Compact Accelerators for Security and Medicine

Indications for accelerator-based alternatives to radioisotopes

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Workshop report:
https://science.osti.gov/-/media/hep/pdf/Reports/2020/CASM_WorkshopReport.pdf

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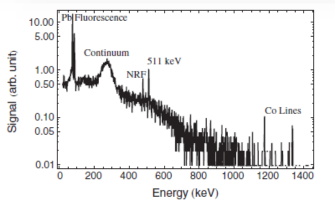
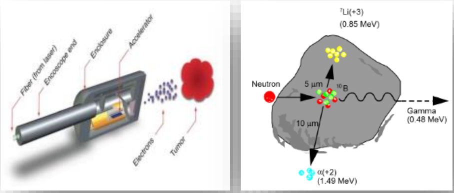
Outline

- Basic Research Needs Workshop (BRN)
  - Sponsors' Interests, Charge, Organization & Participants
- Compact Accelerators for Security
  - NDC in numerous contexts; sterilization of food, medical supplies
    - *Focus on radioisotope source replacement*
- Compact Accelerators for Medicine
  - X-ray and electron machines for clinical and pre-clinical use
    - *Focus on radioisotope source replacement*
- Cross-cutting Technology R&D Themes
  - 5 Priority Research Directions
- DOE Accelerator Stewardship program awards in this area
- Next steps

Motivation and Sponsors of the Workshop



- There is a long history of applying accelerator technology to address challenges in security and medicine
  - Accelerator technology advances of the last decade are not fully adopted in the field
  - New applications have emerged
- Cognizant federal agencies met in 2018 to discuss interests, resulting in the 2019 Workshop
  - Federal agencies wanted to understand the highest impact applications enabled by prior advances and current R&D efforts and to develop a set of Priority Research Directions
  - DOE, DOD, DHS, and NIH participated and co-sponsored the workshop. NSF was briefed on the outcome.



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Workshop Scope

- **Focused on the following security and medical applications:**
  - Replacement of radioisotopic sources by accelerator-based alternatives,
  - Ruggedized low-cost linacs for global applications,
  - FLASH-RT and Very-high energy electron (VHEE) sources for radiotherapy,
  - Source-free brachytherapy (i.e. endoscopic particle accelerators),
  - Portable monochromatic high energy x-ray sources, and
  - Compact neutron generators†.
- **Excluded:**
  - High power accelerators (e.g. >100 kW) and Energy & Environmental applications (both covered by the 2015 BRN on Energy & Environmental Applications of Accelerators)
  - Compact proton and ion accelerators for isotope production, particle beam cancer therapy.
- **Restricted to compact accelerator technologies**
  - Emphasis on accelerator technology that can achieve **TRL-4 within 5 years**
    - But, with **long-term look-ahead** on compact SRF and advanced accelerator concepts
  - Informed by what is possible/feasible on the **detector technology** portion of each application

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† Restricted in this case to conventional technologies for neutron generation such as D-T fusion, DPF, and Z-pinch.

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Basic Research Needs Workshop Charge

A BRN Workshop is an agency-led, agency-charged workshop designed to identify long-term R&D goals and help organize the community to achieve the goals.

- **Assess the state of any existing accelerator and non-accelerator-based technology** currently deployed for the application. **Document cost and performance criteria** to be used as a benchmark for analyzing alternatives based on accelerator technology.
- **Document current and proposed** Federal and State environment, safety, and health **regulatory requirements** for the application and identify any issues with regard to these regulations.
- **Develop performance criteria** for accelerator-based systems for the application. Consider total system costs for production and operation. **Assess the potential** financial and/or application **benefits** if the accelerator technology meets the criteria. **Document specifications** for the accelerator components of the system.
- **Identify technical gaps** between the current state of the art of accelerator technology compared to the above specifications. This may include accelerator-related technologies such as power supplies or magnet technology.
- **Identify synergistic application-side R&D** relevant to the application of accelerator technology to security, medical, and other application challenges.
- **Specify R&D activities needed to bridge technical gaps**, and any additional analysis and testing required to validate their use
- **Develop a prioritized list of R&D**; estimate rough order-of-magnitude costs to complete required R&D

