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High power superconducting electron linear accelerators for industrial applications:

Technology development and experimental results at Fermilab

Jayakar Charles Thangaraj,

IARC,

Fermilab

Superconducting radiofrequency (SRF) technology and discovery science

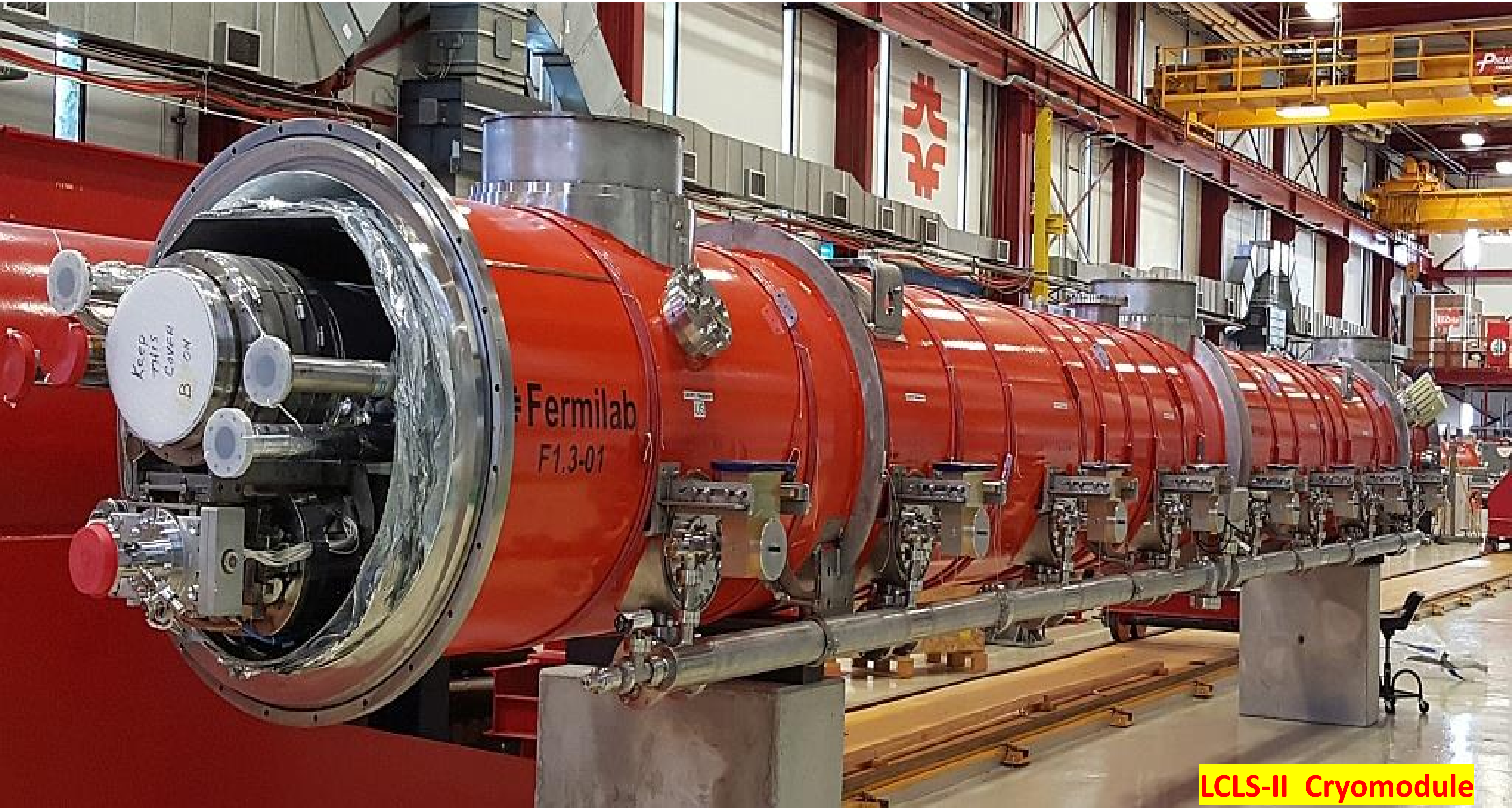
SRF benefits discovery science machines

- High wall-plug efficiency
- High average beam power
- Continuous wave operation

Continues to progress.....

- Niobium cavities achieve >50 MV/m in 2 K liquid helium
- Nb3Sn cavities attain >20 MV/m in 4.5 K liquid helium

Current SRF "science" accelerators are long and complex



~40 feet~school bus (37 cryomodules)

SRF Technology transition for industrial application

SRF tech for discovery science

IARC @Fermilab*

- SRF accelerator relevant industrial applications? (Market pull)
- Adapt SRF tech for industrial settings? (Technology push via partnerships)

Broader use of SRF tech for Industrial and commercial application

*Jlab, Cornell and others are looking into this as well

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

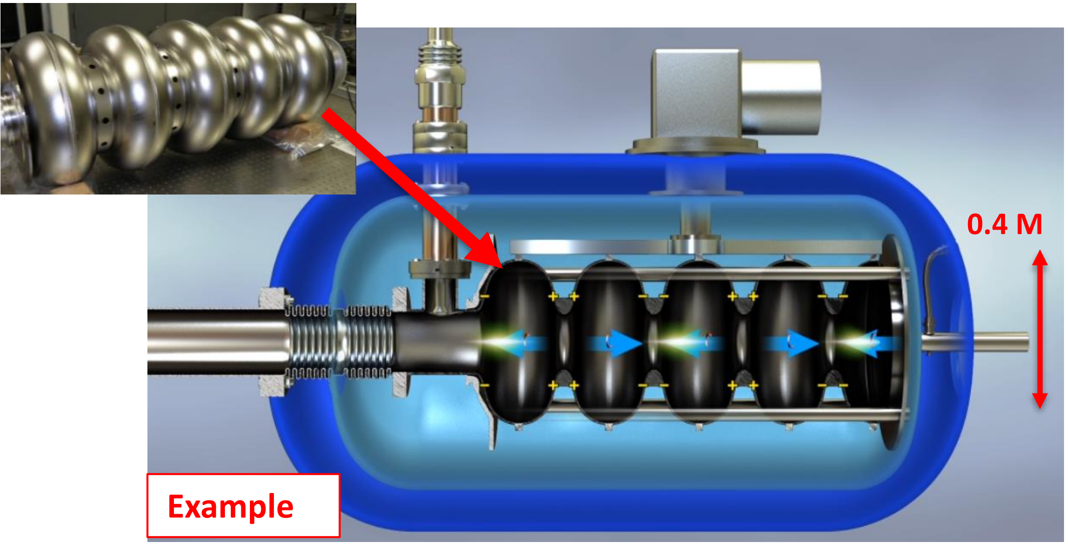
Technology	Energy	Power	Issues/Potential
Room temperature (Copper) technology	Few MeV	Up to few hundred kW's	• Energy efficiency • Heat loss • Mature technology
Superconducting linacs (Niobium)	10 MeV	100 kW- 1+ MW	• CW • Excellent energy efficiency • "Backbone" technology of choice for > $1 B class 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**

