Element Aero

The Center for BRIGHTBEAMS
A National Science Foundation Science & Technology Center

ACCELERATOR DEVELOPMENT FOR GLOBAL SECURITY

SANDRA G. BIEDRON

ELEMENT AERO AND THE CENTER FOR BRIGHT BEAMS (CBB)

1 SEPTEMBER 2022

LINAC2022 LIVERPOOL

THANK YOU FOR THE INVITATION

- Thanks especially to Graeme Burt for considering me to cover several security and defense applications and the accelerator sources that permit them.

OVERVIEW

- From direct interrogation to radiation testing, there are myriad of security applications of particle accelerators.
- This talk will review several accelerator design and technology developments including novel sources being developed.

GLOBAL SECURITY TO *ME* MEANS

- Global security includes military and diplomatic measures that nations and international organizations such as the United Nations and NATO take to ensure mutual safety and security.
- Many tools are required to ensure global security.

A FEW THINGS IN THE WORLD CHANGED SINCE I ACCEPTED THE 13 JANUARY 2022 INVITATION…

- *So I thought pretty hard about how to define security for this talk as the term 'global security' has its own meaning for each individual.*

GLOBAL SECURITY – UNITED NATIONS DEFINITION

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

Human Security Unit, United Nations Office for the Coordination of Humanitarian Affairs, *Human Security in Theory and Practice* (http://hdr.undp.org/en/media/HS_Handbook_2009.pdf); National Security versus Global Security, www.un.org/en/chronicle/article/national-security-versus-global-security

GLOBAL SECURITY

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Accelerators help/can help with several of these items

HERE ARE A FEW AREAS WHY (IN GENERAL TERMS) ACCELERATORS (AND LASERS AND ACCELERATOR PERIPHERALS) ARE INTERESTING FOR GLOBAL SECURITY AND DEFENSE

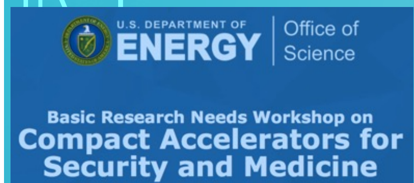
- Chemical, Biological, Radiological, Nuclear, and Explosive (CBRNE) detection, ID, and defense.
- Water – energy – food nexus
- Directed energy (Applications: materials "modification" at a distance, propulsion, power transfer)
- Laser-sensing, communications, etc.
- Materials research
- Stockpile stewardship
- 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.
- Sterilization capability for foods and surfaces to prevent contamination and infection
- Active radiation-belt remediation to improve the lifetime of satellites transiting the radiation belts.

A. J. Angola, "Overview of accelerator applications for security and defense." Reviews of Accelerator Science and Technology 8 (2015) 1-4.
J. E. Borovsky and G. L. Delzanno, "Active experiments in space: the future", Frontiers in Astronomy and Space Science 6 (2019) 31.

CAN'T COVER EVERYTHING TODAY

- *But I can give you guidance as to where to find information and answers.*

STUDIES AND SUBSEQUENT PUBLICATIONS ADDRESS ACCELERATORS, PERIPHERALS AND LASERS IN SECURITY AND DEFENSE



Accelerators for America's Future, Department of Energy Report, March 2010*

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 21 Century, Department of Energy, Office of High Energy Physics, January 2020*

Workshop on Energy and Environmental Applications of Accelerators, Department of Energy Report, 2015

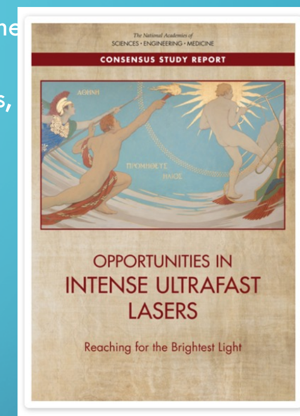
Workshop on Laser Technology for Accelerators, Department of Energy Report, 2013*

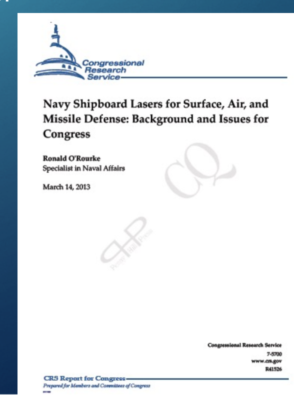
Workshop of Ion Beam Therapy, Department of Energy Report, 2013

Task Force Report on Accelerator R&D commissioned by Jim Siegrist, Associate Director High Energy Physics, Office of Science*

National Research Council. 2009. Scientific Assessment of High-Power Free-Electron Laser Technology. Washington, DC: The National Academies Press*

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"





LINKS TO MANY OF THESE REPORTS

- **Accelerators for America's Future, Department of Energy Report, March 2010**

  https://science.osti.gov/-/media/hep/pdf/accelerator-rd-stewardship/Report.pdf?la=en&hash=4C255E1ED19B65387F6A21910FDD5C16E9FC2A36

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  https://science.osti.gov/- /media/hep/pdf/Reports/2020/CASM_WorkshopReport.pdf?la=en&hash=AEB0B318ED0436B1C5FF4EE0FDD6DEB84C2F15B2

- **Workshop on Energy and Environmental Applications of Accelerators, 2015**

  https://science.osti.gov/-/media/hep/pdf/accelerator-rd-stewardship/Energy_Environment_Report_Final.pdf?la=en&hash=066CE3FA7478A66CEAD65A549D7819CF55B1D92F

- **Workshop on Laser Technology for Accelerators, 2013**

  https://science.osti.gov/-/media/hep/pdf/accelerator-rd-stewardship/Lasers_for_Accelerators_Report_Final.pdf?la=en&hash=764373A86239FC9C905EF0D760D5C445295D141

- **Workshop of Ion Beam Therapy, 2013**

  https://science.osti.gov/-/media/hep/pdf/accelerator-rd-stewardship/Workshop_on_Ion_Beam_Therapy_Report_Final_R1.pdf?la=en&hash=81EC6DE7F07D3FA3F7467AF993EE9FE1A1443FA7

- **Task Force Report on Accelerator R&D commissioned by Jim Siegrist, Associate Director High Energy Physics, Office of Science**

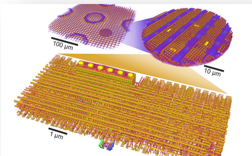
  https://science.osti.gov/-/media/hep/pdf/accelerator-rd-stewardship/Accelerator_Task_Force_Report.pdf?la=en&hash=AC672FCE001DE6720BBFF75B6E37BB2F2A752EA0

- **National Research Council. 2009. Scientific Assessment of High-Power Free-Electron Laser Technology. Washington, DC: The National Academies Press** https://doi.org/10.17226/12484.

- **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"*** DOI: 10.22003/XFEL.EU-TR-2020-001

Courtesy Eric Colby, DOE

Compact Accelerators Applications in Security and Medicine


1.

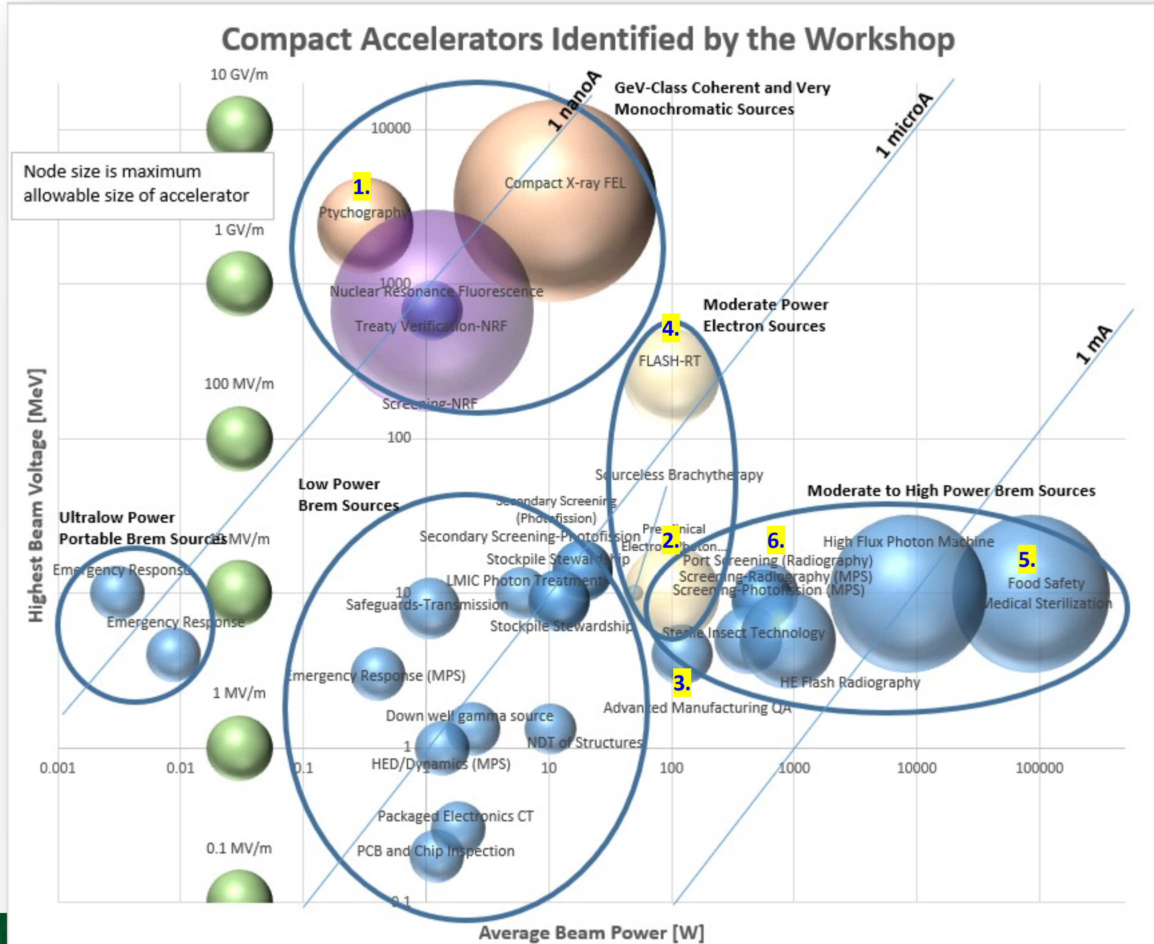
Ptychography


2.

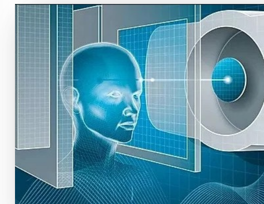
Conv. Radiotherapy


3.

Adv. Manufacturing QA



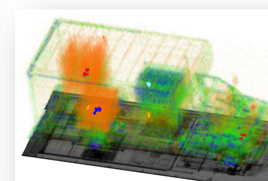
4.


FLASH Radiotherapy

5.


Food Safety

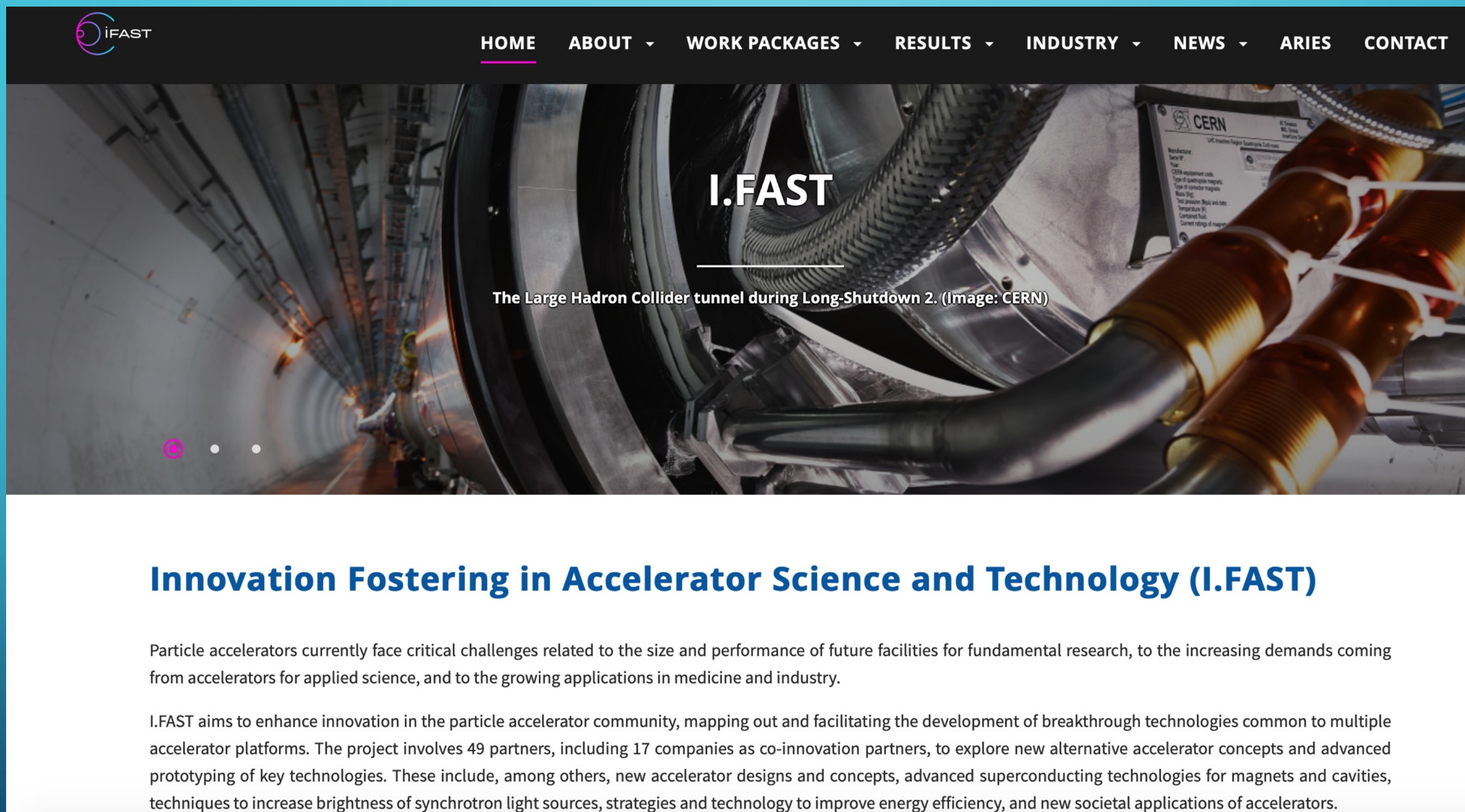
6.


Port Screening

N.B. Electron accelerators are shown on this graph. Neutron sources are not covered

U.S. DEPARTMENT OF ENERGY | Office of Science

EUROPE AND UK



This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 101004730.

WHAT HAS BEEN A MAJOR THREAT SINCE 2019 TO GLOBAL SECURITY?

THE COVID-19 PANDEMIC

AND NOW, MONKEY POX…WHAT'S NEXT

COVID-19 – ACCELERATORS HELP! ONE EXAMPLE

Argonne scientists, working as part of a national consortium of structural genomics experts, have greatly increased our knowledge of the virus that causes COVID-19.

The more you know about an infectious virus, the more tools you will have to fight it. When it comes to the structure of the SARS-CoV-2 virus, which causes COVID-19, much of the world's collected data comes from work performed at the Advanced Photon Source (APS), a U.S. Department of Energy (DOE) User Facility located at DOE's Argonne National Laboratory.

