ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-TH1AA03

ACCELERATOR DEVELOPMENT FOR GLOBAL SECURITY

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Abstract

Many particle accelerator facilities and projects can help with global security concerns, but not all accelerators used for security applications are designed specifically for these security applications. From direct interrogation to microelectronics radiation testing, there are myriad security applications of particle accelerators. This paper reviews several accelerator applications of security as well as design and technology activities to specifically better enable global security. Finally, this paper also points to many references discussing accelerators in global security.

INTRODUCTION

Global security means different things to different people. Global security includes military and diplomatic measures that nations and international organizations such as the United Nations [1] and the North Atlantic Treaty Organization (NATO) [2] take to ensure mutual safety and security. An individual may only focus on their own security.

The United Nations has its own definition of global security [3, 4]: "*With the advocacy of the United Nations Office for the Coordination of Humanitarian Affairs (OCHA) human security elements have acquired a wider dimension, for they go beyond military protection and engage threats to human dignity. Accordingly, it has become necessary for states to make conscious efforts towards building links with other states and to consciously engage in global security initiatives. OCHA's expanded definition of security calls for a wide range of security areas:*

- *Economic: creation of employment and measures against poverty.*
- *Food: measures against hunger and famine.*
- *Health: measures against disease, unsafe food, malnutrition and lack of access to basic health care.*
- *Environmental: measures against environmental degradation, resource depletion, natural disasters and pollution.*
- *Personal: measures against physical violence, crime, terrorism, domestic violence and child labour.*
- *Community: measures against inter-ethnic, religious and other identity tensions.*
- *Political: measures against political repression and human rights abuses.*"

Looking through this broad definition of security that considers the collection of individual security concerns throughout the globe, we immediately recognize that particle accelerators and their peripherals can be of great assistance as a tool for global security applications (including defense).

Here are a few areas that might have come to mind as to why (in general terms) accelerators (and lasers and accelerator peripherals) are interesting for global security and defense [5, 6]:

- The identification and detection of materials, including chemical, biological, radiological, nuclear, and explosive (CBRNE);
- Preserving the water – energy – food nexus;
- Directed energy (applications: materials "modification" at a distance, propulsion, power transfer);
- Laser-sensing, communications, etc.;
- Materials research;
- Stockpile stewardship;
- Electronics testing for space and other applications;
- Medical applications (x-ray technologies, imaging, cancer treatments) to treat individuals located in environments that do not have access to state-of-the-art hospitals to preserve global health;
- Active radiation-belt remediation to improve the lifetime of satellites transiting the radiation belts;
- Sterilization capability for foods and surfaces to prevent contamination and infection.

Although this paper can cover a few ideas, it cannot cover all ideas and applications of accelerators and peripherals for global security. For this reason, many references are provided. Many of these publications have been based on comprehensive community studies and their subsequent publications to address accelerators, peripherals, and lasers, including:

- Accelerators for America's Future, Department of Energy Report, March 2010 [7];
- Workshop on Energy and Environmental Applications of Accelerators, Department of Energy Report, 2015 [8];
- Workshop on Laser Technology for Accelerators, Department of Energy Report, 2013 [9];
- Workshop on Ion Beam Therapy, Department of Energy Report, 2013 [10];
- Task Force Report on Accelerator R&D commissioned by Jim Siegrist, Associate Director High Energy Physics, Office of Science [11];
- National Research Council, Scientific Assessment of High-Power Free-Electron Laser Technology, Washington, DC: The National Academies Press, 2009 [12];
- Summary Report – International FEL Expert Meeting: "Use of free-electron lasers and beyond: Scientific, technological, and legal aspects of dual use in international scientific cooperation" [13];
- The need for compact accelerators has been outlined in numerous documents, including the Basic Research Needs Workshop Report for Compact Accelerators for Security and Medicine: Tools for the 21st Century,

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Department of Energy, Office of High Energy Physics, January 2020 [14].

As a result of these and similar studies, public funding has become available to extend the utility and reach of particle accelerators in the United States with the new Accelerator Research and Development and Production (ARDAP) Office in the Department of Energy (DOE) [15] and in Europe and the United Kingdom with the Innovation Fostering In Accelerator Science And Technology (I.FAST) program under the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No. 101004730 [16].