Legend

Technology Applicability and Readiness

Accelerator Technology

Application-Side Technology

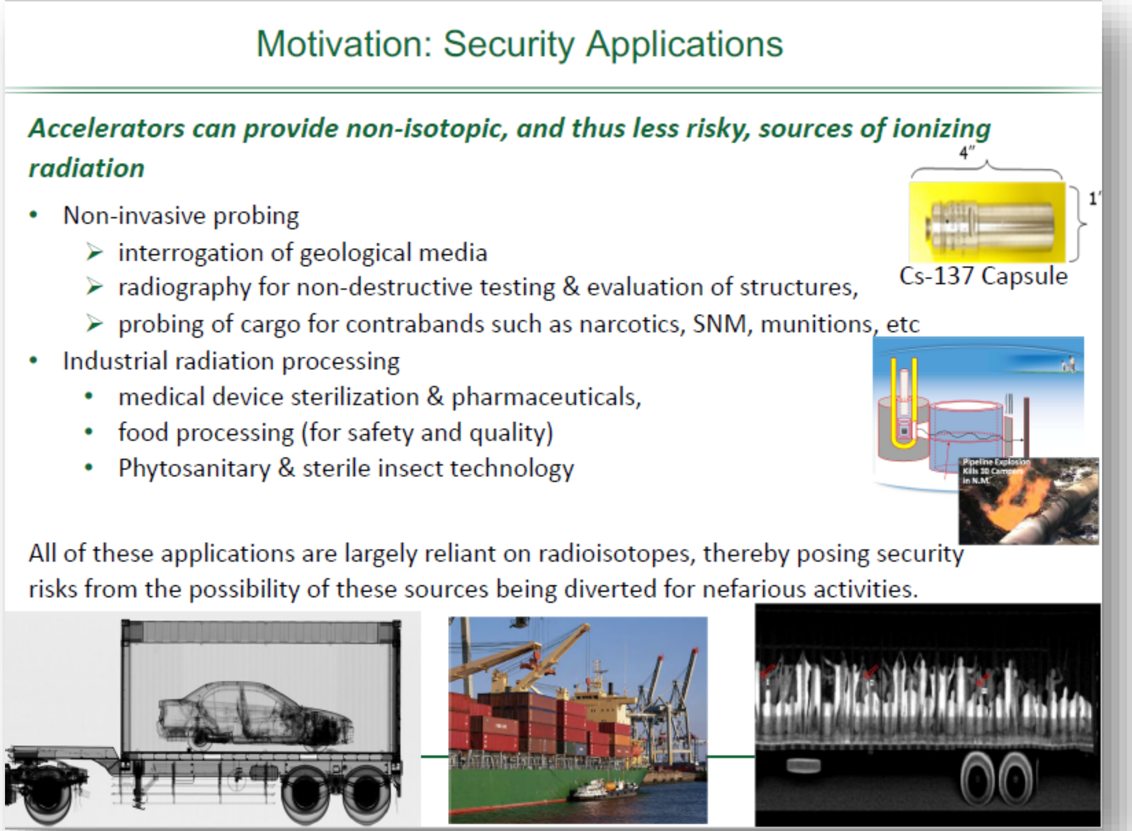
Regulatory Acceptance

Existing Market Conditions

Pathway to a commercial product

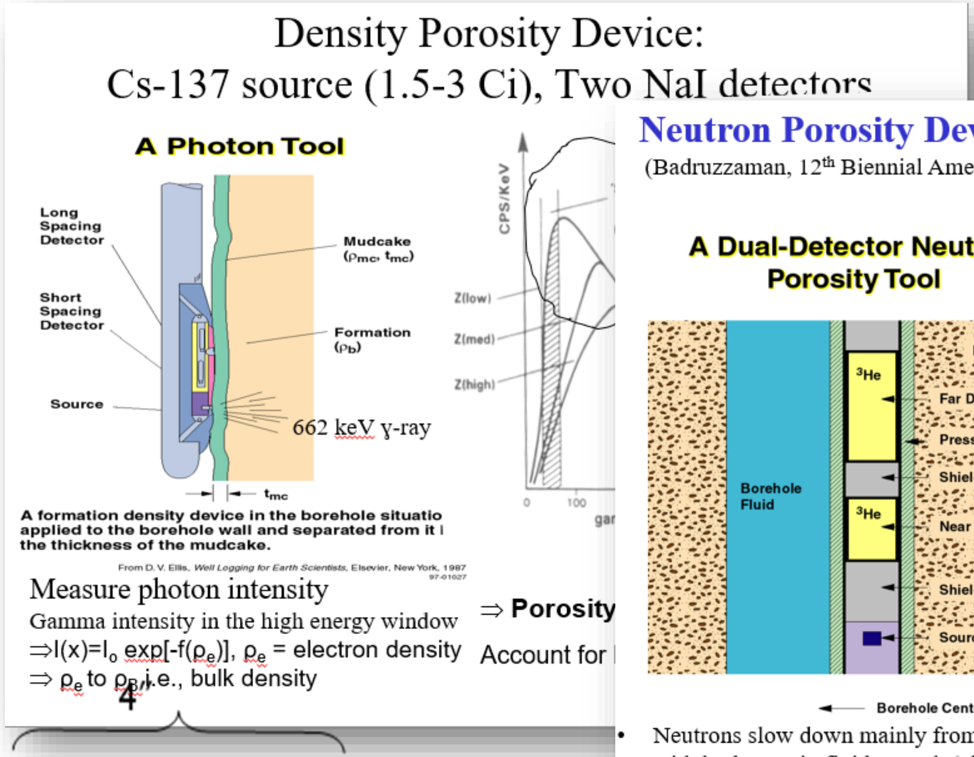
Workshop outcomes: (1) A Report detailing high-impact applications, with the issues and required accelerator R&D for each, and
(2) An R&D roadmap, focused on technology transfer

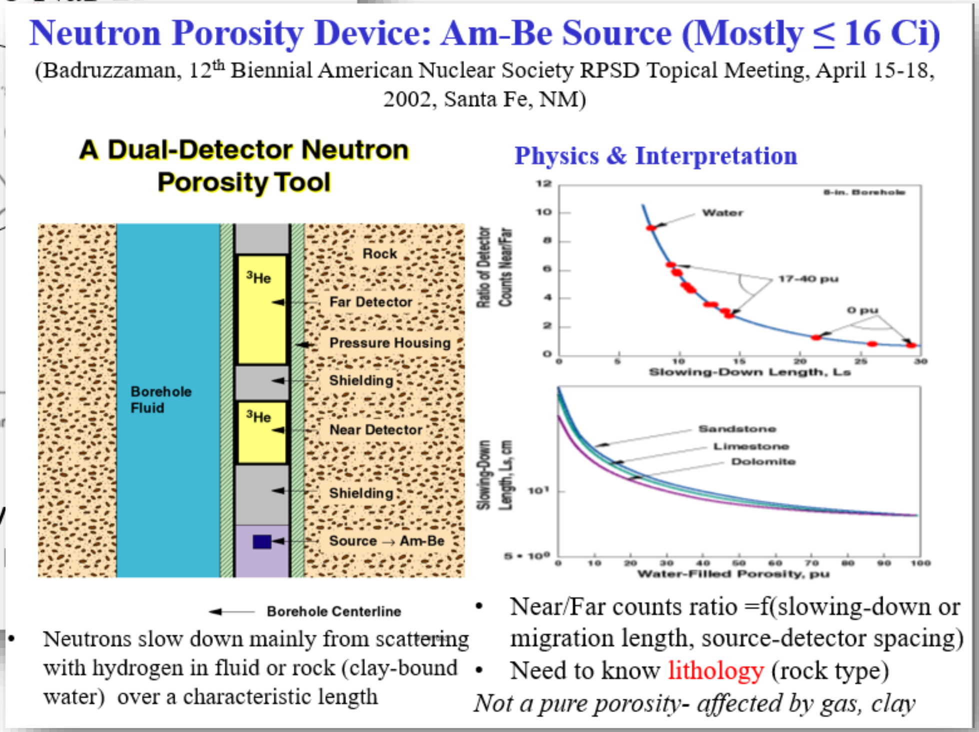
Security Applications -- Overview



Slide credit: M. Fazio, workshop chair

Non-Destructive Testing: Well-logging





Cs-137 Source

Am-Be Source

Accelerator-based replacements for compact sealed neutron sources:
Development of compact commercial D-T sources that are cost competitive with radiological sources.
Rugged tool-specific high-temp components.
2.5 MeV miniaturized/compact D-D source ≥10^7 n/s.
Small-diameter D-T generator platform with agnostic detector integration.
D-^{7}Li generator with 10^7-10^8 n/s neutron yield.
Developments in compact neutron source power supply, electrostatic accelerator, and ion source technology.

