Overview of Accelerators with Potential Use in Homeland Security

Robert W. Garnett

*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

Abstract

Quite a broad range of accelerators have been applied to solving many of the challenging problems related to homeland security and defense. These accelerator systems range from relatively small, simple, and compact, to large and complex, based on the specific application requirements. They have been used or proposed as sources of primary and secondary probe beams for applications such as radiography and to induce specific reactions that are key signatures for detecting conventional explosives or fissile material. A brief overview and description of these accelerator systems, their specifications, and application will be presented. Some recent technology trends will also be discussed.

1. Introduction

Real and perceived threats to homeland security have increased significantly. As a result, innovative active-interrogation methods to detect these threats continue to be developed to protect our borders, airports, and ports. All of these detection methods require a source of energetic particles to induce specific reactions that are key signatures for detecting conventional explosives or fissile material, or to perform imaging. Requirements for the applicable accelerator technology can be directly derived from the requirements of the detection techniques currently in use based on the perceived threats. The most immediate perceived threats and their constituent materials include:

* Corresponding author. Tel.: +1-505-665-2835.
E-mail address: rgarnett@lanl.gov
Conventional Explosives – Important elements include N, O, Cl, Na, S, K, P,
Dirty Bombs – $^{137}$Cs, $^{60}$Co (medical rad waste), Shielding Materials: Pb, W, Fe, Polyethylene ((C$_2$H$_4$)$_n$H$_2$),
Special Nuclear Materials – $^{235}$U (HEU), $^{239}$Pu, $^{237}$Np,
Weapons of Mass Destruction – $^{235}$U (HEU), $^{239}$Pu, $^{237}$Np, Explosives, Tamper Materials,
Chemical Agents – Sarin Gas (C$_4$H$_8$Cl$_2$S), Phosgene (CCl$_2$O), Mustard Gas (C$_4$H$_8$Cl$_2$S),
Contraband – people, illicit drugs and other illegal cargo.

To detect the associated materials for a particular threat requires a broad range of detection processes. These use primarily photon beams as the source of energetic particles to induce a particular reaction or to do imaging, however, some techniques also use neutrons and high-energy or exotic beams such as protons or muons, respectively. Detection methods that use photons include transmission radiography, neutron resonance absorption, neutron resonance fluorescence, and photon-induced fission. Several of the photon-based detection methods are described in detail in Bertozzi, et al. (2011). Detection methods using neutrons include neutron-induced fission, neutron activation, neutron transmission radiography, and (n,$\gamma$) reactions involving capture or scattering. Long-stand-off active interrogation requires protons for radiography or muons to generate K muonic x-rays in $^{233}$U or $^{238}$U, for example, as described in Jason et al. (2010). Most integrated active-interrogation systems in use today incorporate several of these methods of detection to broaden the range of use and to provide detection redundancy that helps minimize “false positives” by improving overall detection accuracy. Therefore, most systems incorporate both an x-ray production target and a neutron converter.

The energy thresholds for the reactions involved in each specific detection method ultimately determine the minimum energies of the photons, neutrons or other particles needed. Photons are generated primarily through the bremsstrahlung process by scattering electrons on a high-Z metallic target such as tantalum. The useful photon energy range for homeland security applications is 1-15 MeV, although present US regulations limit the energy to $\leq$ 10 MeV to protect humans from accidental life-threatening exposures. Neutron beams can be generated through several processes, however the most common uses a D-D or D-T neutron generator, generating 2.5-MeV and 14.1-MeV neutrons, respectively. Required beam energies define the accelerator requirements for these systems.

A review of present homeland security systems reveals that electron linear accelerators are being most widely applied. This comes as no surprise since electrons are easy to accelerate efficiently to high energies in a relatively compact system. Typically, beam energies up to 10 MeV are used with average beam currents up to 1-2 mA and at high beam duty cycle (50%-100%). Proton beams are typically being generated using linear accelerators or cyclotrons. Nominal required beam energies are generally less than 10 MeV (very specific energies and small beam energy spread are required for specific reactions) but can be as high as 500 MeV or greater for long-stand-off active interrogation, with average beam currents also in the 1-2 mA range, as for electrons. Pulsed and continuous-wave (CW) neutron beams can be generated with energies up to using a 4-MeV deuteron linear accelerator through the $^{11}$B(d,n)$^{12}$C reaction. Generally, high average beam currents are desirable to improve detection statistics to speed up the interrogation process. Figure 1 summarizes the detection methods and corresponding beam and accelerator requirements.

