detection systems. Arrays of avalanche photodiodes, generally called “silicon photomultipliers,” are under development that could eventually offer a good alternative to PMTs. Their active areas at the present time are too small to fill such a role in most circumstances.

*Semiconductor Charge Collection*—Readout technology for semiconductors is simpler in principle than for scintillators, since the induced signal originates in the form of an electrical charge. The most important challenges in charge collection are optimization of the geometry of the material and the electrical contacts that carry the charge from the semiconductor to the pulse-processing circuitry. The use of simple ohmic contacts on opposite faces of a cube of material is seldom an appropriate choice. For example, HPGe detectors are typically fabricated in a coaxial geometry with contacts on the inner and outer surfaces of a hollow cylinder. Semiconductor contacts are often shaped into a variety of rectangles or rings in order to achieve a desired geometry for the internal electric field in the material, which determines the trajectories of the electrons and holes produced in the gamma-ray interaction. For this electric field to efficiently collect charge, an electric potential of $O$(100–1,000 V) must be applied. Despite this high voltage, it is necessary to minimize the leakage current through the material since the radiation signal will appear as a charge pulse added to the leakage current. When the bulk resistivity of the material is high, leakage current across the surface also must be limited via measures such as surface grooves or guard rings. Semiconductors such as CZT suffer from limited hole lifetime and mobility compared to the lifetime and mobility of the electrons. This results in large tails that emerge on the low-energy sides of full-energy peaks. This has a significant impact on energy resolution. To mitigate this problem, coplanar grids (shown in **Figure 4**), virtual Frisch-grids, and pixilated anodes have been developed to create a system where the majority of signal derives from electron transport [Kno00][Luk95] [McG98][McG99].

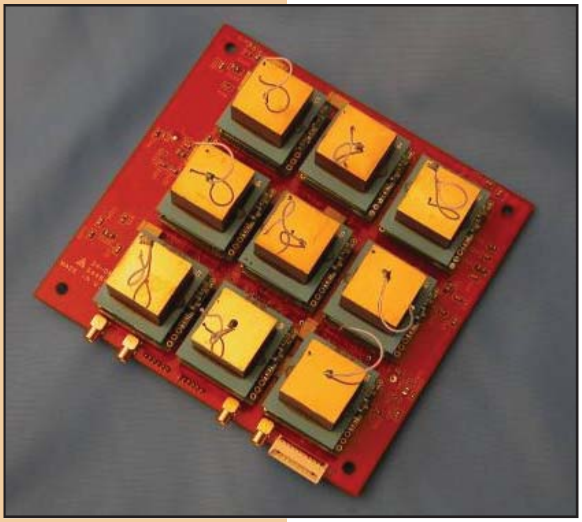


Figure 4. Photograph of nine CZT crystals mounted to a coplanar grid readout (underside of photograph) with cathode wires attached. Figure courtesy of Cari Seifert, Pacific Northwest National Laboratory.

### *Data Analysis Algorithms*

The final step that translates measured events into actionable information relies on data analysis algorithms. In the simplest photon detection systems, an algorithm might consist of a comparison between the counts recorded when a signal is present to a measured background when the signal is absent. More sophisticated analyses make use of a recorded energy spectrum. The vast majority of effort directed at gamma-ray spectroscopy has focused on the problem of unfolding the constituent isotopes in an unknown empirical spectrum.

*Peak Fitting*—Peak fitting segregates a spectrum into its component peaks and continua. This deconstruction process can be very complex and includes extraction of Compton shoulders and the fitting of Gaussian-shaped peaks with tails. After peak identification, the energies and relative proportions are matched to the known energies of a library of gamma-ray sources. This approach is not overly sensitive to a lack of a priori knowledge of the measurement scenarios. The greatest obstacles here are the difficulties that can be encountered in extracting a particular peak from several overlaid peaks plus background plus other continuum effects. Peak fitting has been successfully applied in codes such as FRAM [Sam97] and MGAU [Ber07], which have been developed for safeguards applications where a specific region of well-populated peaks is under investigation. Peak fitting is also effective in high-resolution spectra, such as from HPGe, that possess a very high ratio of counts in the full-energy peak compared to counts in the continuum.

*Template Matching/Basis Vector Fitting*—Template matching uses a pre-existing library of radioactive sources and fits them to the measured spectrum. At a minimum, this involves defining a vector of scaling factors applied to the library spectra and a difference minimization routine that adjusts the scaling factors until a best fit to the measured spectrum is achieved. More complexity can be introduced by including scaling factors that adjust the energy axis of the measurement so that gain differences between the pre-existing and measured spectra can be accommodated. Another improvement to this approach is the addition of spectra that incorporate intervening materials. This effectively creates a two-dimensional library of source type and intervening material.

Template matching works very well if the measurement environment is well-defined; e.g., if the pre-existing library is populated with measurements by the exact detector with which unknowns will be measured and with measurements from sources that will constitute the unknowns. As the measurement scenario increasingly differs from the scenarios detailed in the library, the performance of template matching diminishes. The ability to adjust parameters and, in some implementations, make interpolations between different pre-existing spectra increases the robustness of this approach. An example of a developed algorithm is GADRAS DHSIsotopeID, with example results shown in **Figure 5**, which is a high-performance tool when used by a trained analyst.

*Time-correlation Analysis*—Gamma-ray time-correlation analysis may be used to measure fission gamma rays directly or to measure fission neutrons by detecting gamma-ray emission following neutron capture, but methods are considerably less mature for gamma rays than for neutrons. Neutron-based methods are robust for three reasons that do not apply to gamma ray measurements: (i) neutron backgrounds are low, thus resulting in few accidental coincidences; (ii) fission neutrons readily penetrate metal, thus making valid the assumption of a single detector efficiency connecting the theoretical fission chain to the measured coincidences; (iii) capture-based detectors cannot detect the same neutron twice. Gamma-ray backgrounds from natural activity are much higher than for neutrons, particularly when combined with large solid-angle detectors. One consequence of these higher background rates is that long correlation windows—on the order of milliseconds necessary for measurement of neutron-capture gamma rays—are unlikely to yield statistically significant results in reasonable times for low intrinsic fission rate materials such as HEU. In addition, while the number of fission gamma rays may be much larger than the number of fission neutrons, the number of fission gamma rays that escape from a SNM assembly may be much lower because of self-shielding. Last of all, gamma rays can Compton scatter between two or more detectors, giving a baseline of coincidences proportional to source strength.

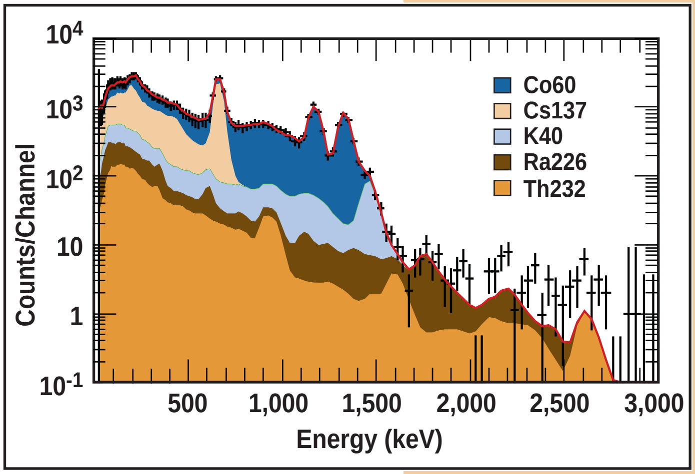



Figure 5. Screen shot of GADRAS DHSIsotopeID results upon analysis of a multi-isotope source. Figure courtesy of Michael Wright, Oak Ridge National Laboratory.

Previous examinations of gamma-ray time correlations focused on the measurement of both gamma rays and neutrons. They have consequently been limited by the detection system's ability to distinguish between gamma-ray and neutron events in detectors that are sensitive to both. Approaches using different detectors for gamma rays and neutrons have struggled to attain adequate absolute collection efficiencies. Because of these measurement challenges, the question remains open as to what value gamma-ray time-correlation measurements add to those exclusively focused on neutrons.

## Identification of Shortfalls

In contrast to advanced materials discovery, R&D in photon detection systems addresses limitations that are not intrinsic to the material or to the fundamental detection interaction. Instead, these limitations are imposed by the methods and tools used to collect or interpret detector response data. For a given radiation detection material, the goal is to improve these methods and tools to maximize the collected signal, energy resolution, timing resolution, and deployability while minimizing the cost. At present, there are no radiation detection materials that can be packaged to simultaneously meet all requirements. This roadmap focuses on filling shortfalls associated with the development of high-resolution photon detection systems since high resolution is an omnipresent requirement spanning essentially all applications. A secondary objective is the integration of time-correlation signatures from the photon domain that could potentially complement their neutron counterparts, whose signature exploitation is considerably more mature.

*Efficient Readout Technology*—Detector systems do not achieve the full resolution available from the detector materials themselves due to limitations in light conversion and charge collection. For example, PMTs do not capture all of the scintillation photons, due to wavelength mismatches between scintillation light and photocathode response, and therefore have reduced sensitivity. In high-count-rate applications, response times of signal collection methods limit sensitivity through the creation of dead time and/or impact resolution through pileup effects. Analogous limitations exist in the collection of charge from semiconductors, most notably in the case of CZT, which requires extensive charge collection schemes to mitigate effects of charge migration and trapping.

Readout technology sometimes fails to meet requirements of compact, robust, low-power systems. For example, absolute collection efficiency may be limited by the physical space required to house PMTs while complex readout electronics consume considerable power and computational resources.

Time resolution shortfalls also exist, particularly in applications exploiting time-correlation signatures or in active interrogation environments.

*Automated Gamma-ray Spectroscopy Algorithms*—Applications where the rate of photon emission is low require the ability to evaluate sparse data. Other applications may not be limited by the amount of data but by the need to filter out artifacts from the data collection process. Underlying both data processing problems is the presence of background. The rich history in development of gamma-ray spectroscopy tools has focused on analysis performed by trained analysts using medium-resolution detectors. Significant shortfalls reside in the area of automated spectroscopy; this situation is complicated by the minimal computational resources available on battery-operated systems. Even with unlimited computational resources, there exists no completely automated system for reliable isotope identification under a reasonable range of background, shielding, and count-rate scenarios.

*Algorithms for Isotope Identification in Active Interrogation Systems*—Algorithm development for gamma-ray spectroscopy in active interrogation systems is a largely unexplored area. While prompt emissions from photofission possess a fairly unstructured continuum, delayed signatures from fission daughters possess significant structure. At the other extreme, emissions from nuclear resonance fluorescence are discrete and occur at only a handful of energies. Successful demonstration of active interrogation systems will require the capability to extract these signatures from complex and high-rate backgrounds. In the case of pulsed interrogation systems, algorithms may need not only to examine energy spectra but also include temporal information.

*Gamma-ray Time Correlation and Related Signatures*—Examination of signatures that arise from timing and multiplicity of gammas could lead to extraction of more actionable information from data that can already be collected by existing hardware. The fundamental shortfall here is the absence of both an accepted estimate of the value of using gamma-ray multiplicity and a proven approach to exploiting gamma-ray multiplicity (with or without neutron correlations). A necessary component to developing algorithms is assembly of a proper quantification of the underlying signature space, especially since questions remain about exactly what additional information gamma-ray multiplicity adds to existing gamma-ray spectroscopy and neutron multiplicity.

## Prioritized Investment Options

Detection of gamma rays is ubiquitously applied in SNM detection scenarios. This state will likely persist with the potential deployment of active interrogation systems. Development of photon detection systems is thus a critical high-priority area of R&D, but it is also a mature one with wide applicability beyond SNM detection. The investment options identified by a group of SMEs reflect this reality, and their prioritization by NA-22 addresses the need to target niche areas of photon detector development, including assessment of high-risk approaches that may represent unconventional system development paths. This prioritization scheme, which largely consisted of first ordering options based on their priority in the *SNM Movement Detection Portfolio—Technology Roadmap* and subsequently estimating impact levels, is listed in **Table 3**.

**Table 3. Prioritized investment options for photon detection systems.**

| Investment Option | Priority | Impact | Summary |
|---|---|---|---|
| Alternate radiation detection and readout concepts | High | High | Most of the traditional and non-traditional detector materials discussed earlier rely on scintillation or direct ionization charge collection processes in solids, and much of the research to be done in pursuit of advances in those areas is in the materials science of crystal growth, materials processes, and photon and charge transport. Beyond work on the performance of existing detector materials are novel detection approaches that either use different physical processes or classes of materials not previously developed for SNM detection applications. A high-risk, long-term R&D effort investing in these entirely new approaches might produce revolutionary advances if one of these concepts proves successful. In radiation detection, there exists a handful of intriguing photon-detection methods that have not been explored to a degree that allows a determination of their potential value. Potential avenues of signal extraction include, for example, magnetic properties and response, electromagnetism susceptible devices, and acoustic/piezoelectric properties and response. |
| Spectroscopy algorithms for signal-starved spectra | High | High | There is a long history in the development of analysis methods for high-count, low-background, low-noise data from high-resolution, and even medium-resolution, detection systems. To fully exploit the potential of spectroscopic systems, further investment is needed to develop new spectroscopy algorithms for signal extraction from noisy and sparse spectra, specifically in automated analysis that does not involve the immediate support of an analyst. No completely automated and reliable system currently exists for isotope identification. One of the largest challenges stems from analysis of spectra with imprecise energy calibrations resulting from gain shifts. Successful development of automated algorithms for fielded systems experiencing gain shifts could provide significant capability advancement. |

**Table 3. Prioritized investment options for photon detection systems. (cont.)**

| Investment Option | Priority | Impact | Summary |
|---|---|---|---|
| New strategies for charge collection in semiconductors | High | Medium | In the absence of large-volume, room-temperature semiconductor materials, detector systems will continue to exploit multi-pixel arrays of small-volume crystals. Optimizing the readout of these multi-pixel arrays in a manner that reduces complexity and power consumption is an important near-term objective. Example techniques considered to date include a virtual Frisch grid, pixilation, and co-planar grid readout, but each of these introduces considerable complexity. |
| Stable, solid-state readout technology for scintillators | High | Medium | PMTs are a well-established commercial technology with considerable ongoing industrial investment, but a viable solid-state replacement with reduced size, increased durability, and the ability to be scaled to large areas does not presently exist. Avalanche photodiodes and solid-state photomultipliers represent two potential solutions. Currently, avalanche photodiodes have limited areas and are unstable with changes in the temperature and bias voltage. Solid-state photomultipliers that count individual scintillation photons have shown promise, but two remaining challenges are increased packing fraction of readout pixels and reduced cross-talk between pixels. Useful implementations of either technology need to have an active area greater than of $O(10\ cm^2)$. Another possible replacement for PMTs is organic semiconductor-based photodiodes. Performance of these materials is currently limited by noise issues and high capacitance for large areas. |
| Assess deployment feasibility of proven non-traditional radiation detectors | High | Medium | There are several proposed measurement techniques used in fields such as high-energy physics that have evolved to the point where further consideration for application to SNM detection is appropriate. Two examples are cryogenic detection media based on liquid argon and xenon. Liquid xenon offers the potential for a large-volume spectroscopic or tracking detector with good theoretical resolution; liquid argon offers the potential for a large-volume detector with good pulse-shape discrimination between neutrons and gamma rays. Other examples include Cerenkov/transition detectors that have very fast timing and can easily be scaled to large sizes, although they suffer from low light yield and poor energy resolution. Other candidates are bubble chambers for fast neutron detection and gas-filled tracking detectors that may be useful for imaging applications. While well understood in the laboratory, applications development for all of these complex detectors needs to focus on deployment challenges. |
| Detection limit mapping | High | Medium | In developing detection systems, a balance between sensitivity (the capability to capture signal) and selectivity (the capability to differentiate between signals) dictates what detection media are potential candidates. Detection media with medium resolution that are available in large volumes, e.g., NaI, dominate field deployments because they possess both appreciable sensitivity and selectivity. A comprehensive study of the detection limits as a function of the sensitivity and selectivity parameter space would help guide the development of new detection materials and systems. Of specific interest are crossing points in detection limits between high-resolution but small-volume detectors and medium-resolution but large-volume detectors that directly incorporate energy resolution, linearity, and collection efficiency of existing and emerging detection systems. |
| Algorithms for active interrogation signatures exploitation | Medium | High | Specifically addressing two of the *SNM Movement Detection Program—Technology Roadmap* priorities is development of algorithms that exploit active interrogation signatures and photon time-correlation data while minimizing the effect of large dynamic range in detector response. An inherent component of algorithm development is the quantification of both the signature and background signal space. A significant contribution to the “background” results from limitations on the dynamic range that may be tested by the high acquisition rates resulting from interrogation sources, for example. Open questions remain regarding how to fully exploit the multiplicity information contained in gamma rays emitted both passively and in response to an interrogating source. |

# Neutron Detection Systems

## Technology Requirements

Since neutron interaction cross sections are modest, especially in the case of fission neutrons, systems must be designed to yield a sufficient number of signal counts in a reasonable time. This requires a combination of scalability to large area and adequate intrinsic detection efficiency. Each of these development objectives were identified as first-priority items in the *SNM Movement Detection Portfolio—Technology Roadmap*. Modest interaction cross sections also lead to two ancillary requirements. First, since gamma rays are omnipresent in large numbers, it is crucial for neutron detectors to be insensitive to gamma rays or to be able to distinguish them from neutrons, at a level of $O(10^{-5})$ or greater when neutron detection is of exclusive interest. This is especially the case for interdiction of SNM where high-activity gamma-ray sources are common in many applications. Second, the large-volume nature of neutron detectors in monitoring applications mandates a low cost per unit volume. Although this may preclude some techniques that can in principle be scaled but in practice have limitations, modern technology can enable complex systems to be fabricated economically.