Accelerator-based replacements for compact sealed gamma ray sources
Higher frequency ultra-compact accelerating structures (in particular dielectric-loaded structures), Ultra-compact vacuum electronic RF sources at higher frequencies (≥ 20 GHz).
Solid-state driven accelerators with new types of high temperature-compatible wide-bandgap microwave transistors.
Alternative methods of creating gamma rays by induced nuclear reactions in targets; New types of higher efficiency electron beam to photon conversion targets.
Adapt additive manufacturing concepts into the accelerator and RF source fabrication, including depositing thin-films onto AM-structures for high-Q cavity and low-sparking surface finish.

Slide credit: A. Badruzzaman, Pacific Consultants & Engineers

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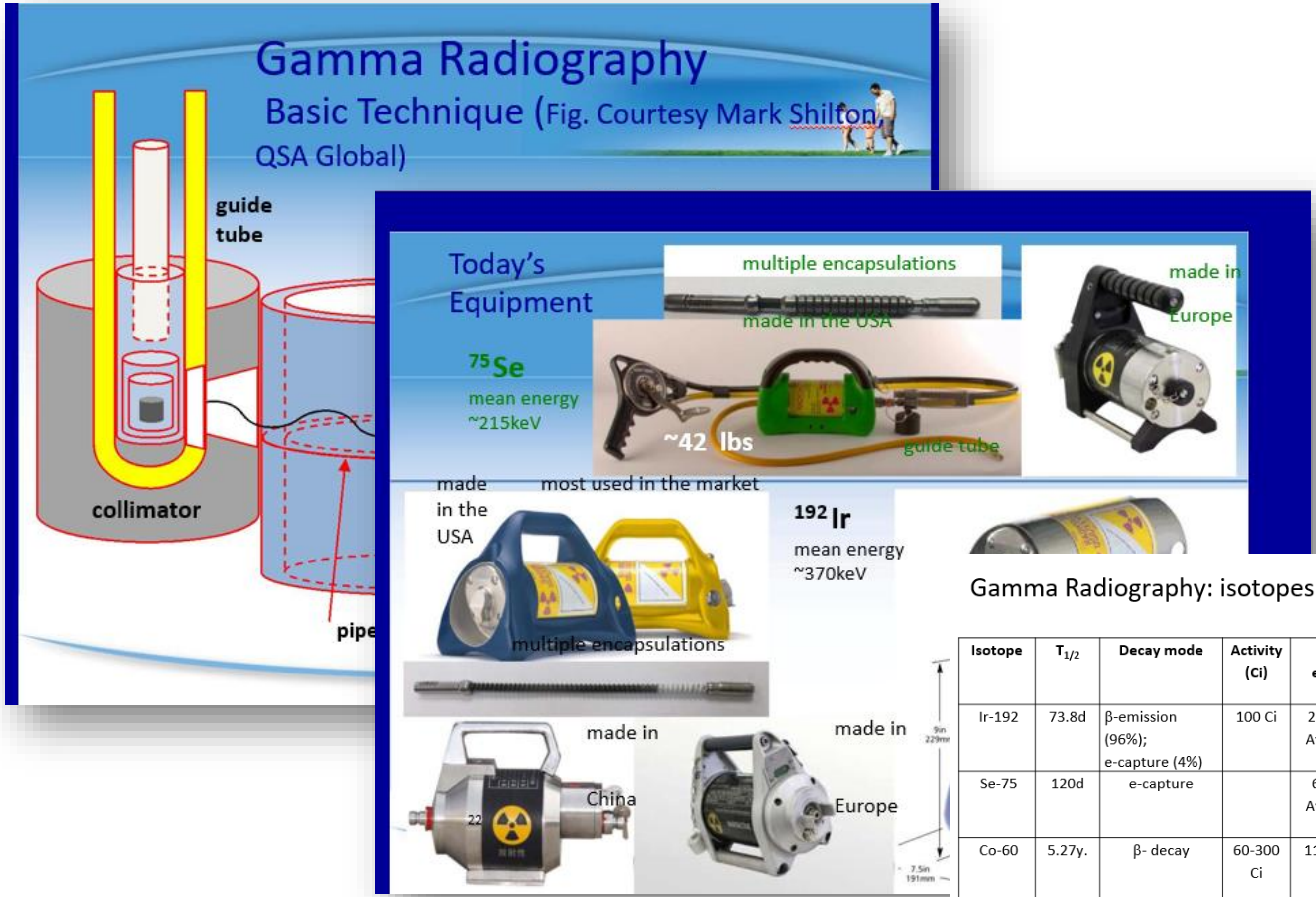
Non-Destructive Testing: Gamma Radiography



Gamma Radiography: isotopes and applications

Isotope	$T_{1/2}$	Decay mode	Activity (Ci)	γ-ray energy (keV)	App'n	Device (weight/ Dimensions)
Ir-192	73.8d	β-emission (96%); e-capture (4%)	100 Ci	206-612 Average: 370	< 6 cm Pipes; welds	50 lbs. 13in x8in x 9in
Se-75	120d	e-capture		60-401 Average: ~215	<3.5 cm	42 lbs.
Co-60	5.27y.	β- decay	60-300 Ci	1173 and 1332	≥ 14 cm thick (building, bridges)	≥700 lbs.
Yb-169	32d	e-capture		63- 308	Thin metals ~ 1.5 cm (5-30 mm)	

Slide credit: M. Shilton, QSA Global

Accelerator-based replacements for compact sealed neutron sources:

- **Development of compact commercial D-T sources that are cost competitive with radiological sources.**
- **Rugged tool-specific high-temp components.**
- **2.5 MeV miniaturized/compact D-D source ≥10^7 n/s.**
- **Small-diameter D-T generator platform with agnostic detector integration.**
- **D-^{7}Li generator with 10^7-10^8 n/s neutron yield.**
- **Developments in compact neutron source power supply, electrostatic accelerator, and ion source technology.**

