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Compact, high power SRF Accelerators for Industrial Applications

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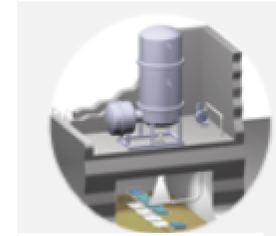
Superconducting Radio Frequency (SRF)

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

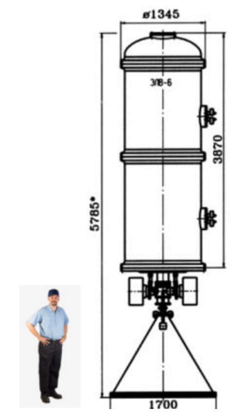
- Why?
  - Because ~all RF power → beam power vs heating RF resonators
  - SRF→ Higher gradient, more energy per unit length
- But current SRF “science” accelerators are large and complex

Current vs New Accelerator Technology



IBA Dynamitron

IBA Rhodotron



Budker ELV-12

- Bulk materials processing applications require multi-Mev energy for penetration and 100's of kW (or even MW) of beam power
- > few MeV accelerators are typically copper and RF driven
  - Inherent losses limit efficiency (heat vs beam power) = ops cost
  - Heat removal limits duty factor, gradient and average power ➔ physically large "fixed" installations = CAPEX

New Technology: Superconducting Radio Frequency (SRF)

- High wall plug power efficiency (e.g. ~ 75%)
  - Large fraction of the input power goes into beam
  - High power & efficiency enables new $ 1 Billion class SRF-based science machines ➔ driving large R&D efforts at labs
- Currently SRF-based science accelerators are huge with complex cryogenic refrigerators, cryomodules, etc. But this is changing!
- Recent SRF breakthroughs now enable a new class of compact, SRF-based industrial accelerators (lower CAPEX and OPS cost)

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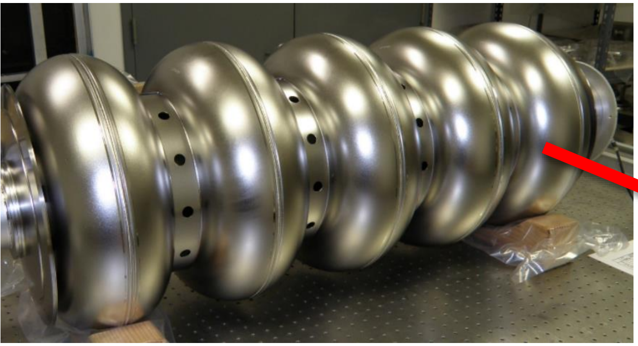
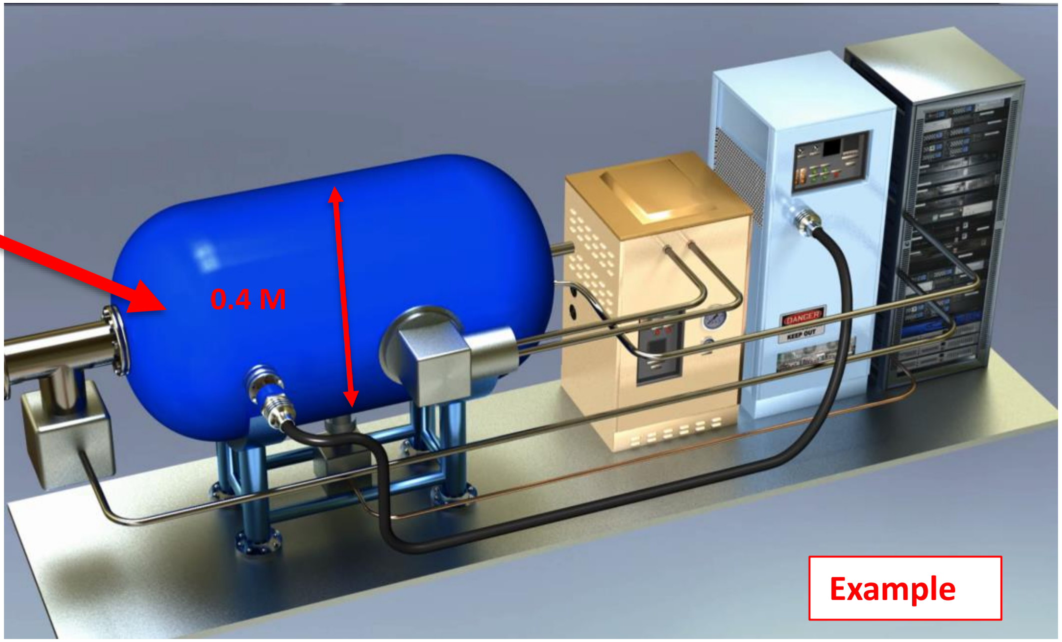
Recent SRF Technology Breakthroughs:

- 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**

Can now contemplate a simple SRF accelerator*





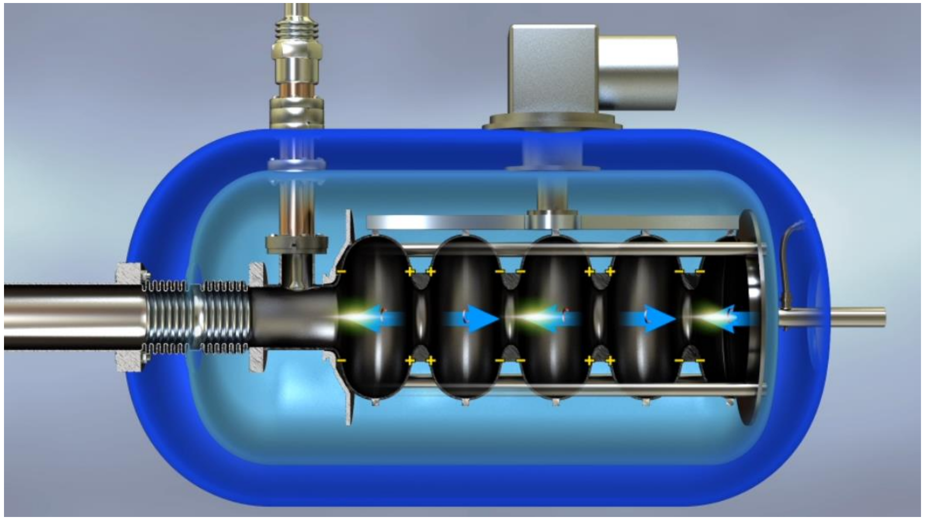
- 650 MHz elliptical cavity (well understood, industrial vendors)
- Commercial 4K cryo-coolers (2.5 W available now, 3-5 W soon)
- Modular design scales to MW class industrial applications
- Compact → lower shielding cost, lower CAPEX
- Accelerator system <3000 lbs enables mobile applications

* FNAL patents pending

Vision: Build a high power SRF industrial accelerator*

We will combine state-of-the-art technological advances to create a simple, compact, high power, superconducting RF based industrial accelerator.

- Efficient
  - > 75%,mains to e-beam
- Turn key operation
- High reliability
- ~10 MeV electron beam
- > 250 kW
- ~ 0.7m ∅ x 1.5 m long



Future Accelerator Applications

Energy and Environment

- Treat Municipal Waste & Sludge
  - Eliminate pathogens in sludge
  - Destroy organics, pharmaceuticals in waste water
- In-situ environmental remediation
  - Contaminated soils
  - Spoils from dredging, etc
- Upgrade of heavy oil, flare gas

Industrial and Security

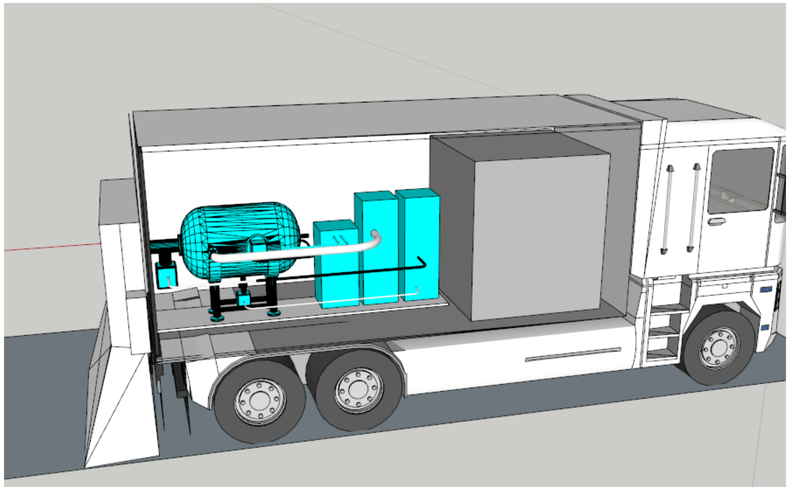
- Catalyze Chemical reactions to save time and energy
- In-situ cross-link of materials
  - Improve pavement lifetime
  - Instant cure coatings
- Medical sterilization without Co60
- Improved non-invasive inspection of cargo containers

These new applications need cost effective, energy efficient, high average power electron beams.