Argonne crystallographer Karolina Michalska works at the Structural Biology Center (SBC) at the Advanced Photon Source. SBC is an important site for the Center for Structural Genomics of Infectious Diseases, which marshals resources from various institutions to fight viral outbreaks. (Image by Mark Lopez / Argonne National Laboratory.)

As a user facility, the APS has made its ultrabright X-ray beams available to more than 70 research teams around the country since January, each team using the APS remotely or mailing in samples to be analyzed. The APS is so critical to the effort to combat the pandemic that it operated for 10 percent more hours this year than usual, with the additional time supported by the DOE Office of Science through the National Virtual Biotechnology Laboratory, with funding provided by the Coronavirus CARES Act.

Argonne's Advanced Photon Source plays pivotal role in development of new COVID-19 vaccine now in trials

Clinical trials have begun on a new vaccine candidate that may protect against variants of the SARS-CoV-2 virus. Protein structures determined at the Advanced Photon Source helped to guide the development of this vaccine.

Human clinical trials have begun on a new vaccine candidate that may protect against not only SARS-CoV-2, the virus that causes COVID-19, but against at least two of the variants emerging around the world. The development of this new vaccine was guided by structural information on the virus obtained at the Advanced Photon Source (APS), a U.S. Department of Energy (DOE) Office of Science User Facility at DOE's Argonne National Laboratory, and other light sources.

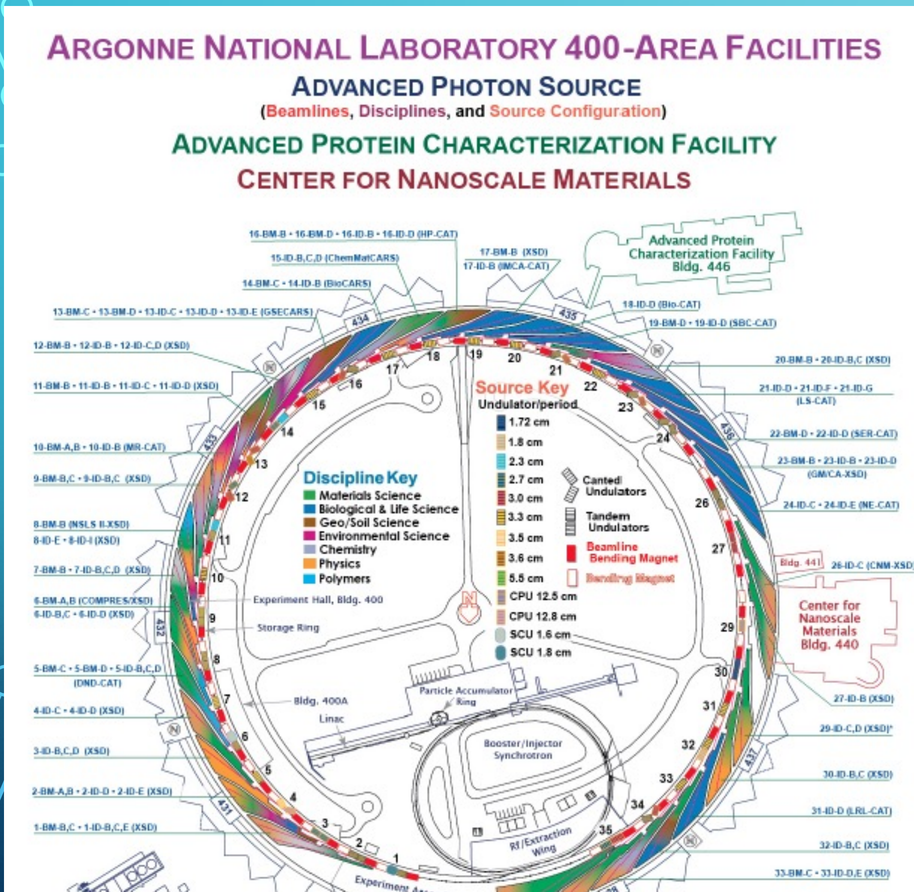
Clinical trials have begun on a new vaccine candidate at the Walter Reed Army Institute of Research. The vaccine design was guided by structures obtained at the Advanced Photon Source. (Image by Tong_stocker/Shutterstock.)

Trials are taking place at the Walter Reed Army Institute of Research (WRAIR), part of the U.S. Army Medical Research and Development Command, following up on early tests that showed promising results.

Since January of 2020, the APS has made its resources available to the worldwide scientific community for COVID-19 research, and the ultrabright X-rays it generates have helped scientists determine more than 160 structures of the proteins that make up SARS-CoV-2.

"We used the APS to generate high-resolution protein structures, and we used that information as a major component of the pipeline to develop our vaccine," said Dr. Gordon Joyce, chief of the Structural Biology Section at the Henry M. Jackson Foundation for the Advancement of Military Medicine (HFJ), supporting the WRAIR. Joyce developed this new vaccine with Dr. Kayvon Modjarrad, director of the Emerging Infectious Diseases Branch (EIDB) at WRAIR, who leads the Army's COVID-19 vaccine research efforts.

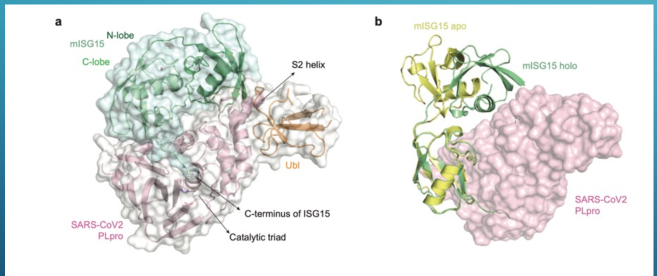
THE ADVANCED PHOTON SOURCE



MANY OTHER ACCELERATORS TOO

- **Great summary by the League of European Accelerator based-Photon Sources (LEAPS) - Research at LEAPS facilities fighting COVID-19**
- https://leaps-initiative.eu/wp-content/uploads/2020/05/LEAPS_fighting_COVID19_May2020.pdf
- The Swiss Light Source, XFEL, Swiss FEL Aramis, FELIX, and FERMI@Elettra made major contributions to help the COVID-19 efforts.

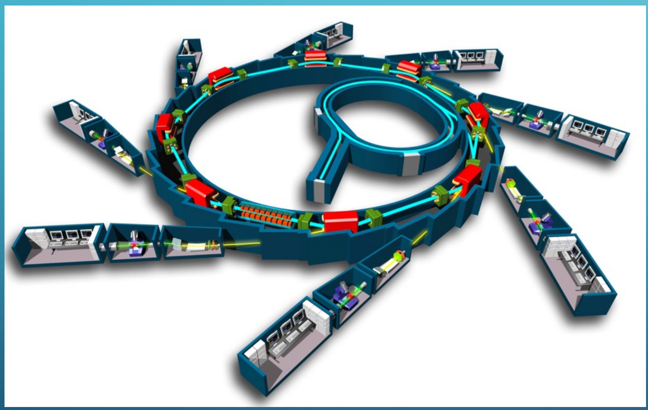
Inhibition of papain-like protease PLpro blocks SARS-CoV-2 spread and promotes anti-viral immunity

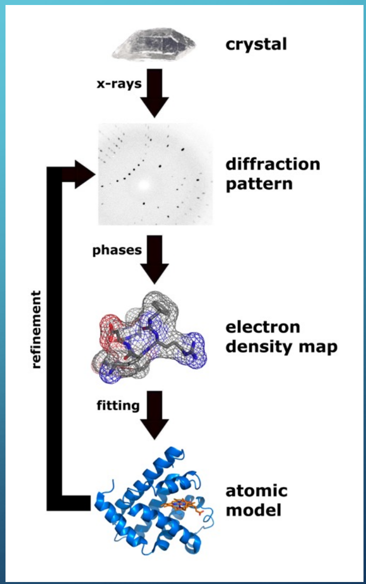


Crystal structure of a PLproCoV2 – ubiquitin-like protein ISG15 complex.
From the paper under review in Nature, Donghyuk Shin, et al. I. Dikik DOI:10.21203/rs.3.rs-27134/v1

Diffraction data were collected on single frozen crystal in a nitrogen stream at 100 K at beamline PXI as Swiss Light Source, Villigen.

COMMUNITY PURSUING SEVERAL COMPLEMENTARY PATHWAYS FOR COMPACT SOURCES (3RD AND 4TH GENERATION) THAT COULD ENABLE MUCH SCIENCE, TECHNOLOGY AND ENGINEERING INCLUDING PERHAPS A DEDICATED, RAPID RESPONSE FACILITIES, PERHAPS AT BSL-3 OR OTHER "ON-SITE" FACILITIES



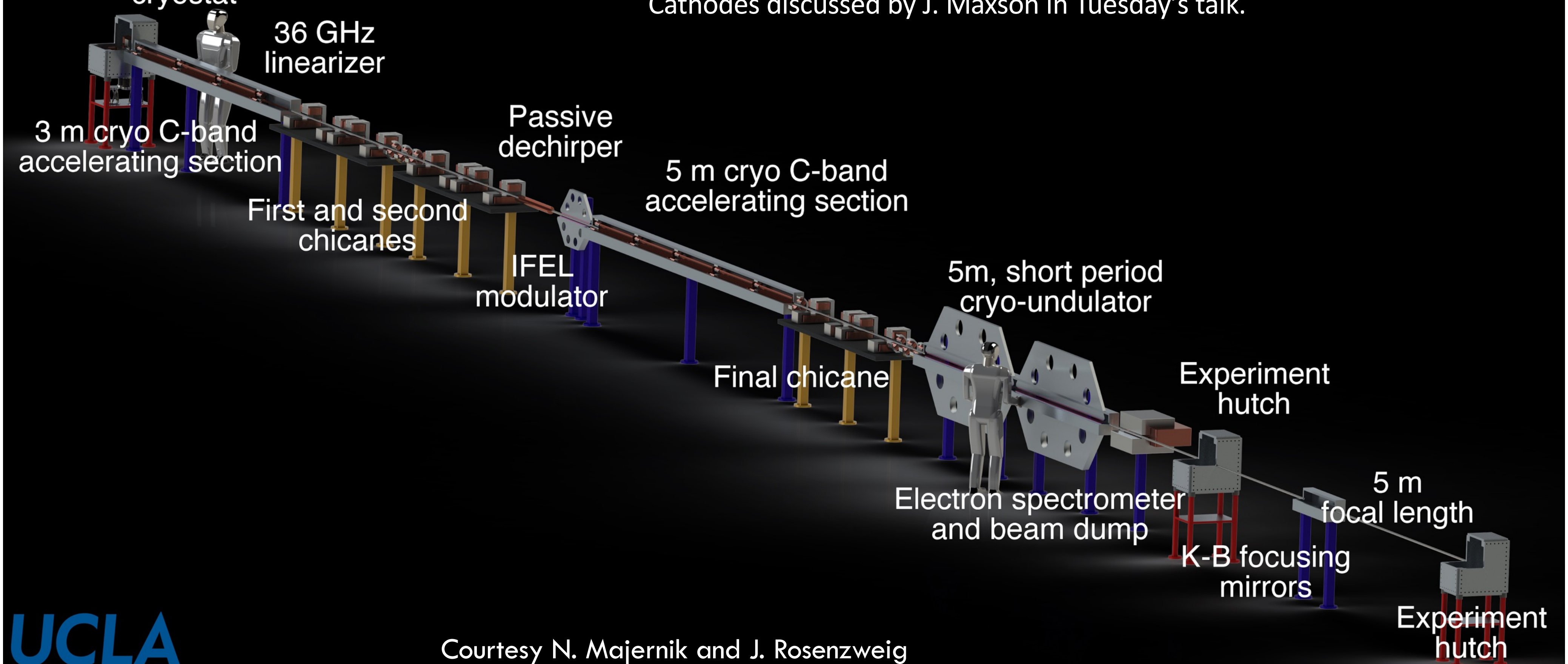


X-ray protein crystallography

Courtesy N. Majernik and J. Rosenzweig

Ultra-compact x-ray free electron laser

J B Rosenzweig *et al* 2020 *New J. Phys.* **22** 093067
Cathodes discussed by J. Maxson in Tuesday's talk.



UCLA

Courtesy N. Majernik and J. Rosenzweig

LASER-DRIVEN ACCELERATOR ACTIVITIES FOR ACHIEVING MORE COMPACT FEL LIGHT SOURCES PRESENTED AT LAST WEEK'S FEL CONFERENCE

- 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)
- Free-electron Lasing Based on a Laser Wakefield Accelerator (Wentao Wang, SIOM, CAS)

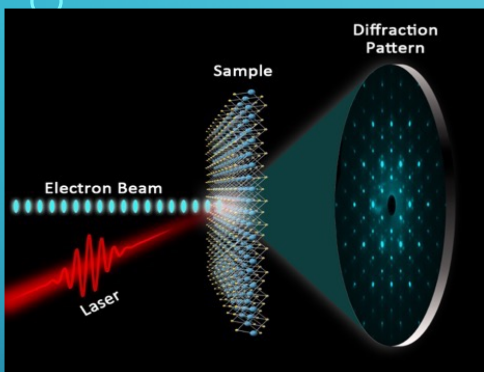
https://www.fel2022.org/programme/program

Other accelerators have promise in pandemic and security applications

WHAT IS MEV ULTRAFAST ELECTRON DIFFRACTION (MUED) – BNL-BASED

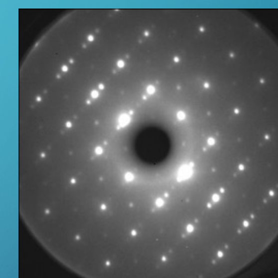
ALSO SEE CLARKE'S TALK AND FAZIO'S TALKS

- **It is a pump-probe structural measurement technique for exploring time-resolved, ultrafast processes in different material systems.**
- **We couple the BNL-based source to the computational resources at the Argonne Leadership Computing Facility for rapid analysis**



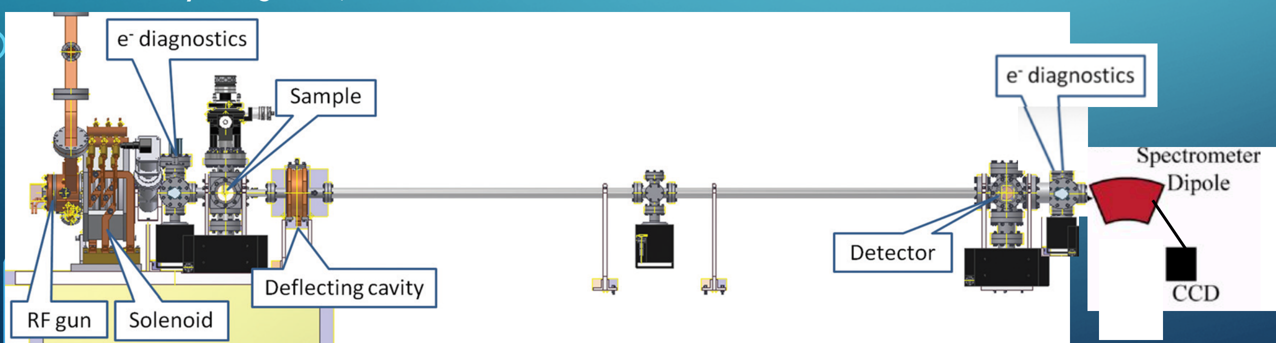
Courtesy Jing Tao, BNL

- ✓ High scattering cross-section
- ✓ Extremely short wavelength (diffraction patterns contain many reflections)
- ✓ Reduced space charge effects
- ✓ Less multiple scattering effects



Source parameters for typical operation

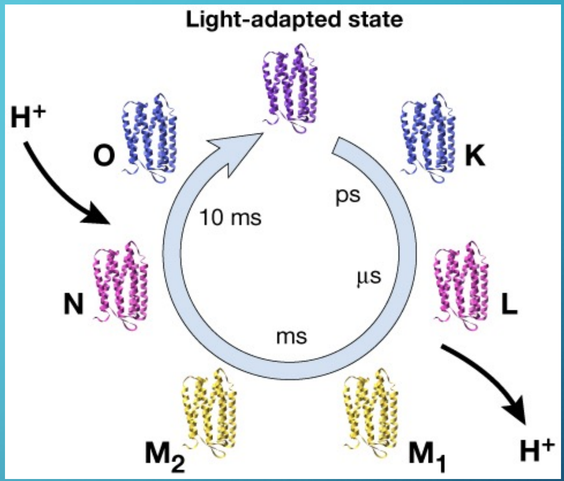
Beam energy	3 MeV
N e- per pulse	1.25×10^6
Temporal resolution	180 fs
Beam size diameter	300 (100 best) μm
Max repetition rate	5 – 48 Hz
N e- per sec per μm²	88-880



Schematic of BNL's MUED

POSSIBLE APPLICATIONS OF MUED: SOFT MATTER AND BIOLOGICAL SAMPLES (E.G. PANDEMICS)

- MUED's ultra-high resolution (0.1 – 0.2 Å) is currently not accessible for most soft matter synchrotron beamlines.
- Current commercial TEM instruments (ThermoFisher Krios) operate in the 20-300 keV range
- Radiation induced damage can be minimized with pulsed electron beams, this can open the possibility of studying samples at room T
- Time-resolved studies will be possible (ms resolution with current repetition rate)



Hirai and Subramaniam, PLOS One, 2009

MUED can lead the way for time-resolved biology to characterize membrane fusion processes, dynamics of large biological assemblies and much more.

