Synergies with NNSA Applications

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Operated by Triad National Security, LLC for the U.S. Department of Energy's NNSA

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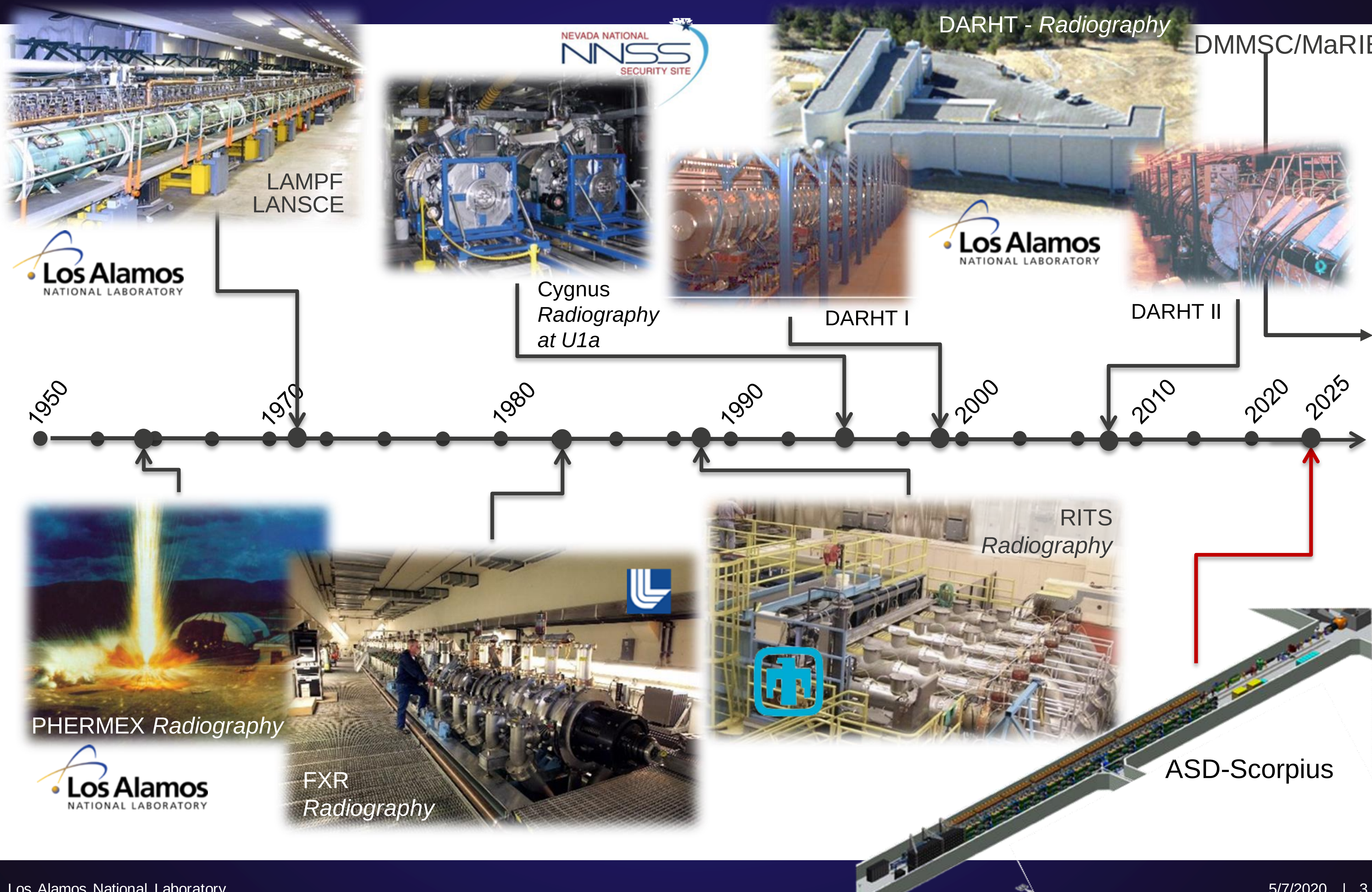
Outline

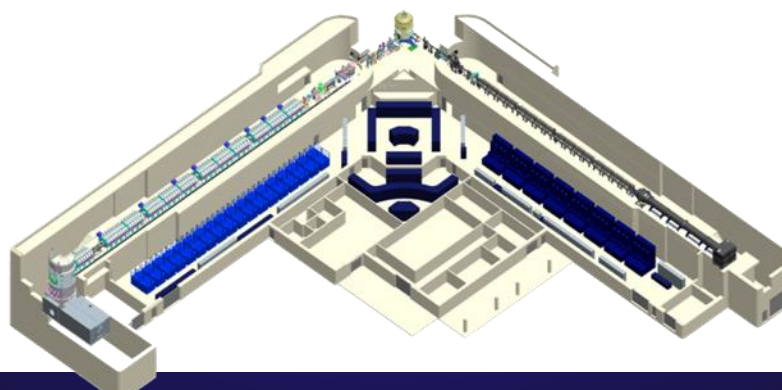
- Drivers behind NNSA accelerator needs
- DARHT and Scorpius – induction accelerators for hydrotest radiography
- LANSCE and pRad
- DMMSC/MaRIE X-ray Free-Electron Laser
- Compact electron accelerators
  - Space accelerator technology
- Compact neutron sources

Accelerators have long been used to support the core NNSA mission



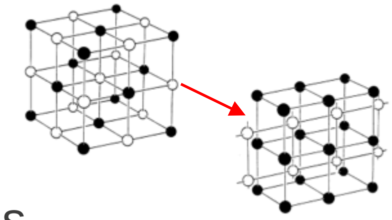
The core NNSA mission needs accelerators as tools for:

- Control the performance and the production of materials vital to national security missions.
- Diagnose dynamic experiments in weapon configurations with nuclear and surrogate materials that meet the (classified) requirements of nuclear weapon designers.
- Obtain nuclear data for stockpile assessment, forensics, criticality analysis, and radiochemistry.
- Develop next-generation predictive physics models used to assess and certify the present and future stockpile with low uncertainty and high confidence.
- Address emerging stockpile stewardship challenges and global nuclear threats.

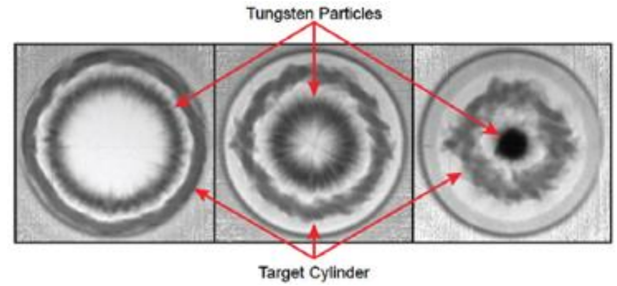


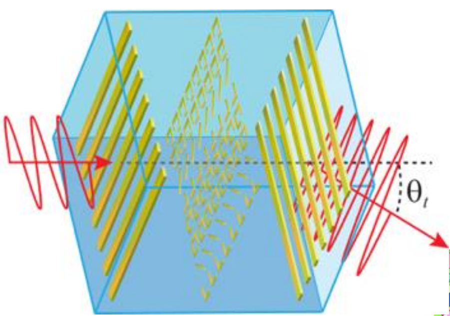
To address these materials science needs requires the ability to interrogate at vastly different time scales

ps – ns
Metastable electronic states

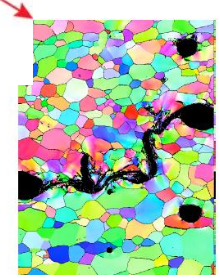


ps – 100 ns
Phase Transformations

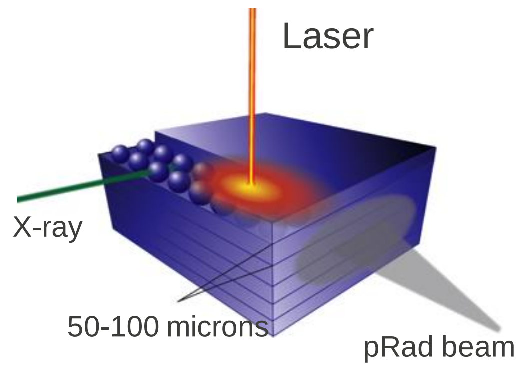




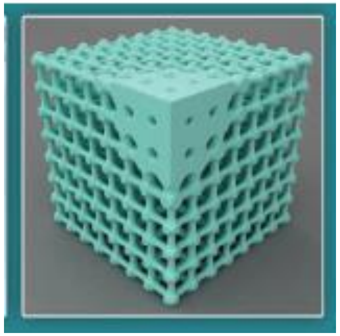
ns – 100 ns
Shock transit across grain; Hydrodynamic instability



100 ns – 10 μs
Shock transit across sample



10 μs – 1 ms
Thermal pulse evolution

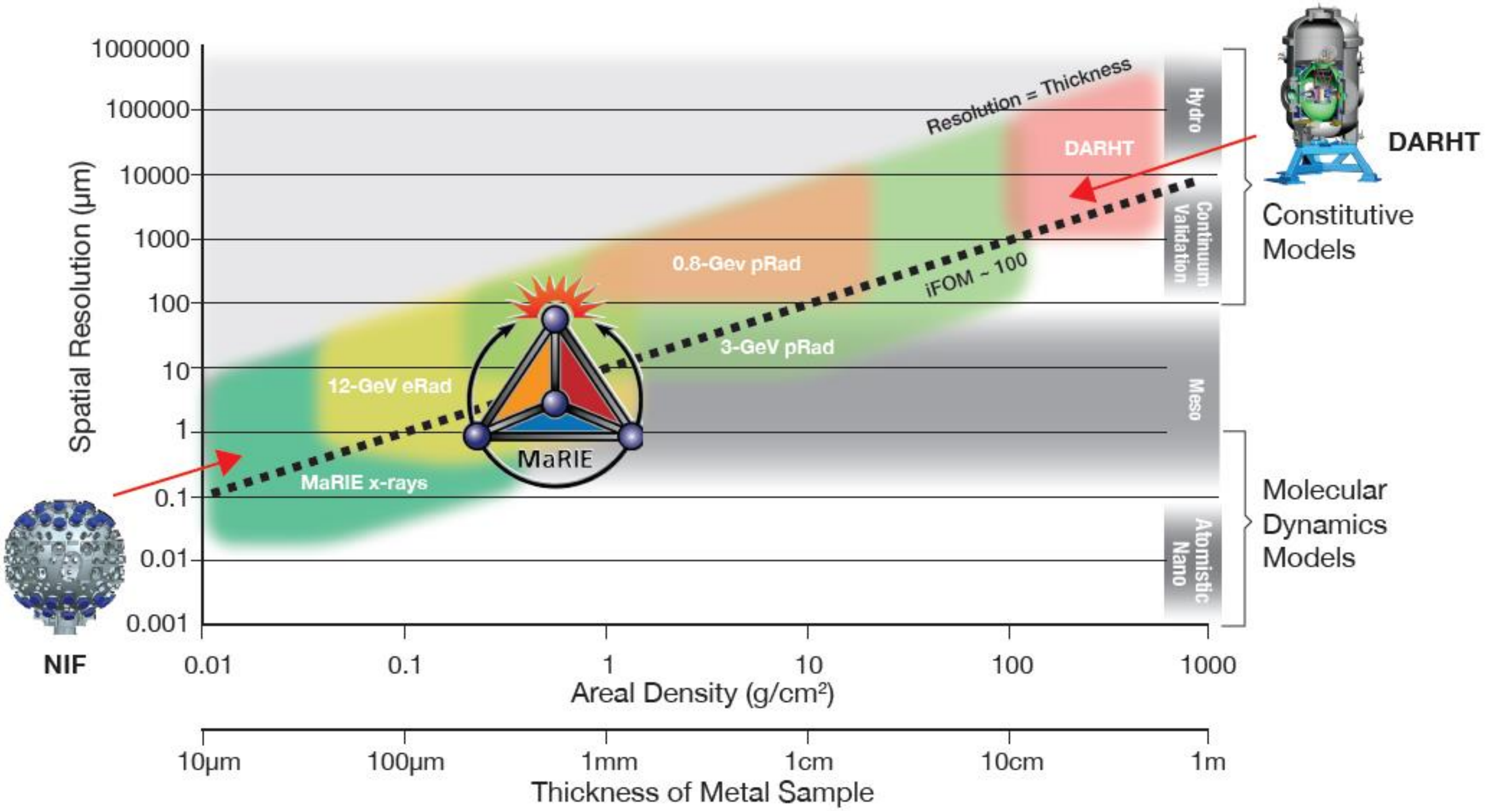


10 s – 10 hour
Additive manufacturing build

months – years
Aging effects

Key Requirement: a flexible linear accelerator pulse structure that can span from electronic/ionic (sub-ps) through acoustic (ns) to shock transit across samples (μs) to thermal (ms) to manufacturing (secs and above) event time scales