2. Accelerator Technology Overview

2.1. General Requirements

While specific accelerator requirements can be derived from the detection method being applied, general accelerator requirements for a practical homeland security system can also be specified that need to be met in order for such a system to be fielded. These general requirements include large beam momentum and/or beam energy acceptance which allows acceleration to a wide range of final beam energies, high beam transmission which limits beam losses, reducing accelerator activation and allows for hands-on maintenance, a small or compact footprint, portability, dynamically-variable beam energy and/or beam current, variable duty factor and output beam current, high reliability and availability, and finally if possible, low cost. As might be expected, many of these requirements are technologically orthogonal and very difficult to meet simultaneously.
Applicable electron linear accelerator (linac) technology is readily available and is perhaps the most mature technology due to its use in medical x-ray generation and non-destructive testing in industry. Both normal-conducting and superconducting standing-wave and traveling wave RF electron linacs are available from multiple vendors including Varian, Radiabeam Technologies, and Niowave, Inc. Other commercially available accelerators applicable to homeland security include DC accelerators such as tandem Van de Graaffs and Pelletrons, compact cyclotrons, compact neutron generators, and low-power proton and ion Radio-Frequency Quadrupole (RFQ) linacs.

Advanced technology that shows promise but is still mostly relegated to the R&D environment includes various laser-acceleration schemes, induction linacs including the dielectric wall accelerator, high-average-power RFQs, Fixed-Field Alternating Gradient (FFAG) induction and RF accelerators, and Inverse-Compton-Scattering (ICS) photon sources, to mention a few. Many of these accelerator technologies show great promise for the future to meet many of the general system requirements such as compact footprint, dynamically-variable beam energy and/or beam current and lower cost. The challenge for the future is to move many of these technologies from the R&D environment to commercialization. Both new and innovative applications of present technology, as well as continuing development of new technologies is expected to impact the application of accelerators to homeland security in the near future.

2.3. Electron Linac Technology

Figure 2 taken from Gozani et al. (2011) shows a representative electron linac-based system for active interrogation. This is a combined x-ray, photoneutron source built by Rapiscan Laboratories, Inc. using a 9-MeV Varian Model L2000 S-Band electron linac. Shown are the major components of such a system including the electron source (electron gun), the RF linac, the RF source (grided tube, magnetron, klystron or inductive output tube), and the x-ray target (usually tantalum) plus neutron converter (in this case, a heavy-water converter). The dimensions of this system are approximately 1.5m x 1.5m x 2.5m.

Room-temperature electron linac technology is very mature as mentioned earlier. Typical accelerating structures operate at RF frequencies of 2-4 GHz (S-band) with 2.856 GHz being the common US frequency (2.998 GHz in Europe). Generally, the accelerating structure operating frequency is selected to match RF tube availability which has historically been determined by the communications industry or military radar system requirements, with S-band being the most commonly used for commercial applications. Room-temperature RF electron linacs have also been
built in other frequency ranges, but are less common. Both C-band (5.712 GHz) and X-band (11.424 GHz) linacs have been built and RF sources are available. The higher frequencies such as X-band offer higher accelerating gradients (up to approximately 100 MV/m) and a factor-of-four reduction in transverse structure size since the accelerating structure diameter scales proportional to the RF wavelength.

Common features of these linac structures include: use of an iris-loaded structure which is most common due to its simplicity (see Fig. 3), traveling-wave mode (RF dumped to a load), $2\pi/3$ operating mode, energy gain up to 60 MeV/m, and use of a single RF source (typically a magnetron or klystron). Design methods for these accelerating structures are very mature with a well-established set of relationships that define the structure dimensions parameterized by RF wavelength and structure quality factor (Q). Also shown in Fig. 3 is an X-band structure developed at SLAC by Wang (2011).