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 (covered by Tom Kroc talk)
- 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: 200 kW – 1 MW
- Compact
- Simple, reliable
- Affordable

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

Staged approach: First demonstrate a 20 kW prototype including all the key technologies

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

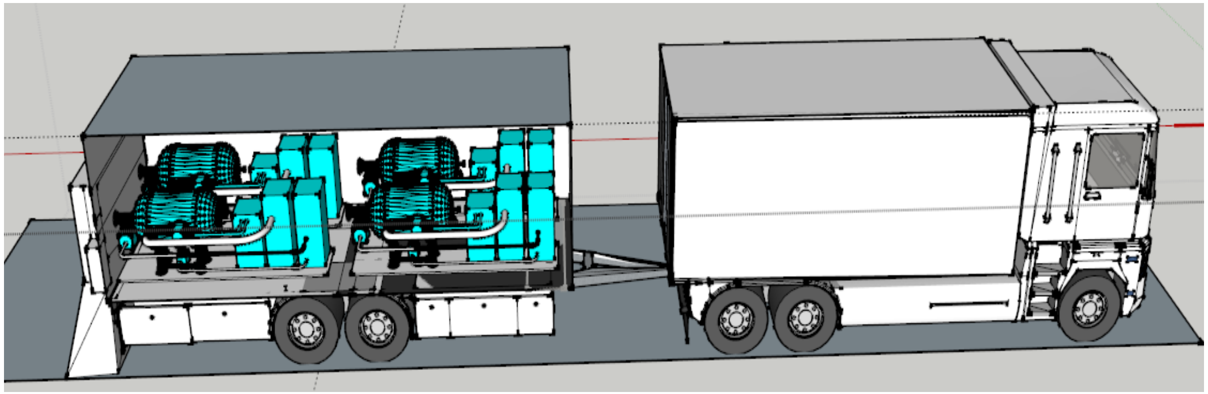
- Currently we are designing and building a 650 MHz, 1.5 cell, 20 kW prototype for integration for medical device sterilization

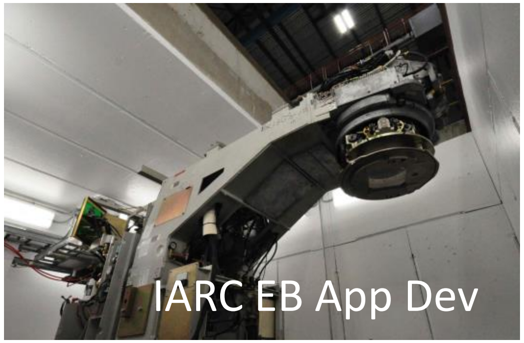
- New Possibilities:
  - Cheap, compact, simple, industrial electron accelerators can enable “in line” sterilization at the point of manufacture

In-Situ Cross-Link of Materials

Electron accelerators are widely used to cross link materials

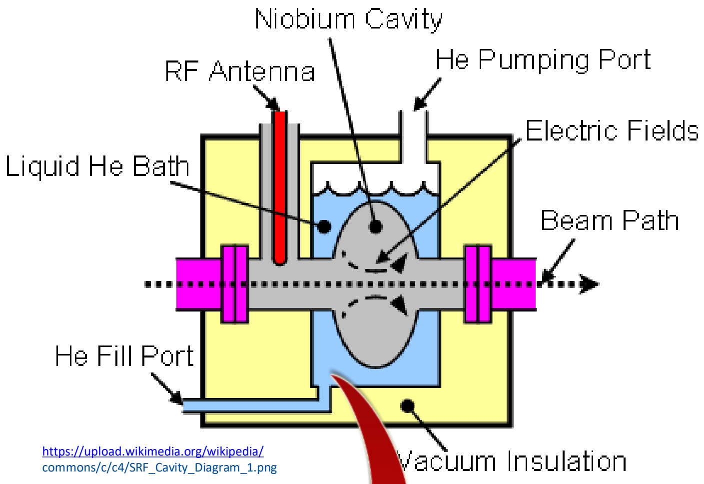
- High power mobile accelerators enable entirely new construction techniques that can alter materials properties <u>after</u> placement
  - e.g. Improve the strength, toughness, and/or temperature range
- One application: Improved Pavement





- Collaborating to create a tough, strong binder with improved temperature performance vs bitumen to extend pavement lifetime
- We are designing a 1.3 GHz external injected electron accelerator to deliver 8 MeV beam.

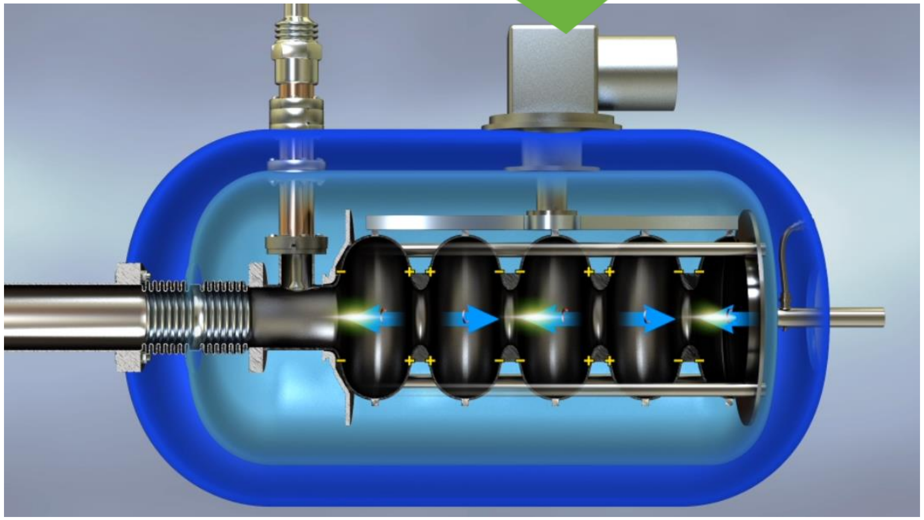
Vision: Access SRF technology minus the complexity



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)



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

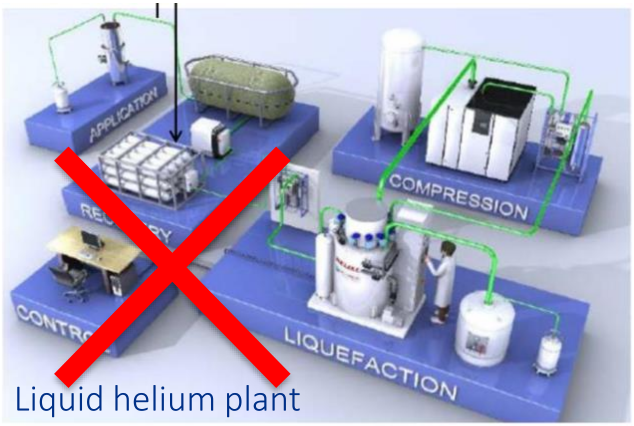
Small SRF surface resistance enables continuous wave (cw) operation, leading to high average beam power

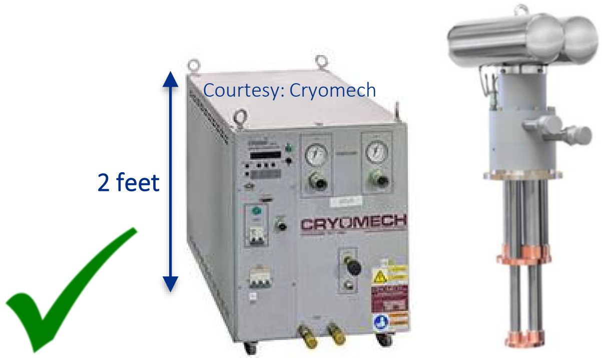
At present, SRF accelerators are designed to operate with complex liquid helium cryogenic systems!

