FERMILAB-SLIDES-19-004-DI

IMRP19 | STRASBOURG FRANCE
19th INTERNATIONAL MEETING ON RADIATION PROCESSING

iia INTERNATIONAL IRRADIATION ASSOCIATION

Compact, high-power superconducting electron linacs as irradiators for materials and radiation processing

Jayakar ‘Charles’ Tobin Thangaraj,
Illinois Accelerator Research Center (IARC),
Fermilab

Fermilab

Fermi National Accelerator Laboratory (Dept Of Energy)

- 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

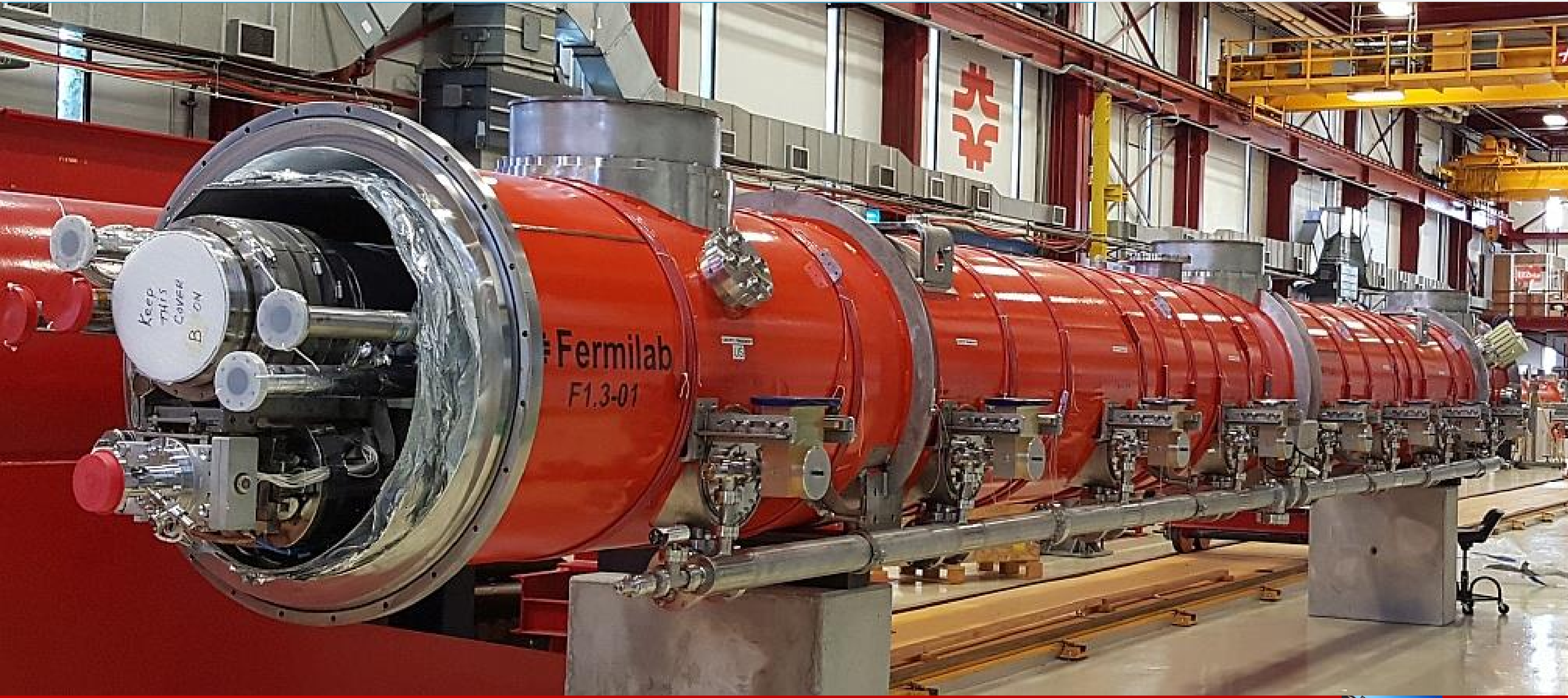
New Technology: Superconducting Radio Frequency (SRF)

- 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)

Current SRF “science” accelerators are large and complex



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

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.

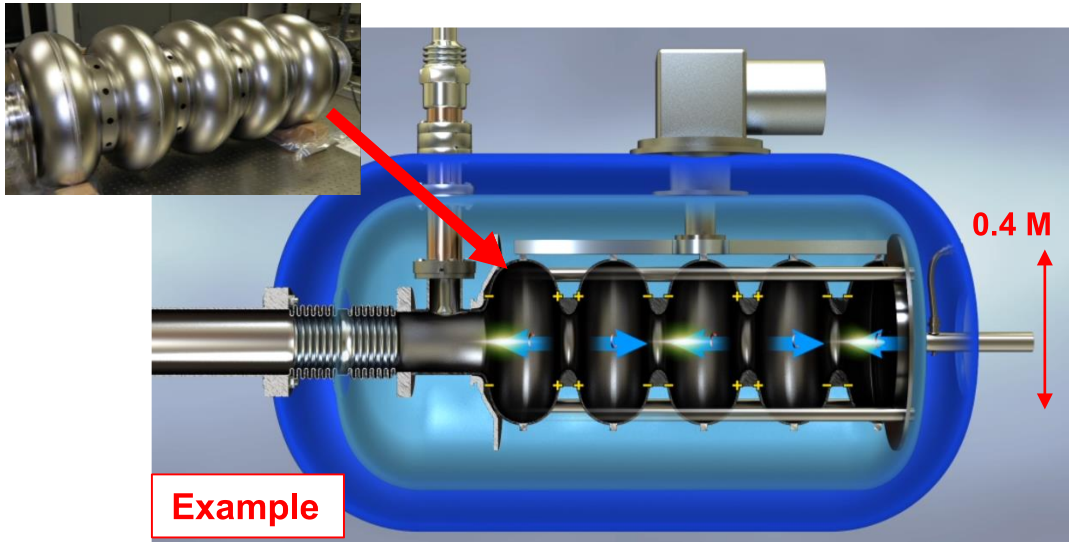
Recent SRF breakthroughs now enable a new class of compact, SRF-based industrial accelerators
(lower CAPEX and OPS cost)