New technology can enable new applications (including mobile apps)

In-situ Environmental Remediation

- Since e-beams can disinfect or destroy organic compounds
- One can envision mobile SRF based accelerators for environmental remediation & decontamination.
- Examples
  - Clean soil contaminated by chemical spills
  - Remove hydrocarbons from soil
  - Destroy biohazards or toxins
  - Remove PCB's from dredge spoil
  - Provide an alternative to incineration



- Requires robust, reliable, compact, mobile accelerators that can be "brought to the problem"

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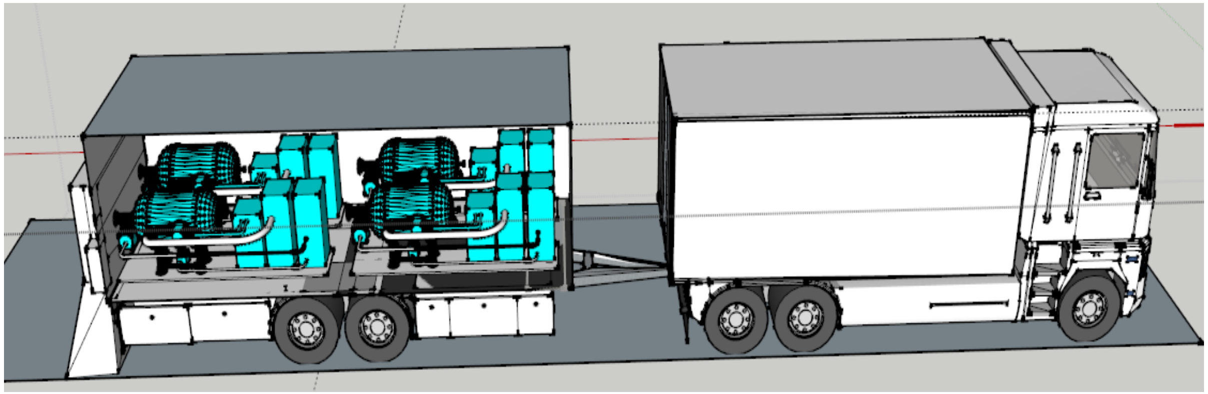
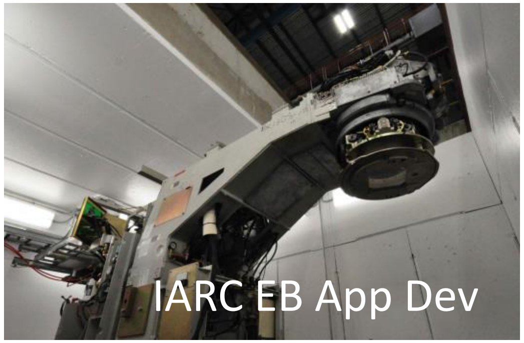
In-Situ Cross-Link of Materials

Electron accelerators are widely used to cross link materials

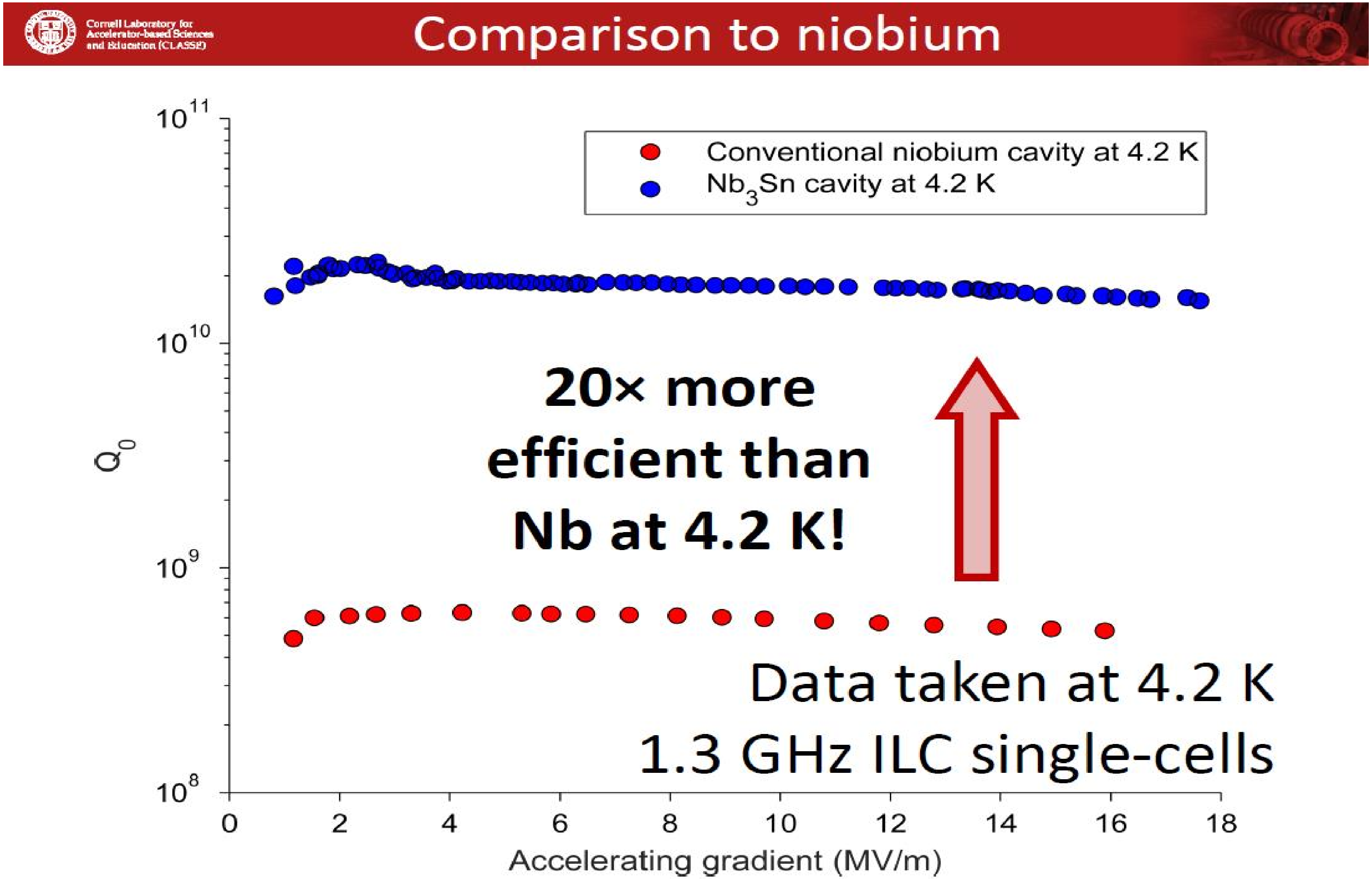
- High power mobile accelerators enable entirely new construction techniques that can alter materials properties after placement
  - e.g. Improve the strength, toughness, and/or temperature range
- One applications: Improved Pavement
  - US Army Corps of Engineers partnership (FY17 ERDC funding)





- Collaborating to create a tough, strong binder with improved temperature performance vs bitumen to extend pavement lifetime
- U.S. spends > $ 50 B/yr to grind off and replace asphalt!

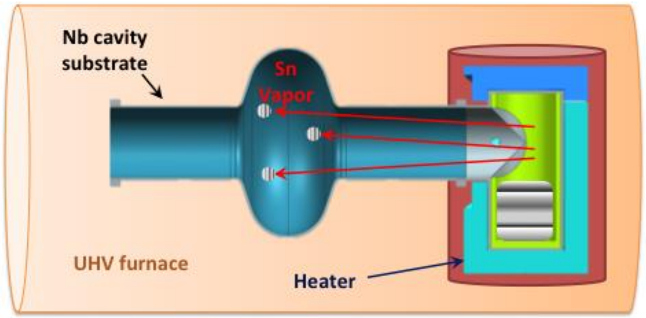
Nb3Sn vs Nb

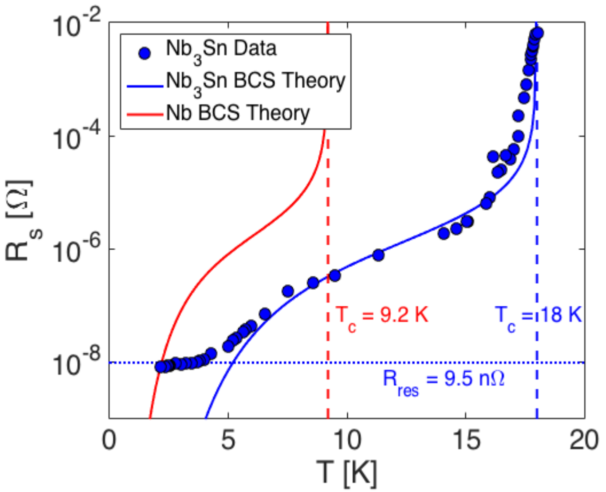

Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)
Comparison to niobium
Conventional niobium cavity at 4.2 K
Nb3Sn cavity at 4.2 K
20× more efficient than Nb at 4.2 K!
Data taken at 4.2 K
1.3 GHz ILC single-cells
Q0
Accelerating gradient (MV/m)

Higher temperature SRF cavities

Nb_3Sn Coated SRF Cavities

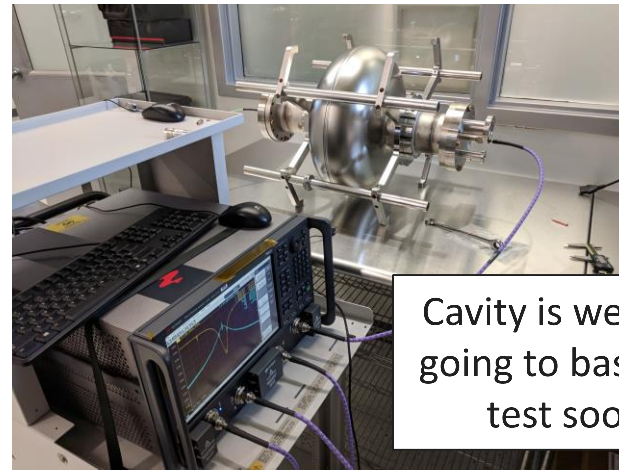
- 1.3 GHz, 14 MV/m, $Q=2x10^{10}$ @ 4K
- At 650 MHz, we predict < 2.5 W @ 4K
- Sam Posen
  - $2.5M DOE Early Career Award
- First article @ FNAL within factor of 3 of Cornell performance