The vast majority of nonproliferation applications aim to detect the presence of fission neutrons. The common requirement is thus for discrimination between fission neutrons and those at low energies, which dominate background. This implies that the capability of reliably sorting neutrons into low-energy and high-energy categories is highly desirable. For field applications focused on SNM detection, there is limited benefit to neutron spectroscopy over the range of the fission spectrum since empirical backgrounds possess an energy distribution almost identical to the fission spectrum [Gor04]. Applications focused on source characterization can benefit from neutron spectrometry. Two examples include the need to discern a fission spectrum from one produced by an americium-beryllium (AmBe) source and the need to identify the presence of oxide materials—a task that requires high-resolution neutron spectroscopy. The required fidelity of the spectrometer is thus highly application-specific.

Measurements exploiting time-correlation signatures bring additional requirements. The first revolves around the time scale of the fission processes that emits bursts of neutrons with characteristic time scales approximately ranging from 1 ns up to 10 μs. To exploit these correlations, detectors must also possess time-resolving capability at this level. In addition to fast detectors, dual-particle detectors are of interest for time-correlation measurements since emissions very often consist of both gamma rays and neutrons. While current practice relies on separate detectors with separate readouts, future systems must possess the capability to detect both species in the same active detection volume. A further desired feature is the capability to explicitly distinguish between the two types of radiation.

Active-interrogation methods also impose unique requirements. Detectors must function at high event rates to extract the stimulated neutron signal and/or operate during interrogating radiation bursts. Very high gamma-ray discrimination capability may be necessary to distinguish the interrogating radiation from the emitted neutron signal, especially in cases where the induced signal flux is much smaller than the interrogating radiation. Crude neutron energy selectivity, similar to that noted above, may also be necessary to discriminate neutron signals from interrogating radiation. For example, it may prove effective to categorize neutrons as low-energy, fission, and high-energy in the case of interrogation with a 14-MeV generator. For pulsed interrogation scenarios, triggering or gating of the neutron detector may be required.

From the fieldability standpoint, low power consumption, the absence of pressurized gases, and straightforward systems setup are important in some nonproliferation contexts.

## Survey of Field

The nature of interaction cross sections inherently bifurcates neutron detection systems into those sensitive to thermal neutrons and those directly sensitive to high-energy neutrons from fission (hereafter referred to as fission neutrons). This section discusses detection methods in this order. Following this is a brief discussion of spectroscopic neutron detectors, which consist of thermal and high-energy detection systems configured in such a manner to extract incident energy.

### *Thermal Neutron Detectors*

Thermal neutrons are most efficiently detected via neutron capture reactions that convert thermal neutrons into high-energy charged particles. Commonly used nuclides include $^{3}$He (5,330 b), $^{6}$Li (940 b), $^{10}$B (3,840 b), and $^{157}$Gd (49,000 b) because of their large capture cross sections and the fact that subsequent charged particles are energetic enough to allow discrimination from gamma-ray energy depositions [Kno00]. Detection of fission neutrons using these capture agents requires the positioning of moderating material between source and capture agent. This is generally accomplished using organic polymers or other hydrogen-rich materials with thicknesses of $O$(1–10 cm).

*Gaseous Detectors*—Detectors incorporating $^{3}$He or $BF_3$ gas that operate in a proportional-counting mode have seen widespread deployment. Due to the higher cross section, capability of operating at higher pressures, stability with respect to temperature, and environmental and safety concerns, $^{3}$He detectors are most common since they have proven to be a robust and reliable detection medium. The technical shortcomings of $^{3}$He are the need to operate at high pressure and, being ionization chambers, the response and recovery times of such detectors are limited to microseconds, so that they are suitable for some, but not all, multiplicity measurements. To some degree, subdividing the detector volume into multiple readout channels can increase the overall rate capability without significantly increasing cost or operating complexity. This response time may also limit utility in some active-interrogation methods. Due to their low-$Z$ composition and high-reaction $Q$ values, gaseous detectors have excellent gamma-ray discrimination. At thermal energies, the discrimination power of $^{3}$He detectors at $O(10^{-5})$ appears sufficient for most signal-starved applications [Cra91].

*Conversion-layer Detectors*—The concept of placing neutron-capture agents in intimate contact with a semiconductor or other charge-collecting device is attractive because it obviates the need for high-pressure cells and would be, in principle, both scalable and position sensitive. Various attempts have been made at producing these conversion-layer detectors, but success has been slow in developing.

Two techniques have shown some recent promise. The first relies on coating silicon semiconductors with $^{10}B$. To maximize both the ability to capture neutrons and the amount of energy captured from the reaction products, coatings of $^{10}B$ and $^{6}LiF$ have been applied to semiconductors with etched holes or trenches [Shu06], as shown in **Figure 6**. Similar concepts use pillar geometries [Nik08]. Neutron detection has been demonstrated using this technique, but overall system size has been restricted to areas of $O(1\ \mathrm{cm}^2)$. The affinity of gamma rays for Compton scattering in Si presents a potentially significant discrimination challenge.

Figure 6. Photograph of an array of silicon-based conversion layer detectors, the 6-mm-diameter circles attached to each circuit board. Figure courtesy of Douglas McGregor, Kansas State University.

The straw detector concept applies similar logic, and it may hold more promise for large-area detection since it does not rely on a semiconductor [Lac06]. Straw detector prototypes are being fabricated in 1-m lengths to create a detector panel 1 m$^2$. The straw concept consists of a $^{10}B_4C$ coating, ~1 μm thick, which is sputtered onto thin ribbons of aluminum. These ribbons are then fashioned into straws that are filled with a gas, creating an ionization chamber. The thermal neutron detection efficiency is reported to be 50%, while the gamma discrimination has been observed to reside at $O(10^{-7})$. The cost and fabrication challenges associated with this technology may be a limiting factor in its deployment.

*Materials with Embedded Converters*—Embedding neutron capture agents in semiconductors or scintillators provides a more efficient system for collecting the energy released by reaction products, but this technology is immature. One attempt at such an approach tested pyrolytic boron nitride with a natural abundance of $^{10}B$ at 20 percent [McG08]. These detectors possess reduced mass, exhibit potential for development into 2-dimensional flat-panel arrays, and can be adapted to Si read-out electronics. Fast, gamma-insensitive semiconductor detectors such as SiC are also being developed as fast neutron detectors for active interrogation systems [Rud09]. These detectors can operate in intense radiation fields and have been shown to be capable of neutron-photon discrimination through the use of pulse-shape discrimination techniques.

A great deal of effort has been directed at the development of scintillation-based thermal neutron detectors, primarily for applications in neutron radiography that require high spatial resolution and the capability to operate in large fluxes [Eij04]. Perhaps the most promising of these are $Cs_2LiYCl_6$:Ce and $Cs_2LiYBr_6$:Ce, which exhibit neutron-capture pulse-heights well above the terrestrial gamma-ray background ending at ~3 MeV. These materials are presently in the early stages of development and limited to small sizes of $O(1\ \mathrm{cm}^3)$ that precludes them from many applications, but significant optimism surrounds these materials, especially due to the potential to provide both gamma-ray spectroscopy and thermal neutron detection.

## Neutron Detection Systems

An older scintillator is ZnS:Ag/$^{6}$LiF which can be painted onto a sheet and read out by wavelength shifting fibers. Recent advances in this approach have led to reports of thermal neutron detection efficiencies of ~40 percent [Koj04], but gamma-ray rejection remains an issue. Recent commercial developments focused on border security have demonstrated success in applying pulse-shape discrimination [IAT09].

Figure 7. Photograph of lithium-doped scintillating fibers. Figure courtesy of Mary Bliss, Pacific Northwest National Laboratory.

*Fiber Detectors*—Cerium-activated, lithium-silicate glass scintillates upon thermal neutron capture by $^{6}$Li (**Figure 7**) [Cra00]. The triton and alpha particles each interact with the glass matrix to produce an ionization trail. This scintillation light at ~400 nm can then by collected by a PMT. The scintillating glass is sensitive to Compton electrons and photoelectrons produced by gamma rays as well as neutrons, but electrons produce much smaller pulses than neutrons. Fiber detectors have achieved some infamy due to the fact that, under exposure to large gamma-ray fluxes, pileup amongst gamma-ray events becomes indistinguishable from neutron events, especially when fibers are fabricated in long lengths. Recent developments in pulse-shape analysis may provide a considerable improvement in the separation between gamma-ray and neutron distributions.

*Water Cerenkov Detectors*—Construction of high-efficiency, large-volume, and low-cost neutron (and high-energy gamma) detection systems may be possible through the use of water Cerenkov detectors doped with trace quantities of neutron capture agents. This technique relies on the photo-detection of Cerenkov radiation created by gamma-ray emissions from neutron capture agents held in a water solution. This technique has been demonstrated in various experiments, using $^{10}$B and $^{157}$Gd dopants, in the 250-L prototype shown in **Figure 8** [Daz08]. The use of $^{157}$Gd (in natural Gd) is promising because its 8-MeV cascade of gamma-ray emissions provides sufficient Cerenkov radiation to be detectable even with modest (10%) PMT coverage.

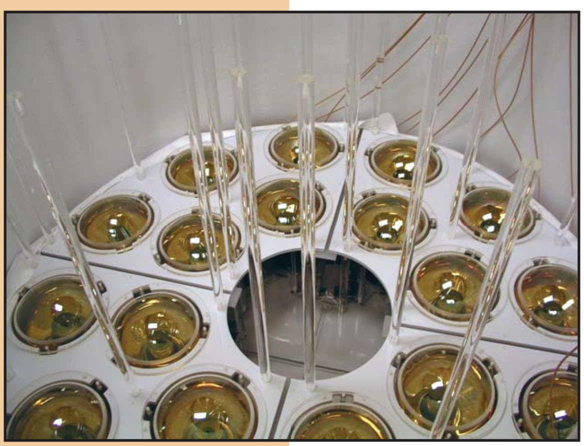


Figure 8. Photograph of prototype water Cerenkov neutron detector. Figure courtesy of Steve Dazeley, Lawrence Livermore National Laboratory.

### Direct Fission Neutron Detectors

Methods to detect fission neutrons generally rely on elastic scattering between neutrons and hydrogen. The amount of absorbed energy is a crucial parameter for signal extraction and differentiation from gamma-ray depositions. While any nucleus could, in principle, function as a recoil detector, the amount of energy a target nucleon can absorb quickly decreases with increasing atomic number. Fast neutron detection systems have thus almost exclusively relied on hydrogen-rich (organic) compounds.

*Organic Scintillators*—Plastic or liquid organic scintillation detectors are common tools used when counting of high-energy neutrons is the goal. Organic scintillators possess advantages in terms of low cost and fabrication into large sizes. Since they are both neutron detection and moderation media, layers of these detectors can be used to measure crude neutron energy distributions, in a similar manner to gaseous detectors inside moderators (discussed below). With their excellent response and recovery time of $O(0.1\text{–}1\ \text{ns})$, they are useful for fission neutron multiplicity counting. When doped with neutron capture agents, they can be made sensitive to thermal neutrons as well [Swi08].

Organic scintillators are sensitive to gamma rays, particularly via Compton scattering. This presents the possibility of dual gamma-ray/neutron counting at relatively low cost but also requires the development of gamma-neutron discrimination techniques. Pulse-shape discrimination is fairly mature and successful in liquid scintillators but is a strong function of energy (see [You09] and references therein). Fieldability is a prominent issue since some liquid scintillators are toxic and flammable. Their light output can be affected by temperature variations at the level of a percent per degree Celsius, but mitigation techniques are quite practical.

Plastic scintillators have seen much wider deployment, but normally as gamma-ray detectors due to the inability to perform pulse-shape discrimination. One exception is stilbene, which is a unique (and expensive) solid organic scintillator. Stilbene has excellent pulse-shape discrimination capabilities [Esp04] but is problematic due to its high cost and a manufacturing process that involves the use of toxic and carcinogenic materials. Recent advances in alternate materials have shown promise, for example in the case of triphenylbenzene, whose pulse-shape discrimination relative to stilbene is shown in **Figure 9**. Attempts have been made at gamma-neutron discrimination in traditional plastic scintillators based on the delay between multiple neutron scatter events instead of pulse-shape discrimination [Ree99], but no recent results have been reported.

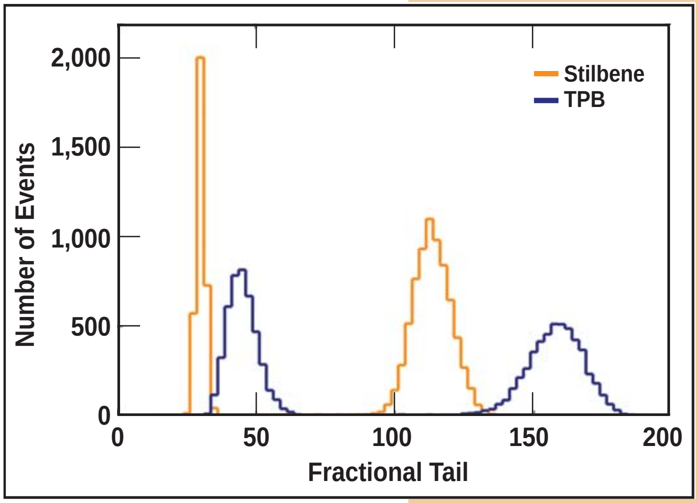



Figure 9. Plot comparing neutron-gamma discrimination for stilbene and tetraphenylbutadiene. Data courtesy of Natalia Zaitseva, Lawrence Livermore National Laboratory.

*Time Projection Chambers* (TPCs)—Light gas-based (H or He) TPCs have been used for many years in the high-energy and particle physics communities to detect and characterize products of exotic, high-energy particle reactions. The principle of operation of TPCs is discussed further in the *Imaging Methods* section. There are ongoing efforts to convert these large and complex detectors into fieldable detection systems for nuclear search and monitoring applications [Hef09], as shown in **Figure 10**. The benefit of this approach is scalability to large detection volumes, nearly $4\pi$ field-of-view, high-efficiency (10% or better), and the ability to deduce directionality from a limited number of neutron events, as discussed in the *Imaging Methods* section. The major challenge here is the development of a pressure cell that is both practical and safe. Ruggedized and reliable electronics, which also simplify operation and provide largely automated operation, can be implemented.

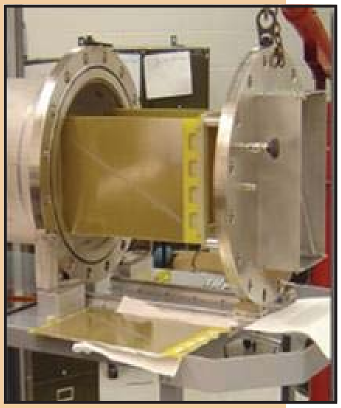


Figure 10. Photograph of prototype TPC including the aluminum pressure vessel and wire grid for charge collection. Figure courtesy of Mike Heffner, Lawrence Livermore National Laboratory.

