Fermilab U.S. DEPARTMENT OF ENERGY Office of Science
FERMILAB-SLIDES-19-052-DI

Accelerator Research and Technology Developments for Industrial Applications (excluding medicine)

Jayakar "Charles" Thangaraj , Fermilab

Thanks: Gianluigi Ciovati (Jlab) , John Lewellen (LANL), Arun Persaud (LBNL), Cameron Geddes (LBNL), Andrea Schmidt (LLNL), Mark Palmer (BNL), Dushyant Shekhawat (NETL), Aaron Tremaine (SLAC)

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

Accelerators comes in several sizes and shapes.

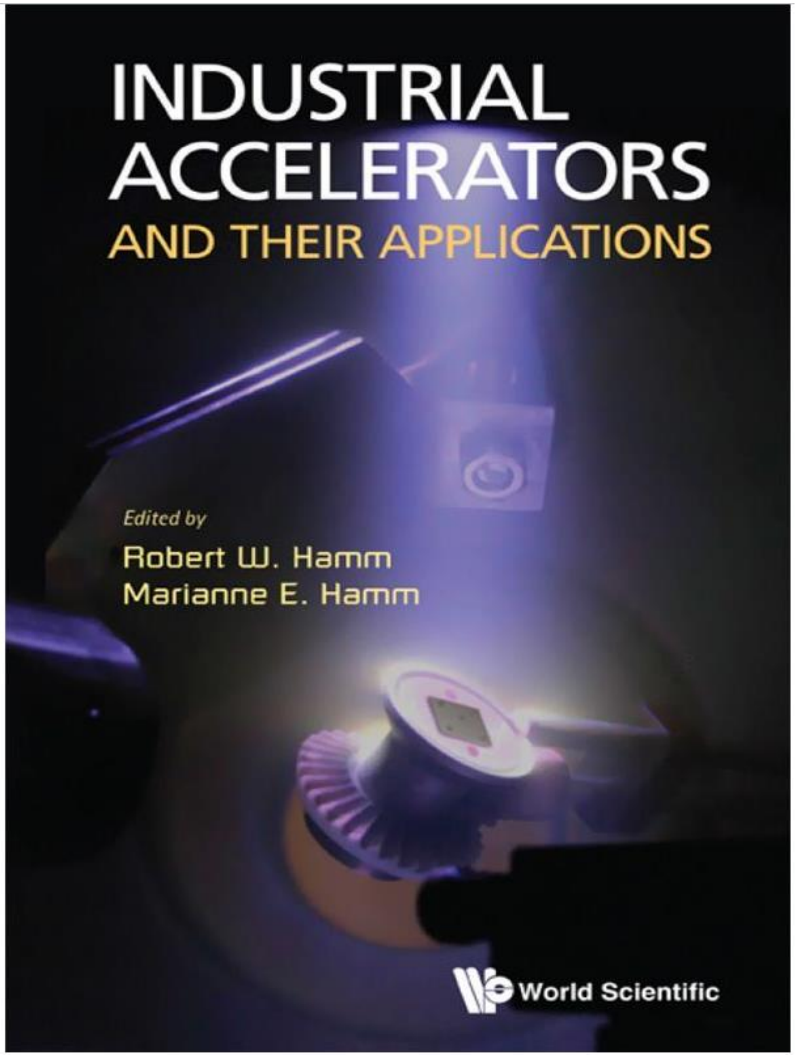
- Electrostatic (few keV – 10 MeV) – e.g. Dyanmitron, Cockroft-Walton, Pelletron

- Microtron – a cross of cyclotron but uses multi-pass
- Betatron – essentially a transformer but circular can reach several MeV's
- Rhodotron – recirculating through a coaxial cavity
- RF Linac (several MeV's) – normal conducting cavities
- Synchrotron
- Ion accelerators (different species)
- Laser plasma accelerators

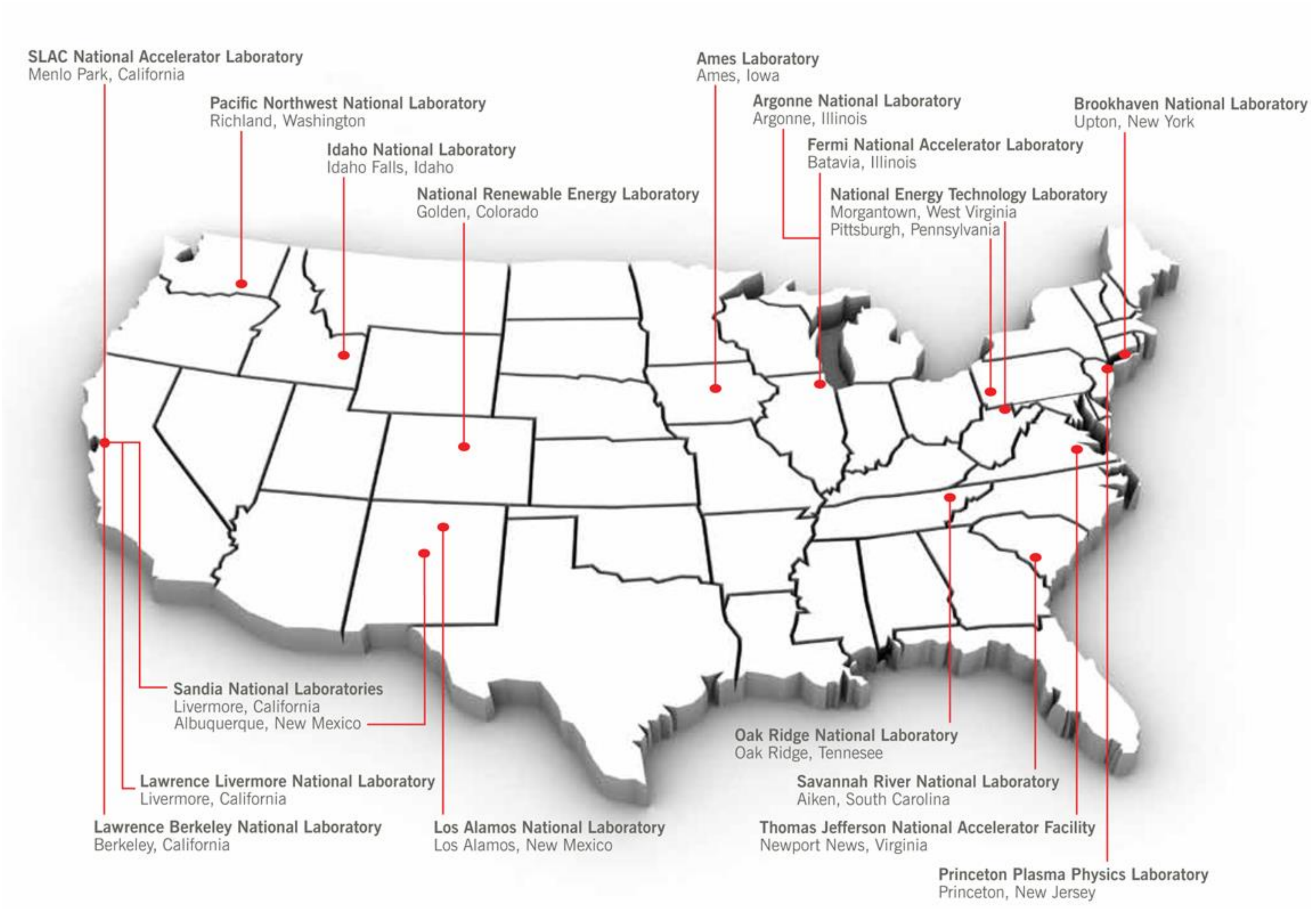
A steady market

Commercial EB accelerator applications are vast

- EB welding
- EB melting
- EB sterilization
- EB curing
- Non-destructive testing
- Medical imaging
- Cargo inspection



DOE Labs: A Reservoir of Talent for Science and Technology



Graphic taken from "A Decade of Discovery" DOE. 2008

Scope of the talk: Disclaimer and practical limitations

- This is just *a sample* of the work from the DOE labs that I am most familiar with and is selection biased.
- There are a lot of efforts on-going that includes medical applications which is not the focus of this talk
- The materials were prepared by each contact at the respective lab who were willing to consolidate the laboratory efforts in this area. If something piques your interest, let me know I will be happy to connect you the right person.
- Universities, several other agencies, and industries are working on modern machines some of which I am aware of but was not the focus of this talk.
- Books, national and international conferences, workshops are active on every single topic mentioned here. Please contact me and I will do my best to assist you to the right ones.

Many thanks to these folks!

Lab	Contact
Jefferson Lab	Gianluigi Ciovati
LANL	John Lewellen
LBNL	Arun Persaud, Cameron Geddes
LLNL	Andrea Schmidt
BNL	Mark Palmer
SLAC	Aaron Tremaine
NETL	Dushyant Shekhawat
Fermilab	Jayakar Thangaraj

They had to put up with me for emailing them back and forth…Thanks

Development of Environmental Accelerators at Jefferson Lab

- Design of compact, high-efficiency, low-cost normal and superconducting RF LINACs for the treatment of wastewater and flue gases
- Development of prototypes conduction-cooled SRF cavity and normal-conducting cavity
- Development of 100 kW high-efficiency magnetrons
- Hosted an Industry Day event with participation of over 70 representatives from Industry, Military, Medical, Shipping, Universities, Cities and State Agencies

https://www.jlab.org/indico/event/297/

DOE-HEP Accelerator Stewardship Awards:

FY16-17 "Design of a low-cost, compact SRF accelerator for flue gas and wastewater treatment"

FY18-20 "Development of a high-efficiency and high-power magnetron RF Source for accelerators"

FY19-20 "High Efficiency, Normal Conducting LINAC for Environmental Water Remediation"

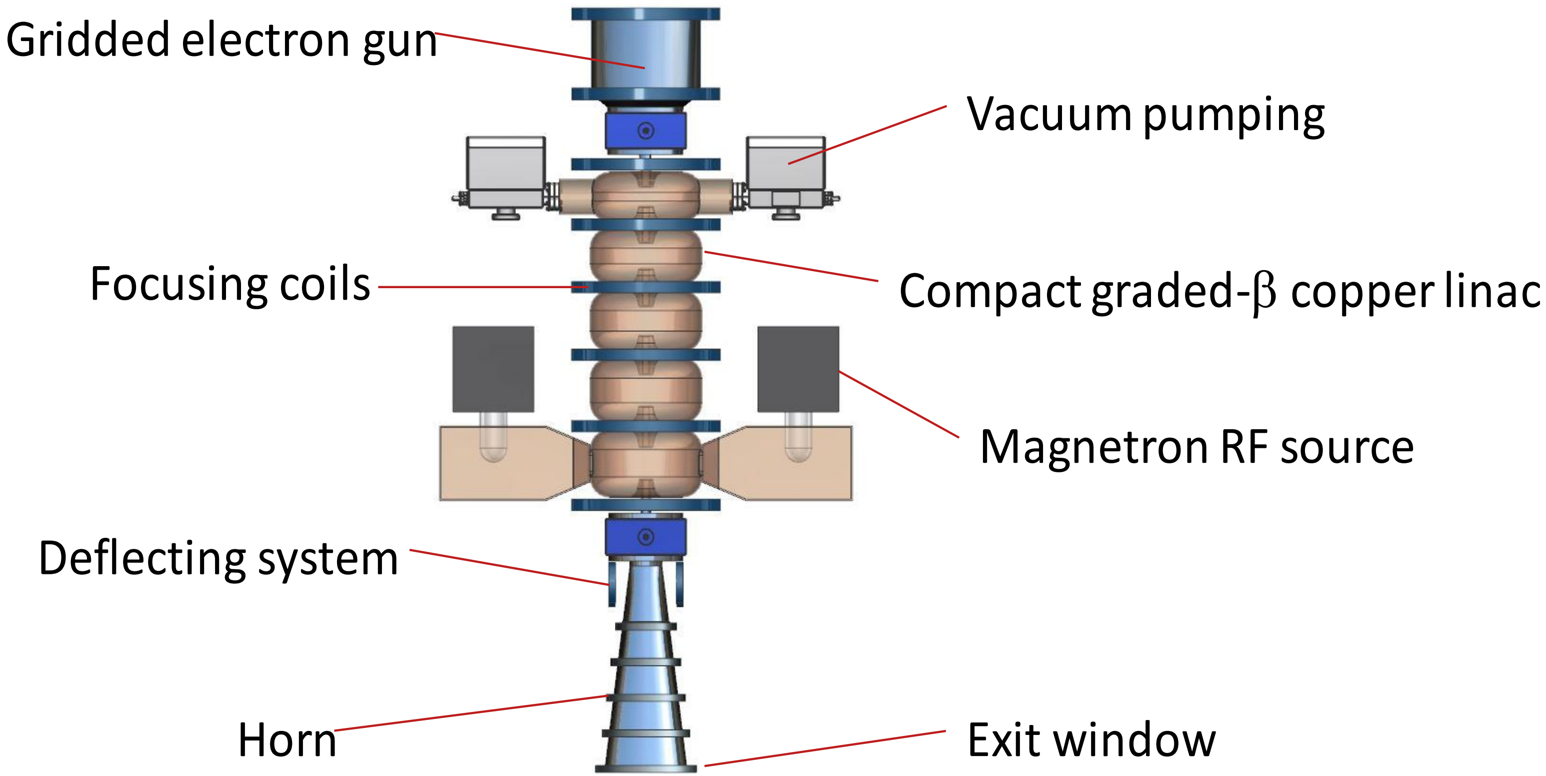
FY19-21 "Design, prototype and testing of a SRF cavity for a low-cost, compact accelerator for environmental applications"

Virginia State Funding

FY19-20 "Accelerator for Environmental Materials Processing"

