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OVERVIEW OF ACCELERATOR APPLICATIONS FOR SECURITY AND DEFENSE

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Particle accelerators play a key role in a broad set of defense and security applications including warfighter and asset protection, cargo inspection, nonproliferation, materials characterization and stockpile stewardship. Accelerators can replace the high activity radioactive sources that pose a security threat for developing a radiological dispersal device and be used to produce isotopes for medical, industrial, and research purposes. An overview of current and emerging accelerator technologies relevant to addressing the needs of defense and security is presented.

Keywords: National security, particle accelerator.

1. Introduction

From the earliest days of their development, accelerators have played key roles in security and defense as well as in other fields such as astrophysics, medical physics, and nuclear science. Universities and national laboratories, including defense laboratories, developed increasingly powerful and sophisticated accelerators for national security applications that address nuclear device characterization, detection of contraband materials, and the enrichment of nuclear materials. Examples include the induction linear accelerator (linac), originally developed for accelerator-induced fusion, used today for radiographic imaging, accelerator mass spectrometry contributions to isotope separation technology, and accelerator facilities for defense-related nuclear physics research. The early application of megavolt-energy electron linacs for photofission-based nuclear reactor fuel inspections later expanded to characterizing hazardous materials in waste drums and eventually to cargo inspection systems. Nearly all security and defense accelerator applications have their roots in basic science research and development. Future accelerators will continue to rely on advances in basic science and its need for more powerful and sophisticated systems. These next-generation systems will provide cost effective and safer alternatives to traditional industrial processes, safe nuclear power-based energy with less waste, a cleaner environment, advanced new materials, and a strengthened national security and defense program.

2. Accelerators in Security and Defense

Accelerator laboratories and technologies continue to make significant contributions to the diverse needs of security and defense. These applications range from providing fundamental databases for radiation interactions with materials, nuclear forensics, isotope production, and high energy density physics to system-level technology developments of directed energy system concepts, cargo inspection and interrogation, industrial and medical radiological source replacement, and stockpile stewardship.

2.1. *Physical data*

An important component of security and defense programs is the availability of high quality databases for materials characterization, material modification, and radiation interactions with materials. These data are necessary to reliably simulate systems for detecting chemical, biological, and nuclear threats and provide benchmarks for simulation codes needed to certify the safety and reliability of the aging stockpile. Gaps exist in the current databases related to temporal and angular distributions and correlations, high-resolution spectroscopy, and reaction cross sections. Accelerator-based measurements are filling these gaps, but some materials, e.g., special nuclear material, present health, safety, and licensing challenges making national laboratory accelerator facilities more suitable for this work.

2.2. *Directed-energy technology*

Many countries have interest in developing a robust defense against attack from intercontinental ballistic missiles (ICBMs), area missiles, or cruise missiles. During the "Star Wars" era, efforts were made to intercept missiles in boost, mid-course or terminal phase with a particle beam rather than another missile. Such a directed-energy weapon uses a high-energy beam of particles to damage the structure of the target or simply overheat it until it is no longer operational. The high-power beam could originate either from a space-based or earth-based accelerator, or it could be a photon beam generated by an earth-based free electron laser driven by an induction accelerator, or a spaced-based chemical laser-produced photon beam [1]. Since charged particle beams diverge rapidly due to mutual repulsion, neutral particle beams are more commonly proposed for directed-energy weapons. Cyclotrons, linacs, and synchrotrons can accelerate protons until their velocity approaches the speed of light. The high energy protons can capture electrons from electron emitter electrodes and become electrically neutralized. A neutral particle beam traveling at near the speed of light and containing giga-joules of kinetic energy will nullify any realistic means of defending the target (missile).

A benefit of the Star Wars research was that it also led to several important accelerator-related developments, among them the radio-frequency-quadrupole (RFQ). Induction accelerators were also tested for propagating charged particle beams through the atmosphere for missile defense due to their capability for handling kilo-ampere beams. Induction accelerators were later used to drive free electron lasers and as flash x-ray sources for dynamic radiographic imaging. The dielectric wall accelerator promises a compact form factor and accelerating gradients on the order of 100 megavolts per meter for short pulses. This technology will enable field deployable directed-energy technologies such as high power microwave sources, electron accelerators for producing highly directional gamma-ray beams through Compton scattering, and GeV proton accelerators for long standoff interrogation.