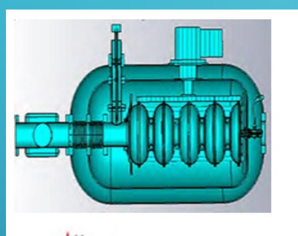
<u>We will develop solutions for sample environment that will enable MUED for biological applications</u>:

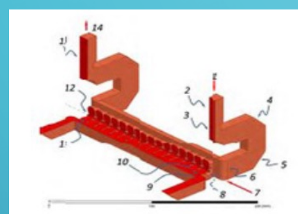
- Flow cells for serial crystallography
- Single-crystal studies (rotatable / tiltable mounts)
- Sample cells for membranes / whole cells

Concept team includes UNM and LANL: *M. Fazio, J. Chen, S. Biedron, A. Hurd*

WATER/ENVIRONMENTAL – ALL ELECTRIC

- Several activities ongoing, some funded by the now US DOE Accelerator Research and Development and Production (ARDAP) Office



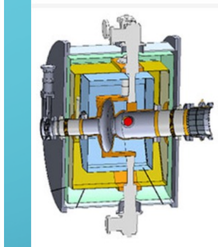


Concept Studies of Accelerators for Energy & Environmental Applications

Three teams were awarded funds to complete technical and economic feasibility design studies of very high average power electron accelerator technologies that can drive new methods of wastewater, bio-solid, flue gas, and medical waste cleanup.

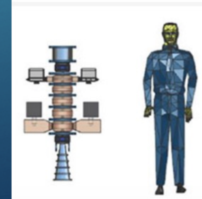
1. **Fermi National Accelerator Laboratory, Colorado State University, Northern Illinois University, Calabazas Creek Research, Euclid TechLabs, Advanced Energy Systems**, and the **Metropolitan Water Reclamation District of Greater Chicago** have teamed up to develop a concept for a high power superconducting accelerator that could transform water treatment, improving quality and lowering consumer costs;
2. **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
3. **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.

High-Efficiency High Power Electron Accelerator Technology
Technologies capable of providing megawatt-class electron beams for industrial use are rare and expensive. Research in this topic area aims to significantly increase the power and reduce the cost of very high power electron accelerator technology.



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.

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.



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.

JLAB/ADVANCED ENERGY SYSTEMS/GENERAL ATOMICS

PHYSICAL REVIEW ACCELERATORS AND BEAMS **21,** 091601 (2018)

Design of a cw, low-energy, high-power superconducting linac for environmental applications

G. Ciovati,[1] J. Anderson,[2] B. Coriton,[2] J. Guo,[1] F. Hannon,[1] L. Holland,[2] M. LeSher,[2] F. Marhauser,[1] J. Rathke,[3] R. Rimmer,[1] T. Schultheiss,[3] and V. Vylet[1]

[1]*Thomas Jefferson National Accelerator Facility (Jefferson Lab), Newport News, Virginia 23606, USA*
[2]*General Atomics, San Diego, California 92186, USA*
[3]*Advanced Energy Systems, Inc., Medford, New York 11763, USA*

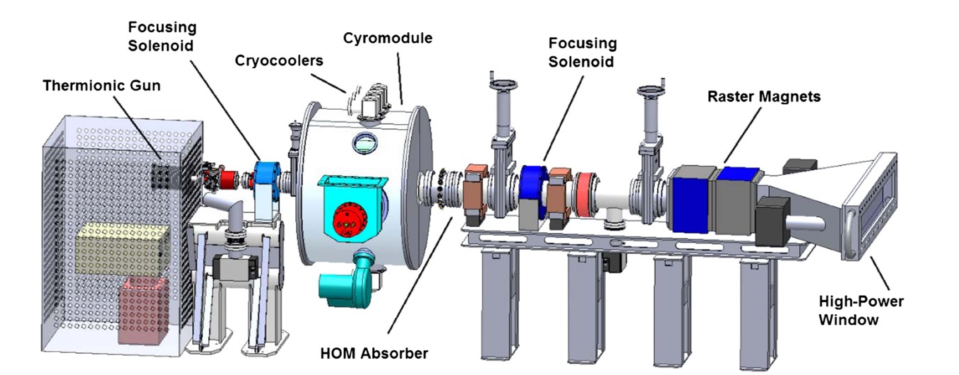
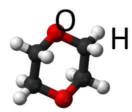


FIG. 1. Schematic layout of the 1 MeV, 1 MW, cw SRF electron accelerator for wastewater and flue gas treatment. The estimated overall length of the accelerator is 6 m.

Other examples -> R. Kephart,, 2015, "SRF, Compact Accelerators for Industry & Society," In: Proceedings of SRF2015, www.JACoW.org, paper FRBA03, 1467-1473. R. C. Dhuley, Phys. Rev. Accel. Beams 25, 041601, DOI: 10.1103/PhysRevAccelBeams.25.041601 and "Compact, turn-key SSRF Accelerators," talk Tuesday N. Stilin

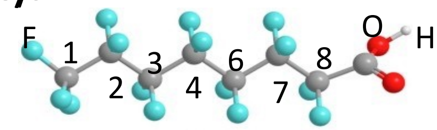
- Evaluate e-beam irradiation as a possible method to reduce or eliminate emerging contaminants in wastewater

1,4-dioxane



- Widespread
- A likely human carcinogen

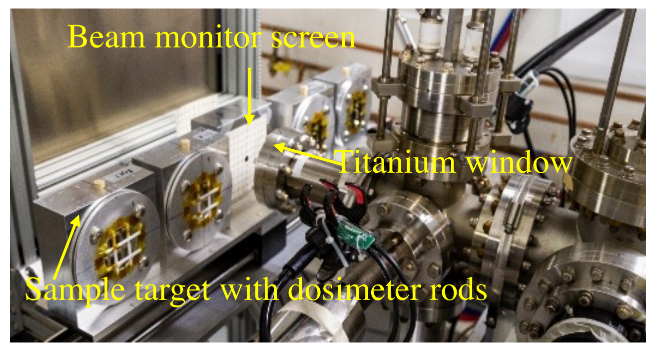
Perfluoroalkyl and polyfluoroalkyl substances (PFAS)



PFOA

- A family of >5,000 synthetic substances

- Collaboration between Jefferson Lab and Hampton Roads Sanitation District (HRSD)
- Installed an irradiation beamline at the UITF accelerator at JLab (10 MeV, CW SRF Linac)
- More than 95% of 1,4-dioxane was removed for a dose < 2 kGy
- PFAS studies are ongoing



Xi Li *et al*., Nuclear Inst. and Methods in Physics Research, A **1039** (2022) 167093

Courtesy Eric Colby, DOE

Energy & Environmental Accelerator Applications

1. Treating the sludge for a city of 100,000: 1.2 kW
- 7 tons/day @ 10 kGy (per 40 CFR 503); *Cost $70/dry ton (CC: $100-300/dt)*
- Class-A sludge can then be used as fertilizer in many states; methane yield increases with irradiation

2. Treating the regulated medical waste for 10 cities of 100,000 ea: 5 kW
- 5 tons/day @ 50 kGy; *Cost: 4¢/pound (CC: 18¢/pound)*

3. Sterilize water & medical waste at a WHO emergency site of 500 people: 33 kW (P)
- 100 gal/person/day → 0.05 MGD = 2.1 kg/s @ 10 kGy
- 200-bed hospital ⇔ 1000 lbs of RMW/day ⇔ .01 kg/s @ 50 kGy; *Cost: $1,500/day*

4. Sterilizing U. S. Government Mail 130 kW
- New Jersey facility 5 MeV x-rays/10 MeV electrons

5. Treating the power plant SOX/NOX emissions for a city of 100,000: 150 kW
- 3300 MW-hr/day from coal ⇔ @ 9 kGy [SOX↓95%, NOX↓70%];
- Process byproduct is 17 tons/day of high-grade fertilizer; *Cost: 0.12 ¢/kW-hr (CC: 0.27 ¢/kW-hr)*

POSSIBLE WITH CURRENT TECHNOLOGY

6. Upgrading heavy crude oil at a single wellhead 550 kW
- 500 BBL/day @ 500 kGy (cf. thermal refining requires ~2 MGy); *Cost: $11/barrel (CC: $5/barrel)*

7. Treat entire industrial effluent stream of DuPont Circleville, OH Plant 1.3 MW
- 0.9 MGD @ 25 kGy; *Cost: $3/m^3 (CC: $0.30-0.70/m^3)*

8. Hardening 3 lane-miles per day of interstate highway: 1.4 MW (P)
- 2 cm depth @ 100 kGy dose; *Cost: $14k/lane-mile (resurface CC: $310k/l-m)*

9. Emergency water treatment for Elk River, WV MCHM spill (2014) 2.4 MW (P)
- 5 gal/person/day, 300,000 people, @ 25 kGy; *Cost: $5/m^3 (trucked-in: $13/m^3)*

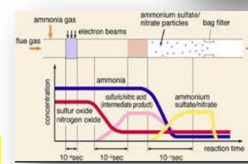
10. Cleaning up an oil drilling site in two weeks: 3.5 MW (P)
- Treating soil within 50m radius to depth of 0.5 m
- 6,300 tons/2 weeks @ 500 kGy; *Cost: $0.6M/cleanup site (haul-away cost: $1.1M)*

11. Treating entire domestic water supply for a city of 100,000: 6.3 MW
- 100 gal/person/day → 10 MGD @ 10 kGy; *Cost: $0.65/m^3 (CC: Chlorine: 9¢/m^3 Desalination: $1.25/m^3)*

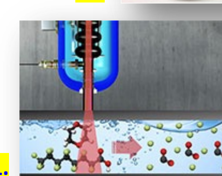
NOT POSSIBLE WITH CURRENT TECHNOLOGY

1.


4.


5.


10.


11.


U.S. DEPARTMENT OF ENERGY | Office of Science

N.B. Cost estimates are approximate.
CC= current cost of existing process

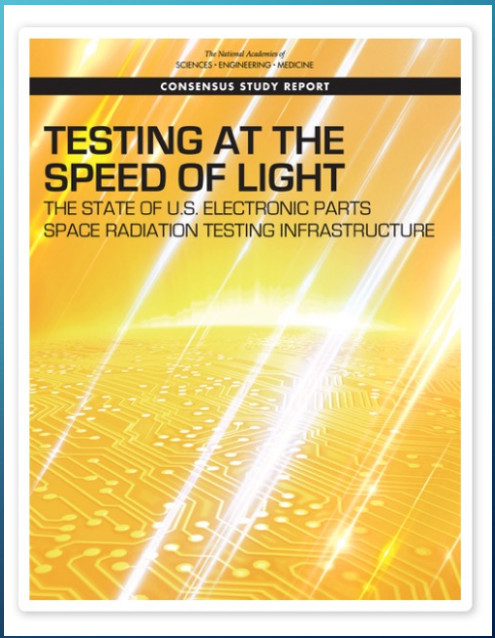
(P) – portable system required

RADIATION TESTING OF ELECTRONICS

Lots of interest and the take-home message from multiple recent meetings absolutely in no uncertain terms does not have the radiation test capabilities and access demanded by the government and industry.

NASA Electronic Parts and Packaging (NEPP) Program
2021 Domestic High-Energy Single-Event Effects (SEE) Testing Users Meeting

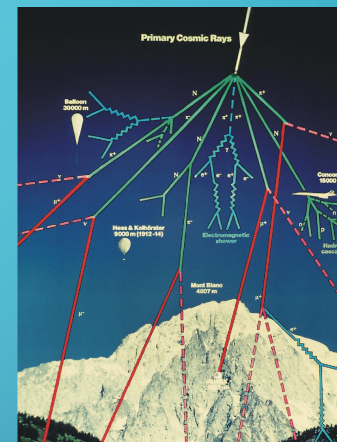
https://nepp.nasa.gov/workshops/dhesee2021/presentations.cfm



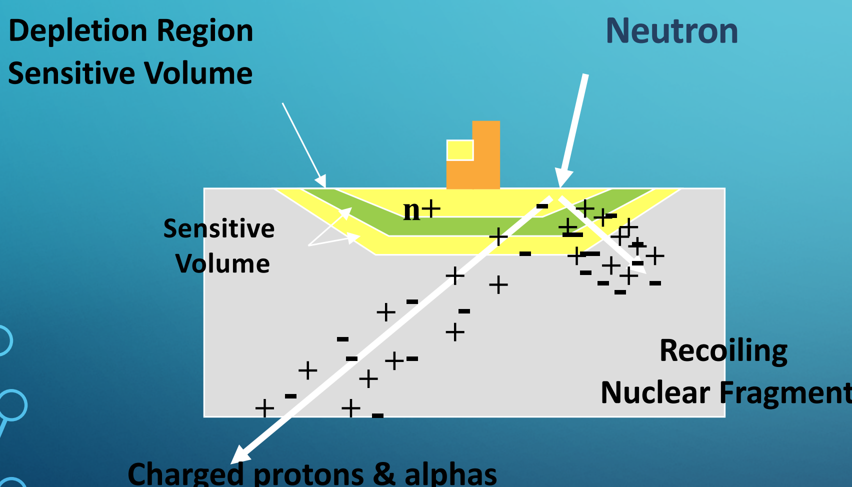
Spacecraft depend on electronic components that must perform reliably over missions measured in years and decades. Space radiation is a primary source of degradation, reliability issues, and potentially failure for these electronic components. Although simulation and modeling are valuable for understanding the radiation risk to microelectronics, there is no substitute for testing, and an increased use of commercial-off-the- shelf parts in spacecraft may actually increase requirements for testing, as opposed to simulation and modeling.

