FERMILAB-SLIDES-20-120-DI

Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Compact, high-power superconducting electron linacs for industrial applications

Jayakar Charles Thangaraj,

IARC,

Fermilab

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.

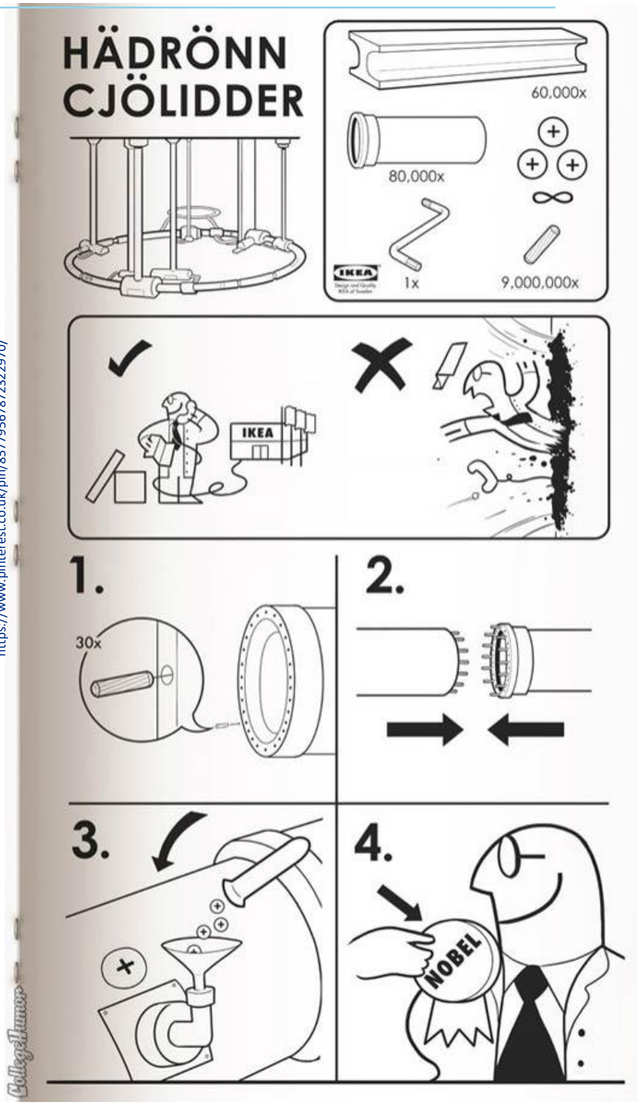
Accelerators for industry are different from collider machines!

- Accelerators for industrial applications:
  - Modest energy: few MeVs – tens of MeV
  - Modest power: tens of kW – hundreds of kW.

- Specific requirements:
  – Simplicity
  – Low cost
  – Reliability
  – Work in industrial environment (harsh!)
  – Easy to operate
  – Small sizes
  – High efficiency

Think IKEA!

https://www.pinterest.co.uk/pin/857795678723222970/



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)

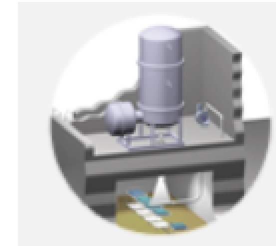
Commercial electron beam (EB) accelerator applications are vast

- EB welding
- EB melting
- EB sterilization
- EB curing
- Non-destructive testing
- Medical imaging
- Cargo inspection
- Accelerators beyond electrons: Ion-implantation, boron neutron capture therapy, etc..

…..A steady market

Current vs New Accelerator Technology

- Bulk materials processing applications require multi-MeV 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 ➔ physica large “fixed” installations = CAPEX

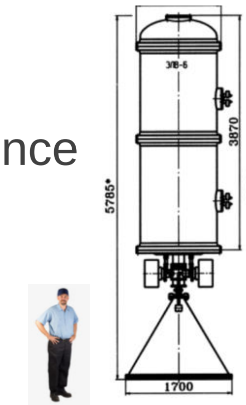


IBA Dynamitron

IBA Rhodotron

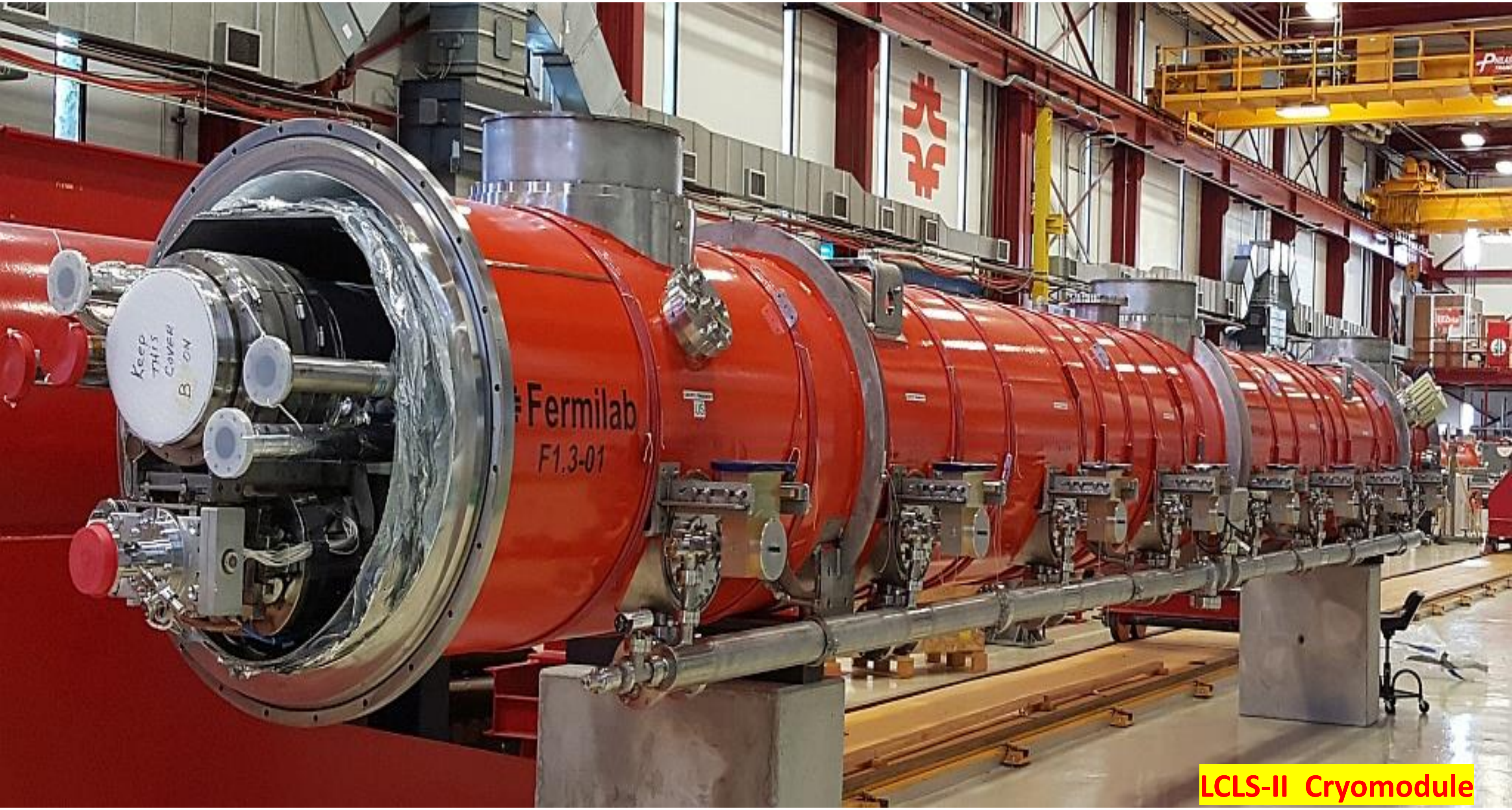
New Technology: Superconducting Radio Frequency (SRF)

- 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)



Budker ELV-12

Current SRF “science” accelerators are long and complex



~40 feet~school bus (37 cryomodules)

IARC is building a simple, compact SRF accelerator for industrial applications

Technology	Energy	Power	Issues/Potential
Room temperature (Copper) technology	Few MeV	Up to few hundred kW's	• Energy efficiency • Heat loss • Old(er) technology
Superconducting linacs (Niobium)	10 MeV	100 kW- 1+ MW	• CW • Excellent energy efficiency • "Backbone" technology of choice for > $1 B class modern science machines • ~~Complex cryogenics~~ • ~~100 m structures~~
Compact SRF (Niobium-Tin)	10 MeV	1 MW	• Simple cryogenics • ~ 1-m structure • All benefits of SRF minus the complexity

Fermi National Accelerator Laboratory (DOE)

- Mission: Discovery Science High Energy Physics ➔
- Build & operate: High Energy & Power (MW) Accelerators
- 6800 acre site, ~$360M/yr, Staff of 1700, > 2200 users
- 650 Accelerator scientists, engineers + technical staff
- Broad skills in accel. design, simulation, fabrication, & test
- NEW: The Illinois Accelerator Research Center (IARC)
  - Mission: Exploit technology developed in pursuit of science to enable new industrial accelerator applications & businesses

Accelerator Applications enabled by modern advancements.

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

Industrial and Security

- In-situ cross-link of materials
  - Improve pavement lifetime
  - Instant cure coatings
- Medical sterilization without Co60
- Improved non-invasive inspection of cargo containers
- Additive manufacturing refractory metals

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

SRF-based science accelerators are huge with complex cryogenic refrigerators, cryomodules, etc.

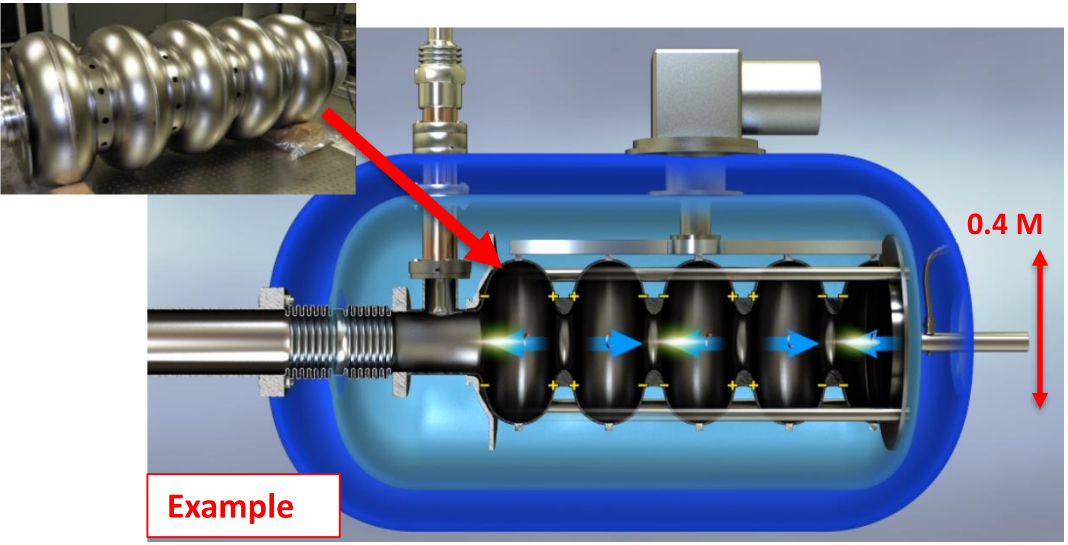
Recent SRF breakthroughs now enable a new class of compact, SRF-based industrial accelerators (lower CAPEX and OPS cost)

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 <u>simple</u> SRF accelerator