Accelerator-based replacements for compact sealed gamma ray sources

- **Miniaturized electron LINACs (including dielectric-loaded accelerators) and betatrons immune to shock, vibration, and high ambient temperatures.**

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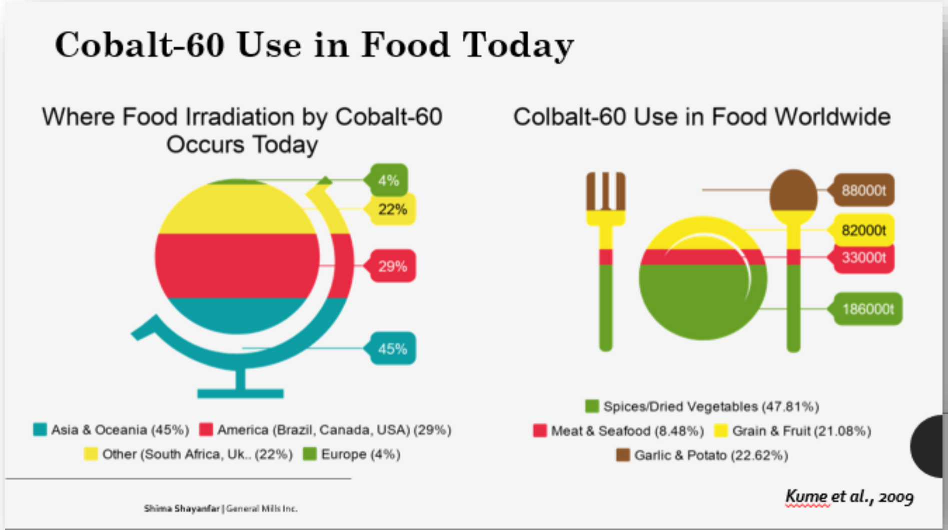
Food Security



Ionizing Radiation Technology Use for Food in North America

Gamma facilities

- Primarily in large commercial service provider facilities - cobalt-60 (1 million Curie facilities)
  - Spices, ingredients, ground beef, fresh produce

Panoramic (10 MeV) eBeam facilities

- National Center for Electron Beam Research
  - Fresh produce, pet food
- Sadex
  - Pet food, ground beef

Panoramic X-ray facility

- Calavo Growers - Hawaii

Shima Shayanfar | General Mills Inc.

Accelerator technology development
Theoretical research ideas and exploratory simulations on new accelerator designs.
Efficient RF sources >10 GHz.
Improved solid-state RF sources with higher power and efficiency at 2-6 GHz frequencies.
Initial proof of principle SRF accelerator systems.
Higher frequency compact accelerators with greater compactness.
Improved cathode technology, especially more rugged cathodes.
Development of smart controls for accelerators.
Performance improvement and cost reduction using advanced manufacturing techniques.
Electron beam to x-ray photon conversion
Improved efficiency x-rays generation techniques.
Theoretical and modeling research on methods that allow energy recycling.
Alternate shielding materials
Transportable x-ray shielding technologies for portable accelerators beyond solid concrete and lead, including pumpable liquids, emulsions, muds, and slurries.
New computational codes to include the radiation shielding simulations and help find the best solutions for the genre of machine, size, space, etc.
Advanced light-weight metal foams, polymer-composites, and embedded glassy matrix materials that show promise for cost effective, compact shielding applications.
Improved shielding materials compatible with small footprint, high throughput in-line/in-house accelerators.

Slide credit: S. Shayanfar, General Mills Product Stability Scientist

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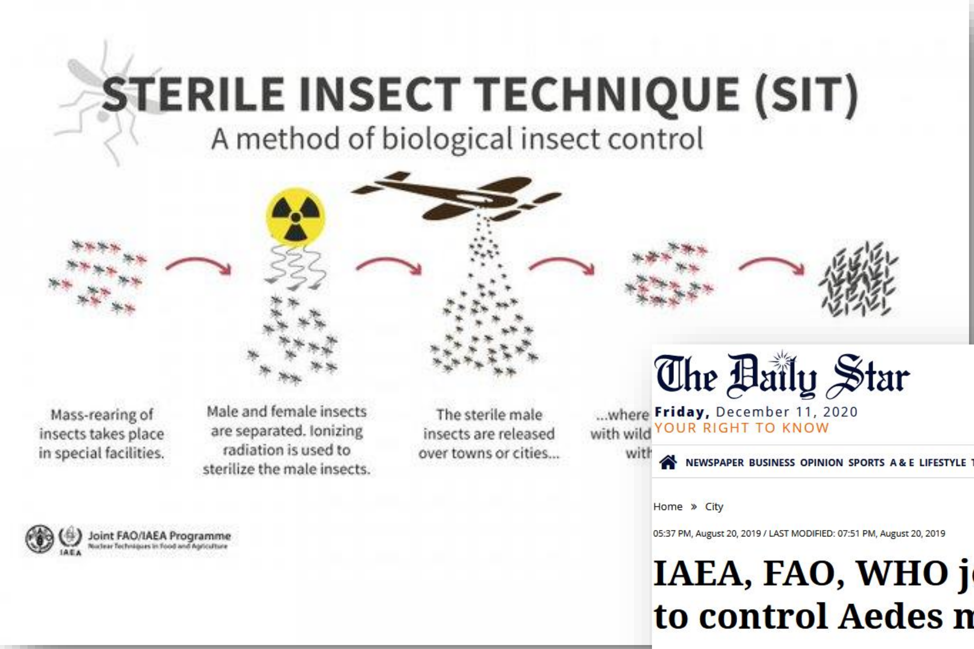
Sterile Insect Technology



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IAEA, FAO, WHO joint team to help Bangladesh to control Aedes mosquitoes

UNB, Dhaka

A joint expert team of International Atomic Energy Agency (IAEA), Food and Agriculture Organization (FAO) and World Health Organization (WHO) of the United Nations will assess the feasibility of Sterile Insect Technique (SIT) in controlling Aedes mosquitoes in Bangladesh.

To tackle the diseases caused by Aedes mosquitoes, the joint IAEA-FAO-WHO expert team will visit Bangladesh from August 21 to 23, said the Ministry of Foreign Affairs today.