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 simple SRF accelerator



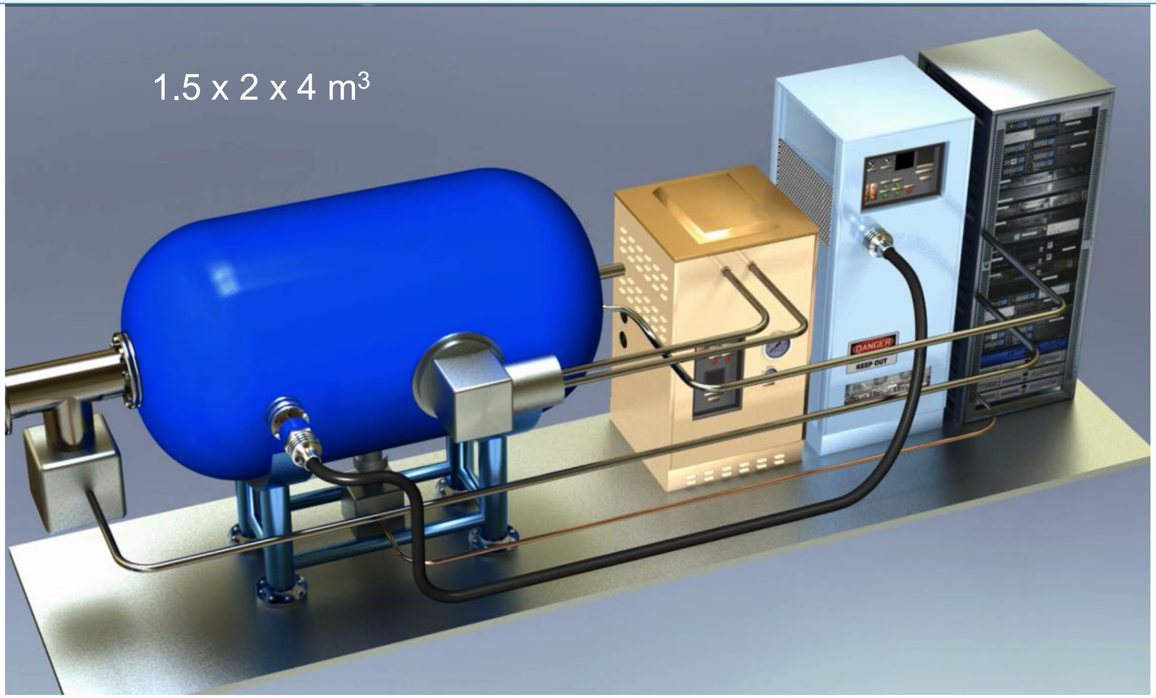
Final machine parameters

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

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

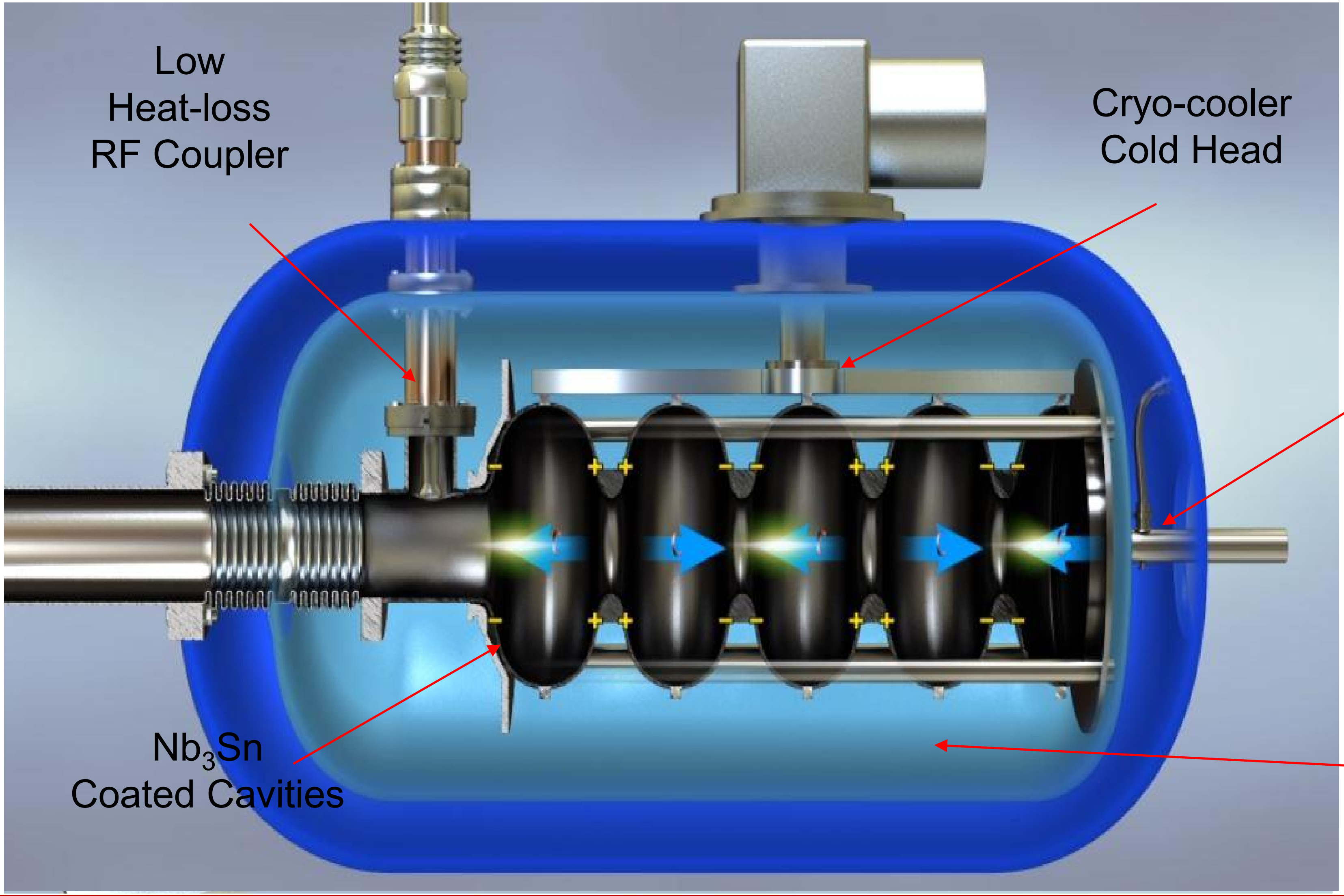
Staged approach: First demonstrate a 30 kW prototype