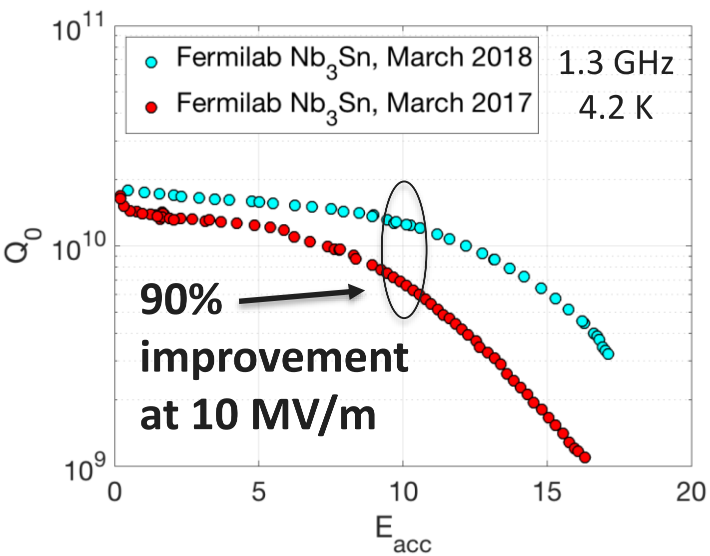
Progress of Nb_3Sn Films

Substantial progress in performance over last year



Cavity is welded, going to baseline test soon

650 MHz 1-cell: First 650 MHz coating



Machining completed on multicell sample cavity

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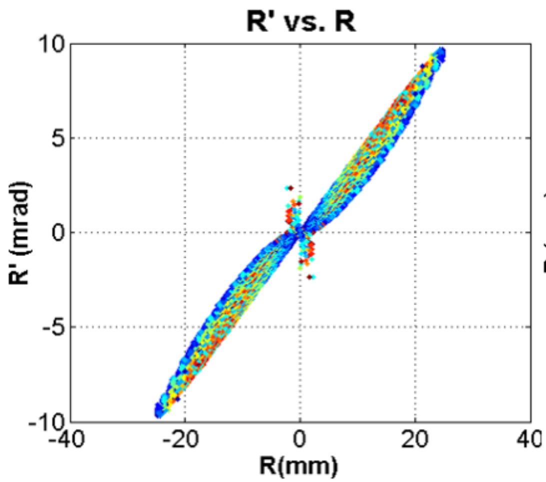
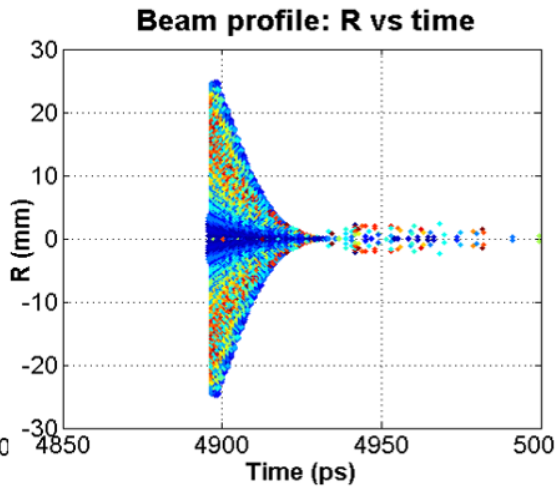
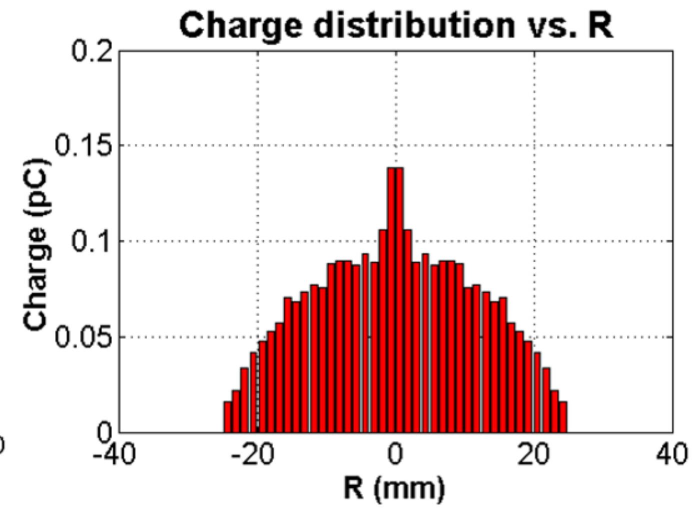
Beam Physics: Simulated Integrated Electron Gun

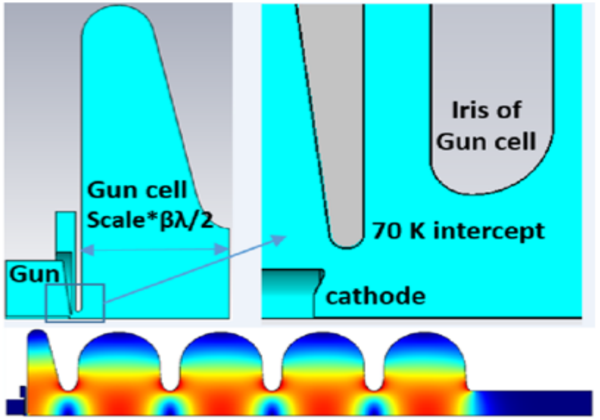
Reduces size and complexity







	Value
Electron energy	9 MeV±5%
Current modulation range	0.1 µA - 1 mA
Beam loss at 4K	<0.5 W
Cathode backward bombardment	<1 W
Cathode blackbody radiation	< 200 mW



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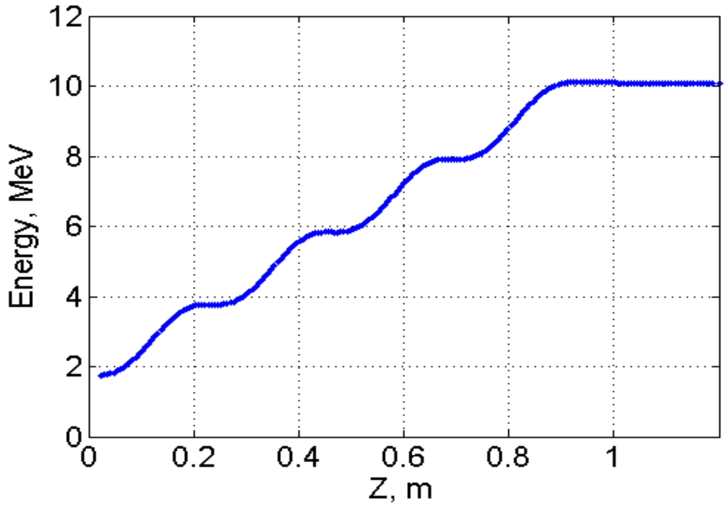
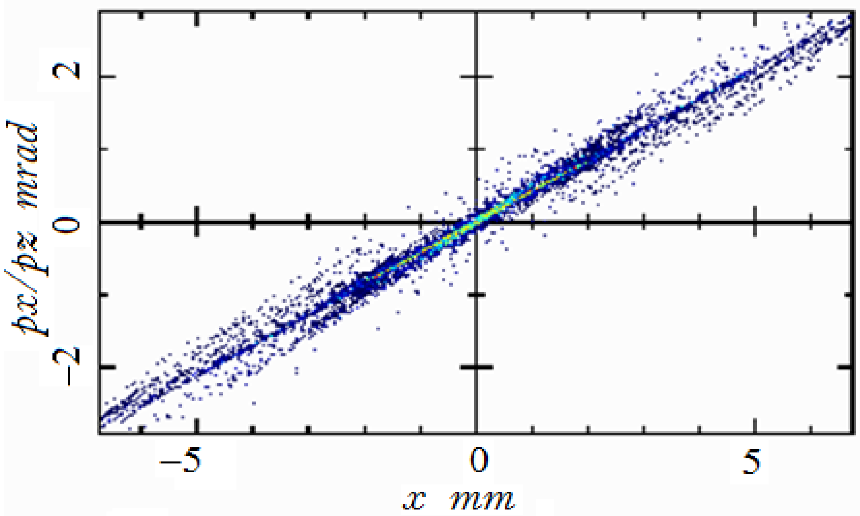
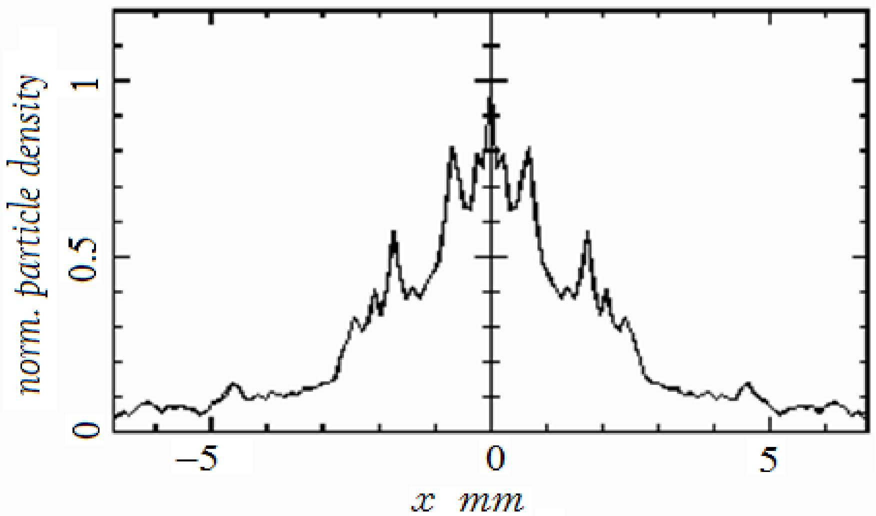
Simulations of the Cavity

:

- *(Top) Bunch acceleration along the cavity (RMS energy).*
- *(Bottom Left) Transverse (x-x') phase-space distribution.*
- *(Bottom Right) Transverse beam charge density distribution.*