National Academies of Sciences, Engineering, and Medicine. 2018. Testing at the Speed of Light: The State of U.S. Electronic Parts Space Radiation Testing Infrastructure. Washington, DC: The National Academies Press.https://doi.org/10.17226/24993.

NEUTRONS FOR INDUSTRIAL USERS: ENSURING ROBUSTNESS OF ELECTRONICS AGAINST COSMIC-RAY BOMBARDMENT



- **Neutrons produced by cosmic rays penetrate the atmosphere**
- **Can interact with electronics and can cause single event upsets or latch ups**
- **At LANSCE the neutron flux is 1 million times that experienced at 35,000 ft**
- **We operate 2 flight paths dedicated to industrial users paying full cost recovery**

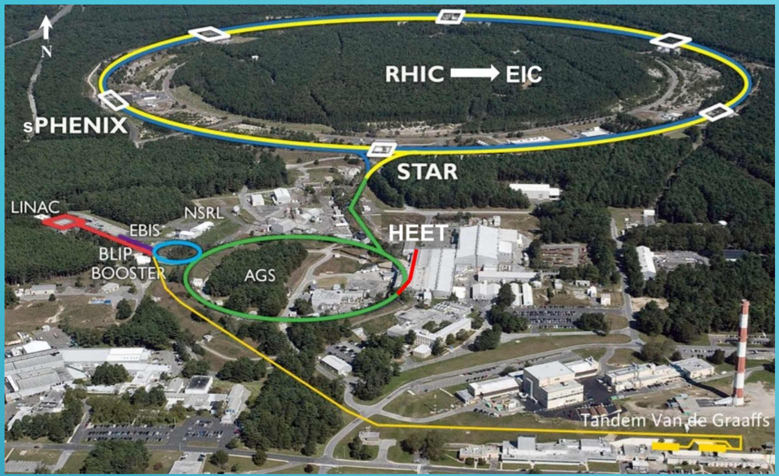


Advanced Micro Devices
Marvell Semiconductor, Inc.
Arista Networks
Prairie View A&M University
Honeywell
Infineon Technologies, AG
Rockwell Collins, Inc.
Sandia National Laboratories
KVA Engineering, Inc.
Texas Instruments
University of South Dakota

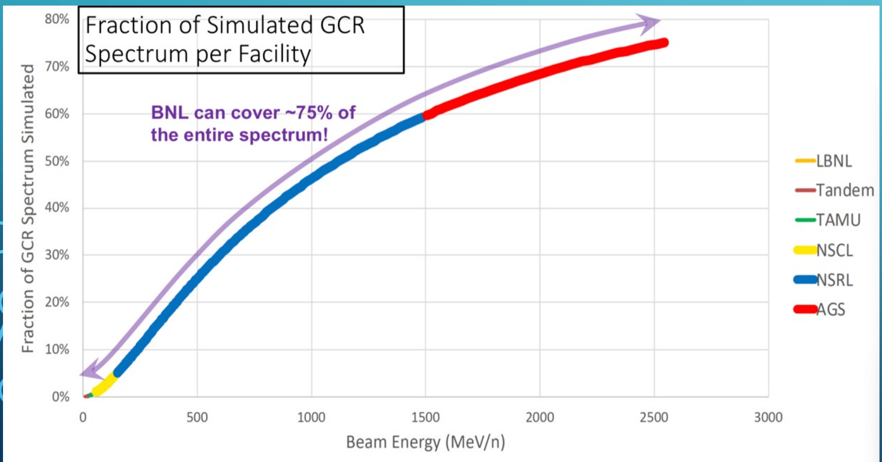
Courtesy LANL

Upgrades to the LANSCE facility expected in late 2020s

BNL COMPLEX: NSRL AND THE NEW PROPOSED HEET



NSRL Target room



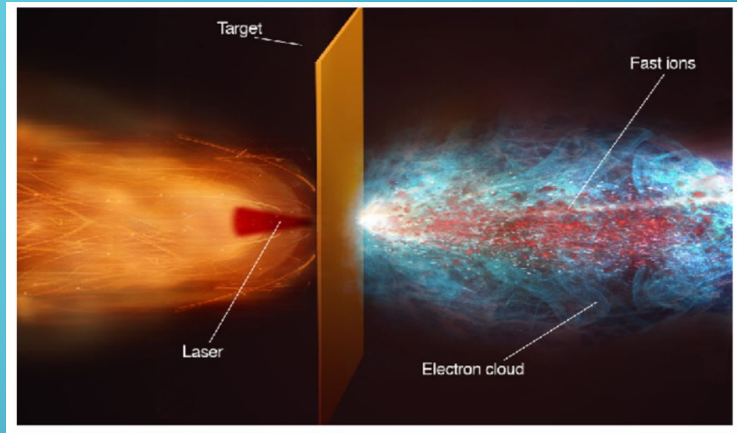
- The proposed High Energy Events Test facility would have
  - Beam energies from **40 MeV/n** to **2000 MeV/n** and possibly higher will be available
  - **Ions from H to U [Z = 1 to 92]**
  - Beam quality tailored for single event effects testing requirements
- Facility can be available **6000 hours/yr**
- Target Room & User Facility - plenty of space for all needs
- Highly professional and experienced team for building, operating, and supporting experimenter needs
- Once construction begins, **could be operational within 3 to 4 years**

Courtesy Kevin Brown, BNL

ONE APPROACH - LASER-DRIVEN IONS IS ONE APPROACH THAT REALLY LOOKS TO THE FUTURE INFRASTRUCTURE DRIVER (LASERS)

ELEMENT AERO

- Physics is proven. (Lasers can drive ion accelerators.)
- Laser needs to be architected to be optimized for this application.
- Can meet many needs in radiation testing gap.
- Can provide multiple species simultaneously over a spectrum of energies.
- Complementary to standard accelerators.
- Seeks to reduce the footprint and buy-in cost to increase access.
- Using industry and DOD systems engineering approaches as a disruptive tool.



Artists view of a typical experiment on proton emission from laser-irradiated solid targets. From Macchi, A., M. Borghesi and M. Passoni. "Ion acceleration by superintense laser-plasma interaction." Reviews of Modern Physics 85 (2013): 751-793.

ELEMENT AERO AND BROOKHAVEN NATIONAL LABORATORY, ONGOING

Brookhaven National Laboratory

EVEN COMBINED E-BEAM AND NEUTRON BEAMS NEEDED

Cornerstone Initiative Request CS-22-1302 - Radiation Combined Environments Test Capability

The Department of Defense (DoD) requires a test capability with (1) a sufficiently intense burst of neutrons of suitable spectrum of energies delivered within a short timeframe and (2) a high dose-rate, suitable energy, Linear Accelerator (LINAC). The two capabilities are to be properly synced together with variable timing and low jitter to create a Combined Environment testing capability for microelectronic components. Proposed prototype demonstration would help close the gap of uncertainty associated with the effects of strategic neutrons combined with prompt-gamma dose on advanced electronics nodes by providing a facility to test and evaluate component-level assemblies. Deploying this capability will further allow strategic programs to assess and manage their risk to ensure high confidence of mission success.

Call from the Army

RADIATION BELT REMEDIATION

- Not unrelated to the radiation effects
- Here the idea is to reduce the electrons in the radiation belts to reduce these radiation effects
- See 2018 International Particle Accelerator Talk by Bruce Carlsten https://accelconf.web.cern.ch/ipac2018/talks/frygb2_talk.pdf

RADIATION BELT REMEDIATION

- **What is Radiation Belt Remediation (RBR)?**
  - Enhanced electron flux in the radiation belts can happen ***naturally*** or be induced by a ***high-altitude nuclear detonation***
- **Why do we care about RBR?**
  - Enhanced electron flux can lead to a rapid degradation/loss of satellites in low-Earth orbit (LEO)
- **How do we fix this?**
  - Driving VLF waves in the ionosphere can drive electrons out of the radiation belt (VLF=Very Low Frequency, 3-30 kHz)
  - VLF waves can be generated by antennas and electron beams

Radiation Belt Remediation is a "no-kidding" national security mission

UNCLASSIFIED

Los Alamos National Laboratory

Courtesy B. Carlsten

RADIATION BELT REMEDIATION

The Threat Has Been Well Known For Decades

2001 DTRA study "High Altitude Nuclear Detonations (HAND) Against Low Earth Orbit Satellites (HALEOS)"

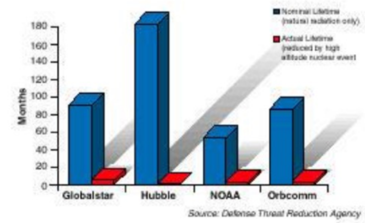
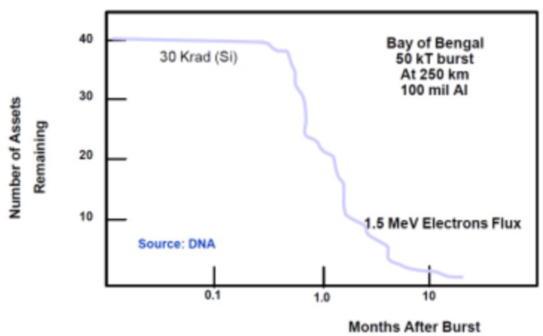


Figure 13: Impact of a nuclear detonation on the lifetime of satellities

2001 Rumsfeld Space Commission Report



2002 Tether Panel HAARP Study (recommendation: *reduce MeV electron lifetime to a few days)*

Although this problem has been recognized for a long time, a solution has yet to be implemented

Courtesy B. Carlsten

RADIATION BELT REMEDIATION

Trapped MeV Electrons Can Damage LEO satellites

Electrons can cause ionization effects in electronics (i.e., forms electron-hole pairs in transistors' gate insulation layers, gate biasing, etc)

Electrons also cause internal charging of dielectric surfaces

Types of single-event effects (SEE):

- **Single-event transient**
- **Single-event upset (as many as the rest put together)**
- **Single-event latchup**
- **Single-event snapback**
- **Single-event induced burnout**
- **Singe-event gate rupture**

~ 1 US satellite lost/year from natural flux enhancement to 10^8 $e^-/cm^2/sec$

Damage from energetic particles is a very active research area, including mitigation techniques

Man made effects can be 4-6 orders of magnitude higher

Electrons linger for about 6 months

Courtesy B. Carlsten

RADIATION BELT REMEDIATION

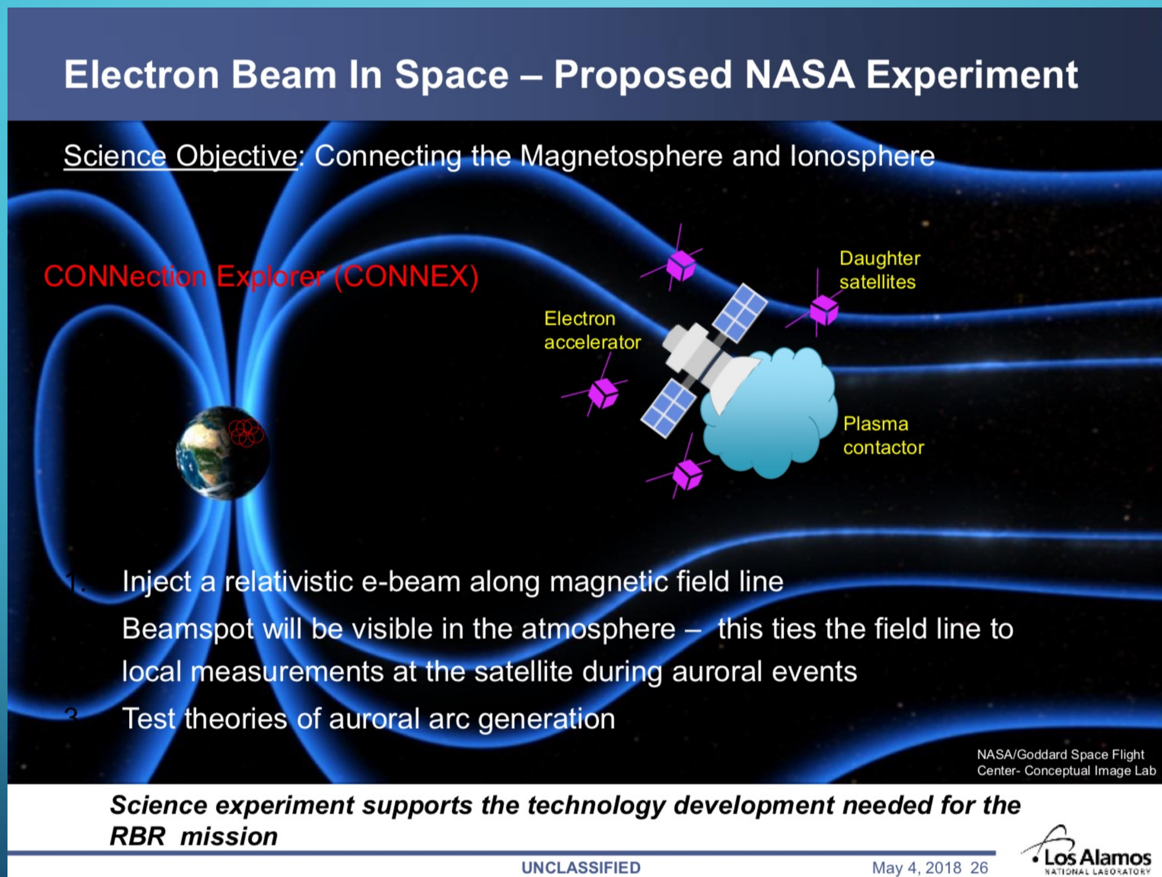
How Do We Generate VLF Modes?