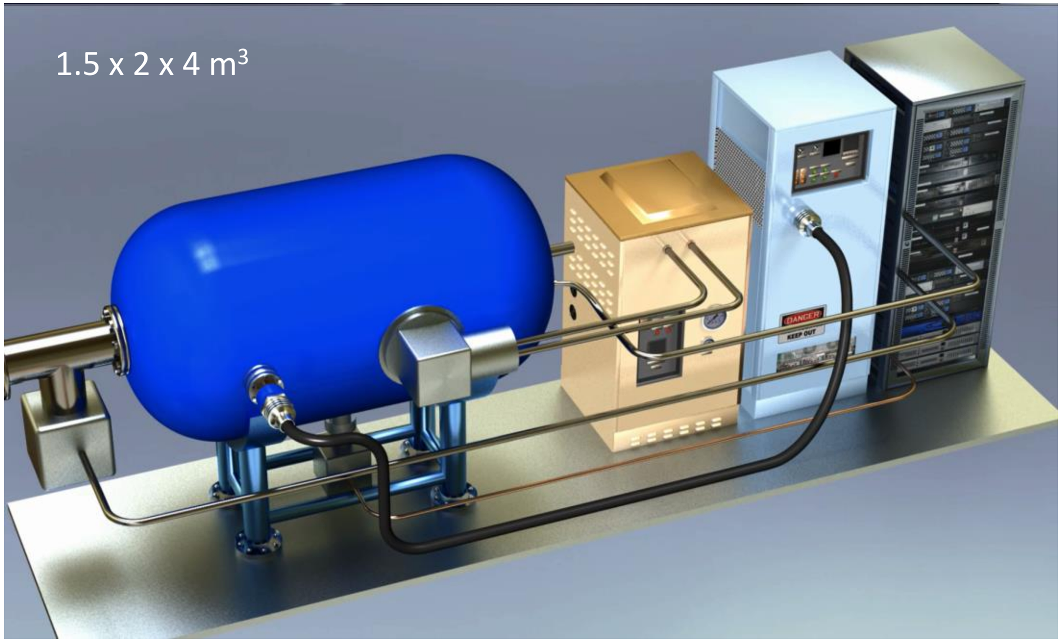
Final machine parameters

- 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

<u>Staged approach</u>: First demonstrate a 30 kW prototype including all the key technologies

Developing a 250 KW skid mount Version

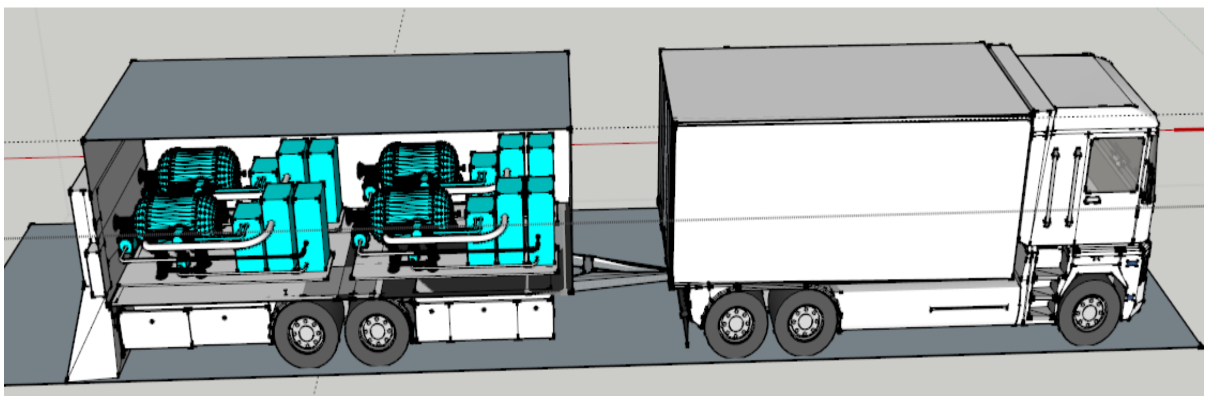


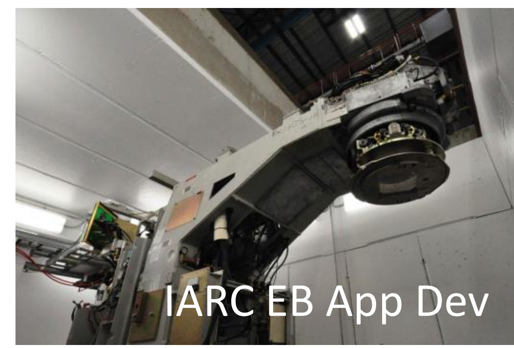
- Mobile high power accelerators enable new applications
- In-situ environmental or cross link applications
- DOE funds for conceptual design & key technologies
- Funded from DOD (USACE), interest from DHS, NNSA
- Goal: Create a new class of <u>industrial</u> SRF accelerators!

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 <u>after</u> placement
  - e.g. Improve the strength, toughness, and/or temperature range
- One applications: Improved Pavement
  - US Army Corps of Engineers partnership (FY17 ERDC funding)

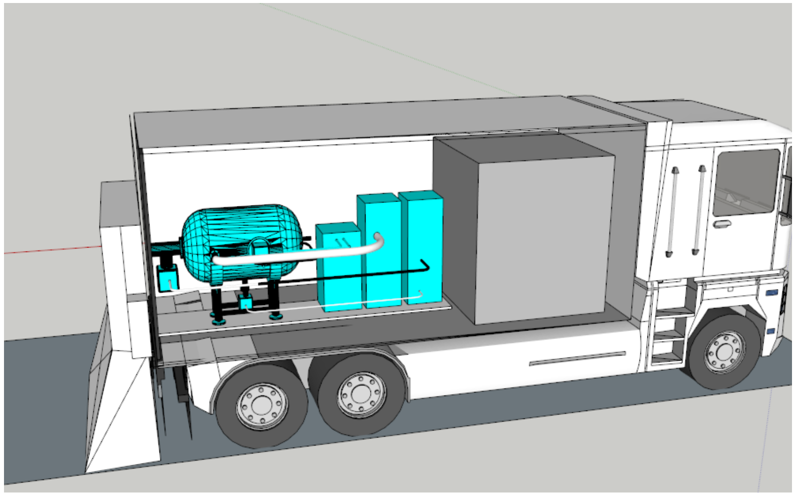




- Collaborating to create a tough, strong binder with improved temperature performance vs bitumen to extend pavement lifetime
- We have a small development facility A2D2 for rapid sample testing.

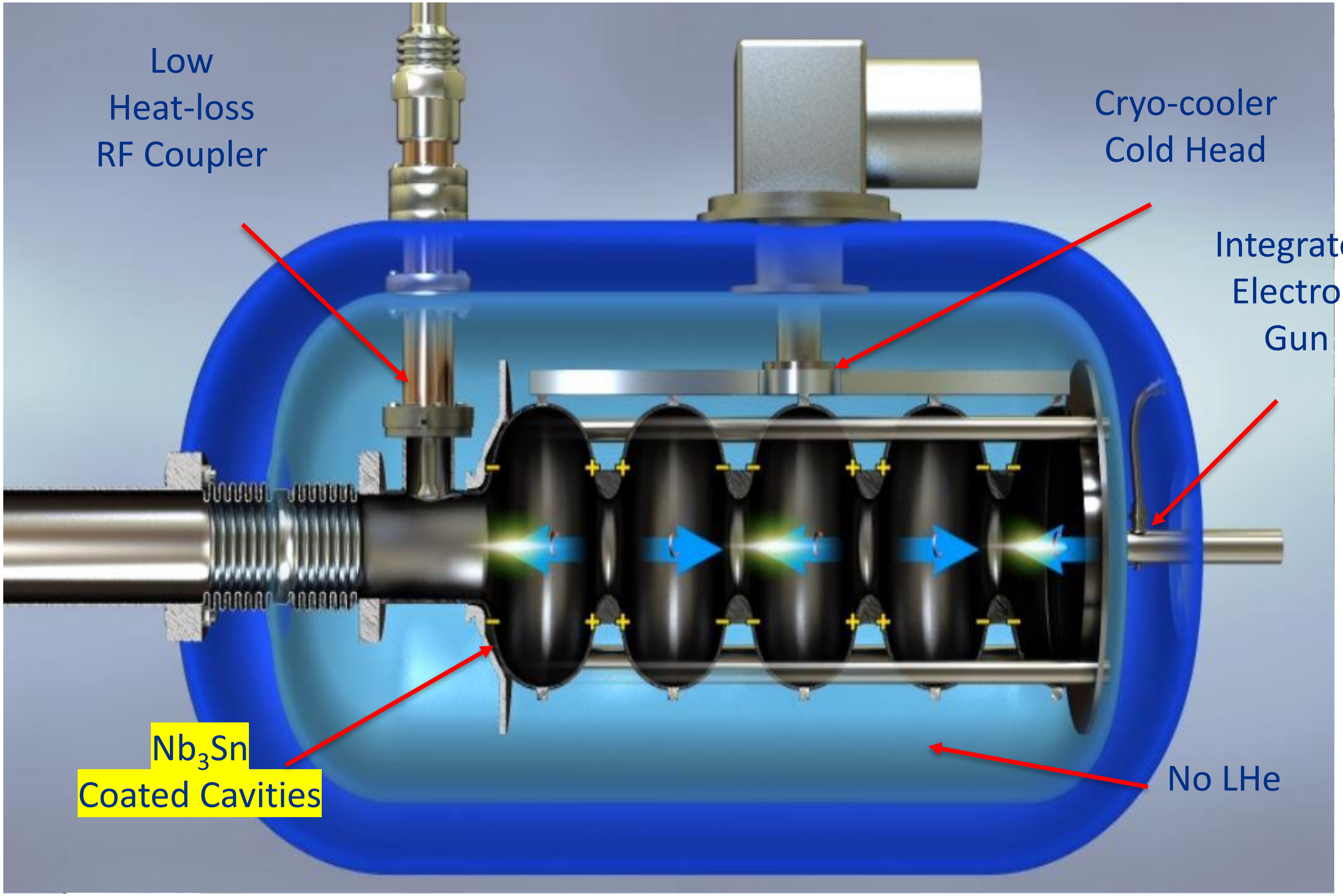
In-situ Environmental Remediation

- 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
  - Destroy biohazards or toxins
  - In-situ decontamination of equipment, HAZMAT suits, area
  - Wastewater treatment



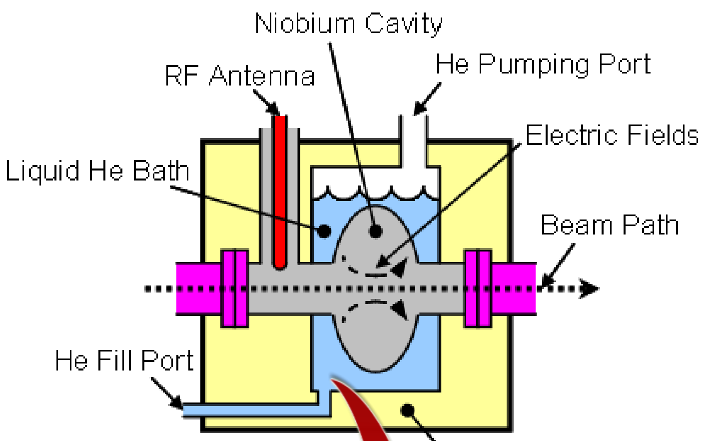
- Requires robust, reliable, compact, mobile accelerators that can be "brought to the problem"

The Compact SRF Accelerator



Current SRF “science” accelerators need complex infrastructure

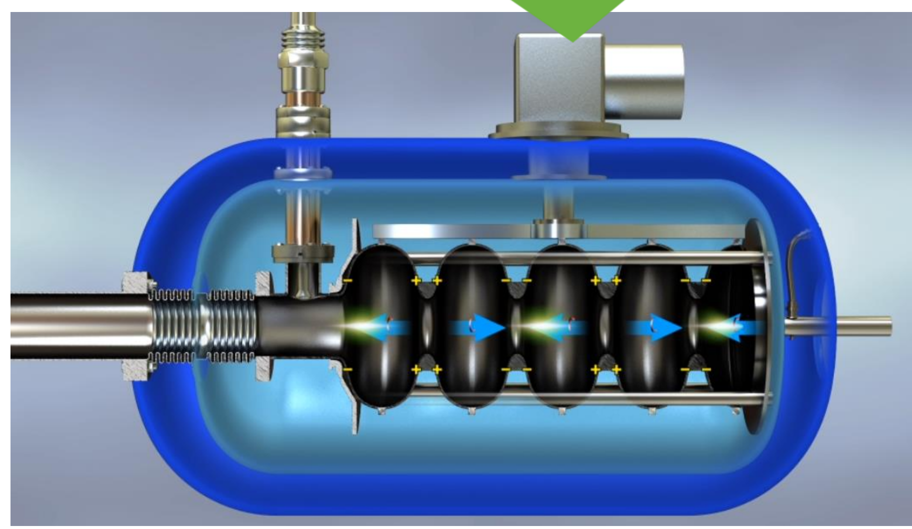
Vision: Access SRF technology minus the complexity



https://upload.wikimedia.org/wikipedia/commons/c/c4/SRF_Cavity_Diagram_1.png

Take out liquid helium (and its complexities)

Cool with a cryocooler (simpler refrigerator)



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Constraints from the application side help us push!!