Developing a 250 kW skid mount Version



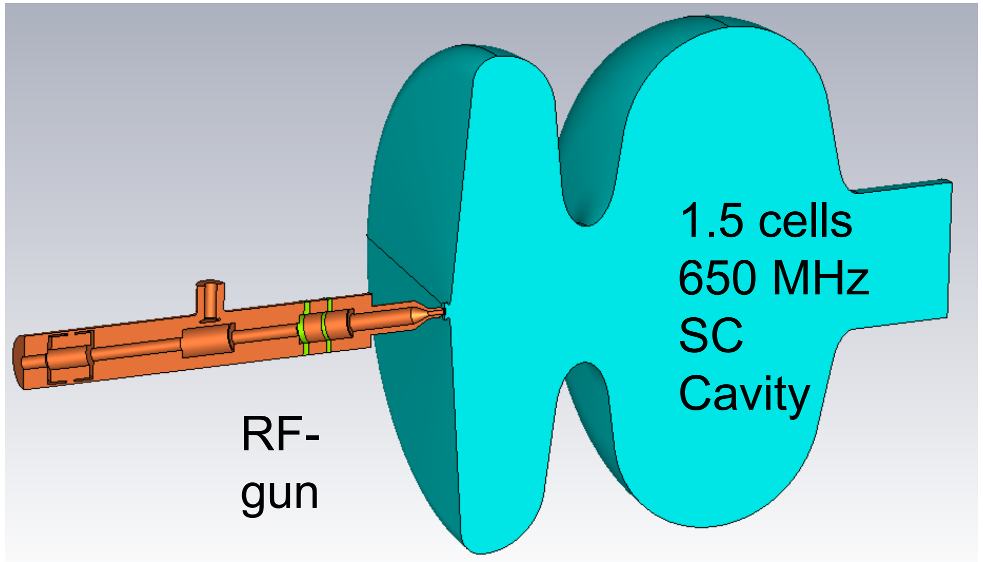
- Mobile high power accelerators enable new applications: In-situ environmental or cross link applications
- DOE funds for conceptual design & key technologies. Funding from DOD (USACE), interest from DHS, NNSA
- Goal: Create a new class of <u>industrial</u> SRF accelerators!

The Compact SRF Accelerator



General concept of RF Gun design

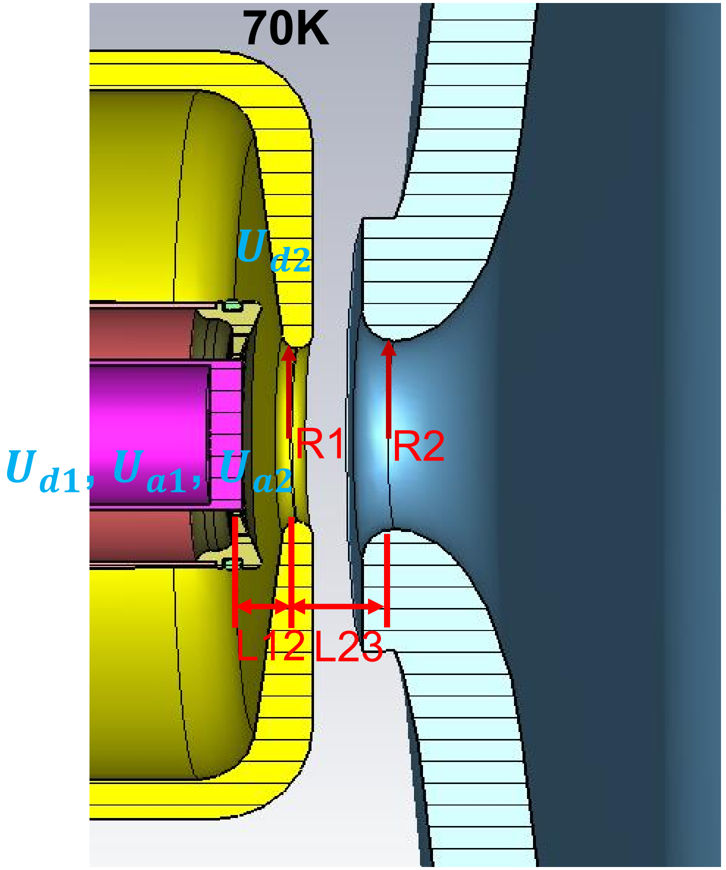
Prototype for a 30 kW project employ internal injection, i.e. electron gun placed directly next to the SC 650 MHz 1.5 cells cavity.



RF – Gun parameters

F	650	MHz
Energy	1.6	MeV
Current	18.5	mA
Power	30	kW
Duty factor	1-100	%
Beam loss at 4K	< 1	W
Cathode radiation	< 0.5	W
Beam energy spread	< 10	%
Beam phase size rms	< 10	°

Progress of RF Gun design

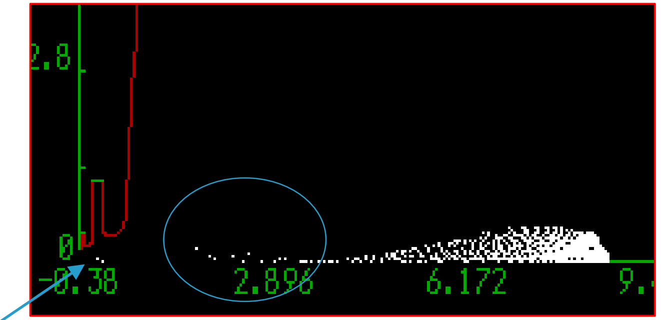


No grid option 2D SMASON Design
2 harmonic case of RF and DC bias

Cathode Ø=3 mm
trade off:
Current density vs
Radiative heating

Parameters	Values	
R1/R2	1.75/3.0	mm
L12/L23	1.65/2.8	mm
Bias cathode Voltage U_{d1}	-4.9	kV
Bias 70K Voltage U_{d2}	-8.05	kV
RF Voltage 1st Harm. U_{a1}	1.85	kV
RF Voltage 2nd Harm. U_{a2}	1.7	kV
Phase shift	-20	deg
Current density	5.9	A/cm^2
Power losses at cathode	~4	W
Sigma E	5.4	keV
Sigma phase	7.5	°

SMASON plot of bunch profile



back bombardment

Progress of RF Gun design

grid option 2D/3D SMASON/MICHELLE

The control cathode-grid gap voltage has the following time dependence:

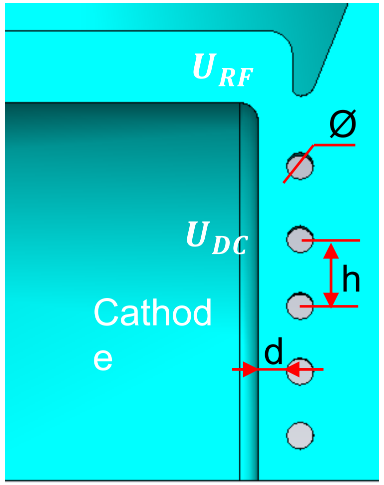
$$U(t) = U_{DC} + U_{RF}\cos(\omega t + \varphi)$$

Where U_{DC} is constant bias voltage, U_{RF} is amplitude of the bias RF voltage, and φ is phase shift of the bias RF voltage at operating frequency.