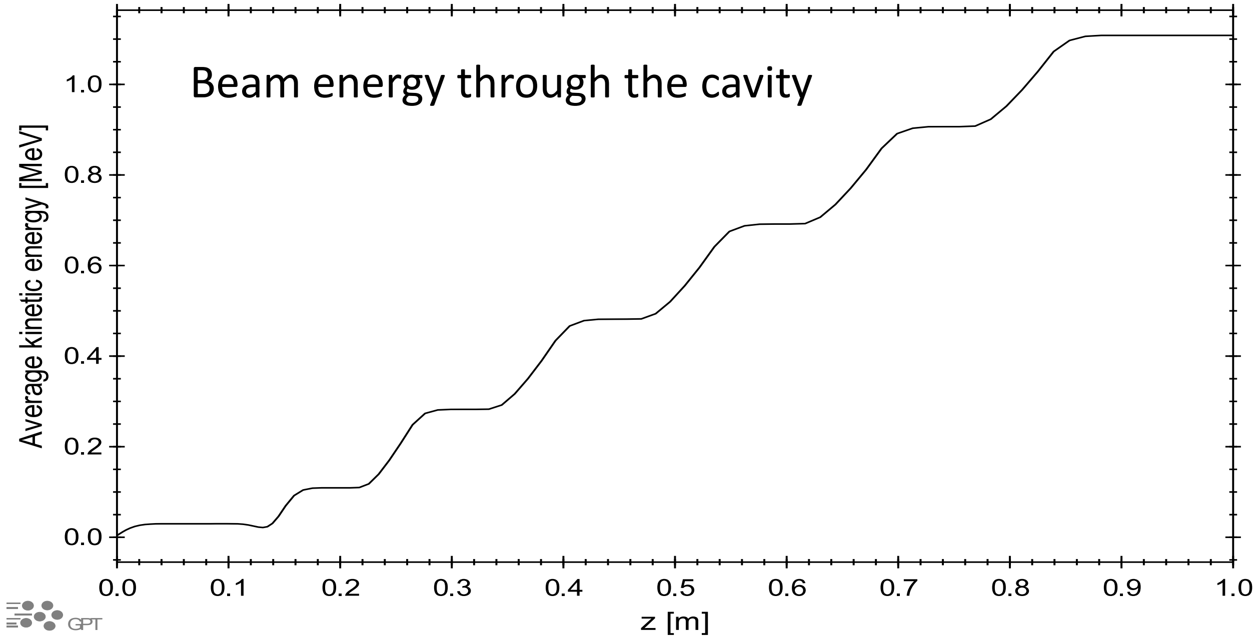
Design of a High Efficiency, Normal Conducting LINAC for Environmental Remediation

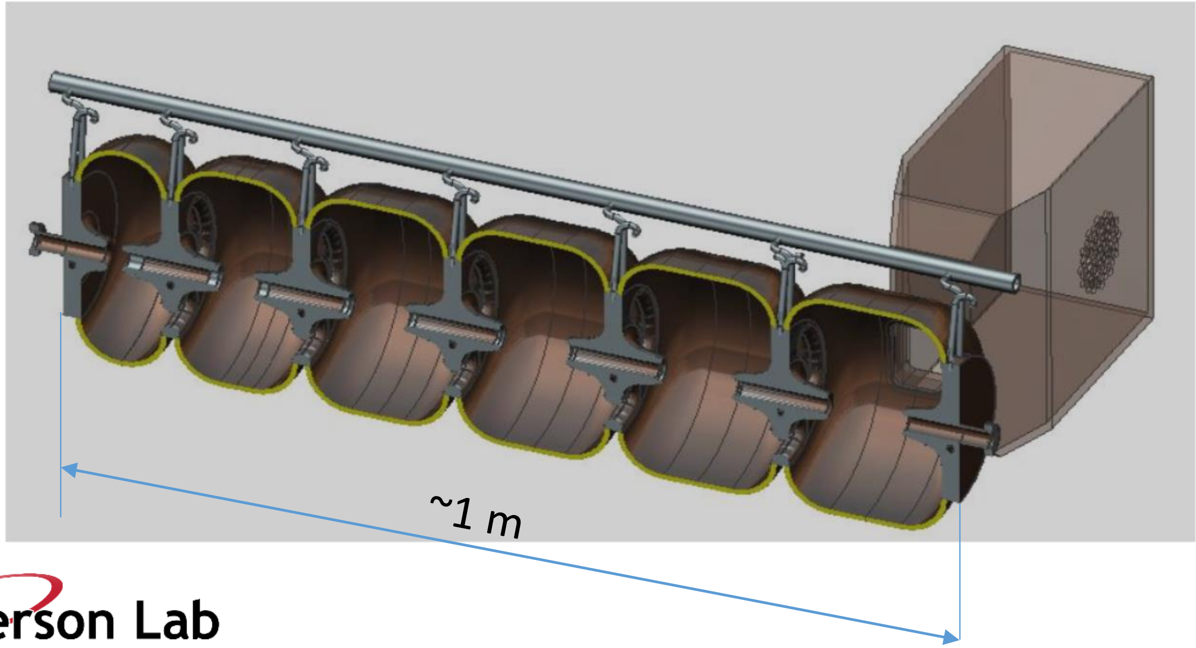
Beam current (mA)	**10-500**
Final energy (MeV)	1
Beam power (kW)	10-500
Fundamental RF (MHz)	915
Source energy (keV)	50-100

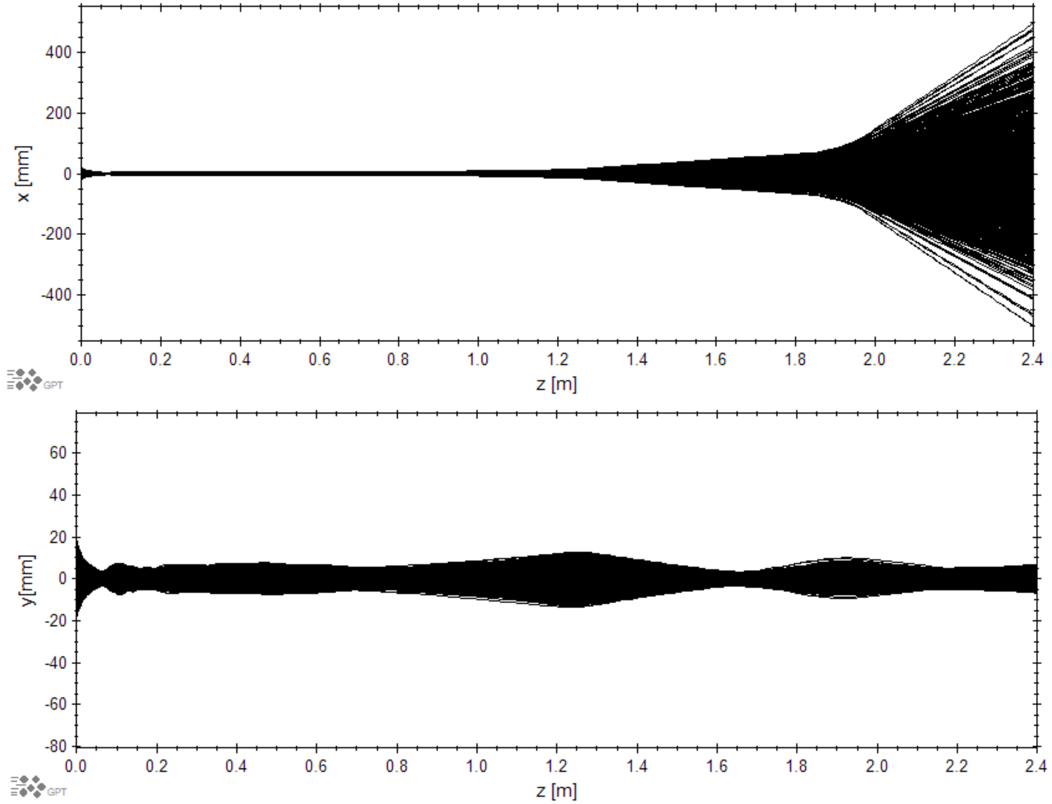


F. Hannon, R. Rimmer, S. Wang

Jefferson Lab US Patent 9,655,227 *Slot-coupled CW standing wave accelerating cavity*





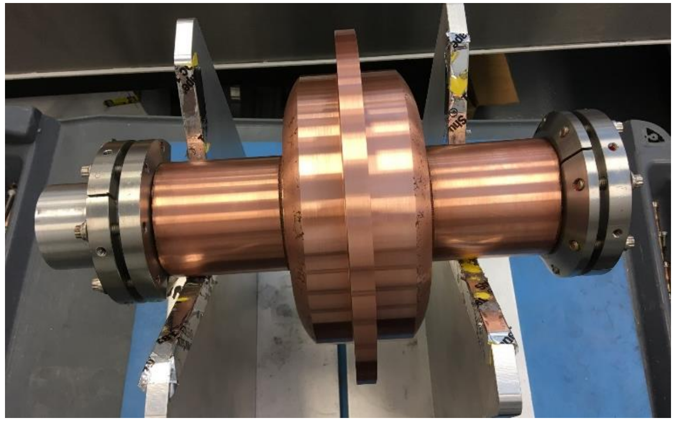


Transverse beam size along the LINAC, calculated with GPT

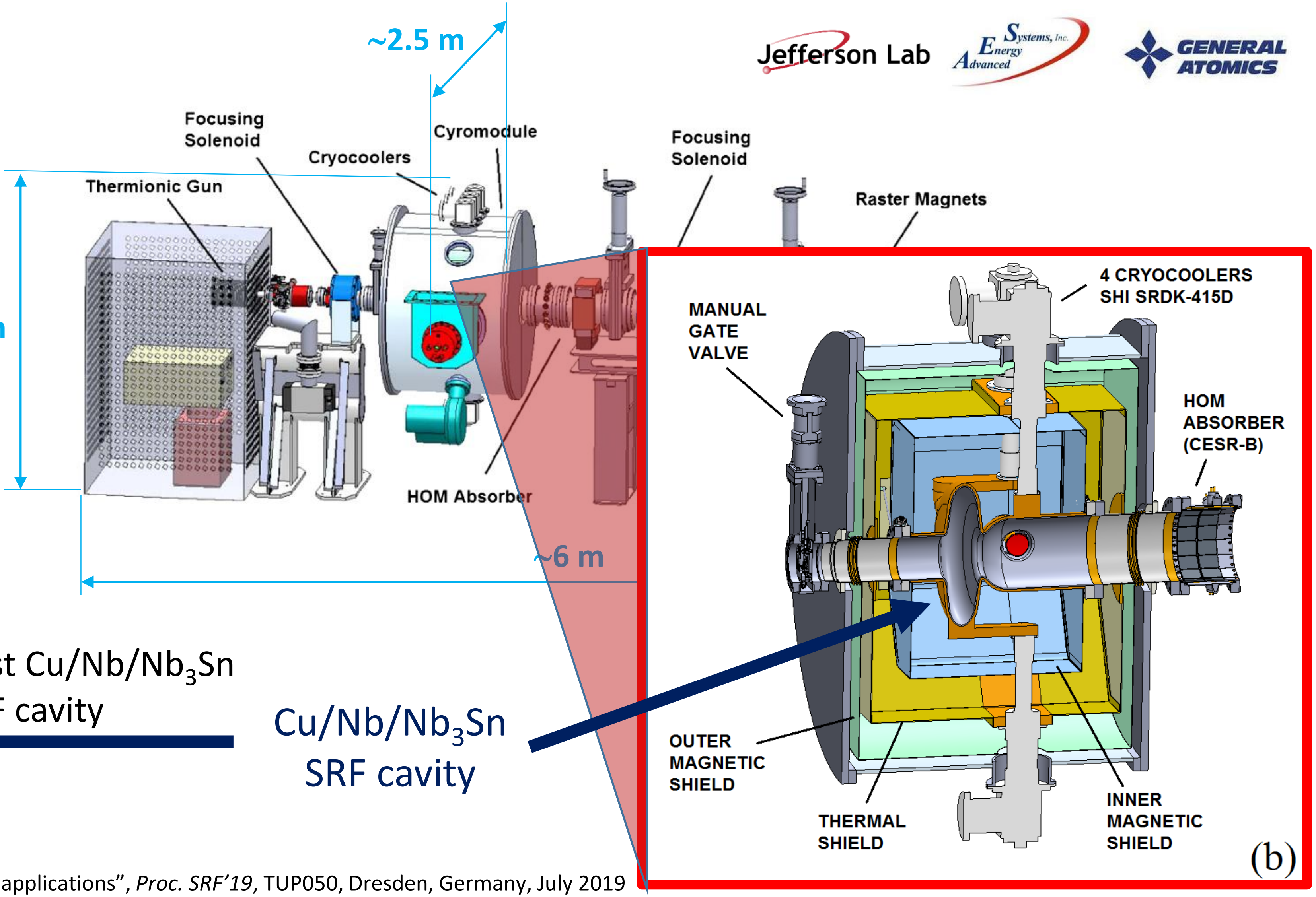
Design of a compact, low-cost SRF LINAC for Environmental Remediation

Jefferson Lab · Advanced Energy Systems, Inc. · General Atomics

Beam current (mA)	1000
Final energy (MeV)	1
Beam power (kW)	1000
Fundamental RF (MHz)	750
Source energy (keV)	100



First Cu/Nb/Nb_3Sn SRF cavity



Cu/Nb/Nb_3Sn SRF cavity

G. Ciovati *et al.*, *Phys. Rev. Accel. Beams* **21**, 091601 (2018)
G. Ciovati *et al.*, "A multi-layered SRF cavity for conduction cooling applications", *Proc. SRF'19*, TUP050, Dresden, Germany, July 2019

Development of 915 MHz industrial magnetron for high-power accelerator applications

- Use industrial 75 kW magnetron for R&D tests
- Design of high-power combiners with General Atomics
- Injection phase locking with electromagnet control by LLRF/AC/DC digital controllers developed by JLab
- Noise reduction from cathode heater, the mains (SCRs) and high frequency switching