*Chemical Vapor Deposition (CVD) Diamond*—A fission neutron detection technique distinct from those above exploits the $^{12}C(n,\alpha)^{9}Be$ reaction. One prototype detector consists of thin CVD diamond films of $O(100\ \mu m)$ mounted onto a conductive layer of boron-doped CVD as a backing contact [Alm08]. Silver electrodes are then attached to this conductive layer. Positive observations of peaks associated with the $^{12}C(n,\alpha)^{9}Be$ reaction along with $^{12}C(n,n')3\alpha$ scattering have been reported. The efficiency of such a detector is a major challenge because of the low cross section for the $^{12}C(n,\alpha)^{9}Be$ reaction and the cost associated with CVD diamond fabrication.

*Threshold Detectors*—Threshold detectors exploit neutron interactions that occur only above specific energies and thereby provide direct sensitivity to fission neutrons, along with intrinsic insensitivity to gamma rays and low-energy neutrons. One example is the pressurized-liquid bubble chamber, shown in **Figure 11**, which detects neutrons via nucleation [Jor05]. Detection systems based on threshold-detection methods reside in an immature state due to challenges associated with pulse-mode operation, event readout, and/or low duty cycles.

### *Neutron Spectroscopy*

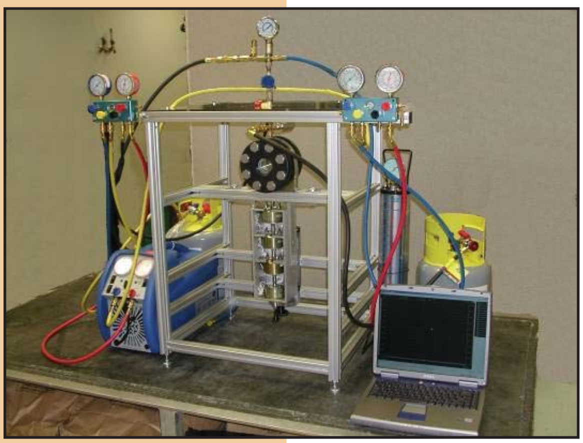


Figure 11. Photograph of a pressurized bubble chamber assembly. Figure courtesy of David Jordan, Pacific Northwest National Laboratory.

There exist several methods to determine the distribution of an incident neutron energy spectrum. They are presented here roughly in order of increasing spectral resolution.

*Bonner Spheres*—While more frequently used as counters, it is possible to extract spectroscopic information from gaseous proportional detectors. The method is based on deconvolution of signals from multiple "Bonner spheres" that consist of thermal neutron detectors surrounded by varying thickness of moderators [Gol02][Aro97]. This technique requires careful modeling of the detection system and application of complex unfolding algorithms that incorporate response functions, efficiencies, and geometrical dependences. Such spectroscopic systems are in some respects operationally simple, since the neutron energy is selected according to the thickness of the moderating material, but cumbersome due to their extensive size. The principal drawbacks toward their application to nonproliferation are extended measurement times and the need for extensive modeling and simulation to support deconvolution.

*Time of Flight*—The velocity, and thus the energy, of a neutron can be deduced by measuring the time of flight between two scattering events. Estimates of neutron energies are an integral part of the neutron scatter camera discussed in the *Imaging Methods* section. The time-of-flight technique has been used in nuclear physics experiments for some time, but the development of a recent transportable system has allowed for higher-fidelity environmental measurements, such as the ambient neutron spectrum shown in **Figure 12** [Mas08].

*Bolometry*—Present research is investigating the use of superconducting transition edge detectors for neutron spectroscopy [Nie04]. These devices operate on exactly the same principle as described in the *Photon Detection Systems* section, but they use materials with large neutron-scattering cross sections, e.g., $Ti^{10}B_2$ and $^6LiF$. Energy resolution with a 50-keV full-width half-maximum has been demonstrated for thermal neutron capture [Hau06]. The use of $^6Li$ allows for fast-neutron spectroscopy, but the cross section for capture above thermal energies is small. These devices have very high resolution but are limited in size and hence overall efficiency by the heat-conducting properties of the neutron-absorbing elements they contain. Attempts to circumvent this shortfall by multiplexing large arrays of such sensors are now being pursued [Hor07].

*Nuclear Recoil*—In liquid scintillators that have pulse-shape discrimination capability, limited spectroscopy can be performed on neutron events down to the ~0.5-MeV threshold for reliable pulse-shape discrimination. Although the recoil spectrum is approximately flat for monoenergetic neutrons, spectroscopy may be accomplished by unfolding the induced recoil spectrum from the detector response. Zimbal et al. discuss this process in standard NE213 liquid scintillator, demonstrating 11% resolution for monoenergetic 2.5-MeV neutrons (see [Zim04] and references therein). This approach is greatly complicated by shielding and neutron scattering, but further analysis of reconstruction methods in liquid scintillator may provide additional characterization capability for SNM.

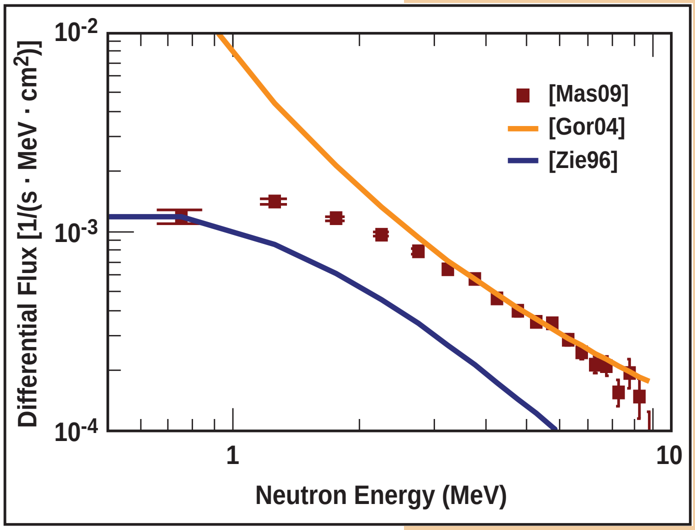



Figure 12. Empirical energy spectrum of ambient neutron background as measured by the neutron scatter camera. Data courtesy of Nick Mascarenhas, Sandia National Laboratories.

## Identification of Shortfalls

Neutron detection systems play a crucial role in nonproliferation, especially in scenarios with significant attenuators, because of their ability to penetrate many materials. In spite of this fact, deployments of neutron detection systems almost universally consist of gaseous $^3He$ proportional counters. While the capability of advanced systems, such as those based on liquid scintillators that directly detect fast neutrons with fast timing, has been clearly demonstrated, present shortcomings prevent the widespread deployment of these capabilities. Deployable technologies must be developed before the high-level objectives of detecting shielded material can be achieved, if complex signatures such as neutron and gamma-ray time correlations are to be exploited.

*High Gamma-ray Rejection in Real-time Detectors*—The single largest impediment to deploying next-generation neutron detectors is the need for high gamma-ray discrimination. This shortfall exists in both the detection of thermal and fission neutrons. For fission neutrons, state-of-the-art discrimination capability is of $O(10^{-3})$ using liquid scintillator detectors. Further research is necessary to improve discrimination in this energy regime to rejection powers of at least $O(10^{-5})$. These improvements are especially needed for detectors deployed in active-interrogation environments. Additionally, the particle identification capability of fast neutron detectors is energy dependent, and, for them to be versatile, the energy threshold at which discrimination can be achieved must be lowered.

While neutrons from fissile material are produced with typical energies around 1 MeV, interactions with shielding materials or surroundings often reduce the neutron energy to the 10-keV scale. In this regime several things occur: thermal neutron detectors are insensitive; conventional pulse-shape discrimination techniques in scintillators fail; and gamma-ray backgrounds increase compared to the MeV scale. As such, the ~10–500-keV neutron energy region is a “blind spot” in current radiation detectors for nonproliferation. In this regime, radiation detectors lack either efficiency, particle identification, or both. In specific applications, for example those with neutron sources emitting discrete energies, detection systems with particle discrimination down to the 10–100-keV level could improve SNM detection capabilities.

Performance of fiber-based systems is considerably worse, and development of improved detection materials and/or pulse-shape discrimination is necessary. Some threshold neutron detectors, such as bubble chambers, possess excellent discrimination, but real-time detection has yet to be accomplished in an automated fashion.

*Replacement for $^3$He Proportional Counters*—Increased demand and vanishing supply of $^3$He has resulted in significant cost increases for $^3$He-based systems. With the expectation that $^3$He will not be available in the coming years, development of replacement systems is a high priority. Next-generation systems need to maintain efficiency and scalability to large area. Ideally, future systems would be directional fast neutron detectors.

*Time-correlated Signatures and Observables*—The *SNM Movement Detection Portfolio—Technology Roadmap* assigns first priority to the exploitation of time-correlated signatures as a means to detect shielded SNM. Further improvement in the understanding of the joint probability distributions on the number, energy, time scales, and angle of both neutron and gamma-ray emissions may enhance the exploitation of time-correlation signatures and allow for maximally selective detection systems. Simulation capabilities are required to understand these correlated emissions, especially from complicated source geometries possessing multiplication. The development of algorithms to discriminate these emissions from cosmic-induced backgrounds, which also need further quantification, is a present shortfall that must be addressed in parallel with systems development.

*Neutron Spectroscopy*—There is at present no robust, practical method of performing neutron spectroscopy in situ. Thermal neutron detectors with variable moderators require extended measurement times, physically large systems, and challenging deconvolution algorithms. The emerging technique of microcalorimetry possesses high resolution but minimal detection efficiency. Recoil-based detectors possess reasonable efficiency and can be assembled to cover large areas. In these detectors, resolution on monoenergetic sources can be as good as 11% at 2.5 MeV [Zim04], but, as with thermal systems, spectral deconvolution is a challenge. To date, the method that has come closest to meeting deployment needs are time-of-flight systems, but these systems suffer from a cumbersome geometry, the requirement of two well-separated detector planes, and high-fidelity time resolution.

## Prioritized Investment Options

Development of improved neutron detection capabilities is an active field of endeavor. While many potential R&D avenues exist, the following options are those identified by a group of SMEs and prioritized by NA-22 to best meet the broad range of requirements and fill shortfalls. This prioritization scheme, which largely consisted of first ordering options based on their priority in the *SNM Movement Detection Portfolio—Technology Roadmap* and then by estimated impact levels, is listed in **Table 4**.

**Table 4. Prioritized investment options for neutron detection systems.**

| Investment Option | Priority | Impact | Summary |
|---|---|---|---|
| Large-area, thermal neutron detection systems | High | High | Replacements for $^{3}He$ proportional tubes would have broad applicability to almost all SNM detection scenarios. Scalability at reasonable cost and complexity is essential. Gamma-ray rejection may not need to match the performance of $^{3}He$ initially, but it must in principle have the potential to do so. In addition to traditional applications, these detectors are of interest for time-correlation studies, but to be useful here they must possess segmentation and μs-scale timing. |
| Large-area, fission neutron detection systems | High | High | Considerable advancement of detection capabilities would occur if neutron detection systems could be developed that are insensitive to low-energy backgrounds and can be scaled into large-area systems. These detectors must be robust, fieldable, non-toxic, non-flammable, and preferably capable of resolving multiplicity for time correlation. The capability to operate in active environments is desirable but not required. These objectives create the need for high gamma-ray discrimination and reasonable power consumption. The potential of threshold detectors toward meeting these goals should be considered, but a clear path toward overcoming present development challenges must be addressed. Coherent system design is crucial and prototype systems are essential in the R&D phase to identify potential capabilities. |
| Algorithm development for exploitation of time-correlation observables | High | Medium | The existence and partial character of time-correlation signatures have been documented, but the value of fully exploiting such signatures for nonproliferation has not been firmly established. This is partially due to the need for more precise quantification of signature properties on both the theoretical and empirical fronts. The ultimate goal of quantifying the benefits of time-correlation observables in specific applications requires the development of signal-extraction algorithms and of particular interest here is the development of algorithms that effectively discriminate SNM fission observables from those of ambient background and cosmic-ray events. |
| Measurements and phenomenological modeling of SNM fission signatures | High | Medium | Proper exploitation of time-correlated signatures requires a thorough understanding of the joint probability distributions of the energy, number, angle and arrival time of neutrons and gamma rays emitted by the various isotopes of interest. Time-correlated signatures arise not only from spontaneous fission but also after induced fission. For both passive and active cases, collection and analysis of nuclear data will allow more sophisticated detection algorithms to be developed and influence detector development. Signature knowledge is especially important for shielded HEU detection, and exploiting such knowledge requires faster and higher-fidelity simulation tools. |

**Table 4. Prioritized investment options for neutron detection systems. (cont.)**

| Investment Option | Priority | Impact | Summary |
|---|---|---|---|
| Measurements and phenomenological modeling of cosmic-ray induced neutron backgrounds | High | Medium | The structure in energy, time, and spatial distributions of cosmic rays is an important and poorly understood background for SNM detection using neutrons. This is particularly true for low-signal applications, such as nuclear search and portal monitoring but may also be relevant for characterization and verification applications where rates are generally higher. A thorough understanding of the joint probability distributions of the energy, number, angle, and arrival time of neutrons and gamma rays emitted by cosmic events is needed. |
| Solid-state thermal neutron detection systems | Medium | High | Robust replacement detectors for $^3He$ proportional counters are needed for small-scale systems, such as handheld and human-carried units. Solid-state detection systems, which may not be scalable to large sizes at a reasonable cost, are particularly desirable. Such detectors must possess comparable intrinsic efficiency to $^3He$ and would preferably operate at lower bias voltages and consume less power. Excellent gamma-ray discrimination would considerably increase deployment capabilities. Fast timing at the µs scale is not required. Semiconductor-based detectors may be particularly good candidates with those based on embedded neutron absorbers possessing considerably more promise than those based on converter layers due to the requirement of high intrinsic efficiency. |

# Imaging Methods

## Technology Requirements

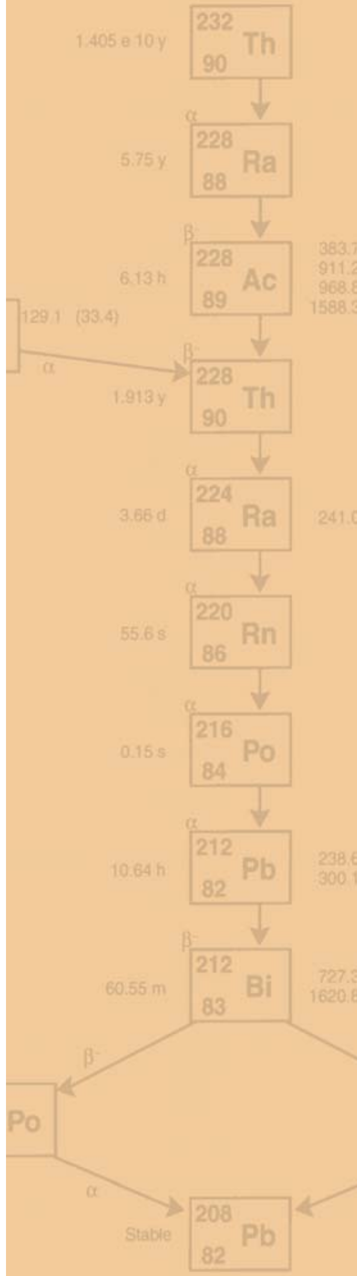
Gamma-ray imaging continues to be a robust field of R&D despite its inception over 50 years ago, particularly in medical imaging and astrophysics. Although developments from other fields, most notably astrophysics, have catalyzed the development of gamma-ray imagers for SNM detection, SNM detection presents unique problems that have not been adequately addressed. For instance, the use of gamma-ray imagers for SNM detection often involves detection of higher-energy gamma rays (up to 3,000 keV) than in medical imaging applications (≤ 100 keV).

Applications in need of location technologies range from directed search, where a source potentially resides in a bounded region, to safeguards and verification, where it is necessary to understand the distribution and quantity of SNM. While this broad application space presents a wide range of requirements, imaging systems have not seen widespread deployment because of their inability to suitably trade off two key parameters: angular resolution and detection efficiency.