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)



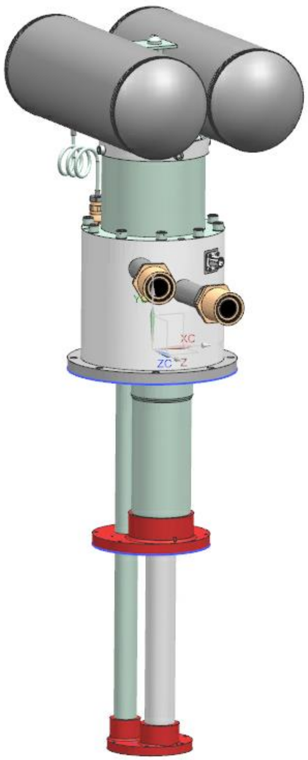


Cryocoolers offer

- 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)

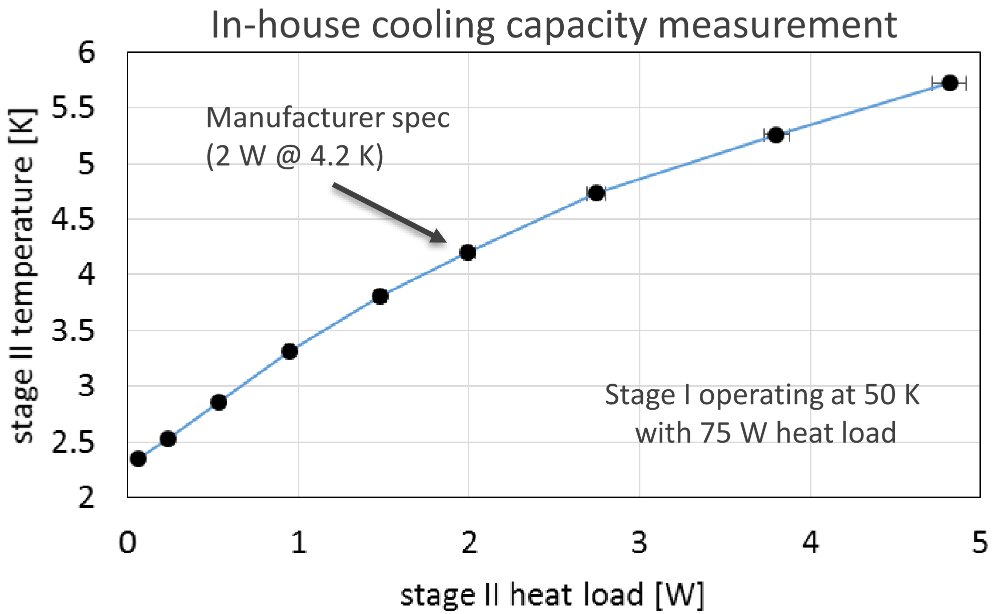
Push of a button to reach 4.2 K

- Selection, procurement, and test of cryocoolers



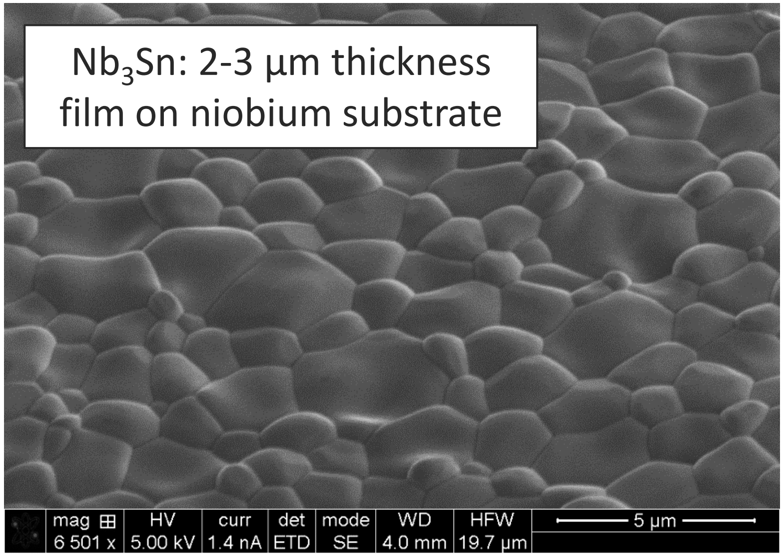
Cryomech PT420

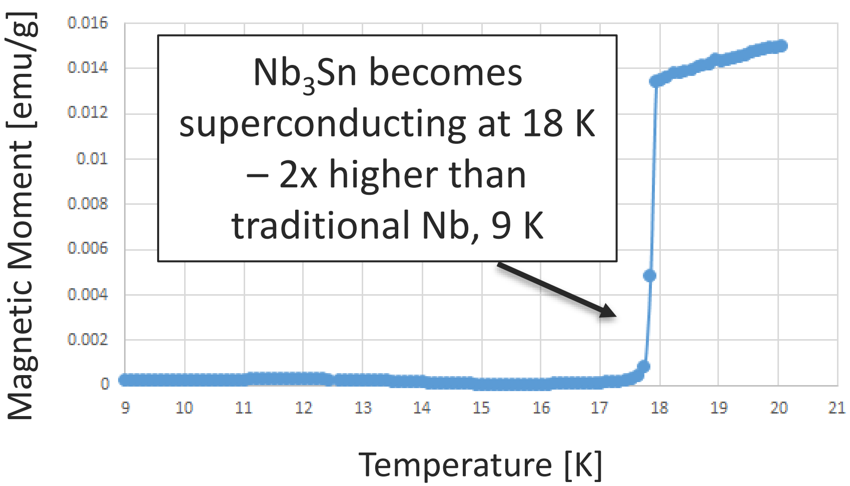
- Highest cooling power in the market
- Low vibrations, low maintenance