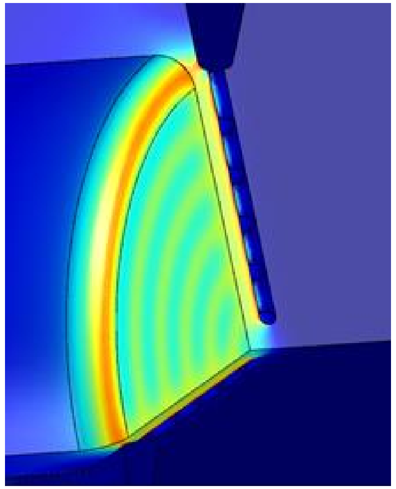
U_{DC}/U_{RF} V	J A/cm^2	Sigma E keV	Phase rms deg
300/370	9.6	7.6 (4%)	7.3
400/480	11.5	5.0 (2.6%)	5.7
500/590	13.6	3.6 (1.9%)	4.8

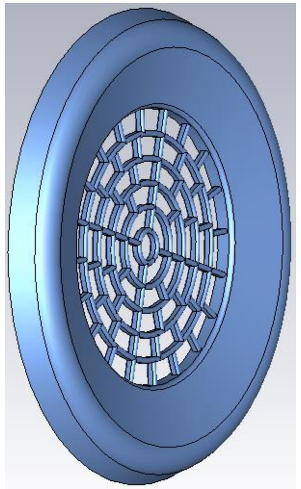
SMASON results , I=18.5 mA. W=0.2 MeV 1st cell

2D SMASON



3D MICHELLE

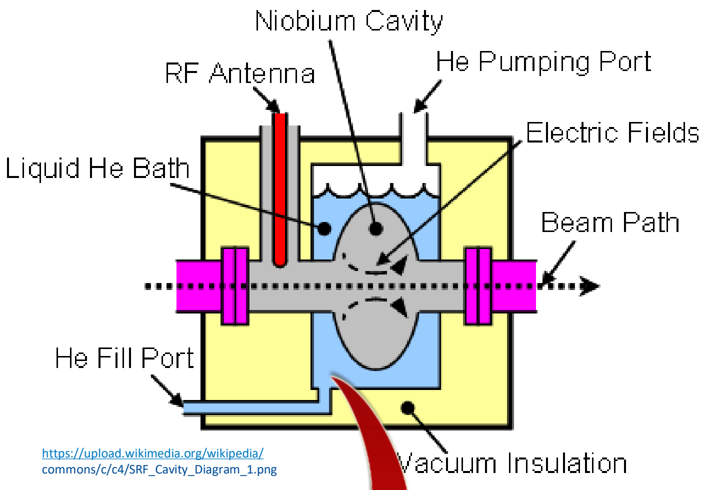




Cathode-grid design:

- grid profile
- cathode-grid distance
- emission uniformity
- losses on the grid

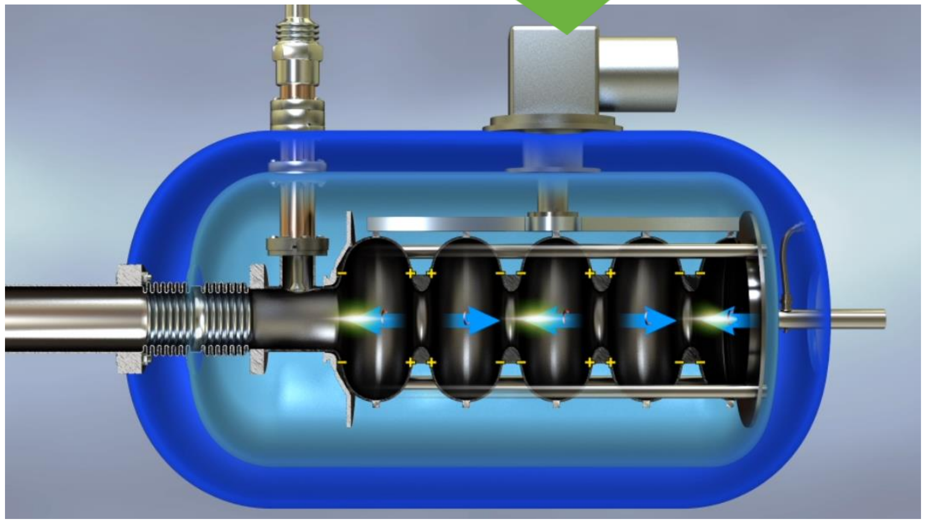
Vision: Access SRF technology minus the complexity



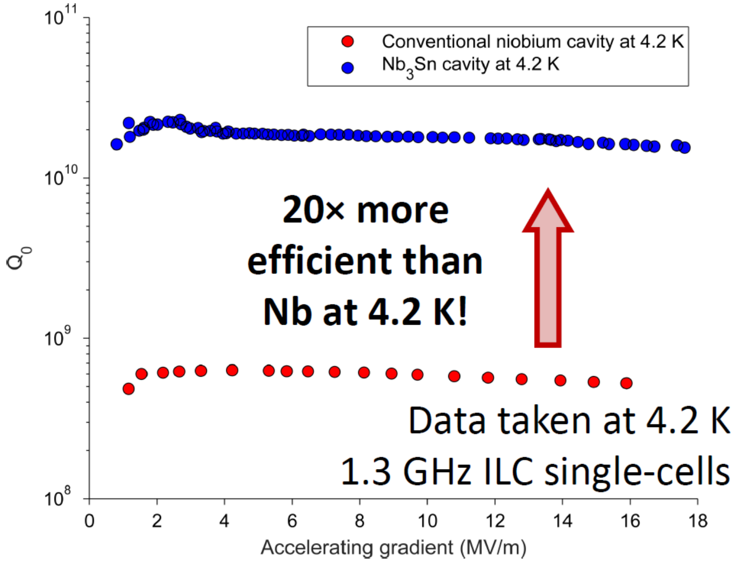
https://upload.wikimedia.org/wikipedia/commons/c/c4/SRF_Cavity_Diagram_1.png