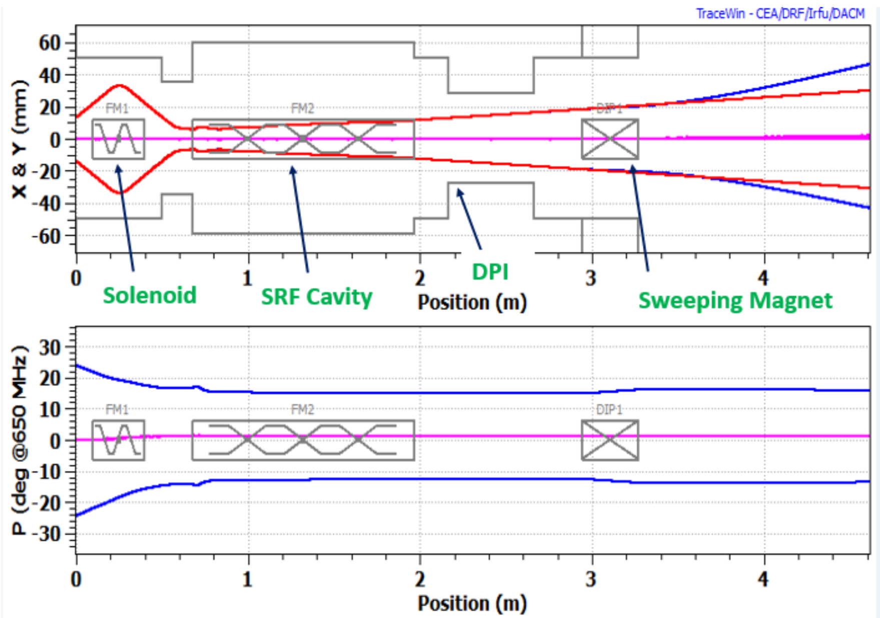




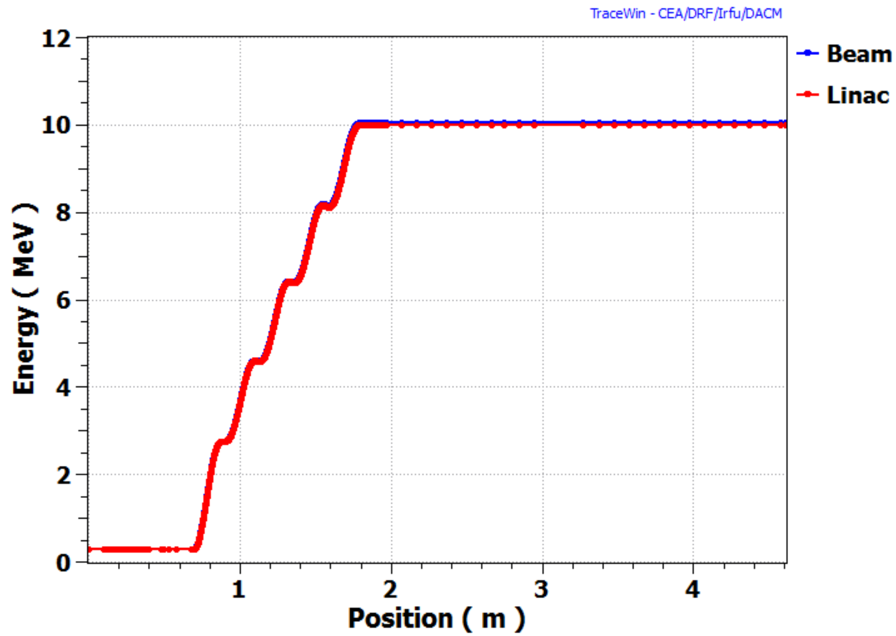
Particle losses in simulations < 10-5. (This is important for the heat budget)

Beamdynamics Simulation from external injection (1)

3σ beam envelopes

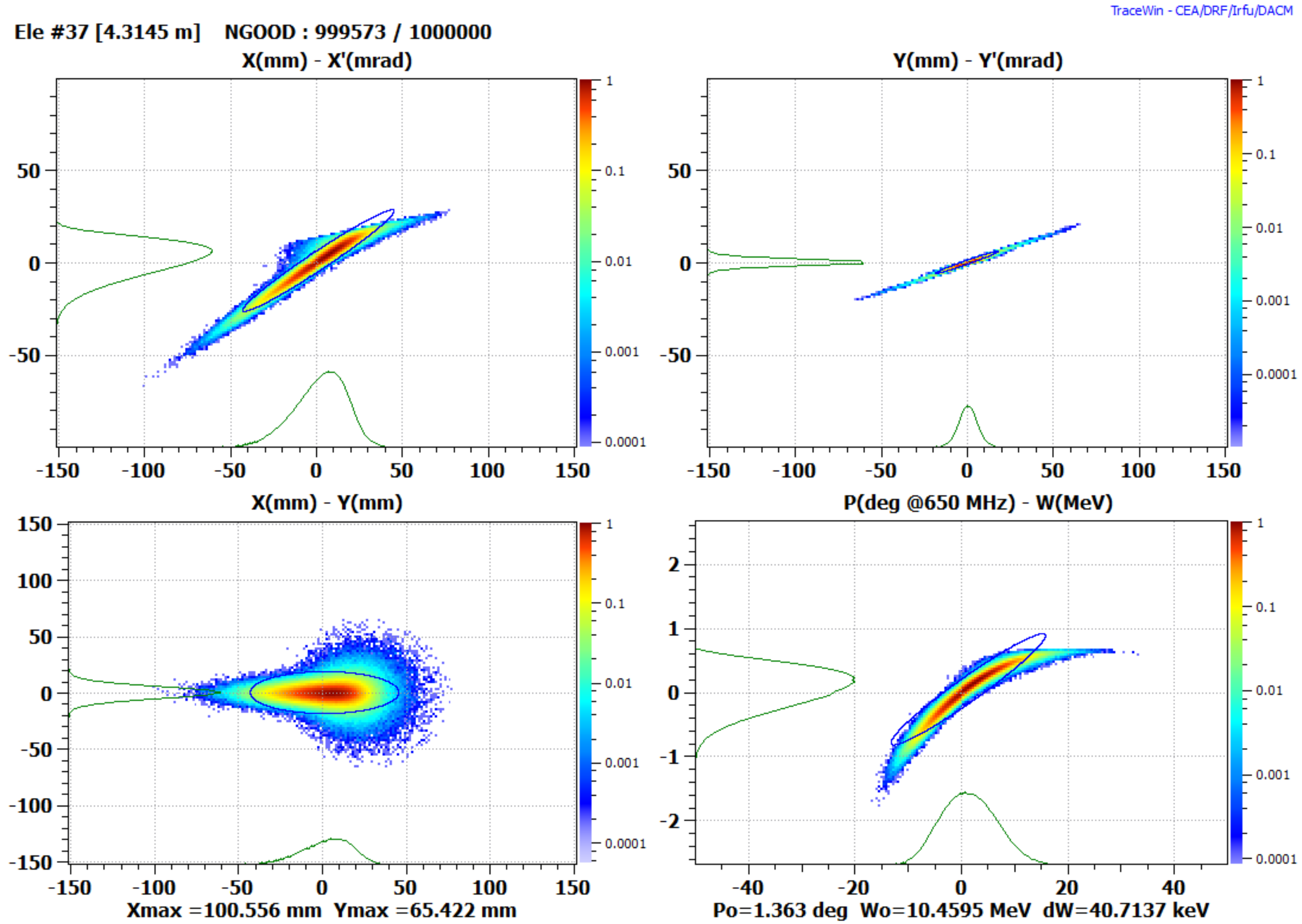


Beam Energy



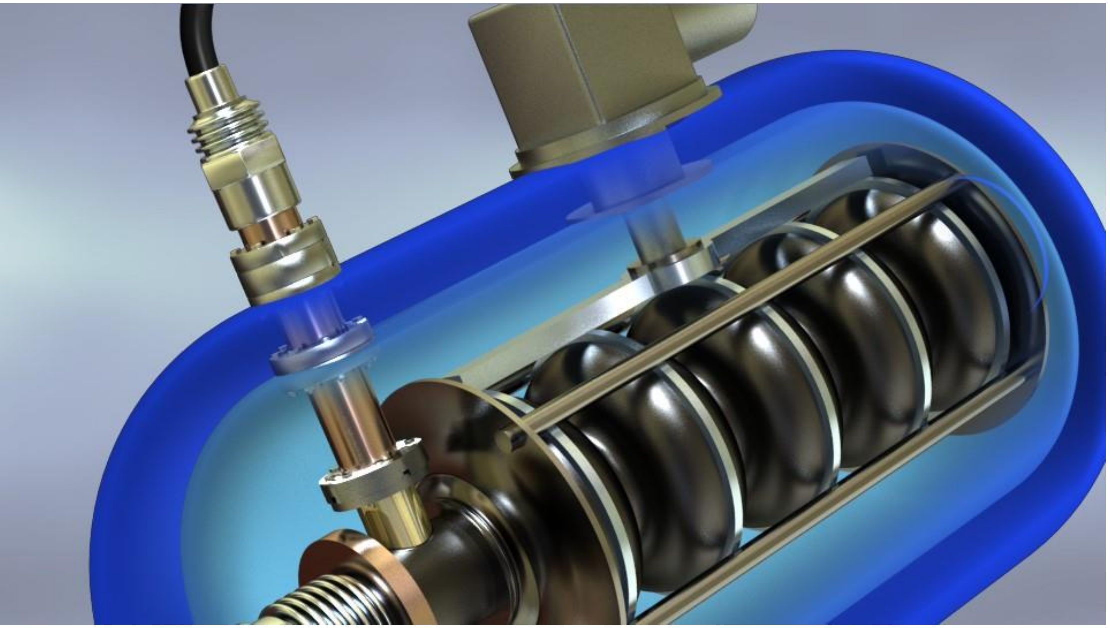
- Beamdynamics simulation was performed using TRACEWIN.
- 1M macro particles corresponds to 100mA beam current was tracked through the beamline.
- Initial distribution was generated using Twiss parameters and beam emittance obtained from RF gun simulation .

Beamdynamics Simulation from external injection (2)



- Output beam distribution at the end of the beamline

Conduction Cooling R&D



Cold head(s) of the cryocooler(s) connected to cavities by high purity aluminum

Estimated heat budget for entire accelerator = 4 – 6 W @ 4K

Remove heat by conduction only!