915 MHz magnetron

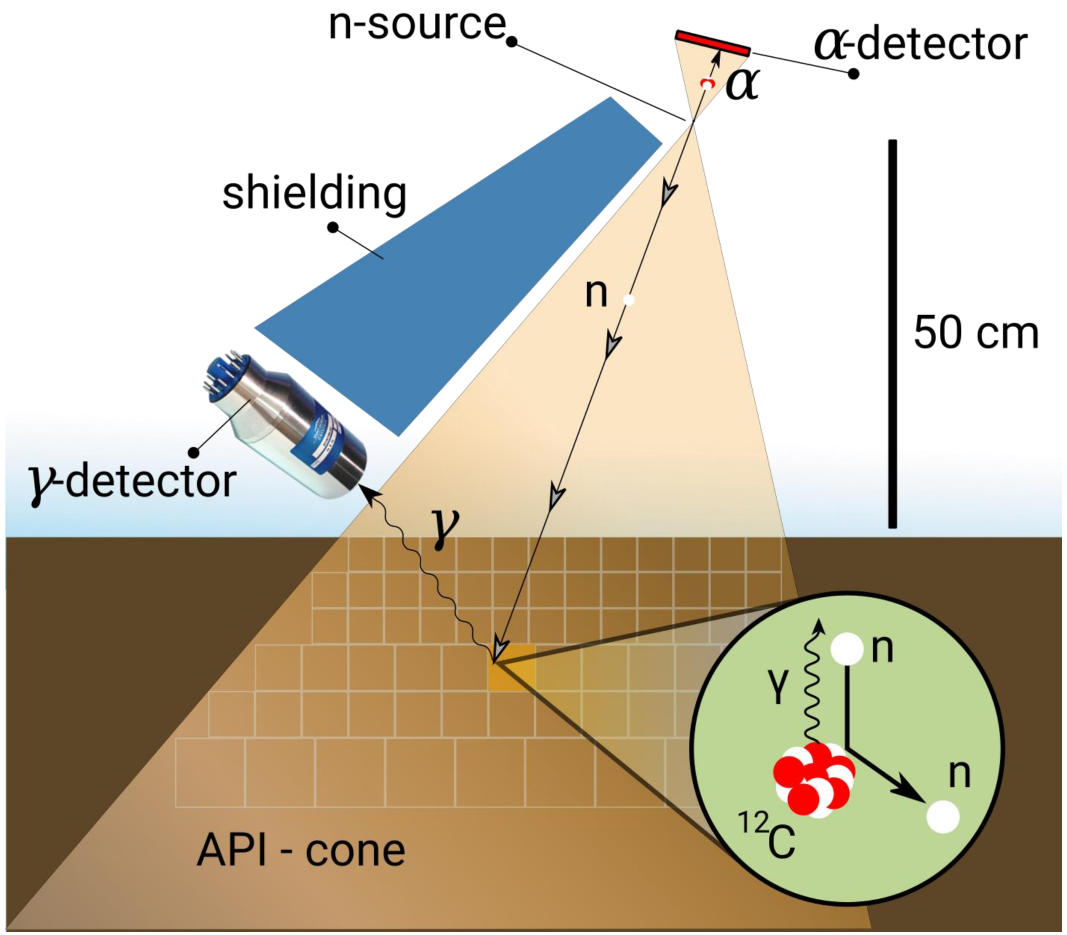
Jefferson Lab

H. Wang, R. Rimmer, R. Nelson

GENERAL ATOMICS

B. Coriton, R. Moeller

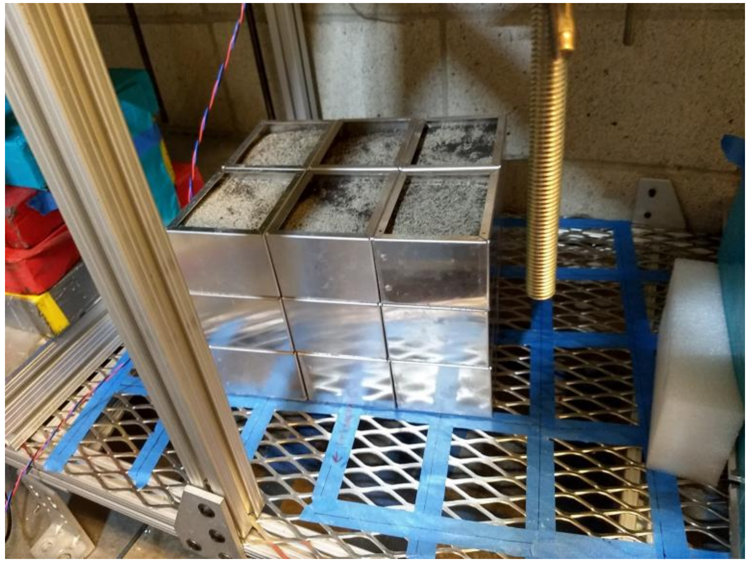
Utilize isotope-specific response to fast neutrons to measure carbon distribution in soil

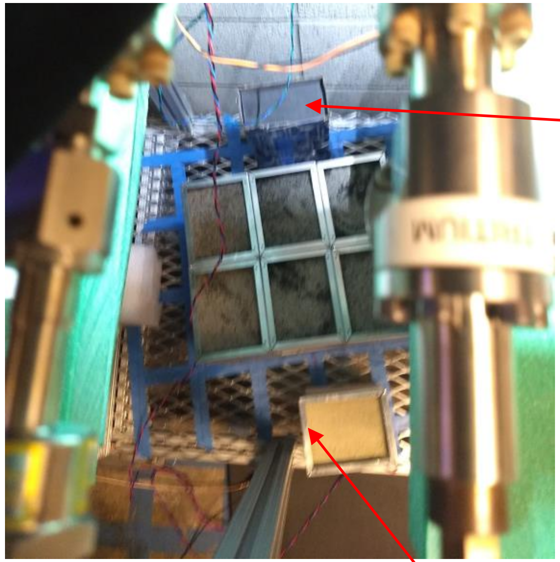


- Fast neutrons excite isotopes by inelastic scattering leading to emission of characteristic gamma rays of isotope-specific energies
- Associated Particle Imaging combined with time-of-flight analysis enables correlation of measured gamma ray with nucleus location in the soil
- Measured gamma rates reflect carbon concentration

https://arxiv.org/abs/1908.00950
https://arxiv.org/abs/1811.08591

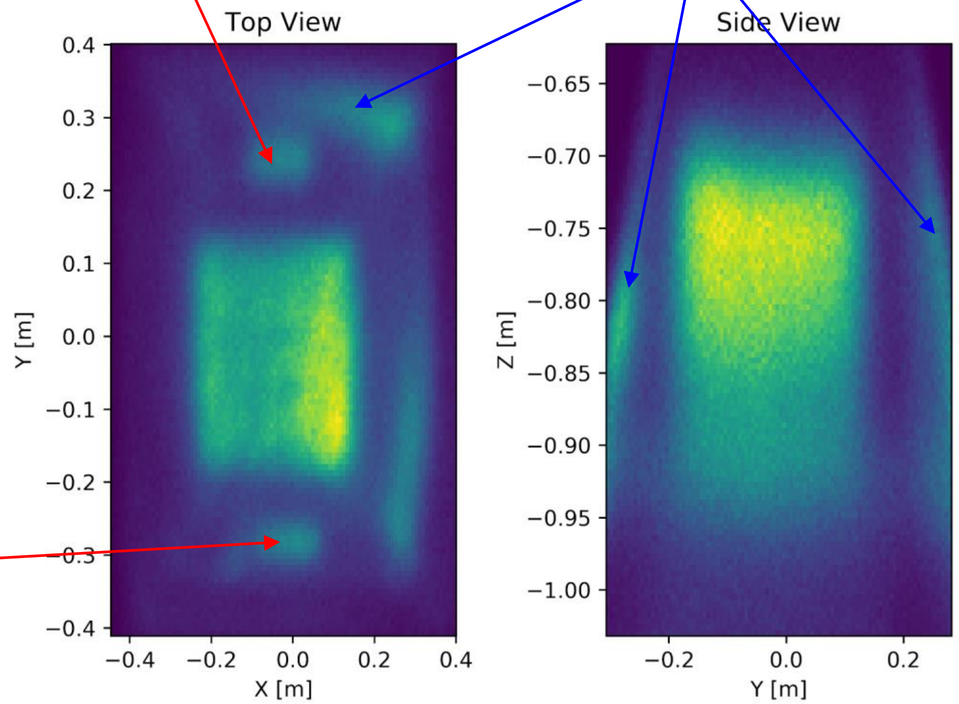
API results using pre-mixed soil sample provide high spatial resolution





Graphite

Detector shielding/wall



Sand

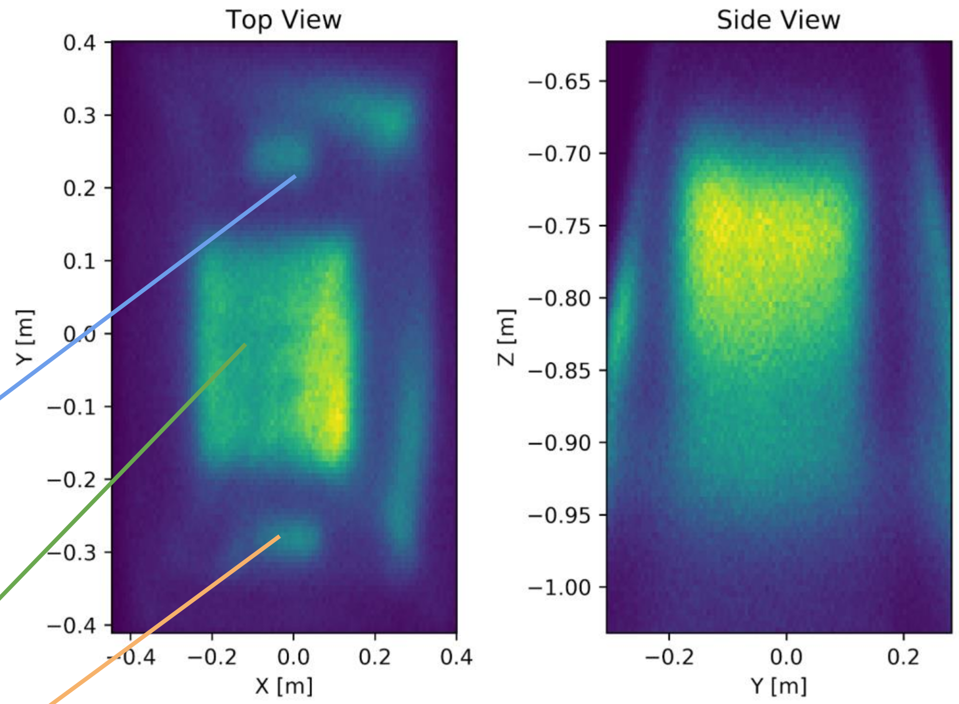
We use a mixture of sand and worm casting to generate a soil proxy with varying carbon content (here 4%).

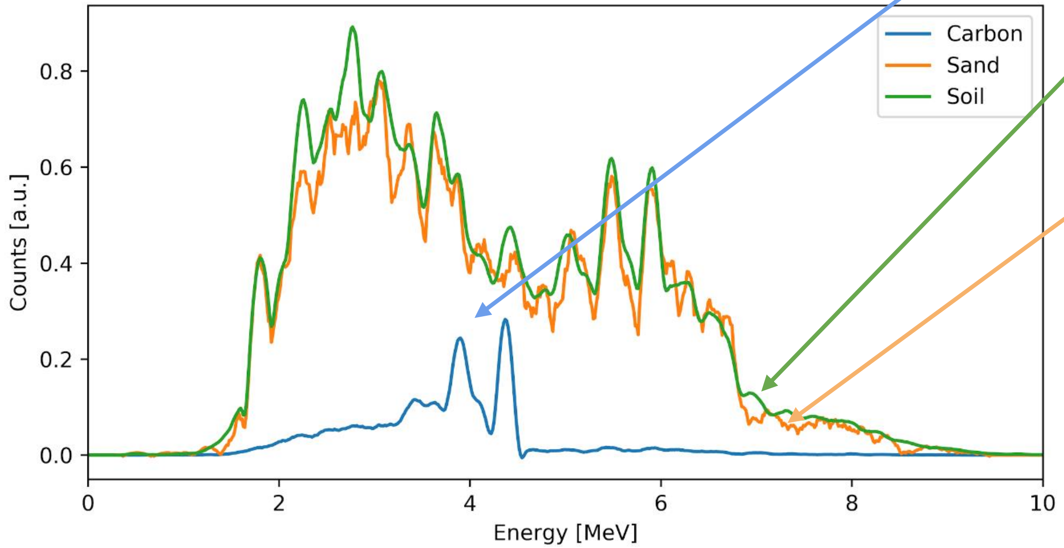
XYZ resolution on the order of 5 cm.

The information, data, or work presented herein was funded by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Contract No. DE-AC02-05CH11231.

API energy spectra allow to identify isotopes

- Analysing count rate per voxel for each isotope
- Combine this data with neutron/gamma attenuation model
- Data acquired over 9h at 50 kV (reduced neutron rate). Equivalent to ~ 30 minutes at full rate.

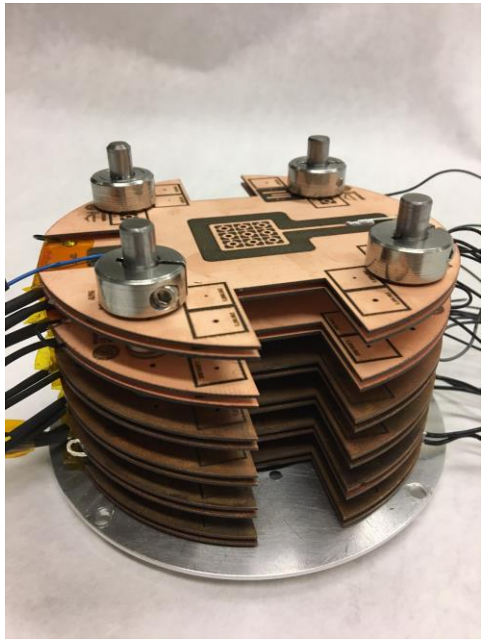




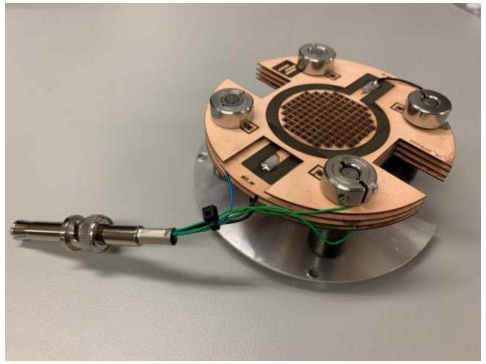
Smoothed energy spectra of the LaBr detector

5” NaI and 3” LaBr detectors

Modular Compact Accelerator



9 beamlet version



latest version: 112 beamlet

- Wafer based acceleration and focusing elements
- Current can be scaled up by multiple beamlets
- Current project focuses on demonstrating 1 mA, 100 keV, but higher currents and voltages are feasible (up to 1 MeV)
- Possible applications: neutron generators, medical applications, mass spectrometers

K. B. Vinayakumar *et al.*, Demonstration of waferscale voltage amplifier and electrostatic quadrupole focusing array for compact linear accelerators. *J. Appl. Phys.* **125**, 194901 (2019).

A. Persaud *et al.*, Staging of RF-accelerating Units in a MEMS-based Ion Accelerator. *Phys. Procedia*. **90**, 136–142 (2017).

P. A. Seidl *et al.*, Multi-beam RF accelerators for ion implantation. *arXiv [physics.acc-ph]* (2018), (available at http://arxiv.org/abs/1809.08525).

A. Persaud *et al.*, A compact linear accelerator based on a scalable microelectromechanical-system RF-structure. *Rev. Sci. Instrum.* **88**, 063304 (2017).

P. A. Seidl *et al.*, Source-to-accelerator quadrupole matching section for a compact linear accelerator. *Rev. Sci. Instrum.* **89**, 053302 (2018).

The information, data, or work presented herein was funded by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Contract No. DE-AC02-05CH11231.