Current and future accelerators span the needs of the core NNSA mission



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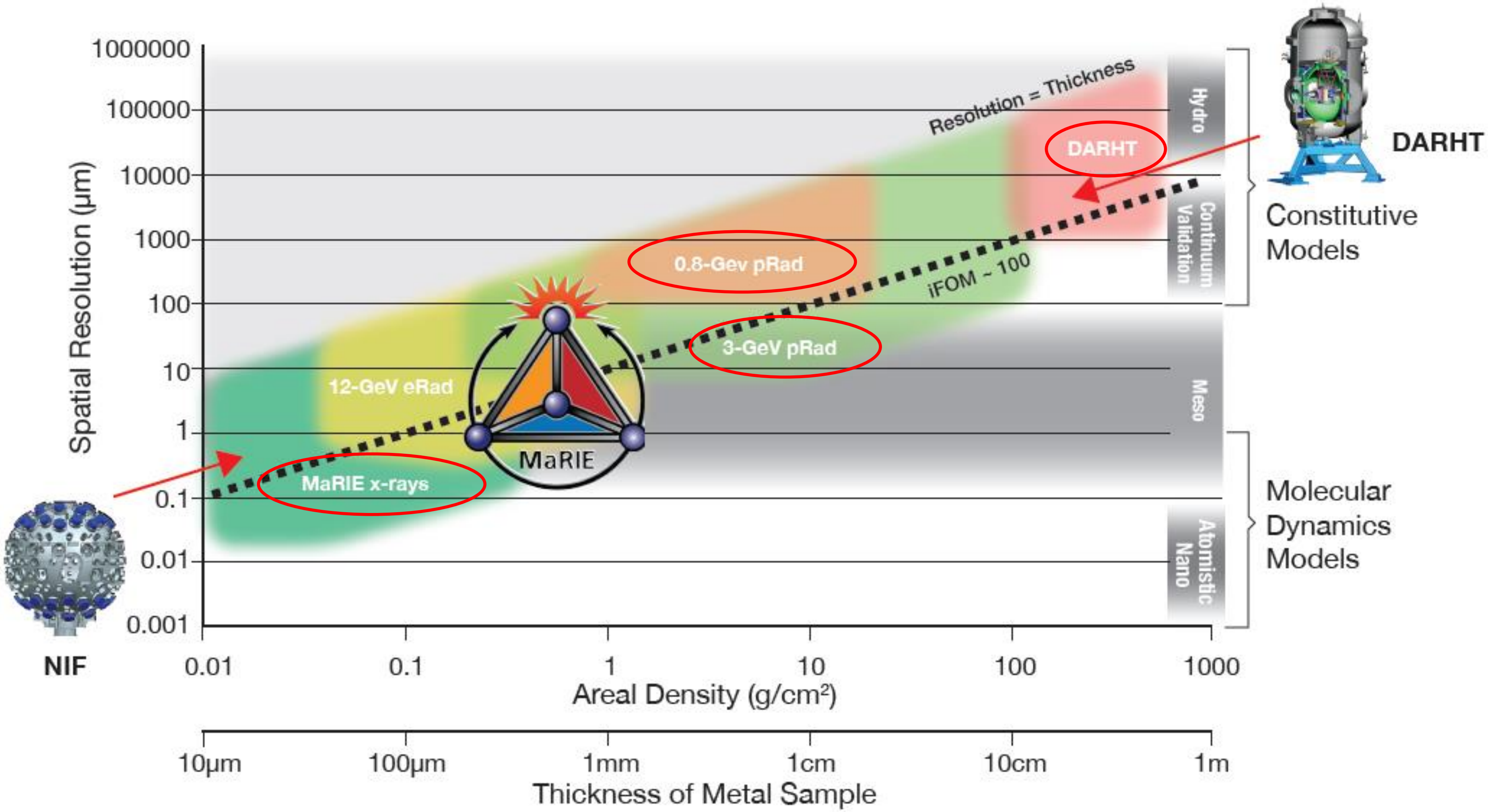


DARHT/Scorpius are fast radiographic tools

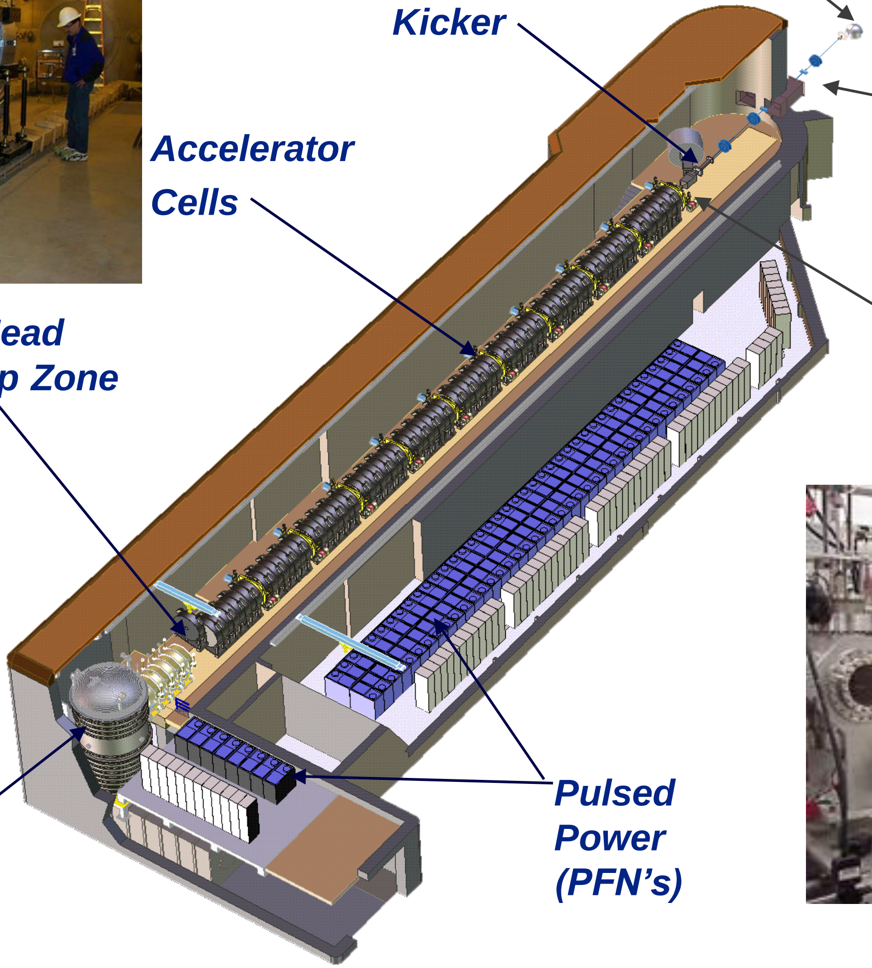

Aerial view of DARHT

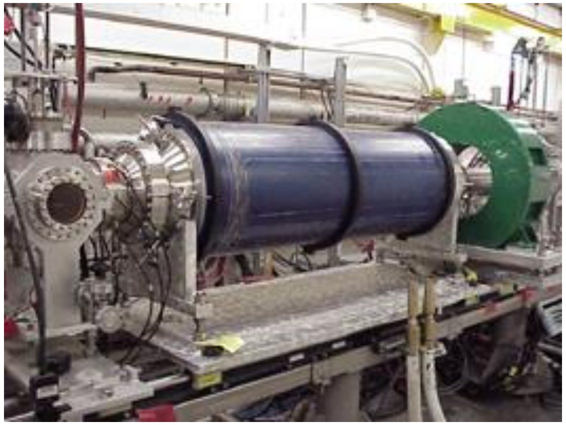

A “hydrotest” on the operational first axis of DARHT

DARHT is the premiere US radiographic hydrotest facility

- **Flash radiography measurements require 3 essential capabilities :**
  1. ***high-resolution***
  2. ***multiple-views (3D reconstruction)***
  3. ***multiple times (dynamic code benchmarking)***
- **DARHT is the first U.S. facility providing these capabilities :**
  1. ***high-resolution (0.2-mm - 0.5-mm rms edge location)***
  2. ***multiple-views (2-axes, can be simultaneously viewed)***
  3. ***multiple-times (single-pulse 1st axis, 4-pulse in 2-μsec 2nd axis)***

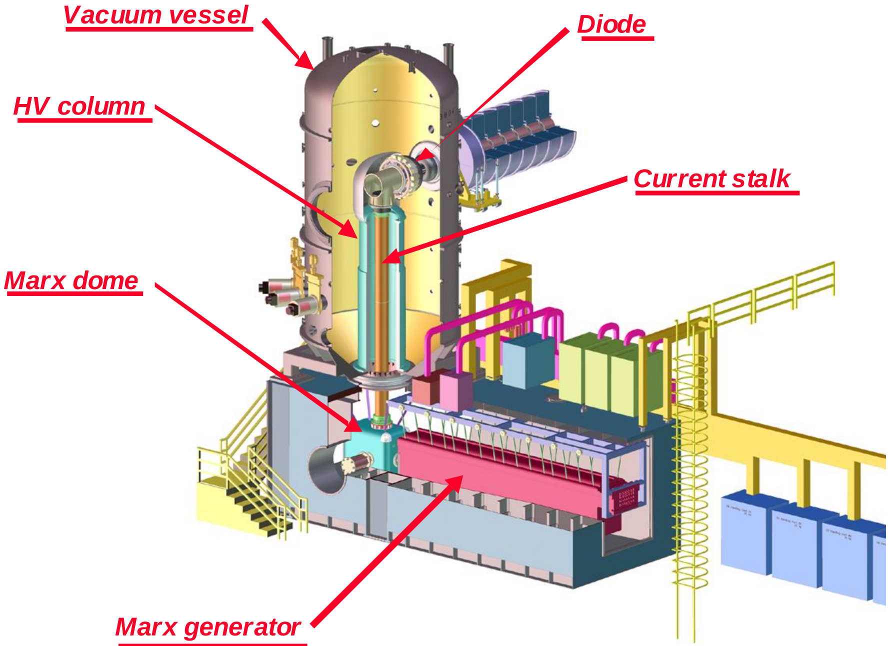
DARHT long-pulse second axis





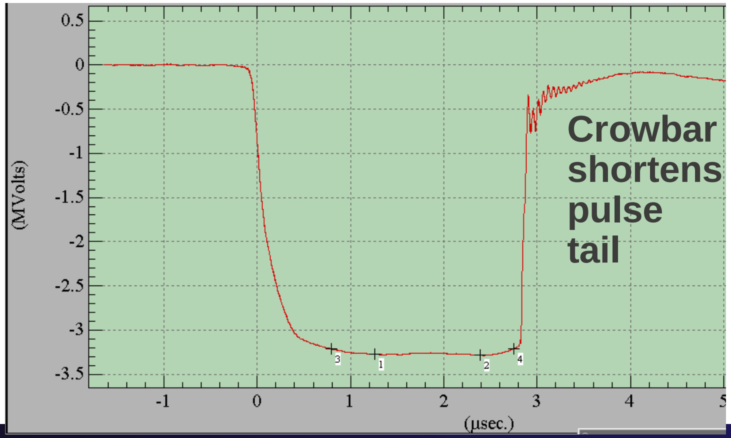
Kicker

DARHT injector



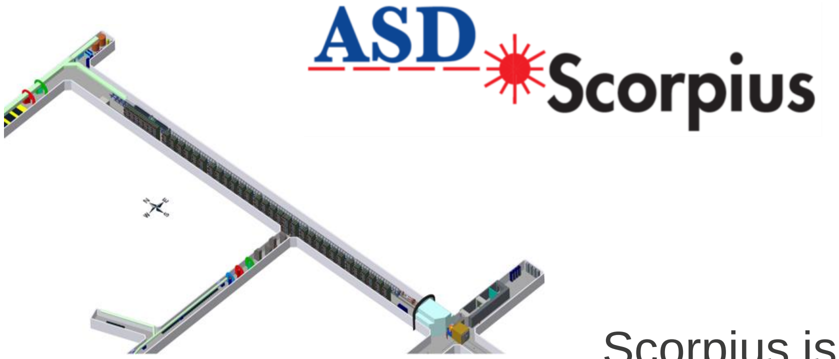
- 3.2 MeV diode
- 16.5-cm-dia. Thermionic cathode
- Marx bank with 88 type E PFN stages
- 444.5-cm tall insulating column with Mycalex and ceramic rings
- Generates beam emittance of ~ 100 μm at ~ 2 kA
- Test results indicate fully space charge limited emission, 9.4 A/cm^2, < 5% emission variation across cathode

Output into dummy load is ±1% for 2-μs

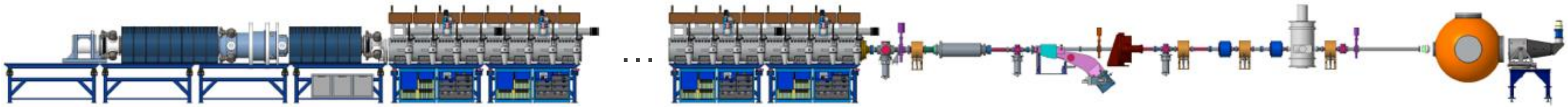


Enhanced Capabilities for Subcritical Experiments (ECSE) is developing new capabilities to diagnose subcritical experiments (~$B-class project)

2 – 2.2 MeV radiography machines (Cygnus) at the U1a Underground Complex



Scorpius is ~100 m



Injector | Accelerator Cell Blocks | Downstream Transport | Detector

Understanding the dynamic response of plutonium is critical in our continued certification of the stockpile

A new radiographic capability coupled with Neutron Diagnosed Subcritical Experiment (NDSE) measurements will fill a critical gap in experimental capabilities: the ability to measure plutonium during the final stages of implosion

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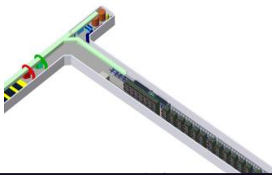