Angular resolution is the figure of merit that distinguishes imaging systems from conventional detection systems. In some applications, the necessary resolution is a function of the measurement geometry but could be of *O*(1–10°). These rather stringent requirements stem from cases where one actually desires to attain an image of the environs, such as in the case of warhead dismantlement verification. Another application class uses angular resolution to discriminate against ambient background, in addition to gamma-ray spectroscopy for example. Here, the added value of imaging systems is their ability to analyze emissions in terms of intensity and spectral character from different regions of space, which may be as coarse as distinguishing between forward and rear fields of view. Irrespective of whether an actual "image" is reconstructed, imaging systems have the ability to encode spatial information from detected events, and this information substantially improves the signal-to-noise ratio in many applications [Zio02b] [Wur06].

Spatial information is of great value, especially in applications involving large standoff distances, but it is not a singular requirement. Detection efficiency is an essential requirement that plays just as critical a role in the development of imaging systems as it does in the case of spectroscopy. In spectroscopy, mid-resolution scintillators dominate system deployments because of the capability to fabricate large-area detectors. An analogous paradigm will likely govern deployment of imaging systems: a balance must be found between imaging efficiency (the fraction of events interacting in the detector that can be reconstructed) and angular resolution. The key figure of merit in imager development is thus the ability to attain spatial information without sacrificing more than a commensurate amount of detection efficiency.

When considering deployment of an imaging system in a specific application, the signatures of interest must be understood. Consider the case of gamma-ray detection, where some applications require detection systems be efficient across a broad range



of energies from 50 to 3,000 keV. These present considerable challenges to imaging systems whose operating principles may possess the necessary sensitivity only in specific energy ranges. Other applications may focus on discrete lines of interest, such as a hold-up measurement of the 186-keV line from $^{235}$U. When pondering the development of imaging systems for applications, it is crucial to understand the interplay between signatures and the energy dependence of both the angular resolution and detection efficiency, especially in the case of gamma rays.

Now that an array of imaging systems have been tested and evaluated in laboratory settings, a major requirement for development of next-generation systems is deployability. Imaging systems must be converted into automated systems not reliant on exhaustive data processing and analyst interpretation. Overall system sizes must be manageable and allow mobility.

## Survey of Field

This section surveys a range of methods, technologies, and design concepts for gamma-ray and neutron imaging systems. Gamma-ray imaging methods are enumerated first, because these methods are generally more advanced, and many of the neutron imaging methods derive from their gamma-ray brethren.

### *Gamma-ray Imaging Systems*

*Occluded Arrays*—The occluded array is not an imaging system in the purest sense, since it does not produce an image, but systems based on this concept provide directionality and are a potentially powerful method of detecting SNM. The simplest form of an occluded array consists of one or more detectors surrounded by one or more collimators (e.g., see [Ste05] [Mer07]). Using this simple approach of suppressing the background with a collimator, it may be possible to improve system performance, especially in search applications. Because of the high energy of gamma rays, collimators require considerable mass and volume to effectively shield detectors, and this precludes their use in some applications.

A variation of the simple collimator is an array of detectors that shield themselves, as shown in **Figure 13**. (Similarly, a monolithic detector, in which the locations of gamma-ray interactions can be determined, would serve the same purpose (e.g., see [Kay07]). There are two different ways that a self-shadowing array might be operated. The simplest method is to infer source direction from the difference in the total counts recorded in each detector. Another approach relies on timing methods to note near-coincidence events between detectors. The coincidences are then rejected, which enhances the differential counts. Alternatively, the coincident events provide a simple Compton scatter modality. The lack of a collimator makes this concept more efficient per unit mass, but scenarios arise in which the attenuation of a detector is not sufficient, and collimators are a more effective choice.

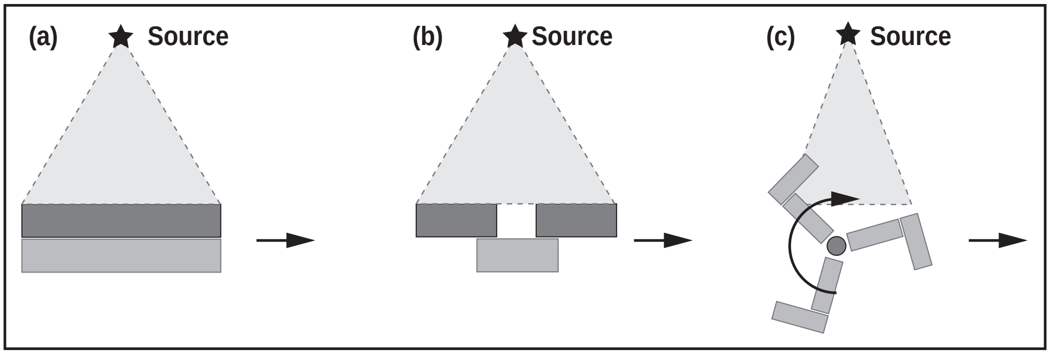



Figure 13. Simple detector configurations provide rudimentary directionality information without using a collimator. The configuration in (a) allows the determination of source direction by the difference in count rate between two detectors. In (b), detectors in the top layer act as attenuating elements as well as detectors. In (c), a rotating collimator with a single detector at the center produces directional information. Figure courtesy of Kai Vetter, Lawrence Berkeley National Laboratory.

*Spatial Modulation*—There are considerably more sophisticated methods of using collimators that provide spatial modulation. The simplest example of a modulator—and one particularly relevant to radiation imaging—is a pinhole camera that consists of a position-sensitive detector placed behind a pinhole aperture in direct analogy to production of optical images. With exquisite performance in terms of angular resolution, such a system possesses minimal detection efficiency.

More sophisticated versions of the pinhole camera consist of masks that impart a shadow onto position-sensitive detectors by attenuating the gamma-ray flux [Fen78]. The logic here is that if a pattern of pinholes are used, and the pattern can be completely deconvolved from the image, one will attain essentially the same angular resolution and contrast as a pinhole camera but with increased efficiency. The development of these coded-aperture instruments was largely driven by x-ray and gamma-ray astronomy. Coded apertures are well-suited to the problem of imaging distant point like objects in settings with modest background. In contrast, coded apertures were less successful in medical imaging where the object is in the near field, large in extent, and often situated in a highly diffuse background. Development of imaging systems for detecting gamma rays from SNM resides in a space between these two cases: point sources are often of interest, but they are located in a diffuse background.

Coded apertures capable of imaging SNM have been successfully developed and demonstrated. **Figure 14** shows an example coded-aperture imaging system [Zio02]. One important technical challenge in developing imagers is the design of an attenuator that operates efficiently across the gamma-ray energy spectrum. Attenuation of low-energy emissions in the 100-keV range may be achieved with a reasonable mask thickness. As the energy increases to the MeV range, coded apertures necessarily become massive [Zio04].

*Compton Scattering*—Compton cameras are popular for imaging applications with energies in excess of ~500 keV where the Compton scattering cross section is dominant. Compton cameras were invented by gamma-ray astronomers for use in balloon-borne

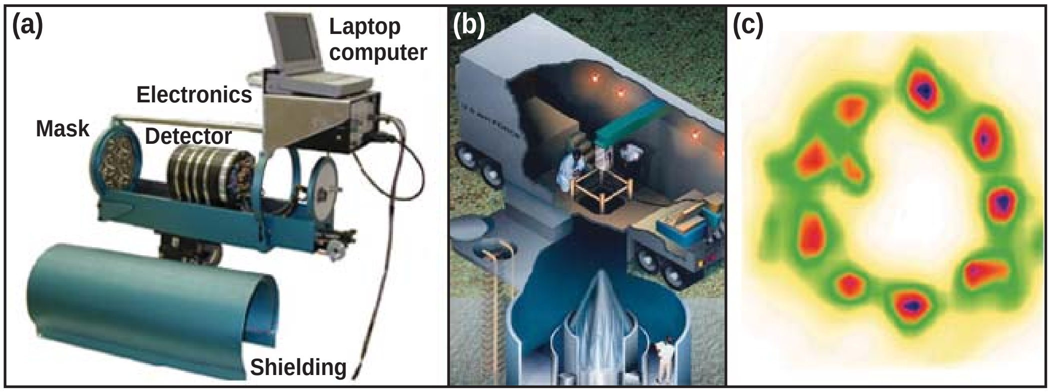



Figure 14. The Gamma-Ray Imaging System (GRIS) is a coded-aperture system developed for treaty verification purposes [Zio02]. It consists of a NaI scintillator viewed by a position-sensitive photomultiplier modulated by a tungsten mask. Pane (a) shows a photograph of the instrument with the light and gamma-ray shield removed. Pane (b) depicts the concept of operation. Pane (c) shows a reconstructed image of gamma-rays from a MIRV'ed ICBM taken with the instrument; the number of warheads (10) can be discerned from the image. Figure courtesy of Klaus Ziock, Oak Ridge National Laboratory.

or satellite-deployed gamma-ray observatories. These cameras rely on inverting the kinematics of Compton scattering. By measuring the energy of the scattered electron and the scattered photon along with their locations, it is possible to reconstruct one of the angles of incidence of the gamma ray. In determining one angle of incidence, the source's position can be limited to a conical surface—as opposed to a line in a perfect imaging system. One method of reconstruction then relies on back-projecting cones from multiple events. The artifacts produced by back-projection are substantial in a Compton camera and dramatically reduce the contrast in the reconstructed image. Higher-resolution images are possible with iterative reconstruction methods (such as maximum likelihood estimation) at the cost of increased computing resources.

Scatter cameras often consist of two detection planes: the front plane measures the position and energy of the scattered electron, a.k.a. the scatter plane, while the rear plane measures the position and energy of the scattered photon, a.k.a. the absorber. In the scatter plane, one is only interested in Compton scattering events; there is thus a disadvantage in increasing figures of merit familiar to spectrometers, such as the atomic number (and consequently photoelectric absorption). Some incarnations of Compton cameras thus employ two different materials: a low-*Z* material in the scatter plane and a high-*Z* semiconductor for the absorber. While there are several design parameters that determine the angular resolution of a scatter camera (e.g., see [Phi95]), the angular resolution is in practice dominated by the energy resolution of its detector elements. A variation on this theme that does not rely on the presence of an absorber layer consists of multiple layers of low-*Z* scattering planes that foster multiple scattering events (e.g., see [Row06]).

In terms of angular resolution, the highest performance Compton cameras incorporate semiconductor arrays because they offer superior energy resolution. Compton cameras based on semiconductors were first constructed from germanium but later from silicon-germanium hybrids, where the low-*Z* silicon is located in the scatter plane and germanium is the absorber [Vet04]. Although the first semiconductor Compton cameras were constructed from arrays of discrete detector elements, it became apparent early in the development of this technology that the use of monolithic detectors is advantageous. One design entails the use of a two-sided strip detector, such as the one shown in **Figure 15**.

There has also been a great deal of effort directed at development of CZT imaging systems. These include Compton cameras developed from discrete detectors [Ded07] and those developed from monolithic systems [Leh04] [Xu06]. The latter do not rely on discrete scattering and absorption detectors but instead on the reconstruction of scattering and absorption positions within a single element using depth-sensing techniques. This depth-sensing approach offers a compact design alternative which might be ideal for applications that do not require large absolute collection efficiencies since crystal sizes are presently restricted to $O(1\ \mathrm{cm}^3)$. Recent developments of CZT imaging systems consist of arrays of discrete detector elements whose events are combined to essentially create a larger monolithic element [Myj08].

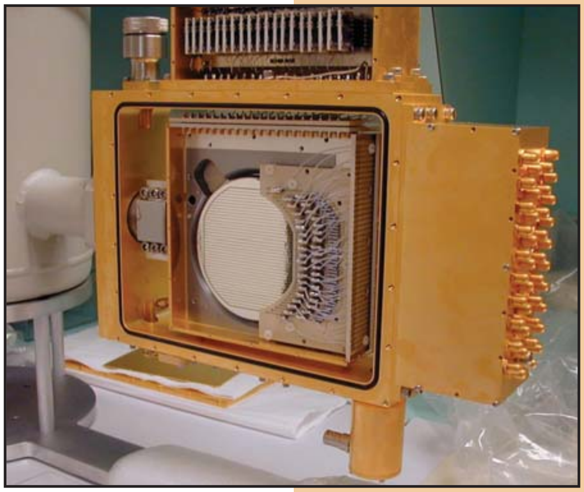


Figure 15. Photograph of a germanium double-sided strip detector [Vet06]. This particular detector has 38 strips on each side and thus contains 1,444 effective pixels, yet is read out into only 76 channels. This particular detector has an active area of about 50 $\mathrm{cm}^2$ and is 11-mm thick. Figure courtesy of Kai Vetter, Lawrence Berkeley National Laboratory.

*Recoil Particle Tracking*—Reconstruction of a three-dimensional track from Compton-scattered electrons creates the potential for more precise event reconstruction. For example, contemporary Compton cameras reconstruct one of the two incident angles of a detected gamma ray. If the trajectory of the scattered electron could be determined in the scattering detector, then both incident angles of the gamma-ray interaction could be reconstructed, which would result in a set of pointing vectors as opposed to overlapping cones.

One method of employing such electron-track-based reconstruction techniques involves pressurized time projection chambers (TPCs) because of their capability for three-dimensional track reconstruction of electrons. Ueno et al. recently demonstrated the feasibility of a Compton camera using a TPC as the scatter detector and an array of scintillators as the absorption detector [Uen07]. An alternate mode of operation in these detectors involves reconstructing the electron track alone, in analogy to neutron TPCs. Such a method would yield reduced, but potentially sufficient, angular resolution. On the semiconductor front, investigation of the possibility of tracking the direction of the scattered electron in silicon is under way using a variant of the silicon drift detector [Cas06][Cas07]. Yet another method for electron tracking in the scatter plane entails using crossed scintillating fibers to reconstruct the electron track [Bol98], but no recent results have been reported.

TPCs may prove difficult to apply to gamma-ray detection because of their limited stopping power and, in some high-rate applications, possible dead-time limitations. The prodigious data production from a gamma-ray TPC would be a challenge to process and reconstruct with limited computational power. Though such reconstruction is routinely performed in high-energy physics experiments, the computing cost per channel would have to be adapted to the relatively small unit costs that are relevant for field-deployable devices

*Hybrid Modulator Scatter Camera*—Because modulator-based systems are most practical at low gamma-ray energies and scatter-based systems are advantageous at higher energies, hybrid systems that use both modulation and scatter elements have been developed to operate over a wide energy range. A novel variant of the hybrid approach uses a combined "active coding aperture" and Compton camera. In this approach, aperture elements are themselves detectors that serve as modulators in the coded-aperture mode of operation and as a scattering plane in Compton-scattering mode. Theoretically, the active mask approach could also offer increased effective mask opacity over passive mask elements by actively vetoing low-angle scatter events that would otherwise pass through the coding mask and interact with the imaging plane. Recent studies indicate that the active mask approach may not in practice increase opacity substantially at higher energies [Cun07], but such an instrument might offer substantial performance increases in terms of performance per unit instrument mass (compared to hybrid approach with a passive collimator), since most of the mass of the instrument would be comprised of active detector elements.

### *Neutron Imaging Systems*

*Spatial Modulation*—Imaging of thermal neutrons has relied exclusively on spatial modulation schemes. While it is in principle possible to modulate high-energy neutrons, the relative transparency of materials at high neutron energies has deterred such development. Effective passive masks for high-energy neutron modulators would have to be very thick of *O*(10 cm), and, if respectable angular resolution were required, masks would have to be of *O*(1 m) in size. These thickness requirements may be reduced by the use of active masking elements, but it is not clear by how much.

*Scatter Cameras*—Neutron scatter cameras operate on a principle similar to Compton cameras: they deduce directionality from two discrete events in two detector planes. The crucial design difference arises from the fact that neutrons have a rest mass that allows their energy to be deduced from their velocity. Instead of the second detector plane acting as a calorimeter to measure the scattered neutron's total energy, its energy can thus be measured via time of flight between the first and second scatter planes. This is an essential element of a neutron imager, since effective neutron spectrometers do not yet exist. **Figure 16** illustrates this process.

If the energy of the scattered neutron is not excessive and the distance between scattering planes is not too small (equal or greater than tens of centimeters), time-of-flight energy deduction can be accomplished with modern PMTs and readout electronics. But because neutron scatter cameras rely on elastic scattering of neutrons, the pool of candidate detector materials is effectively limited to organic scintillators. Because they are well understood, readily available, inexpensive, and capable of pulse-shape discrimination, liquid scintillators have been the detector material of choice for neutron scatter cameras to date [Mas08]. Although it is possible to reject gamma-ray events in a plastic-scintillator-based scatter camera using time of flight between detector elements, and this approach has been used with some success [Van07], time-of-flight alone cannot provide the discrimination required to operate in high-gamma backgrounds due to naturally occurring radioactive material.