Take out liquid helium
(and its complexities)

Cool with a cryocooler
(simpler refrigerator)



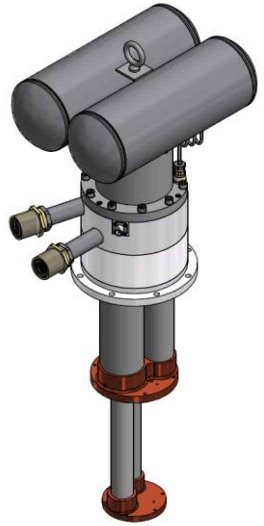
Why now? I heard High-Tc superconductors are decades old



Nb3Sn coated SRF cavities

(S.Posen et al.):

dramatically lower cryogenic losses and allow higher operating temperatures (e.g. 4 K vs 2 K)



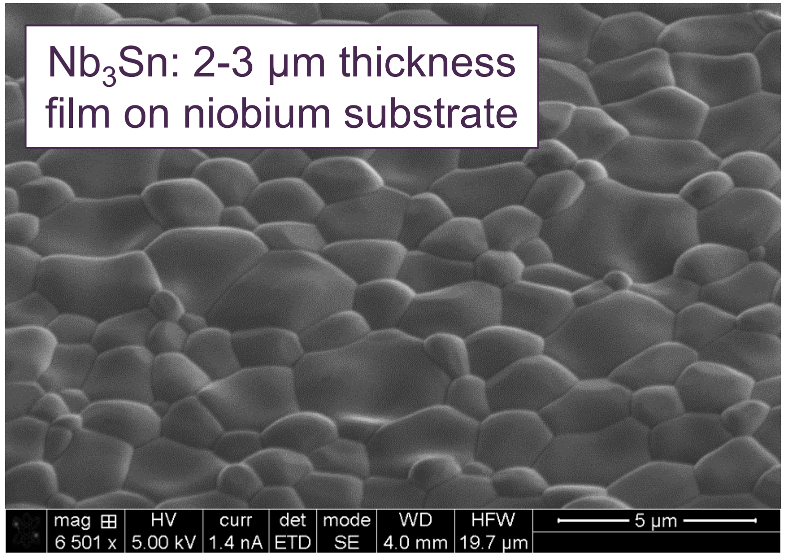
http://www.cryomech.com/coldhead/PT420_ch.pdf

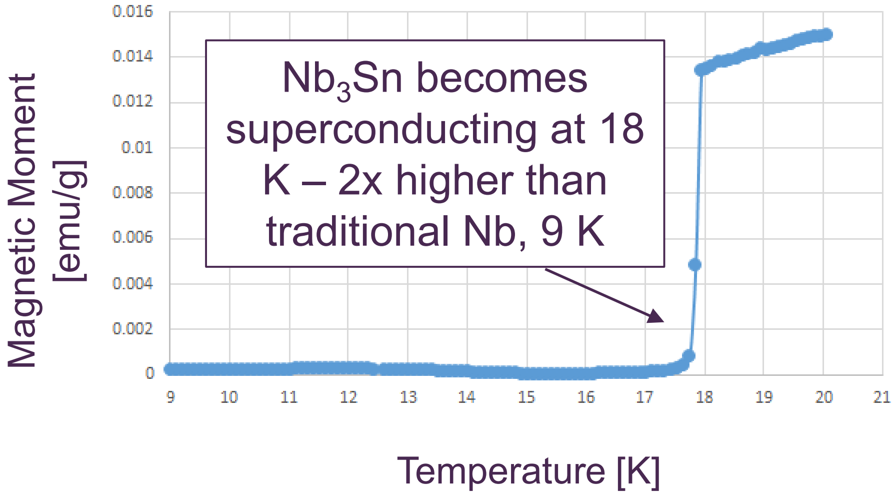
Commercial 4 K cryocoolers:

- Compact refrigerators operating near 4 K, **no liquid helium**
- High reliability (MTTS 20000 hrs), turn on and off with push of a button