The sterile insect technique is an environmentally-friendly insect pest control method involving

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~60 kCi Co^{60} source

Lower cost compact accelerators and RF sources
Investigations of methods to make lower cost accelerators and RF source structures by incorporating additive manufacturing.
New types of ultra-compact vacuum electron RF sources at higher frequencies (> 20 GHz), and corresponding higher frequency accelerating structures.
Research on higher powered solid-state RF sources at microwave to mm-wave frequencies with characteristics optimized for driving SIT accelerators.
Efficient conversion of e-beam to x-ray
Discovering and developing methods of production of x-rays (or gamma-energy photons) more efficiently from novel target structures.
Research on methods that allow energy recycling.
Control Systems and Computation
Develop an HPC physics and engineering, multi-physics software suite capable of taking advantage of computational accelerators (e.g., GPUs) for end-to-end optimization and design of x-ray generating compact accelerators.
Develop machine learning framework.
Adapt machine learning framework to simulation data.
Incorporate operational data and machine learning into a controls system.

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Medical Applications

Motivation: Medicine Applications

Three parallel agendas for the medical application space

- New technologies allowing complexity of radiation therapy to be hidden from the user for greater access and quality globally
  - Lack of medical physicists
  - Power outages
- New technologies for robust systems (i.e. low cost and with very high reliability)
- New technologies to explore the power of radiation in biology (e.g. radiation allowed us to discover cancer stem cell paradigm, and there are new emerging frontiers- e.g. flash RT)

Global Incidence of cancer cases grows from 14M to 25M per year between 2012 and 2030.

Animal experience before human applications

Tumor between eyes - great test for Intensity modulated RT- CT and treatment

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Slide credit: M. Fazio, workshop chair

Lower cost compact accelerators and RF sources
Investigations of methods to make lower cost accelerators and RF source structures by incorporating additive manufacturing.
New types of ultra-compact vacuum electron RF sources at higher frequencies (> 20 GHz), and corresponding higher frequency accelerating structures.
Research on higher powered solid-state RF sources at microwave to mm-wave frequencies with characteristics optimized for driving SIT accelerators.
Efficient conversion of e-beam to x-ray
Discovering and developing methods of production of x-rays (or gamma-energy photons) more efficiently from novel target structures.
Research on methods that allow electrical energy recycling
Development of endoscope-scale 'micro-accelerators' in the 1-10 MeV range.
Control Systems and Computation
Develop an HPC physics and engineering, multi-physics software suite capable of taking advantage of computational accelerators (e.g., GPUs) for end-to-end optimization and design of x-ray generating compact accelerators.
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Priority Research Directions are strategic R&D goals meant to guide basic R&D for a decade or more.

Priority Research Direction 1:
Revolutionize accelerator design to produce modular, interoperable, robust systems

- **Key questions to address:**
  - *When is start-to-end system co-design essential, and when is component optimization appropriate?*
  - *Can engineering standards be defined to increase reliability and interoperability?*
  - *How can systems engineering ideas be incorporated into part designs to ease repair, shipping, inventory, manufacturing, and recycling challenges, and to ultimately drive down costs and downtime?*
  - *Can affordable, ruggedized, compact accelerators be designed that facilitate autonomous dose delivery and that can be built with sufficient modularity, ease of repair, and robustness for use around the world?*
- ***Enabling Intermediate Goals:***
  - **Establishing engineering standards** that enable multiple sources of components (RF power sources, power supplies, accelerator structures, targets, control systems, diagnostics) and software to be used interchangeably;
  - **Modularity in design** so that when improved components become available that increase capability and reliability they can be easily inserted;
  - Employing **advanced manufacturing** approaches that enable more capable component performance, faster availability to remote locations, and lower cost;
  - **Eliminating as much as possible the need for highly skilled operators** that in many locations are simply not available or affordable.

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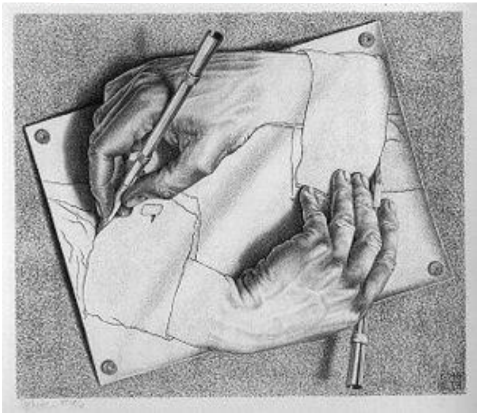
Priority Research Direction 2:
Develop "smart" accelerators that produce expert results in difficult environments



- **Key questions to address:**
  - *Can machine learning enable real time energy and dose tailoring to provide the best quality data and outcomes, and provide early detection and self-diagnosis of needed repairs?*
  - *How "autonomous" can accelerator-based systems be made?*
  - *Can data science, including artificial intelligence techniques, provide appropriate cybersecurity protection of accelerator control and data storage systems?*
  - *Can engineering standards be defined to ensure data systems interconnect and interoperate across subsystems and vendors?*
- ***Enabling Intermediate Goals:***
  - Collecting **real-time dynamic data that is tagged** with the metadata that is needed for machine learning (and secures patient-identifiable information) will facilitate the development of better models;
  - Develop **systems that continually self-assess and adjust for dynamic variation** in their function is inherently desirable. One can envision machines that can repair themselves or change operating parameters to compensate for degradation;
  - Future accelerator systems must be properly designed to include **advanced data science** attributes (sensors, algorithms, and computational hardware) to accommodate thousands of data streams that the human brain alone cannot process.

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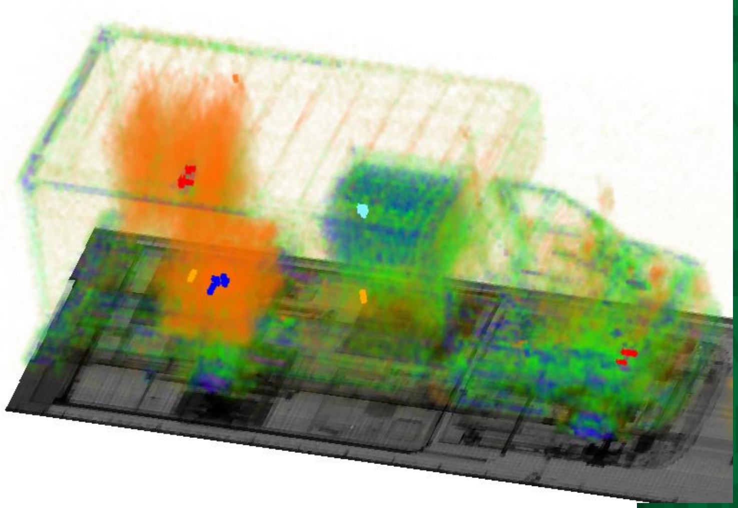
Priority Research Direction 3:
See beyond present technological limits