Electron beam radiation processing applications

- Water/sludge/medical waste decontamination
- Flue gas cleanup
- Medical device sterilization
- Strengthening of asphalt pavements

Radiation processing requires:

- Beam energy: 0.5-10 MeV
- Beam power: >>100 kW

Industrial settings demand:

- Low capital and operating expense
- Robust, reliable, turnkey operation

http://accelconf.web.cern.ch/AccelConf/napac2016/talks/thb3io02_talk.pdf

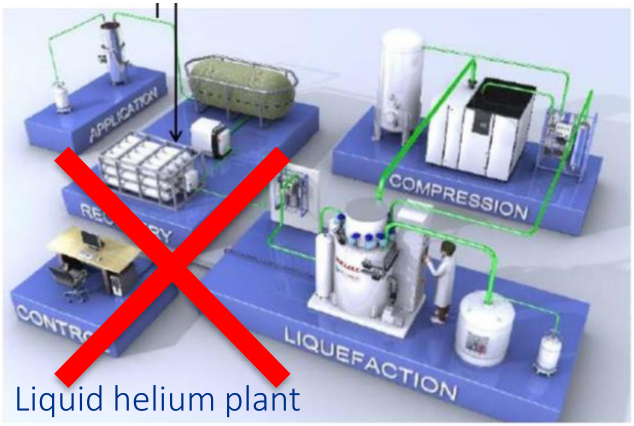
1-meter long SRF linac (niobium or Nb_3Sn cavities) operating at 10 MV/m can provide the required energy

Small SRF surface resistance enables continuous wave (cw) operation, leading to high average beam power

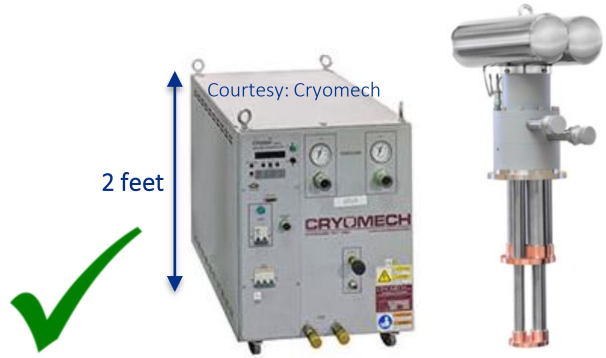
At present, SRF accelerators are designed to operate with complex liquid helium cryogenic systems!

Simplifying SRF cryogenics for industrial settings

Nb_3Sn cavity dissipates ~6-8 W @ ~4.5 K
(1 m x 10 MV/m cw; 650 MHz/1.3 GHz)



Use commercial, off-the-shelf 4 K cryocoolers
(helium plant not required)



Cryocoolers offer

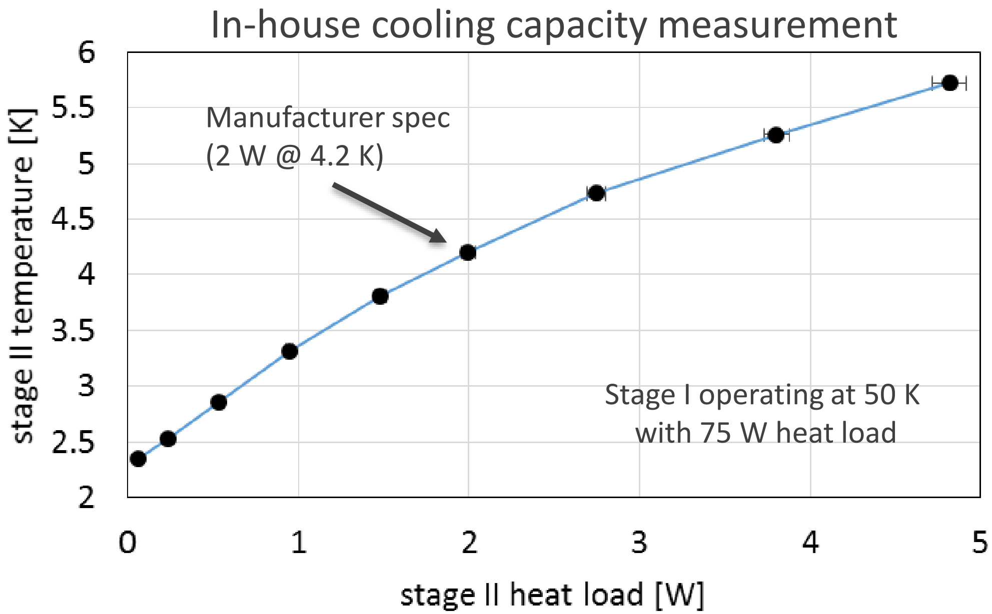
- Closed cycle cooling at ~45 K and ~4 K
- Compact, small footprint
- Reliability (MTBM > 2 years non-stop operation)
- Turnkey operation (no trained operator needed, turn ON/OFF with push of a button)

Push of a button to reach 4.2 K

- Selection, procurement, and test of cryocoolers

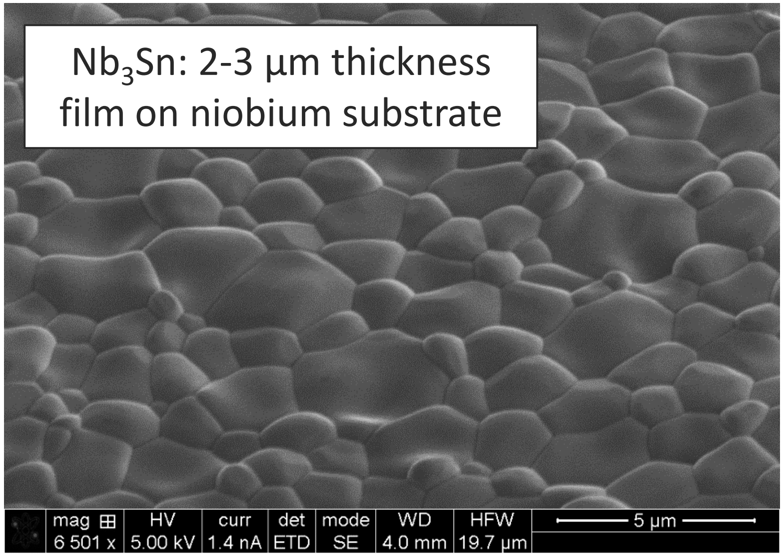
Cryomech PT420

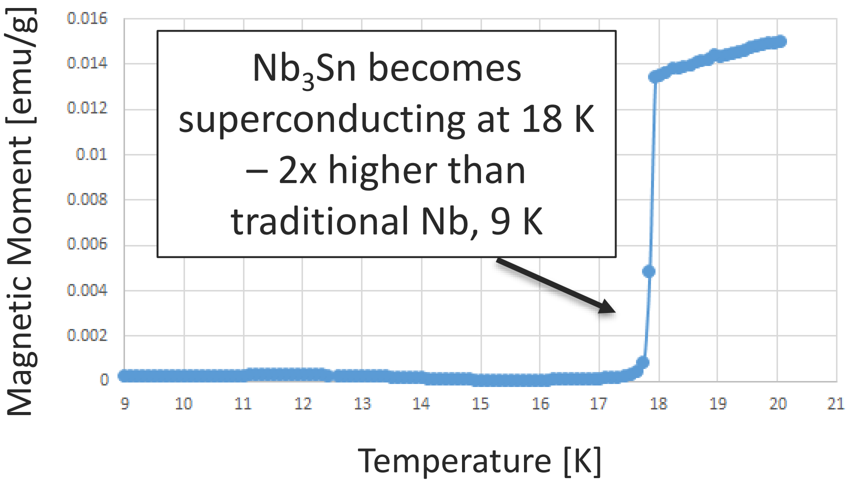
- Highest cooling power in the market
- Low vibrations, low maintenance



General concept of Nb_3Sn Films

- Traditional niobium has tens of watts of dissipation at 4.4 K
- Nb_3Sn film provides ~order of magnitude smaller heat load for same conditions
- Nb_3Sn goals:
  - Establish capability of coating cavities with high performance at Fermilab
  - Develop Nb_3Sn coating at 650 MHz (larger cavity)
  - Develop Nb_3Sn coating of multicell cavities





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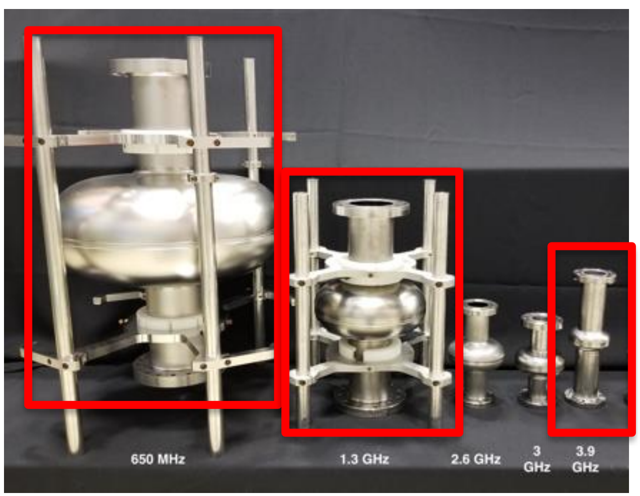
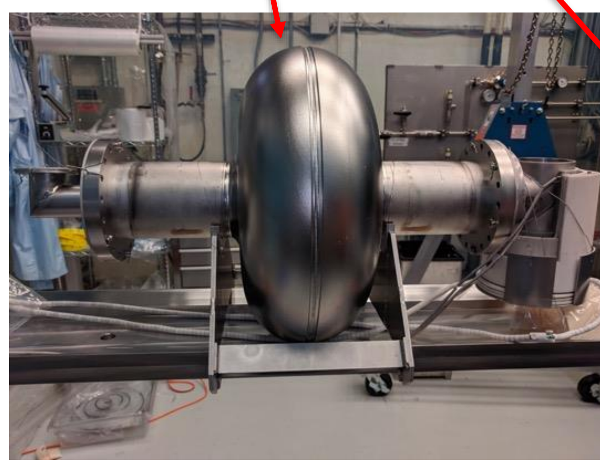
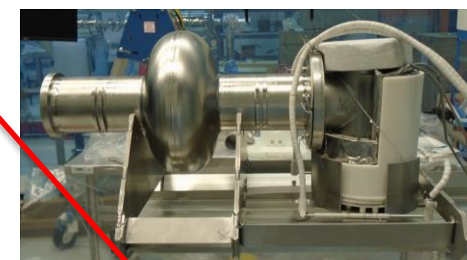
Progress of Nb_3Sn Films

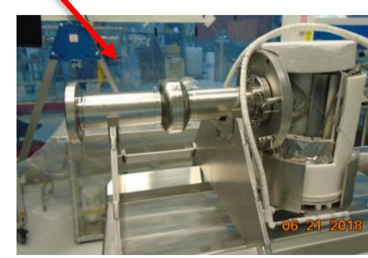
- Frequency dependence of R_{BCS}, R_{res}, quench, sensitivity
- 650 MHz is an interesting step between scaling up form a 1-cell 1.3 GHz to a 9-cell 1.3 GHz cavity
- Better understand how vapor diffusion process scales with different sized substrates