ACCELERATORS AS TOOLS FOR GLOBAL SECURITY

For Pandemics

What has been a major threat to global security since 2019? The COVID-19 pandemic. And now the world is worried about monkeypox, and even paralytic poliovirus is now being detected in wastewater in New York state.

Particle accelerators, such as the Advanced Photon Source at Argonne National Laboratory, were used to study the structure of the SARS-CoV-2 virus that causes COVID-19. The APS x-rays, as one example, were used by more than 70 research teams, including those from military research teams.

Other groups in Europe teamed together to promote knowledge of and use of their facilities for the efforts to combat COVID-19. A great summary by the League of European Accelerator-based Photon Sources (LEAPS) was made immediately available to the worldwide scientific community [17]. The Swiss Light Source [18], the European XFEL [19], the Swiss FEL's Aramis beamline [20], FELIX [21], and FERMI@Elettra [22] made major contributions to help the efforts to combat COVID-19. For example, diffraction data were collected on a single frozen crystal in a nitrogen stream at 100 K at the Swiss Light Source's PXI beamline, illustrating the inhibition of papain-like protease PLpro blocking the SARS-CoV-2 spread and promoting anti-viral immunity [23].

For the Future – Science and Technology Pieces and Systems Conceptual Designs

The workhorse machines at the national laboratories helped science combat COVID-19. The accelerator community is pursuing several complementary pathways for compact sources (3rd and 4th generation) that could enable much science, technology, and engineering including perhaps dedicated, rapid response facilities, possibly at BSL-3 or other "on-Site" facilities.

This development covers a wide variety of activities including overall system designs, such as the ultra-compact x-ray free electron laser (UC-XFEL) [24] study being led by UCLA and its collaborators. There are also myriad studies being performed on the science and technologies that can feed into these proposed more compact sources that can be used for global security, such as high-performance and robust photocathodes as well as improvements to superconducting cavities. Many examples of such accelerator improvements are illustrated; as one example, in the research outcomes of the National Science Foundation's Center for Bright Beams (CBB) [25], their list of publications involve the many CBB members, affiliates, and affiliate institutions, including national and international laboratories and industries [26].

In terms of several examples of advanced accelerator-driven, free electron lasers, three such first-lasing talks were given the week before this LINAC 2022 conference at the 40th International Free Electron Laser Conference (FEL2022) in Trieste, Italy [27]:

- First Lasing of the COXINEL Seeded Free Electron Laser Driven by the HZDR Laser Plasma Accelerator (Marie-Emmanuelle Couprie, SOLEIL);
- SASE and Seeded FEL Powered by PWFA Electron Beam (Vladimir Shpakov, INFN-LNF); and
- Free-electron Lasing Based on a Laser Wakefield Accelerator (Wentao Wang, SIOM, CAS).

Many examples of technology developments that can feed into future accelerator sources can be found in these proceedings and all the accelerator conference proceedings and journals in which we publish. This fall will bring the 20th Advanced Accelerator Concepts Workshop (AAC'22) [28], where many of these advanced concepts will be covered. There are simply too many excellent contributions to our field to cover them all here.

For Pandemics – Don't Forget about Electron Diffraction

An MeV ultrafast electron diffraction (MUED) system is a unique pump-probe characterization technique for studying ultrafast processes in a variety of materials. The use of relativistic (typically multiple MeV) beams leads to decreased space-charge effects compared to typical ultrafast electron diffraction experiments employing energies in the keV range [29, 30]. MUED has a very high scattering cross section with material samples as compared to other ultrafast probes such as XFELs, and as such allows access to higher-order reflections in the diffraction patterns due to the short electron wavelengths. The Brookhaven-based MUED system was discussed in this conference by Mariana Fazio [31, 32], and other concepts for a future MUED and microscopy (MUEM) system at Daresbury Laboratory were discussed by Jim Clarke [33].

Possible applications of MUED include soft matter and biological samples (e.g., pandemics) [34]. MUED can lead the way for time-resolved biology to characterize membrane fusion processes, dynamics of large biological assemblies, and much more.