Other candidate materials for neutron scatter cameras are the organic crystals anthracene, *trans*-stilbene, and their relatives. Unlike plastic scintillators, organic crystals are capable of effective gamma-ray rejection through pulse-shape discrimination, but these organic crystals are not readily available, have only been fabricated in small sizes, and are relatively expensive. Researchers have reported an anisotropy in the response of these crystals depending on the direction of neutron scatter from the crystal [Bro74]. If observations of the decay characteristics of the scintillation pulse could correct the anisotropy, then it is possible that organic crystals could become candidates for use in high-energy neutron imagers. Size, cost, and availability issues must be resolved for these to be competitive with organic liquid or plastic scintillators.

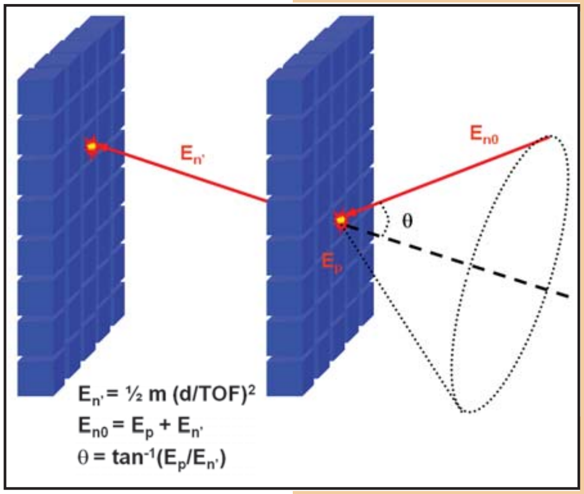



Figure 16. Diagrammatic representation of neutron scatter camera operation. $\boldsymbol{E_{n0}}$ refers to the energy of the incoming neutron, and $\boldsymbol{E_{n'}}$ the energy of the neutron scattered from the front detector plane to the rear. Figure courtesy of Nick Mascarenhas, Sandia National Laboratories.

The energy range over which neutron scatter cameras can effectively operate is determined largely by the operating range of the detector elements. For typical scintillator elements, this range is $\gtrsim$ 100 keV. If unscattered fission neutrons are of exclusive interest, then this threshold is acceptable. If one desires to detect downscattered neutrons, then a lower threshold may be desirable.

*Recoil Particle Tracking*—It is possible to perform neutron imaging by using the double scatter of non-relativistic neutrons off of ambient protons by tracking the recoil protons. This technique can perform both neutron imaging and spectrometry. To achieve this, the detector must be capable of resolving the path of the recoiling particle after having been scattered by an incident neutron. The neutron angular and energy resolution depends upon the precision with which one can determine the recoil proton direction and energy. When depositing their energy via ionization, protons exhibit a "Bragg peak," which is a phenomenon where a large fraction of energy is deposited at the end of the proton's track. Since the Bragg peak occurs at the end of the track, it can be used to determine the track's orientation. The length of the track provides an estimate of the energy of the proton. By combining the proton energies and directions from a double neutron scatter, the energy and direction of the incident neutron can be determined in a way similar to a neutron scatter camera. This technique is, in principle, more precise since the path of the first recoil proton constrains the direction of the incident neutron to lie on a segment of a cone (an arc). This could lead to an improvement in angular resolution and thus improve signal to background.

One method that has been used for proton tracking uses a stack of crossed scintillating fibers to reconstruct the proton track [Mil03]. Recent results show that such instruments can operate at high energies ~20–250 MeV. At fission neutron energies, the smaller proton recoil energy available limits performance. The proton will fully deposit its energy in a very short distance, ~1 mm in a plastic fiber, and one needs several hits to determine a track. This requires the fibers to be small of $O$(100 μm). The sensitivity of this technique is thus constrained by limits on detection volume that can be obtained using crossed scintillating fibers of this size. High channel counts also lead to associated readout challenges. Since plastic scintillation fibers are sensitive to neutrons, gamma rays, and muons, discriminating backgrounds from cosmic muons and ambient gamma rays poses another challenge.

*Time Projection Chambers*—Another technology with potential to track recoil protons and thus image incident neutrons is the TPC, which was introduced in the *Neutron Detection Systems* section. TPCs consist of a gas-filled chamber with multi-wire proportional counters at the ends. A high electric field is held across the length of the chamber such that an ionization track left by a recoiling particle in the gas will drift the length of the chamber, where it is detected by the wires at the end. The horizontal directions of the track can be reconstructed by the location of charge deposition in the wires, while the vertical direction is determined by differences in the drift time in the gas. The resolution with which horizontal directions can be determined is limited by the pitch of the wire grid, while the inferred vertical direction is limited by the timing resolution of the measurement.

Because the recoil particle deposits less energy per unit distance in a gas, the length of the track will be longer than in a solid- or liquid-based recoil-particle tracking detector. This allows for a lower energy threshold with the possibility of tracking recoil protons from fission-energy neutrons. One of the drawbacks of a gas is the low density of target particles. This is especially problematic when requiring two scatters to fully determine the incident direction. Thus, to be sensitive in a multi-scatter regime, a TPC must be large or operate at very high pressures, and both factors complicate field deployment. Alternatively, TPCs can operate in a single-scatter mode where directionality is achieved via collection of multiple single-scatter events, thus reducing the requirement of enough stopping power to induce multiple scatters in a single event.

Because neutrons deposit the most energy on average to low-mass gasses, high-pressure hydrogen TPCs were first considered, but safety concerns have led to other gases. For example, alkane gases have been used to combat perceived safety issues and have the added benefit of higher hydrogen density compared to $H_2$ gas. Other potential drawbacks include the complexity of the readout system due to the large number of readouts and the possibility for microphonic noise in wire-based systems, although it is important to note that other readout methods exist, such as pad plane readouts.

The lower rate of energy deposition ($dE/dX$) of electrons (scattered by gammas), compared to nuclear recoils producing the same amount of ionization, could make a TPC less susceptible to gamma-ray backgrounds. Signal to background issues for these detectors are currently under study. Current development is underway to understand some of these issues and develop an instrument suitable for nuclear search and monitoring applications.

## Identification of Shortfalls

Imaging systems hold the potential for significant advantages in terms of signal to noise because of their ability to examine both the spatial and spectral character of events. Despite this potential and a fairly mature technological state, imagers have experienced very limited deployment. The reason for this stems from two major deficiencies: efficiency and deployability. A third shortfall related to detection efficiency stems from the fact that imaging systems struggle to perform well over the full range of particle energies emitted by SNM.

*Efficiency*—The most pressing shortfall of conventional imaging systems is their general dearth of detection efficiency, imaging efficiency, or both at high gamma-ray and neutron energies. Although imaging methods generally have higher signal-to-noise performance than non-imaging techniques, the efficiency with which they collect and reconstruct events from both sources and background can be very low.

Efficiency presents challenges to different imaging systems in different ways. In Compton cameras, detection efficiency can be a challenge, and, in both Compton cameras and neutron scatter cameras, typical imaging efficiencies are less than 5–10% [Sei07]. Modulation systems can in principle maintain a large imaging efficiency, but modulation is challenging at high gamma-ray energies. If the efficiency of imaging systems, particularly spectroscopic systems, could be increased substantially, then imaging systems could play an important role in a variety of applications.

*Deployability*—Overall system size is an important constraint (but one that is highly application-specific) when considering deployability, and many gamma-ray and neutron imaging systems are intrinsically large. For instance, coded-aperture imaging systems for high-energy particles must have a minimum mask thickness on the order of the attenuation length of the particle to be detected (and preferably larger), which is of *O*(1–10 cm) for high-energy photons. This results in a large size that can impede their deployability, particularly in cases where mass is constrained. A similar scaling rule applies to neutron scatter cameras because the probability of a neutron scattering off of one detector element and being successfully detected in another is minimal. Unless a scatter camera is large and densely populated with detectors, the probability of interacting with more than one detector element is small. Secondary shortfalls associated with complexity challenges include the need for multiple channels and their associated instrumentation, complex readout software, ruggedness, and power consumption. Event reconstruction algorithms often require significant computational resources to mitigate the effects of artifacts that mimic source signatures. It should be noted that although these are significant, similar engineering challenges have been solved for imaging systems in other applications with deployments to fixed installations with considerable infrastructure, such as medical diagnostics. An important challenge remains, however, that is unique to SNM detection: namely the automated analysis of spectroscopic image data to provide actionable information without user input or expert analysis.

*Dynamic Range*—Gamma-ray and neutron emissions from SNM span a large range of energies, in the case of gamma rays from ~50 to 3,000 keV and in the case of neutrons from thermal energies to 10 MeV. Since imaging methods tend to exploit a particular interaction mechanism that is dominant over a specific energy range, imaging systems struggle to maintain sensitivity across this range. In the case of gamma rays, Compton cameras have maximum sensitivity at energies in between the dominant photoelectric and pair-production mechanisms. Modulation systems need to fully attenuate gamma rays in their masks and thus perform best at low energies. Analogous principles apply to neutron imaging systems where modulation techniques are well-developed for thermal neutrons, but there exist no effective modulation schemes for high-energy neutrons. Conversely, energetic neutrons have recently been successfully imaged with scatter cameras, but scatter technologies are useless for imaging at low energies.

## Prioritized Investment Options

The fields of gamma-ray and neutron imaging are complex, and their combination with constraints of operational users creates perhaps the most difficult area in which to prioritize investment options. While many potential R&D avenues exist, the following options are those identified by a group of SMEs and prioritized by NA-22 to best meet the broad range of requirements. This prioritization scheme, which largely consisted of first ordering options based on their priority in the *SNM Movement Detection Portfolio—Technology Roadmap* and then by estimated impact levels, is listed in **Table 5**.

**Table 5. Prioritized investment options for imaging methods.**

| Investment Option | Priority | Impact | Summary |
|---|---|---|---|
| Imaging systems not reliant on discrete detector elements | Medium | High | The largest deficiency of existing gamma-ray and neutron imaging systems is their lack of efficiency partially brought about by the need to modulate or segment detectors. Exploration of methods for the tracking of scattered particles without using individual discrete detector elements may create new systems that offer sufficient efficiency and angular resolution. One existing approach in this spirit relies on time projection chambers, but their gas-filled nature limits overall efficiency. Bubble chambers offer similar advantages in principle, and, if continuously sensitive bubble chambers could be devised, they would present a potential solution. Other possibilities include encoding angular trajectories in pulse shape. |
| Scatter cameras that track secondary particle production | Medium | Medium | Existing scatter cameras, both for neutrons and gamma rays, reconstruct a single angle of the incident particle being imaged. The resulting image reconstruction, based on cone projection, is an inefficient and noisy process. If both angles of the incident particle could be deduced, image reconstruction and source location could be performed more efficiently. By tracking the secondary particle produced in scattering events, it would be possible to determine both incident angles for the incoming particle—thus constraining its trajectory to a line instead of a conic surface. If methods could be devised to track protons (in neutron scatter cameras) and individual electrons (in gamma-ray Compton cameras), higher performance imaging devices could be constructed. |
| Simultaneous gamma-ray and neutron imaging | Medium | Medium | The detection of heavily shielded SNM or SNM at large standoff distances in the presence of natural radioactive background presents a challenging signal-to-noise problem. If an effective system could be developed to simultaneously image neutrons and gamma-rays, the signal-to-noise ratio might increase considerably to the point that only a few events would be necessary for positive detection of SNM. While two separate imaging systems achieve this same goal, the efficiency of such a system and its deployment challenges would be serious impediments. The development of imaging technology simultaneously sensitive to energetic neutrons and gamma rays would introduce a new capability. |
| Solid, high-energy neutron imaging systems | Medium | Medium | Existing high-energy neutron imaging systems rely on liquid organic scintillators as detector elements. While necessary to perform pulse-shape discrimination against interfering gamma rays, these liquid scintillators are difficult to deploy. Single-crystal organic scintillators, such as anthracene and *trans*-stilbene, could solve many of the problems inherent with liquid scintillators while simultaneously offering higher performance. The successful development of systems based on single-crystal organic scintillators requires concurrent developments in crystal growth and instrument development. |

# Photon Sources



## Technology Requirements

Application of photon sources to the detection and characterization of SNM is a relatively new R&D objective. Requirements for field-deployed systems in nonproliferation are considerably different than the requirements under which today's laboratory systems were developed. The need to develop photon source technology outside of the laboratory led to the prioritization of both broad-spectrum and monoenergetic photon sources as first-priority items in the *SNM Movement Detection Portfolio—Technology Roadmap*.

Photon energy is the most fundamental requirement for SNM detection, and sources must provide significant fluxes at an inspected object in the range of 1 to 3 MeV for nuclear resonance fluorescence (NRF) and in the range of 10–20 MeV to maximally induce photofission, as shown in **Figure 17**. Due to attenuation and energy downscattering through air, standoff applications may even require significantly higher energies. Control over the emitted energy spectrum is also an important requirement. For photofission applications, bremsstrahlung photons less than the photofission threshold energy will contribute to unwanted dose, while, for NRF, photons with off-resonance energies solely contribute to continuum background underneath regions of interest in detector response functions. These unwanted photons could be eliminated from the incident flux itself or via signal processing, e.g., time tagging.

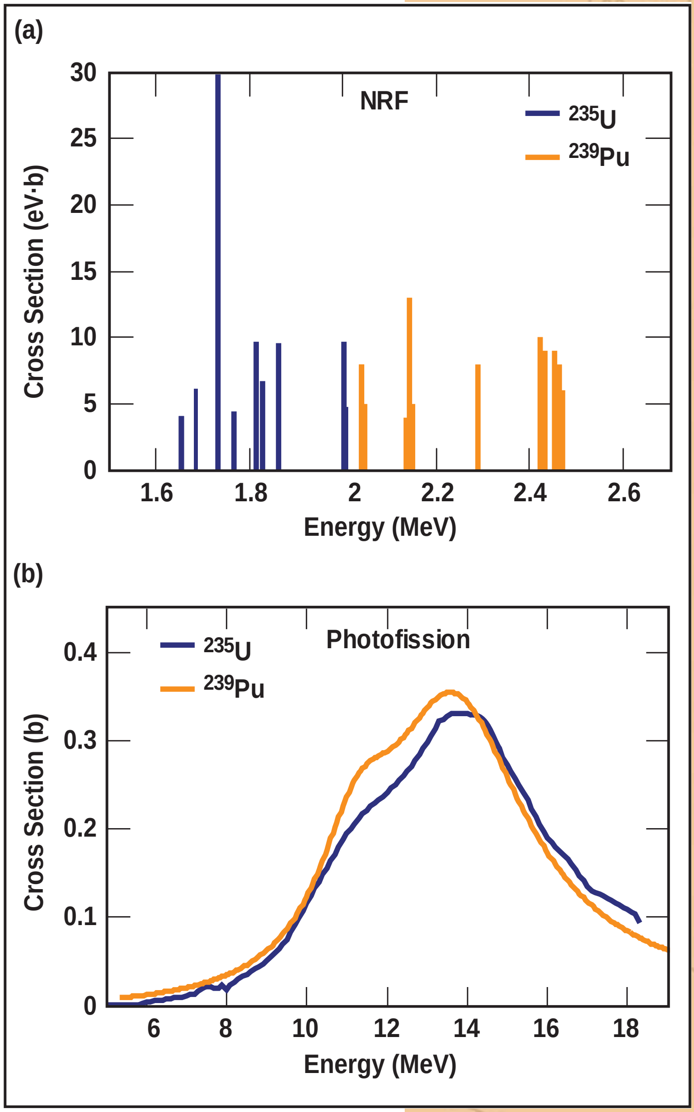



Figure 17. Cross sections for NRF (a) [Ber08] and photofission (b) [T2N09] as a function of energy. Note the different energy regimes associated with each process.