Fermilab Nb_3Sn SRF program: a number of 1.3 GHz cavities already coated and tested; these are the first 650 MHz and 3.9 GHz cavities

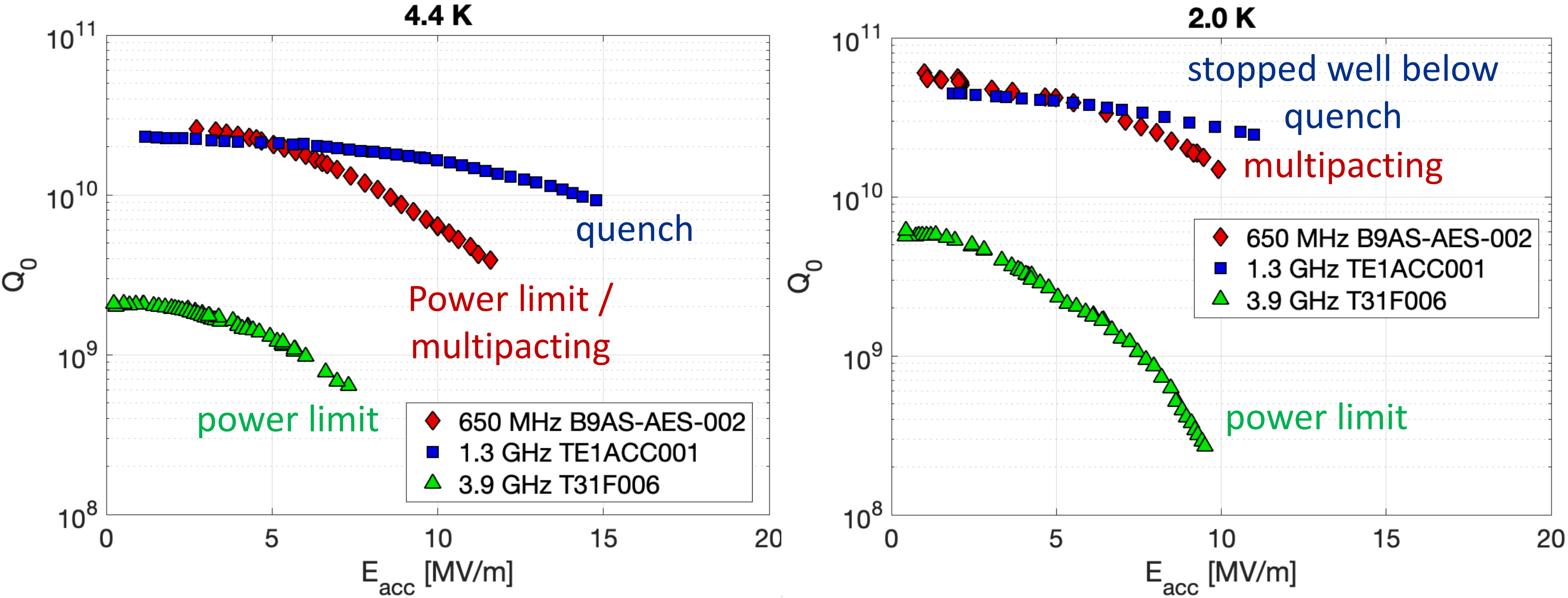








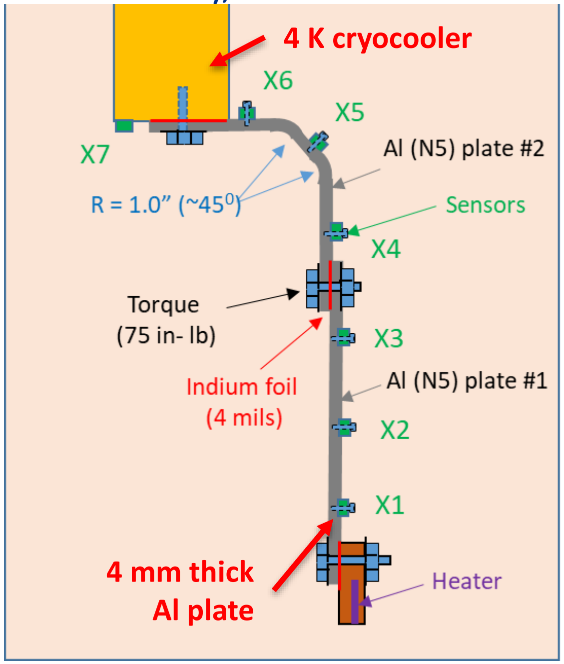
Q vs E: 4.4 K and 2.0 K (ongoing work: not the latest!)

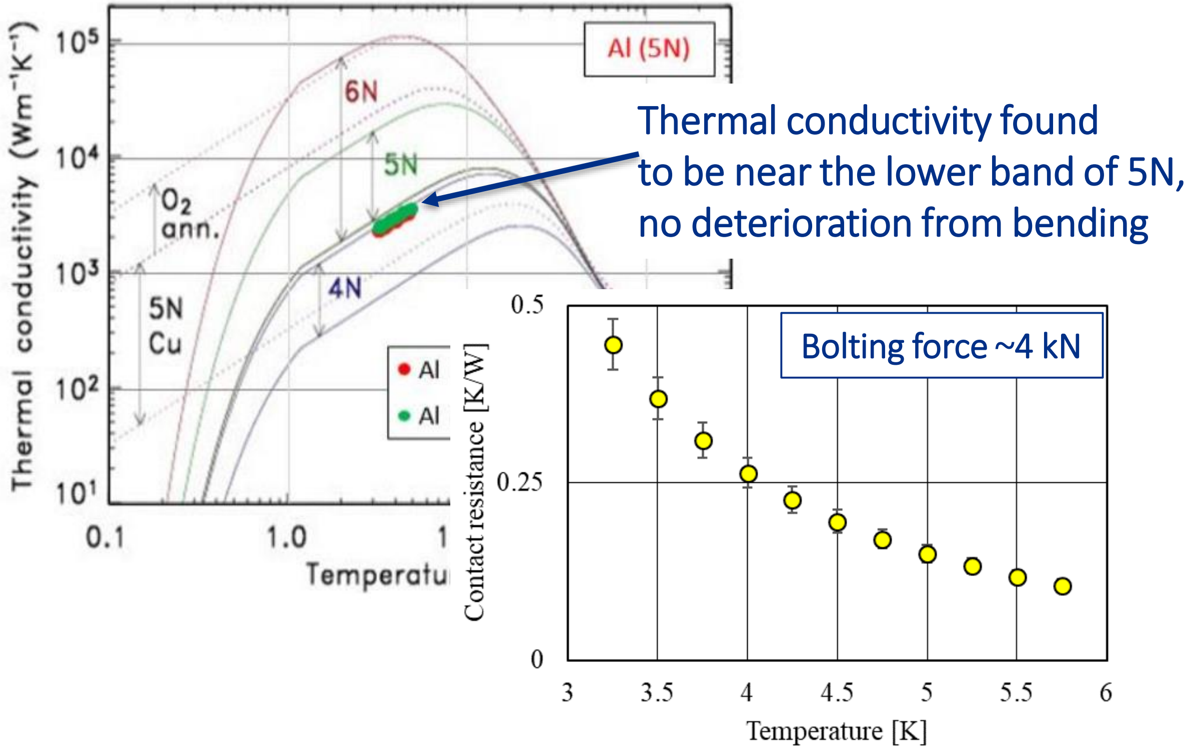


- Q-slope is strong in 3.9 GHz cavity – will re-coat to try to avoid defects
- 650 MHz: some Q-slope and multipacting but still very good – Q_0(5 MV/m) >10 higher than expected for Nb at 4.4 K

Conduction cooling: Characterization of thermal resistance

Setup for measuring 4 K thermal conductivity, contact resistance



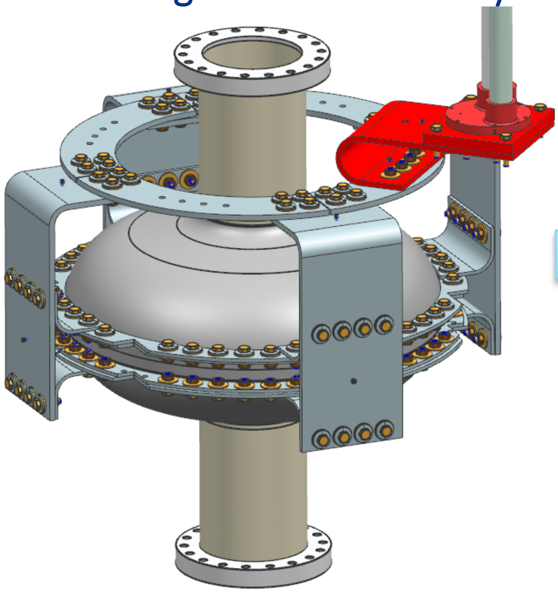


R.C. Dhuley, M.I. Geelhoed, J.C.T. Thangaraj, ***Cryogenics***, 2018.
https://doi.org/10.1016/j.cryogenics.2018.06.003

Design of the conduction link design

Mechanical design; verification *via* multiphysics simulations

Al conduction link bolted to the Nb rings around the cavity

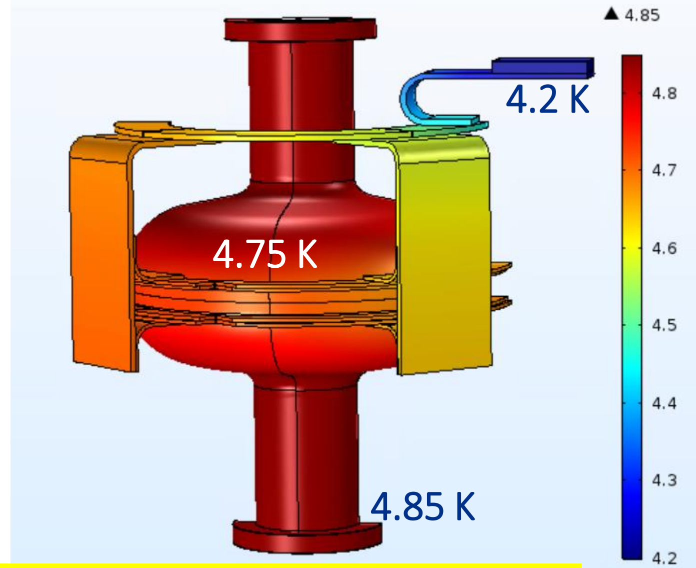


Nb_3Sn surface resistance (BCS from SRIMP + 10 nΩ)

RF + thermal simulations

Thermal conductivities, contact resistance, cryocooler capacity

Steady state temperature profile at 10 MV/m cw (P_{diss} ≈1.45 W)

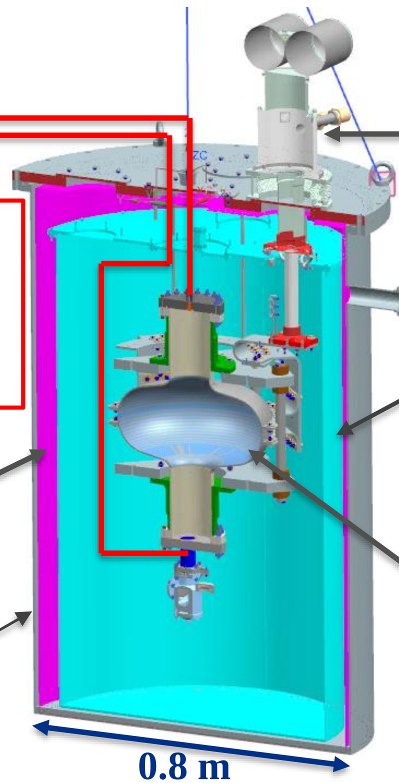


Simulated conductance ($P_{diss}/\Delta T$) ≈ 2.6 W/K

J. Thompson and R.C. Dhuley, 2019. https://doi.org/10.2172/1546003
R.C. Dhuley *et al.*, ***IEEE Trans. Appl. Supercond.***, 2019. https://doi.org/10.1109/TASC.2019.2901252