ASD Scorpius

2 -
ma
Ur

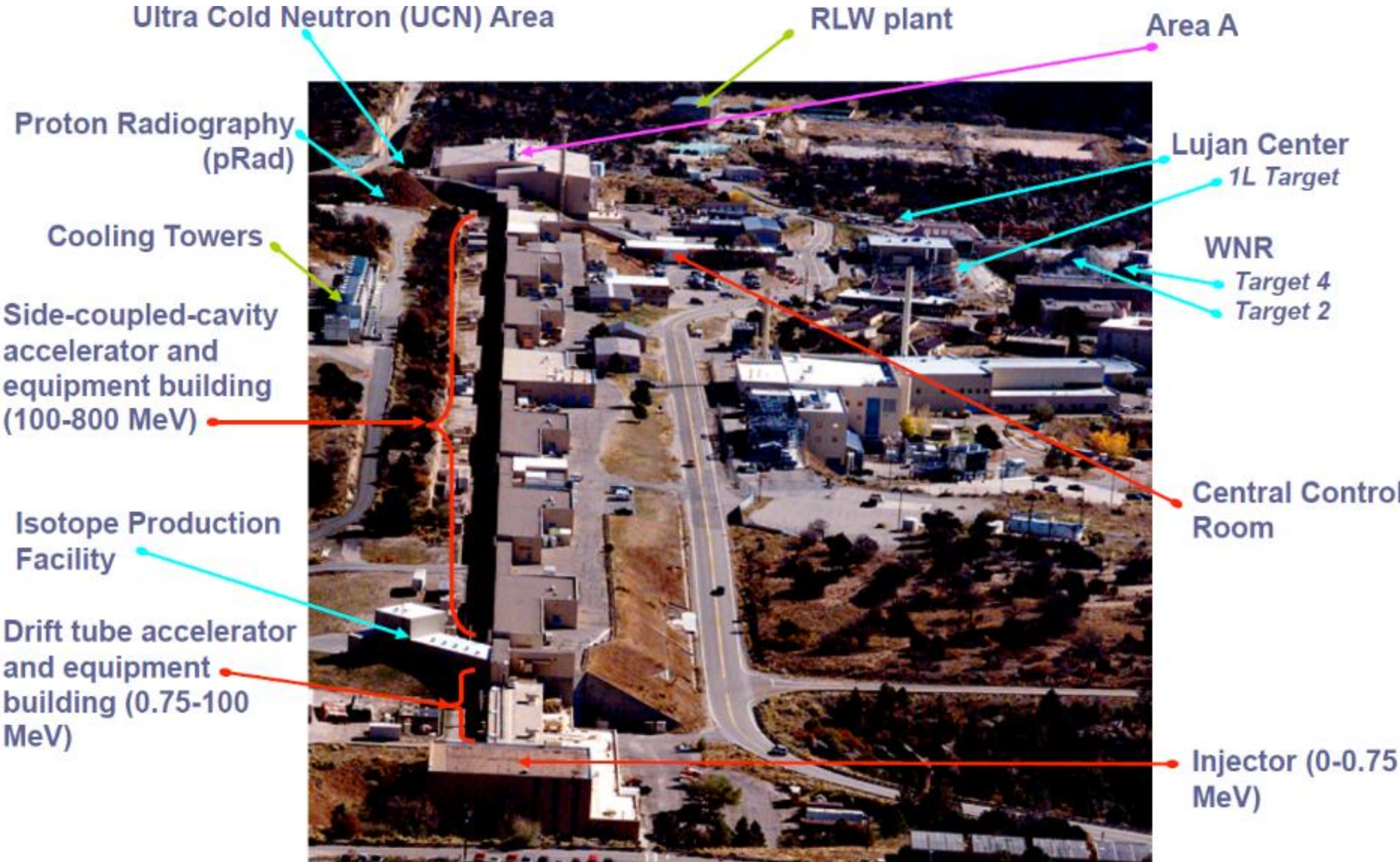
DARHT/Scorpius overlap with GARD technology development areas is small – mostly pulsed power

Other synergies may exist with other SC projects

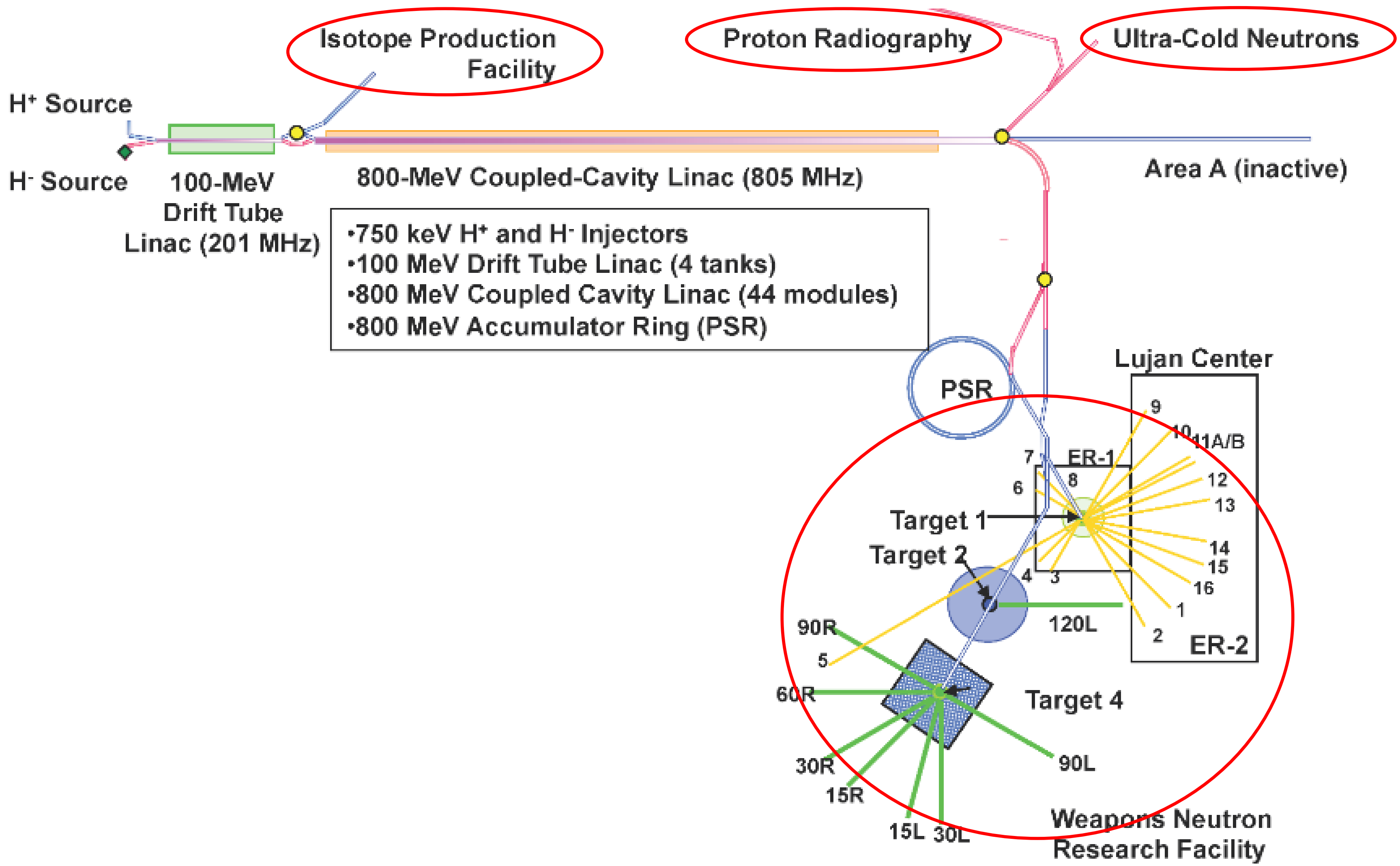
continued certification of the stockpile

A new radiographic capability coupled with Neutron Diagnosed Subcritical Experiment (NDSE) measurements will fill a critical gap in experimental capabilities: the ability to measure plutonium during the final stages of implosion

LANSCE is a km-long, 800 MeV H- and H+ accelerator



LANSCE supports > 20 active experimental stations



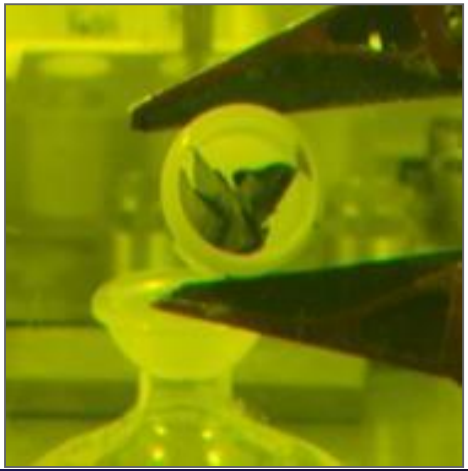
Isotope production is the only part of LANSCE running during the LANL COVID-19 reduced operations

- **The Los Alamos Isotope Program uses the proton beam at LANSCE to produce medically urgent isotopes when the commercial sector cannot meet the need**

People worldwide depend on medical isotopes for their medical needs (with a $10B/year global market):

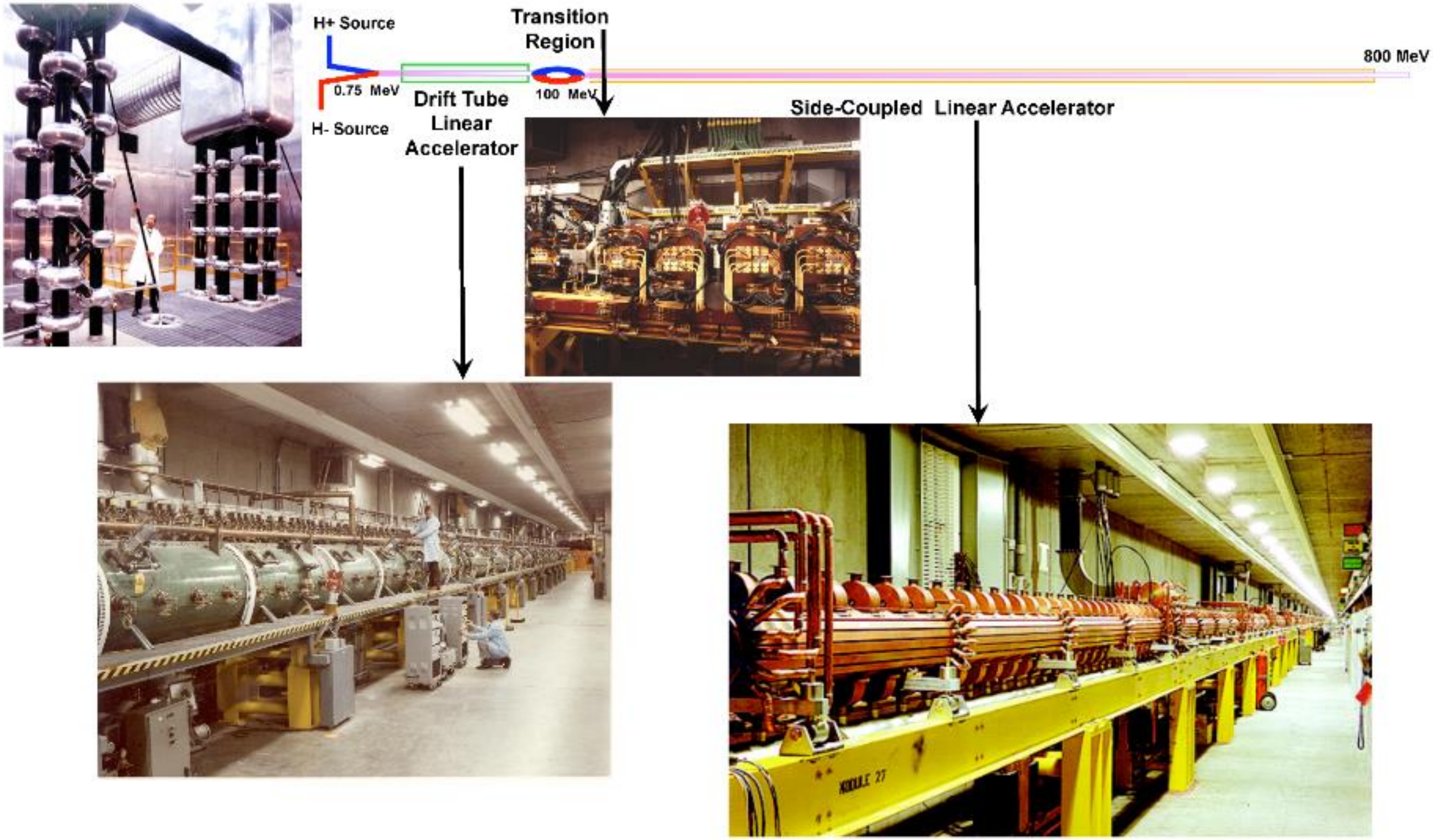
- 50M procedures/year for imaging
- 5M procedures/year for cancer radio-therapy

LANL is the largest domestic supplier of Sr-82 for cardiac imaging (supplying ~ 30,000 patients/ month) and Ge-68 for cancer imaging studies

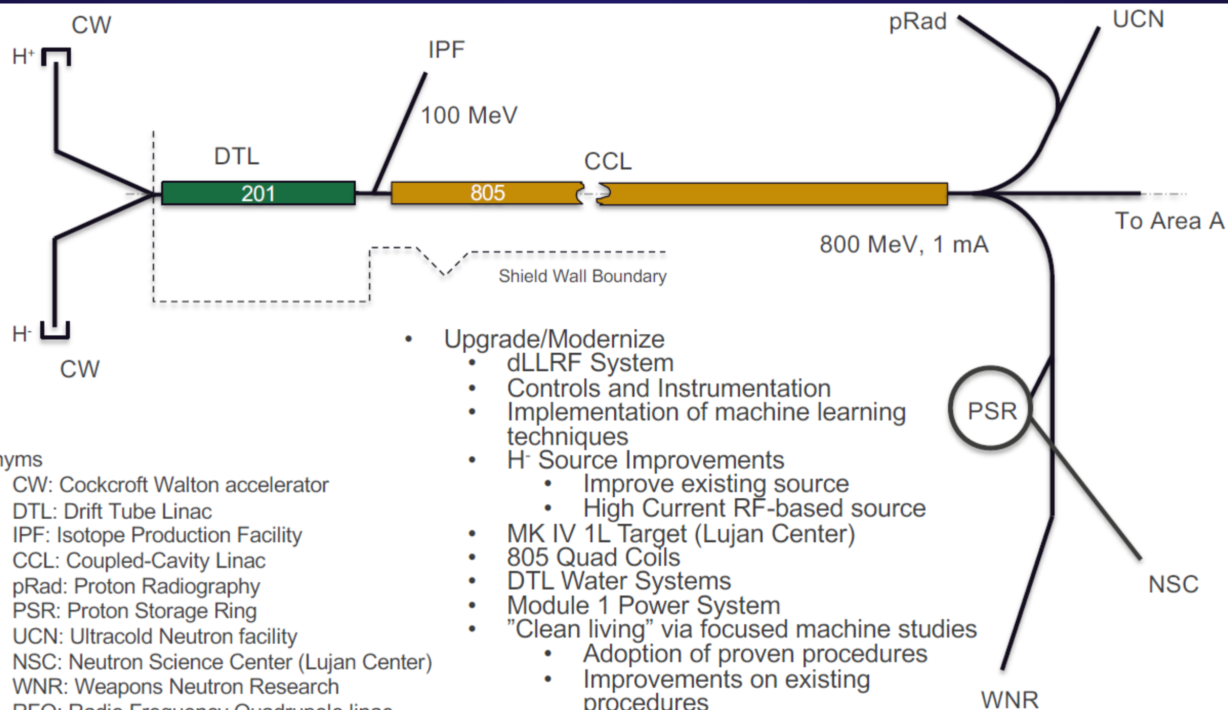


LANL had a special run of Sr-82 and Ge-68 in April and will do a second 2-week run for Sr-82 in May, operating at 250 μA at 100 MeV