Conventional room-temperature electron linac systems are available from many commercial sources. These systems are efficient and relatively compact. Present limitations include low-average beam currents (typically less than 100 $\mu$A) and low duty factor (0.1-1.0%). High average currents and high duty factor require more attention to detail of structure cooling that generally increases structure cost and complexity.

The use of superconducting (SC) niobium accelerating structures for homeland security is increasing now due to the availability of these systems through commercial vendors such as Niowave, Inc. These structures have been used worldwide to efficiently accelerate both electrons and ions. For electrons, simple structures can be used such as the multi-cell elliptical cavity. Figure 4 shows a representative example of such a cavity. A common frequency for these cavities is 1.3 GHz due to their development for the International Linear Collider (ILC). The number of cells for these structures usually ranges from 5 to 9. They can be operated at both 4K and 2K, but typically are operated at 4K.
due to the lower cryosystem cost. These are \( \pi \)-mode structures \((\text{TM}_{010})\) with accelerating-gap spacing of \( \beta \lambda / 2 \) where \( \beta = v/c \) and \( \lambda \) is the RF wavelength. Other SC structure types such as the spoke resonator, half-wave resonator, or quarter-wave resonator are needed to efficiently accelerate low-velocity ions. A particular advantage of SC structures is their large apertures and the capability to operate CW (100% duty factor) due to the low ohmic losses of the structure compared to normal-conducting structures. Systems are currently available that can provide average beam currents up to 1 mA. A significant breakthrough in increasing superconducting gradients is needed for these systems to have significantly smaller footprint. Progress in increasing superconducting gradients has stalled over the last decade but some approaches such as hydro-forming multi-cell cavities to reduce the number of surface defects that contribute to RF breakdown sites and surface coatings are beginning to show promise.

![Fig. 4. a) Typical multi-cell superconducting elliptical cavity used to accelerate \( \beta = 1 \) electrons. b) Prototype 1.3-GHz ILC cavity.](image)

2.4. Neutron Generators

Compact neutron generators are available over a broad range of neutron fluxes. This is a well-developed technology generally incorporating the use of a Penning ion source producing a supply of deuterons which are then accelerated in an electrostatic field and scattered from either a deuterium or tritium target to produce neutrons through the reactions \( \text{D} + \text{D} \rightarrow ^{3}\text{He} + n \) or \( \text{D} + \text{T} \rightarrow ^{4}\text{He} + n \), generating 2.5-MeV and 14.1-MeV neutrons, respectively (see Fig. 5). Alternatively, cold-cathode sources have also been used. These compact neutron generators offer steady-state neutron production, high pulse repetition rates up to \( \sim 1 \text{kHz} \) and nominal duty factors up to \( \sim 10\% \). Very high neutron fluxes, up to \( 10^{14} \) n/s (D-T) and \( 10^{12} \) n/s (D-D), have been demonstrated by Phoenix Nuclear Labs. Several commercial vendors exist making this technology available for several applications, including homeland security. More details about compact neutron generators can be found in Chichester et al. (2003).

![Fig. 5. Schematic design of a sealed-tube neutron generator with a Penning ion source.](image)

2.5. Compact Cyclotrons

Innovations in cyclotron design continue with the goal of increasing extracted beam currents, increasing beam energy while reducing footprint, and reducing overall cyclotron weight. An example of an innovative design is the modern resistive coil cyclotron. These are efficient ferromagnetic structures that can operate at high magnetic fields
and have been designed to fields as high as 9T. An operating example is the IBA C230 proton cyclotron in use for proton beam radiation therapy shown in Fig. 6. It operates at 3T, is 3.5m in diameter, and cost $4M to complete. Also shown in Fig. 6 is an alternative design, 250-MeV superconducting isochronous cyclotron built by Varian, also for medical proton therapy. While not compact enough to be portable, they certainly meet many of the requirements for homeland security active interrogation use such as in a port inspection facility or on a ship for long stand-off active interrogation. Extracted beam currents are generally < 1mA, but a broad range of beam energies can be delivered using the appropriate design. Attempts at ultra-compact footprints (≤ 1m) for high beam energies have been generally unsuccessful due to limitations in turn-to-turn separation of the particle trajectories and associated beam extraction difficulties. An example of an ultra-compact, 10-MeV superconducting design developed at MIT can be found in Lanza (2009).