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

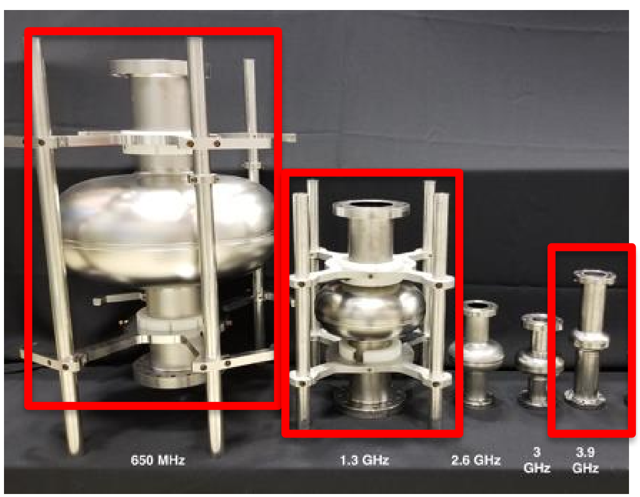


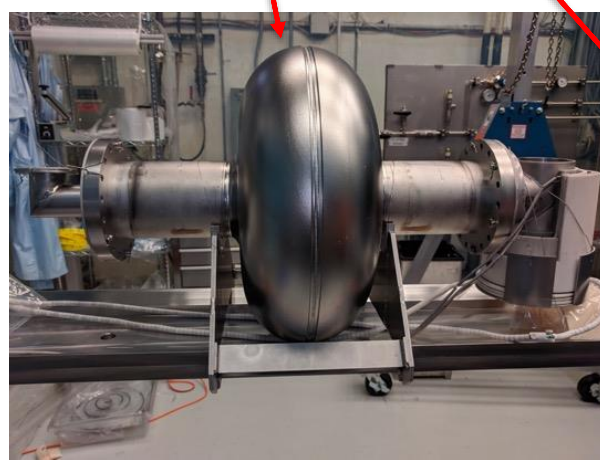


Progress of Nb_3Sn Films

- Frequency dependence of R_{BCS}, R_{res}, quench, sensitivity
- 650 MHz is an interesting step between scaling up from a 1-cell 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

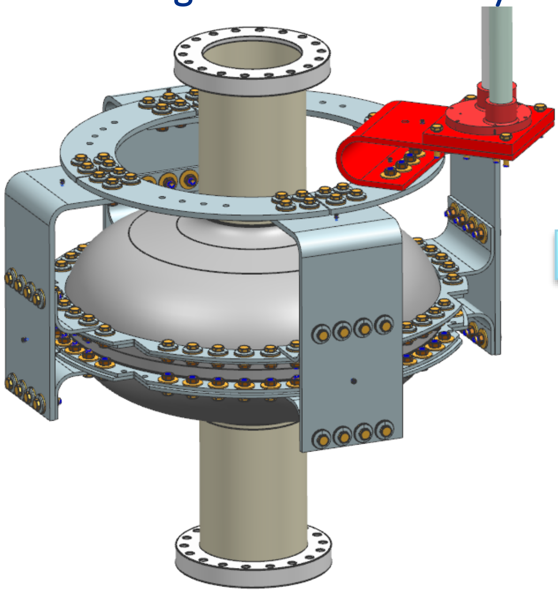




Design of the conduction link design

Mechanical design; verification *via* multiphysics simulations

Al conduction link bolted to the Nb rings around the cavity

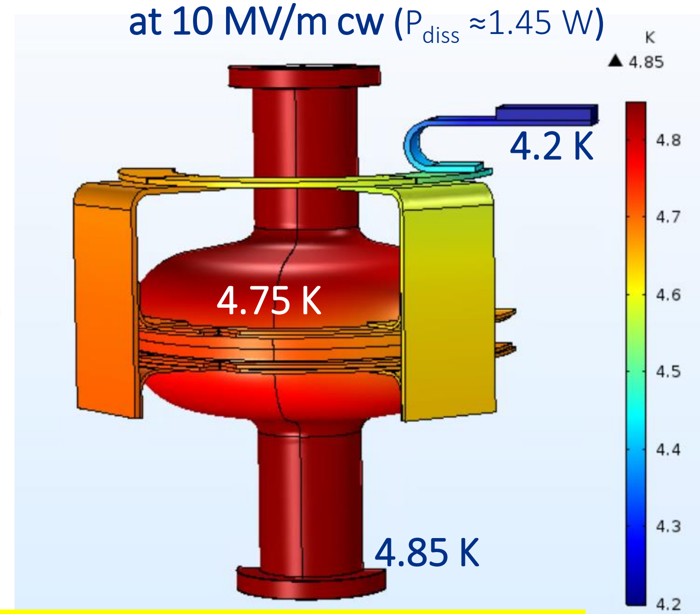


Nb_3Sn surface resistance (BCS from SRIMP + 10 nΩ)