An ideal photon source for photofission applications consist of no photons having energies less than ~7–8 MeV and with higher-energy photons in either discrete energy regions or with a continuum of energies providing direct and/or downscattered flux interactions in the 10–20-MeV photonuclear interaction region of interest. An ideal source for NRF applications will only allow photons within a narrow bandwidth surrounding discrete lines of interest to contribute to measured spectra. One method of achieving this is the development of tunable, quasi-monoenergetic sources with narrow bandwidths (defined as $\Delta E/E$) ideally of $O(10^{-4})$.

## Photon Sources

Required photon fluxes vary considerably among applications, especially as a function of standoff distance, but, given that measurement times are typically of $O(10–100\text{ s})$, SNM detection in the field requires fluxes well above systems designed for laboratory-style analysis. Mainly for NRF signatures, but potentially for prompt photofission signatures as well, continuous-wave or quasi-continuous-wave operation is desirable due to the response time of high-resolution signature detectors. For pulsed sources, detector recovery can become a significant challenge requiring further development to enable accurate detection of these signatures. Standoff-detection applications impose the additional requirement of forward-directed photons with precision alignment.

Ultimately, sources must be integrated into operations that require transportability, provide limited physical space and infrastructure, and set operator dose limits. System-wide footprints of $O(1–5\text{ m}^2)$ with power consumption of $O(25\text{ kW})$ will support portability. Reduced radiation exposure to both the environment and operators is mandatory, and reducing flux from photons that do not induce signatures of interest is thus an important area of development.

### Survey of Field

Contemporary photon sources rely on acceleration of particles, either electrons or ions, and the subsequent conversion of their energy into photons. This process occurs in four generic stages. The first stage consists of an ion source that creates free electrons or ions. A low-energy accelerator, coupled to the electron/ion source, extracts the electrons/ions. The next stage accelerates particles to the desired energy via various electrostatic, radio-frequency, or plasma-based acceleration methods. Particle beams must then be transported or drifted to the final stage that converts the electron/ion energy into photons, most often by bombarding a target material. A few key parameters describe accelerator capabilities: the particle accelerated (electron/ion mass and charge), the final energy of the accelerated particle, the beam emittance (or focusability and energy spread), the average beam current, and, for delayed signal analysis, duty factor and/or repetition rate can be a critical factor.*

Several methods have been used to accomplish the first three stages and produce accelerated electron/ion beams. These include:

*Linear Accelerators (LINACs)*—LINACs are microwave-driven resonant-cavity devices that exploit the large electric field gradient for short-wavelength electromagnetic waves. When charged particles are injected into such a field, some of them (~¼ to ½) are accelerated to high energies by the microwave's electromagnetic field, at which point they can be extracted and used. LINACs are widely used for both electron and ion particle acceleration. Contemporary magnetron/klystron-driven electron LINACs can readily produce electrons at 10 to 20 MeV/m acceleration gradients with 50 to 250 μA average beam currents. Various transportable designs are commercially

* Another quantity, the beam power, is the product of the energy and average current of the accelerated beam. For example, a 10-MeV electron beam operating with and average 10-μA beam current will generate a 100-W beam. Peak beam current is also a key parameter for some detection schemes, e.g., in "single-shot" detection.

available [Lin09]. Flexible design parameters enable LINACs to support many application-specific needs (e.g., **Figure 18**). For photon-inspection applications, LINAC performance is in practice limited by environmental dose management and available system power. Largely due to higher beam current needs and reliable operational performance, the S- and L-band frequencies have been common in LINAC designs; however, the use of X-band and higher-frequency LINAC systems can significantly reduce any overall inspection system design. A radio-frequency quadrupole (RFQ) linear accelerator is a more sophisticated device, and, for typical commercial, transportable applications, RFQs can provide up to 7-MeV ions with a peak current of ~25 mA [Acc09], yet it is still limited by dose management and available power. They are also considerably less rugged and require more maintenance.

Figure 18. A transportable, forward dose-controlled, photon inspection system prototype using a nominal 30-MeV LINAC mounted on a 2.4 × 1.2-m beam targeting assembly for standoff nuclear material detection. Figure courtesy of James L. Jones, Idaho National Laboratory.

*Electrostatic Accelerators*—Electrostatic accelerators operate by maintaining a fixed terminal voltage that attracts or repels charged ions. To maximize ion beam energy with a minimum terminal voltage, a "tandem" configuration can be used to double the ion energy. In the tandem configuration, electrostatic accelerators have two stages of acceleration—first "pulling" negative ions and then "pushing" positive ions that are created upon interaction with thin foils that strip electrons from the ion. Insulation of multi-MeV high voltages has traditionally been accomplished using high-pressure vessels that are large and massive. For this reason, near-term, transportable systems with electrostatic accelerators will be restricted to lower ion beam energies. Compact systems have been developed capable of accelerating protons up to 500 keV with average beam currents up to $O$(1 A) [Lud09]. These types of systems, such as the one shown in **Figure 19**, are generally acceleration gradient-limited due to breakdown complications from the large applied voltage, but are also limited by the lack of compact high-voltage power supplies.

*Cyclotrons*—In the cyclotron, particles are confined to a circular trajectory, typically using electromagnets, until they reach sufficient energy. This method has the advantage of continuous acceleration, since the particle can remain in transit almost indefinitely. Another advantage for higher-energy applications is that a circular accelerator has a smaller footprint than a linear accelerator of comparable energy and power (i.e., a LINAC must be extremely long to have the equivalent high-energy acceleration capability of a cyclotron). Commercial, multi-meter-scale cyclotrons with masses of $O$(10,000 kg) accelerate protons up to 30 MeV with average beam currents up of $O$(1 mA) [Adv09]. Using state-of-the-art magnet technology, including variation of the cycle time to accommodate increasing velocity and/or superconducting technologies, these systems can produce higher-energy particles within a reasonably compact configuration.

## Photon Sources

*Laser-driven Wakefield Accelerators (LWFAs)*—These accelerators have received recent attention because of their ability to accelerate electrons to very high energies in very short distances. The unique LWFA technology exploits the radiation pressure of an intense laser to excite a space charge wave in a plasma. The induced electric field has been demonstrated to accelerate electrons to 1,000 MeV in distances of 3 cm as compared to distances of *O*(30 m) for the aforementioned conventional accelerators [Lee06]. Present electron energy spread and stability are of *O*(1–3%) [Rec09]. It is expected that detailed control of electron injection and accelerator structure will improve beam quality in the next several years, but duty factor, average beam power, and minimizing ion energy spread are all major challenges that must be addressed before applications will benefit from LWFAs. LWFAs have a demanding laser pulse-length requirement, ~50 fs, that is required to match the plasma wake.

Figure 19. A 165-keV electrostatic accelerator with high-voltage power supply (in background on left). Figure courtesy of Arlyn Antolak, Sandia National Laboratories.

After producing electron/ion beams, several techniques are available for conversion into photons. The simplest approach exploits the bremsstrahlung process and produces a broad energy spectrum. A more speculative approach, which is also broad in its energy distribution, exploits the fusion process. Production of monoenergetic photons is a significantly more challenging proposition. Two production methods, one based on particle-induced nuclear reactions and the other laser Compton scattering, are currently under development.

*Bremsstrahlung*—Perhaps the most common method of high-energy photon production is the bremsstrahlung process whereby energetic electrons interact in an electron/photon converter material and emit a portion of their energy in the form of photons. Bremsstrahlung sources produce photons with an exponentially decreasing energy spectrum that extends up to the maximum energy of the electron. The efficiency of energy conversion varies, and the fraction of converted energy increases with electron energy and is proportional to the square of the converter's atomic number ($Z^2$). If the ion-to-photon interaction in the converter is directionally controlled, the emitted photons will have a forward-directed flux with decreasing opening angle as the electron beam energy increases. It should be noted that the converter material could incorporate photon-energy filtering methods and even consist of the object under inspection or surrounding objects, if dose constraints can be adequately managed.

*Fusion*—In principal, "mirror-type" fusion reactor designs using magnetically confined plasmas could isotropically generate photons with a Maxwellian energy spectrum. Such an energy distribution would induce more photofissions per unit dose than a bremsstrahlung spectrum. While large fluxes of relatively low-energy photons have been demonstrated with this type of device [OTo83], the systems are of *O*(10 m) in size and cost billions of dollars. The feasibility of system scaling to generate photons of $O$(10 MeV) remains unclear since such photon energies have not been the focus of fusion technology development. In addition, with a harder photon flux comes more difficulty in meeting shielding requirements for a transportable system.

*Particle-induced Nuclear Reactions*—Reactions between accelerated ions and low-$Z$ materials emit monoenergetic photons that correspond to specific states within the compound nucleus. These nuclear reactions require a stable (or long-lived) target nucleus and an incident particle beam that can be easily produced and accelerated to an appropriate energy—often corresponding to a reaction's resonance energy. Over 500 nuclear photon-emitting reactions have net energy production greater than the photofission threshold energy, but the vast majority of these reactions produce dual-particle emissions consisting of both photons and neutrons (or other particles). Pure photon sources can be generated from proton-capture reactions with low-energy narrow resonances, and **Table 6** identifies those most applicable to photofission. One drawback of reaction-based photon sources is that, aside from those mentioned above, the emitted photons are nearly isotropic. Only a small fraction of emitted photons are thus incident on the object of interest—a fact exacerbated in standoff applications. Achieving large fluxes at the object of interest requires directing copious amount of protons onto the reaction target. This creates significant engineering challenges in target design.

*Laser Compton Backscatter*—The head-on scattering of relativistic electrons and laser photons produces a forward-scattered beam of nearly monoenergetic photons. The energy of the scattered photon ($h\nu_{\text{scatter}}$) is a function of the electron energy (via $\gamma$) and laser frequency ($h\nu_{\text{laser}}$):

$$h\nu_{\text{scatter}} = 4\gamma^2 h\nu_{\text{laser}} \; .$$

Hence, higher electron energies of $O$(100–1,000 MeV) will be required to achieve the desired energetic photon beams via any laser Compton backscatter-conversion process. For example, scattering between 800-MeV electrons and 1-µm laser light produces a beam of 15-MeV photons. Photon beams produced in this process have two attractive characteristics. First, the beam divergence can in principle be small enough to project a cm-size spot at a 100-m standoff distance. Second, if both the electron beam and laser

**Table 6. A sampling of low-energy, proton-capture reactions capable of producing pure photon beams. Bold font indicates gamma-rays emitted with the highest probability.**

| Reaction | $E_\gamma$ (MeV) | $E_p$ (keV) | $\sigma$ (mb) | Width (keV) |
|---|---|---|---|---|
| $^{7}Li(p,\gamma)^{8}Be$ | **17.7, 14.8** | 441 | 6 | 12 |
| $^{11}B(p,\gamma)^{12}C$ | 16.1, **11.7**, 4.4 | 163 | 0.16 | 7 |
| $^{13}C(p,\gamma)^{14}N$ | **8.06**, 4.11 | 550 | 1.44 | 33 |
| $^{19}F(p,\alpha\gamma)^{16}O$ | 7.1, 6.9, **6.1** | 340<br>484<br>597<br>672 | 160<br>32<br>7<br>57 | 3<br>1<br>30<br>6 |

are monoenergetic, the resulting photon bandwidth, defined as $\Delta E/E$, can be of $O(10^{-3})$ and potentially smaller. Small photon bandwidths lead to a large signal-producing photon flux per unit dose imparted to the surrounding environment, especially when compared to a bremsstrahlung source. Laboratory sources have produced $10^6$ photons/laser pulse on an item of interest at multi-MeV energies with a bandwidth of ~0.1 [FEL09]. At lower energies, laser Compton scatter sources produced $10^9$ photons/laser pulse with a bandwidth of 0.1 at 70 keV [Gib04]. More recent work produced $10^6$ photons/laser pulse at 700 keV [Alb08].

*Time-Tagged Sources*—It is possible to have both monochromatic and broad spectrum sources simultaneously. The method of "tagging" photons (either bremsstrahlung-generated or laser-Compton scattered) has been developed in several nuclear physics labs since the 1970s (e.g., see [Vog93][Elv08]). Photon tagging involves analysis of the scattered electrons after photon production. By measuring the energy/momentum of the photon-creating electrons, the photon energy and time of production can be deduced. This technique has contributed an enormous amount of information to the world's photonuclear data, and it enables simultaneously using the entire spectrum for photofission measurements, for example, while also defining quasi-monoenergetic portions of the spectrum that are relevant for NRF. Photon tagging requires high duty factor electron beams. Bremsstrahlung-based tagging systems typically employ a magnetic spectrometer to momentum-analyze the photon-creating electrons and to dump the non-interacting electron beam. The energy resolution, $\Delta E/E$, of each photon-beam channel depends upon properties of the electron spectrometer (e.g., momentum dispersion, position resolution of the electron detectors in the focal plane, magnetic field non-uniformities and fringe fields), the electron beam emittance, and possible sources of electron multiple-scattering in systems that are not completely vacuum-coupled. Resolutions of $O(10^{-3})$ to $O(10^{-2})$ at central tagged photon energies in the range from 10 MeV to several hundred MeV are typical. The maximum useful tagging throughput depends upon the response time of the electron spectrometer, the coincidence resolving time between the tagger and detectors registering products of the photon-induced reaction of interest, and the throughput of the data acquisition system. Tagged photon intensities reported in the literature range from $O(10^7)$ photons/second integrated over a 3-MeV window centered at ~10 MeV [Elv08] to $O(10^8)$ tagged photons/second in a 62-channel tagger spanning ±20% in energy around 100 MeV [Vog93].

## Identification of Shortfalls

The aforementioned requirements will challenge technology development in terms of producing necessary photon fluxes, managing overall system size and mass in conjunction with developing compact and efficient power supplies, and limiting environmental dose. Technology development to date has produced progress in each of these areas, but progress has been spread over a range of technologies. A comprehensive photon source solution does not yet exist. For example, while monoenergetic photons can reduce the dose on target required for a successful inspection, they have to date struggled to deliver sufficient photon fluxes to the item of interest. Bremsstrahlung sources are approaching the capability to deliver sufficient broad-energy fluxes at standoff distances, but they must be made compact with reduced power consumption. In total, the shortfalls that must be overcome reside in four broad areas:

*Photon Flux*—Increasing flux generally means increasing the beam energy and current delivered by an accelerator. However, there are practical limits to any accelerator design, at a given energy, for which further beam current increases are not feasible. Hence, the beam current and accelerated electron/ion energy are closely intertwined by physical design constraints, rather than being independently tunable parameters. Near-term advances toward efficient power supplies, increased acceleration gradients, and robust target designs are needed to advance capability. For bremsstrahlung sources to be feasible in photofission applications, enhanced acceleration gradients are needed for compactness, low-energy photon production management is needed for dose control, and higher beam currents may be required for interaction optimization; for NRF measurements, the bremsstrahlung sources must operate at high frequencies to emulate quasi-continuous-wave sources. In the realm of nuclear-reaction-based sources, the primary near-term technical challenge revolves around stability of the reaction target. Achieving reasonable fluxes on items of interest requires that significant amounts of beam power be placed on a production target to achieve a reasonable photon flux. While bremsstrahlung sources must match higher beam currents with higher beam energies, effective ion sources must find an appropriate balance between high-energy, low-current operation and low-energy, high-current operation. In the long term, the development of pseudo solid-state or laser-driven accelerators may enable combined high-energy, high-current operations.

*Tunable, Monoenergetic Beams*—While optimism surrounds the potential of laser Compton scattering to provide high fluxes of monoenergetic photons, shortfalls exist in the ability to produce tunable beams that are stable during day-to-day operation. Continued development relies heavily on advances in lasers that are compact, high power, energetic of $O$(1–10 J), and have short pulse widths of $O$(1 ps). The electron-laser interaction also requires further engineering to increase flux and decrease the bandwidth. In the long term, transitioning these sources out of the laboratory requires advances in accelerator development to reduce overall system size.

*Transportable and/or Fieldable Designs*—Today's accelerator technologies are over 60 years old and were developed for laboratory operation. For example, high-energy electrostatic accelerators are physically large and massive to reduce breakdown between acceleration stages. Accelerators of all types must now be transformed into compact, efficient systems with low overall costs. Necessary advances include development of compact high-voltage power supplies and associated power-conditioning stages, thermally limited cathode photoguns to support high-repetition-rate applications, and radio-frequency and non-radio-frequency acceleration waveguides and cavities that reduce size. In the long term, high-gradient LINACs or laser-driven accelerators may be important to provide high gradients and, hence, be important in achieving small footprints.