Compact Mono-Energetic Compton Photon Sources via Laser-Plasma Accelerator
Revolutionary Xray applications, Strong synergy with other LPA applications

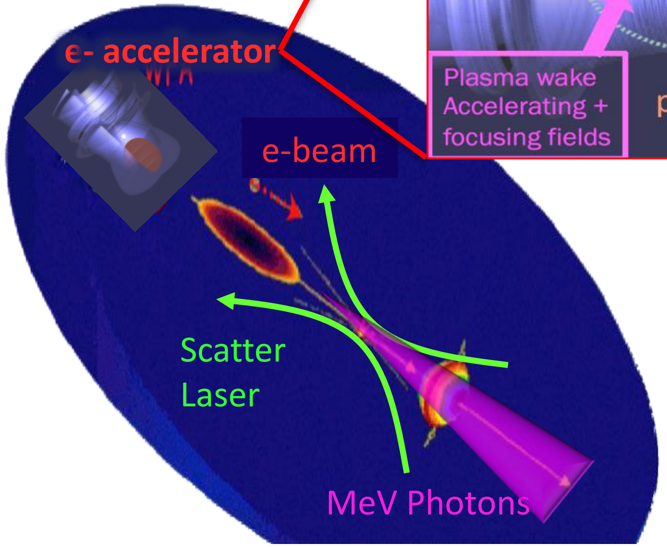
Compton (ICS, Thomson) advanced X-ray sources[1]

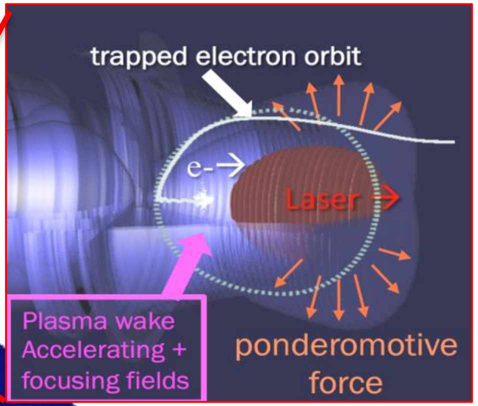
- Low energy spread: enhanced signal, lower dose
- Tunable energy: material contrast, Photofission, and NRF
- mrad divergence: mitigate scattering, reduce & adapt dose
- Adjustable per-shot: flux, energy, polarization
- µm and sub-picosecond emission: resolution

Transformational for security, industry, medicine[2]

- Drop dose 10-100x, resolve material (bone/flesh...)
- Increase resolution to µm/fs, 3D without CT
- New signatures – polarization, timing…

GeV LPA in cm enables advancedXray source



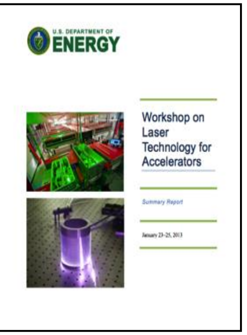


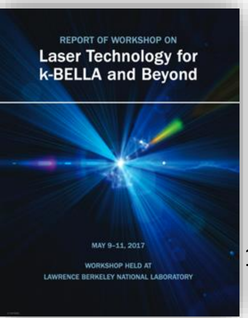
Require 0.5 GeV class accel. for MeV photons… Laser plasma accelerator driven compact system could enable applications use & benefits[1]

1:: C.G.R. Gedes et al., NIM B 350, 116 (2015)

2: Final report of project "Impact of Monoenergetic Photon Sources on Nonproliferation Applications ," C. Geddes, et al, (2017)

Compact Mono-Energetic Compton Photon Sources via Laser-Plasma Accelerator
Revolutionary Xray applications, Strong synergy with other LPA applications





LPA driven sources operating at few-Hz rates

- Proven GeV-class LPAs, photon production
- Path to: scatter control (higher flux, reduced energy spread towards ≤ 2%), electron beam disposal

Common methods w/future LPA colliders, FELs[1]

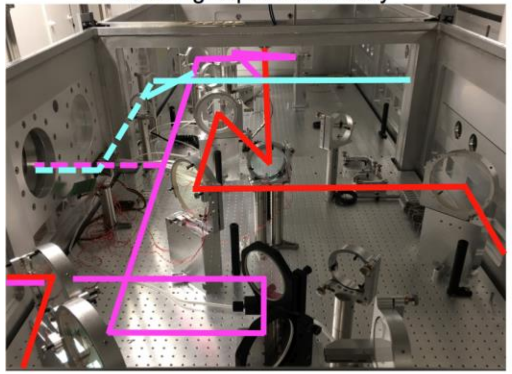
- GeV LPA – energy spread, emittance
- Electron refocusing – energy spread
- Hollow plasma channels – yield
- Deceleration (staging) – reduce shielding
- Diagnostics: pectrum reads out emittance evolution

Next: kHz laser: flux, active feedback control[2]

- Techniques developed, proposals in progress to build

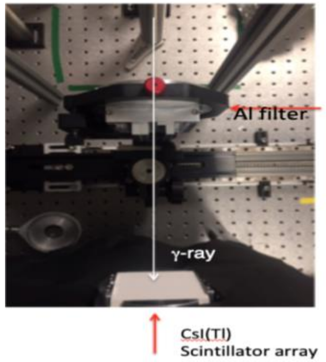
NNSA DNN R&D projects

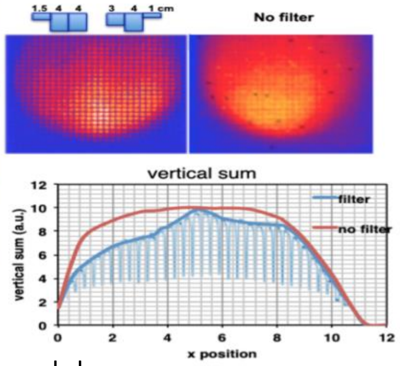
Proved principles, constructed facility



Mev photons generated

Establishes path for kHz system





1::https://www.osti.gov/biblio/1358081-advanced-accelerator-development-strategy-report-doe-advanced-accelerator-concepts-research-roadmap-workshop

2: https://www2.lbl.gov/LBL-Programs/atap/Report_Workshop_k-BELLA_laser_tech_final.pdf

Microwave Applications in Reaction Science at NETL

Dushyant Shekhawat, Christina Wildfire

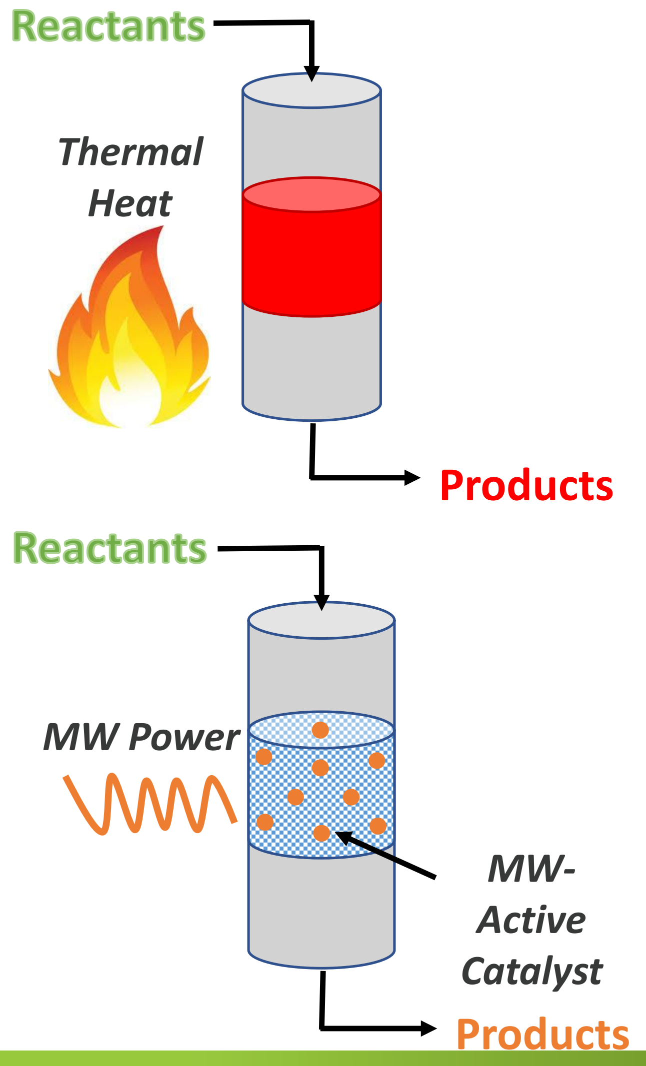
NATIONAL ENERGY TECHNOLOGY LABORATORY

Aug. 16, 2019

Advantages of Microwaves

- **Benefits include:**
  - Selective heating
  - Volumetric heating (efficiency savings)
  - Product selectivity
  - Lower bulk temperatures for reactions
  - Lower activation energy
  - Mechanistic changes not available with conventional thermal reactors

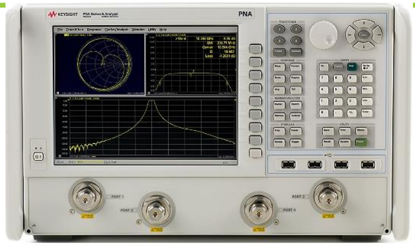
- **Goal: Evaluate and develop electromagnetic energetic systems (microwave, etc.) for conversion of materials into energy and/or value-added products.**



NETL MW Capabilities

Reactors and Characterization

NATIONAL ENERGY TECHNOLOGY LABORATORY

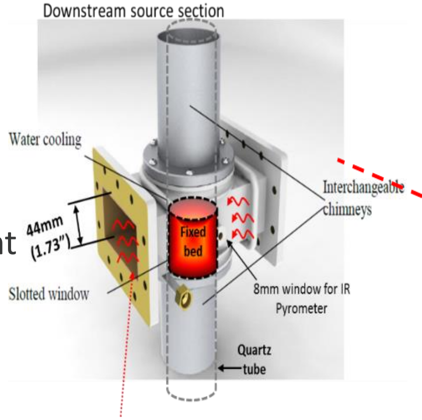


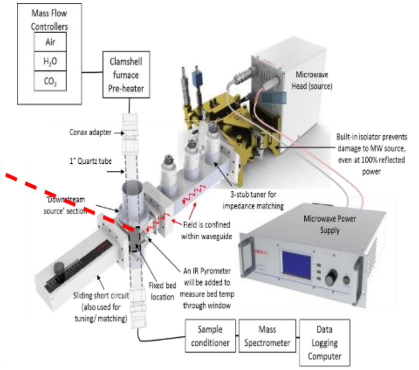
Vector Network Analyzers

VSM magnetometry

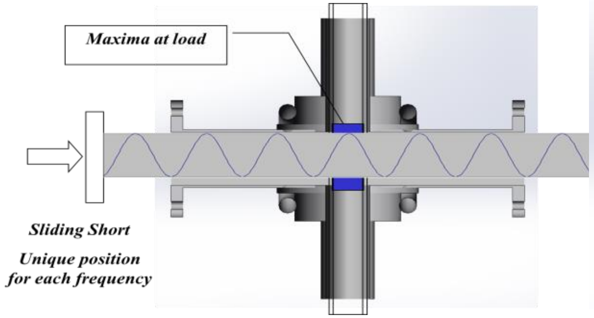
OceanOptics Spectrometer

Cell for EM measurement

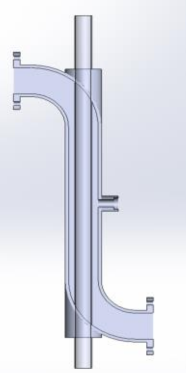




- **Reactor Systems**
  - **Fixed frequency MW system**
    - Frequency: 2.45 GHz & Power: 0 - 2kW
  - **Variable frequency MW system**
    - Frequency: 2 to 8 GHz & Power: 0 – 0.5 kW
    - Two different applicator configurations: Horizontal and vertical
- **Microwave Characterization**
  - Vector Network Analyzers (Keysight N5231A PNA-L & N5222A PNA)
    - Maximum Frequency: 43.5 GHz
    - To measure electromagnetic (EM) properties of materials
  - Developing a cell to measure the electromagnetic properties up to 1200 C
  - VSM magnetometry and field dependent electrical transport properties from cryogenic up to elevated temperatures
  - Spectrometers



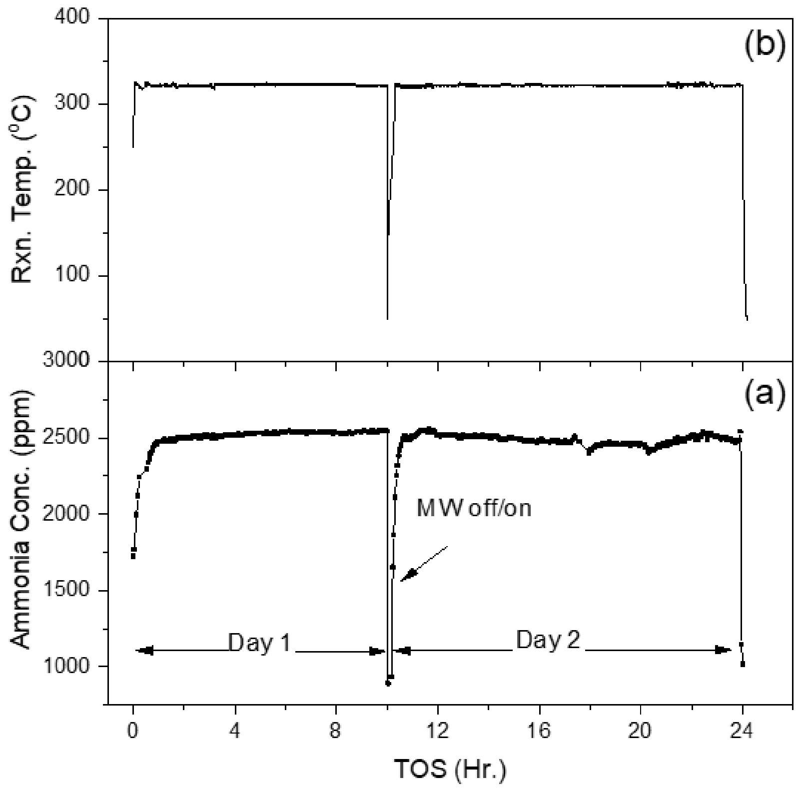
Standing Wave applicator



Dual E-Band Applicator

Microwave-Assisted Ammonia Synthesis

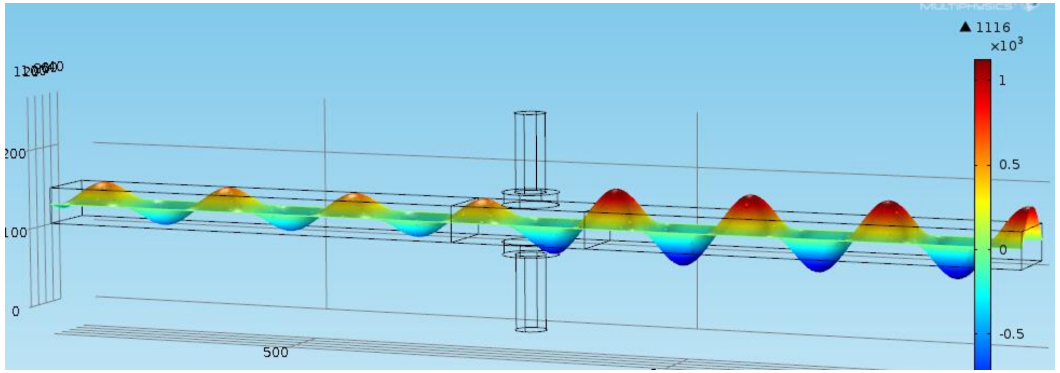
- **Funded by ARPA-E**
- **Tasked to make modular, on-demand, ammonia synthesis at atmospheric pressure**
- **Microwave active catalyst developed that is stable, responsive, and active at 300°C and ambient pressure**
  - Traditionally ammonia synthesis is carried out at >500 C and >200 bars
- **Microwave reactors allow for intermittent power shutdowns associated with renewable energy sources**
- **Phase II project focused on designing scaled, increased efficiency reactor**
- **Other topics: converting NG to value-add Chemicals**
  (AMO thru AIChE's RAPID institute)
- **Other topics: Coal conversation in the presence of MW**