- **Key questions to address:**
  - *Is better inspection and imaging possible with closely integrated, higher-capability sources, detectors, and computing resources?*
  - *How can detection algorithms be improved in speed and accuracy?*
  - *How can spectrum agility, bandwidth control, coherence and polarization control be optimally exploited?*
  - *Can compact new sources of x-rays be developed that offer unprecedented monochromaticity, coherence, and tunability?*
  - *Can high-fidelity imaging simulations for x-ray sources with a range of energy spreads and energy-integrating detectors be developed?*
- ***Enabling Intermediate Goals:***
  - Compact, multi-energy (MeV – GeV), intense, **monochromatic high-energy x-ray** sources, and **high flux, short pulse neutron sources**;
  - **Improved computational tools for NDC** that allows modular yet cross-platform integration and also allows for expanded simulations. Similar computational tools are needed for full system operations that can emulate the systems real-time;
  - Beam output in terms of spectrum, dose rate, flux, and stability can be improved through research in source and detector technology and development of an **integrated systems approach to accelerator design incorporating high level data-science techniques and tight integration** with sensors, controls, analysis, and computational resources.



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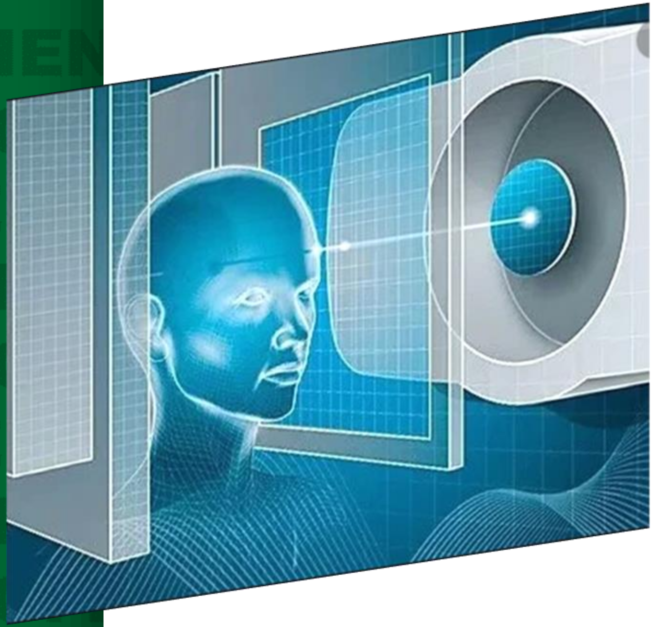
Priority Research Direction 4:
Control effects and outcomes beyond present technological limits



- **Key questions to address:**
  - *Are better treatment outcomes, better preclinical results, and better control of pathogens and contaminants possible with closely integrated, higher capability sources, detectors, and computing resources?*
  - *How can dose rate be increased without sacrificing accuracy or safety?*
  - *What new sources, detectors, and controls are needed to support ultrahigh dose rates in a clinical setting?*
  - *What radiobiology must be studied?*
  - *How can energy spectrum and real time dose control be optimally exploited to reduce collateral dose?*
  - *How can the flux and efficiency of x-ray sources be increased?*
  - *Can very low cost, high flux sources be developed?*

Enabling Intermediate Goals:

- **Improved collimation and control** of electrons and photons is needed that requires minimal moving parts and can address the challenge of high dose rate delivery;
- Different methods for photon production will need to be explored as "**targets**" currently cannot address this demand;
- Compact, **preclinical R&D systems(e.g. <1 MeV)** are needed to study the biology of FLASH;
- **Imaging technology** must be developed to accurately capture **high speed dose delivery**. Electronics will need to be able to calibrate doses at these dose rates very precisely.

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Priority Research Direction 5:

Revolutionize the size to enable new and emerging applications

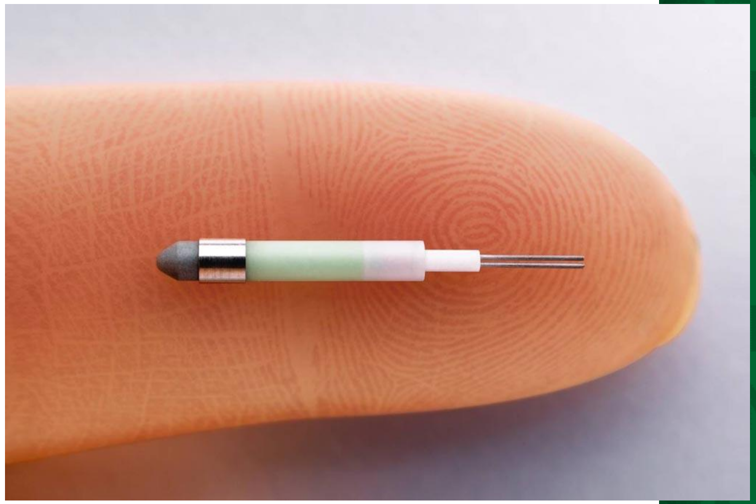
- **Key questions to address:**
  - *What are the key components that drive the Size, Weight, and Power requirements for each application?*
  - *Can accelerator-based systems be miniaturized to function in tight crawl spaces, in pipes, down boreholes, and on the tip of an endoscope?*
  - *Can systems be engineered to provide accurate performance in hostile environments?*
- ***Enabling Intermediate Goals:***
  - Advance the maturity of **new accelerator concepts** such as laser-driven accelerators, and compact SRF.
  - **Improve the efficiency** of:

    (1) the **target** in converting the particle beam to the radiation of choice,

    (2) the **accelerator structure** in coupling the RF or laser energy into the beam to accelerate it,

    (3) The **power source** that generates the RF or laser energy that provides the power to the accelerator structure, and

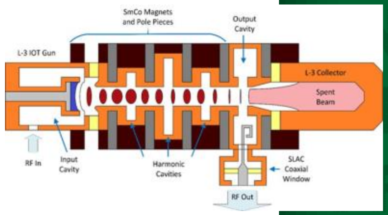
    (4) the **power supplies and power modulators** that energize these RF or laser power sources using wall-plug AC power.