Three approaches to generating VLF waves have been considered:

- **Antenna on Earth**
- **Antenna in space**
- **Electron beam in space**

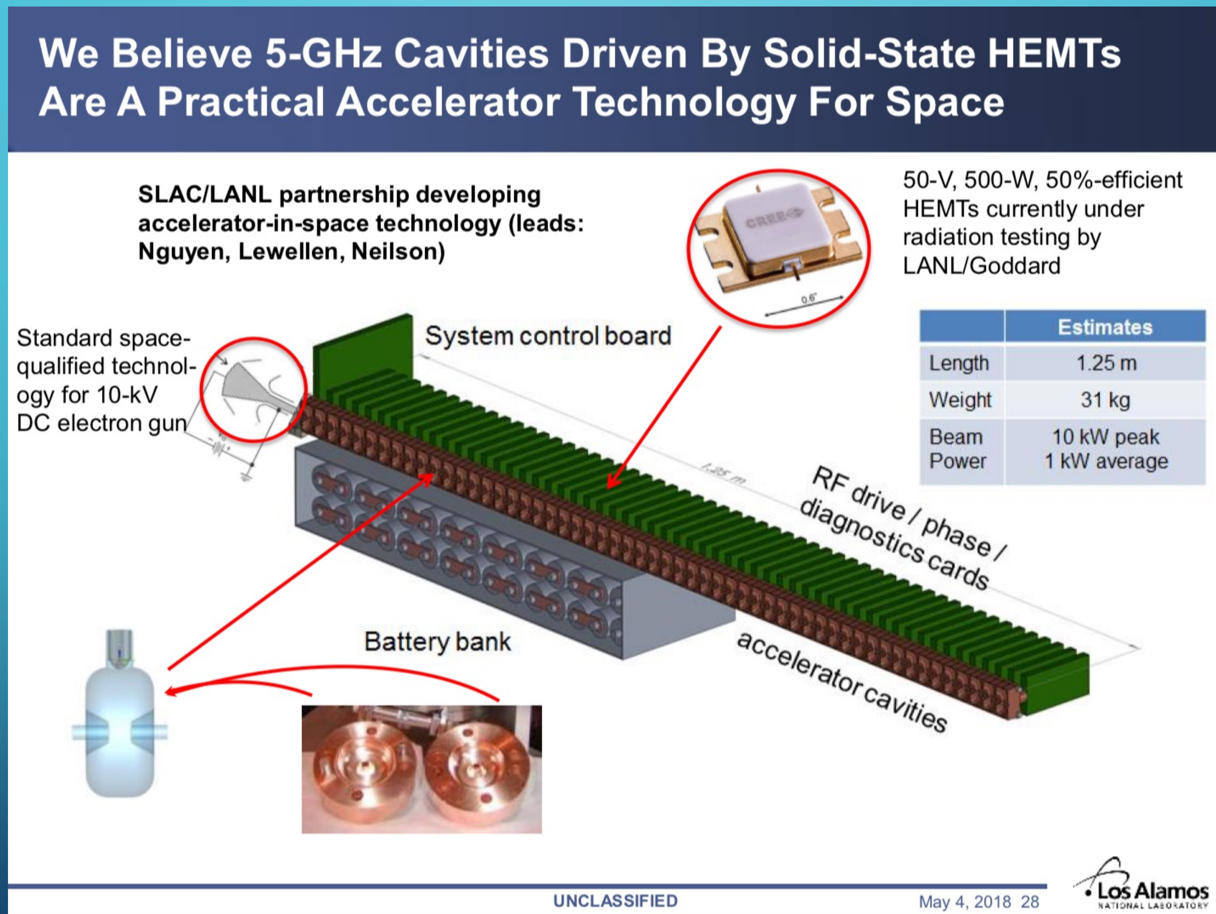
Courtesy B. Carlsten

RADIATION BELT REMEDIATION



Courtesy B. Carlsten

RADIATION BELT REMEDIATION



LANL and SLAC collaboration for this experimental work

March 2023 launch with a HEMT-based system

Courtesy B. Carlsten

CONTINUING WITH MATERIALS EFFECTS

FOR DOE NNSA

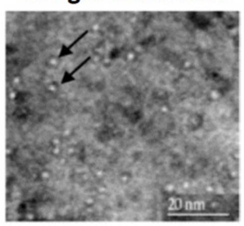
U.S. DEPARTMENT OF ENERGY

Materials structure *at the mesoscale* affects weapons performance and behaviors across the stockpile lifecycle

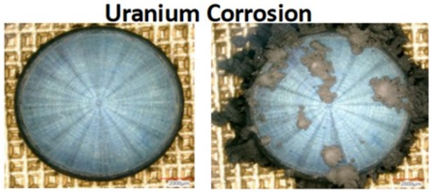
NNSA

- **We need a predictive understanding of how mesoscale structure impacts performance**
  - Aging modifies all the materials inside our existing nuclear weapons
  - Modern approaches to manufacturing are different than in the legacy stockpile (pits, cases, HE…)

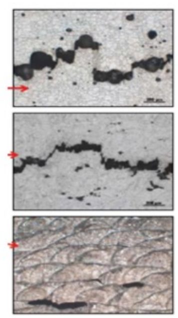
Helium Bubbles in Aged Plutonium



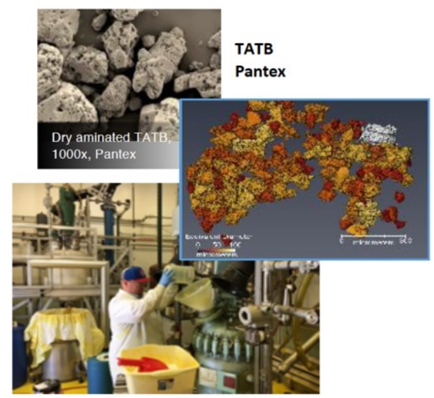
Uranium Corrosion



Damage in wrought vs additively-manufactured steel



High explosives

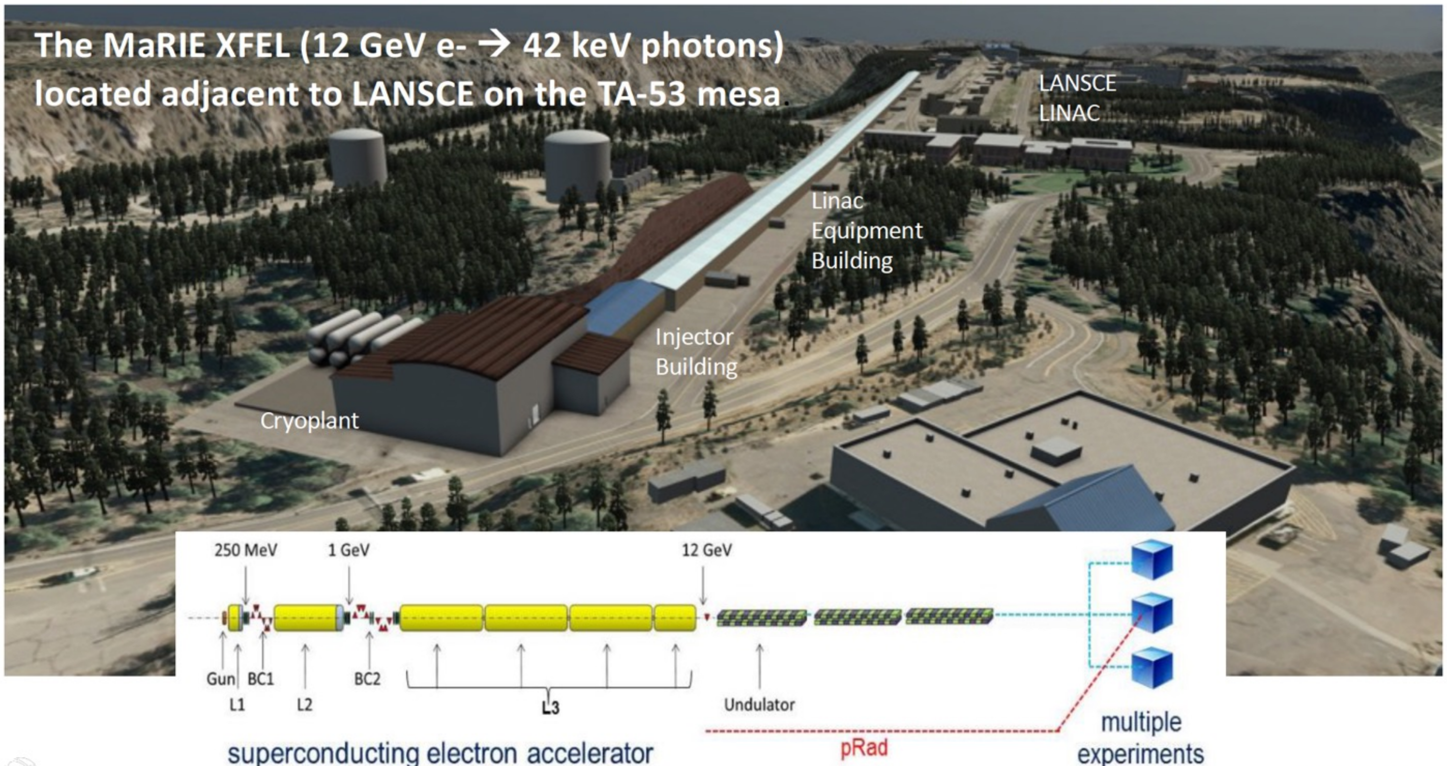


NNSA must certify that these changes do not impact weapons performance, safety or reliability

9

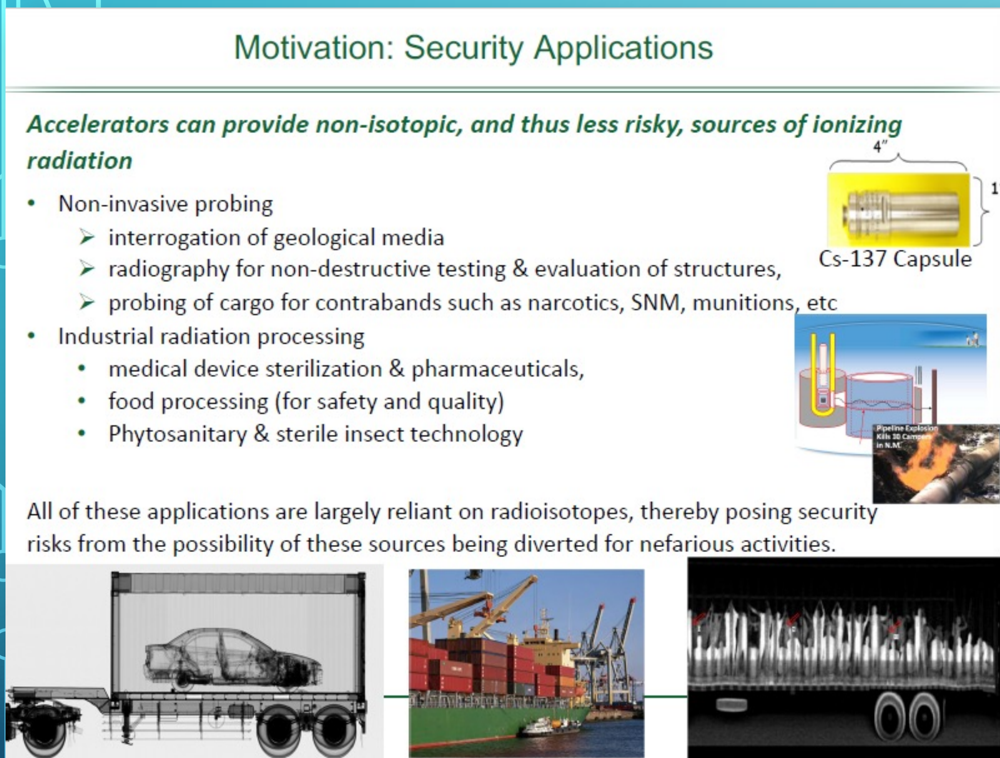
Courtesy John Louis Sarrao

MaRIE is a specific facility concept that would comprehensively meet the DMMSC capability gap



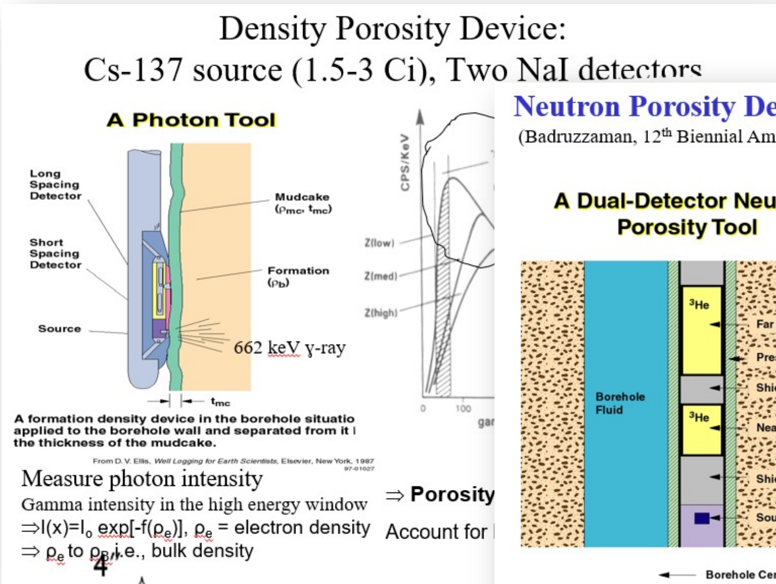
May 28, 2021 12

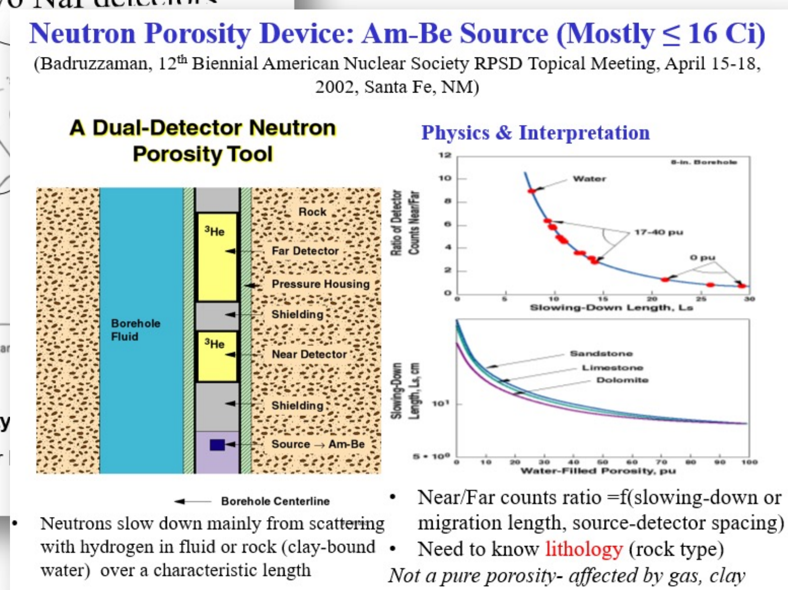
Courtesy John Louis Sarrao



Courtesy Eric Colby, DOE

Non-Destructive Testing: Well-logging





1″

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.