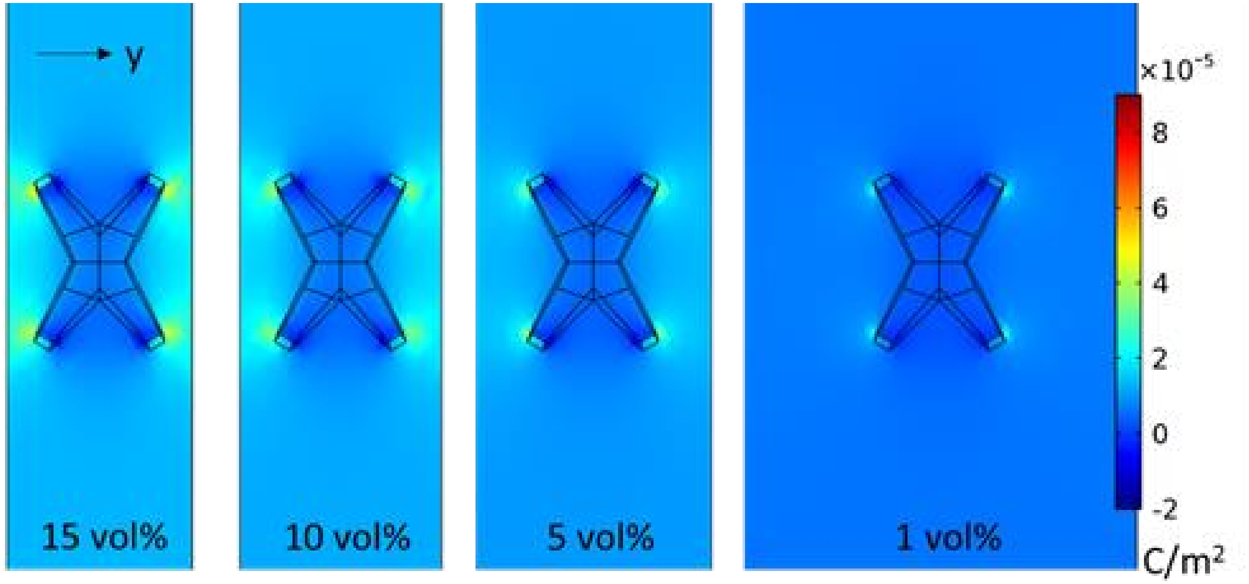


Microwave Modeling

- **Electromagnetic Field Characterization**
  - Fundamental understanding of the science behind these phenomena is needed for an optimal design of an efficient microwave system for conversions
- **Microwave + material/catalyst – fundamental interaction study**
  - Understand how the geometry and surfaces interact with the microwaves

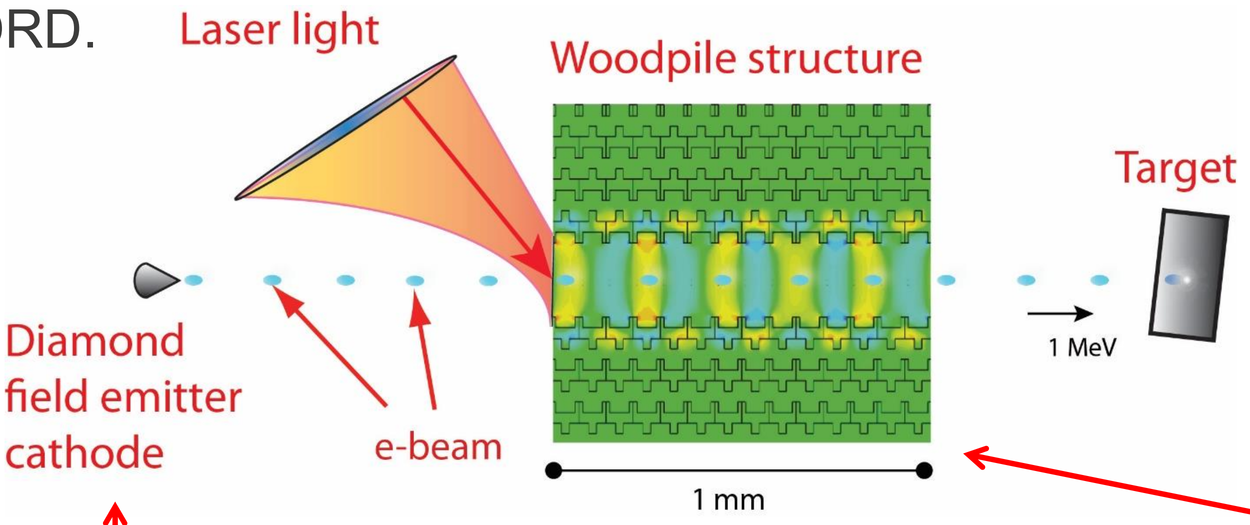
Macroscopic Electromagnetic Waveguide Interaction

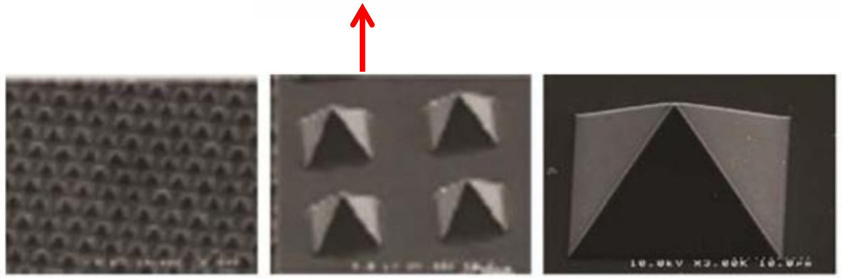


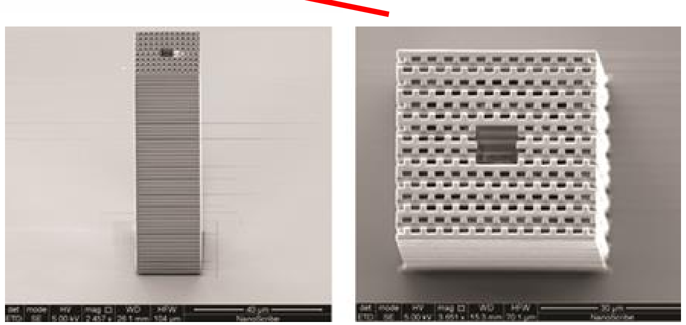


Dielectric Laser Accelerators

- Diamond field emitter array cathodes and additive manufacturing technologies developed at LANL lead to practical demonstration of dielectric laser accelerators (DLAs).
- Ultra-compact DLAs for the national security missions sponsored by LANL LDRD.







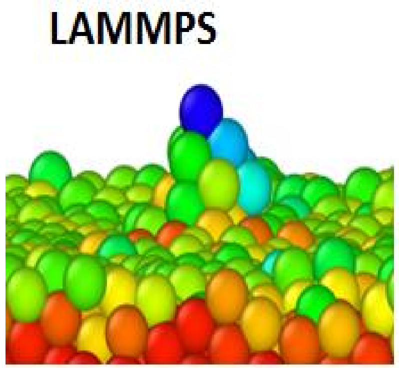
E. Simakov

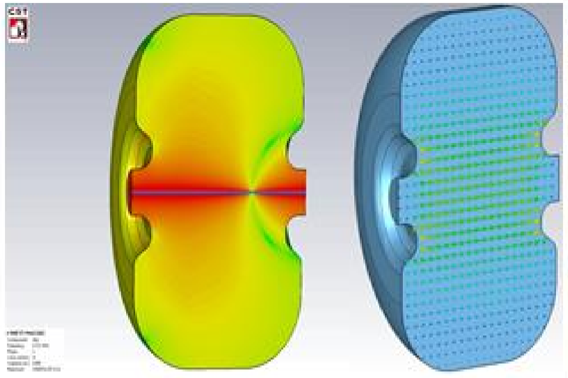
C-Band Ultra-High Gradient Activities

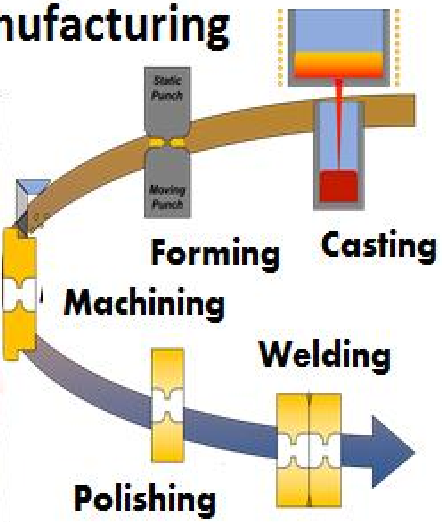
Multi-disciplinary effort on RF-technology for ultra-high gradient (< 100 MV/m) and long pulse operation (funded through FY22)

- Molecular dynamics simulation tools to custom design materials for suppression of RF-breakdown
- Advanced manufacturing compatible with material properties
- Cryo-cooled operation for long pulse operation > 10 μs

Material Science + RF Engineering + Advanced manufacturing





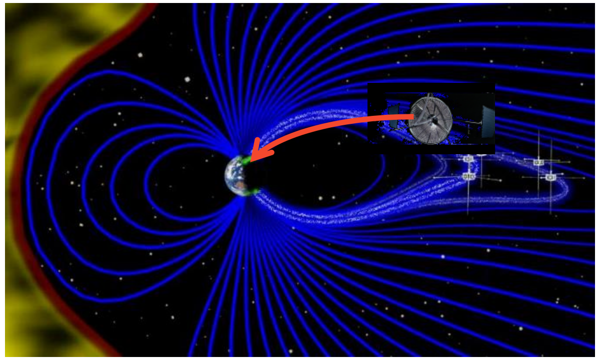


LANL applications

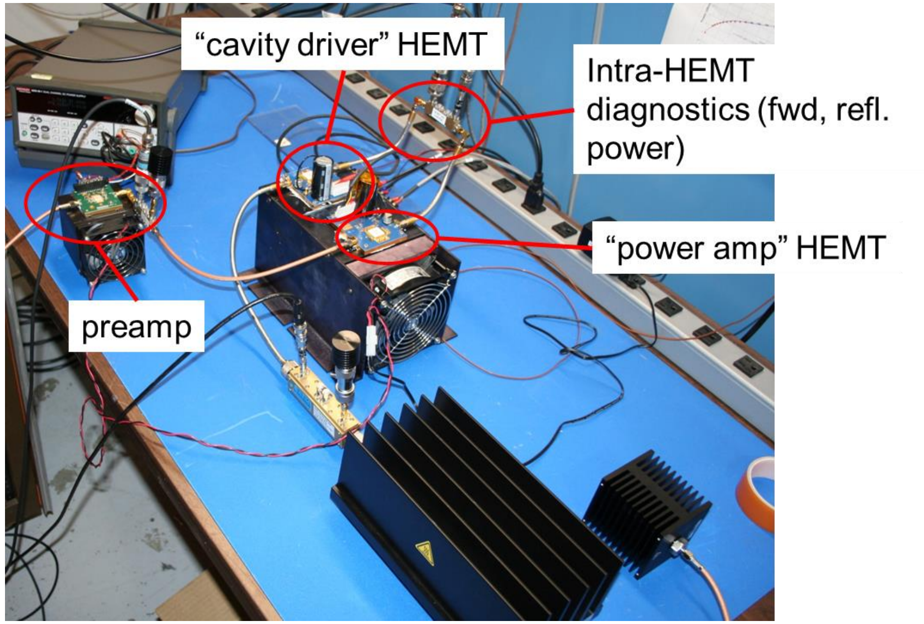
- Ultra-high gradient operation to meet DMMSC needs with an XFEL
- Reduced-β structures for modernization of LANSCE and 20 GeV pRAD
- Compact accelerators for defense applications (e.g ICS for SNM detection)
- Establish permanent test beamline for technology development