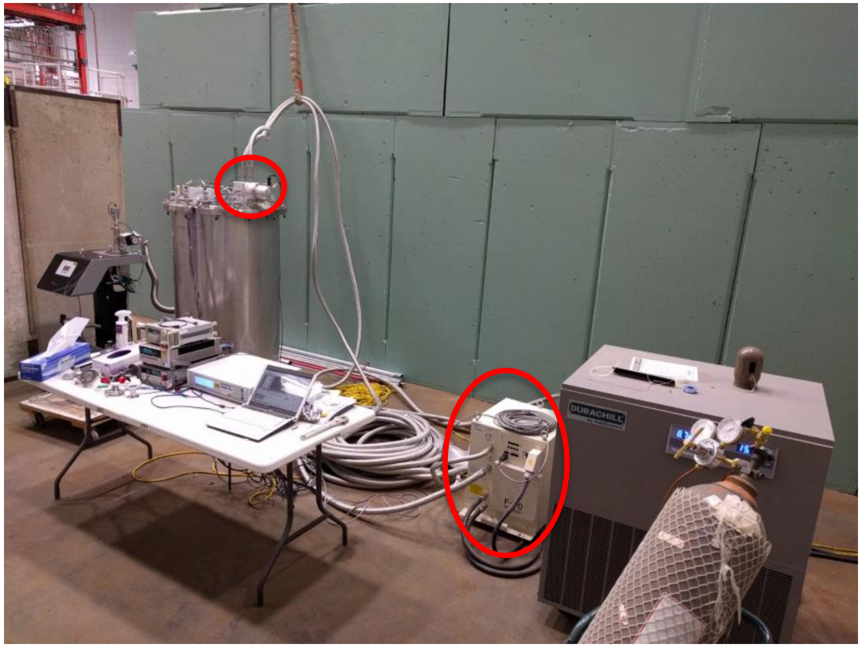
US patent applications

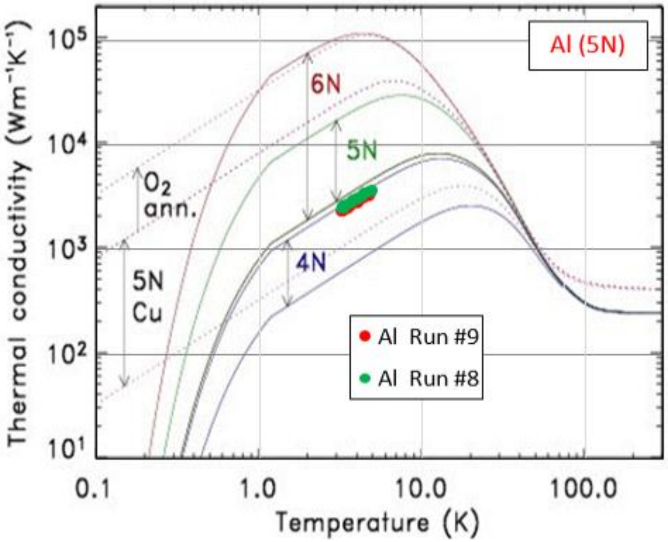
#15/280,107

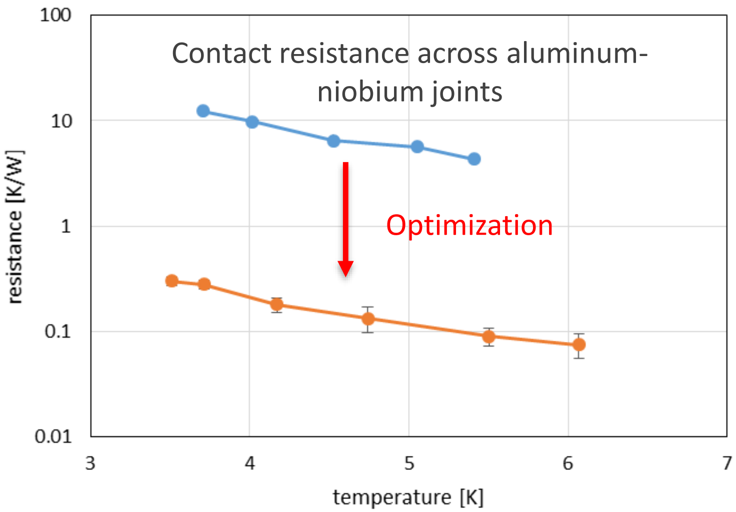
#14/689,695

Conduction Cooling R&D

- Testing with commercial cryocooler
  - Goal = eliminate liquid cryogens
  - Materials and technology Development in progress



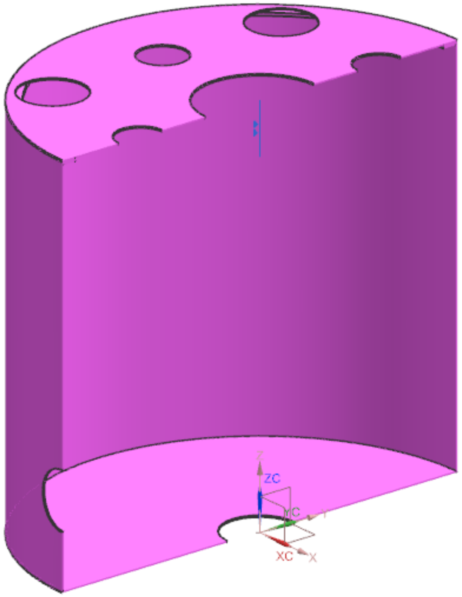




- Funded by $ 1.4 M LDRD Project

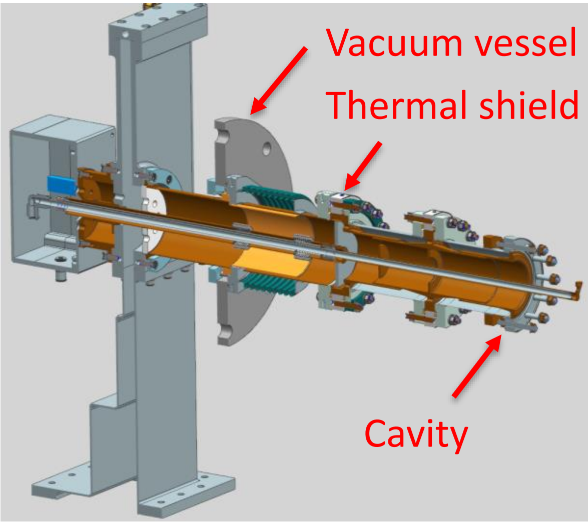
Challenges

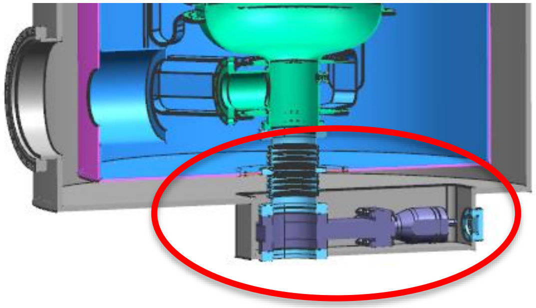
- Magnetic shield
  - SRF cavities are very sensitive to trapped magnetic fields
  - need < few mG to keep RF heat dissipation under cryocooler budget
  - penetrations and access ports are to be carefully designed