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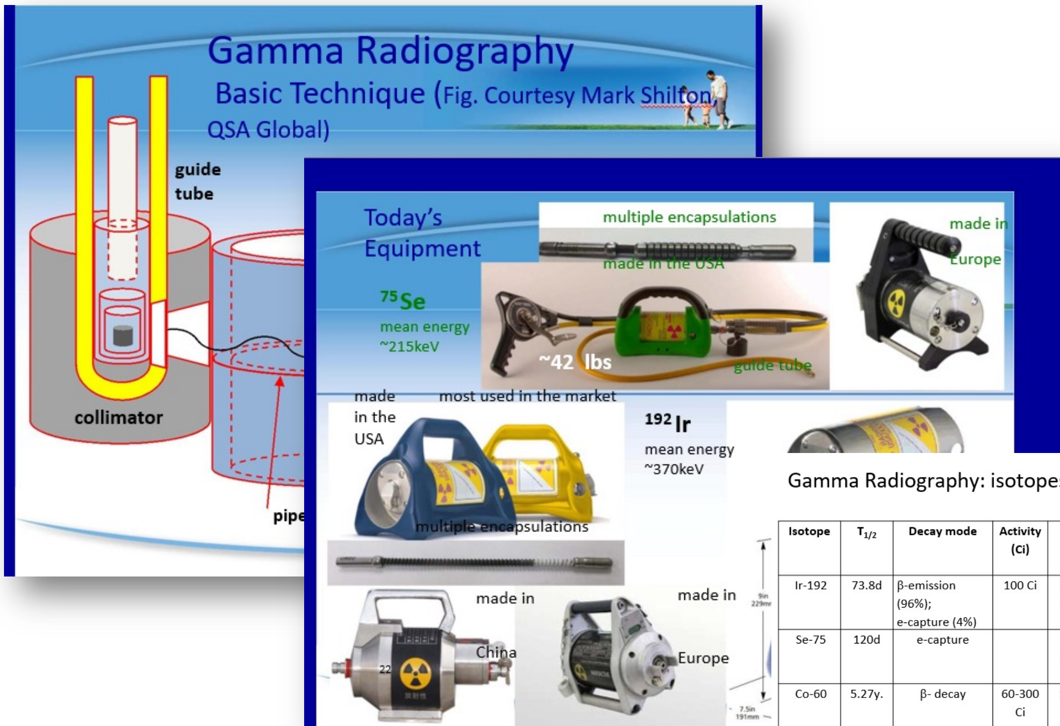
Slide credit: A. Badruzzaman, Pacific Consultants & Engineers

Non-Destructive Testing: Gamma Radiography



Slide credit: M. Shilton, QSA Global

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)	

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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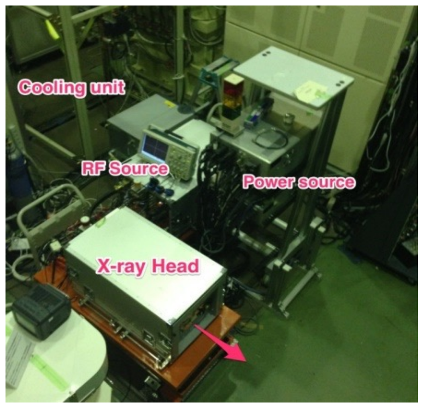
Courtesy Eric Colby, DOE

SUSTAINABILITY
CHECK FOR SAFETY, FIX ONLY WHAT IS NEEDED TO BE FIXED

Portable 3.95MeV X-band linac X-ray source of University of Tokyo



Main unit	Accelerating tube	RF Source	HVPS Control
Weight (kg)	80+62 (Collimator + Accelerating tube)	62	116
Parameters	Electron gun output current 300mA	Frequency 9.3GH z	
	Electron gun voltage 20kV	Pulse width 4μs	
	Beam current 100mA	Repetition rate 200pps	
		RF power output 1.5 MW	

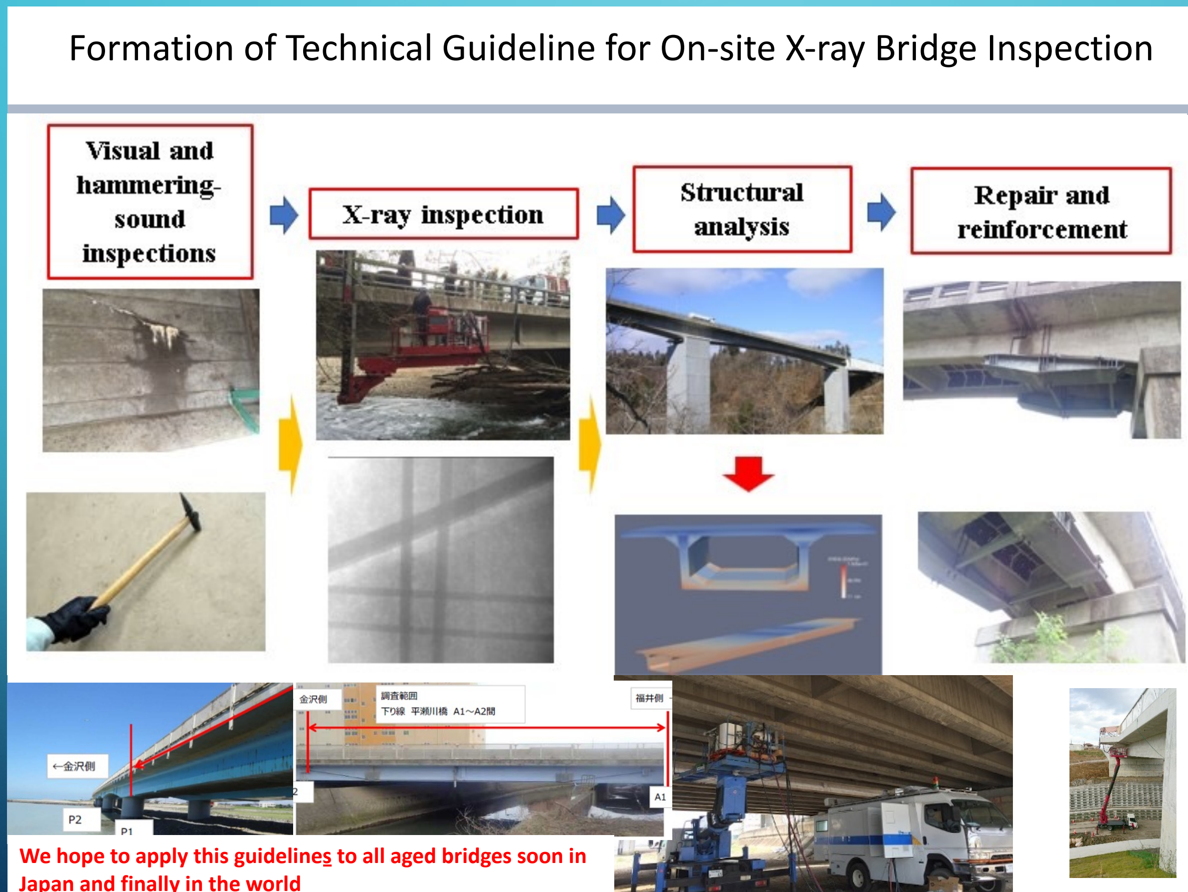
Amendment of the law that allows use of accelerators below 4 MeV accelerator for only for on-site bridge inspection was implemented in Japan in 2005. That is why we set its energy 3.95 MeV just below 4 MeV.

This machine can be also used as a neutron source with 10^7 neutrons / sec by using a solid Be target for water detection in concrete.

Courtesy Mitsuru Uesaka, worked performed at the University of Tokyo

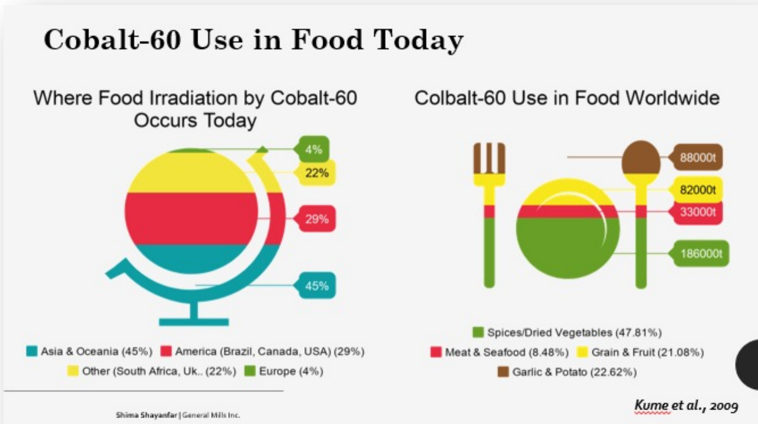
SUSTAINABILITY

CHECK FOR SAFETY, FIX ONLY WHAT IS NEEDED TO BE FIXED



Courtesy Mitsuru Uesaka, worked performed at the University of Tokyo

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.

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

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.

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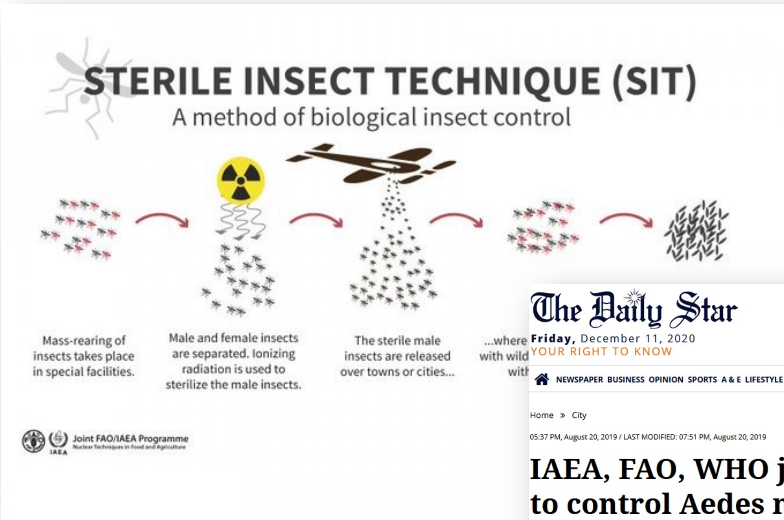
Courtesy Eric Colby, DOE

Sterile Insect Technology



Slide credit: IAEA

The Daily Star

Friday, December 11, 2020

YOUR RIGHT TO KNOW

NEWSPAPER BUSINESS OPINION SPORTS A & E LIFESTYLE TOGGLE SHOWBIZ SHOUT SATIREDAY STAR YOUTH EPAPER ALL SECTIONS বাংলা

Home » City

05:37 PM, August 20, 2019 / LAST MODIFIED: 07:51 PM, August 20, 2019

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

TOP NEWS

- 'The bridge will boost SDGs'
- Distribution of admission forms for govt secondary schools starts Dec 15
- GSK, Sanofi say Covid-19 shot won't be ready until late 2021
- Award-winning South Korean director Kim Ki-duk dies with Covid-19
- Maldivian airlines fined Tk 2.38 lakh for bringing passengers without Covid-19 negative certificates
- Argentina's lower house approves bill legalising abortion

VIEW MORE

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.

~60 kCi Co^{60} source

U.S. DEPARTMENT OF ENERGY | Office of Science

Courtesy Eric Colby, DOE

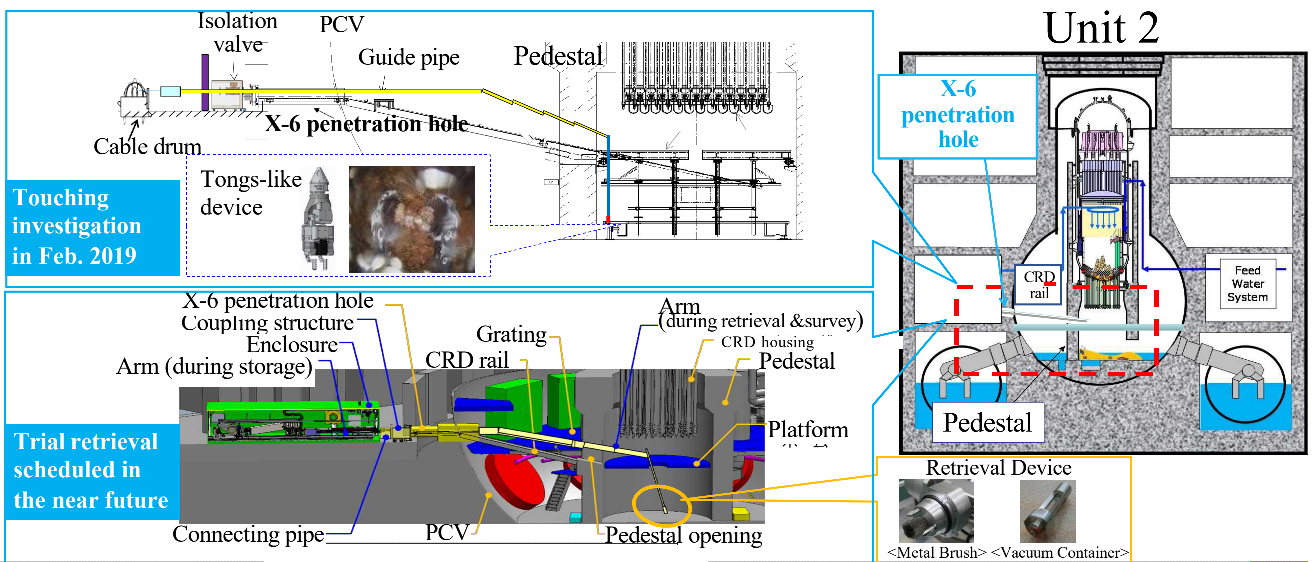
DECOMMISSIONING OF TEPCO FUKUSHIMA DAIICHI NUCLEAR POWER STATION (FDNPS)

- Courtesy of Chairman Mitsuru Uesaka, Japan Atomic Energy Commission

TEPCO

Trial retrieval of fuel debris at Unit 2 scheduled in the near future

- **We will insert an arm-type device through the same access route as the investigation in 2019.**
- **A metal brush or vacuum container will be attached to the device to collect the grain debris we observed in a touching investigation.**



Source: Materials for Meeting of Secretariat of the Team for Countermeasures for Decommissioning, Contaminated Water and Treated Water held in Jan. 2019, Feb. 2019 & May 2022 provided by TEPCO HD & IRID

Ref) M. Ishikawa, "Fukushima Dai-ichi Nuclear Power Plant's Decommissioning -Current Status and Challenges-", Asian Youth Nuclear Symposium 2022, July 10, 2022 in Remote.