LANSCE was commissioned in 1972 and was the world’s first MW average power accelerator



LANSCE/pRad upgrade path – ongoing plus new injector section to replace CW with RFQ's



- Upgrade/Modernize
  - dLLRF System
  - Controls and Instrumentation
  - Implementation of machine learning techniques
  - H^- Source Improvements
    - Improve existing source
    - High Current RF-based source
  - MK IV 1L Target (Lujan Center)
  - 805 Quad Coils
  - DTL Water Systems
  - Module 1 Power System
  - "Clean living" via focused machine studies
    - Adoption of proven procedures
    - Improvements on existing procedures

- Acronyms
  - CW: Cockcroft Walton accelerator
  - DTL: Drift Tube Linac
  - IPF: Isotope Production Facility
  - CCL: Coupled-Cavity Linac
  - pRad: Proton Radiography
  - PSR: Proton Storage Ring
  - UCN: Ultracold Neutron facility
  - NSC: Neutron Science Center (Lujan Center)
  - WNR: Weapons Neutron Research
  - RFQ: Radio Frequency Quadrupole linac

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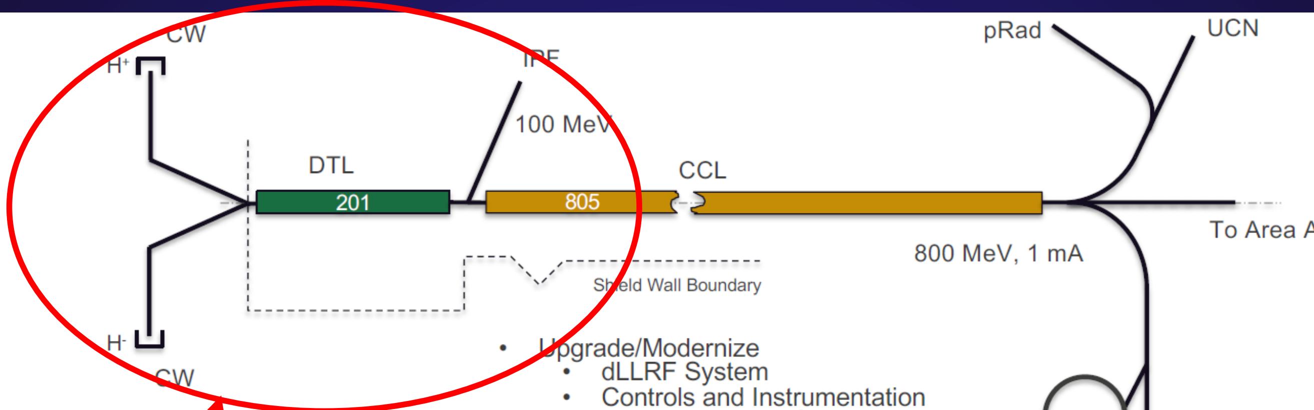

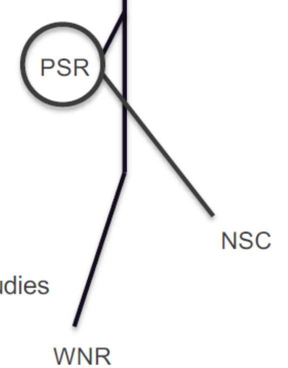

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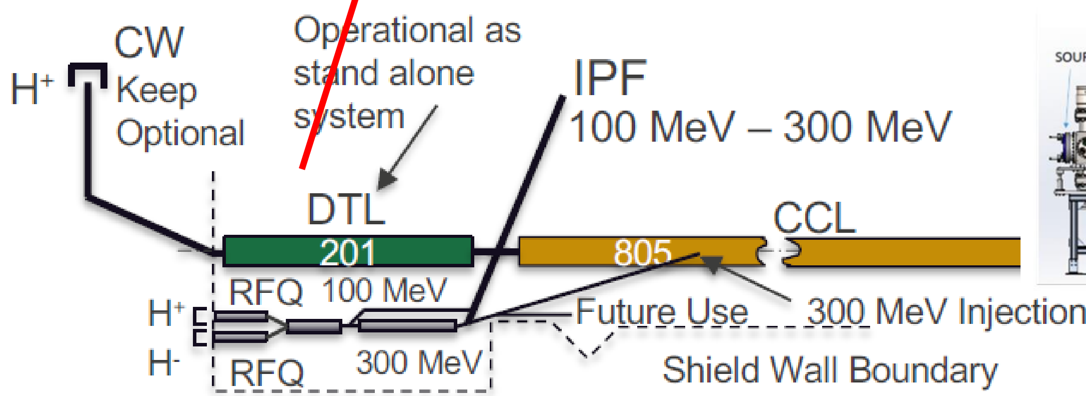
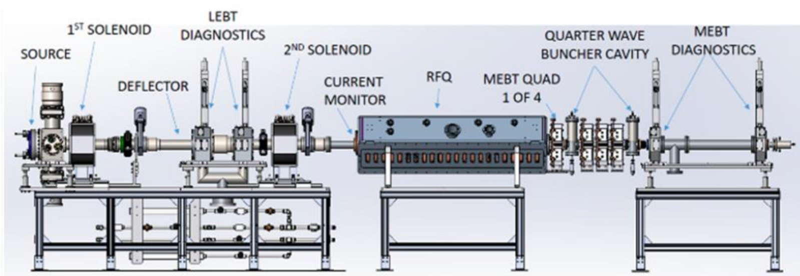
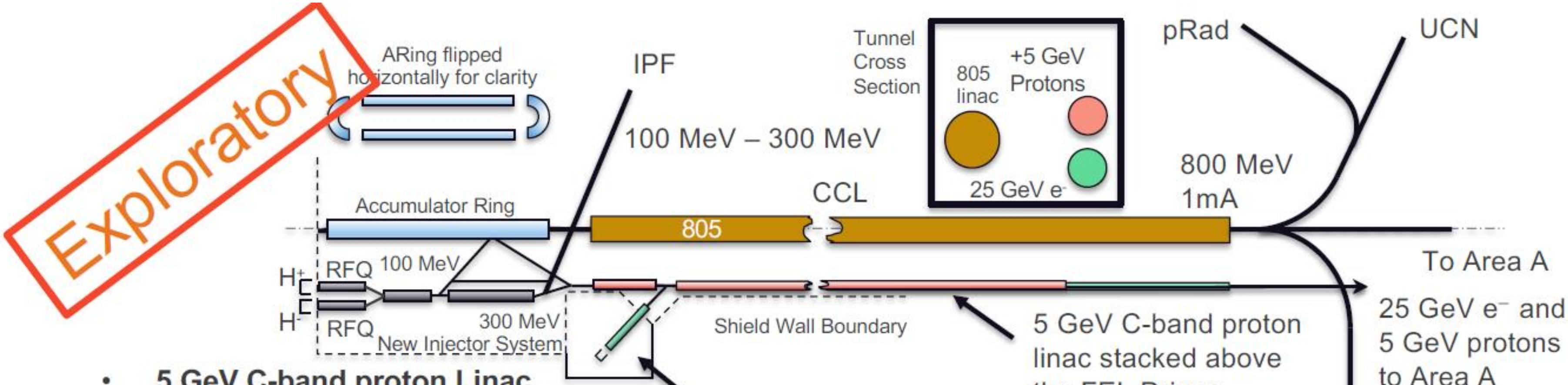




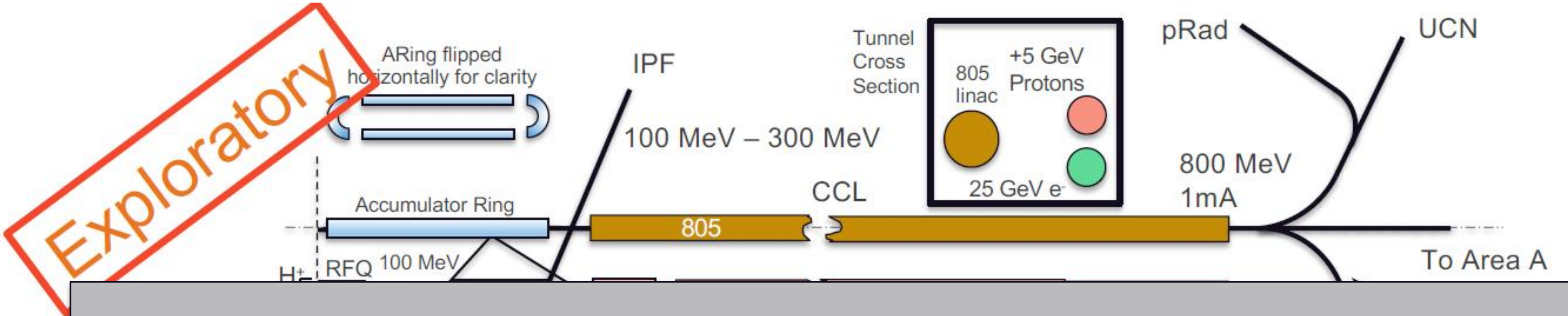
Preliminary LANSCE/pRad 2050 concept



- **5 GeV C-band proton Linac**
  - High Gradient C-Band System
    - Variable beta structure
    - Stacked above the electron linac
    - Waveguide switching to "existing" C-band power
  - Single axis to area A
    - (Dual axis requires building extension for this energy)
- **Optional: Low energy accumulator ring**
  - Beta ~ 0.5
  - Stack protons for high res pRad pulses
  - Built vertically along the wall in place of existing DTL

Maintains all LANSCE capabilities plus provides many enhancements

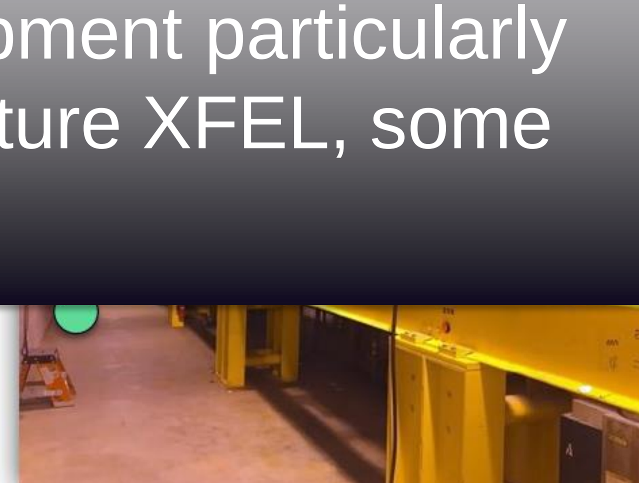
Preliminary LANSCE/pRad 2050 concept



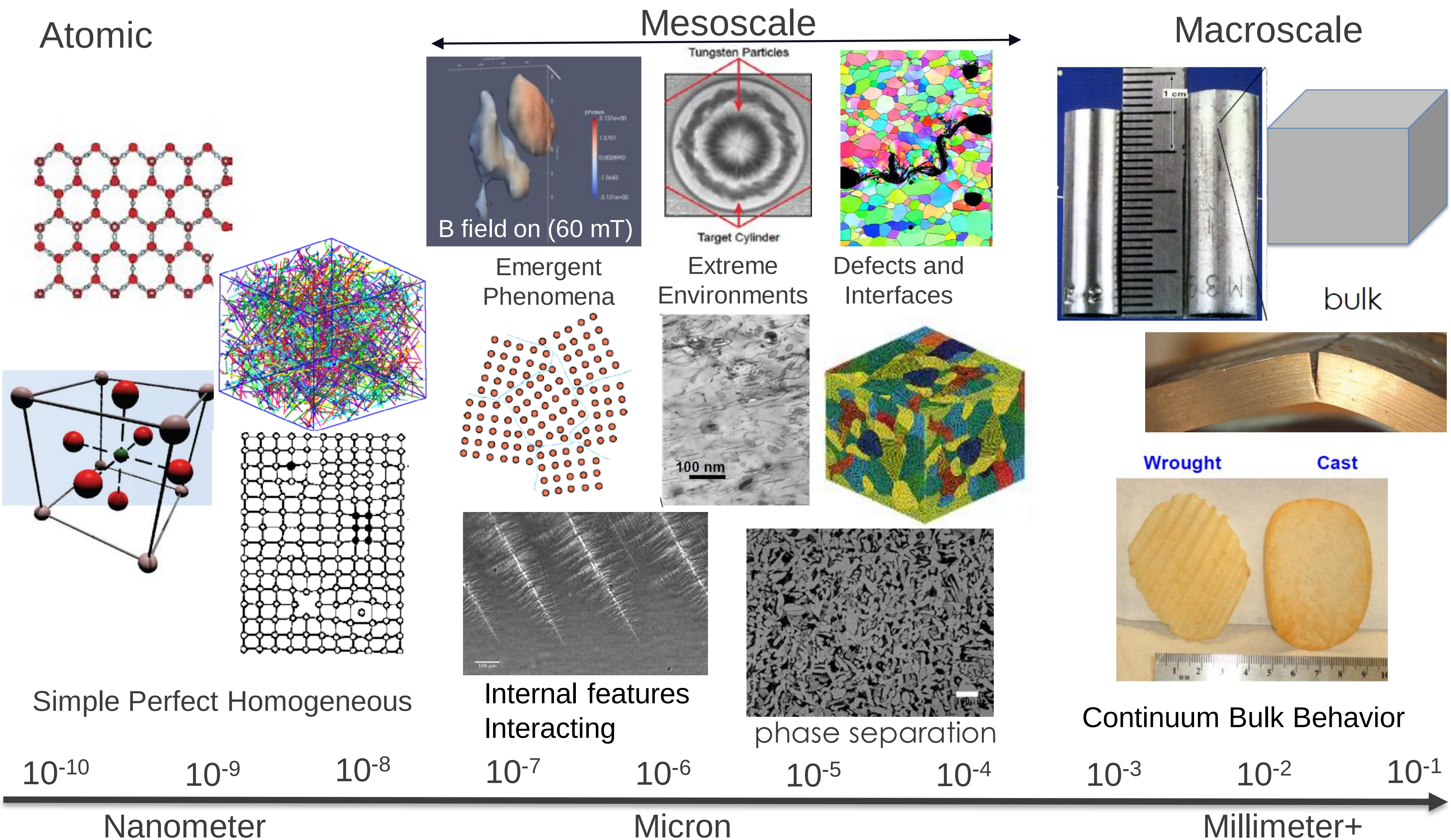
LANSCE upgrade may have significant overlap with GARD technology development particularly with C-band technology and future XFEL, some overlap with PIP-II and PIP-III