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

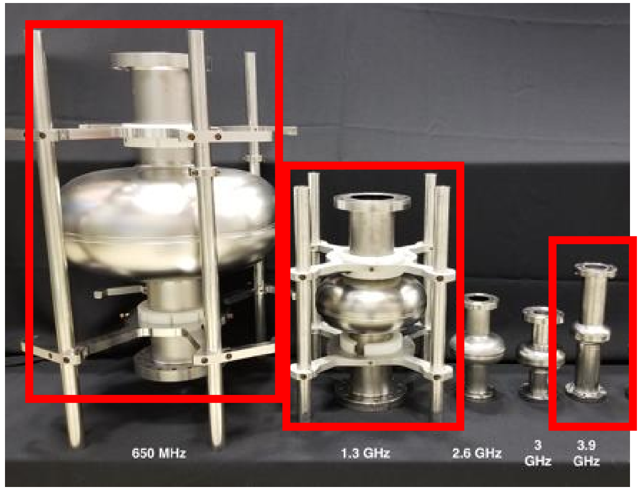


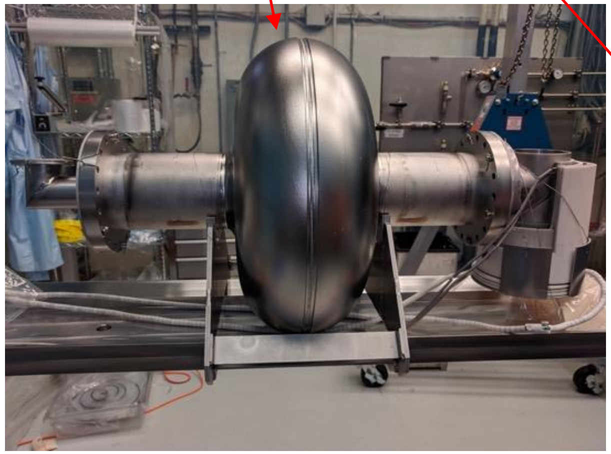


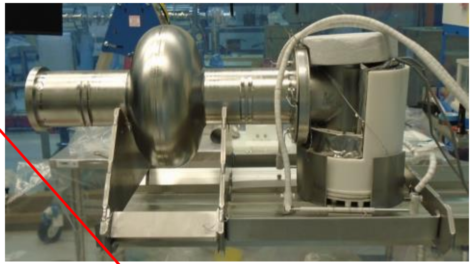
Progress of Nb_3Sn Films

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

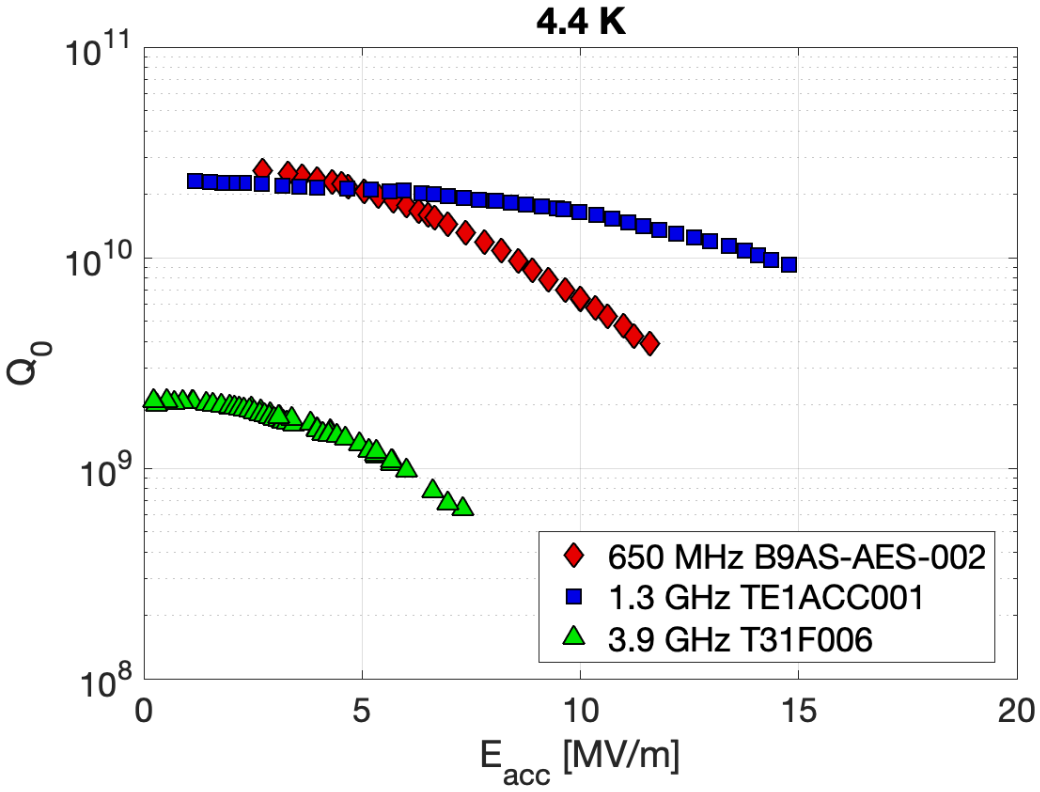
Fermilab Nb_3Sn SRF program: a number of 1.3 GHz cavities already coated and tested; these are the first 650 MHz and 3.9 GHz cavities