*Dose Control*—All electron and ion accelerators will produce radiation dose at the photon source, at the item of interest, and in any intervening material between source and interrogation target. In delivering the necessary photon fluxes, it is expected that background-type dose limits will be exceeded. Thus, essentially all applications will require radiation control, and shielding (coupled with technology-specific enhancements) emerges as one of the paramount issues for accelerator-system design.

## Prioritized Investment Options

The development of monoenergetic and broad-spectrum photon sources were both first-priority items in the *SNM Movement Detection Portfolio—Technology Roadmap*. The role of these sources in nonproliferation is evolving, with feasibility studies for active interrogation presently underway that will inform future investments in source technology. In recognition of this state, the prioritization by NA-22 of investment options identified by a group of SMEs (**Table 7**) consisted of estimated impact levels derived from the capability to produce a balanced improvement of the technology as a whole.

**Table 7. Prioritized investment options for photon sources.**

| Investment Option | Priority | Impact | Summary |
|---|---|---|---|
| Next-generation accelerator concepts | High | High | Development of photon sources meeting all of the requirements of being monoenergetic, tunable, high flux, and mobile may require investment in accelerator concepts different from those emerging from contemporary R&D. Significant potential may reside in recent developments, such as in the case of powerful, ultra-short laser systems that have permitted study of a new approach to generating energetic, forward-directed photon beams. Similarly, the high-energy electron accelerators needed for laser Compton scatter sources may be greatly reduced in size using LWFA technology. Further development of these emerging accelerator technologies will require long-term investments but also offers the potential of revolutionary accelerator concepts. Other accelerator concepts may be considered with one potential example being photon production via direct laser-material interactions within materials near or surrounding an interrogation target. |
| Monoenergetic, tunable sources | High | High | Tunable photon sources with extremely narrow bandwidths of $O(10^{-5})$ would dramatically increase the signal per photon in NRF applications if the energies could be matched to NRF states. Such sources would also reduce continuum backgrounds and minimize dose per incident photon. Development efforts should continue to further decrease electron energy spread, increase laser photon flux, and decrease photon bandwidths. One short-term objective is the investigation of methods to increase and control laser-electron interactions. |
| Development of compact, mobile photon sources | High | High | Development of sources for applications with stringent size and mass constraints will require considerable advances in present source technology. Human-portable systems will be especially challenging since battery power operation may be required. For these sources, near-term goals focus on photofission exploitation. Tunability is thus not a requirement, but minimal dose is. A target size for such systems is in the range of 100 kg and 1 $m^3$. In the case of bremsstrahlung sources, compact power supplies with more-efficient, higher-frequency acceleration gradients and enhanced higher energy, electron-photon production with low energy photon tailoring are needed to reduce system size and weight. In the case of nuclear-reaction-based sources, high-current power supplies must be developed, e.g., in the range of 180 kV and 1 A. Further work should also identify other viable nuclear reactions, assess optimal photon production targets and material types (thermal properties, cross section, manufacturability, etc.), and address operator shielding constraints. |
| Development of high-energy, quasi-monoenergetic sources | High | Medium | Existing technology provides the capability to exploit photofission but only using bremsstrahlung-based accelerators that impart significant dose to the interrogation target and the ambient environment. Reducing the dose, while maintaining high photon flux on target, is an important objective that could be achieved through the development quasi-mono-energetic sources (~0.1 $dE/E$) residing in the 6–15-MeV range. |
| High-repetition-rate LINACs | High | Medium | Increased photon flux from LINACs could be achieved via operation at high repetition rates of $O$(1–10 kHz). Such operation will allow the full exploitation of both prompt signatures (occurring during or immediately after an interrogation pulse) and delayed signatures (occurring between inspection pulses or after the interrogation process). This includes NRF signatures that are at presently accessible only with continuous-waveform accelerators. High-repetition-rate LINACs would also advance time-tagged photon systems that have not yet been developed for high-flux applications. Given a fixed rate of charge injected per unit time, it is preferably, for the purposes of reducing pileup and/or accidental coincidences), to distribute such charge over a relatively large number of small pulses so that the peak rate in any give pulse is minimized. |

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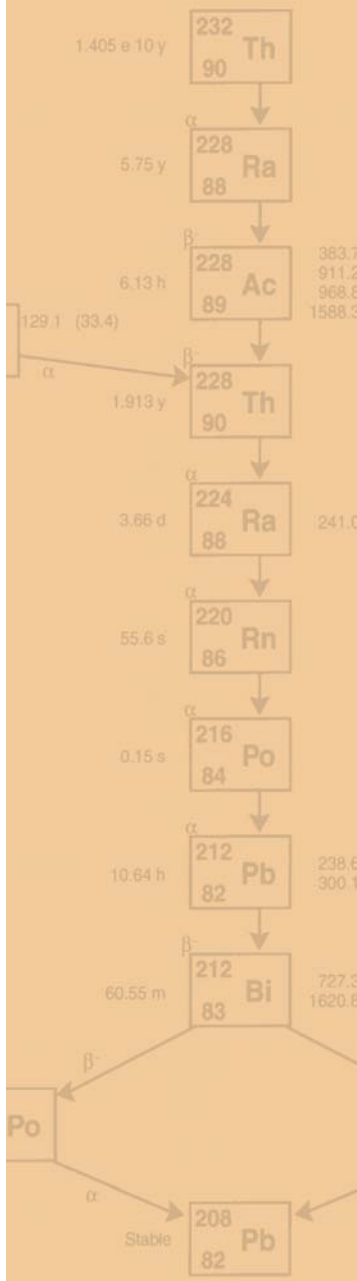
# Neutron Sources






## Technology Requirements

Requirements for neutron sources derive from the expected applications for detection, identification, and characterization of interrogation targets in close proximity using portable systems that can be setup in short time periods (e.g., minutes). The application of neutron sources to this end in fixed settings has a long history in nuclear material assay, waste measurements, and pulsed neutron analysis [Goz81]. The primary difference between the constraints of these environments and those of shielded SNM detection revolves around measurement conditions, measurement time, standoff distance, and the fidelity of results (e.g., in terms of detection, identification, or quantification).

Requirements for proximate detection, where an interrogation target resides a few meters or less from the source, generally fall into two categories. The first category stems from applications where neutron sources are delivered to field settings, such as in maritime boarded search. Since measurement times are of $O$(100–1,000 s) and standoff distances are of $O$(1 m) in this case, neutron yields greater than $O(10^9/\text{s})$, in either pulsed or continuous modes, are a reasonable goal for systems development. This goal is subject to the constraint that individual components of lightweight systems must be of $O$(10 kg) or less, and the overall size of each component must be compatible with backpacks or shipping cases, with a goal for a total system package of $O(1{,}000\ \text{cm}^3)$. Sources must operate on battery power but not necessarily for extended periods of time (e.g., days).

The second category includes fixed-site applications, such as treaty-monitoring environments, that impose requirements more similar to traditional assay environments. In these cases, interrogation targets reside within several meters, but interrogation targets may be denser and often filled with hydrogenous material. This, combined with reduced measurement times of $O$(10–100 s), requires large neutron yields of $O(10^{11}/\text{s})$ in systems capable of operating in a continuous mode or pulsed mode up to 10 kHz. Neutron sources must still be transportable, but they need not operate on battery power. For temporary deployments, minimizing system footprint is important, and a reasonable goal is the reduction of the footprint to $O(1\ \text{m}^2)$. Extending the operational lifetime beyond that of current generation systems, in the $O(10^7\ \text{s})$ range, to approach $O(10^8\ \text{s})$ is another important goal that requires significant advances to various system components.

Longer-term requirements stem from the ultimate desire to use neutron sources in standoff applications that require multi-MeV sources with directional beams. It may also be necessary to perform associated particle tagging to further define the direction of outgoing neutrons. The ability to pulse the beam for background reduction might also be necessary, further complicating the detector systems used in associated particle imaging neutron sources. Production of tagged beams at higher fluxes, e.g., from a $10^9$/s generator, requires detectors that are capable of detecting alpha particles at the same rate; in pulsed systems, the instantaneous beam currents are significantly

*Neutron Sources*

higher and avoiding pileup becomes more challenging. Alpha particle detectors must then be segmented, extremely fast with nanosecond-scale recovery time, and the data acquisition system must operate on a clock rate of at least 100 MHz.

## Survey of Field

Neutrons must be produced in nuclear reactions via spontaneous fission of actinides such as californium or curium; reactions between hydrogen, helium, and other light nuclei; or even the induced fission of SNM in nuclear reactors. Neutron source concepts suitable for use in SNM detection include radioisotope neutron sources, vacuum-sealed charged particle accelerators, vacuum-pumped charged particle accelerators, accelerator photo-neutron sources, and plasma-fusion devices.

*Radioisotope Neutron Sources*—Materials that undergo spontaneous fissions, such as the actinide nuclei $^{238}$Pu, $^{240}$Pu, $^{242}$Cm, $^{244}$Cm, and $^{252}$Cf, constitute one class of neutron sources. The most common material in use is $^{252}$Cf, which has a half-life of 2.7 years and a high specific activity compared to competing isotopes. The neutron energy spectra from spontaneous fission sources are typically peaked around 1 MeV with mean energies near 2 MeV and a characteristic fission energy distribution, as shown in **Figure 20**. In addition to neutrons, the fission process also leads to energetic gamma rays and heavy, energetic fission fragments. All of the particles are emitted isotropically. Detection of either the gamma rays or the fission fragments can be used to "tag" the outgoing neutrons with a coincident signal. Spontaneous-fission sources are deployed to industrial settings where the advantages of zero power consumption, minimal weight, reduced size, and reliability are critical. Future availability of these sources may be problematic since the only domestic production of $^{252}$Cf takes place at Oak Ridge National Laboratory [Mar99], and the future of the production program is not guaranteed.

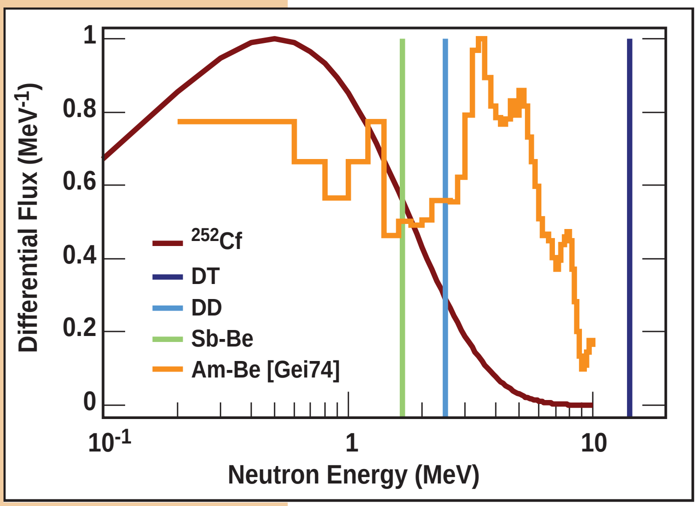



Figure 20. Comparison of normalized neutron energy spectra emitted by various nuclear reactions. Note that energies for the DD and DT reactions correspond to emissions at zero degrees.

Another class of radioisotope-based neutron sources consists of those that rely on ($\alpha$,$n$) reactions. In these sources a radioisotope that decays with the emission of alpha particles is mixed together with a low-$Z$ material that emits neutrons upon capture of the alpha particle. $^{9}$Be is most common, but other target materials such as $^{7}$Li, $^{10}$B, and $^{11}$B are present in specialized sources. Typical alpha-emitting nuclei used in these sources include $^{238}$Pu, $^{239}$Pu, and $^{241}$Am. Since the energy of emitted alpha particles is isotope-dependent and target nuclei have different reaction thresholds, each ($\alpha$,$n$) source produces a neutron energy spectrum having distinct and non-continuous neutron energy distributions. This is a distinct contrast with the smoothly varying distribution of the spontaneous fission sources. These sources emit gamma rays as well, e.g., the 4.44-MeV gamma ray from $^{9}$Be. Due to the mixing of the alpha-emitter and the target material, all of the particles are emitted isotropically. Beryllium comingled with either plutonium (PuBe) or americium (AmBe) is by far the most common source of this type since beryllium has a large ($\alpha$,$n$) reaction cross-section and produces the highest-energy neutrons. These sources are commercially available and common to applications such as well logging [QSA09]; however, a relatively large mass of actinide material of $O$(1 g) is required to make sources having neutron yields greater than $O(10^7/\mathrm{s})$, which necessitates addressing unique safety and security issues. The production, transportation, use, storage, and disposal of these sources are becoming problematic. For example, many high-intensity PuBe sources have been developed that contain up to 50 g of plutonium, and even the use of americium-based sources is rapidly becoming problematic due to increased security concerns during transportation and use.

*Vacuum-sealed Charged Particle Accelerators*—A distinctly different source of neutrons uses vacuum-sealed charged particle accelerators to exploit the $^2$H($d$,$n$)$^3$He (DD fusion) and $^3$H($d$,$n$)$^4$He (DT fusion) reactions, as well as the less-common $^2$H($t$,$n$)$^4$He and $^3$H($t$,2$n$)$^4$He reactions. DD fusion generates a quasi-monoenergetic neutron spectrum at 2.5 MeV; DT fusion generates a quasi-monoenergetic neutron spectrum at 14.1 MeV. Both reactions are primarily isotropic in nature, although the rate and energy have notable angular dependencies in the DD spectrum. Alternatively referred to as electronic neutron generators (ENGs) or sealed-tube neutron generators (STNGs), devices in this category incorporate small particle accelerators with acceleration gaps measuring less than a few centimeters in length, as shown schematically in **Figure 21**. They have internal, solid-state vacuum pumps that serve the dual purposes of maintaining vacuum inside the accelerator tube while also regulating the deuterium/tritium gas pressure within the ion source. An ion source produces a beam of deuterium and/or tritium. Extracted ions are accelerated and directed into a metal hydride target loaded with deuterium and/or tritium. Typical accelerating potentials for these devices are in the 50 to 350 kV range, while typical ion beam currents are in the 0.05 to 5 mA range. Sources possessing only deuterium are more desirable from a logistical standpoint, but tritium has significant performance advantages since neutron-production yields are 50–100 times greater than those from comparable DD systems. Further, the higher-energy neutrons from the DT reaction have greater penetration depth, but they produce high-energy gammas in non-fissionable material that may cause

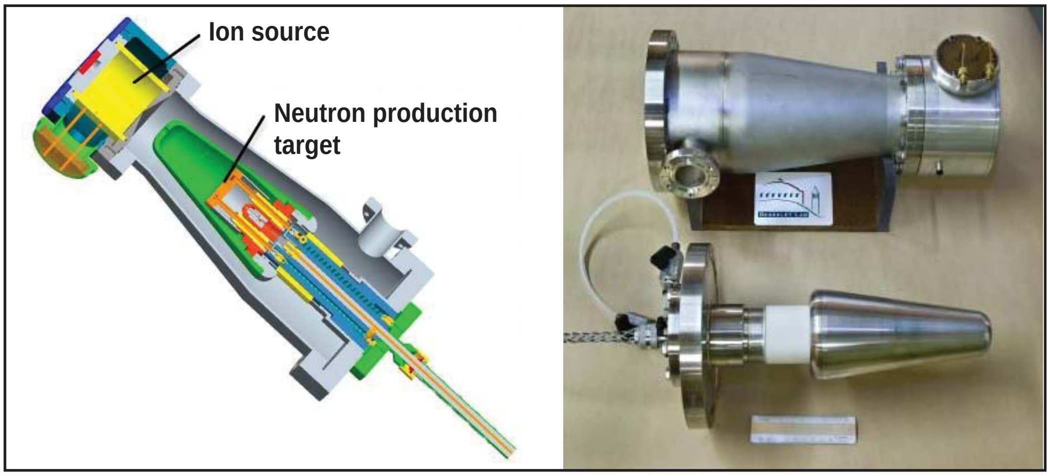



Figure 21. Schematic and photograph of compact neutron generator under development. Figure courtesy of Bernhard Ludewigt, Lawrence Berkeley National Laboratory.

interference with some SNM detection methods. A potential drawback with the use of DT systems for SNM detection is the possibility of creating the beta-delayed gamma-ray-emitting isotope $^{16}N$ (half-life = 7.13 s) in oxygen via the reaction $^{16}O(n,p)^{16}N$, which can act as in interference under some circumstances when beta-delayed fission product gamma-ray data is collected [Sla03].