- Beta ~ 0.5
- Stack protons for high res pRad pulses
- Built vertically along the wall in place of existing DTL

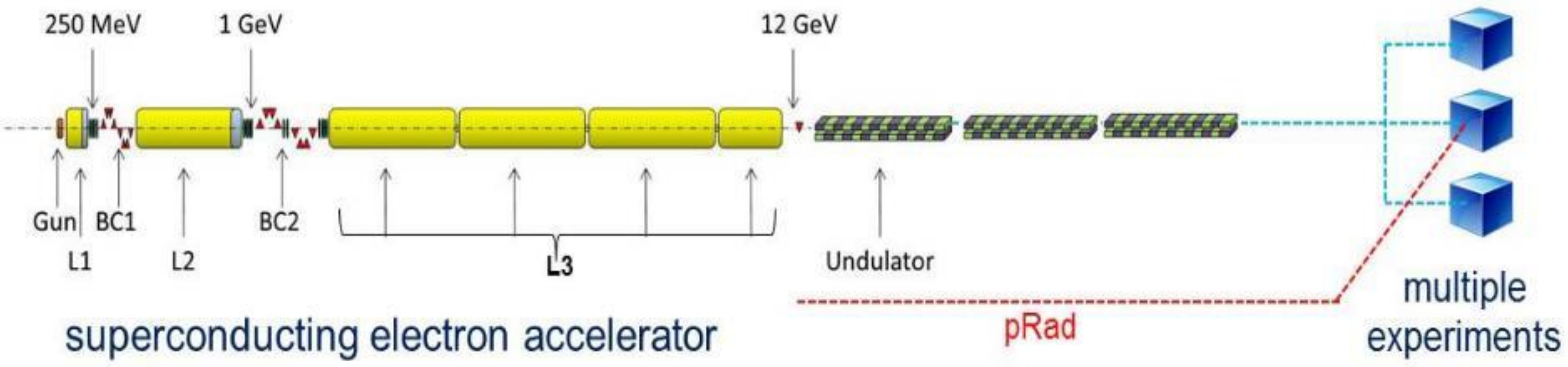
Maintains all LANSCE capabilities plus provides many enhancements

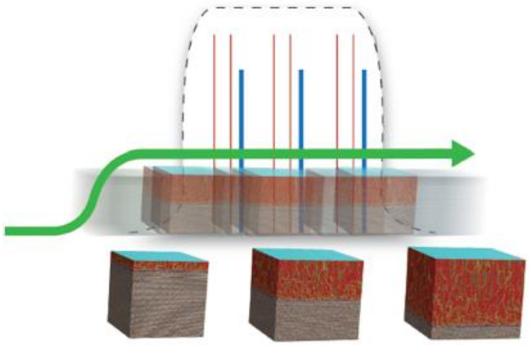


Revolutionizing materials in extremes requires understanding material behaviors at the mesoscale



A tool for understanding and controlling materials is an 12-GeV electron linac feeding a 42-keV XFEL with supporting experimental facilities





The concept features multiple probes (x rays, protons, electrons, optical photons) to maximize the scientific data return

Unique Complementary Characteristics:

- ***Harder in energy for mesoscale, high-Z materials, e.g. Pu***
- ***Higher in repetition rate to make movies of microstructure evolution***
- ***Multiple probes to support maximum scientific return***

42-keV X-rays with a 12-GeV accelerator requires an exceptionally small emittance and energy spread

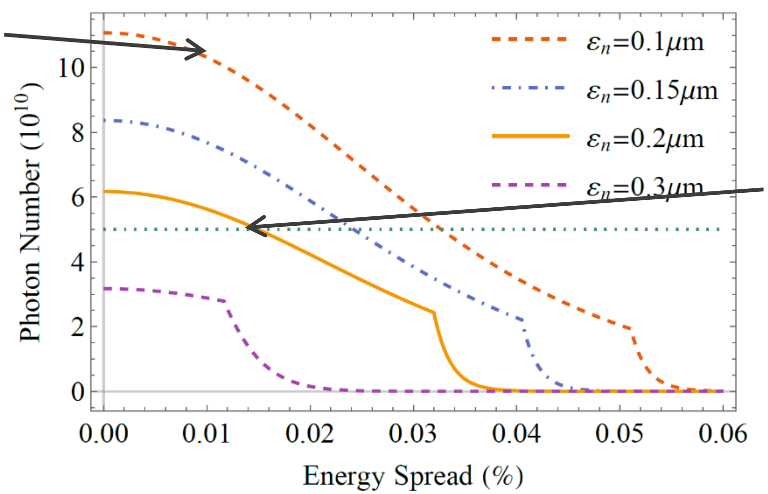
- Both the emittance and energy spread requirements become harder at low energy

$$\varepsilon_n < \frac{\gamma\lambda_{x-ray}}{4\pi} \qquad \delta\gamma_{\max} \le \frac{\rho\gamma}{2} = \gamma^{3/2}\frac{\lambda_{x-ray}}{8\pi\varepsilon_n}\sqrt{\frac{I}{2I_A}}\left(\frac{K}{1+K^2/2}\right)JJ$$

Linac target:
ε_n= 0.10 μm, $\delta\gamma/\gamma$ = 0.01%
100 pC

Photon requirements:
5x10[10] 42-keV photons
0.02% bandwidth

(about 30% decrease in flux in plot from being time dependent)



XFEL requirement:
ε_n < 0.2 μm, , $\delta\gamma/\gamma \sim$ 0.015%
(*factor of 2 decrease in flux*)

Δ*E*=1.8 MeV
$\delta\gamma$=3.5

Pre-conceptual design for “CD-0” was based on TESLA-style superconducting RF cyromodules

Beam parameters for lasing

- 12 GeV beam energy
- 100 pC bunch charge
- 13 fs bunch duration
- 3 kA peak current
- 0.015% energy spread
- 0.2 um rms emittance

SRF LINAC parameters

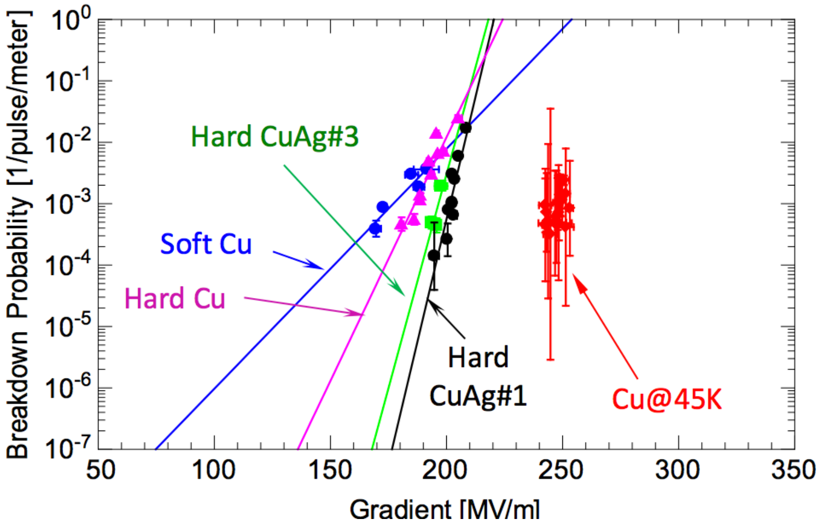
- 1.3 GHz operating frequency
- 31.5 MV/m accelerating gradient
- 20:1 compression ratio, BC1
- 25:1 compression ratio, BC2
- 1 msecRF pulse duration

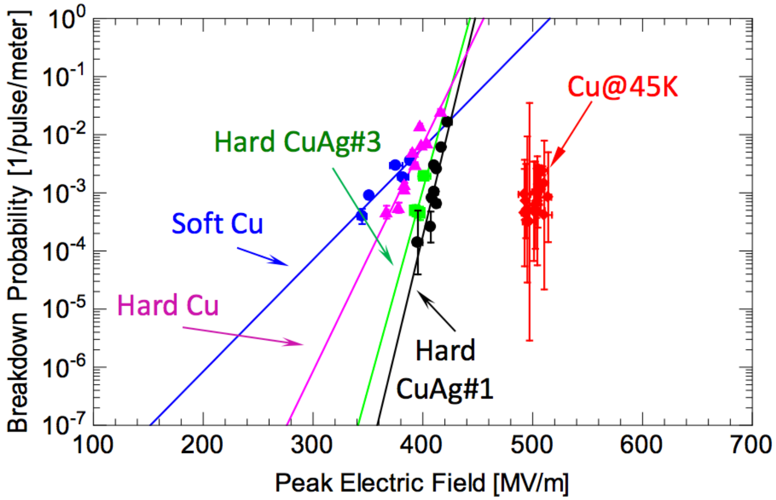
Other requirements

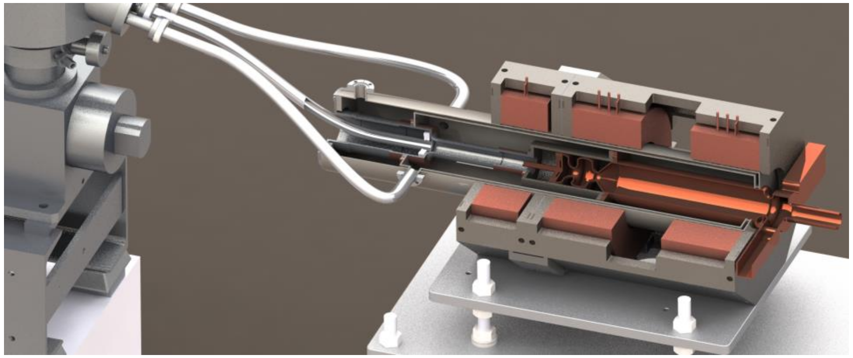
- Multiple bunches per RF macropulse (up to 100s total over 1 msec, up to 10s in ~ 20 nsec burst mode)
- 5×10^{10} X-rays/pulse
- 2-nC bunches interleaved for radiography

Cryo-cooled NCRF technology can reduce the required total compression ratio and suppress LSC/transverse emittance growth

20-A RF gun (UCLA's TOPGUN at 240 MV/m – 55 nm at 100 pC)







Simulations show it can produce up to 20 A with our emittance requirement

Target linac gradient: 120 MV/m real-estate gradient

LANL is part of an international collaboration on cyro-cooled NCRF technology

- Joint SLAC/UCLA/LANL effort (plus international partner INFN)
  - SLAC – GARD
  - UCLA – Stewardship
  - LANL – LDRD-DR, other internal funding, GARD
- LANL focus areas
  - Materials development for RF breakdown suppression (custom copper alloys)
  - Advanced manufacturing for compatibility with material properties
  - Cryo-cooled operation for long pulse (*10s of μs*) operation
  - Established extension of Molecular Dynamics simulation tools to include RF fields and study macroscopic materials
  - Identified C-band as best choice for efficiency, wakes, FEL operation

Compact accelerators for national security

- Flash radiography for hydrotests (replace Cygnus)
- Compact electron accelerators in space for radiation belt remediation (RBR)
- Compact electron accelerators for SNM detection via radiography and nuclear resonant fluorescence
- Compact neutron generators

The threat of a high-altitude nuclear detonation to US satellites has been known for decades

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

2001 Rumsfeld Space Commission Report

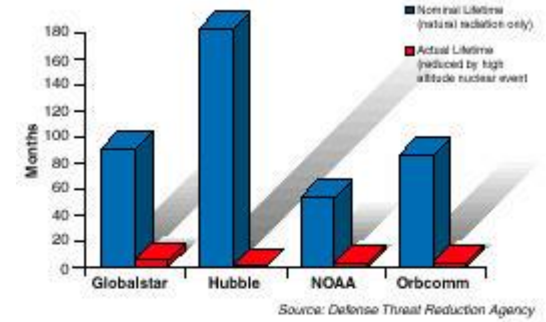
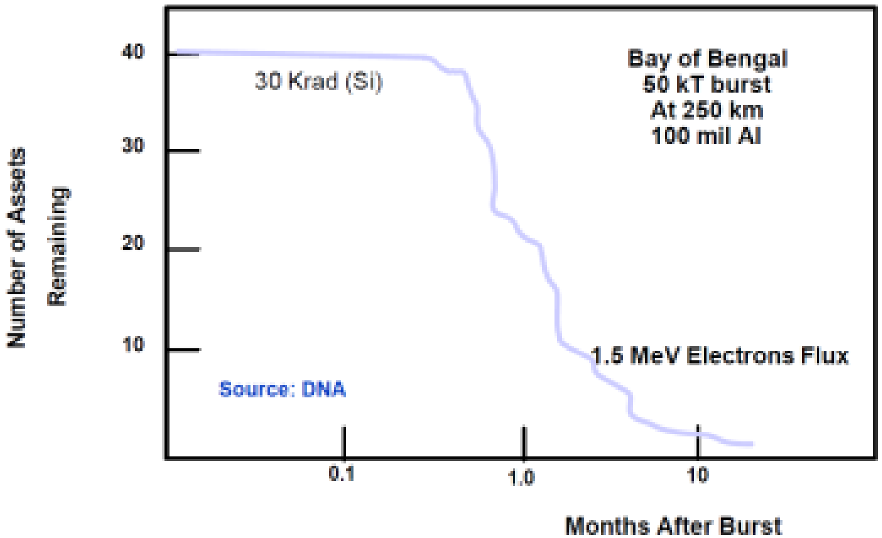