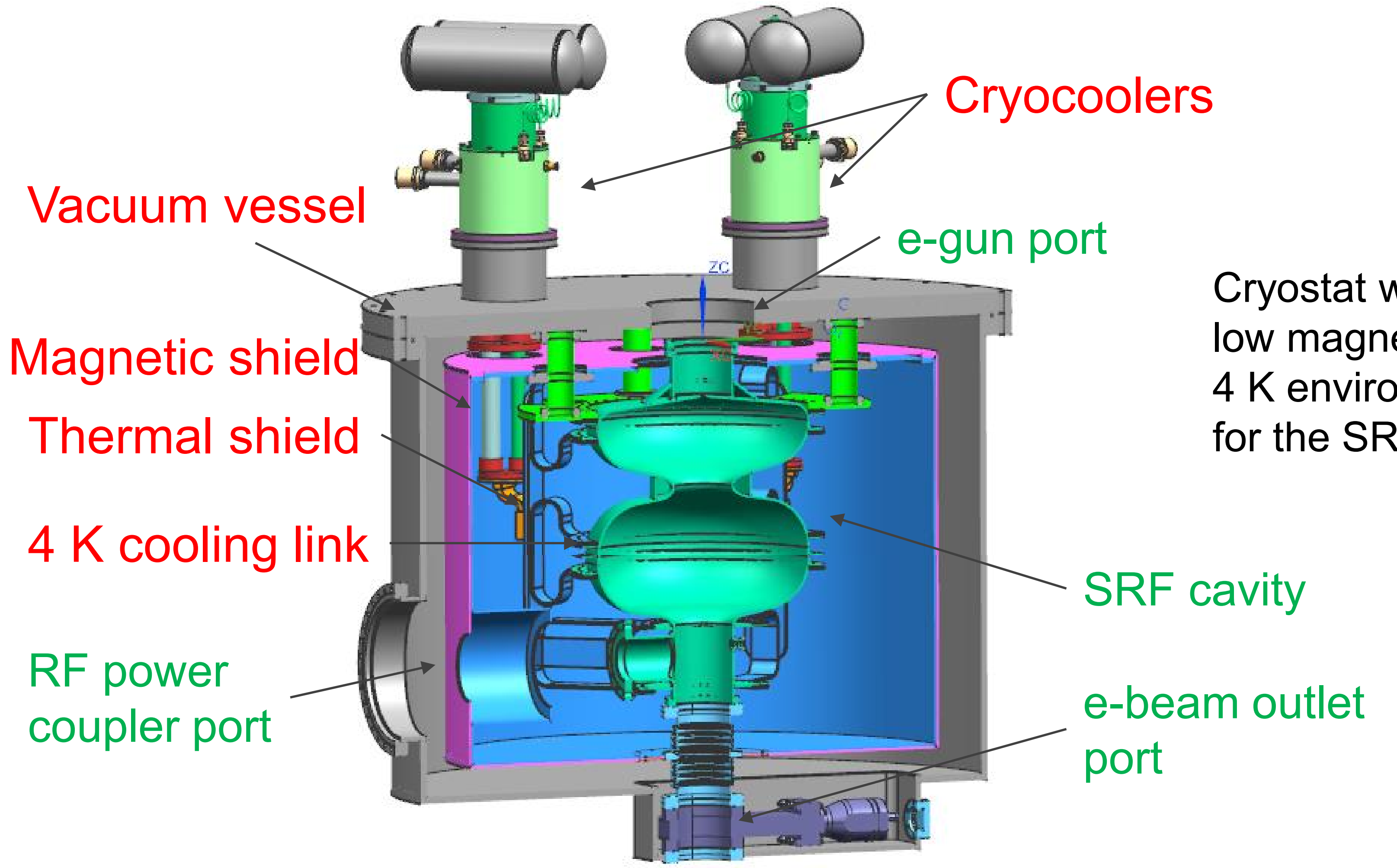


Quality Factor vs Accelerating gradient @ 4.4 K



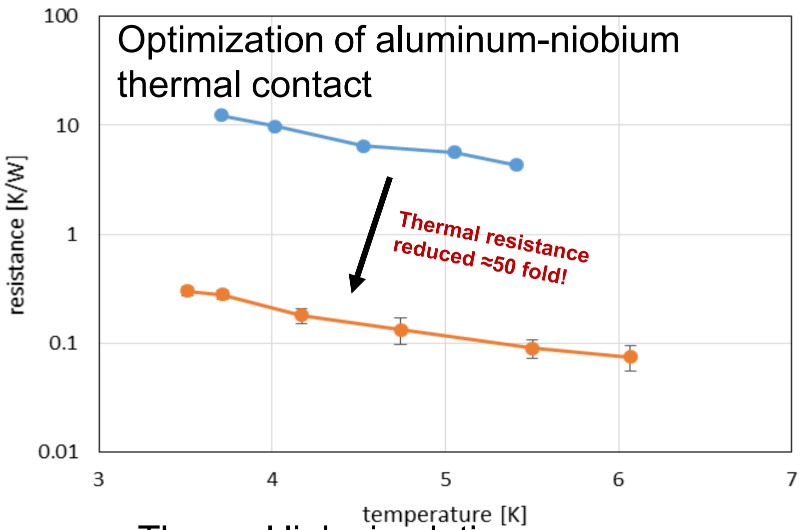
- Q-slope is strong in 3.9 GHz cavity – will re-coat to try to avoid defects
- 650 MHz: some Q-slope and multipacting but still very good – Q_0(5 MV/m) >10 higher than expected for Nb at 4.4 K

Design of the conduction cooled cryostat

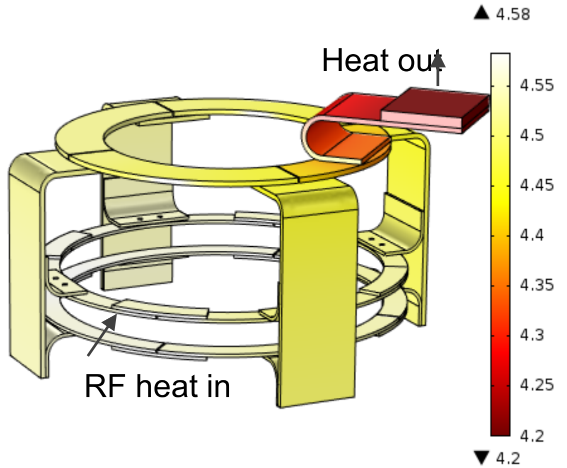


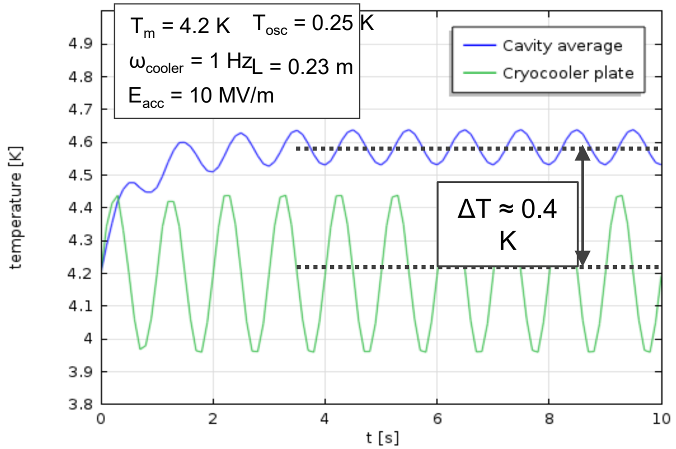
Cryostat will provide vacuum,
low magnetic field,
4 K environment
for the SRF accelerator cavity

Order of magnitude reduction in contact resistance



Thermal link simulations





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

LDRD grant $1.4 M

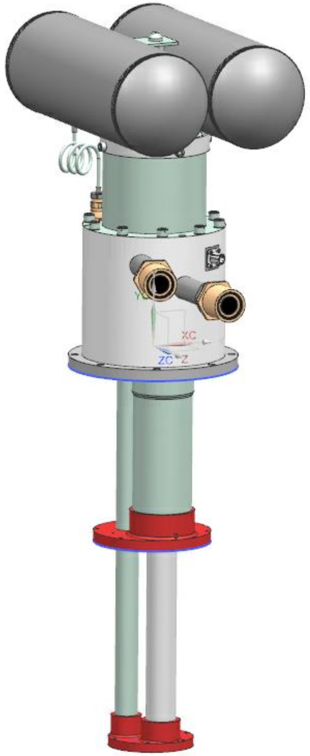
Single cell SRF cavity ready for 4 K RF testing with a cryocooler