2.3. *Cargo inspection*

Accelerators play a key role in addressing many of the challenging problems related to inspecting cargo at ports-of-entry, airports, seaports, and other areas. High-energy penetrating radiation (photons and/or neutrons) from a particle accelerator are needed for effective high-throughput inspections. Accelerator systems vary in size and complexity depending on the specific application requirements. Electron accelerators are typically used to produce x-rays for radiographic scans, while active interrogation techniques, using neutrons, photons, protons, or muons, can be employed to induce detectable characteristic signals for materials discrimination. The useful photon energy range for radiographic scans of bulk cargo is 1-15 MeV, although present federal regulations limit the energy to $\leq$10 MeV to protect humans (e.g., stowaways) from accidental high dose exposures and also reduce the activation of surrounding materials. Megavolt-energy photon beams are produced by electron linear accelerators (linacs) which are readily available due to their use in medical x-ray imaging and industrial non-destructive evaluation. Both normal conducting and superconducting standing-wave and traveling wave radio frequency electron linacs are available commercially [2]. Typical electron linacs operate at radio frequencies of 2-4 GHz (S-band), but more compact X-band systems are also being used. In recent years, the performance of compact X-band linacs has become comparable to the more common S-band machines and, thus, X-band linacs are being used in fieldable applications including systems for screening dense cargo [3].

Although large in size, superconducting accelerating structures are also being explored for some fixed site cargo inspection techniques that require continuous wave mode operation and beam currents up to 1 mA (e.g., nuclear resonance fluorescence).

At airports, carry-on baggage is scanned with dual-energy x-rays enabling both radiography and some materials discrimination of the contents, thereby reducing the number of false alarms during rapid scans. Checked baggage is commonly inspected with intermediate energy x-rays in a computer tomography scanner to give three dimensional information. Mail, palletized cargo, and packages are radiographically inspected in large scanners with x-rays having energies of several hundred kilovolts. Whole-body scanners using accelerator-produced low-energy x-rays screen persons at civilian and military facilities and measure the backscattered x-rays to reveal concealed objects.

Particle accelerators enable long stand-off interrogation of nuclear materials at long distances. Passive detection is difficult since the natural radioactive emissions of nuclear materials are low; detection of interrogation-induced fission signatures can be done at long distances. An interrogation system consists of detectors and a dedicated high-power particle accelerator producing a beam of high-energy particles such as x-rays, gamma-rays, neutrons, or protons. Conventional electron linacs can be used as forward-directed high-energy (>10 MeV) x-ray sources, but more advanced high-current, high-brightness systems are needed to accelerate other particle types. For example, a high-energy (>100 MeV) S-band RF linear accelerator can provide an interrogation beam of mono-energetic gamma-rays via inverse laser-Compton scattering when coupled to high power laser. High-energy proton beams can be produced with compact superconducting cyclotrons or other high-gradient accelerators. Stand-off interrogation at extremely long distances (~1 km) could be achieved with gigavolt-energy protons at milli-ampere beam currents utilizing high gradient/high temperature superconducting technologies.

Next-generation accelerators for cargo inspection include various laser-acceleration schemes, induction linacs including the dielectric wall accelerator, high-average-power radio frequency quadrupoles, fixed-field alternating gradient induction and radio frequency accelerators, and inverse-Compton-scattering photon sources. Advancements made in present technology combined with the development of these new technologies will have a significant impact for accelerators in future non-intrusive cargo inspection systems.

2.4. *Radiological source replacement*

High activity radioactive sources are currently used in the medical community for treating disease and irradiating blood/tissue, in industrial radiography to non-destructively evaluate critical structures, and in sterilization and research irradiators to manage food safety programs. Collectively these applications account for over 99% of the Category 1 and 2 sources in commercial use. The security of these radiological sources and their potential for use in a radiological dispersal device (RDD) is of great concern to national security [4]. Other radioactive sources used in high dose rate brachytherapy, well logging, and nuclear gauges are also under consideration for source replacement. It is therefore important to overcome both the technical and security challenges that currently exist in restricting the use of these sources with functionally equivalent alternatives or by imposing significant additional security measures.