Commercially available ENGs range from portable systems of $O(10^4\ cm^3)$ that generate yields of $O(10^8/s)$ to fixed-installation systems with masses of 1,000 kg that produce yields up to $O(10^{10}/s)$ [The09]. Higher-yield DT-based ENGs, with fluxes exceeding $10^9/s$, typically require active cooling to dissipate heat generated in the ion source and/or at the target. ENGs can be built as rugged, battery-powered, portable units. Instruments in this class operate in either continuous or pulsed mode with typical pulsing frequencies ranging up to 20 kHz. Having been widely produced by commercial vendors over several decades [Chi03], they exist in specialized form factors. Units for down-hole well logging in the oil exploration industry are typically packaged in long tubes with diameters of ~5 cm. In round numbers, these units are widely available in packages with total volumes of $O(10^4\ cm^3)$ and masses of approximately 10 kg.

*Vacuum-pumped Charged Particle Accelerators*—A closely related but significantly different class of neutron source relies on charged particle accelerators that are not vacuum sealed but have active vacuum pumps to maintain the internal vacuum within their accelerating column. At the simplest level, one category of this class of devices is essentially the same as the ENGs described above, using deuterium and/or tritium, but with external vacuum pumps. Today, vacuum-pumped ENGs almost exclusively use deuterium, due to hazards of tritium release.

Accelerators in this class can also produce neutrons using reactions of hydrogen isotopes with low-$Z$ nuclei such as in the $^7Li(p,n)^7Be$ and $^9Be(d,n)^{10}B$ reactions. The $(p,n)$ or $(d,n)$ charge exchange reactions require energies of $O(1\ MeV)$ while $(d,pn)$ deuteron breakup reactions require energies of $O(10\ MeV)$. These high energies, which are not attainable in STNGs, enable the selection of a reaction for characteristics including forward-peaked yield, high-reaction cross section, and the ability to tune the ion energy to produce a range of desired neutron energies. Neutron beams can be formed using inverse kinematics at energies of $O(10\ MeV)$ where the large momentum of the incident ion leads to forward kinematic focusing of the reaction products, e.g., accelerating the $^7Li$ ion rather than the proton in the $^7Li(p,n)$ reaction. A wide variety of accelerator systems have been developed including electrostatic accelerators, cyclotrons, and linear accelerators. Several commercial vendors offer systems for accelerator mass spectroscopy, surface analysis, material characterization, and medical isotope production. While these systems are suited for laboratory installations and are often capable of producing a variety of beams, they typically require a large, fixed infrastructure. Systems utilizing $(p,n)$ and $(d,n)$ reactions are capable of producing large neutron yields of $O(10^{13}/s)$ with lifetimes of $O(10^7\ s)$ [Acc09].

One type of charged particle accelerator found in an increasing number of industrial and field applications that exploit these reactions is the RFQ accelerator. RFQs are compact, robust, and well-suited for producing beams of protons and deuterons of $O(1\ MeV)$. RFQ technology can accelerate high beam currents and is now being offered for medical isotope production; one vendor offers a multi-MeV system in a trailer for portable radioisotope production [Acc09]. RFQ accelerators have also been designed and built for generating 6 to 8 MeV, forward-directed, high-intensity neutron beams via the DD fusion reaction for cargo screening applications [Hal07]. While they have advantages compared to other accelerators such as cyclotrons that require heavy magnets, or electrostatic accelerators that require significant spacing between components due to the multi-MV applied voltages, RFQ accelerators still require significant infrastructure. For methods that require beams in the MeV range, RFQ-based systems are attractive choices.

Another notable accelerator type in this category is the compact cyclotron. While conventional cyclotrons are large and heavy instruments due to the use of conventional electromagnets, new superconducting magnet designs have been proposed that may change this situation. Recent design work suggests the possibility of building a cyclotron using superconducting magnet technology capable of producing a 100-μA proton beam accelerated to 10 MeV. Such a system could produce a neutron output of $10^{10}$/s with a mass of $O$(100 kg) [Ant08].

At the extreme end of the spectrum, the particle physics community is pursuing new technologies such as laser wakefield acceleration, which can produce accelerating gradients orders of magnitude larger than achievable with conventional accelerating cavities driven with RF amplifiers. Such technologies, once further developed, may offer opportunities for new particle beam sources in the future. While neutron beams have been produced for several experiments in nuclear physics, many of these beams are produced using spallation reactions on high-$Z$ targets with subsequent collimation to form the beam rather than using the kinematics of the reaction [Blo07]. Only a few university laboratories have routinely produced neutron beams of $O$(10 MeV) for research applications.

*Photoneutron Sources*—Photons stimulate neutron emission when comingled with materials possessing neutron binding energies less than the energy of the photons. One method exploiting this phenomenon incorporates high-energy gamma-ray-emitting radioisotopes with low-$Z$ target materials [Wat47]. The quasi-monoenergetic nature of the neutron energy spectrum of these sources is often particularly advantageous, but the neutrons are emitted isotropically. These sources most often use deuterium ($E_{threshold}$ = 2.23 MeV) or beryllium ($E_n$ = 1.67 MeV) as target materials. The most common photon source is $^{124}$Sb, which has a 60-day half-life. These photoneutron sources are not in widespread use; they possess significant drawbacks associated with their intense gamma-ray flux (which creates deployment challenges) and their short-lived gamma-ray-emitting isotopes (which must be replaced on a regular basis). The practical use of these sources in SNM detection scenarios is limited.

Another method of photoneutron production replaces the gamma-ray source with a high-energy electron accelerator that generates high-energy x rays (via a high-$Z$ target). Materials with low neutron binding energies such as deuterium and beryllium are most commonly employed as conversion materials. For high neutron yield, high-current electron LINACs with beam energies above 6 MeV are typical, and the application of pulsed accelerators allow for time-of-flight spectroscopy. In these systems, high-intensity photon fields also exist, which may either be advantageous or disadvantageous depending upon the SNM detection method. An alternative is high-energy, sealed-tube electron accelerators that provide modest neutron production. Unlike most of the techniques using ion beams, this technique tends to produce neutrons with a broad energy spread, which is not particularly advantageous for most SNM detection scenarios [Lak08].

*Plasma-Fusion Devices*—The last class of neutron sources considered here are those that generate neutrons directly from plasma fusion. One example is the inertial electrostatic confinement device that uses electrostatic and sometimes magnetic fields to generate and confine deuterium and/or tritium plasma and induce fusion. These devices may be arranged in spherical or linear geometries. In an inertial electrostatic confinement device, ions accelerate across a low-pressure gas volume many times, producing neutrons in DT or DD reactions. These devices have the potential to operate in sustained modes of operation for very long periods of time. While similar to ENGs in their neutron generation characteristics, some drawbacks are their larger size and far greater complexity when compared with ENGs. Neutron yields exceeding $10^7$/s have been achieved in open vacuum-pumped DD systems [Yos07]. These devices are not in widespread use, with one likely reason being that they require more than ten times the power per neutron compared to conventional ENGs.

Another type of neutron source using direct fusion is the plasma focus device [Kra89]. This type of neutron source uses pulsed-power technology to generate extremely high-current electrical arc plasmas between electrodes. Deuterium and/or tritium gas is either naturally present in the cavity between the electrodes or stored on the surfaces of the electrodes prior to discharge. A distinct performance advantage of these sources is the fact that they produce neutrons in short pulses with characteristic widths of $O$(1 ns). A distinct disadvantage of this type of neutron source is that they require regular maintenance to replace worn components; in particular, the operating lifetime of the electrode components is rarely longer than a few hundred shots.

## Identification of Shortfalls

Detection methodologies using neutron sources are not fully developed for nonproliferation applications, but it is fair to say that existing technology that is field-deployable (for oil-well logging, density gauges, or SNM detection) and technology that is readily used in the laboratory for the production of neutrons both have shortfalls when considered for use in SNM detection in a range of scenarios spanning person-portable methods to standoff detection. The shortfalls associated with contemporary technology are thus qualitative at present and subject to further refinement pending more detailed definitions of the systems that will use them and the applications in which they will be used. While neutron source instrumentation shortfalls cannot be assessed in detail in the absence of a good understanding of the problems to be solved and the methods to be employed, major increases in neutron flux, generator lifetime, generator size, push-button use, neutron energy distribution, neutron directionality, etc. will require substantial improvements in any of the major components of neutron generators including power sources, targets, accelerating methods, and ion sources.

*Increased Neutron Production*—Present commercial products, in particular those that are portable, are limited to fluxes of $O(10^8/\text{s})$ and possess lifetimes of $O(10^7\ \text{s})$ when operating at these rates. The need to increase neutron production rates is thus both a combination of greater neutron yield and operational lifetime while maintaining the same mobile capabilities. Increasing the neutron yield is not simply addressed by scaling present systems but will require improvements in high-voltage power supplies, target design, and accelerated ion beam quality. High-yield sources will require more capable power supplies and support systems that can be made available in fixed installations or transportable systems. For example, a technical barrier to increased flux is target stabilization that requires active cooling in the case of metal hydride targets and other nuclear reaction targets. Increasing the atomic fraction of the accelerated ion beam over current commercial technology is another parameter that would increase neutron flux.

*Portability*—Exploitation of neutron interrogation in some applications of particular interest to nonproliferation requires person-carried and vehicle-mounted systems. Present technology does not meet size, mass, and power-consumption requirements at required fluxes. One underlying issue with all present-day sources is the power supply. Even with major advancements in conserving power during the production of neutrons, power supplies are still the largest component of all of the existing methods.

*Directional Beams*—Delivering high-intensity neutron fluxes to targets at standoff distances while limiting radiation dose to nearby personnel and the environment requires intense and highly directional beams. While the DD reaction is forward peaked at energies of a few MeV, a large fraction of the total neutron output is emitted outside of a 15° forward cone, thus making these sources unsuitable for standoff applications. Alternate methods exploit kinematics and heavier beam ions to induce directionality. Producing directional beams using these reactions requires production of ion beams with energies greater than 10 MeV. At these energies electrostatic accelerators are not suitable, and conventional cyclotrons are large, fixed in location, and require extensive infrastructure. RFQ accelerators, other linear accelerators, and superconducting cyclotrons may reach the needed energies and the other associated requirements for deployment in nonproliferation applications, but the engineering design issues required to achieve this are challenging.

## Prioritized Investment Options

Development of compact neutron generators for field deployment is a fairly mature field, especially when compared to photon sources. Due to their utility at inducing fission, development of accelerator-based neutron sources was a first-priority item in the *SNM Movement Detection Portfolio—Technology Roadmap*. The role of these sources in SNM movement detection, however, remains ill-defined. Development of detection methods now underway will inform future investments in source technology. In recognition of this, the prioritization scheme applied to neutron source investment options (**Table 8**) consisted of estimated impact levels derived from the capability to produce a balanced improvement in neutron source technology as a whole, with some emphasis on directional neutron sources.

**Table 8. Prioritized investment options for neutron sources.**

| Investment Option | Priority | Impact | Summary |
|---|---|---|---|
| Next-generation ion sources | High | High | At the heart of neutron sources is the presence of accelerated ions that produce neutrons via nuclear reactions. Revolutionary advances in ion-source capability may require innovative methods of ion production, for example, by dramatically increasing the efficiency of ion generation, operating for longer lifetimes with greater stability, and optimizing accelerator and target performance. Recent breakthroughs in micro-scale ion sources offer the possibility of revolutionary advances in overall system size, mass, and power consumption. One area of research exploits field desorption wherein micro-electro-mechanical/nanomaterial manufacturing techniques or other approaches are used to populate an anode area with a large number of nanoscale tips. Deuterium and/or tritium ions can be desorbed from the surface of these tips and accelerated toward a high-voltage target [Sch05]. Another potentially advantageous approach creates deuterium ions by heating a pyroelectric crystal in a vacuum. Upon heating, temperature changes cause a migration of positive and negative charges. When outfitted with sharp electrodes, this charge creates fields large enough to ionize and accelerate deuterium [Nar05]. These immature techniques possess potential to increase present neutron source capabilities. |
| Robust, human-portable systems | High | High | Development of neutron sources with yield in excess of $O(10^9/s)$ that reduce system mass, size, and power consumption by an order of magnitude is an important near-term goal. It is likely for these sources to rely on DD and DT reactions, but switchable radioisotope sources may fill a need in specific applications where system size is the paramount specification and high neutron yield is not required. Component technologies may need to be developed as part of an overall systems development effort, such as advances in high-voltage power supplies to enable a 150-kV system operating up to 100 μA in compact system of size less than 1,000 $cm^3$. |
| Directional beams of high-energy neutrons | High | High | Directional beams of high-energy neutrons will be required for standoff interrogation applications. Traditional approaches, for example, rely on lithium ion beams for inverse kinematics using the $p(^7\mathrm{Li},n)^7\mathrm{Be}$ reaction. These approaches must be incorporated into a transportable system with reasonable footprint and operational requirements. Other innovative approaches to directional beams are also of interest. |
| Transportable, high-flux sources | High | Medium | Some applications require intense neutron yields of $O(10^{11}/s)$, but such sources must be transportable (i.e., capable of being set up and torn down in time scales of days while maintaining reliability). Alternatively, plasma-focus neutron sources are attractive due to their potential of producing very intense and very short neutron pulses. All sources require the development of more efficient and compact high-voltage power supplies, such as those capable of up to 10 mA at 150 kV in a package of $O(10^5\ cm^3)$ for a transportable system. |
| Scenario definition for standoff applications | High | Medium | Further investigation into the role of neutron sources in standoff detection is required prior to fully directing technology investments. The same considerations apply to interrogation using other particles, such as muons and high-energy protons. It must first be made clear how each of these proposed interrogation techniques address the requirements of standoff detection. All these methodologies should be carefully modeled and benchmarked to experiments. Upon completion, it will then be possible to make a detailed technology recommendation for neutron- and other particle-beam technology development as it applies to standoff detection. |
| Advances in time-tagged neutron sources | High | Medium | Time-tagged sources present unique capabilities due to the ability to correlate individual interrogation particles with detection events. The associated particle imaging technique is one example that is particularly useful in the characterization of SNM [Bey90] [Hau07]. In this application, there is a need for small, portable DT systems that have tighter beam spots (~1 mm) and higher yield of $O(10^9)$. More generally, time-tagged sources may provide a viable path toward modestly increasing the standoff distance since detectors could be triggered only by events coincident with neutrons incident on the interrogation target, but this needs careful study and modeling. |

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## Office of High Energy Physics Accelerator R&D Task Force Report

## Appendix 15

## DTRA –
## Accelerator Technology for Long-Range Detection of Nuclear Material

**Accelerator Technology for Long Range Detection of Nuclear Material**

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The Defense Threat Reduction Agency's (DTRA) mission is to safeguard the United States and its allies from global threats due to weapons of mass destruction. This mission requires the capability to detect from a distance nuclear material located in a target object, such as a ship, vehicle or building. One technique being explored to aid the long-range detection of nuclear material is active interrogation using beams of energetic photons, protons, or muons from an appropriate accelerator to stimulate detectable signatures on the target objects. Since the Department of Defense requires a capability to respond to situations anywhere in the world, accelerators used to generate particle beams for active interrogation must be extremely compact and transportable. They must also generate precise beams of sufficient quantity and energy with high efficiency. Photo-interrogation with bremsstrahlung is the most mature technology because an appropriate electron accelerator system can be constructed from off-the-shelf components. Although other beams, such as protons or muons, may be more effective because of low-loss transmission and penetration of shielding or other material surrounding the target, compact and mobile accelerators needed to produce these beams are not presently available. DTRA supports development of accelerators-such as compact, high-current cyclotrons, high-gradient linac cavities, and Fixed Field Alternating Gradient (FFAG) accelerators. DTRA is developing test ranges where accelerator based active-interrogation methods can be studied with relevant test objects. This presentation describes DTRA's unique requirements for accelerator technology and seeks to establish or promote collaboration to leverage other ongoing or planned work. Although DTRA's requirements are unique, spinoff technologies would support non-security applications such as medical therapy and other industrial applications along with fundamental research in developing novel acceleration methods. Advances in accelerator technology may enable applications previously found to be impractical such as accelerator-based actinide disposal, accelerator production of tritium and $^3$He, or production of technetium-99 from accelerator-generated fission fragments.