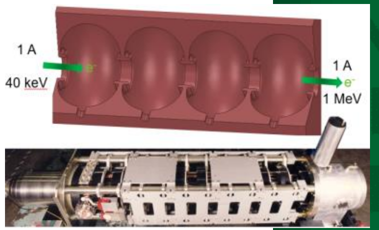


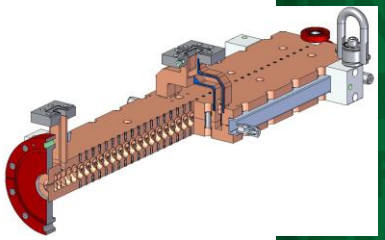
DOE SC Accelerator Stewardship Program Awards

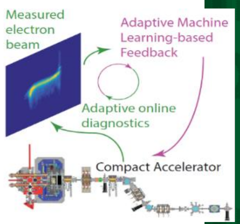
$19.3M awarded 2016-present for use-inspired basic R&D

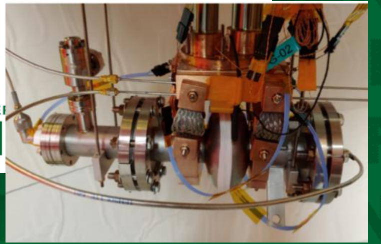
Year	Type	Description
2018	RF Source	**Thomas Jefferson National Accelerator Facility** and **General Atomics** are funded to develop a compact high-power high-efficiency radio frequency (RF) power source for next generation particle accelerators for energy, environmental, medical, scientific, industrial and defense applications. The modular power source will take advantage of low cost commercially available magnetron RF sources (similar to those found in home and industrial microwave ovens), state of the art control techniques, and highly efficient combiners to demonstrate a pathway to megawatt-class power.
2018	RF Source	**Los Alamos National Laboratory** and the **University of Maryland** will design a novel radio-frequency klystron amplifier with the promise of greatly increased wall-plug efficiency (reducing the power bill for high power accelerators). The new concept is based on decelerating the electron beam in the klystron and letting the electron beam undergo nonlinear bunching due to its own space-charge forces - once highly bunched, the beam is then re-accelerated with a low energy spread which allows more efficient power extraction.
2020	RF Source	**SLAC National Accelerator Laboratory**, **L3Harris Electron Devices**, and **L3Harris Applied Technologies** will demonstrate an 80 percent efficient, 100 kW CW High Efficiency Inductive Output Tube at 1.3 GHz and develop a conceptual design for a ten-beam, 1 MW version. The approach combines L3Harris' proven broadcast amplifiers with modern high efficiency klystron design methods, and will significantly improve the overall efficiency of high power accelerator systems for environmental, medical, and food sterilization applications.
2020	RF Source	**SLAC National Accelerator Laboratory** and **General Atomics** will develop a compact, cost-effective, and energy-efficient linear accelerator for industrial waste treatment and sterilization with high energy and high power electron beams. Novel concepts will be used to achieve continuous wave, 1 MeV, 1 MW electron beam with an rf-to-beam efficiency greater than 95%.
2016	Compact SRF	**Fermi National Accelerator Laboratory, Colorado State University, Northern Illinois University**, **Calabazas Creek Research, Euclid TechLabs, Advanced Energy Systems,** and the **Metropolitan Water Reclamation District of Greater Chicago** have teamed up to develop a concept for a high power superconducting accelerator that could transform water treatment, improving quality and lowering consumer costs;
2016	Compact SRF	**Thomas Jefferson National Accelerator Facility, Advanced Energy Systems**, and **General Atomics** have teamed up to develop a concept for a high power superconducting accelerator for SOx and NOx removal in flue gases, and waste water treatment.
2016	Compact SRF	**Michigan State University, Florida State University, Ohio State University, Arizona State University**, the **National High Magnetic Field Laboratory**, and **Thomas Jefferson National Accelerator Facility** have teamed up to take an interdisciplinary approach to studying the fundamental properties of niobium as a superconductor. Better understanding of the underlying material properties will significantly improve the performance and reduce the cost of accelerators.
2017	Compact SRF	**Fermi National Accelerator Laboratory,** and the **Metropolitan Water Reclamation District (MWRD) of Greater Chicago** have partnered to develop a conceptual design for a very high power (~10 MW-class) superconducting accelerator to address the requirements of a large municipality for treating wastewater and biosolid streams.
2017	Compact SRF	**Florida State University, University of Texas–Arlington**, and **DMS South / Bailey Tool LLC** will team to develop methods to form superconducting Nb_3Sn coatings inside copper accelerating cavities. The outcome could lead to reduction of materials cost by a factor of 20, enhanced flexibility of cavity design, and operation of high-power accelerated beams for industrial applications without complicated helium cryogenics.
2019	Compact SRF	**Thomas Jefferson National Accelerator Facility** and **General Atomics** will prototype and test a single-cell superconducting radiofrequency accelerating cavity inside a cryostat cooled by conduction using cryocoolers. The aim is to demonstrate achieving an accelerating gradient usable for a 1 MeV, 1 MW-class continuous-wave electron accelerator for treatment of wastewater or flue gases.
2019	Compact SRF	**Fermi National Accelerator Laboratory** and **General Atomics** will team up to design an economical superconducting accelerating structure capable of producing high-power, high-energy electron beams for environmental applications. The team will adopt a new cryocooling technology to demonstrate operation of the prototype accelerating structure at cryogenic temperatures.
2020	Compact SRF	**Cornell University** will develop and test key technology needed for realizing turn-key, high-power accelerators based on superconducting accelerating cavities for a wide range of compact accelerator applications in industry and science, cutting across disciplines. This work will explore next-generation microwave cavities based on the superconductor Nb3Sn, cooled by conduction using commercial cryocoolers.
2016	Compact NCRF	**SLAC National Accelerator Laboratory, General Atomics**, and **Texas A&M University** have teamed up to develop a concept for highly efficient, high average power industrial systems with reduced construction and operating costs for energy & environmental applications; and
2017	Compact NCRF	**Los Alamos National Laboratory** and the **Air Force Research Laboratory** will investigate a new accelerator design – the radial RF beam source. Capable of generating an annular electron beam, the new source design may present advantages for waste-stream processing if scaled to high average power. LANL and AFRL will model the performance of the new accelerator design, and perform initial scoping studies for efficiency and cost of operations;
2019	Compact NCRF	**Thomas Jefferson National Accelerator Facility** in partnership with **ScanTech Sciences Inc.** and **Hampton Roads Sanitation District** will develop 500 kW-class highly-efficient industrial accelerators using a newly designed room-temperature accelerating structure. These accelerators are tailored for use in cleaning up wastewater streams, but are also beneficial for many other applications including fracking fluid remediation, medical sterilization and food pasteurization.
2020	Compact NCRF	**SLAC National Accelerator Laboratory**, **Stanford University School of Medicine**, and **TibaRay Inc.** will develop a particle accelerator system to deliver very high energy electrons (up to 100 MeV) in a clinical setting. The results of this R&D will enable, for the first time, direct electron beam therapy for tumors throughout the body at an ultra-fast "FLASH" dose rate that could allow more healthy tissue sparing and overcome challenges of patient motion.
2019	Application R&D	**Stony Brook University, Fermi National Accelerator Laboratory, Brookhaven National Laboratory** and the **U.S. Environmental Protection Agency** have partnered to test the application of e-beam accelerator to treat emerging contaminants such as perfluoroalkyl substances (PFAS) and 1,4-dioxane in drinking water.
2016	Advanced Techniques	**University of California, Los Angeles** is funded to conduct a broad R&D program in novel techniques for particle generation, acceleration, and radiation generation. These techniques will lead to new tools for material science and future generations of compact accelerators.
2018	Advanced Controls	**University of New Mexico** and **Ion Linac Systems** will use machine learning and artificial intelligence to develop accelerator control algorithms that will enable new applications in industry, medicine, and other fields. The work will focus on both algorithmic development and deployment on operational accelerators.
2020	Advanced Controls	**Los Alamos National Laboratory** and **Lawrence Berkeley National Laboratory** -will develop adaptive machine learning-driven diagnostics and controls for compact accelerators with a focus on ultrafast electron diffraction (UED) for mesoscale material science dynamics. The goal is to develop algorithms that automatically and autonomously adjust for time variation, unmodeled changes, and disturbances to continuously achieve optimal control without the need for constant intervention from beam physics experts, a capability which is of great importance for space-based and medical accelerators.