2.4.1. *Medical applications*

Each year, tens of millions of patients receive accelerator-based diagnoses and therapy in hospitals and clinics around the world. Particle accelerators are used to produce radioisotopes for medical diagnosis and therapy, and as sources of beams of electrons, protons and heavier charged particles for medical treatment. Medical applications that utilize high-activity radioactive sources include blood irradiators, external-beam radiation therapy units, gamma knife stereotactic surgery systems for treating brain cancer, high-dose-rate brachytherapy systems for intra-cavitary irradiation, and research gamma irradiators. The most common radionuclides used in these systems are the gamma emitters

Co-60 ($T_{1/2}$ = 5.3 y), Cs-137 ($T_{1/2}$ = 30 y), and Ir-192 ($T_{1/2}$ = 74 d). Co-60 and Cs-137 are commonly used as sources for external high-dose irradiators while Cs-137 and Ir-192 are used as brachytherapy "seeds" for intra-cavitary applications in cancer treatment.

Linear accelerators and x-ray systems have replaced Cs-137 and Co-60 in most external-beam radiotherapy applications in the United States and Europe. However, in much of the rest of the world, Co-60-based units are still used, with over 10,000 in service. These devices have an average radioactivity of 2000 curies and therefore represent significant risk for the development of a radiological dispersal device. The earliest electronic radiotherapy systems used bare cathode ray tubes with a simple self-rectified x-ray circuit. Prior to 1950, most external-beam radiotherapy was performed using x-ray generators operating in the 200 to 500 KVp range at 10 to 20 mA. Higher voltage x-ray and radioisotope teletherapy units were first manufactured around 1945. The first modern rotating-head radiation therapy systems were produced in 1951 when Cs-137 and Co-60 became available. Electronic systems quickly replaced Cs-137 and Co-60 because the energy, spectral quality, and beam shape could be tailored for cancer treatment. Other radiation-generating machines used cyclotron-accelerated deuterons, betatron-accelerated electrons, and x-ray beams from accelerated electrons produced by Van de Graff generators. Over time, the betatrons and Van de Graff generators were replaced by higher energy electron linear accelerators.

Self-shielded blood irradiators that utilize Cs-137, Co-60, or electronically-generated X-rays are most commonly used to irradiate blood products. While accelerator-based x-ray and electron beam systems are commercially available for irradiating blood, the medical community generally prefers radionuclide-based irradiators due to their radiation quality, relative ease of operation, reliability, and system cost. Irradiation inactivates T-lymphocytes in blood and blood components to prevent Graft-Versus-Host Disease (GVHD), which occurs when lymphocytes in donated blood engraft, multiply and damage the recipient's organs and tissues. GVHD is usually fatal and there is no treatment. Operational requirements specific to each gamma irradiator system include unit portability, proximity to clinical care, source activity needed to achieve dose and dose rate requirements, irradiation uniformity and quality, ease of operation, throughput, safety of operation, system maintenance and replacement, and user training. To date, tube x-ray and electron-beam alternatives have typically required more system maintenance and are more costly to operate than radionuclide-based irradiators.

Practical radiological source alternatives are not yet available for high-dose-rate brachytherapy and stereotactic gamma-knife radiosurgery systems. Although linear accelerators are used in stereotactic radiosurgery, comparable accelerator-based alternatives do not have the full functionality of multiple Co-60 source gamma-knife systems used for treating brain tumors and also cost around ten times more. Miniaturized x-ray systems have not been sufficiently developed to provide a practical alternative to Cs-137 and Ir-192 sources in high dose-rate brachytherapy which requires an isotropic radiation field for intra-cavitary radiation therapy.