Magnetic shield with penetrations

- Interfaces with e-gun, power coupler, beam outlet port



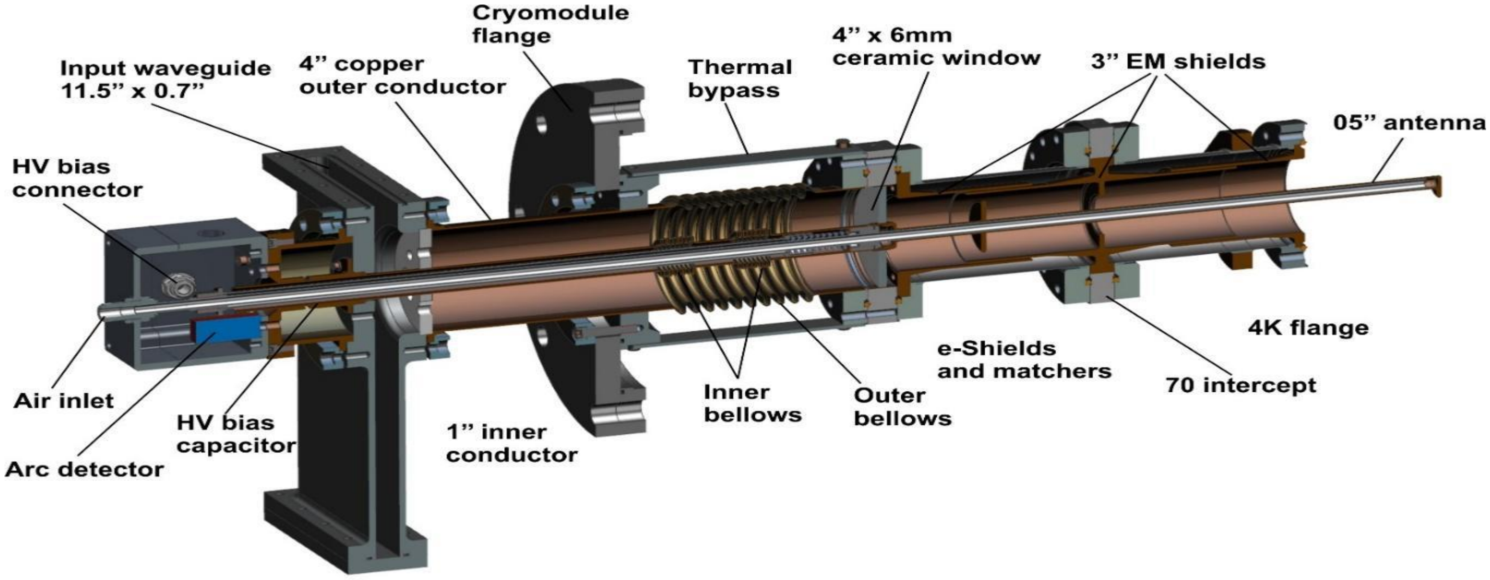


Shut-off valve at beam outlet

Low loss RF power couplers

FNAL and Euclid TechLabs

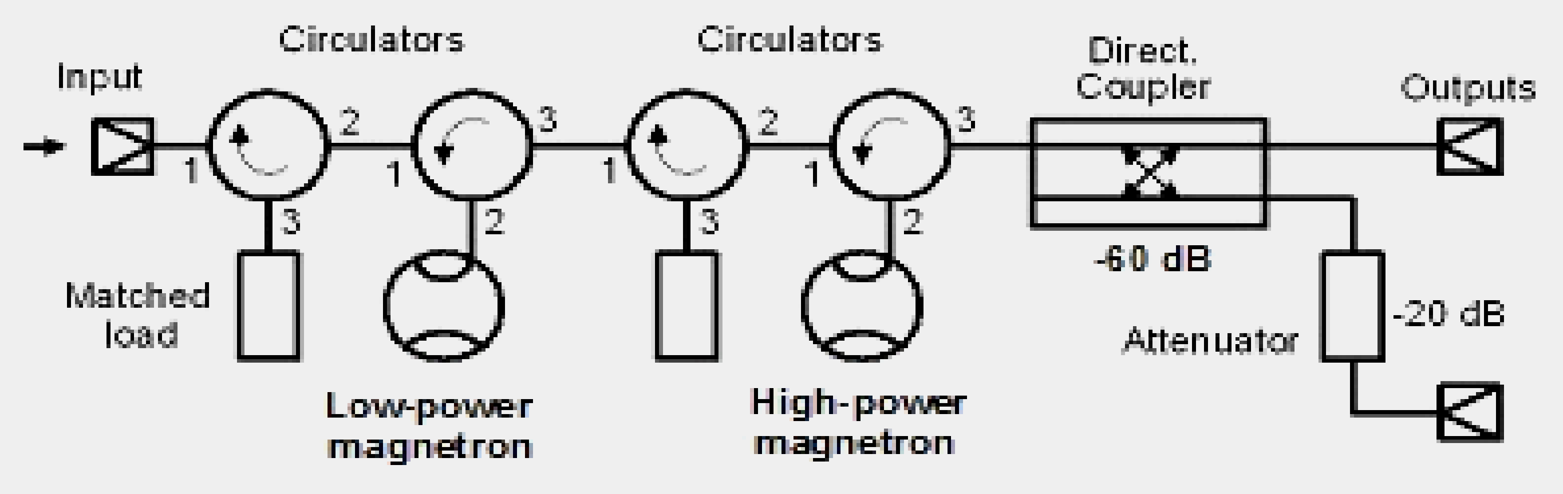
- Patent application # 15/278,299
- DOE OHEP grant to fund fabrication of two 1.3 GHz prototypes
- Testing this year
- Eliminates copper plating



Reduce cost

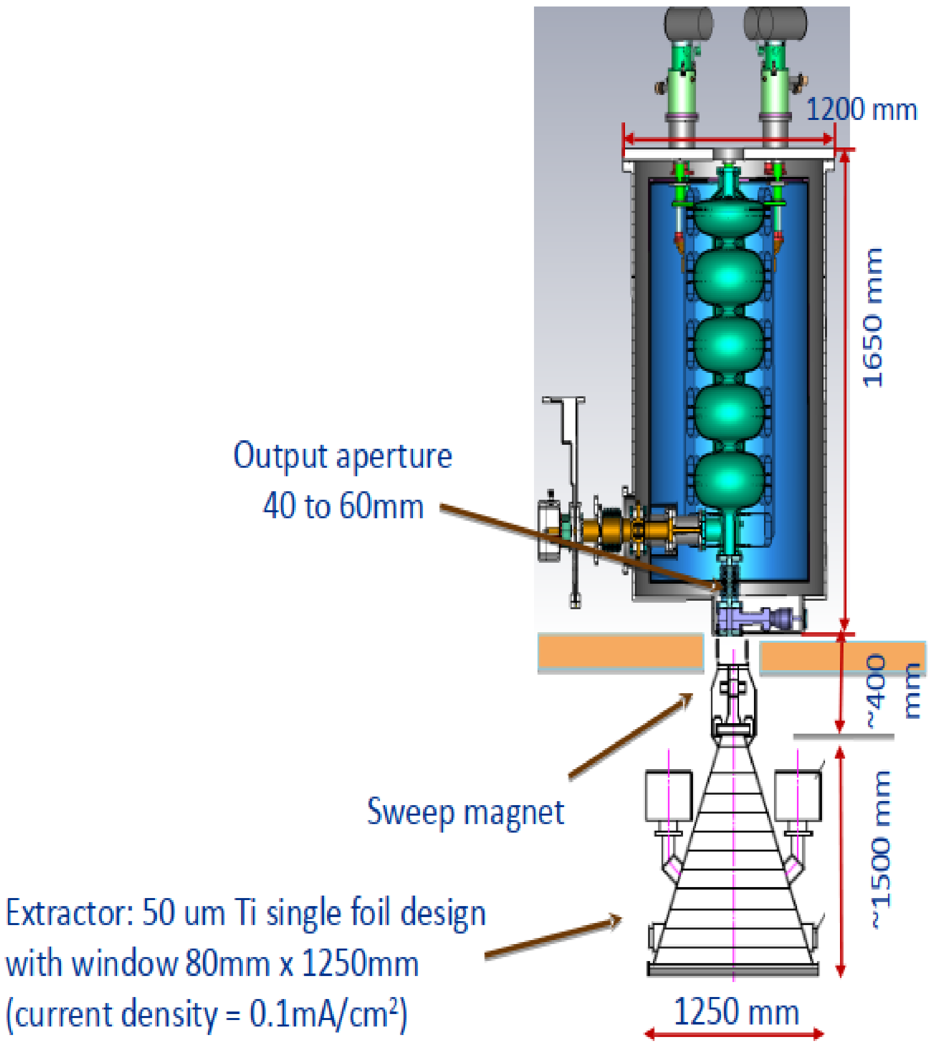
Injection locked magnetron (PCT/US2014/058750)

- Reduce cost/watt by factor of 5 over IOT and solid state
- Efficiency > 80%
- Excellent phase and amplitude control



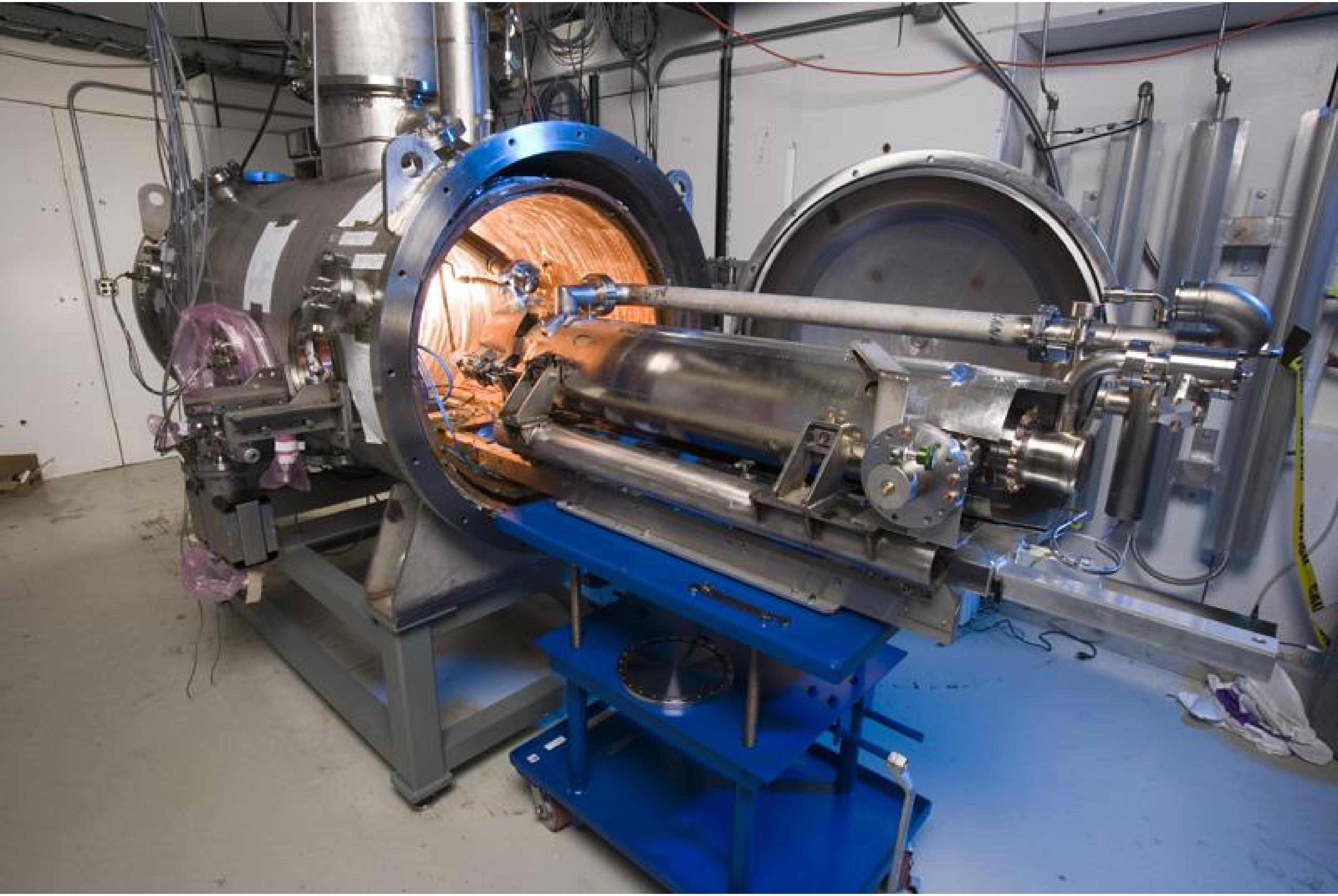
Conceptual scheme of a single 2-cascade magnetron transmitter allowing dynamic phase and power control