F.L. Krawczyk

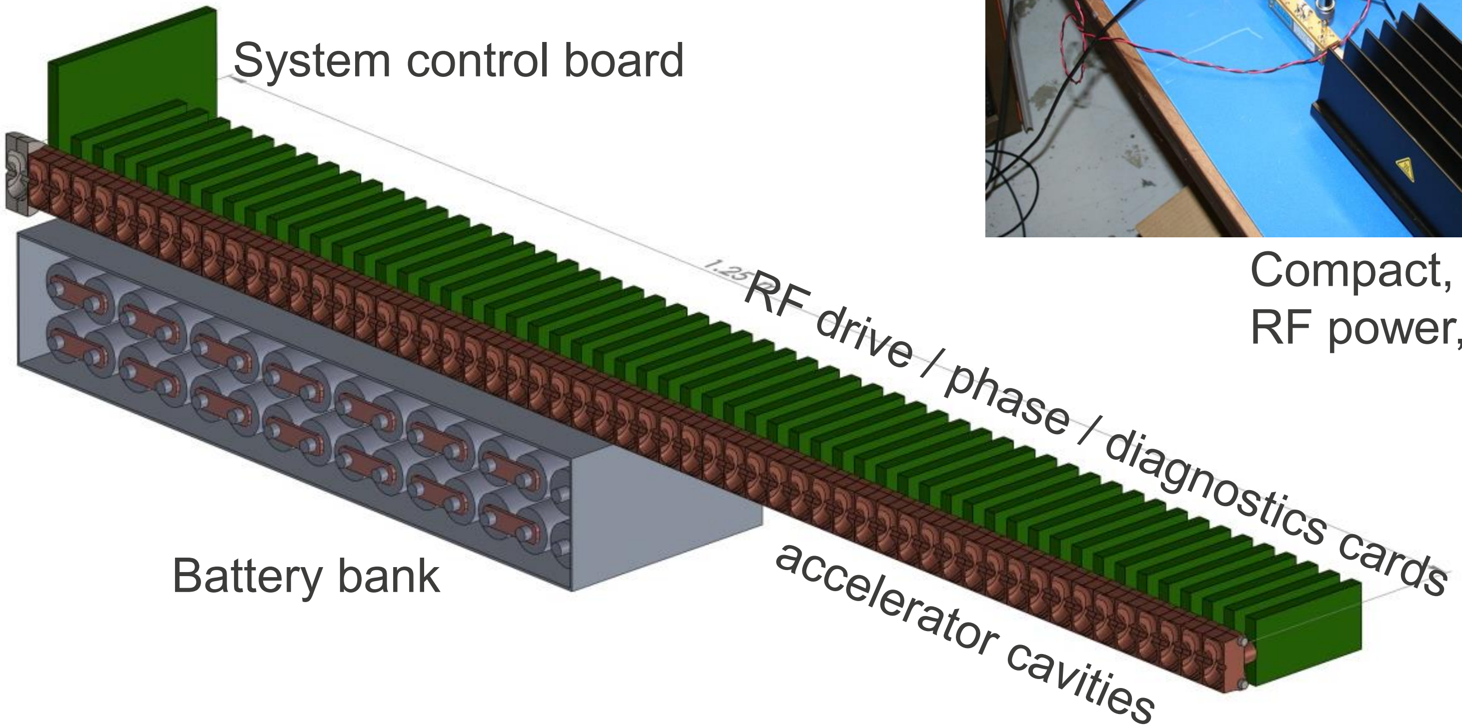
Accelerators in Space



Artificial Aurora: Mapping the Magnetotail



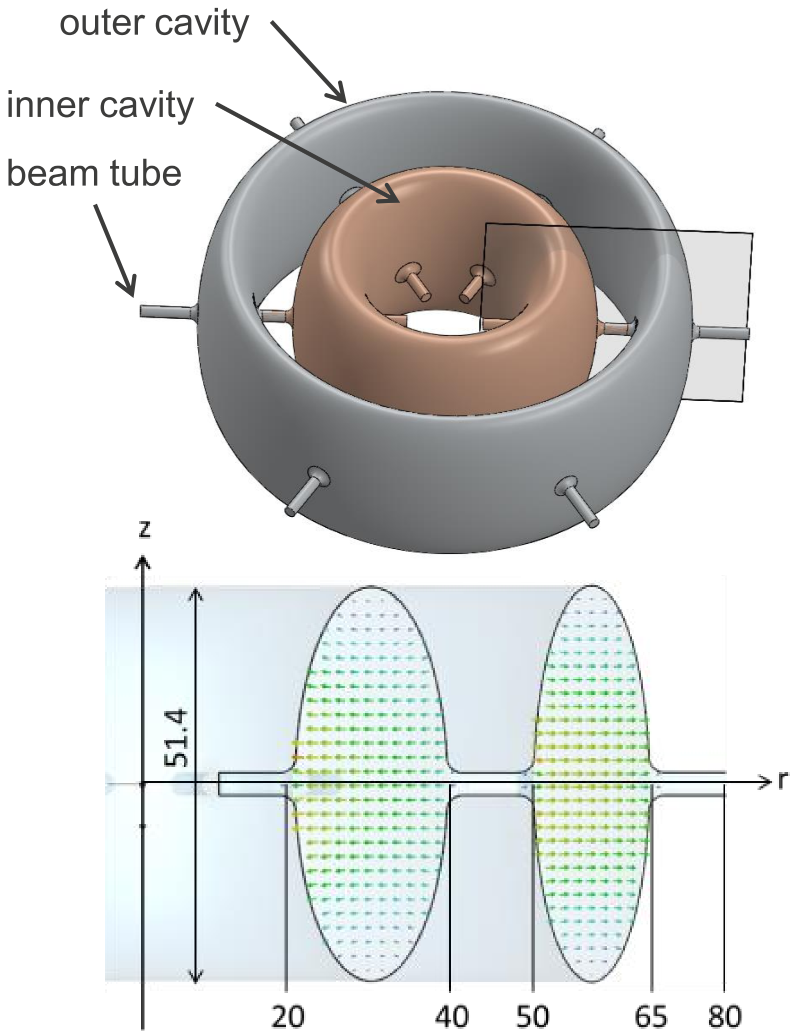
Compact, high-power C-band RF power, running at 50 VDC



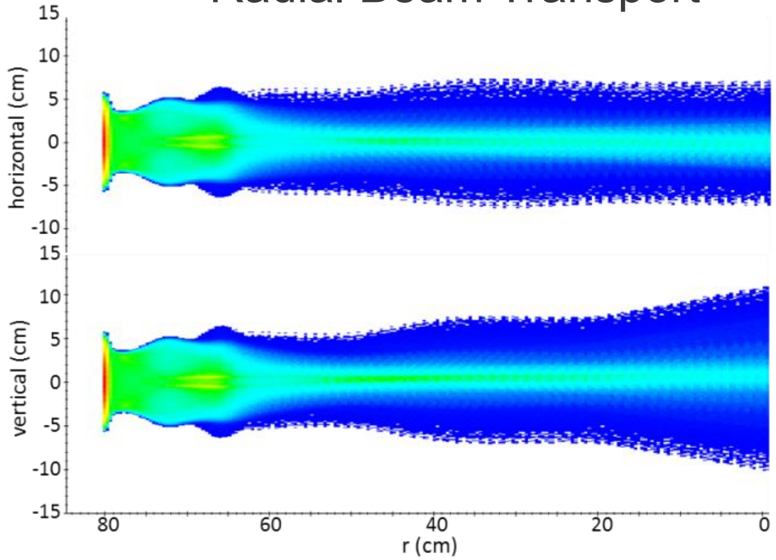
D.C. Nguyen & J.W. Lewellen

Radial Accelerators for Waste Treatment

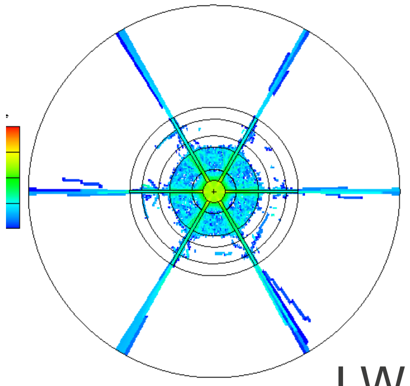
Toroidal cavities



Radial Beam Transport



"self-shielding" structure design



J.W. Lewellen & J.R. Harris

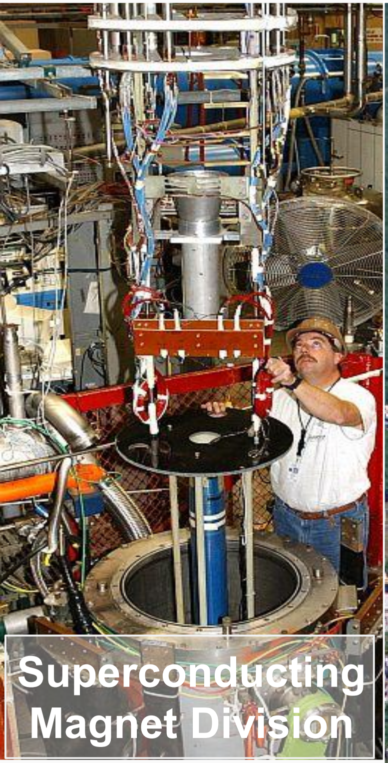
Industrial Support with the BNL Accelerator Complex

Accelerator Science & Technology Initiative

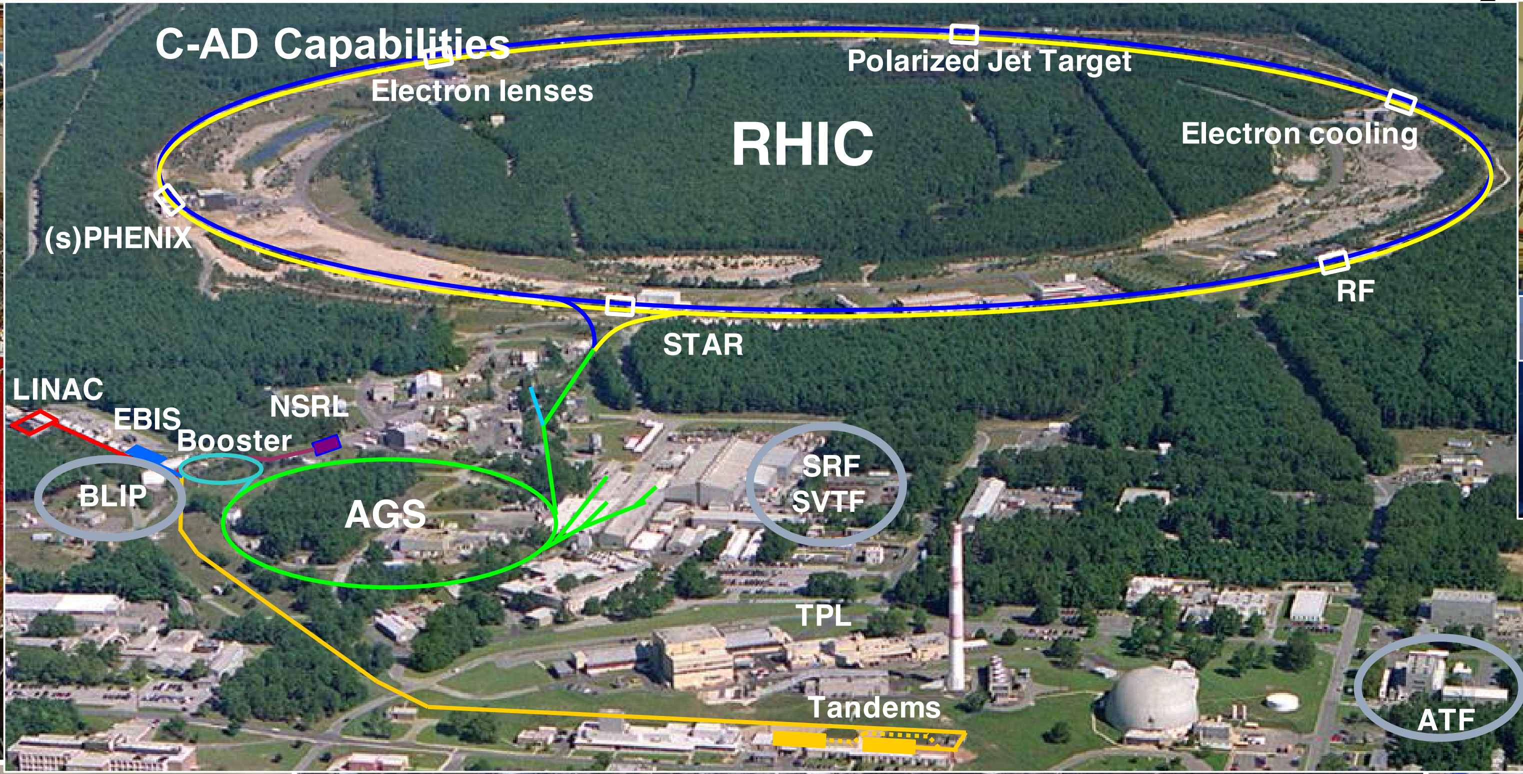
BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

The BNL Suite of Accelerator Capabilities



Superconducting Magnet Division

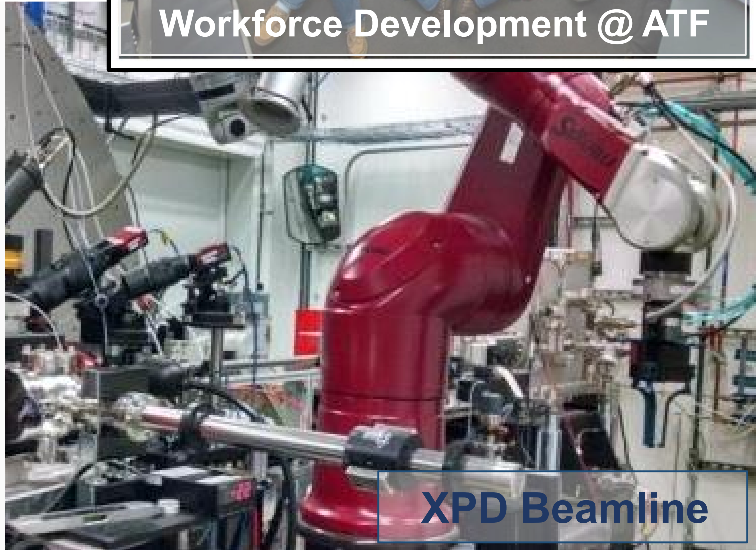


NASA Space Radiation Laboratory

Workforce Development @ ATF

Brookhaven Linac Isotope Producer

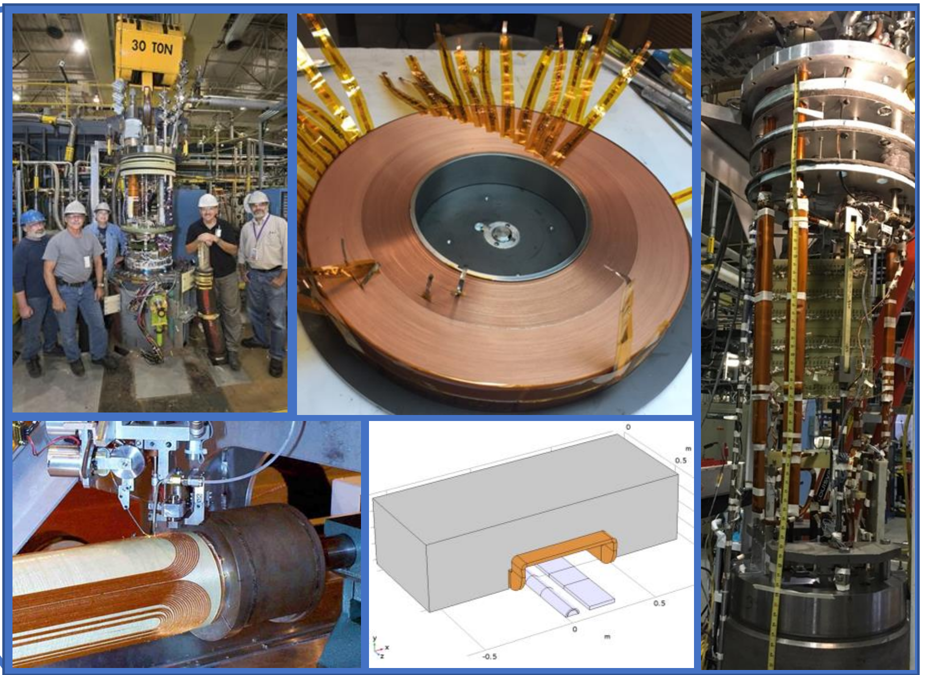
NSLS-II

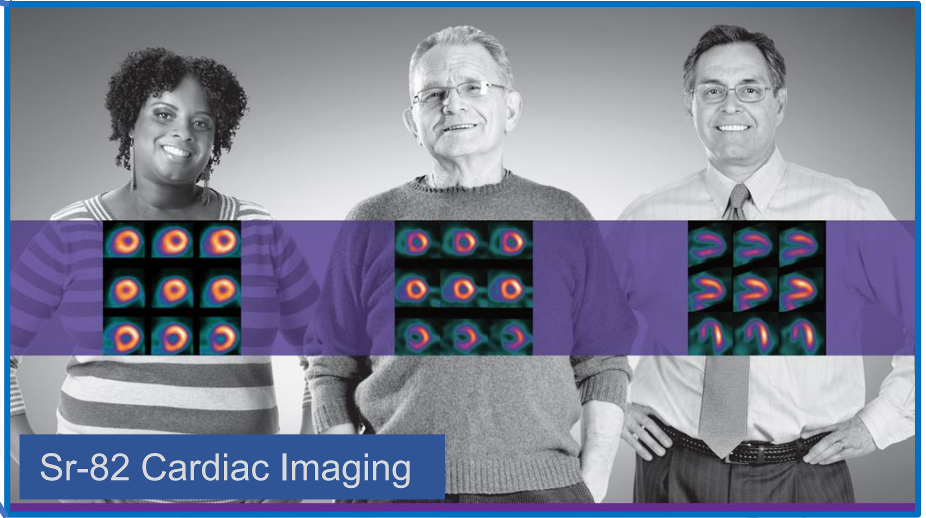


XPD Beamline

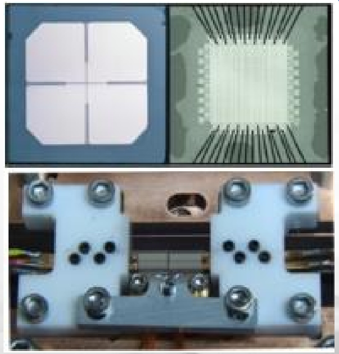
BNL Accelerator Technology Supporting Industry