2.4.2. *Industrial radiography*

The discovery of x-rays in 1895 led to a new radiographic imaging capability that allowed one to look inside opaque objects without the need for destructive serial sectioning. Radioactivity was discovered shortly after x-rays and, by using radioactive sources such as radium, higher photon energies could be used to look through much thicker objects. New radioisotopes became available after World War II and the use of radium and radon decreased. Co-60 and Ir-192 are currently the most widely used isotope sources for radiography; some sources having activities exceeding 1000 Ci which is a national security concern for developing a radiological dispersal device. The advantages of radionuclide sources are their small size, ease of use, and low power requirement. Alternative technologies based on electron accelerators in conjunction with other imaging modalities have replaced many radionuclide-based systems. The effective gamma-ray energies from Ir-192 decay are around 300 keV which is approximately equivalent to an electron accelerator with 900 kV endpoint energy. Similarly, a Co-60 source is functionally equivalent to a 2-3 MeV x-ray system. For practical purposes, factors that must be taken into account when replacing a high-activity radioisotope source with an accelerator-based x-ray source include overall system cost, maintenance requirements, and engineering issues associated with the shape, size, shielding and operational power needs.

Neutron radiography is also used in industrial applications for materials that are not easily imaged with x-rays and, therefore, complements conventional radiography. The attenuation of neutrons as they pass through an object depends on the isotopes present, rather than on density or atomic number as in x-ray radiography. High activity Am-241/Be or Cf-252 sources are commonly used in neutron radiography because they can be collimated to a small beam spot thereby enabling high fidelity imaging. Replacing the radioactive sources with accelerator-based versions often results in technical compromises related to neutron output and energy, beam spot size, system size, and power requirements. Current accelerator-based neutron radiography sources include compact ion accelerators that produce neutrons via deuterium-tritium fusion reactions, electrons linacs producing high-energy x-ray beams that subsequently strike a photoneutron convertor target, and even larger accelerators that accelerate protons to extremely high energies and cause spallation neutrons to be produced when they strike a target.

2.4.3. *Panoramic irradiators*

Commercial radioisotope-based panoramic irradiators are used to irradiate single-use medical devices and products, food items, plants, insects, and for other purposes. A typical irradiator can contain around 3 million curies of Co-60 making it a high risk for a possible terrorist attack. Irradiators that utilize lower activity sources are also used to calibrate dosimeters and irradiate materials for research. The latter irradiators usually use Cs-137 to irradiate biological specimens and Co-60 for other materials or hardware. During an exposure, the radiation field of the gamma irradiator is kept uniform, but the dose delivered to the sample depends on the composition, density, and thickness of the item being irradiated (the medical community require doses of at least 25 kGy for sterilization).

Electron beam irradiators, employing a scanned beam of accelerated 5- to 10-MeV electrons, are a common accelerator-based source replacement technology. Since nearly all of the electron energy is deposited in a shallow depth, electron beam irradiators can achieve much higher dose rates compared to other techniques. High-energy x-ray irradiation can also be performed with the same electron beam irradiator by installing a bremsstrahlung convertor target. X-ray irradiators have primarily been used to irradiate food products, but systems have also been developed for irradiating mail (e.g. to sterilize bio-weapon spores). The maximum x-ray energy in these systems is less than 10-MeV due to concerns with neutron production and induced radioactivity in the irradiated item. Power consumption, functionality equivalence, and economic competitiveness with gamma irradiators must be taken into account with the accelerator-based replacement technologies, although costs associated with availability, regulation, and disposal of radioisotope sources are increasingly important factors.

2.4.4. *Well logging*

In the petroleum industry, nuclear and non-nuclear well logging tools are used to obtain information about the geologic media through which a borehole has been drilled. Nuclear tools measure formation density and porosity (Cs-137 gamma sources), porosity and elemental composition (Am/Be neutron sources), and neutron absorption and compositional information (pulsed deuterium-tritium neutron accelerators). The Cs-137 source in a density tool is a vitrified Category 3 source (1.5 to 2 Ci), while Am/Be neutron sources range from Category 3 to Category 2 (4 to 20 Ci).