For Water and Waste Streams

Several activities are ongoing. Some, funded by the former Accelerator Stewardship program (now the U.S. DOE ARDAP Office), have focused around energy and the environment, particularly on treating waste streams with high-average power electron beams. The awards from these programs are outlined and detailed on the program website [35].

More advanced activities have been more extensively detailed [36-38]. An excellent overview of this genre of accelerator is provided in this conference [38].

One key water treatment collaboration activity is between Jefferson Lab and Hampton Roads Sanitation District (HRSD). Jefferson Lab (JLab) installed an irradiation beamline at the Upgraded Injector Test Facility (10 MeV, CW SRF Linac). This irradiation beamline is being used to evaluate e-beam irradiation as a possible method to reduce or eliminate emerging contaminants in wastewater [39, 40]. They explored eliminating 1,4-dioxane, which is widely spread in wastewater streams and a likely human carcinogen. More than 95% of 1,4-dioxane was removed for a dose < 2 kGy. They are performing testing on perfluoroalkyl and polyfluoroalkyl substances (PFASs) that constitute a family of over 5000 synthetic substances.

For Microelectronics Testing

There is an increasing demand by the private and public aerospace and defense communities for radiation testing of electronics. These effects are caused either by natural background radiation or are manmade. Discussions on this topic are many. For instance, a plenary talk was presented on this subject at the 2022 North American Particle Accelerators Conference by Jonny Pellish of NASA [41]. The recent federal report from the National Academies of Sciences, Engineering, and Medicine [42] and dedicated conferences such as the IEEE Nuclear & Space Radiation Effects Conference (NSREC) [43] all illustrate the dire need for new test beds to meet this growing demand.

Let's explore a couple of examples of existing and proposed facilities and research in this area. This is by no means a comprehensive list, but merely a couple of activities for expanding the test capabilities at accelerators.

The Los Alamos Neutron Science Center (LANSCE) facility at Los Alamos National Laboratory (LANL) [44] produces a neutron flux that is 1 million times that experienced at 35,000 feet. Neutrons produced by cosmic rays penetrate the atmosphere and interact with electronics causing single event upsets or latch ups. LANSCE hosts many users seeking to ensure robustness of electronics against cosmic-ray bombardment. Possible upgrades to LANSCE in the future are expected to enable expanded testing.

Brookhaven National Laboratory already operates several radiation test facilities including the NASA Space Radiation Laboratory (NSRL) [45]. They are now considering building the High Energy Events Test (HEET) facility that would produce ion beams (H to U) from 40 MeV/n to 2000 MeV/n and higher for electronics testing.

Laser-driven ions is another approach that looks to the future infrastructure driver of high-contrast laser systems to drive ions. Such future devices are complementary to standard accelerators. They can provide multiple species simultaneously over a spectrum of energies. Our own team has been pursuing methods for the generation of ions.

For Radiation Belt Remediation

Not unrelated to the radiation effects is the idea of reducing electrons in the radiation belts to also reduce their possible radiation effects in space. The 2018 talk by Bruce Carlsten illustrates the details of electron-beam-based remediation schemes [46] to combat the more than one satellite a year (2018 data) being lost due to electrons (only from background radiation). Should there be a man-made event, these effects can be 4-6 orders of magnitude higher than the natural background radiation, and the electrons linger for about six months. LANL, in collaboration with the SLAC National Accelerator Laboratory, is using high-electron-mobility transistors (HEMTs) to drive specialized rf cavities for electron sources that could be used in this space-remediation method.

Stockpile Stewardship

The particle accelerator and materials research communities have long enjoyed a synergistic relationship, dating back at least to the first studies of materials using synchrotron radiation produced at particle accelerators. At present a new generation of advanced synchrotrons and x-ray free electron lasers are emerging. These advances are co-incident with a push in materials research to understand phenomena at unprecedented length and time scales, including a focus on the mesoscale properties of materials. Further, photons are not the only accelerator-produced particles of interest to materials research, both as a probe and as a means of generating perturbed states of matter. Future opportunities can be met through the application of much-needed advanced accelerator technologies for future accelerator-driven devices.