![IBA C230 resistive-coil proton cyclotron. b) Varian 250-MeV superconducting proton cyclotron.](image)

Fig. 6. a) IBA C230 resistive-coil proton cyclotron. b) Varian 250-MeV superconducting proton cyclotron.

2.6. The Radio-Frequency Quadrupole (RFQ) Accelerator

The RFQ accelerator is a compact accelerating structure for proton and ion acceleration that captures, bunches, and simultaneously focuses and accelerates low-energy beams. The RFQ accelerator concept was proposed by Kapchinskii and Teplyakov in 1970 and demonstrated in 1974 at the USSR Institute for High Energy Physics at Protvino, Russia. Design of the RFQ in the US quickly followed in 1977 at Los Alamos National Laboratory with the first proof-of-principle test in 1979 by Stokes et al. Figure 7 shows schematically the features of an RFQ accelerator. There are several types of RFQ accelerators, the most common being the 4-vane RFQ which is typically used at higher RF frequencies (> 200 MHz) for protons or deuterons and at high duty factor because its vane geometry accommodates the necessary cooling channels, and the 4-rod RFQ, typically used at lower RF frequencies (< 200 MHz) to accelerate heavy-ion beams. A main advantage of the 4-rod RFQ is its simplicity of design and electromagnetic mode separation that makes it simpler to fabricate and tune. Attempts are being made to extend the design and operation of the 4-rod RFQ to higher RF frequencies (near 300 MHz) and to higher RF duty factors (see Kubek, et al. 2011).

The design of the RFQ accelerator is well-formalized, allowing designs over a broad range of performance parameters. The parameters of the RFQ can be tailored, for example, to provide very narrow output beam energy spread if needed to induce a particular nuclear resonance such as the \(^{13}\text{C(p,\gamma)^{14}N}\) nuclear resonance absorption proton-capture reaction in which a well-defined 1.75-MeV proton is captured in carbon-13 to form the 9.17 MeV excited state of nitrogen-14 to detect the nitrogen component in high explosives (see Kwan et al. (2010)).

Design and fabrication of RFQ accelerators is a mature technology widely applied world-wide for many applications. Accelerating gradients are typically in the 1-2 MV/m range. Cost of the structure is high, approximately $1M/m for 4-vane structures. An RFQ accelerator is generally designed for a specific particle charge-to-mass ratio, to operate efficiently at a particular design beam current and vane voltage, up to the design current limit, which is typically chosen to be double the design current. Although most commercially-available RFQ accelerators are designed for low-average output beam currents and low RF duty factor, high-intensity, high-duty-factor designs are possible. An example is the Los Alamos 700-MHz Low-Energy Demonstration Accelerator proton RFQ which operated at an output-beam-energy of 6.7 MeV and 100-mA CW (100% duty factor). See Schneider (1999) for more details.
3. Large Stand-Off Active Interrogation

Large stand-off active interrogation assumes stand-off distances of 100 m or more and requires high-energy beam sources. These proposed systems would be primarily focused on the detection of nuclear threats well in advance of their reaching close proximity to US borders. A possible system configuration to sweep a beam throughout a large structure such as a sea-going vessel would entail fitting a high-gradient or compact high-energy accelerator (500 MeV-1000 MeV, 1-mA average beam current) on a large ship coupled with a helicopter-borne detection system (see Jason et al. (2010)).

Approaches using intermediate-energy protons (~1 GeV) to perform radiographic imaging and the delayed-neutron signature from SNM have been proposed. Laboratory measurements have been made by Morris et al. (2010) to demonstrate proof-of-principle, and to understand measurement limitations. Energetic protons are an attractive alternative to photons and neutrons for active interrogation of nuclear threats because they have large fission cross sections, long mean free paths and high penetration even in high-density materials, require much lower doses to produce a signal, and can be manipulated with magnetic optics.