RF + thermal simulations

Thermal conductivities, contact resistance, cryocooler capacity

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

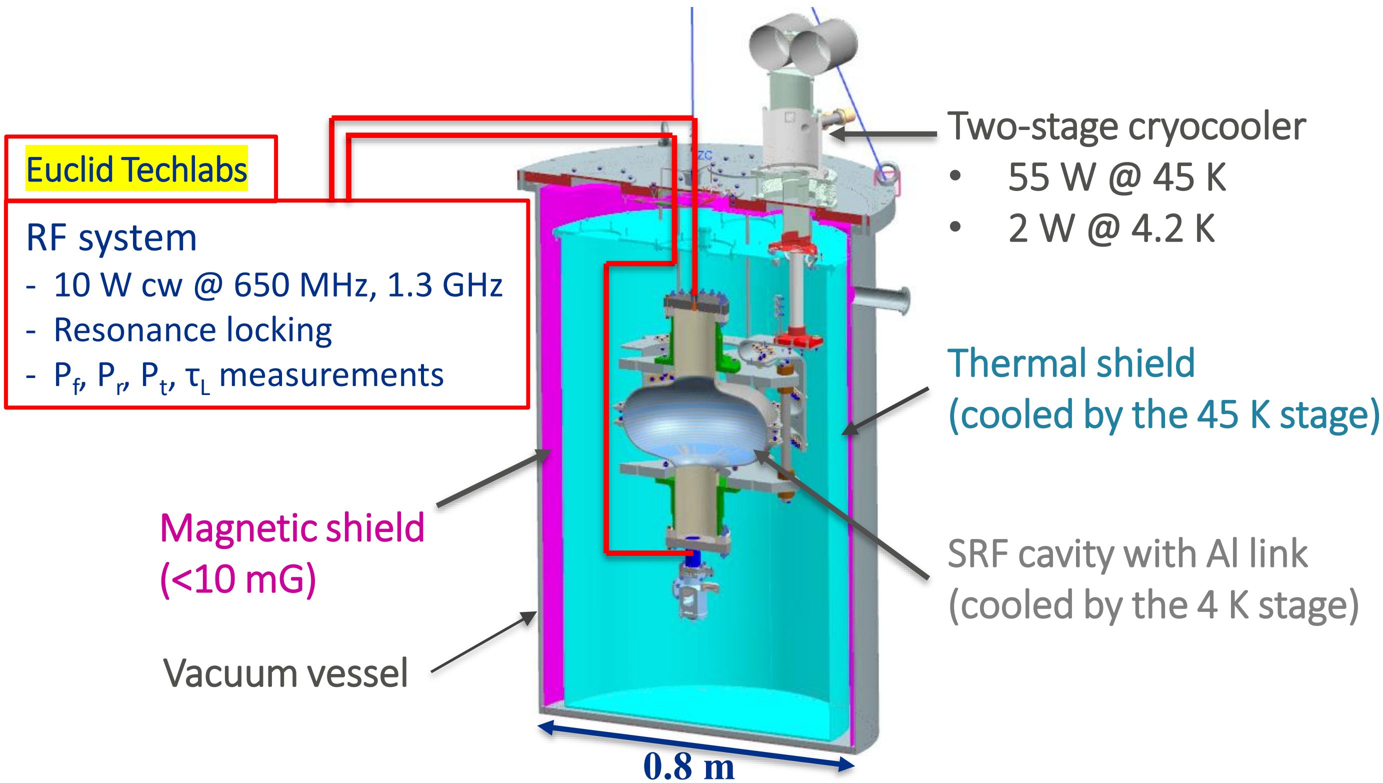


Simulated conductance ($P_{diss}/\Delta T$) ≈ 2.6 W/K ▼4.2

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

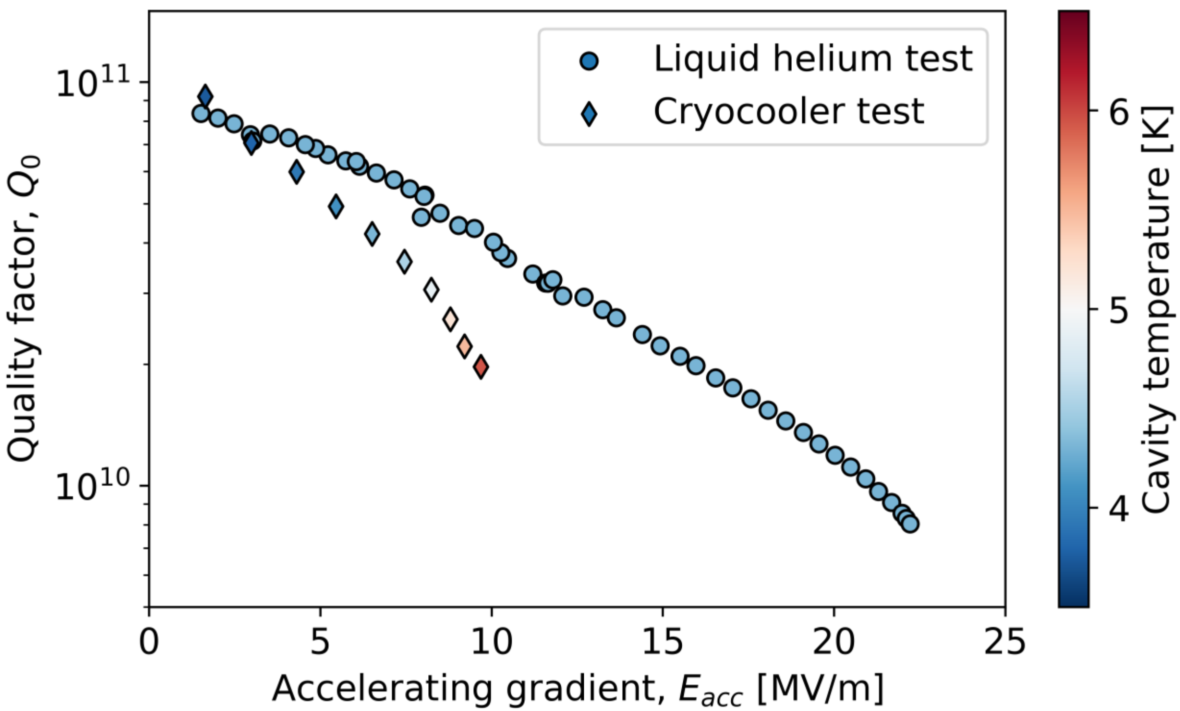
R.C. Dhuley *et al.*, ***IOP Conf. Ser.: Mat. Sci. Eng.***, 2020. https://doi.org/10.1088/1757-899X/755/1/012136



Recent results for the conduction-cooled Nb_3Sn cavity

A three-year program initiated by LDRD

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



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.

ColdFacts INTERNATIONAL

Towards cryogen-free SRF particle accelerators

Reached 10 MV/m!!!

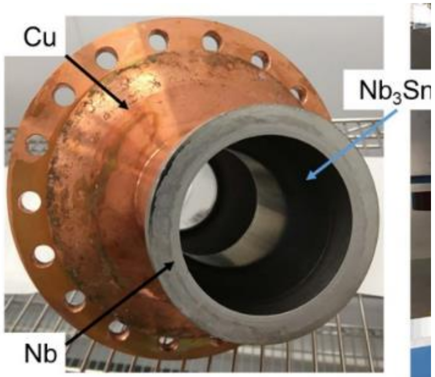
This is the backbone technology for the accelerator prototype

A new frontier in SRF is simplifying the cooling methods!