Figure 13: Impact of a nuclear detonation on the lifetime of satellities

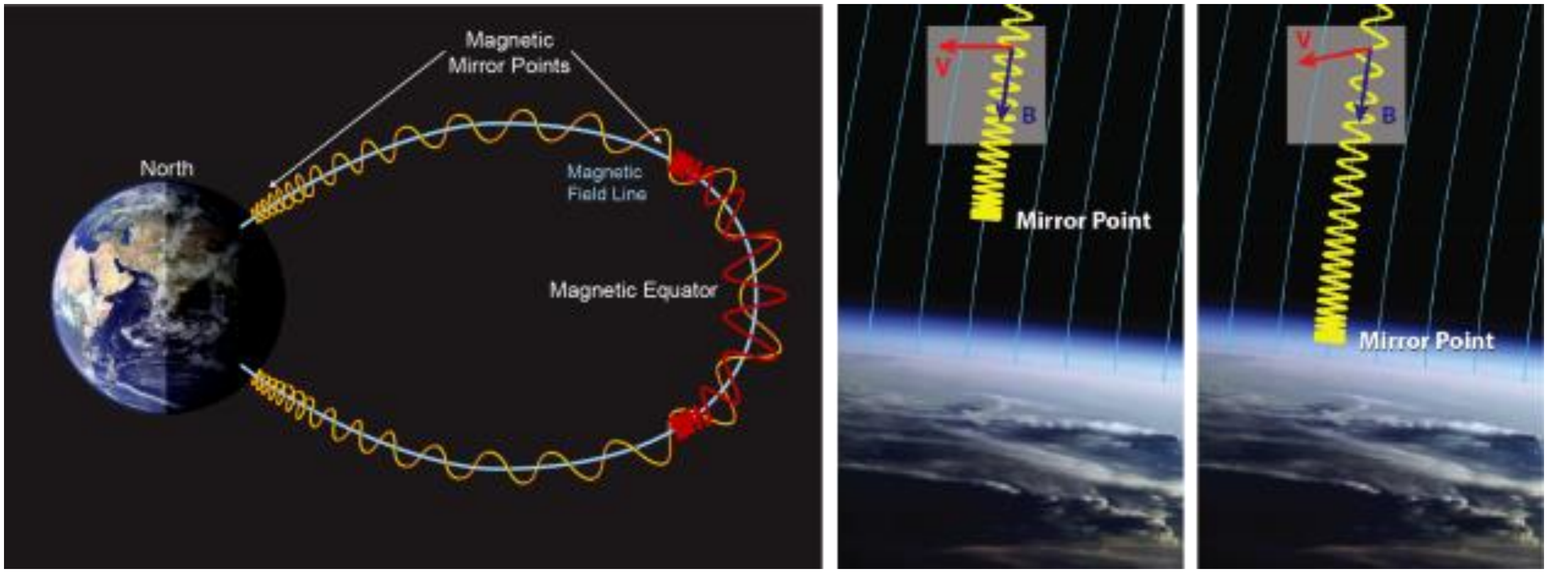


2002 Tether Panel HAARP Study (recommendation: *reduce MeV electron lifetime to a few days)*

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

Radiation belts trap charged particles

"Bounce" period ~ 0.1 to 1 second

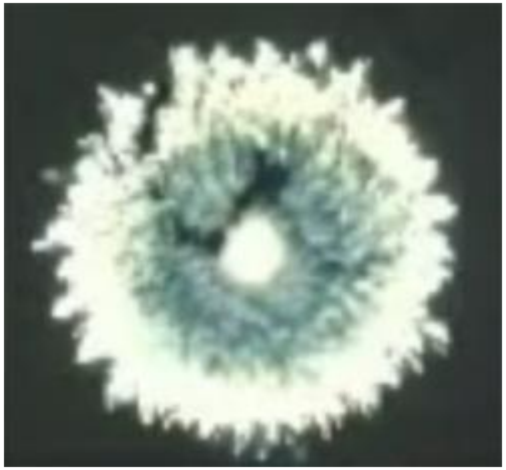


Energetic electrons are trapped in the radiation belts by the Earth's magnetic field lines and are mostly mirrored above the atmosphere due to the electrons' transverse energy because the magnetic field intensifies near the Earth; the red trajectory corresponds to a larger electron transverse energy than the gold trajectory.

Co-propagating VLF waves can modify the electrons' transverse energy by stochastic multiple scatterings; these scatterings sometimes reduces the transverse energy until the electrons are mirrored low enough they interact with the Earth's atmosphere and can precipitate as aurora.

LEO satellites were damaged by early atmospheric tests

Starfish Prime (part of Operation Fishbowl) - July 8, 1962, 400-km altitude, launched from Johnston Island 1200 miles SW of Hawaii



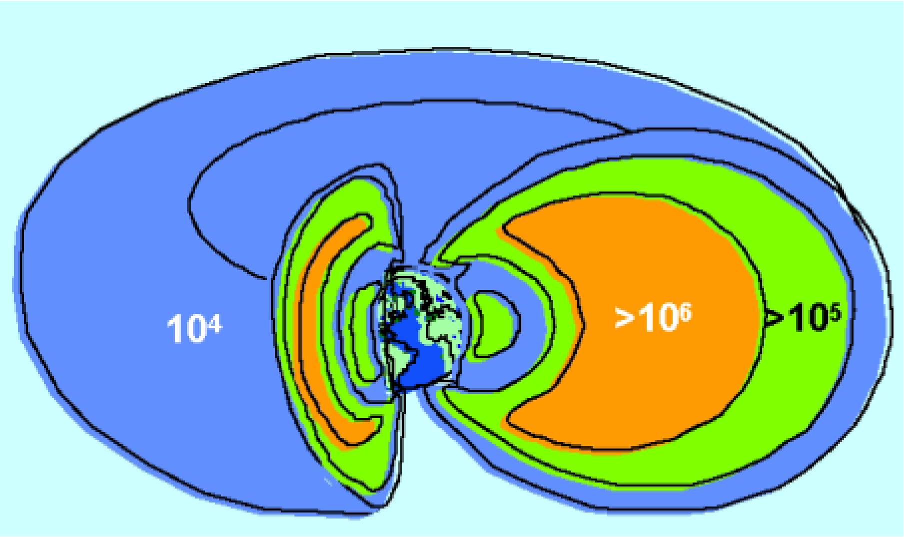
Expanding fireball

Debris fireball plus aurora as electron along field lines enter atmosphere

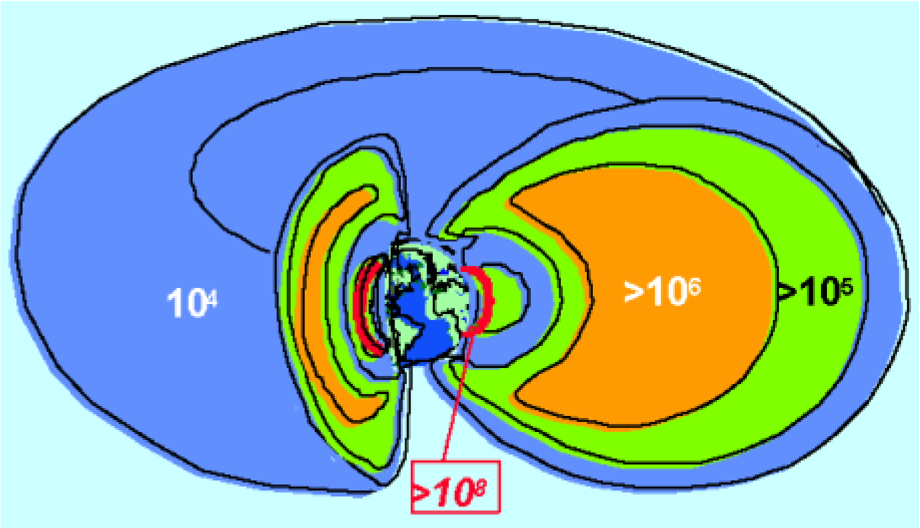
Starfish detonation created a belt of ~ MeV electrons that lasted for >5 years (~60 rad/day for 4 months)

Starfish detonation damaged or destroyed 7 satellites within 7 months (1/3 of all satellites in LEO), including Telstar (first commercial communications satellite), Ariel-1 (the UK's first satellite), and a Soviet satellite (Transit 4B, Traac, Ariel damaged by solar cell degradation, Telstar by command decoder failure by Nov, 1962)

The > 1 MeV electron flux level will increase at LEO altitudes after a nuclear detonation (by ~ 3 orders)



Typical background radiation flux levels ($e^-/cm^2/sec$)



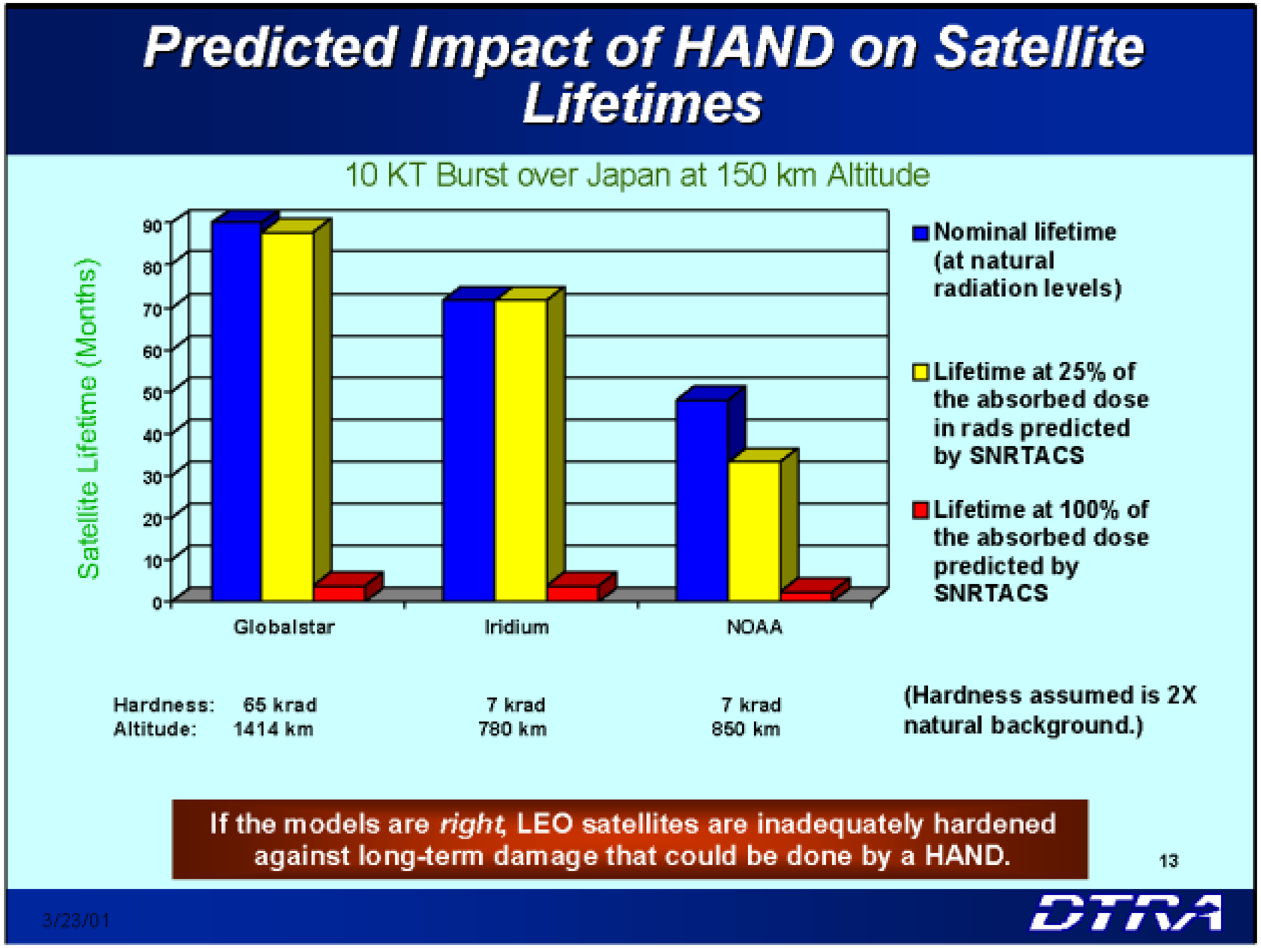
Expected flux levels one day after burst over Korea

Primary source of natural total dose is from protons and electrons trapped in the belts.

HAND raises peak radiation levels in LEO by 3-4 orders of magnitude. Peak flux will remain for 6 months to 2 years at lower latitudes and higher orbital altitudes.