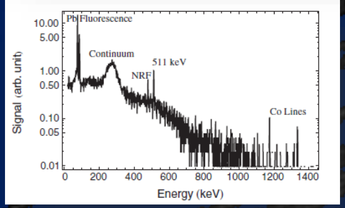








Next Steps

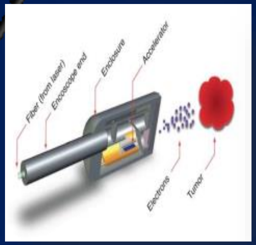


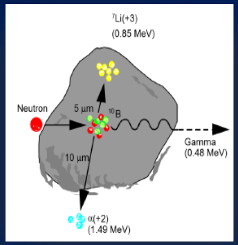
The technical gaps that must be closed to enable accelerator-based replacements for radioisotope sources include:

- Achieving rugged, turn-key operation
  - Failure prediction, self-adjustment, simplicity
- Reducing cost
  - Primarily operating cost and the need for expert operators
  - Secondarily capital cost and the need for costly infrastructure
- Reducing space, weight, and power requirements
  - Especially important for portable and ultracompact applications

The five sponsoring agencies are pursuing R&D on different facets of this complex space

- DHS-CWMD, DOE-SC, DOE-NNSA, NIH-NCI, DARPA





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Reference herein to any specific commercial product, process, or service by tradename, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government.

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Security and medical applications' needs can be met by a few principal Linac Types

Table 5.1. The four principal types of compact electron accelerator identified for security and medical applications.

	Type I	Type II	Type III	Type IV
General Type	Ultra-low Power Portable	Low- to Moderate-Power	Moderate- to High-Power	High Energy
Example Applications	Emergency Response	Portable Conventional Radiotherapy, Radiography, Down well (DW), Chip & Circuit Inspection (CCI), Electronic Brachytherapy (eB), Pre-clinical RT Machine (PCRT), FLASH-RT	Secondary Screening, High Flux Radiography (HFR), HEDP, NDT, Sterile Insect Technology (SIT), Food Safety (FS), Phytosanitary Treatment (PT), Medical Sterilization	NRF, Ptychography, XFEL, MPS for Screening, MPS for Radiography
Energy Tuning Range	LE Radiography: 0.3-0.4 MeV HE Radiography: 1-4 MeV	NDT, DW, CCI, HEDP: 0.1-1 MeV Others: 1-14 MeV FLASH-RT: 6-250 MeV	NDT, HEDP: 0.1-1 MeV SIT: 1-5 MeV Others: 300 keV - 10 MeV	500-1500 MeV
Beam Power	1 W	eB: 50 W FLASH-RT, CCI, DW: 100 W Others: 300-500 W	HEDP: 500 W NDT, Secondary Screening: 1000 W HFR, SIT, FS, PT, Med Ster: 100 kW	100 W
Desired Maximum Accelerator Size (accelerator only)	10x10x30 cm	eB [intra-cavitary only]: 1x1x1 cm NDT, Down well: 10 DIA x 22 L cm PCRT, FLASH-RT: 20x20x25 cm Others: 10x10x60 cm	Inspection, HEDP: 10x10x60 cm ≥10 kW-class: 100x100x250 cm	NRF, Screening : 10x10x60 cm Ptychography: 20x20x250 cm XFEL: <10 m long
Special Features	LER: <12 kg, battery power, <300 W HER: <50 kg, line power, <1.2 kW	eB: Can be sterilized Inspection: 50 micron spot size Down well: 200 C operation	Inspection: Spot size <1 micron	NRF: 1-7 MVp tuning range XFEL: <5 micron spot size, <50 fs pulse length
Target Capital Cost	<$100k	eB: < $600k NDT, Down well <$200k Portable Radiotherapy: <<$3M Others: <$1M	SIT, Food Safety: <$5M	XFEL: <$20M
Assumed X-ray generating mechanism	Bremsstrahlung	Bremsstrahlung, or none (eB, FLASH-RT)	Bremsstrahlung	ICS or XFEL