- Superconducting Magnet Division
  - Magnet design and conductor development capabilities:
    - Wind generator technology
    - Fusion magnet technology
    - HTS cable development and testing
    - Magnetic energy storage
    - Medical magnet design
- Brookhaven Linac Isotope Producer
  - Medical isotope production
  - High dose irradiation testing capabilities
    - Reactor materials (fusion, molten salt,…)
    - Microstructural analysis capabilities at NSLS-II
- Instrumentation Division
  - Detector, data acquisition, and photocathode development for accelerator-based applications



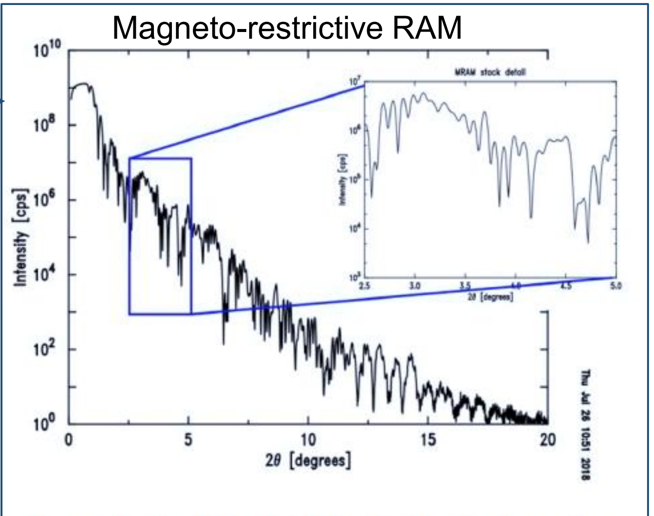


Diamond x-ray BPM

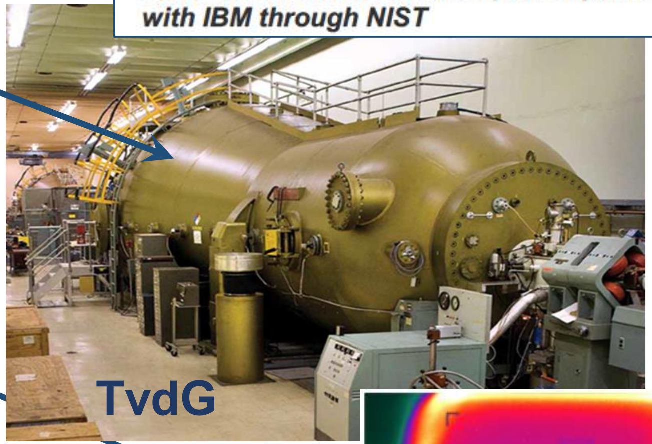


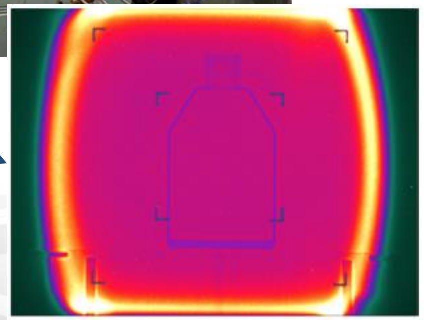
BNL Electron and Ion Beams Supporting Industry

- NSLS-II
  - Supporting a broad industrial community studying material structure
  - XPD beamline provides remote handling capabilities that can characterize highly irradiated materials from BLIP
  - Serving ~30-50 companies/year
- ATF - the US DOE Accelerator Stewardship User Facility
  - Supporting advanced accelerator/laser science & technology R&D
  - A laboratory gateway for advanced accelerator technology partners
- Tandem van de Graaff (TvdG)
  - Supporting ion implantation, electronics testing, track-etched filter fabrication, and High T Superconductor enhancement for industry
  - Serving ~20 companies/year
- NASA Space Radiation Laboratory (NSRL)
  - Supporting space irradiation studies, cancer therapy and electronics testing with ions from H to Au
  - Serving ~30 companies/year
- High Energy Proton Radiography with the BNL AGS
  - Offers unique probing capability to characterize dynamic processes in industrial devices
- Accelerator Center for Energy Research
  - Offers tools to study energy conversion processes and radiolysis effects (e.g. for reactor materials)



Jean Jordan-Sweet (IBM): 1st results from the XRD endstation at BMM, as part of partnership with IBM through NIST





https://www.bnl.gov/accelerators/

BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

Accelerators at Brookhaven Lab

Tools for Innovation

Brookhaven National Laboratory is home to a suite of particle accelerators and sophisticated accelerator-based test facilities—tools for innovation and discovery in fields as diverse as medicine, materials science, electronics production, and national security. We encourage academic and industrial partners to collaborate with our scientists. Draw on our 70+ years of expertise to develop and test new concepts, techniques, and technologies while pursuing your own basic and applied research or industrial goals. And if you're in the business of developing skilled professionals, accelerator facilities are an excellent training ground for the next generation of technology experts.

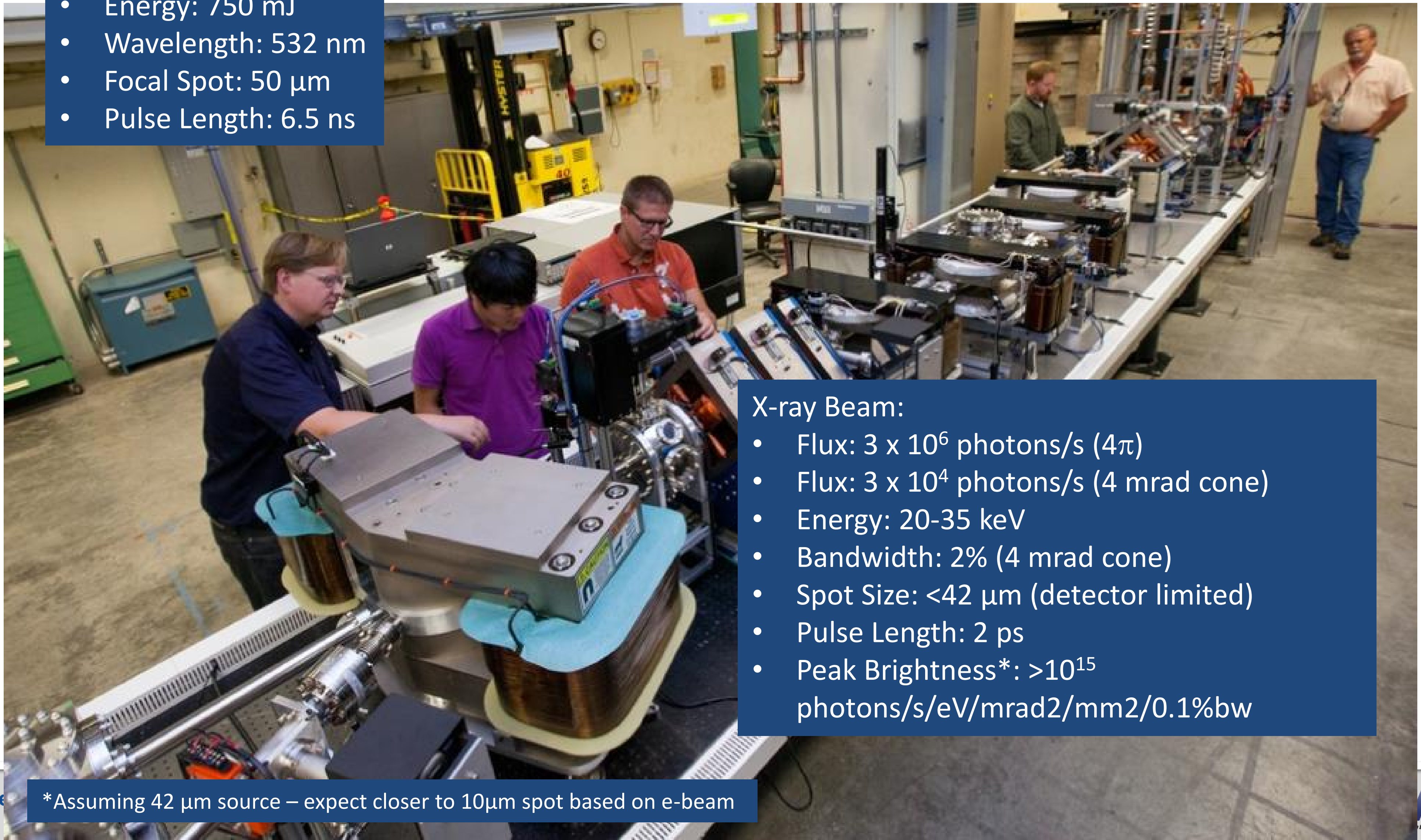
Our accelerator capabilities and technology experts are here to support you. **Contact Us**

LLNL has a number of accelerator capability and effort areas spanning a variety of technologies

- RF driven accelerators (light ions, electrons)
  - Neutron imaging
  - PRISM
  - Megaray
  - B194 e linac
- Linear induction accelerators and pulsed power (electrons)
  - FXR
  - Scorpius
- Pulsed power driven pinch devices for neutron production (ions)
  - DPF
- DC machines and tubes (ions)
  - CAMS

Megaray – a laser Compton backscatter source driven by an X-band traveling wave linac

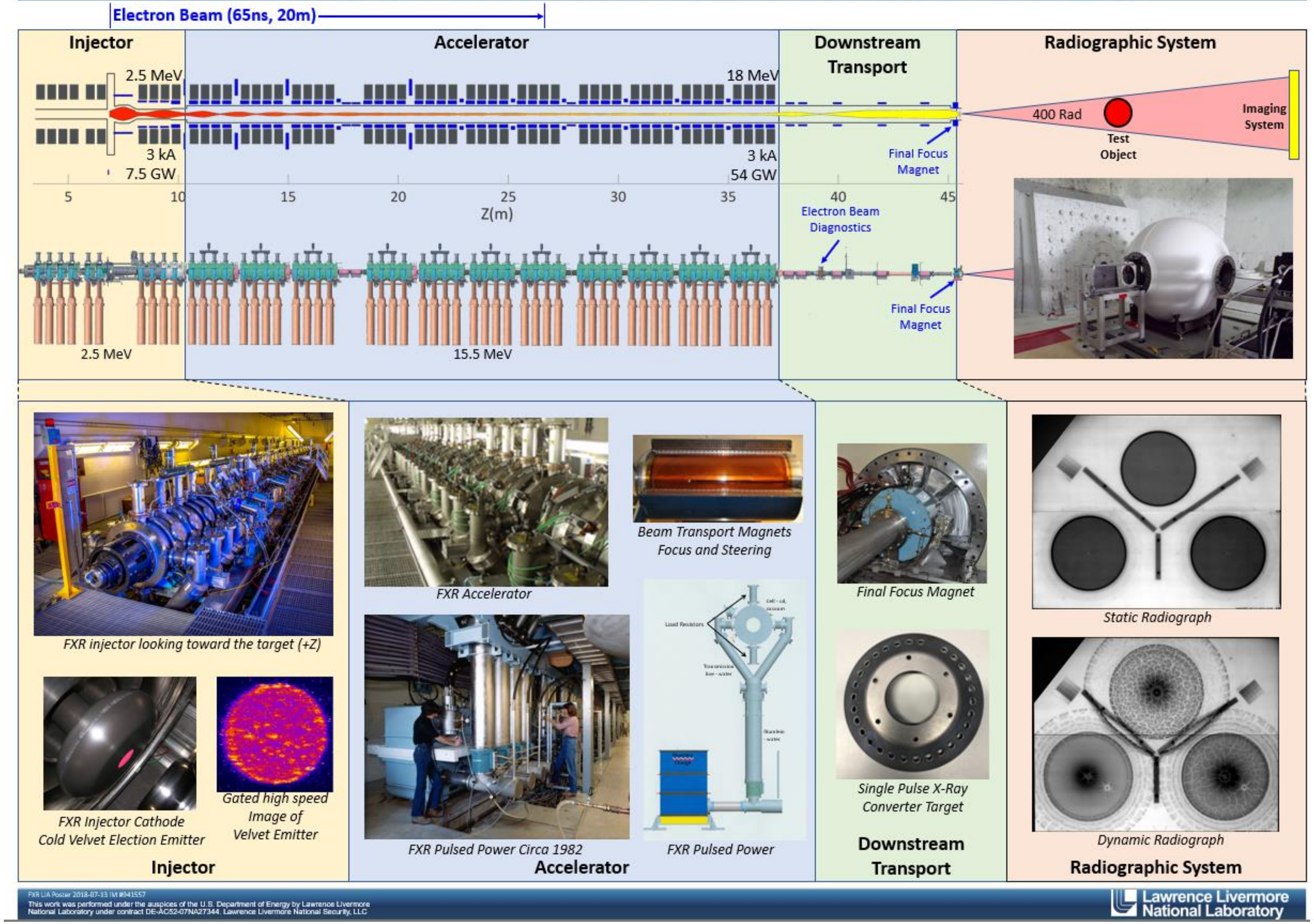
Interaction Laser:
- Energy: 750 mJ
- Wavelength: 532 nm
- Focal Spot: 50 µm
- Pulse Length: 6.5 ns