Fermilab

- 650 MHz
- welded niobium rings

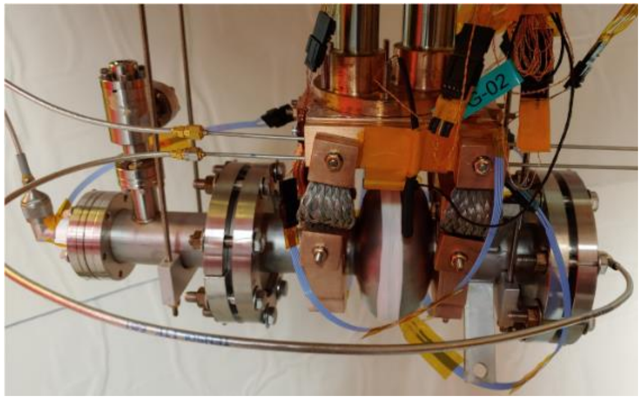
Jefferson Lab



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

- 1.5 GHz
- Cold sprayed + electrodeposited copper

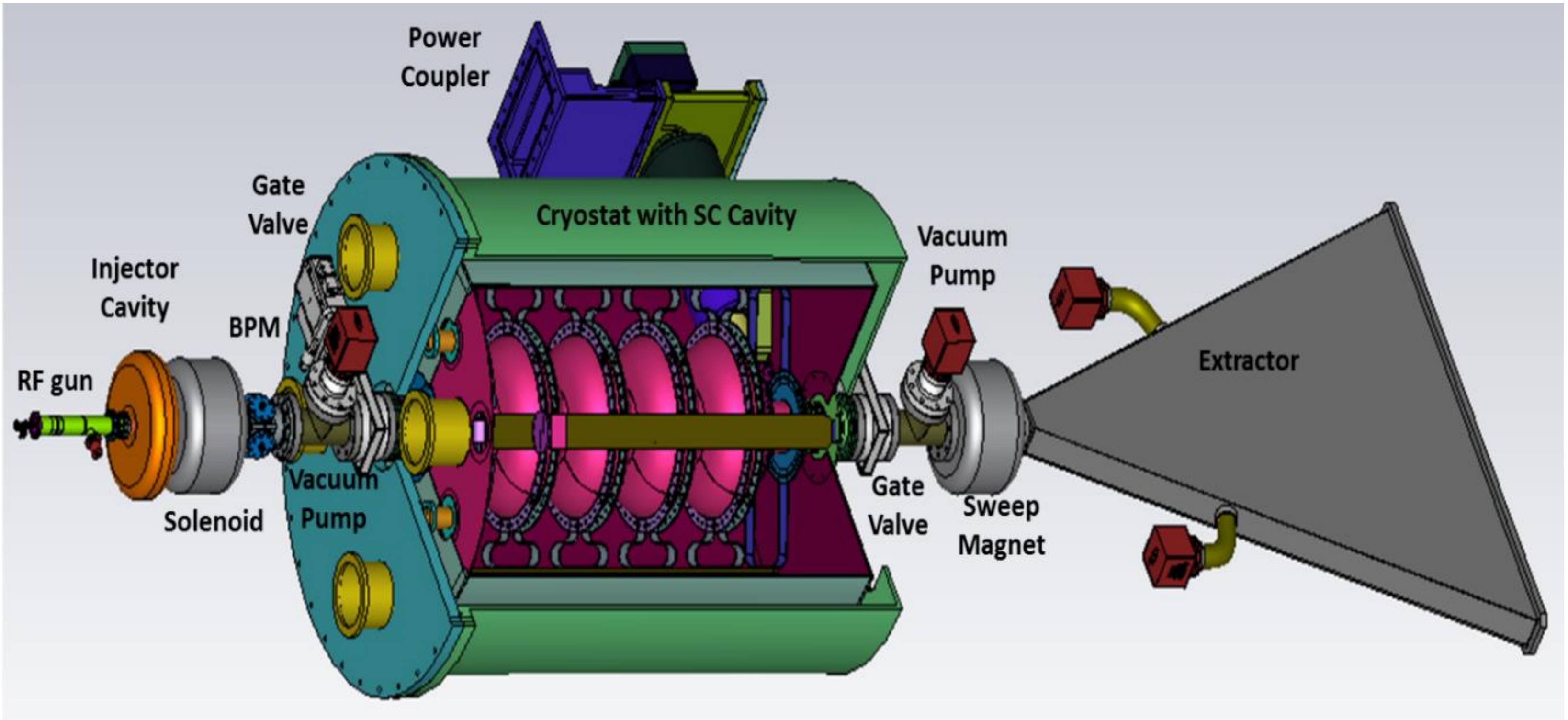
Cornell University



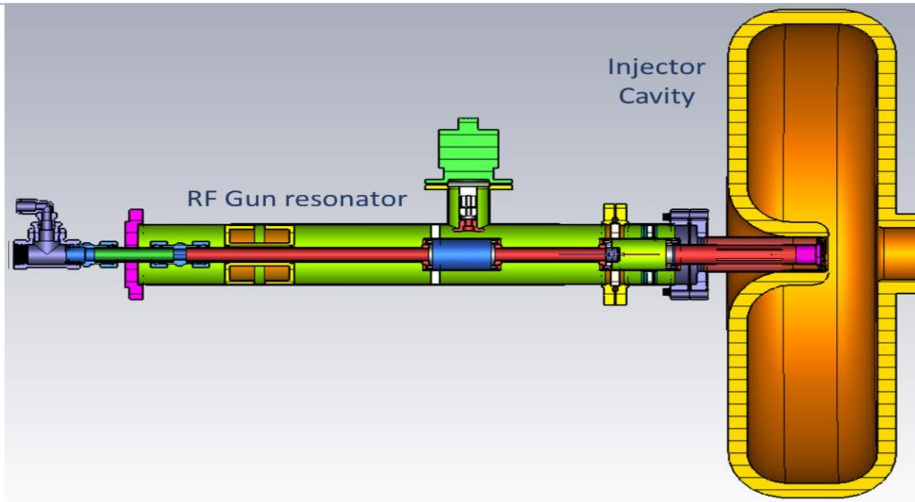
https://arxiv.org/abs/2002.11755

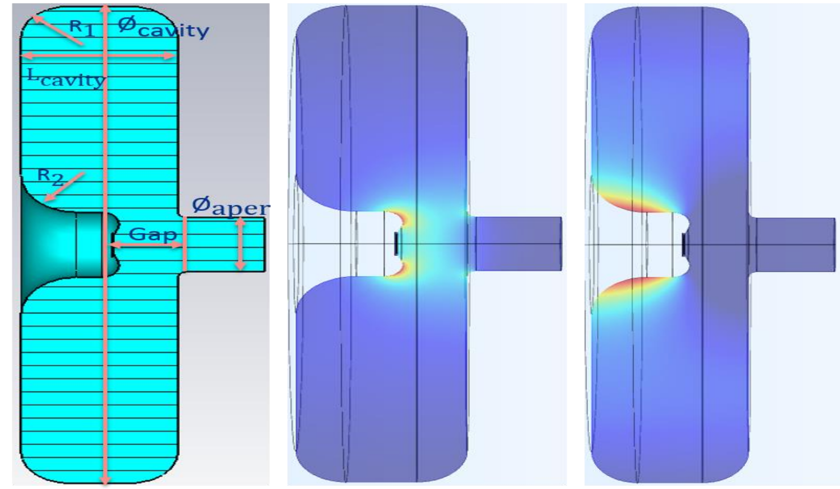
- 2.6 GHz
- Copper clamps

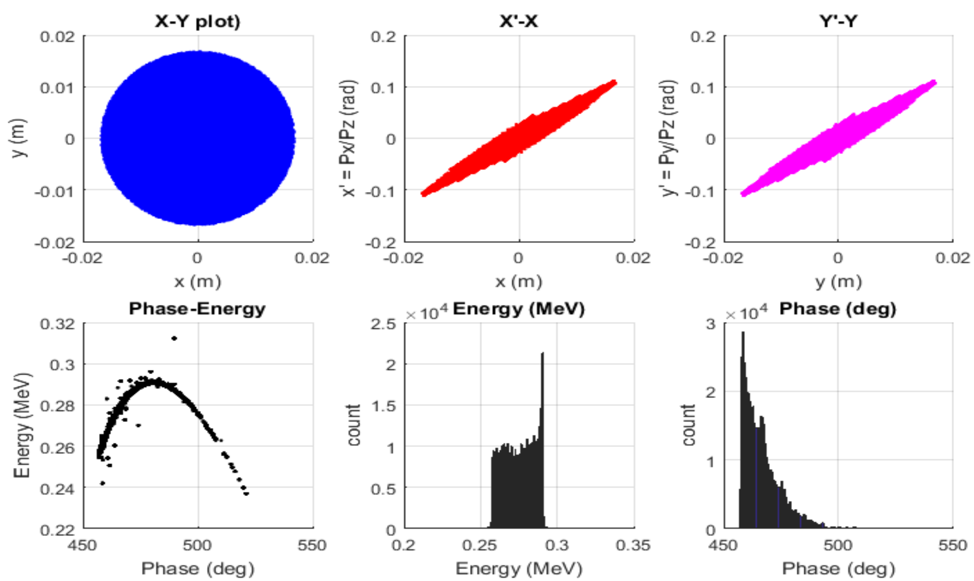
A CASE: CONCEPTUAL DESIGN OF A 10-MEGAWATT ELECTRON BEAM IRRADIATION FACILITY



Beam parameters at the end of injection section.