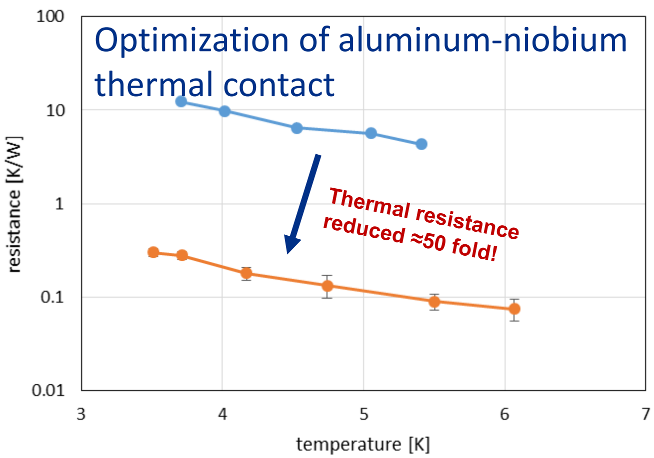
Conduction-cooled SRF cavity measurement setup at Fermilab

R.C. Dhuley *et al.*, ***IOP Conf. Ser.: Mat. Sci. Eng.***, 2020. https://doi.org/10.1088/1757-899X/755/1/012136



LDRD grant for $1.4 M

Order of magnitude reduction

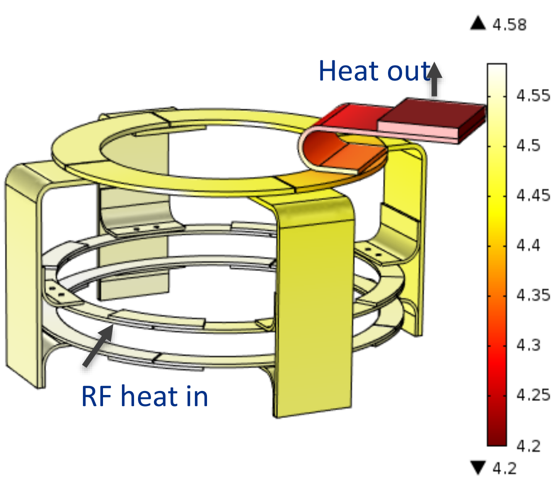


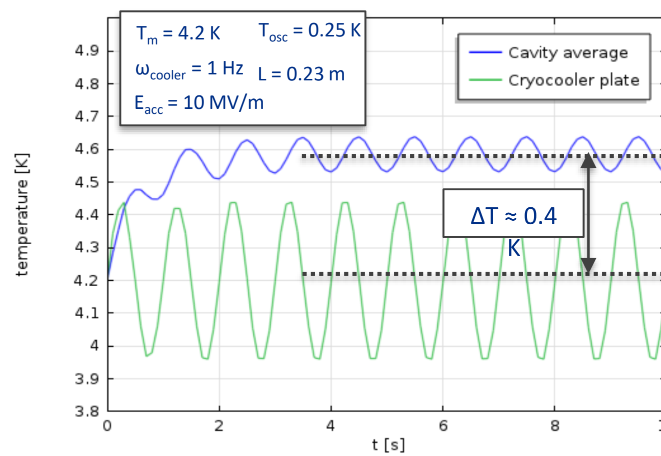
Cold head(s) of the cryocooler(s) connected to cavities by high purity aluminum

LDRD grant $1.4 M

Single cell SRF cavity ready for 4 K RF testing with a cryocooler

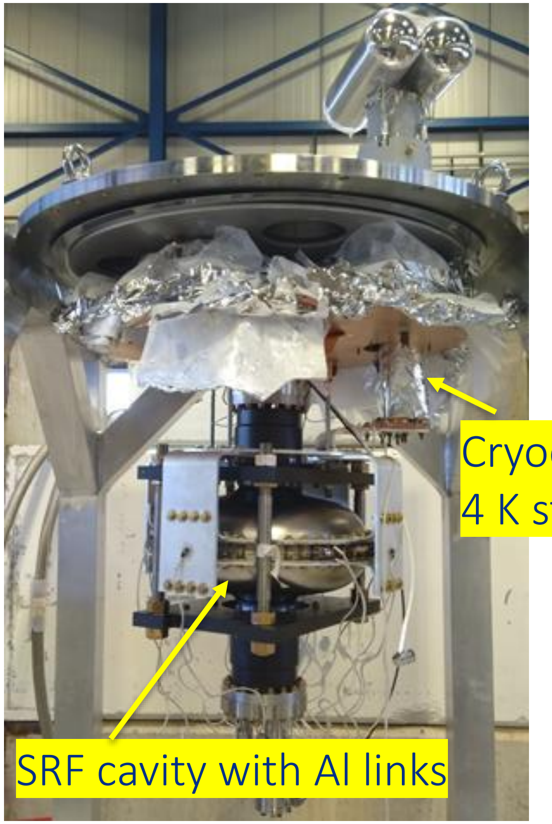
Thermal link simulations

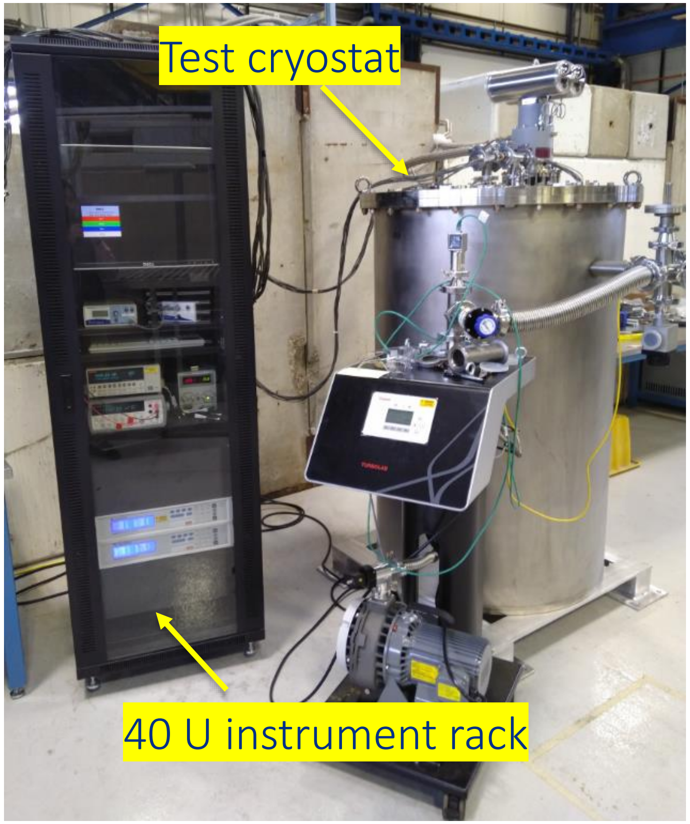




US patent applications
#15/280,107
#14/689,695

Conduction-cooled SRF cavity measurement setup at Fermilab

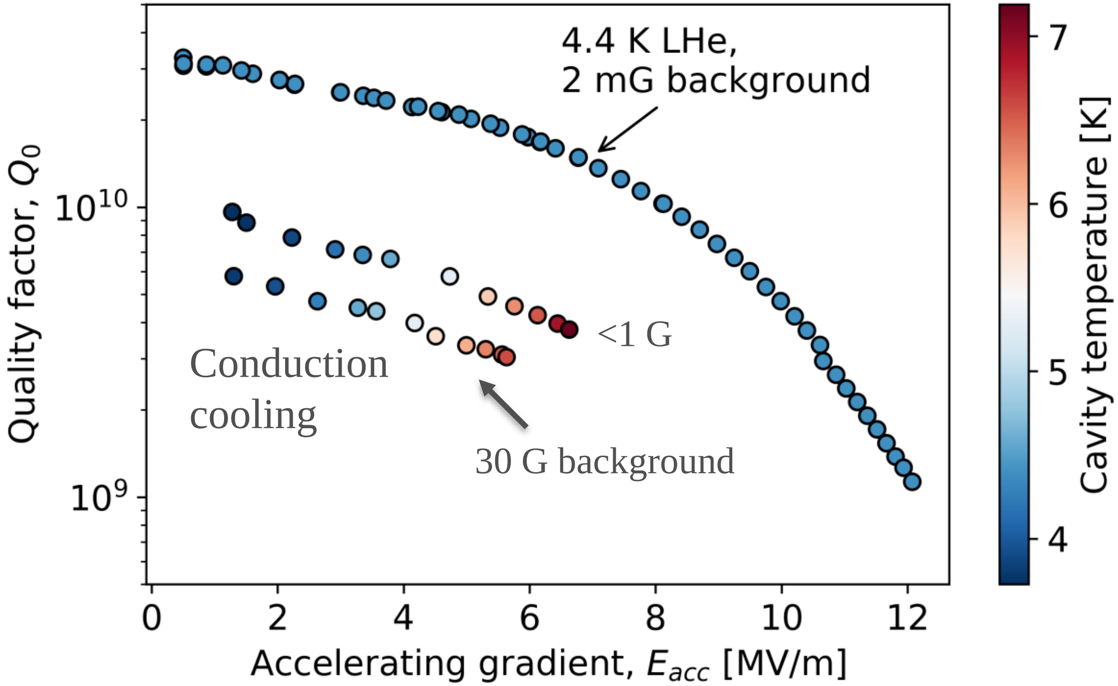




First results for the conduction-cooled Nb3Sn cavity

R. Dhuley, S. Posen, M. Geelhoed, O. Prokofiev, J. Thangaraj, ***Supercond. Sci. Technol.***, 2020.
https://doi.org/10.1088/1361-6668/ab82f0

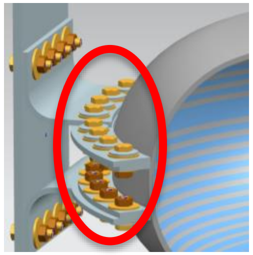
BREAKTHROUGH RESULTS



(max. E_{acc} limited by RF power)

Fermilab VTS baseline with 4.5 K LHe
- $Q_0 = 3\text{x}10^{10}$ at E_{acc} = 1 MV/m
- max E_{acc} = 12 MV/m

Conduction cooling
- $Q_0 = 5\text{x}10^9$ at E_{acc} = 1 MV/m
- max E_{acc} = 5.5 MV/m



disc springs ~30 G led to large flux trapping

Conduction cooling with <1 G disc springs
- $Q_0 = 1\text{x}10^{10}$ at E_{acc} = 1 MV/m
- max E_{acc} = 6.6 MV/m

We have secured 2+ M$ based on this work for an accelerator prototype for NNSA

Impact: publications, talks, and media coverage

ELSEVIER

Contents lists available at ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics

CRYOGENICS

Thermal resistance of pressed contacts of aluminum and niobium at liquid helium temperatures

Check for updates

R.C. Dhuley*, M.I. Geelhoed, J.C.T. Thangaraj

Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

IEEE IEEE Transactions on Applied Superconductivity

Thermal link design for conduction cooling of SRF cavities using cryocoolers

R. C. Dhuley, R. Kostin, O. Prokofiev, M. I. Geelhoed, T. H. Nicol, S. Posen, J. C. T. Thangaraj, T. K. Kroc, and R. D. Kephart

U.S. DEPARTMENT OF ENERGY | Office of Science   Science Highlights

Cryogen-free Superconducting RF Cavity

A team from Fermilab has demonstrated cryogen-free operation of a niobium superconducting radiofrequency cavity.