Nuclear threats can also be detected using muons to perform active interrogation (see Jason et al. (2010)). There are several distinct features of the muon interaction with matter that make their use attractive although generation, capture, and acceleration of the muons are complicated. The unique features of the muon include a low nuclear interaction cross section, allowing long-range propagation of a muon beam, and deep penetration of materials until stopped by ionization loss in a short distance. For large-stand-off active interrogation of a large object, a large beam footprint on target is needed, but at high muon flux. This is possible with muons since a focused muon beam can be propagated through the atmosphere at a range limited primarily by beam-size growth due to scattering with essentially zero attenuation. In contrast, as an example, a 12-m diameter beam of photons propagating through an average density of 0.33 g/cm³ attenuates by a factor of >10⁶ before reaching shielded HEU (50 cm PE, 2.5 cm Pb).

A muon-beam intensity of >10⁹/sec is required for efficient interrogation. Muons are generated through pion decay by scattering a proton or electron beam with energy above the pion-production threshold (~140 MeV) from a refractory target such as carbon (p + C → π → µ⁻). Figure 8a shows the mission space for large-stand-off muon active interrogation parameterized by accelerator beam energy and mass-depth penetration. Figure 8b shows the energy spectrum of K-muonic x-rays in ²³⁵U and ²³⁸U that are the primary signature for detecting special nuclear materials by active muon interrogation.

Figure 9 shows the Los Alamos National Laboratory concept for muon active interrogation. This concept requires a 1-mA, 500-MeV proton accelerator to produce the secondary muons, 0-mode pill-box cavities (aperture closed by thin metal windows; also shown in Fig. 9) used to accelerate the captured muons to 200 MeV, and the 3-5 T capture/confinement field produced by a long segmented solenoid magnet. The muon linac is then followed by a
conventional superconducting linac using elliptical cavities to accelerate the $\mu^-$ beam to high energy (500 MeV-1000 MeV) to be used for long-stand-off active interrogation.

Compact accelerator technology to produce high-energy protons, for example, does not currently exist, although emerging concepts such as the Fixed-Field Alternating Gradient (FFAG) accelerator are showing promise. Present normal-conducting accelerator technology applied at low energy coupled with superconducting accelerator technology at high energy can meet present requirements but requires a large footprint for implementation to reach beam energies near 1000 MeV.

Fig. 8. a) Mission space for muon active interrogation. b) Computed energy spectrum for K-muonic x-rays from $^{235}$U and $^{238}$U.

Fig. 9. a) Los Alamos concept for muon active interrogation. b) 0-mode pill-box cavities used to accelerate the captured muons.

4. Emerging Accelerator Technologies

New accelerator-based technology will be needed for next-generation homeland security applications including innovative applications of present technology as well as development of new technologies. There are several emerging accelerator technologies that have the potential to meet this need in the near future. Advanced machining techniques such as additive manufacturing (3-D printing) may also enable miniaturization of accelerators beyond what is capable today or improve the accuracy of fabrication of existing compact systems. One day we may see accelerators making accelerators. Several of these emerging technologies will be discussed briefly in the sections below.

4.1. Direct Laser Acceleration

During the past decade or so several mechanisms of direct laser generation and acceleration of particle beams have been demonstrated. These include target normal sheath acceleration (TNSA), radiation pressure
(pondermotive) acceleration (RPA), and laser break-out afterburner acceleration (BOA). These methods have been used to generate and accelerate beams of electrons, protons, deuterons, and various ions. Intense neutron beams have been generated using deuterons and low-Z converters (see Roth et al. (2013)). These TW laser-driven accelerators are being enabled by improving optical drive laser performance (higher average power and higher repetition rates), shrinking footprint, and lower cost. Present limitations that impact some application of these systems include difficulty in tailoring the final beam energy distribution—these beams generally have a large energy spread compared to beams from conventional accelerators but on-going efforts continue to improve this. This author believes that application of this technology will increase when it is mated with conventional accelerator technology as is being investigated by Hoffmann (2013). More detailed discussions of laser acceleration can be found in Schollmeier et al. (2008) and Fernandez (2008).