Radiation Shielding: Development of a computer model

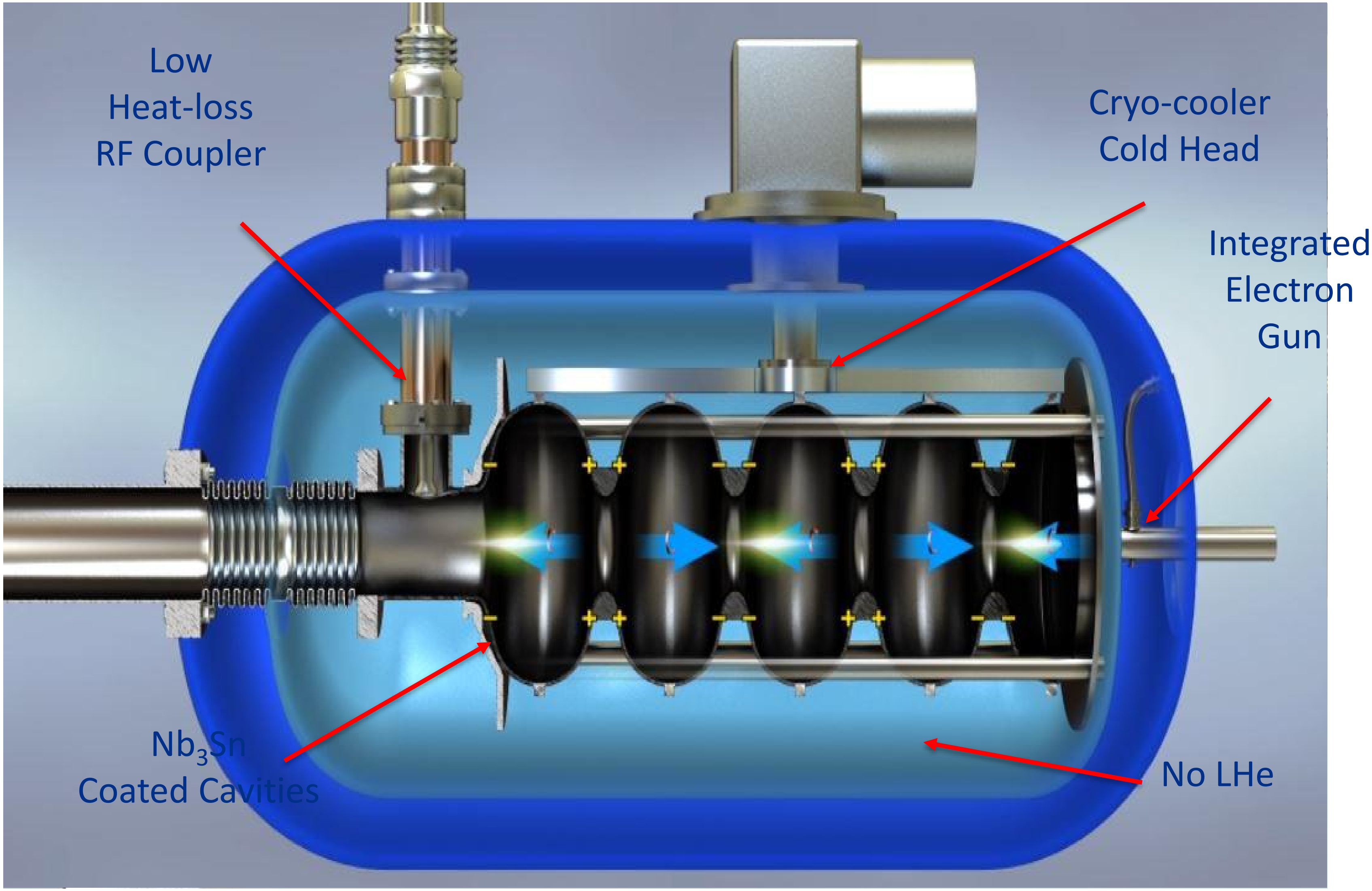


- A 3-D computer model was developed to address absorbed dose rate in the water and evaluation of back scattered particles energy distribution at 4K and 70 K in the cryostat.
- A realistic Model was prepared by accounting EM fields in SRF cavities, 3-D geometry of elements, materials and their thickness.

The Compact SRF Accelerator (for scale)



The Compact SRF Accelerator



Solicitation for advancing industrial accelerators

- Dept. of Energy provided funding to develop novel accelerator designs to address need for industrial application in the energy and environment sectors

Table 2. Target performance for high power electron accelerators for E&E applications:

	Type 1 Demo/Small Scale	**Type 2 Medium Scale Low Energy**	**Type 3 Medium Scale High Energy**	**Type 4 Large Scale High Energy**
Example Applications	*R&D, Sterilization, industrial effluent streams*	*Flue Gas, Waste water*	*Wastewater, sludge, medical waste*	*Sludge, Medical waste, Env. remediation*
Electron Beam Energy	0.5-1.5 MeV	1-2 MeV	10 MeV	10 MeV
Electron Beam Power (CW)	>0.5 MW	>1 MW	>1 MW	>10 MW
Wallplug Efficiency	>50%	>50%	>50%	>75%
Target Capital Cost*	<$10/W	<$10/W	<$10/W	<$5/W
Target Operating Cost†	<1.0M$/yr	<1.5M$/yr	<1.5M$/yr	<12M$/yr

U.S. DEPARTMENT OF ENERGY | Office of Science

*S. Henderson and T.D. Waite, Workshop on Energy and Environmental Applications of Accelerators, U.S. Deptof Energy, June 24-26, 2015. (https://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Energy_Environment_Report_Final.pdf)

Workshop on Application of Electron Beam (EB) Technology to Wastewater and Biosolids Treatment

May 10-11, 2018 (Thursday & Half Day Friday)

10-11 May 2018
Fermi National Accelerator Laboratory
US/Central timezone

Search

- Overview
- Timetable
- Meeting Directions
- Tours
- Registration
  - Registration Form
- Participant List
- Accomodations

Support

conferences@fnal.gov

This two-day workshop will include expert speakers on the current state of wastewater treatment, a summary of the science of using e-beam technology for treatment of waste, the current state of e-beam accelerator technology, a tour of Fermilab National Accelerator Lab, panel discussions with water treatment experts, breakout discussions and a summary close-out session.

Title:
Workshop on Application of Electron Beam (EB) Technology on Wastewater and Biosolids Treatment

Purpose:

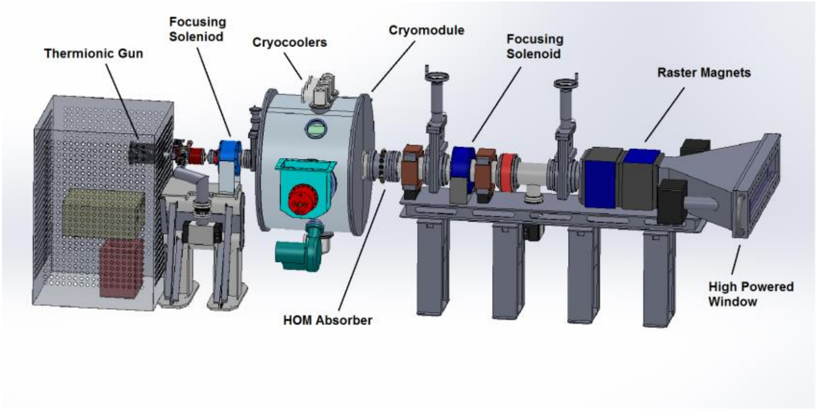
- Promote use of e-beam technology for wastewater and biosolids treatment
- Inform water treatment professionals about e-beam technology and opportunities
- Provide feedback to NSF to open future funding opportunities

Format:
This two-day workshop will include expert speakers on the current state of wastewater treatment, a summary of the science of using e-beam technology for treatment of waste, the current state of e-beam accelerator technology, a tour of Fermilab National Accelerator Lab, panel discussions with water treatment experts, breakout discussions and a summary close-out session.

Post conference a report will be issued with findings and recommendations.

Where:
Illinois Accelerator Research Center, Fermi National Accelerator Lab

1 MeV, 1 MW SRF accelerator



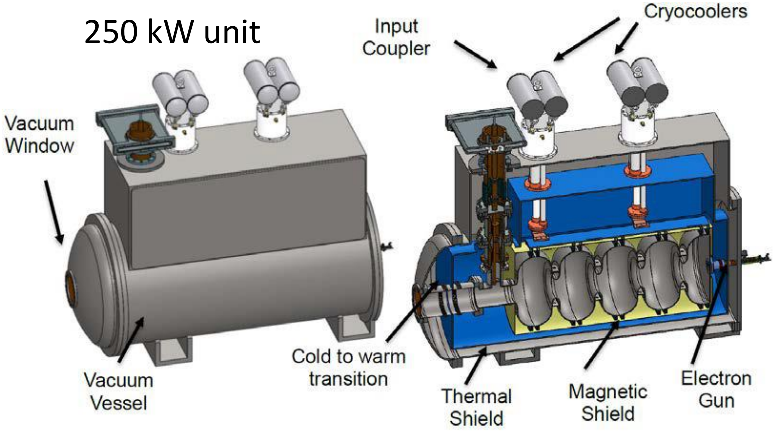
Jefferson Lab — G. Ciovati, R. Rimmer, F. Hannon, J. Guo, F. Marhauser, V. Vylet

Advanced Energy Systems, Inc. — J. Rathke, T. Schultheiss

General Atomics — J. Anderson, B. Coriton, L. Holland, M. LeSher

[2] G. Ciovati *et al., https://arxiv.org/abs/1802.08289*

10 MeV, 1 MW SRF accelerator



Fermilab — R. Kephart , V. Yakovlev, N. Solyak , I. Gonin , S. Kazakov , T. Khabiboulline , O. Prokofiev , S. Posen T. Kroc, C. Cooper, J. Thangaraj, R. Dhuley, M. Geelhoed