X-ray Beam:
- Flux: 3 x 10^6 photons/s (4π)
- Flux: 3 x 10^4 photons/s (4 mrad cone)
- Energy: 20-35 keV
- Bandwidth: 2% (4 mrad cone)
- Spot Size: <42 µm (detector limited)
- Pulse Length: 2 ps
- Peak Brightness*: >10^{15} photons/s/eV/mrad2/mm2/0.1%bw

*Assuming 42 µm source – expect closer to 10µm spot based on e-beam

The High Current Linear Induction Accelerator (LIA) Delivers the Flash X-Rays (FXR) Required for Dynamic Radiographic Imaging



Short-pulsed neutron sources (dense plasma focus/DPF)

MJOLNIR (MegaJOuLe Neutron Imaging Radiography) DPF being developed for flash neutron radiography

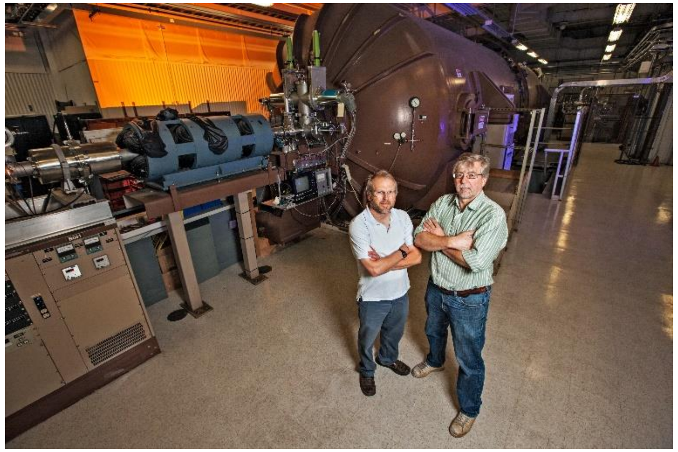
- First plasmas August 2018
- Deuterium only operation to-date, up to 4e11 yield
- 1 MJ installed pulsed power allows for operating currents of 1.5 to 2.7 MA
- Pulsed power upgrade will allow for 4+ MA
- LLNL can use help in transient high-voltage testing of insulating materials, and interferometer/diagnostics deployment

Center for Accelerator Mass Spectrometry

Unique Facilities

Central instrument 10 MV FN accelerator- provides unsurpassed technical AMS capability and has dedicated ion beam analysis and nuclear physics beamlines.

High energy ion implantation capability is a DOE NE supported Nuclear Science User facility (NSUF).

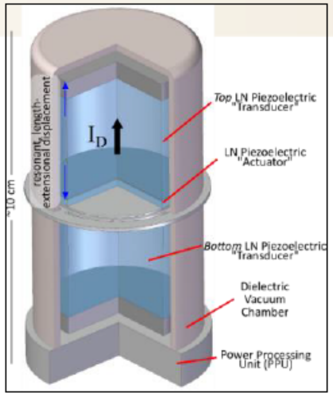


NIH supported National Resource for Biomedical AMS BioAMS spectrometer

Dedicated ^{14}C spectrometer for carbon cycle applications

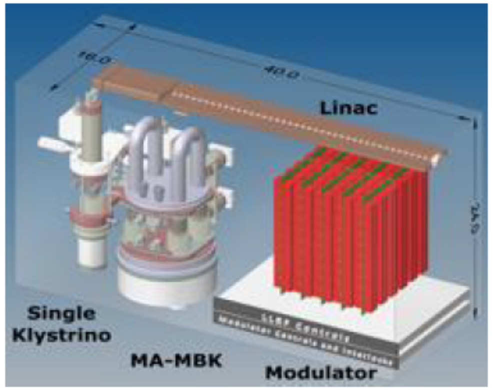
Nuclear microprobe for ion beam (micro)analysis

Examples of Programs based from various accelerator technologies and capabilities

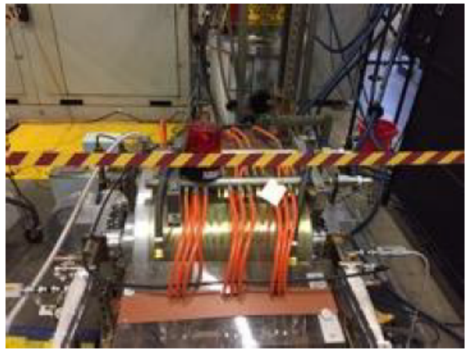


VLF Antenna: **(DARPA)**

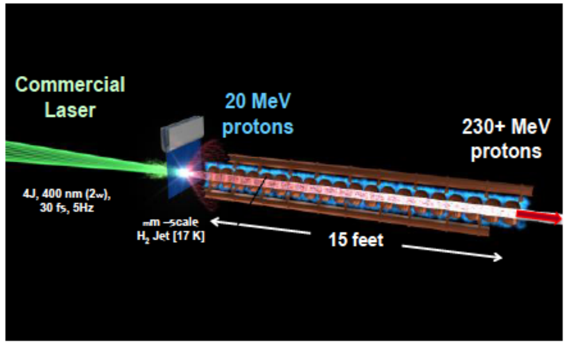
5G evolution (mm wave): (**Major Telecom)**



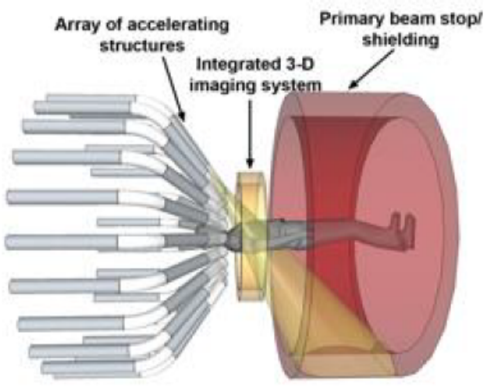
Compact rf/accelerators for active interrogation:
Dept. of Homeland Security/DNDO and NNSA/NA-22



Circulator: (**Varian**)



Compact protons/ion acceleration:
(DOE FES, NNSA, Pharm Co., DOE HEP)



PHASER: (**SU School of Medicine**)

Accelerator Stewardship work

Design of High Efficiency High Power Electron Accelerator Systems Based on Normal Conducting RF Technology for Energy and Environmental Applications

Design Study Report

SLAC National Accelerator Laboratory

SLAC NATIONAL ACCELERATOR LABORATORY

Valery Dolgashev(PI), Sami Tantawi

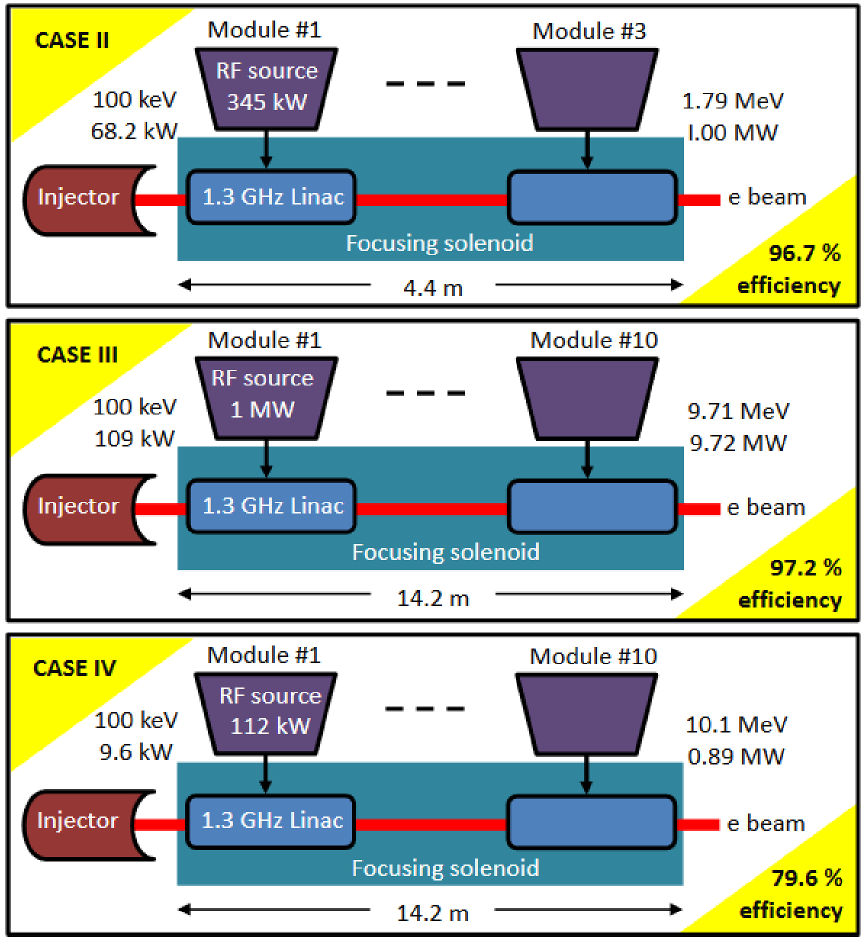


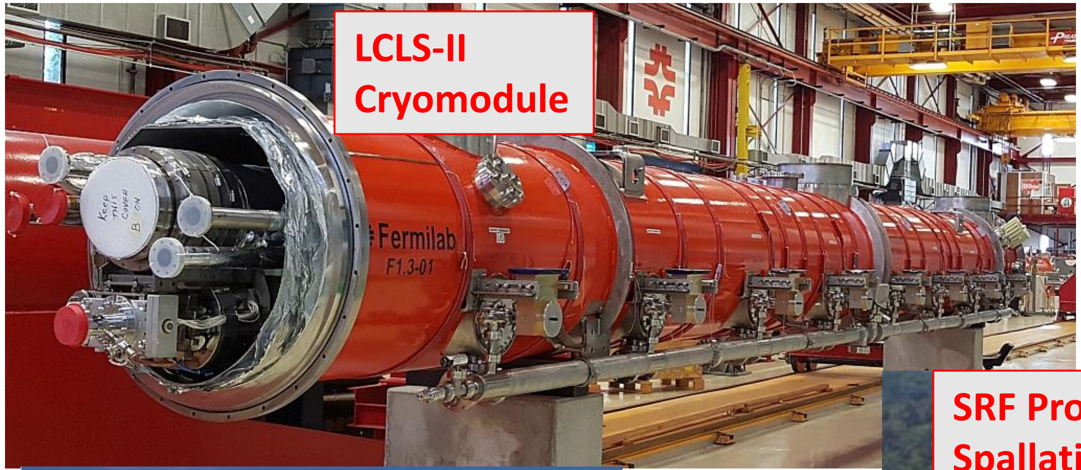
Figure (I): *Layouts of the three extremely high efficiency L-band linacs for energy and environmental applications based on normal conducting radio-frequency technology.*

https://www.osti.gov/servlets/purl/1441166

Superconducting Radio Frequency (SRF)

~ All new high beam power accelerators for discovery science employ SRF

- Why?
  - Because ~all RF power → beam power vs heating RF resonators
  - SRF➔ Higher gradient, more energy per unit length
- But current SRF “science” accelerators are large and complex



LCLS-II
Cryomodule

FNAL FAST ILC
cryomodule with RF

SRF Proton Linac
Spallation Neutron Source at ORNL

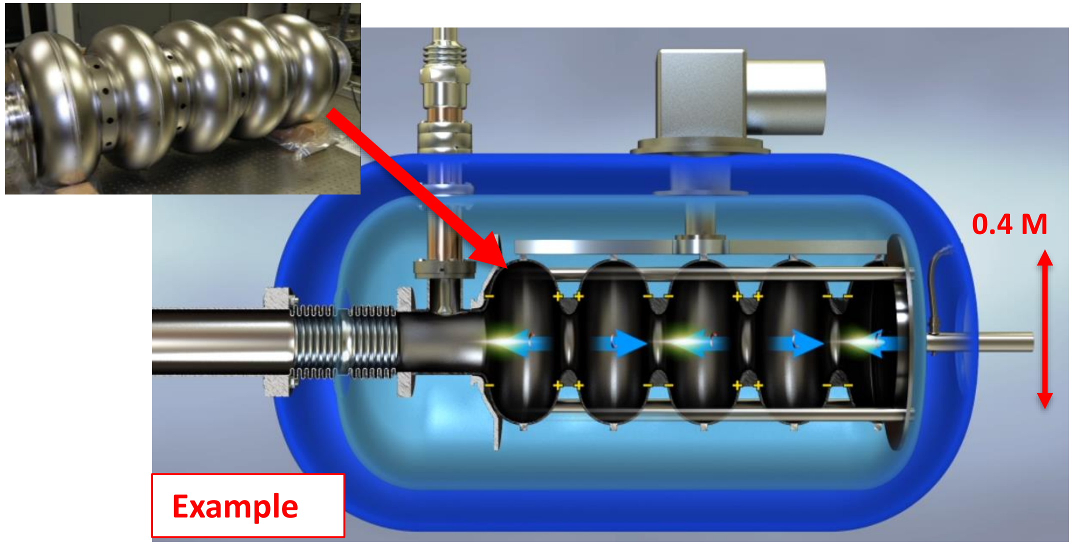
CBEAF CW
electron linac
2 K cryoplant

Recent SRF Technology Breakthroughs:

- Higher temperature superconductors: Nb_3Sn coated cavities dramatically lower cryogenic losses and allow higher operating temperatures (e.g. 4 K vs 1.8 K)
- Commercial Cryocoolers: new devices with higher capacity at 4 K enables turn-key cryogenic systems
- Conduction Cooling: possible with low cavity losses➔ dramatically simplifies cryostats (no Liquid Helium !)
- New RF Power technology: injection locked magnetrons allow phase/amplitude control at high efficiency and much lower cost per watt
- Integrated electron guns: reduce accelerator complexity

- **Enable compact industrial SRF accelerators at low cost**

Ideas integrated into a simple SRF accelerator



Final machine parameters

- Energy: ~ 10 MeV
- Power: 250 kW – 1 MW
- Compact
- Simple, reliable
- Affordable

- 650 MHz elliptical cavity (well understood from PIP-II)
- Modular design scales to MW class industrial applications

Recent news: *Design and demonstration of an economical SRF structure for Continuous Wave (CW), high-energy, Megawatt-class beams*", $370 K
PI: Dr. Dhuley (FY 2020 – FY 2021)

Many emerging areas that SRF accelerators can add value

Thank you…..

- Accelerator R&D work is active across the DOE labs and will continue to apply frontier technologies that are currently powering science for industrial and innovative applications……