TechConnect 20th ANNIVERSARY

WORLD INNOVATION CONFERENCE & EXPO

MAY 13-16, 2018

ANAHEIM, CA

ColdFacts

The Magazine of the Cryogenic Society of America, Inc. INTERNATIONAL

Towards cryogen-free SRF particle accelerators

A new frontier in SRF is simplifying the cooling methods!

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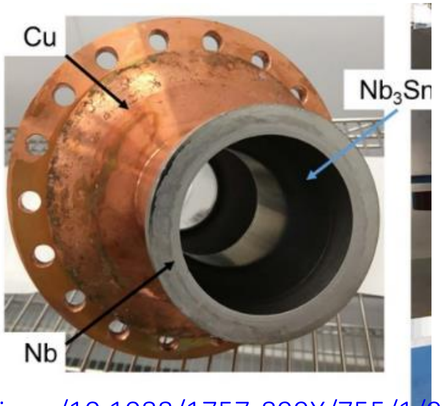
- 650 MHz
- welded niobium rings

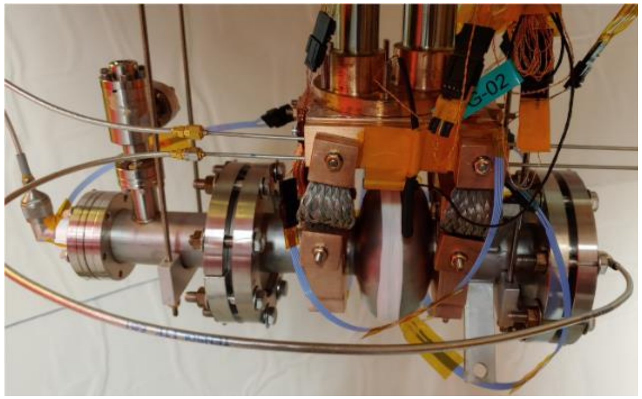
Jefferson Lab



https://doi.org/10.1088/1757-899X/755/1/012136

- 1.5 GHz
- Cold sprayed + electrodeposited copper

Cornell University



https://arxiv.org/abs/2002.11755

- 2.6 GHz
- Copper clamps

Design of a 10 MeV, 1000 kW (100 mA) module

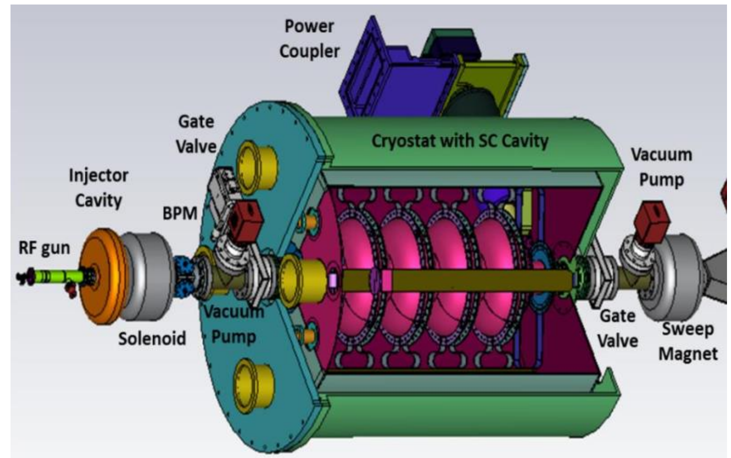
PI: Ram Dhuley

- ✓ RF design of a 5-cell 650 MHz cavity
- ✓ Beam transport simulations (external injection 300 keV --> 10 MeV)
- ✓ Estimation of 4 K heat load, cryocooler selection
- ✓ Design and thermal simulations of conduction link

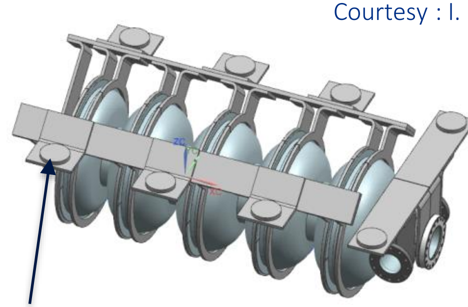
euclid BEAMLABS

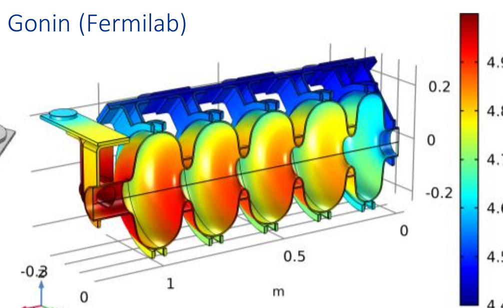
- Cryostat design and integration (thermal and magnetic shield, vacuum vessel, couplers)
- Cost assessment

GENERAL ATOMICS



Courtesy : I. Gonin (Fermilab)


8 x PT420 mounting pads



Courtesy : R. Kostin (Euclid Techlabs)

Recent SRF Technology Breakthroughs:

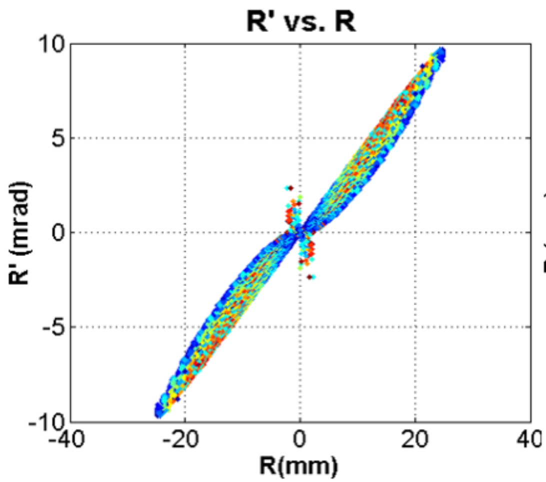
- Higher temperature superconductors: Nb_3Sn coated cavities dramatically lower cryogenic losses and allow higher operating temperatures (e.g. 4 K vs 1.8 K)
- Commercial Cryocoolers: new devices with higher capacity at 4 K enables turn-key cryogenic systems
- Conduction Cooling: possible with low cavity 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

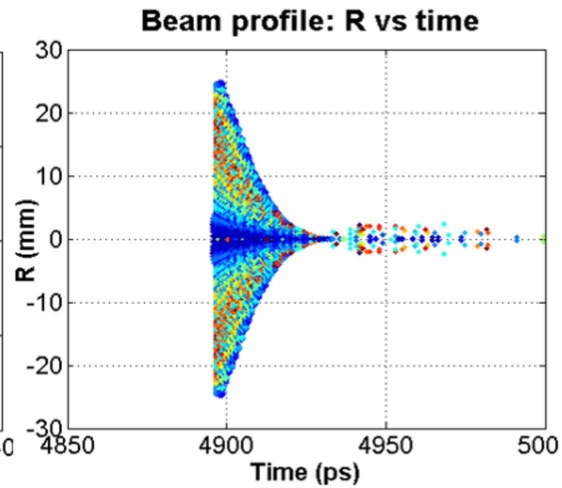
Enable compact industrial SRF accelerators at low cost

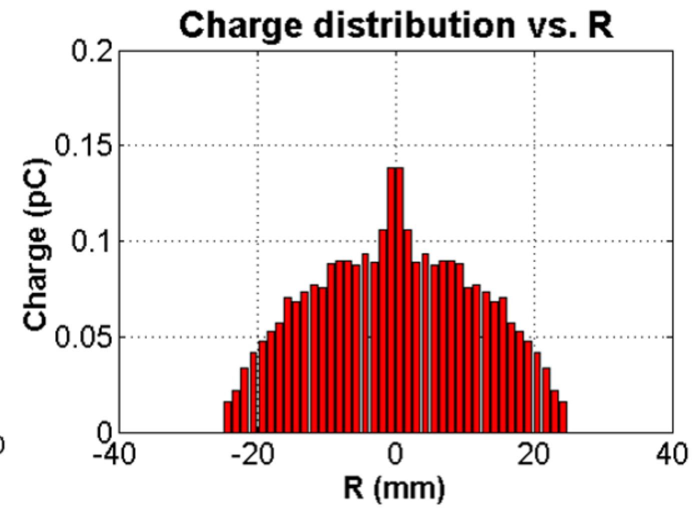
BEAM PHYSICS

Beam Physics: Simulated Integrated Electron Gun

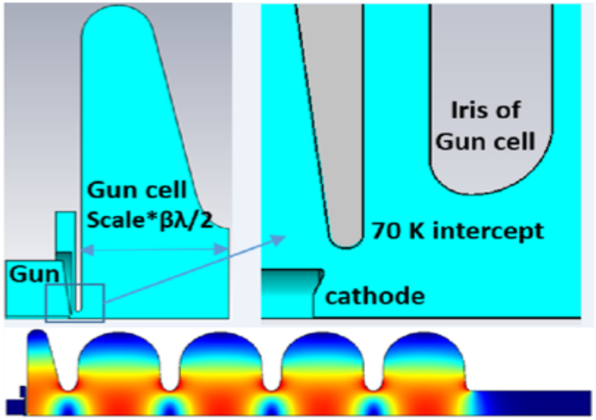
Reduces size and complexity







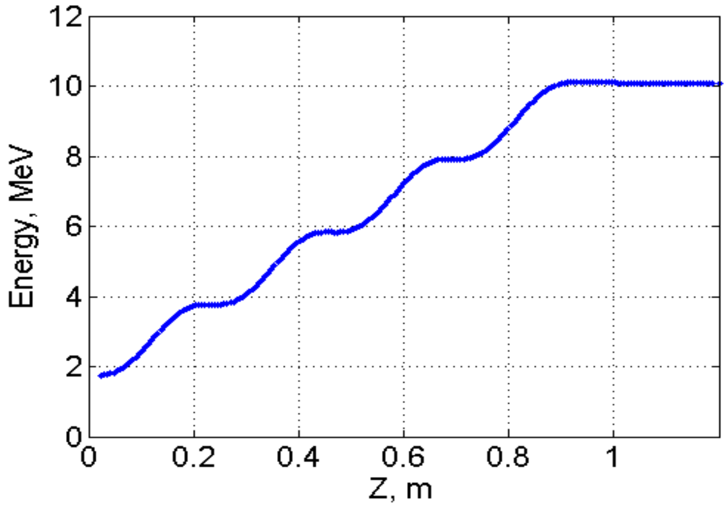
	Value
Electron energy	9 MeV±5%
Current modulation range	0.1 μA - 1 mA
Beam loss at 4K	<0.5 W
Cathode backward bombardment	<1 W
Cathode blackbody radiation	< 200 mW

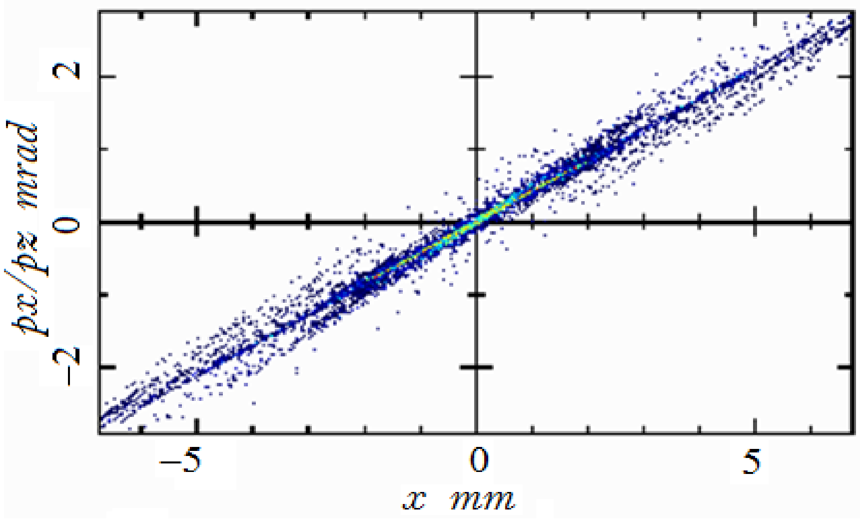


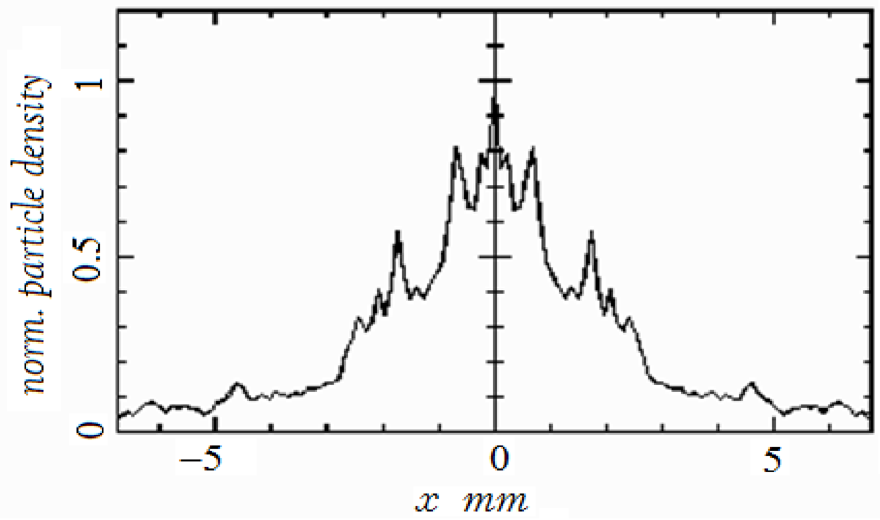
Simulations of the Cavity

:

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



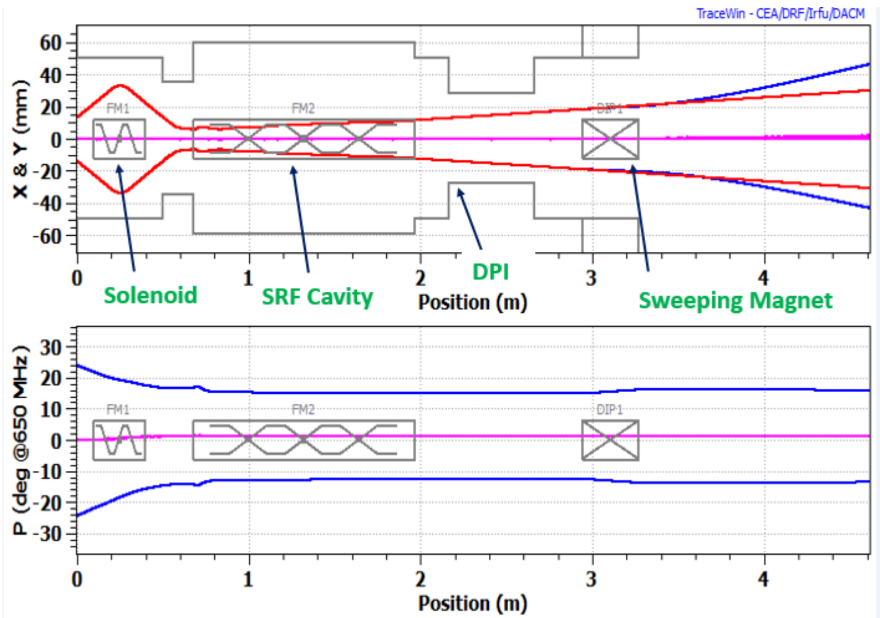




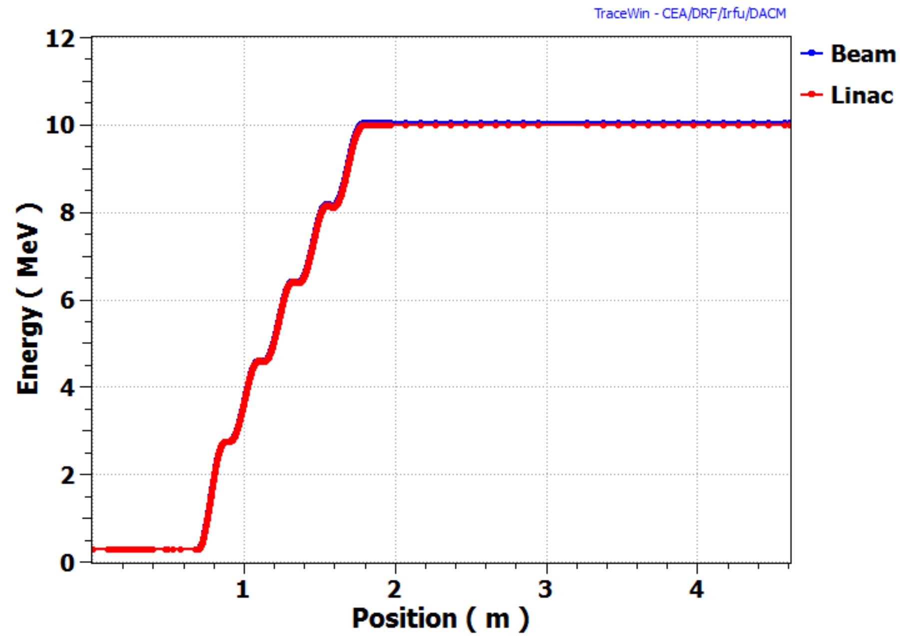
Particle losses in simulations < 10^{-5}. (This is important for the heat budget)

Beam Envelope Simulation from external injection (10 MW)

3σ beam envelopes



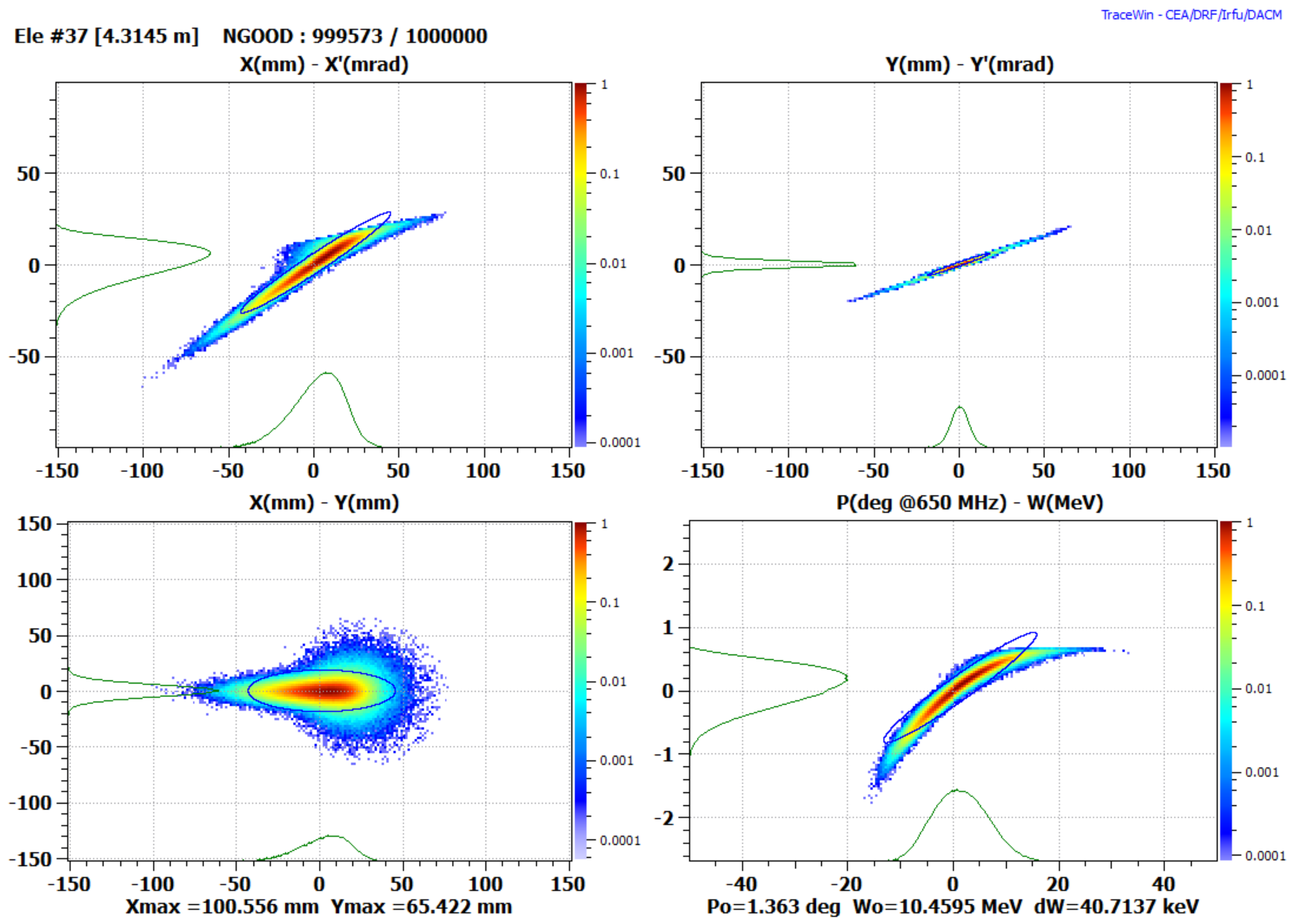
Beam Energy



- 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 .

Fermilab

Beam Simulation from external injection (10 MW)



- Output beam distribution at the end of the beamline (very low losses!)

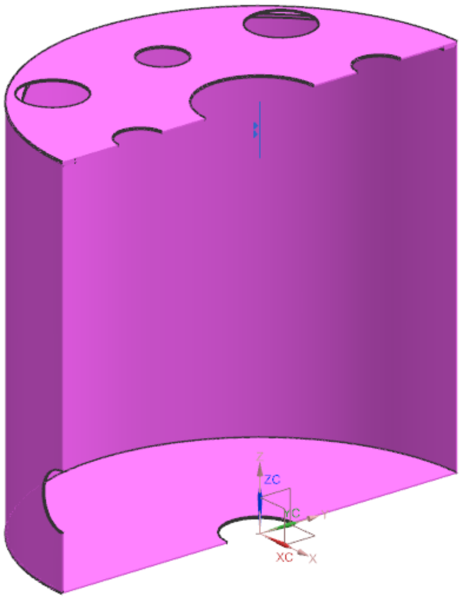
BEAM PHYSICS is on-going

We are looking into

- HOM modes,
- Beam windows
- Radiation shielding
- X-ray targets
- Beam losses - > crucial!
- Integration