Northern Illinois University — Philippe Piot

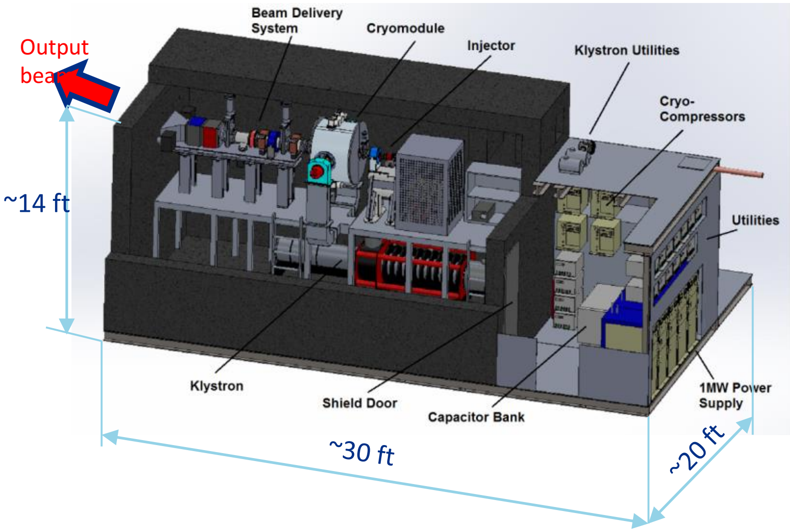
Colorado State University — Sandra Biedron

euclid TECHLABS — A. Kanareykin

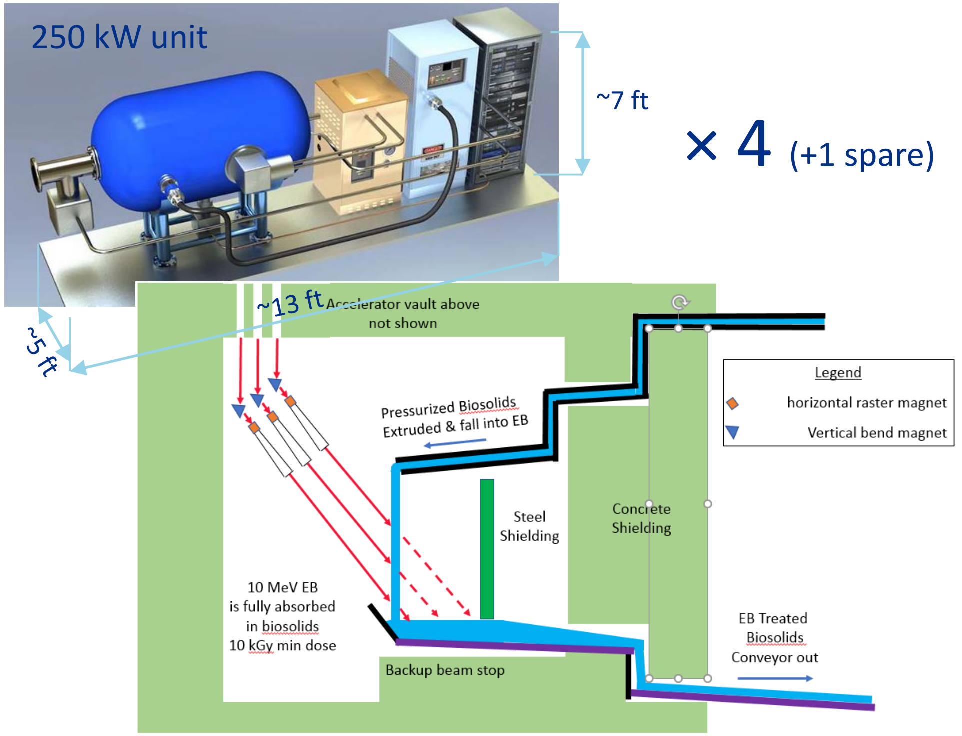
[3] *http://lss.fnal.gov/archive/test-fn/1000/fermilab-fn-1055-di.pdf*

Facilities Layout

1 MeV, 1 MW EB facility



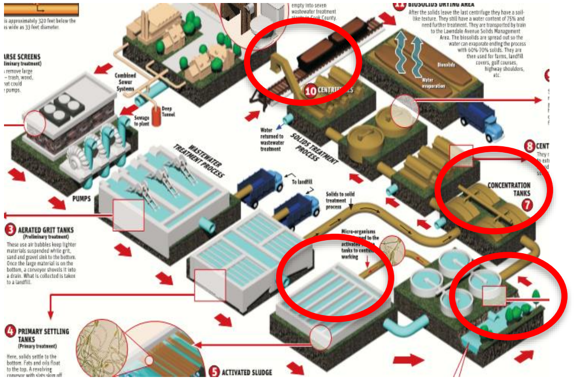
10 MeV, 1 MW EB facility



Application: Waste Water/Sludge Treatment

Accelerator above is 3 stories tall!

- Electron beams create highly reactive species
- Demonstrated effective for:
  - Disinfection of municipal bio-solids
  - Destruction of organics, pharmaceuticals
- Yet, despite demonstrations ~<u>no</u> market penetration
- Why? Municipalities are conservative; don't finance R&D
  - High power, cost effective, industrial accelerators have not been available to deploy* e.g. * http://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Energy_Environment_Report_Final.pdf
  - Compact SRF accelerators can change this situation
- IARC is partnered with the Chicago Metropolitan Water Reclamation District (MWRD)
  - Operate largest treatment plant in the world
  - Identified multiple areas to evaluate EB
  - Bio-solids, cell lysis, destroy pharmaceuticals



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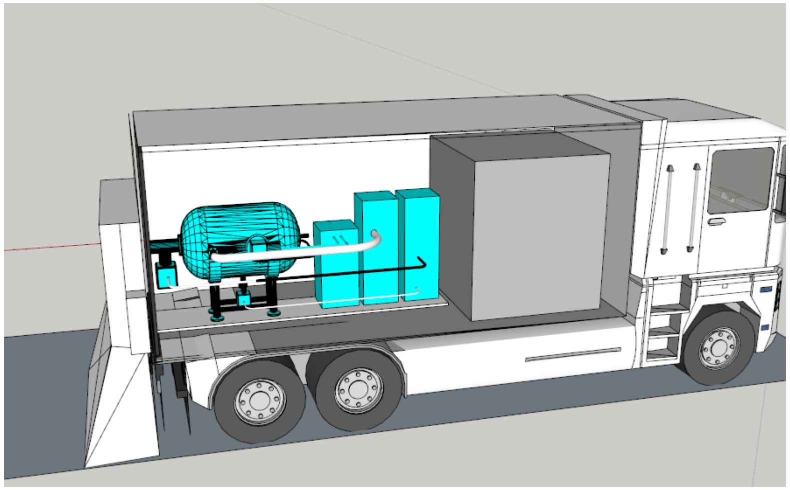
Application: Co ^{60} Replacement

- Electron beams can be used directly or to create x-rays to accomplish many tasks currently accomplished with Co60 radioisotopes
  - National security concerns with radioisotopes in large panoramic irradiators since they could potentially be used by terrorists to create dirty bombs
  - Pressure from congress on NNSA to find alternatives
  - FNAL recently completed a study for NNSA on impediments to change.
    - One impediment is the need for high power, reliable, cost effective electron accelerators
    - Need materials data on effects of gamma, electrons, x-ray to enable recertification of legacy products
- New Possibilities:
  - Cheap, compact, simple, industrial electron accelerators can enable "in line" sterilization at the point of manufacture

In-situ Environmental Remediation

- Since e-beams can disinfect or destroy organic compounds
- One can envision mobile SRF based accelerators for environmental remediation & decontamination.
- Examples
  - Clean soil contaminated by chemical spills
  - Remove hydrocarbons from soil
  - Destroy biohazards or toxins
  - Remove PCB's from dredge spoil
  - Provide an alternative to incineration

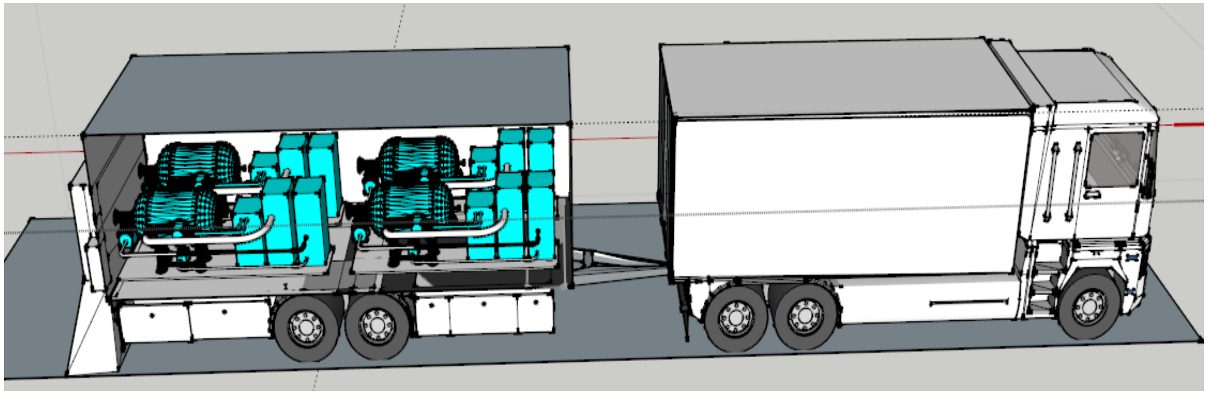


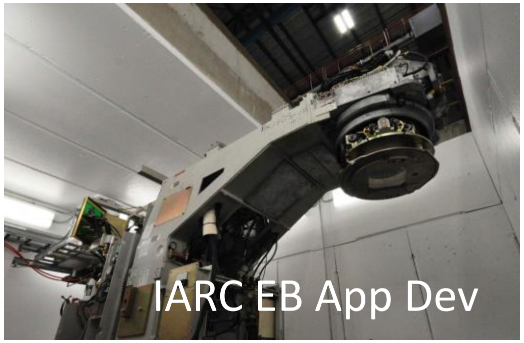
- Requires robust, reliable, compact, mobile accelerators that can be "brought to the problem"

In-Situ Cross-Link of Materials

Electron accelerators are widely used to cross link materials

- High power mobile accelerators enable entirely new construction techniques that can alter materials properties after placement
  - e.g. Improve the strength, toughness, and/or temperature range
- One applications: Improved Pavement
  - US Army Corps of Engineers partnership (FY17 ERDC funding)





- Collaborating to create a tough, strong binder with improved temperature performance vs bitumen to extend pavement lifetime
- U.S. spends > $ 50 B/yr to grind off and replace asphalt!

Conclusions

- Exploiting recent lab breakthroughs one can create high average power, CW, SRF-based electron linacs that are simple and cost effective for industrial applications
- The Illinois Accelerator Research Center at Fermilab is partnered with U.S. government agencies to create the first article of an entirely new class of industrial SRF-based electron accelerators that use no liquid cryogens
- Mobile, high energy, high power electron accelerators can enable a variety of entirely new industrial applications
- Several applications may have enormous market potential