4.2. Inverse Compton Scattering X-ray Sources

Compact high-energy x-ray sources based on inverse-Compton scattering (ICS) sources are now being applied to homeland security due to the recent maturity of new technologies including high-gradient X-band electron accelerators and performance improvements in commercial optical laser systems. These sources require a bright (small emittance, high-peak charge) relativistic electron beam (typically from an electron linac) and high-brightness (small waist, high energy/pulse) photons from a laser. These sources can be extremely bright and narrow bandwidth, enabling their use both in radiography and for nuclear applications requiring excitation of very-narrow, unique nuclear resonances of various isotopes. Photon energies into the MeV energy range can be generated. Such a system is described in Marsh et al. (2012).

These sources rely on the tremendous $4\gamma^2$ upshift in photon energy that occurs as the incident laser photons are scattered from a relativistic electron beam where $\gamma$ is the Lorentz factor. With $10^2 \leq \gamma \leq 10^3$, optical wavelengths can be shifted into the x-ray or gamma-ray range. By combining a laser undulator with ICS, electron beam energies < 100 MeV can be used to produce hard x-ray photons. In this case, the drive laser which supplies the initial source of photons, also provides the undulator magnetic field (See Kim (2010)). A system based on this concept is operating at Lyncean Technologies, Inc. in Palo Alto, California and has demonstrated generation of 12-KeV x-rays using a 25-MeV electron beam. This system combines a laser undulator with a compact electron ring and ICS interaction region.

4.3. Induction Accelerators

Induction accelerators use ferromagnetic (high inductive impedance) cores to provide stored energy to accelerate beams of electrons or ions. These induction cells and the beam act as a one-to-one transformer where the changing magnetic fields generate accelerating electric fields on axis in the gaps between cores. Confining magnetic fields are generally provided by pulsed solenoids integrated into the design of the induction cells. Electrical energy to the induction cores is typically provided by pulse-forming Blumleins or compact pulse-forming networks (PFNs). Because this is a non-resonant form of acceleration, any charge-to-mass-ratio from electrons to heavy ions can be accelerated.

Historically, induction accelerator technology has been used for applications requiring kilo-ampere electron or ion beams such as for heavy-ion fusion or weapons radiography. Recent examples of this technology for large-scale application include the Neutral Drift Compression Experiment-II (NDCX-II) at Lawrence Berkeley National Laboratory and the Dual-Axis Radiographic Hydro Test (DARHT) facility at Los Alamos. However, compact induction accelerators are also being developed for active interrogation. These include compact induction linacs (see Caporaso (2000) and Sampayan et al. (2007)) where the required enabling technologies include use of multilayer high-gradient metal/insulating layers to provide continuous accelerating gaps and the ability to rapidly and precisely trigger stacked pulse-forming networks.

Fixed field alternating gradient (FFAG) accelerators using an induction core to accelerate the beam are also under consideration for homeland-security applications (Bertozzi et al. (2011), Boucher et al., (2008), and Huan-li et al. (2013)), although not yet commercially available. Because an induction core is used, no RF system is needed as in other variations of the FFAG, therefore simplifying the design. Other advantages include a small circular accelerator
footprint for beam energies < 10 MeV, static guide magnet fields, high duty cycle (>50% possible), dynamically-variable output current, and conservative induction core requirements (∼50 keV/turn). Several FFAG topologies are possible including scaling, non-scaling, radial, and spiral. A recent example of an applicable FFAG is the RadiaBeam Radiatron FFAG Betatron.

4.4. Frontier Accelerators

Significant effort would be required to discuss in detail the various frontier accelerator concepts that could eventually have application to homeland security. Most of these are still primarily in the R&D phase and are not yet ready for commercialization, but offer the promise of realizing ultra-compact devices to accelerate electrons to high energies through miniaturization. These include: laser-plasma acceleration (Leemans (2012)), dielectric-wake acceleration (Zhang et al., (1997)), and dielectric laser acceleration (Peralta et al., (2013)).