Proposal of Component Identification for Fuel Debris

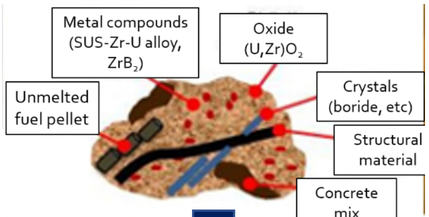
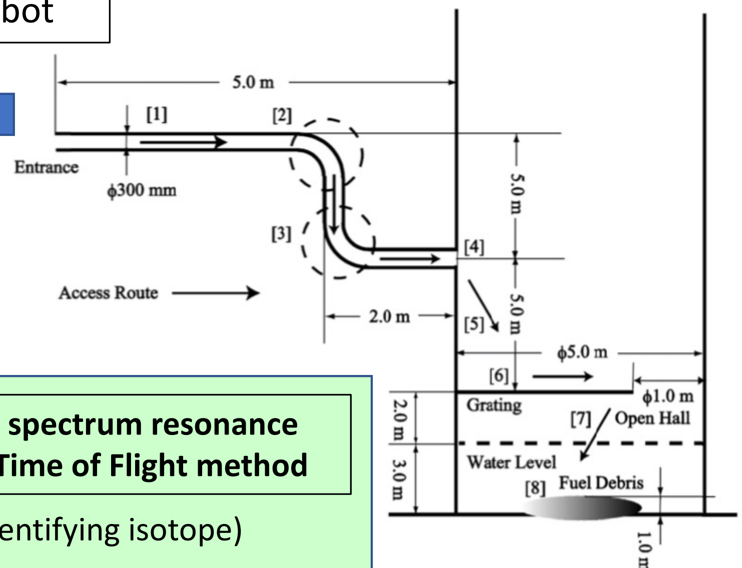


Image of nuclear debris

2. Debris sample taken by robot

1. Reactor pressure vessel

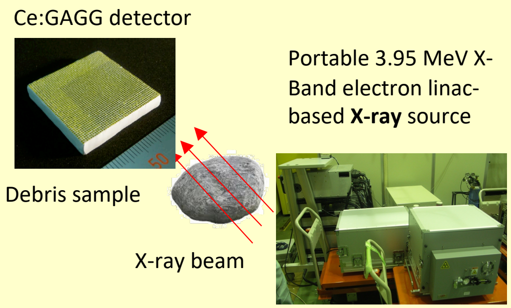


3. Screening and identification of nuclear debris (on-site)

Complement each other

Dual energy X-ray CT inspection

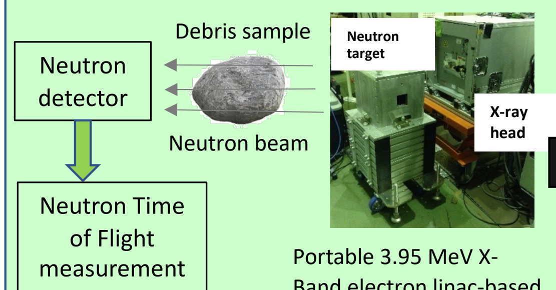
(Identifying atomic number and weight)



Portable 3.95 MeV X-Band electron linac-based **X-ray** source

Neutron spectrum resonance through Time of Flight method

(Identifying isotope)

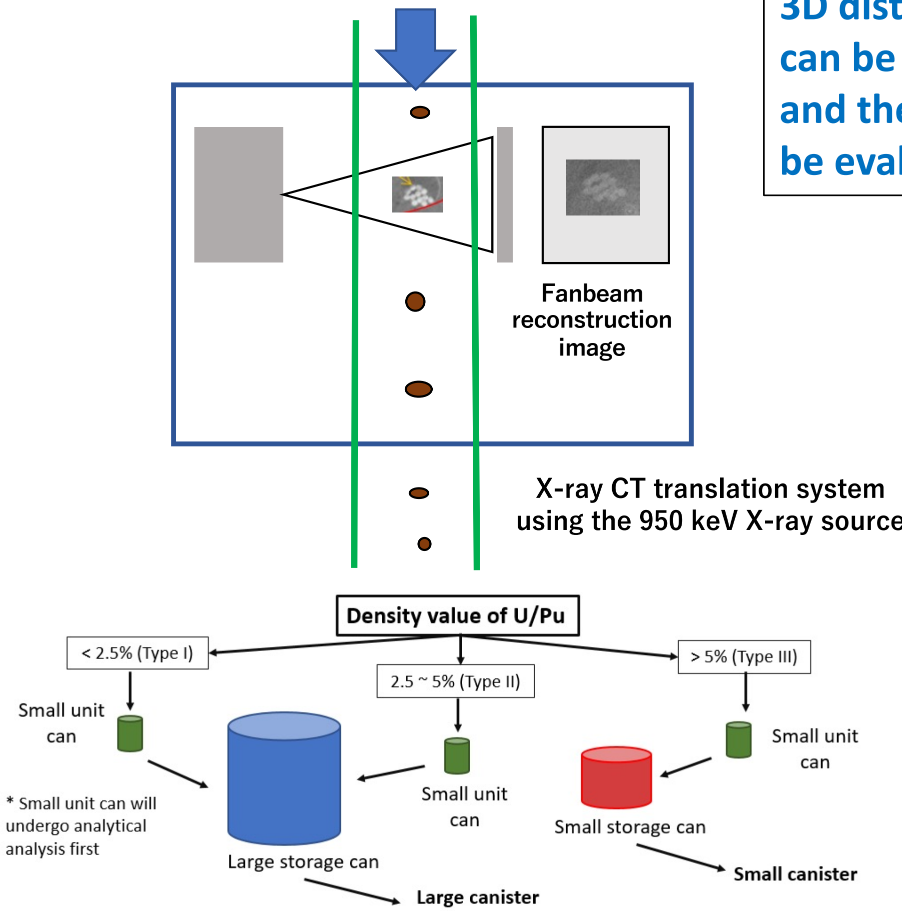


Portable 3.95 MeV X-Band electron linac-based **neutron** source

Evaluation of existence and mass density of U /Pu

Source: Robotic Society HP (http://www.rsj.or.jp/databox/committees/dec/20160907/Decomm_koubo_jishi.pdf)

Schematic scenario of the screening process by the prompt X-ray CT for mass-extraction of nuclear debris

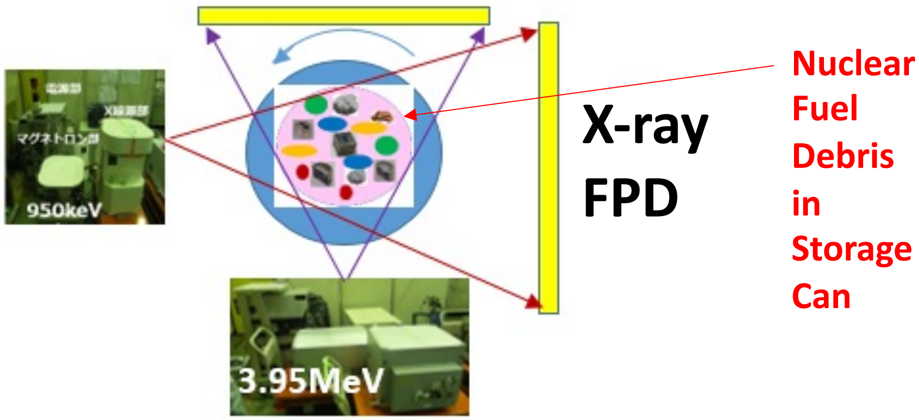


3D distribution of atomic number can be estimated by the X-ray CT and the mass density of U/Pu can be evaluated

With the acquired information of existence and mass density of U / Pu, the debris is discriminated into the two storage systems for spent nuclear fuel with U / Pu with criticality control and normal radioactive wastes without U / Pu

Practical and Reasonable Storage System

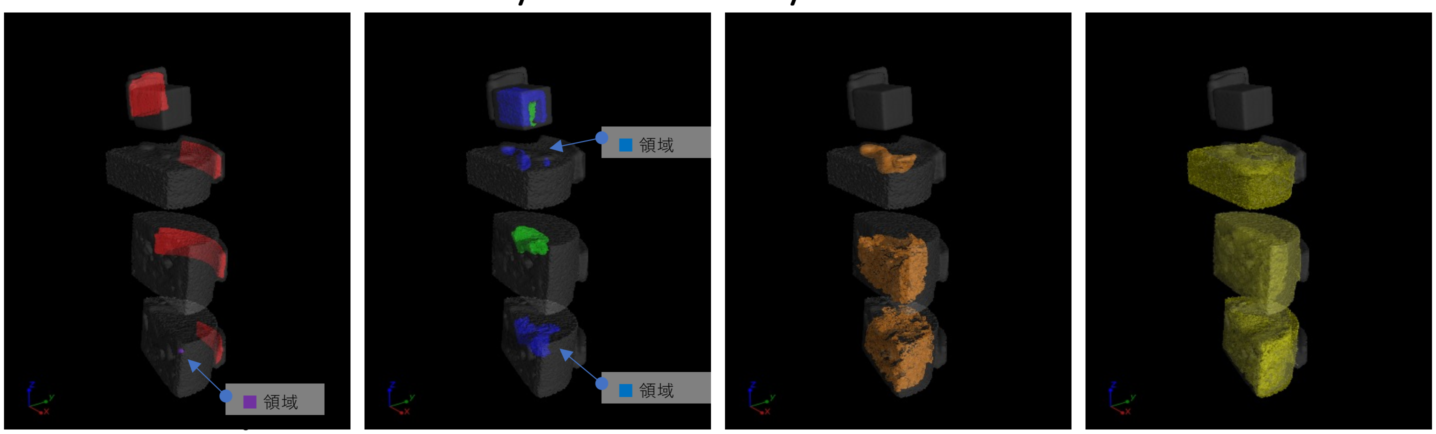
Proof-of-principle X-ray CT Results for Model Melt Nuclear Fuel Debris



3D component data are obtained and the mass density of U / Pu is estimated within mins.

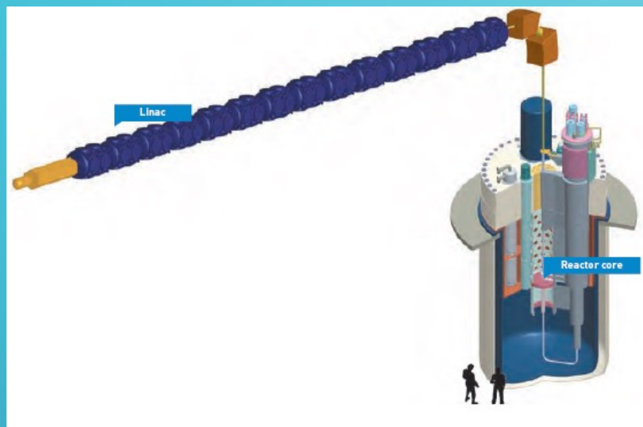
The trial by using the real nuclear fuel debris will be carried out soon.

Results by 3.95 MeV X-ray Source



Pb
Gd+PGM
U / Pu
Fe
Zr
Concrete
Three major components
Polymer

ANOTHER SUSTAINABILITY EXAMPLE



The MYRRHA research reactor in Belgium will test accelerator-driven systems for nuclear power generation.

Proton accelerators to drive nuclear power plants or transmute nuclear waste into shorter lived, more manageable by-products.

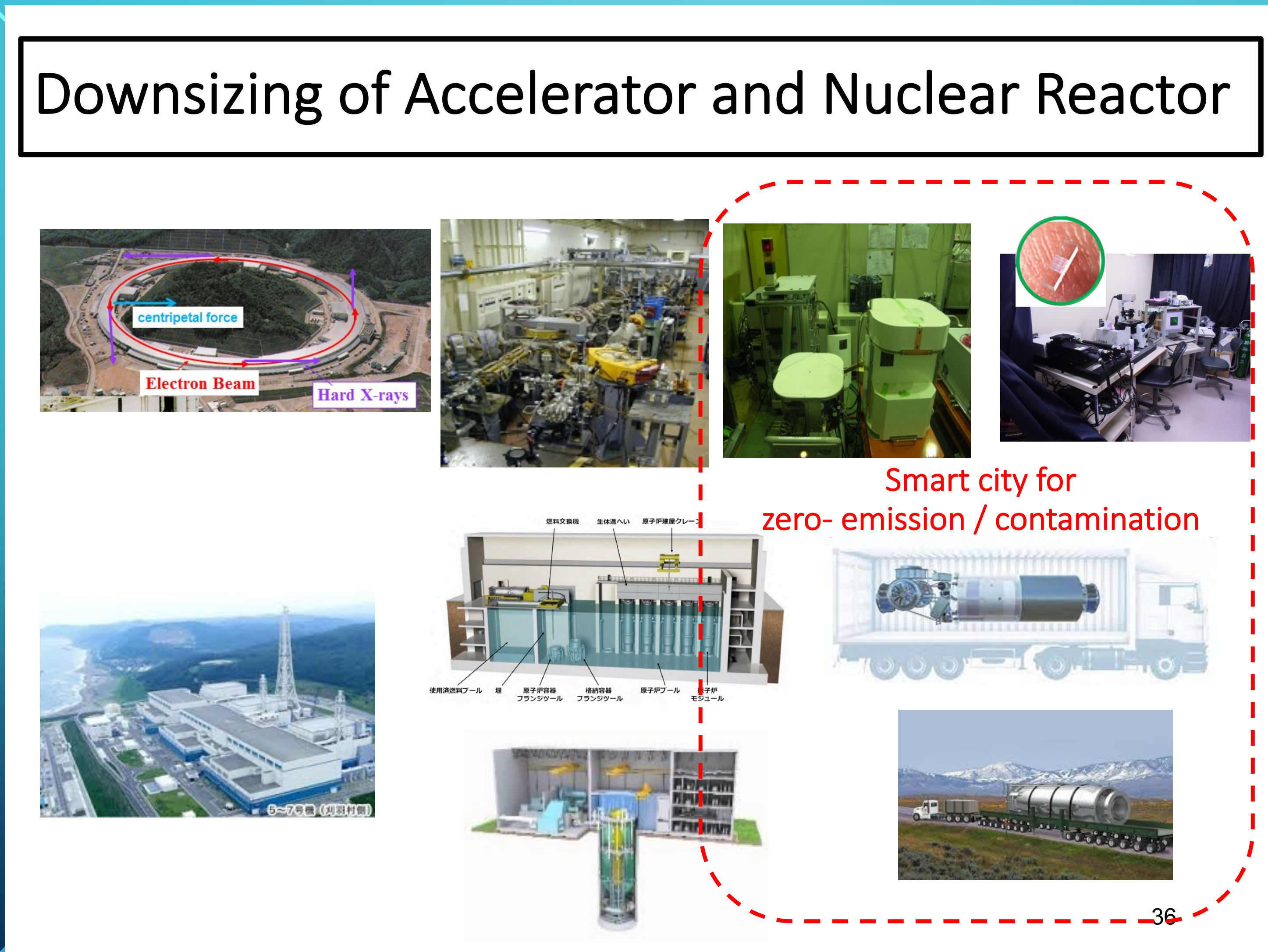
See talk by Bruce Yee Rendon "Overview of ADS projects in the world"

Accelerator-driven Nuclear Energy

(Updated August 2018)

- Powerful accelerators can produce neutrons by spallation.
- This process may be linked to conventional nuclear reactor technology in an accelerator-driven system (ADS) to transmute long-lived radioisotopes in used nuclear fuel into shorter-lived fission products.
- There is also increasing interest in the application of ADSs to running subcritical nuclear reactors powered by thorium.

ENERGY-WATER NEXUS



Courtesy Chairman Uesaka of the Japan atomic Energy Commission

The clean energy and water nexus. *Dream big and let's make these dreams reality.*

- We need dramatic change in our thinking and actions to reduce climate change and reduce/eliminate reliance on energy sources that are not clean.
- Sweden has been decarbonized since the 1970s. Follow suit. *Make this a basis of the energy architecture.*
- The answer is the clean energy and water nexus. One disruptive approach is the marriage of nuclear and particle accelerators - Small modular reactors could power an industrial complex or a small city 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.
- We need disruptive policy changes to field these near-existing technology solutions.

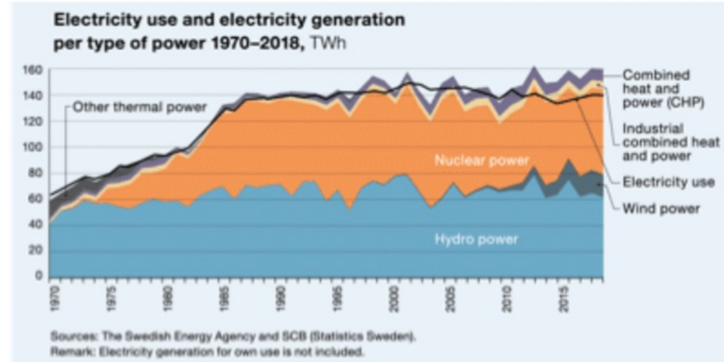
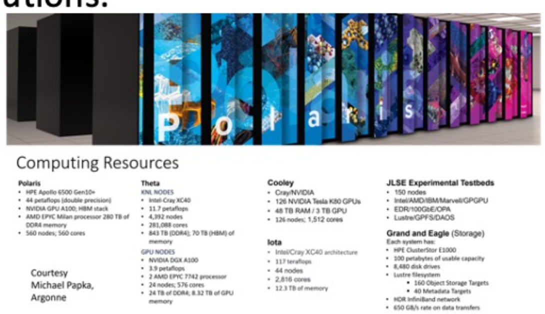


Figure 1: Evolution of Sweden's total electricity energy generation in terawatt-hour (TWh), from 1970-2018.1 Within the past decade, Sweden has generated a surplus of electric power, enabling it to regularly export power to its neighbors (Swedish Energy Agency 2020).