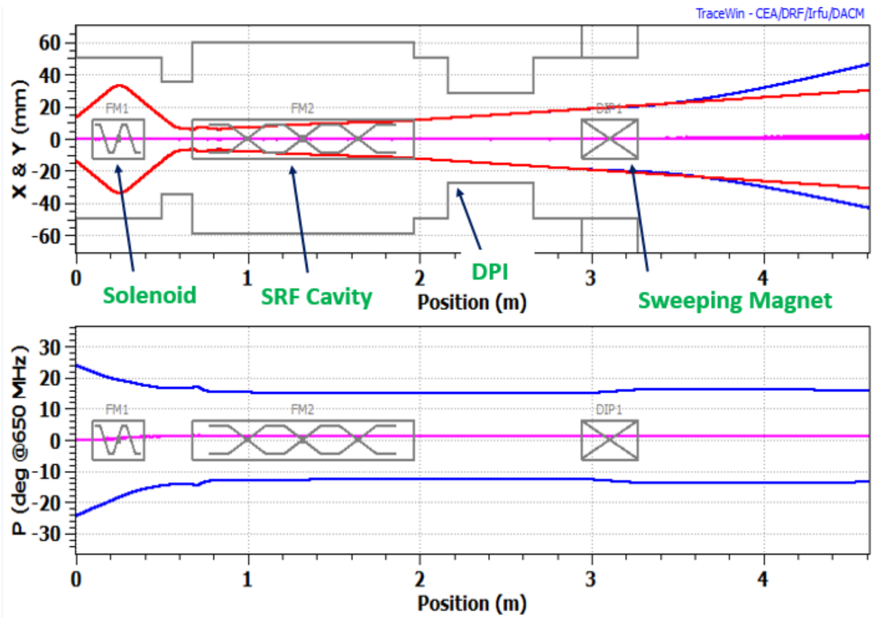




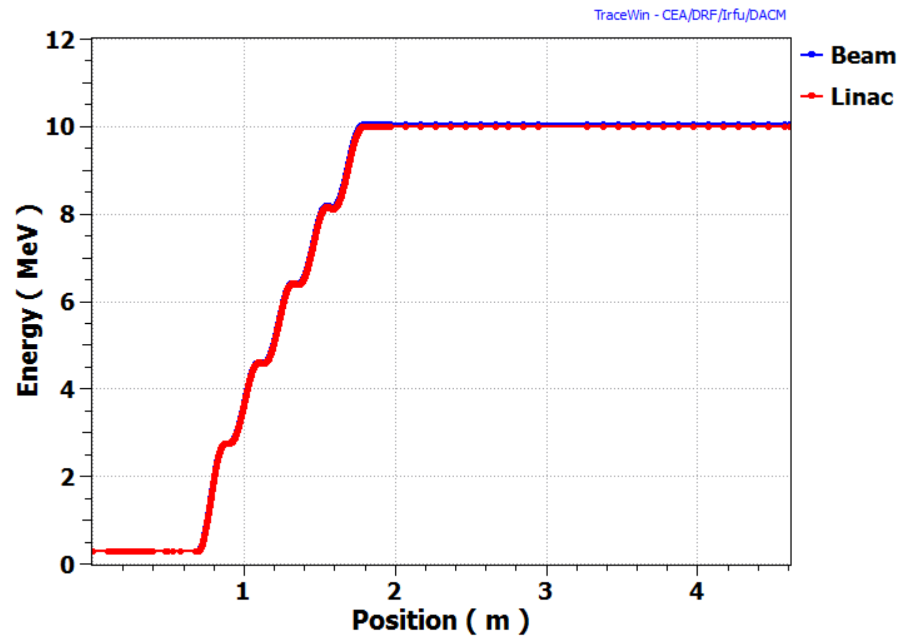
Parameter	Value, mm
$Ø_{cavity}$	308
$Ø_{aperture}$	35
R_1	20
R_2	24
Gap	29.6
L_{cavity}	68.2

Beam Envelope Simulation from external injection (10 MW)