One materials science frontier is that of mesoscale materials science in extreme conditions [47-49]. The mesoscale covers spatial and temporal dimensions bridging the nano- and macroscopic scales, and a multidimensional space that is characterized by the complexity of its phenomena at the transition from the discrete quantum to the continuum macroscopic world [50]. The National Nuclear Security Administration's (NNSA) need to predict and control the microstructure of materials is also a science frontier [51]. The advancements in understanding the atomic-level nanoscale and building up to a perfect lattice are tremendous, but the rules of engagement at the mesoscale for design and manufacture still require much study. At this science frontier, and for NNSA applications, we are interested in the strength and robustness of the materials. Building the perfect lattice by adding atom after atom will not necessarily yield the strongest material. We can look to superconductivity, for instance, for inspiration, as induced defects provide additional current-carrying capabilities. At the mesoscale, as a corollary, defects can provide additional strength.

In response to these science frontiers and NNSA needs that rely on the near-simultaneous ability to synthesize and assemble materials, characterize materials, and understand materials through theory/simulation, the Matter Radiation Interaction in Extremes (MaRIE) facility was conceived at LANL. The MaRIE facility was intended to support key

NNSA goals, including meeting the Dynamic Mesoscale Material Science Capability (DMMSC) gap. From the analysis side, we are not talking about having a perfect sample environment with a perfect material. We are however talking about samples under extreme conditions in an operationally relevant system or emulated system environment. This is echoed in a report for the NNSA [52, 53]: "The National Nuclear Security Administration (NNSA) has an unmet capability need to improve our ability to predict how changes in a material's microstructure impact its performance in weapons environments. Certification of the future stockpile; maintenance of the current, aging stockpile; and qualification challenges associated with materials and manufacturing changes will rely heavily on an understanding of materials in extreme environments." This is also echoed in the recent NAS Materials Decadal study [49]: "Collectively, these new ultrabright sources will drive further advances in the techniques, enabling the transformative studies of materials with nanoscale resolution while under operating conditions and on ultrafast time scales. United States had a significant fraction of all the world-leading capabilities 20 years ago, but that lead has eroded and today's landscape is one of intense competition from both Europe and Asia."

Additional Security Applications

As discussed in reports and papers, including the recent DOE Basic Research Needs Report on Compact Accelerators for Security and Medicine [14], the replacement of less secure sources of ionizing radiation with accelerators is interesting for the following applications:

- Non-invasive probing
  - Interrogation of geological materials
  - Radiography for non-destructive testing and evaluation of structures
  - Probing of cargo for contrabands such as narcotics, CNM, munitions, etc.
- Industrial radiation processing
  - Medical device sterilization and pharmaceuticals
  - Food processing for safety and quality
  - Phytosanitary and sterile insect technology

A group from the University of Tokyo [54, 55] has recently fielded an accelerator device for on-site x-ray bridge inspection using ~4.5-MeV electron sources. This x-ray inspection is coupled with other analytical analyses to help to guide the repair and reinforcement stages of the bridge, extending its lifetime, thus saving on energy and raw materials, which would be the case if completely replaced. It also provides safety to humans and the environment.

Mitsuru Uesaka, Chairman of the Japan Atomic Energy Commission (JAEC), recently discussed the use of particle accelerators for the decommissioning of the TEPCO Fukushima Daiichi Nuclear Power Station (FDNPS) [56, 57]. A trial retrieval of fuel debris at Unit 2 is scheduled soon, and they plan to do the screening and identification of nuclear debris on-site using two particle accelerators. The first is a dual-energy x-ray CT inspection system (based around a portable 3.95-MeV X-band electron linac-based x-ray source) to identify the atomic number and weight. The second is a neutron spectrum resonance through the time-of-flight method for identifying the isotopes. This is based around a portable 3.95-MeV X-band electron linac-based neutron source. With the acquired information of the existence and mass density of U/Pu, the debris is discriminated into the two storage systems for spent nuclear fuel with U/Pu criticality control and normal radioactive waste without U/Pu. This allows for a practical and reasonable fuel debris storage system.