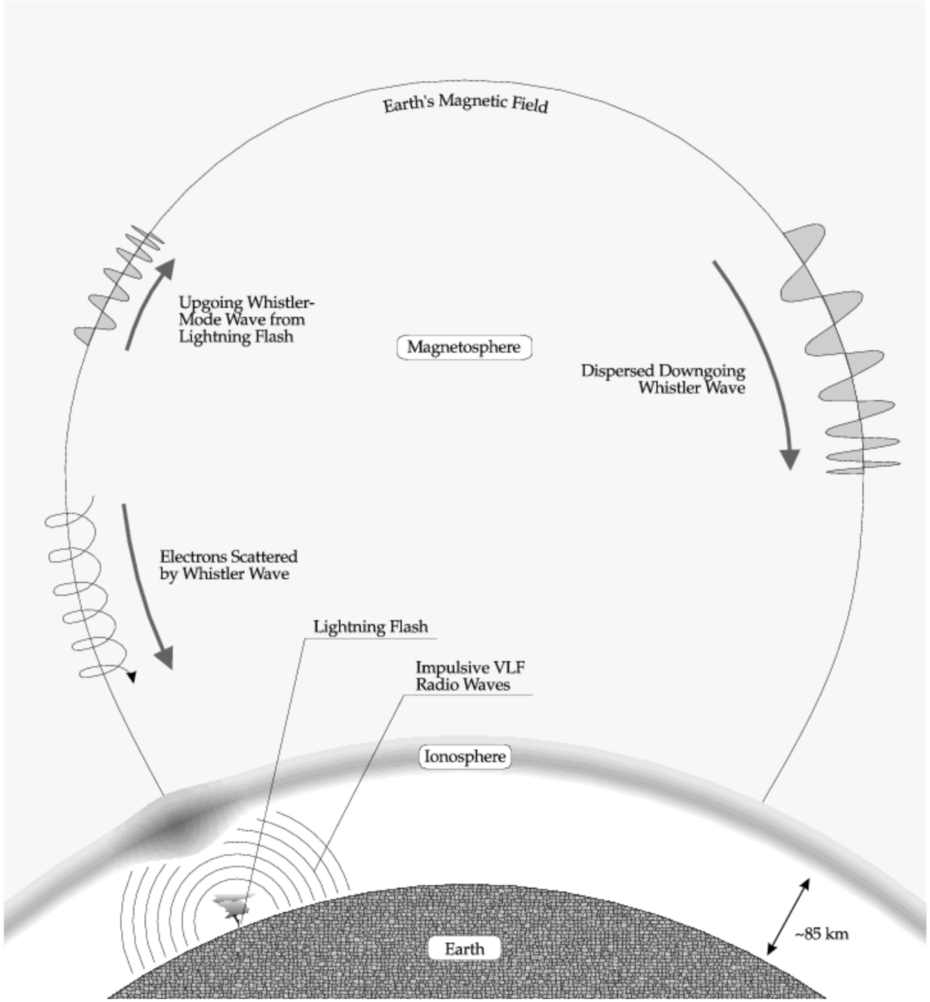
Slot area will also fill in (e.g., high solar activity fills in for weeks to months)

A 10-kT detonation at 150 km and above will greatly decrease satellite lifetimes



Typical low LEO satellites (~800 km) are designed to tolerate ~ 5 krads and high LEO satellites (~ 1400 km) are designed to tolerate ~ 50 krads. For 10 kT detonation at 150 km, enhanced flux leads to about 2.3 krad/month at 800 km.

VLF waves generated by a space-accelerator can remediate the excess electrons in the radiation belts (RBR)



There are several types of VLF modes *(3-30 KHz)* in the *magnetized ionosphere* (whistlers, low-hybrid waves, Bernstein modes, etc).

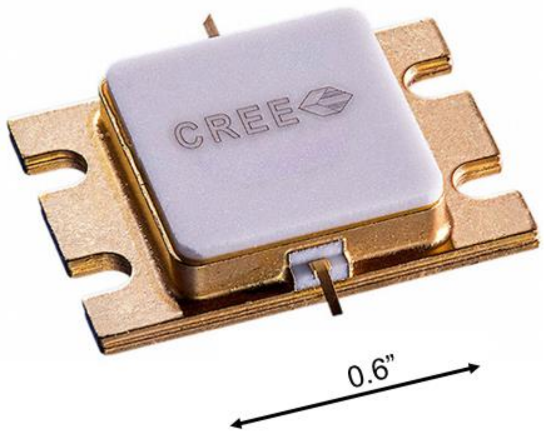
Field-aligned: R and L

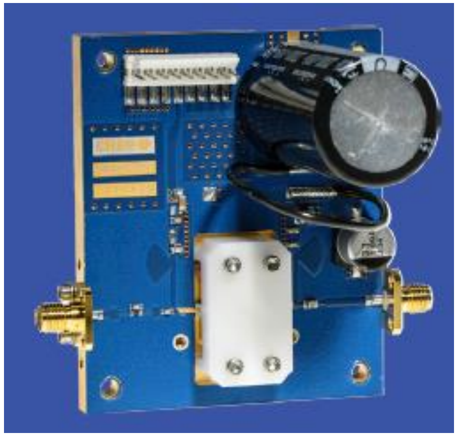
Perpendicular to field: X and O

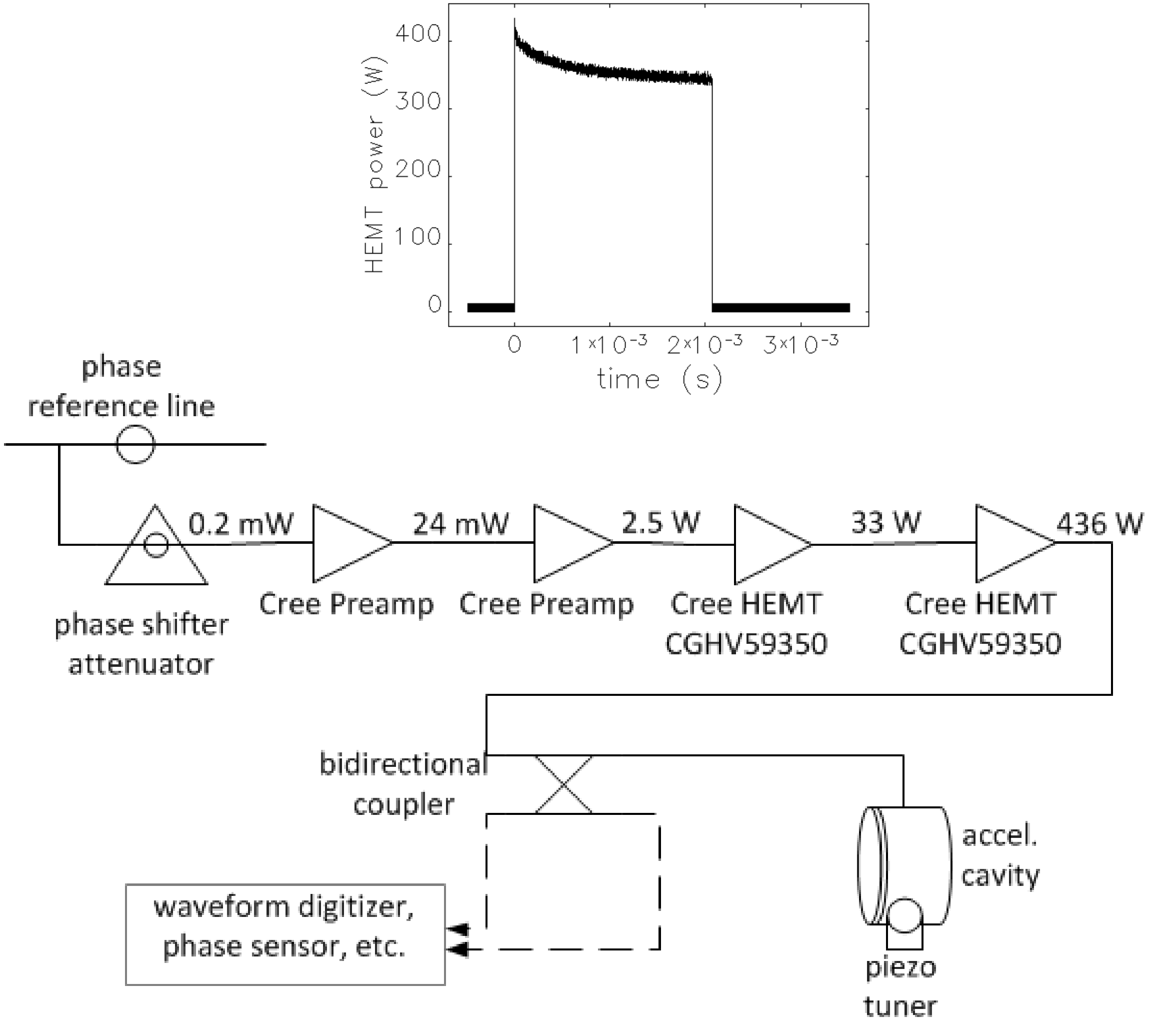
Whistler modes can be generated by lightning strikes and have a characteristic pitch change (from slower velocity of lower frequencies in the ionosphere)

Whistler and X modes can scatter the electrons, changing their transverse energies

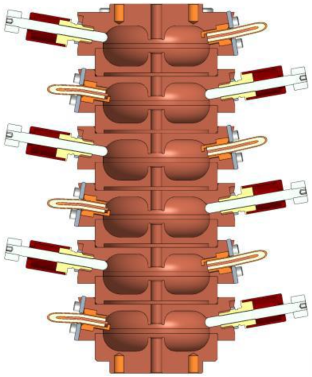
500-W, 50-V DC HEMTs enable a new accelerator architecture suitable for space

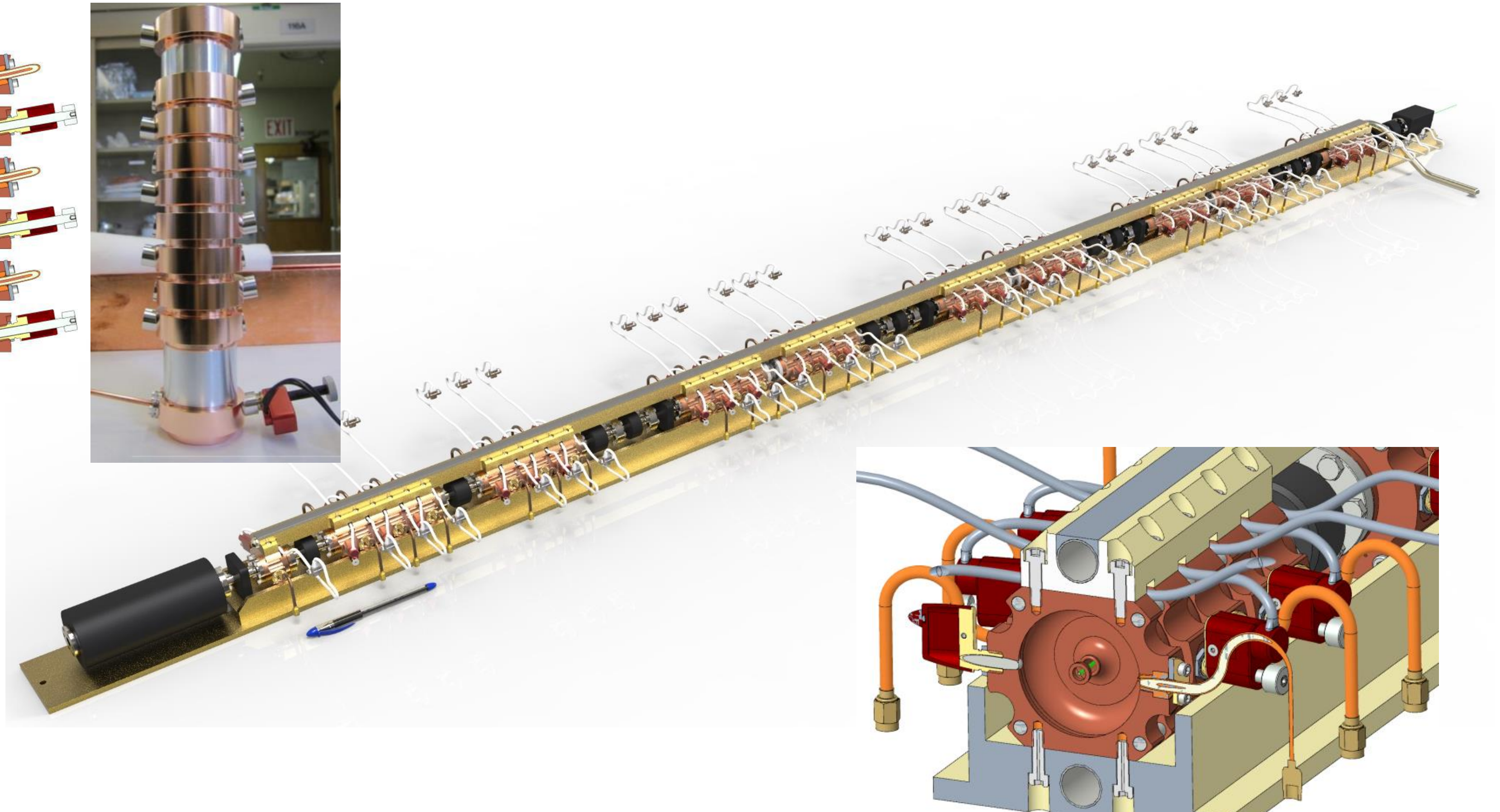






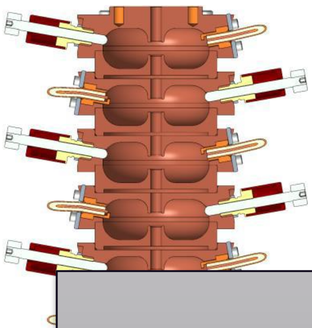
1-MeV accelerator design for space applications is 1.5-m long and 125 kg

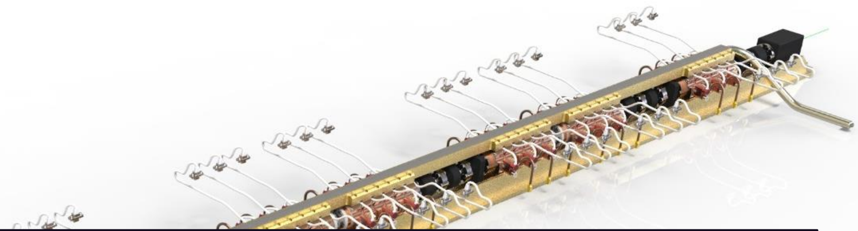




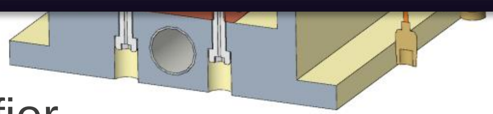
Each RF cell individually driven by 500-W HEMT amplifier