3σ beam envelopes

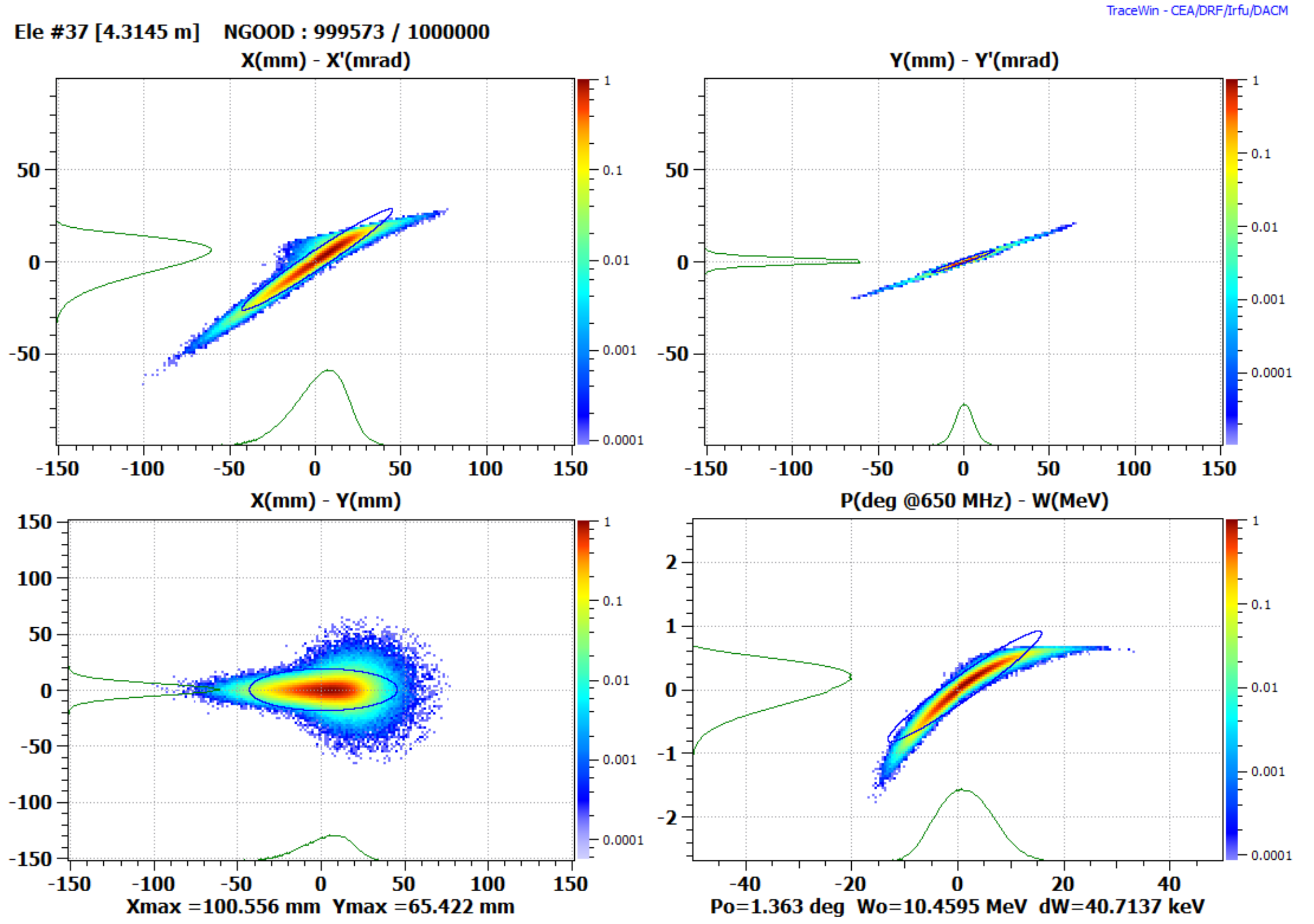


Beam Energy



- 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 .

Beam Simulation from external injection (10 MW)



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

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

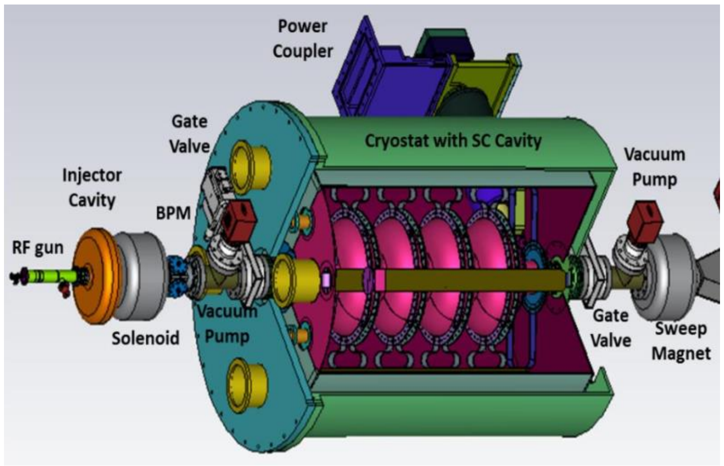
PI: Ram Dhuley

- ✓ 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

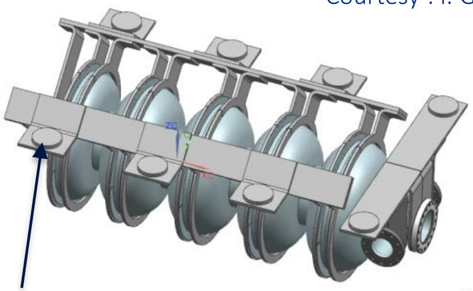
euclid BEAMLABS

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

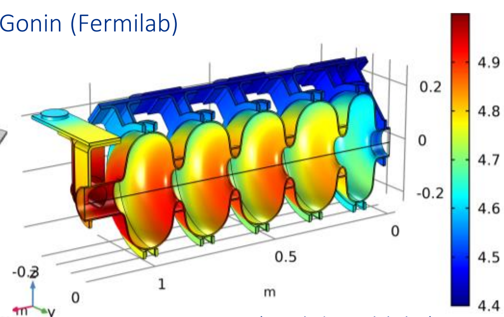
GENERAL ATOMICS



Courtesy : I. Gonin (Fermilab)



8 x PT420 mounting pads



Courtesy : R. Kostin (Euclid Techlabs)

Cost economics of SRF industrial accelerators

1. What type of cost? CAPEX or OPEX? Application driven.

e.g. Mobile or in-line or contract. Energy and power varies.

2.What is the TRL and trends? Where is the cost driver?

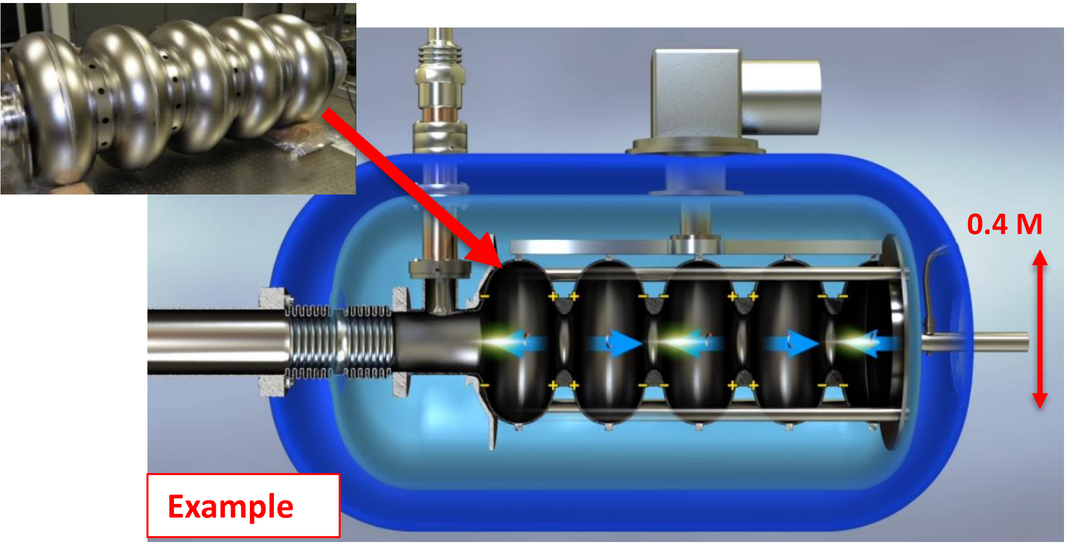
- The major cost-driver is the RF source for MW application. A cheap, long-lifetime, high-efficiency RF source will be significant cost-saving technology for most high-volume application.
- Nb3Sn tech allows more gradient but to reap need higher capacity cryocooler.

Space typically is not an issue for non-portable applications

3. Overhead: Safety and redundancy for certain application? Stand-by module, shielding, complementary assets

Warning: Most of this at R&"D". SRF Tech and customer/application expectations should be kept in focus

A simple SRF accelerator for industrial application



Final machine parameters

- Energy: ~ 10 MeV
- Power: 200 kW – 1 MW
- Compact
- Simple, reliable
- Affordable

The IARC at Fermilab has 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!!!