Computational resources, together with modern simulation and AI software, can help make good energy sources better, predict better materials, analyze experimental data, and optimize operation.

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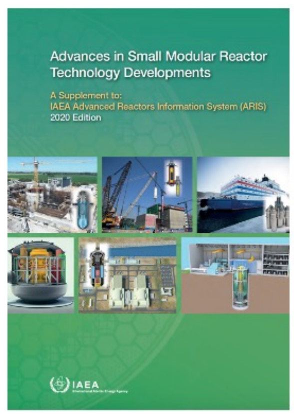

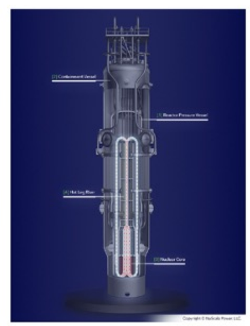

Example, NuScale, https://www.nuscalepower.com

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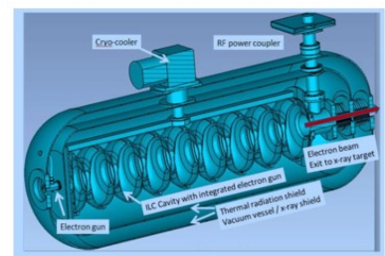


Example high-power, compact, electron accelerator module for purifying waste streams.

+…

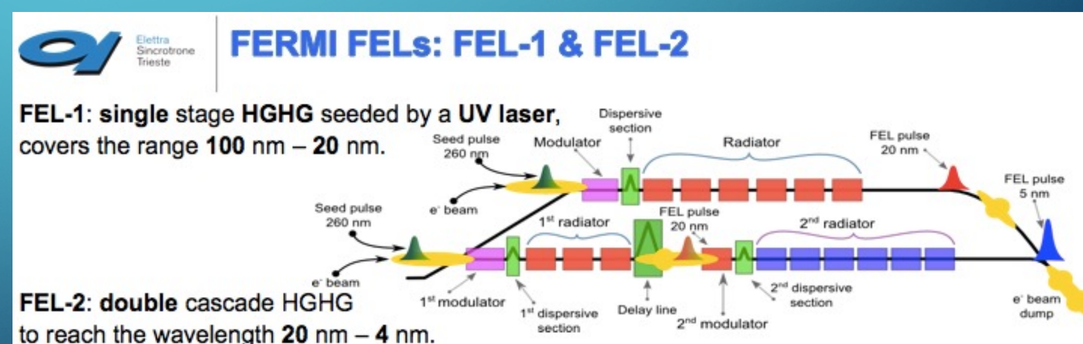
References: Robert Rosner & Sabrina Fields (2021) Is nuclear power sustainable in a carbon-free world? The case of Sweden, Bulletin of the Atomic Scientists, 77:6, 295-300, DOI: 10.1080/00963402.2021.1989196S.G. Biedron, M. Peters, R. Rosner, J. L. Sarrao, "Opportunity to Innovate" SEMICON West Sustainability Summit Breakout Track B: Business Ecosystem Building and Collaboration, 13 July 2022, https://www.semiconwest.org/programs/sustainability-summit.

LABS AS CENTERS OF PARTNERSHIP TO HELP PRESERVE GLOBAL SECURITY
A FEW EXAMPLES

Accelerator Test Facility at Brookhaven National Laboratory

Argonne Leadership Computing Facility

LANSCE at Los Alamos National Laboratory



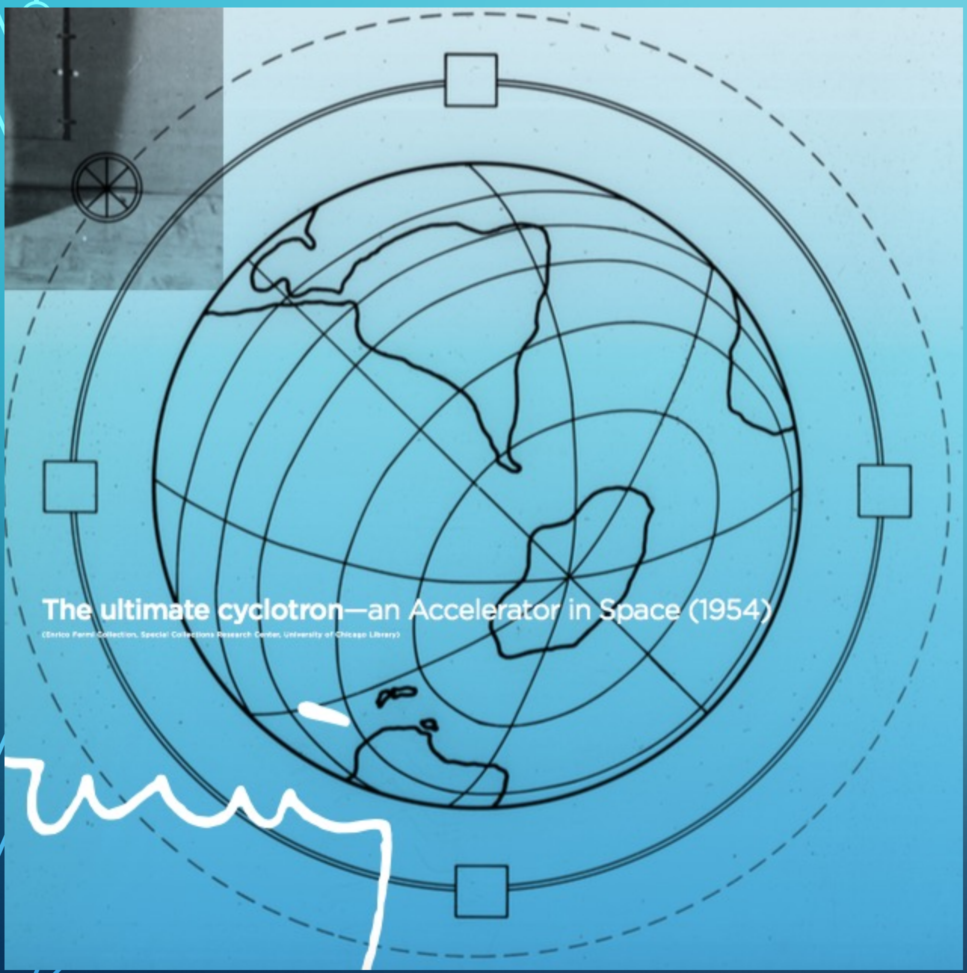
FERMI@Elettra

JLAB, SLAC, etc

SUMMARY

- Accelerators have myriad applications to global security.
- Not enough time today to get to everything in the global security box, left out a lot but we can learn from and transfer several technologies for global security, including but not limited to:
  - Robust cathodes
    - Center for Bright Beam cbb.cornell.edu is designing materials for long-lived cathodes in extreme electric field and high average currents.
    - Nathan A. Moody, et al., "Perspectives on designer photocathodes: influencing emission properties with heterostructures and nano-engineered electronic states" Physical Review Applied 10, 047002 (2018). https://doi.org/10.1103/PhysRevApplied.10.047002
  - Accelerators for quantum information device for advanced computing
    - Bohong Huang, Clio Conzales-Zacarías, Salvador Sosa, Aasma Aslam, Sandra G. Biedron, Kevin Brown, Trudy Bolin, "Artificial Intelligence-Assisted Design and Virtual Diagnostic for the Initial Condition of a Storage-Ring-Based Quantum Information System," in IEEE Access, vol. 10, pp. 14350-14358, 2022, doi: 10.1109/ACCESS.2022.3147727.
    - Fermilab Quantum Institute, quantum.fnal.gov
  - Etc…….

GLOBAL COLLABORATION GLOBAL SECURITY



Accelerator encompassing Earth

Maybe **Enrico Fermi** actually meant by his accelerator encompassing the Earth idea that accelerators (and other analytical research tools) would in a figurative way encompass the Earth.

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

Figure courtesy University of Chicago

ACKNOWLEDGEMENT

- This work was supported in part by the U.S. National Science Foundation under Award PHY-1549132, the Center for Bright Beams.

DIRECTED ENERGY

- As a direct source for defense use
- As a probe for materials

As Chairman of the Joint Chiefs of Staff (CJCS), GEN Milley, said "I would argue that the country that masters all those technologies (artificial intelligence, hypersonic weapons, and directed energy)…will have a decisive advantage in the next conflict." – December 2020.

DIRECTED ENERGY

- Technologies such as photocathode RF guns are employed on architecture concepts for free-electron-laser driven directed energy weapons.
- LWIRs being used for accelerator applications are definitely of interest for kills as well as target/tracking.
- Close association of the Directed Energy Professional Society (DEPS) with several of the accelerator community.

- The Directed Energy Professional Society fosters the research, development, education and operational transition of DE technologies for national defense and civil applications through professional communications, education, and outreach.
- We serve as the premier professional organization that supports the advocacy and exchange of information between academia, industry, services, agencies, laboratories, and the warfighters for the research, development, and application of Directed Energy; while also developing the next generation of scientists and engineers in Directed Energy.

DIRECTED ENERGY

- **DE Definition:** Technology and weapon systems based on the application of force on target with electromagnetic energy vice Kinetic Energy (KE) (no projectile)

- **Advantages**
  - Speed of light delivery
  - Precise engagement
  - Graduated effects
  - Depth of magazine
  - Low engagement cost

- **Energy Classes**
  - High Energy Laser (HEL)
  - High Power Microwave/Radio Frequency (HPM/HPRF)

Courtesy Mark Neice, DEPS

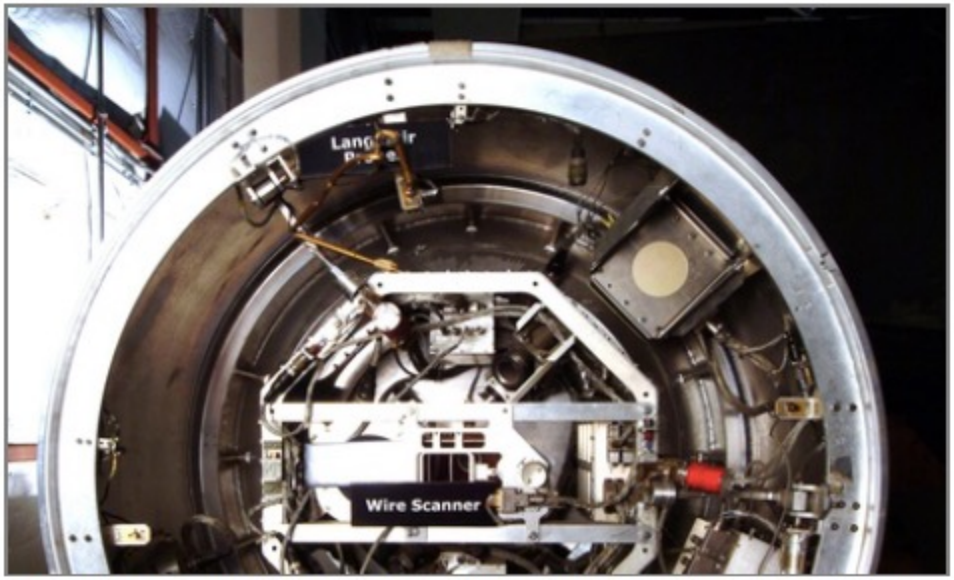
DIRECTED ENERGY

Free Electron Laser Thrust

- Advantages
  - Tunable wavelength for maritime propagation
  - Shipboard protection against asymmetric threat
  - No hazardous gases or chemicals
- Opportunities
  - All electric ship integration
  - Megawatt potential
- Challenges
  - Injectors and Cathodes
  - High Intensity Optical Components
  - Efficient wiggler

DIRECTED ENERGY

- March 2018 - **"Directed energy is more than just big lasers," said Michael Griffin Undersecretary for Defense for Science and Engineering. "That's important. High-powered microwave approaches can affect an electronics kill. The same with the neutral particle beam systems we explored briefly in the 1990s"** for use in space-based anti-missile systems. Such weapons can be "useful in a variety of environments" and have the "advantage of being non-attributable," meaning that it can be hard to pin an attack with a particle weapon on any particular culprit since it leaves no evidence behind of who or even what did the damage.

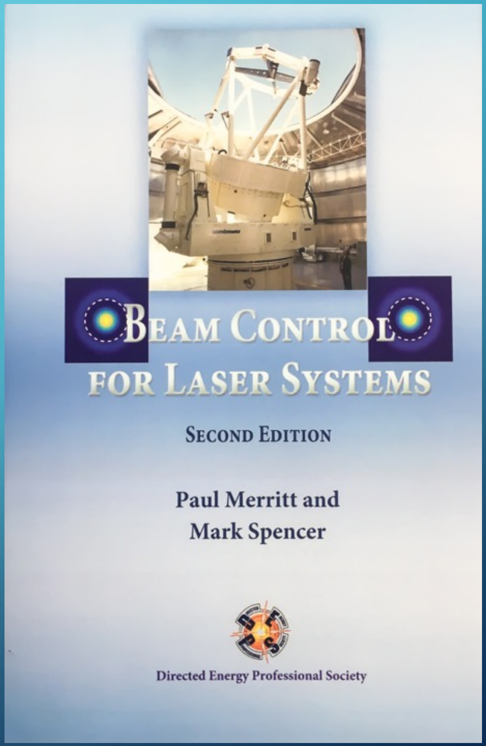


As part of the Beam Experiments Aboard Rocket project, this neutral particle beam accelerator was launched from White Sands in July 1989 to an altitude of 200 kilometers (124 miles), operated successfully in space in July, 1989. National Air and Space Museum Collection

DIRECTED ENERGY

- And speaking of DEPS, there is a deep history of publications
  - **Journal of Directed Energy-** Special Issue MMW/Bio-effects now available online!
  - **Journal of Directed Energy** (Limited Dis. Edition) – ***Watch for forthcoming FEL edition***
  - **The WaveFront- DE Newsletter** (Online)
  - **Effects of DE Weapons***
  - **Introduction to High Power Fiber Lasers** *
  - **Introduction to Laser Weapon Systems** *
  - **Beam Control for Laser Systems***

* Textbooks



Courtesy Mark Neice, DEPS

QUOTE FROM MARK NEICE

- “Robust optical **materials** that can survive in extreme x-ray and radiation environments are critical to the use of high-brightness [electron-based] sources for defense applications.” - *Mark Neice Executive Director of DEPS*

DIRECTED ENERGY

- Directed energy (DE) materials need more exploration
- FELs are analytical tools that can be explored here for gain media, coatings, and counter DE materials.
- **Materials:** *"Understand...laser pulse material interaction/effects due to concentrated strong electric fields through experimentation and observations to understand, validate and document USPL physics."*
- One example is listed on the Office of Naval Research web-site: https://www.onr.navy.mil/en/Science-Technology/Departments/Code-35/All-Programs/aerospace-science-research-351/directed-energy-weapons-uspl-and-atmospheric-characterization.