1-MeV accelerator design for space applications is 1.5-m long and 125 kg



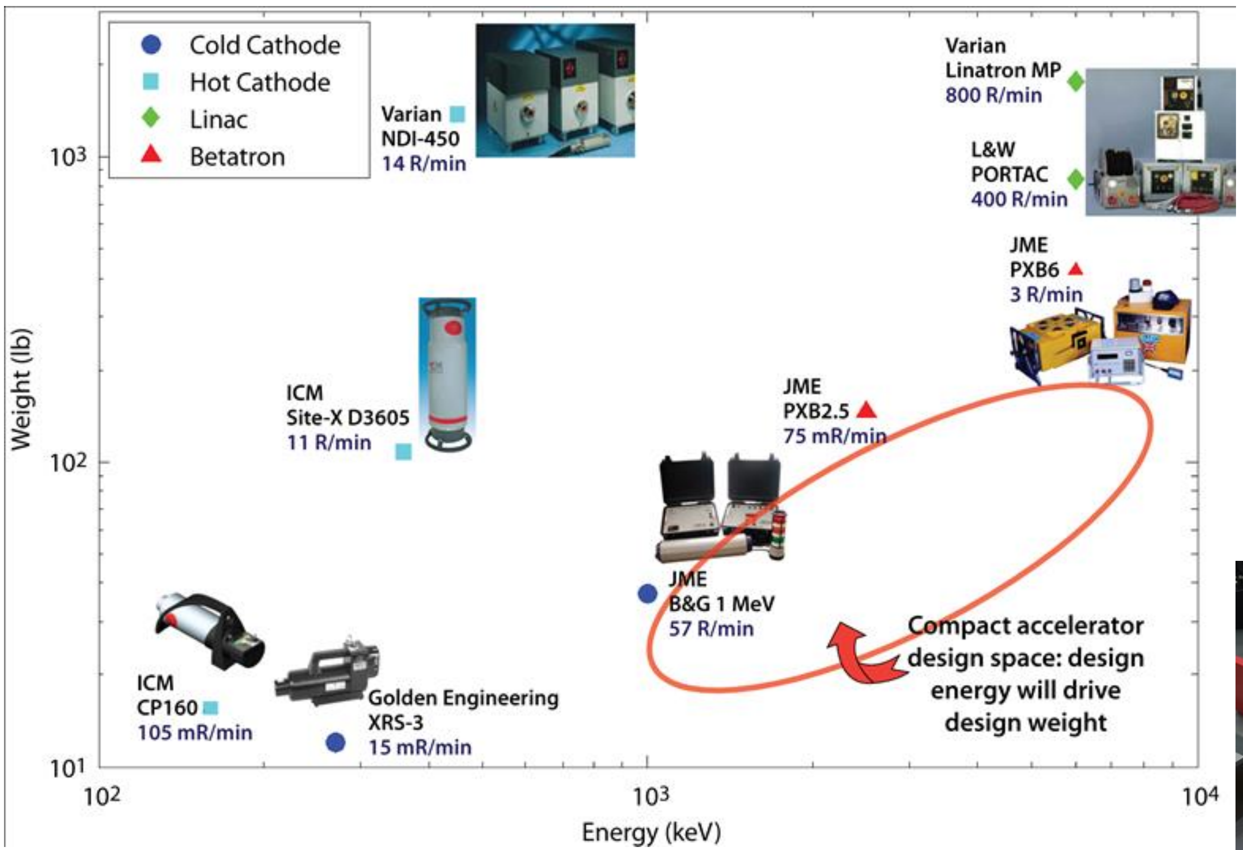


HEMT technology overlap with GARD technology development areas is small



Each RF cell individually driven by 500-W HEMT amplifier

Compact, high-power electron accelerator designs for interrogation and radiography



PORTAC is commercial state-of-the-art 6-MeV accelerator (300 R/m/min)

Made by HEXi (L&W)

6 MeV, 100 mA peak, 25 Hz, 10 usec pulses

(150 W average, 25 uA average)

10-kW class compact 6-MeV electron accelerator is cart-sized

Total weight ~1000 lbs – RF system (magnetron) is 430 lbs, vacuum system is 180 lbs

~25% efficient

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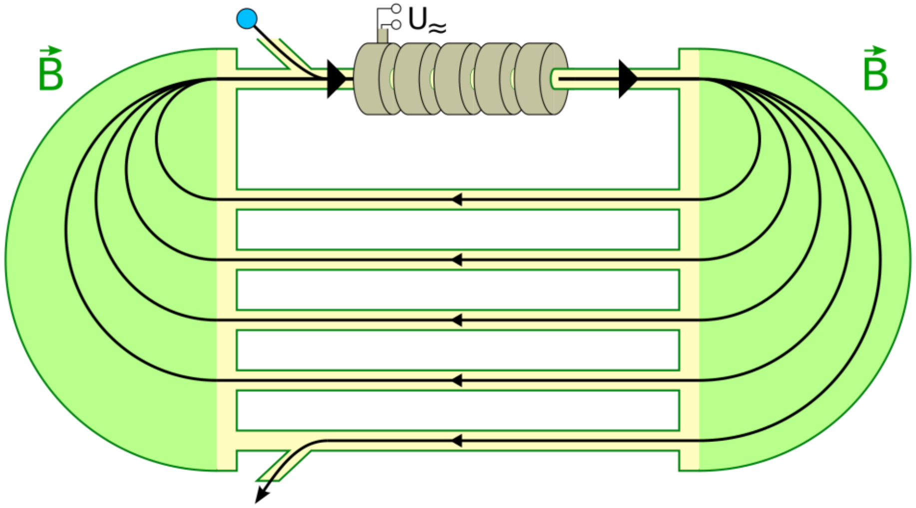
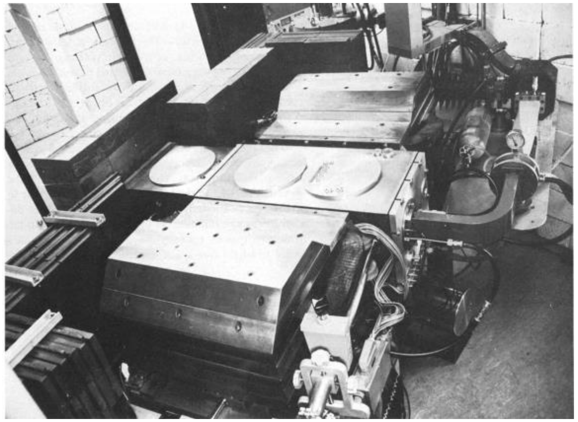
Total weight ~1000 lbs – RF system (magnetron) is 430 lbs, vacuum system is 180 lbs

~25% efficient

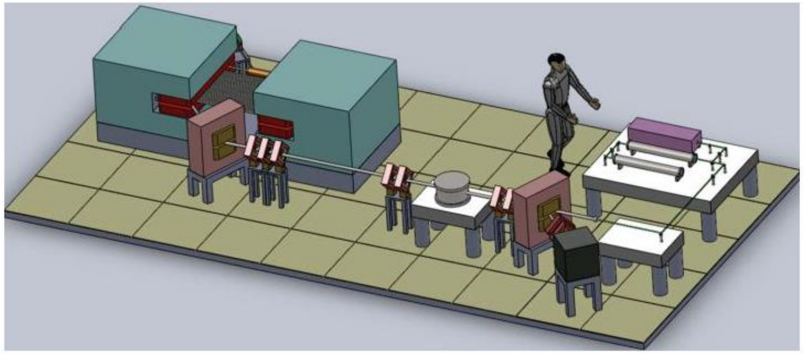
Significant overlap with GARD technology development areas – NCRF novel manufacturing technologies, maybe high gradient

Race-track microtron is likely superior at higher energies (up to ~ 150 MeV)



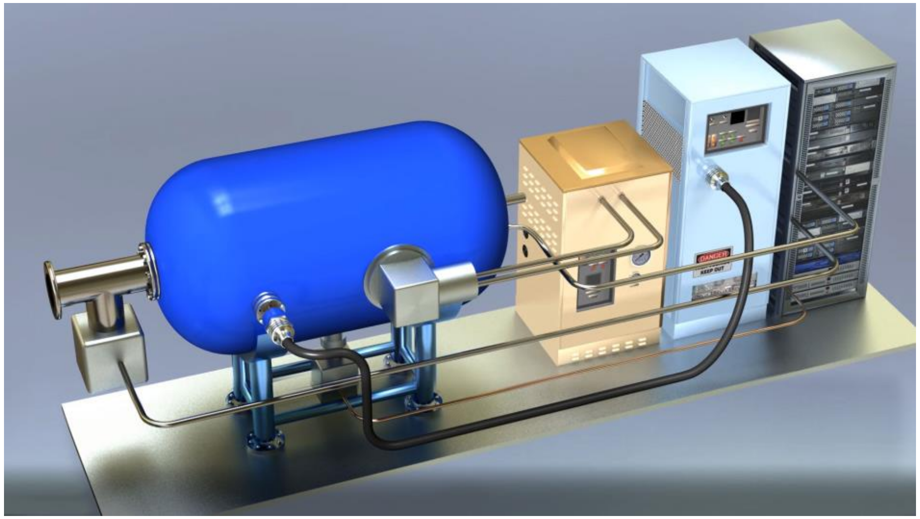


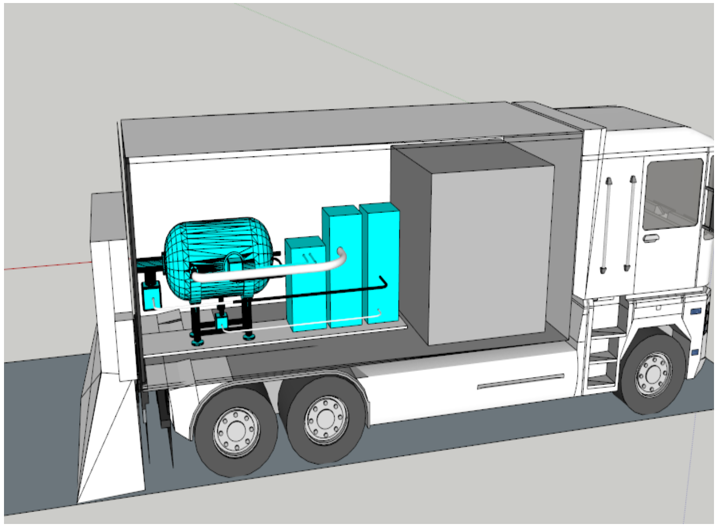
50-MeV microtron at the Royal Institute of Technology in Stockholm



The 150-MeV Sumitomo Heavy Industries RTM has size 4m by 1.5m by 2m, excluding the injector line from the electron gun, using 1.2 T magnets. Their design concept for a 220-MeV RTM for generation of high-energy gamma rays for SNM detection using inverse Compton scattering for a JAEA project uses 1.5 T dipoles.

Superconducting RF has unique capability to deliver very high average powers with larger size and weight

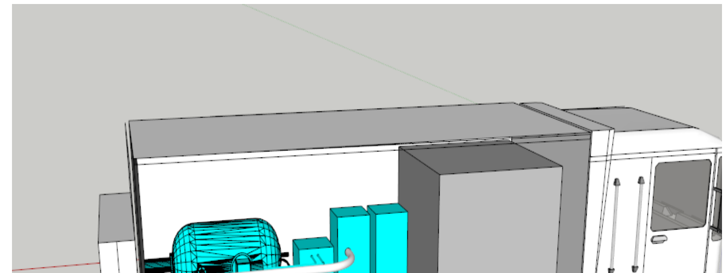




Conduction cooling with 4K cryo-coolers (5W) and highly efficient RF drive

Pursued at both Fermilab and JLab – both demonstrated ~ 6 MV/m gradient using Nb_3Sn coated niobium cavities (650-MHz at Fermilab and 1.5 GHz at JLab)

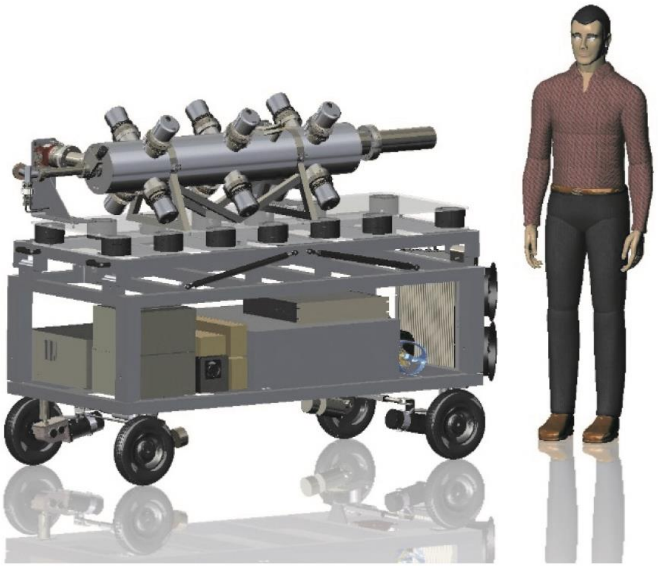
Superconducting RF has unique capability to deliver very high average powers with larger size and weight

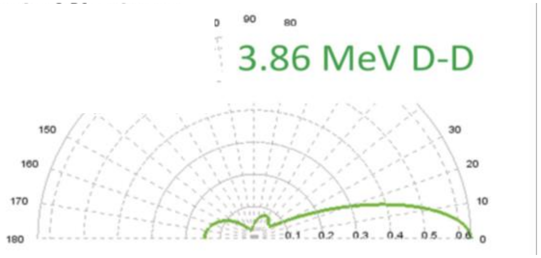


This technology area is all driven by GARD-funded R&D

Pursued at both Fermilab and JLab – both demonstrated ~ 6 MV/m gradient using Nb_3Sn coated niobium cavities (650-MHz at Fermilab and 1.5 GHz at JLab)

Starfire Centurion is state-of-the-art in compact proton/deuteron accelerators – ion source plus RFQ





DARPA-funded development

2e10 n/steradian at 0 degree
4e10 neutrons total
at 0.6% duty (200W beam 3.5 kW prime power)
(~6% efficient)

Can go to 2% duty
(3.86 MeV D on D makes 6 MeV neutrons)

At 6% duty: 2kW beam, 35 kW prime, 2e11 n/steradian