References

Bertozzi, W., et al., 2011. Accelerators for homeland security. International Journal of Modern Physics A, Vol. 26, Nos. 10&11, pp. 1713-1735.
Boucher, S. et al., 2008. The Radiatron: A high average current betatron for industrial and security applications. Proceedings of EPAC08, Genoa, Italy, pp. 1860-1862.
Caroraso, G., 2000. Proceedings of LINC 2000, arXiv:physics/0010011, 3 Oct 2000.
Chichester, David L., Simpson, James D., 2003. Compact neutron generators. The Industrial Physicist, December 2003/January 2004, pp. 22-25.
Fernandez, J. C., 2008. Laser acceleration of MeV-GeV ion beams: the next generation of high-current accelerators. FESAC Workshop on Scientific Opportunities in High Energy Density Laboratory Plasma Physics, Washington DC, August 25-27, 2008.
Gozani, T., et al., 2011. Combined photon neutron and x-ray interrogation of containers for nuclear materials. AIP Conference Proceedings, 1336, 686 (2011); doi: 10.1063/1.3586190.
Hofmann, I., 2013. Performance of solenoids vs. quadrupoles in focusing and energy selection of laser accelerated protons. arXiv:1301.6906v1 [physics.acc-ph] 29 Jan 2013.
Huan-li, L., et al., 2013. Conception design of helium ion FFAG accelerator with induction accelerating cavity. arXiv:1305.2569v1 [physics.acc-ph] 12 May 2013.
Jason, A., Miyadera, H., Turchi, P., 2010. SNM detection by active interrogation. Los Alamos National Laboratory publication, LA-UR-10-04398.
Kapchiskii, I. M., Teplakov, V. A., 1970. Prib. Tekh. Eksp. No. 2, pp.19.
Koubek, B., Schmidt, J., Schempp, A., Groening, L., 2011. RF-design of a 325 MHz 4-rod RFQ. Proceedings of IPAC 2011, San Sebastian, Spain, pp. 2568-2570.
Kwan, et al., 2010. The development of enabling technologies for producing active interrogation beams. Review of Scientific Instruments 81, 103304.
Lanza, R., 2009. Accelerator based techniques for detection of explosives and SNM. IAEA RCM, Neutron Based Techniques for the Detection of Illicit Materials and Explosives, Johannesburg, South Africa, 16-20 November 2009.
Leemans, W., 2012. Proceedings of IPAC 2012, New Orleans, Louisiana.
Linvingston, M. Stanley, Blewett, John. P., 1962. Iris-loaded linac structures, in “Particle Accelerators”. McGraw-Hill Book Company, New York, pp. 324.
Marsh, R. A., et al., 2012. Ultracompact accelerator technology for a next-generation gamma-ray source. Proceedings of IPAC 2012, New Orleans, Louisiana.
Morris, C. L., et al., 2010. Active interrogation using energetic protons. Los Alamos National Laboratory publication, LA-UR-10-04680.
Peralta, E. A. et al., 2013, Demonstration of electron acceleration in a laser-driven dielectric structure. Nature, Vol. 502, November 7, 2013, pp. 91-101.
Roth, M., et al., 2013. Bright laser-driven neutron source based on the relativistic transparency of solids. Physical Review Letters, 110, 044802.
Sampayan, S., et al., 2007. Applications of ultra-compact accelerator technologies for homeland security. Nuc. Instr. and Meth. In Phys. Res. B, 261, pp.281-285.
Schneider, J. David, 1999. Operation of the low-energy demonstration accelerator: the proton injector for APT. Proceedings of the 1999 Particle Accelerator Conference, New York, pp. 503-507.
Schollmeier, M., et al., Controlled transport and focusing of laser-accelerated protons with miniature magnetic devices. Physics Review Letters, 101, 055004.
Stokes, R. H., Crandall, K. R., Stovall, J. E., Swenson, D. A., 1979. IEEE Trans. NS-26, pp. 3469.
Wang, J., 2011. X-band accelerator structures R&D at SLAC. SLAC/LLNL Discussion, March 5, 2011.
Zhang, T-B., et al., 1997. Stimulated dielectric wake-field accelerator. Physical Review E, Vol. 56, No. 4, pp 4647-4655.