Well logging is conducted in both open hole and cased wells (the latter wells are lined with steel pipe and cemented in place). Historically, the most common type of logging is wireline in which the tools are conveyed down hole on the end of a cable. In contrast, logging-while-drilling (LWD) involves incorporating the logging tools directly into the drilling string which allows logging measurements to be made during the drilling process. LWD has become common with the increased need for horizontal drilling and provides log data before extensive infiltration of drilling fluids into the formation. Steel encapsulated americium-beryllium (AmBe) neutron sources used in nuclear well logging consist of americium oxide and beryllium in packed-powder form to increase neutron production efficiency. Other isotopic sources such as Cf-252 spontaneous fission sources and PuBe have also been employed to some extent, but the Cf-252 neutrons are not energetic enough (~2 MeV average energy) for some applications and plutonium presents a proliferation risk. The national security concern for AmBe is that, in a RDD attack, the alpha emitting Am-241 could deliver very large radiation doses through inhalation or ingestion. Consequently, various governmental and regulatory agencies are advocating the replacement these sources with alternate technologies. Accelerator-based neutron logging tools have been developed and used in both wireline and LWD applications [5]. However, these neutron generators are not widely used due to various reasons including their cost, pulsed operation, neutron yield, neutron energy spectra, and industry reluctance to accept different well logs than the historical AmBe-derived data.

Nuclear logging with Cs-137 gamma rays measures the bulk density of geologic formations with high accuracy and can be used to characterize porosity with knowledge of the rock's mineral content and fluid density. Formation lithology can also be inferred with knowledge of pore volume and fluid density. Encapsulated CsCl (0.66 MeV γ's) in a vitrified form is the most commonly used gamma source. Other less common sources include Co-60 (1.17 and 1.33 MeV γ's) and Ra-226 (0.19 to 2.43 MeV γ's). CsCl is particularly subject to malicious use due to its high solubility and dispersibility. Replacement of the CsCl sources with alternative technology that has equivalent functionality is difficult because well loggers prefer mono-energetic gamma rays, small size, low power, and environmental robustness. Commercial electron linac accelerators have been tested as a possible alternative to CsCl [6-8]. However, the system was never commercialized and technical challenges remain associated with their overall system size and power requirements, broad energy spectrum, and stability of the device when operating in the harsh downhole environment.

2.5. *Isotope production*

Accelerator production of both stable and radioactive isotopes plays a key role in security and defense. Radioisotopes are required for calibrating and testing instrumentation used for the analysis of nuclear materials, while enriched stable isotopes are used for calibration and isotope dilution measurements in mass spectroscopy. In recent years, the demand for the stable helium isotope He-3 has increased significantly as a result of its use in portal monitor detectors and other systems for detecting special nuclear materials. Tc-99m is the most commonly used medical isotope today, accounting for about 50,000 medical imaging procedures daily in the United States. This isotope has traditionally been created in a nuclear reactor through the fission of weapons-grade uranium, making it a potential proliferation risk.

Passive detection systems are being deployed in domestic and foreign ports to detect the presence of nuclear materials in cargo. The neutron detectors typically use He-3 due to its stability and high efficiency for detecting neutrons. The military also requires significant amounts of He-3 for their portal monitors. He-3 is produced, in part, as a byproduct of nuclear weapons dismantling where it accumulates, but changes in stockpile management have led to decreased production. During the 1990s, linear accelerators were proposed for producing tritium by irradiating lithium. However, the Department of Energy decided not to proceed with accelerator production of tritium (and, in turn, the production of He-3) [9]. Helium-3 can also be produced directly without tritium in an accelerator, but cost-benefit analysis has indicated that this process would be cost prohibitive so more efficient means need to be explored [10].

The medical isotope Tc-99m is currently produced by the fission of highly enriched uranium (HEU) targets in aging nuclear research reactors. In addition to the proliferation risk associated with

HEU, there is an additional issue associated with the fission by-products from reactor-based production of Tc-99m. These by-products are the same as those produced in a nuclear detonation, the latter of which are monitored worldwide as part of the Comprehensive Test Ban Treaty. Thus, reactor-based production affects the sensitivity to monitor these materials by producing elevated and variable concentrations over large areas around production facilities. Commercial institutions and national laboratories are developing technologies for producing Tc-99m without HEU. For example, direct production of Tc-99m via the ^{100}Mo(p,2n)^{99m}Tc reaction using a medical cyclotron has been demonstrated. Theoretical Tc-99m yields of 15 Ci/h are obtained for 455 μA, 22 MeV protons bombarding an enriched Mo-100 target [11]. A peak (~200 mb) in the cross section was later found at approximately 17 MeV giving Tc-99m production of 100 mCi/μA at saturation [12, 13].