Accelerator-driven nuclear energy is yet another energy-security application of particle accelerators and involves a powerful accelerator that can produce neutrons by spallation. The talk and paper at this conference by Bruce Yee Rendon [58] provides a great summary of the global activities for such accelerator-driven systems (ADSs). These proton accelerators are used to drive nuclear power plants (thorium) or transmute nuclear waste into shorter-lived, more manageable by-products.

There are additional activities in directed energy (DE) using accelerators that are reviewed elsewhere [59] due to space constraints. Further, it is not only the accelerators themselves that contribute to global security. High-Performance Computing, such as the Argonne Leadership Computing Facility, and accelerator test facilities, such as that at Brookhaven, are important for testing and development

Finally, we need a dramatic change in our thinking and actions to reduce climate change and reduce reliance on unclean energy sources. Let's look to a few examples that explore this energy security. Sweden has been decarbonized since the 1970s. Follow suit and make this a basis of the energy architecture [60]. This folds into the clean energy and water nexus. One disruptive approach is the marriage of nuclear and particle accelerators. Small modular reactors (SMRs) could power an industrial complex or a small city or research park, and all-electric decontamination schemes with particle accelerators could reduce emissions. We can create an electric ecosystem encapsulated in an industrial park/small city with the advancements in SMRs [61].

CONCLUSIONS

The term 'global security' has its own meaning for each individual. For the definition put forward by the United Nations, we feel that accelerators can continue to drive global security solutions. We feel that nearly every technology and method discussed at LINAC 2022 can have some impact for global security, including science diplomacy.

In this 80th year of the celebration of the first sustained nuclear reaction underneath Stagg Field, let us think for a moment about Enrico Fermi, who led that project as well as later projects. Fermi's one accelerator project was something he dreamt of close to the end of his short life. He dreamt of an accelerator encompassing Earth. Perhaps Fermi actually meant that accelerators (and other analytical research tools, devices, and probes) would in a figurative way encompass the Earth (Fig. 1). Maybe he meant using accelerators for global security through science diplomacy.

We need the people and collaborations to develop accelerators for global security.

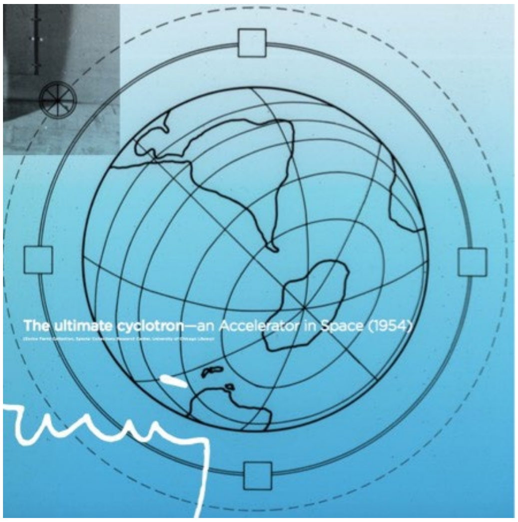

Figure 1: Enrico Fermi's accelerator encompassing Earth, 1954. (Courtesy of the University of Chicago.)

ACKNOWLEDGEMENTS

Many thanks to Eric Colby (DOE), Bruce Carlsten (DOE and LANL), John Louis Sarrao (LANL), Mark Neice (Directed Energy Professional Society), Robert Rosner (University of Chicago), Mark Peters (Battelle), Quentin Saulter (Office of Naval Research), Ritchie Patterson (Cornell), Mark Curtin (ILS and consultant), Graeme Burt (Lancaster University), Stephen Milton (Element Aero and Tau Systems), Stephen Streiffer (Stanford University), Mark Palmer (Brookhaven National Laboratory), Michael Papka (Argonne National Laboratory), Mitsuru Uesaka (JAEC), David Martin (Argonne National Laboratory), Ajit Manocha (SEMI), Mariana Fazio (University of New Mexico and University of Strathclyde), and Trudy Bolin (University of New Mexico and consultant), and many others through the years, for on-going discussions. This work was supported in part by the U.S. National Science Foundation under Award PHY-1549132, the CBB.

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