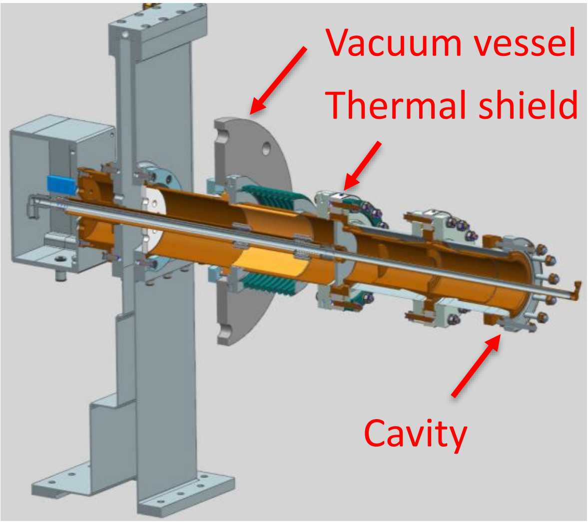
Just a sample challenges

- 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

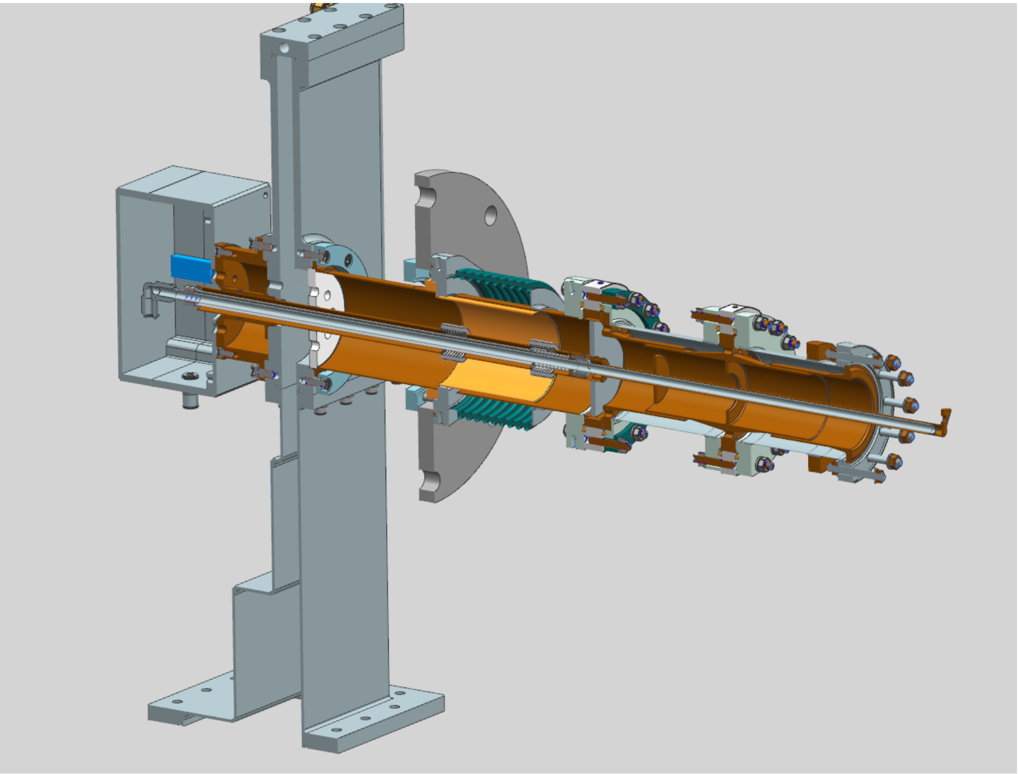
- Interfaces with e-gun, power coupler, beam outlet port



Fermilab

Low-heat loss coupler for compact SRF accelerator.

At the first stage the coupler of PIP-II project – a major science project at Fermilab will be used. We are currently looking at a modified design.



Food and Medical Sterilization

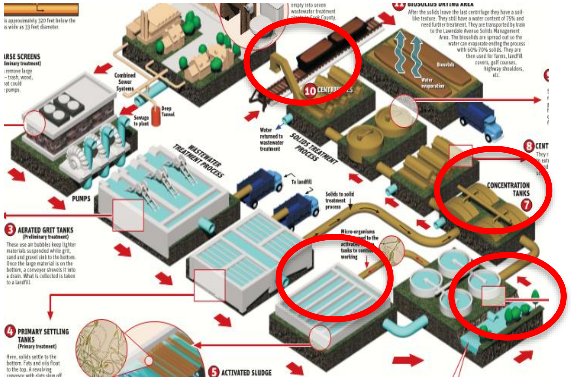
- Electron beams can be used directly or to create x-rays to accomplish many tasks currently accomplished with Co60 radioisotopes
  - FNAL recently completed a study for NNSA on impediments to change.
    - One impediment is the need for high power, reliable, cost effective electron accelerators
    - 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

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



Processing cost per Application

(acknowledgment to: Gianluigi Ciovati, JLab)

	1 MeV, 1 MW		10 MeV, 1 MW
	WASTEWATER		SLUDGE
Dose requirement	1 kGy	4 kGy	10 kGy
Processing cost	$0.13/m^3 ($0.482/kgal)	$0.51/m^3 ($1.93/kgal)	$19.7/dry ton
Daily Processed Volume	45,000 m^3 (11.9 Mgal)	11,250 m^3 (3.0 Mgal)	278 dry ton (1.3 Mgal with 25% biosolid waste)
Required Flow Rate (gpm)	9,050	2,260	984
Comments [1]	Color, Odor, Coliform bacteria removal	Kill >99% of bacteria	Inactivate some radiation resistant organisms

[1] 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)

Many emerging areas that SRF accelerators can add value to

Partnerships and Technology Transfer

Home

- Contact
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- Resources

Partnering With Fermilab

- Becoming a Partner
- Letters of Support
- Partnering Agreements
- Reporting Success

Technology Portfolios

- Accelerator Technologies
  - **Compact SRF Accelerator**
  - Pavement
  - Magnetron
  - 3D Additive Manufacturing with High Power Electron Gun
  - Conduction Cooling
  - Low Heat Leak Power Coupler
  - Fast Faraday Cup
- Computers & Information Science
- Detector Technologies
- Engineering Technologies
- Environmental & Safety

Compact SRF Accelerator

Technology Summary

Accelerators developed for science now are used broadly for industrial, medical, and security applications. Over 30,000 accelerators touch over $500B/yr in products producing a major impact on our economy, health, and well-being. Industrial accelerators must be cost-effective, simple, versatile, efficient, and robust. Many industrial applications require high average beam power.

The Invention

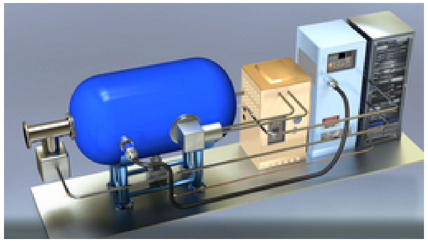
Exploiting recent advances in Superconducting Radio Frequency (SRF) cavities and RF power sources as well as innovative solutions for the SRF gun and cathode system we have developed a design for a compact SRF high-average power electron linac. Capable of >250 kW average power and continuous wave operation, this accelerator produces electron beam energies up to 10 MeV.

Benefit

Small and light enough to mount on mobile platforms, Fermilab Compact SRF accelerators enable new in-situ environmental remediation, in-situ crosslinking of materials, and security applications. More importantly, this accelerator will be the first of a new class of simple, turn-key SRF accelerators.

Applications and Industries

- Industry
- Medicine
- Security
- Science

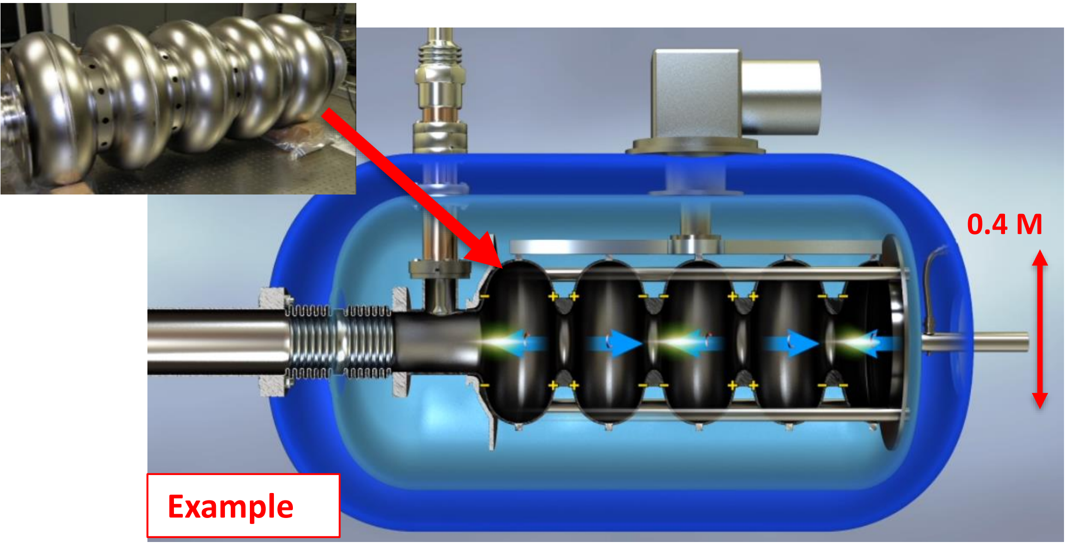


Invention Details

Patent Status: Multiple patents pending

Contact:
Aaron G Sauers, CLP
630-840-4432
asauers@fnal.gov
Fermilab, MS 312- PO Box 500
Batavia, IL 60510

A simple SRF accelerator for industrial application



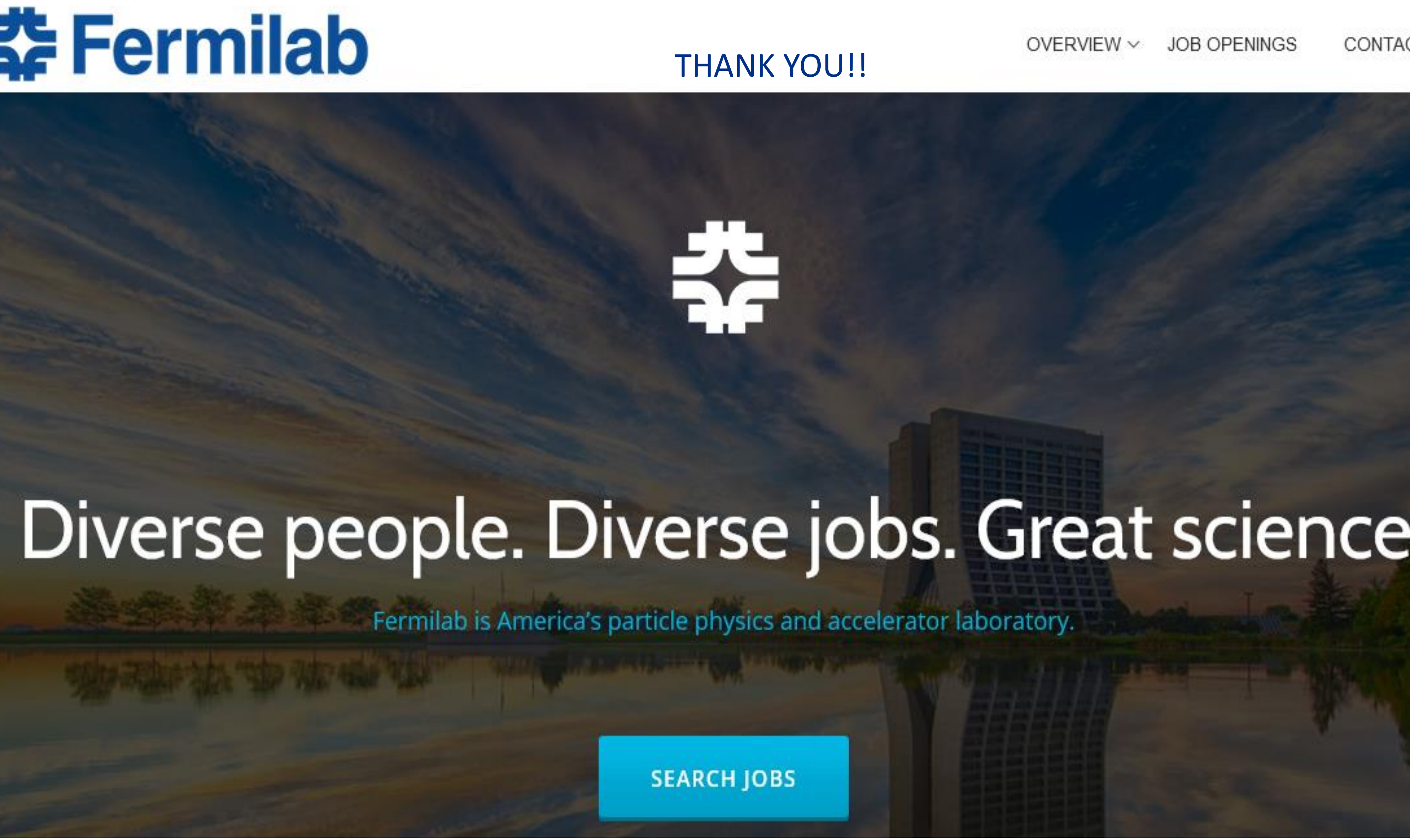
Final machine parameters

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

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

Thank you!!!

THANK YOU!!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