The drawback to direct production of Tc-99m is its short half-life (6 hr) which makes it difficult to transport long distances and, consequently, it must be produced close to its point-of-use. An alternative approach is to produce the radioisotope Mo-99 which subsequently decays to Tc-99m with a 66-hour half-life. Accelerator production of Mo-99 via the ^{100}Mo(p,pn)^{99}Mo and ^{100}Mo(d,p2n)^{99}Mo reactions has been considered, but these reactions lead to low specific activity product [14, 15]. Fission-based Mo-99 production using an accelerator-driven subcritical reactor has been proposed by various groups around the world and offers a potential solution for large-scale Mo-99 production. Another potentially scalable approach bombards an enriched Mo-100 target with 14-MeV neutrons from a high flux neutron generator producing Mo-99 via the ^{100}Mo(n,2n)^{99}Mo reaction. Inducing photofission in low enriched uranium samples with Bremstrahlung radiation from a high-energy electron accelerator has also been investigated for producing Mo-99. Multiple accelerators with a total of hundreds of megawatts of electron beam power would be needed to supply the entire world demand. Another photon-based approach is to utilize the photoneutron ^{100}Mo(γ,n)^{99}Mo reaction. With an enriched Mo-100 target, this reaction can produce almost twenty times more Mo-99 compared to the photofission-based reaction [16].

Commercial cyclotrons are used to accelerate protons and deuterons at energies up to 100 MeV for producing many other medical and research isotopes. These include proton-rich medical isotopes such as F-18, Sr-82, Cu-64, O-15, C-11, Br-77, I-124, Y-86, Ga-66, Cu-60, Cu-61, and Zr-89. Short-lived positron emission tomography isotopes such as Ge-68/Ga-68, Sr-82/Rb-82 and other specialized research radionuclides (e.g., Zn-65, Mg-28, Fe-52, and Rb-83) are produced with up to 200 MeV, 250 mA proton beams in large cyclotron or linear accelerators [17].

2.6. *Nuclear forensics*

Nuclear terrorism is a serious world-wide security threat. In the early 1990s, the first seizures of nuclear material were reported and their subsequent analysis led to the new field of nuclear forensics. The early analyses were performed using methods from nuclear safeguards such as potentiometric titration (uranium content), thermal ionization mass spectrometry (isotopic composition), and optical microscopy (macroscopic parameters). Since that time, the field has rapidly evolved and particle accelerators play a prominent role.

Due to its insensitivity to molecular isobaric interferences, accelerator mass spectrometry provides ultra-trace measurements of radionuclides for nuclear forensics. Isotope ratios of 10^{-12} to 10^{-15} are measured with backgrounds as low as 10^{-17} in some cases. In particular, the ^{236}U/^{238}U ratio in uranium ores has been identified as a forensic signature which can be correlated to geological or geographical sources. Accelerator mass spectrometry is the only technique capable of analyzing ^{236}U/^{238}U ratios in the 10^{-13} to 10^{-10} range. In post-detonation forensics, the relative abundances of neutron activation product debris provide information related to the design and materials used in a nuclear device. Accelerator mass spectrometry has measured neutron activation products such as ^{63}Ni in copper samples to reconstruct the dose associated with the Hiroshima detonation [18]. It can also be applied to measuring other trace activation products such as ^{10}Be, ^{26}Al, and ^{41}Ca for forensic analysis.

The reduction in timelines for the analysis of nuclear detonation debris samples makes rapid methods highly desirable, and nuclear forensics would benefit from remotely controlled field response techniques to characterize this debris, *in-situ*. Present methods require the samples to be dissolved and are labor-intensive and time consuming. Recently a commercial pulsed neutron generator was used to demonstrate neutron-induced inelastic gamma-ray signals from depleted uranium [19]. The approach utilizes time-sequenced data acquisition, operating synchronously with the pulsing of the neutron generator, to partition the characteristic elemental prompt gamma-rays according to either inelastic neutron scattering reactions or thermal neutron capture reactions. Although still at an early stage of development, the preliminary results show promise for developing an in-field sensor for forensic analysis of post-detonation debris. Most accelerator-based systems are affected by environmental conditions and generally have a large infrastructure, so field deployable systems must be made compact and robust. This is especially important for the forensics area, where detection, characterization, and decontamination operations need to occur quickly.

2.7. *Computer model validation*

Sophisticated computational tools are used in security and defense to predict detector response, elucidate unique signatures, optimize system design, and reduce cost and risk [20]. Security and defense applications often have specific requirements that are different from conventional applications of these codes, resulting in fundamental gaps in the underlying physics models and data. Accelerators play an essential role in providing data for reaction cross sections, beam interactions, and material response to validate the models and databases used in the codes.

2.8. *High energy density physics*

High energy density involves the science of matter and radiation under extreme conditions and is generally defined to be an energy density exceeding ~10^{11} J/m^3. Accelerator facilities that produce controllable high energy density environments, such as those found in plasmas, provide phenomenological understanding of radiation effects that is important to security and defense [21]. Specifically, high energy density science ensures that engineered systems are able to operate as intended in the radiation environments they encounter, enables the development of new radiation-resistant systems, and validates models that are used to certify the performance of critical components in extreme temperature and pressure environments. Particularly important to the security and defense mission are accelerator technologies that produce high-energy X-ray sources for radiation effects testing, enable measurement of very high-pressure dynamic material properties, and provide intense radiation environments for high exposure applications.

2.9. *Stockpile stewardship*

The mission of the stockpile stewardship program is to ensure the safety and reliability of the nuclear weapon stockpile without underground testing. To achieve this mission, a more comprehensive understanding of relevant nuclear science and technology is being obtained using an ensemble of advanced laboratory experimental facilities. These facilities, together with the advanced scientific computing tools, will provide the foundational database necessary to certify the safety and reliability of the stockpile.

Pulsed power accelerators with hundreds of terawatt peak beam power have been developed to reproduce the extreme environments relevant to various aspects of nuclear weapons. These accelerators are used to investigate fundamental properties of material, plasma, and radiation at temperatures and pressures similar to those obtained in a nuclear weapon [21]. Fast pulsed power accelerators resulted in major advances in intense pulsed x-ray sources using magnetically driven plasma implosions**.** These facilities enable high-energy plasma implosions driven to completion before instabilities can grow to amplitude sufficiently large to destroy the quality of the implosion.

Accelerator-produced high resolution flash x-ray radiographs are employed to capture the hydrodynamics of high explosives at multiple times and provide information critical to certifying weapon performance [22]. In the late 1960s, a number of high-power bremmstrahlung sources were built to test the effects of radiation from a nuclear weapon on electronic systems and subsystems. Additionally, protons accelerated to hundreds of megavolts are used in proton radiography to study the behavior of materials, ultra-fast phenomena, and explosion transients [23]. Several MeV, 100 kA diode-type accelerators are also used to generate intense electromagnetic pulses that simulate the effects of high altitude nuclear weapons on electronics and control systems.

3. Emerging Technologies

Today's security and defense applications are driving towards the development of more compact, rugged, and low cost accelerators with requisite high efficiency, reliability, and performance. The realization of these characteristics pushes technology innovation in advanced system concepts, novel materials, advanced engineering, high-fidelity simulation tools and improved databases critical to security and defense programs. Some technologies, such as superconducting radio-frequency, x-band, and plasma wakefield accelerators intersect accelerator advancements in other fields, but they also extend to systems such as inverse free electron lasers and induction accelerators that are less actively pursued. Accelerators will also benefit from advances in high energy-recovery efficiency to minimize power consumption and reliable high-current, high-brightness particle sources. While the majority of these accelerator technologies are still in the research and development phase, they promise new and innovative solutions to the most challenging problems in security and defense.

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