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

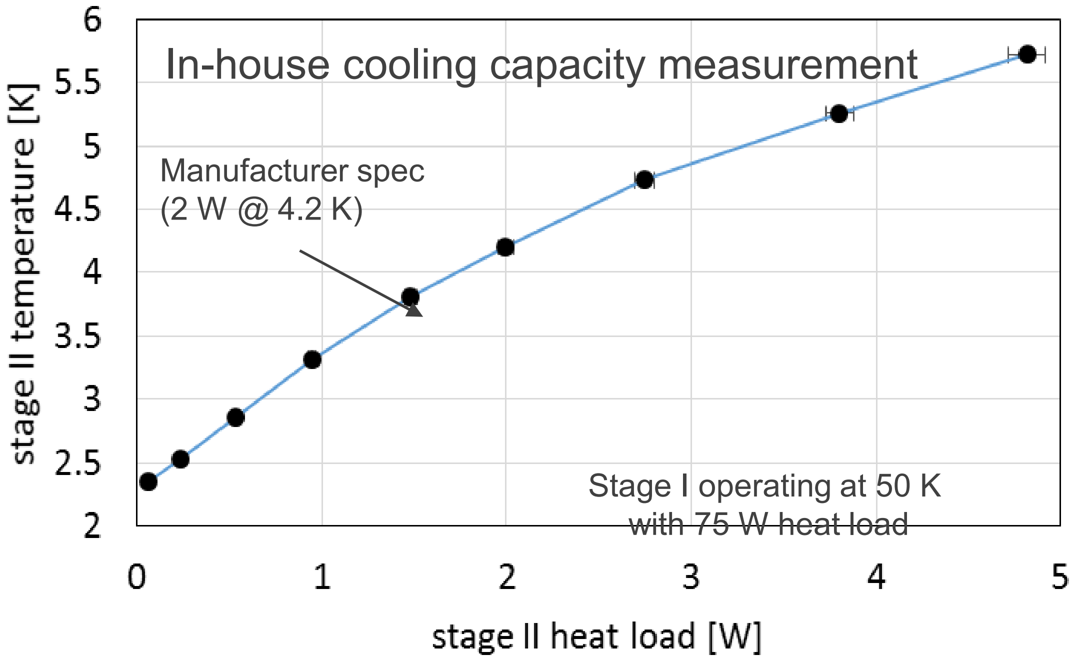
Push of a button to reach 4.2 K

- Selection, procurement, and test of cryocoolers

Cryomech PT420



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



Impact: publications, talks, and media coverage

Contents lists available at ScienceDirect

Cryogenics

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

ELSEVIER

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

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

TechConnect WORLD INNOVATION CONFERENCE & EXPO — 20th ANNIVERSARY — MAY 13-16, 2018 ANAHEIM, CA

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

Cryogen-free Superconducting RF Cavity

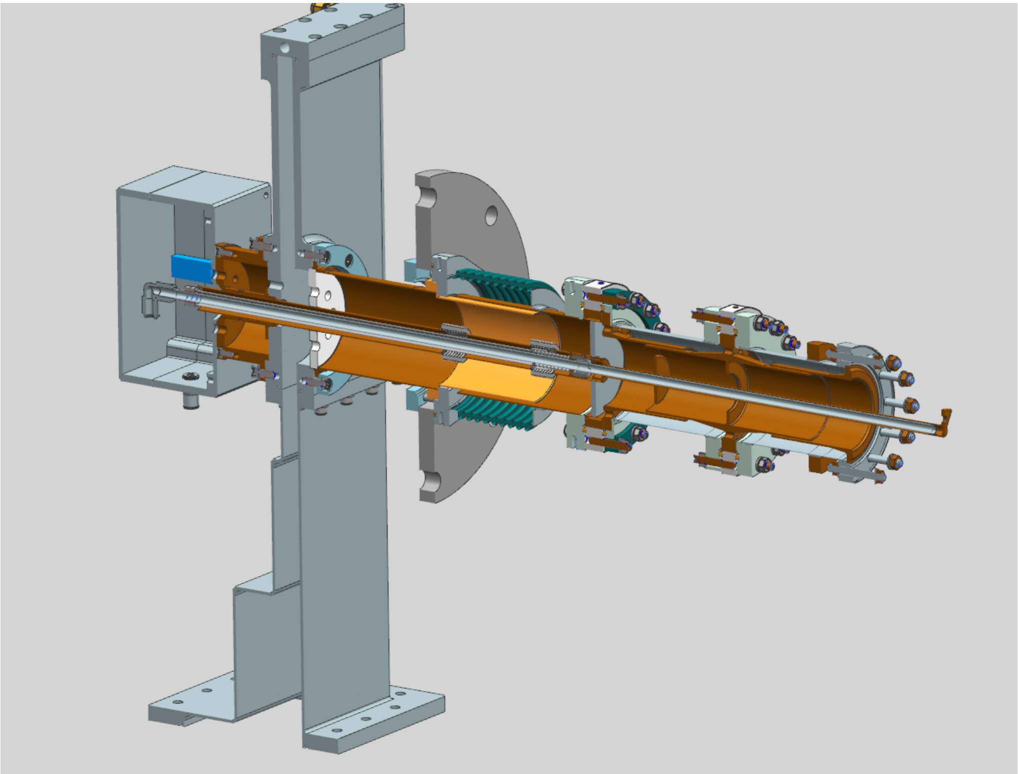
A team from Fermilab has demonstrated cryogen-free operation of a niobium superconducting radiofrequency cavity.

ColdFacts INTERNATIONAL

Towards cryogen-free SRF particle accelerators

Low-heat loss coupler for compact SRF accelerator (in progress).

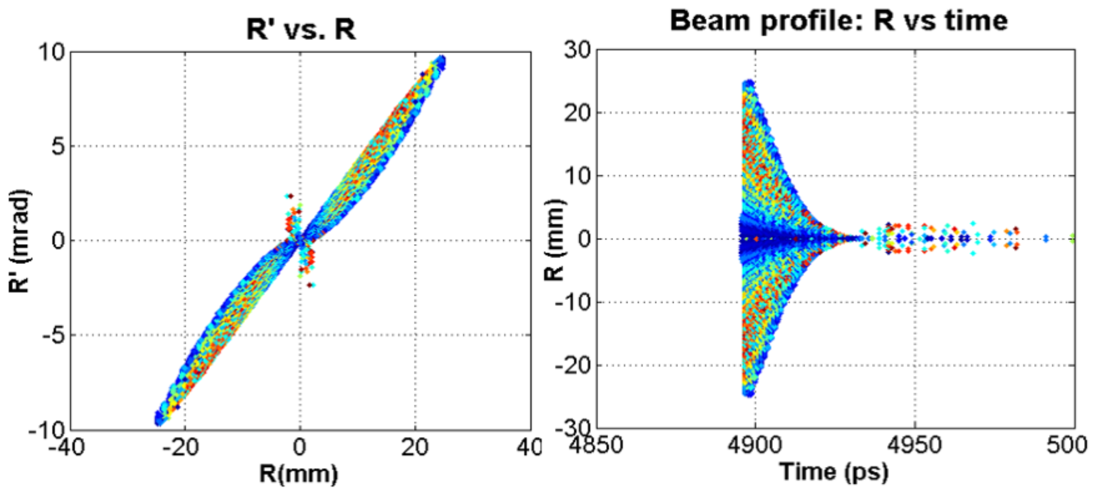
At the first stage the coupler of PIP-II project – a major science project at Fermilab will be used. This coupler has a similar design, but it was designed for 100 kW and cryogenic properties of this coupler are not as good as the properties of (designed) coupler for compact SRF accelerator.



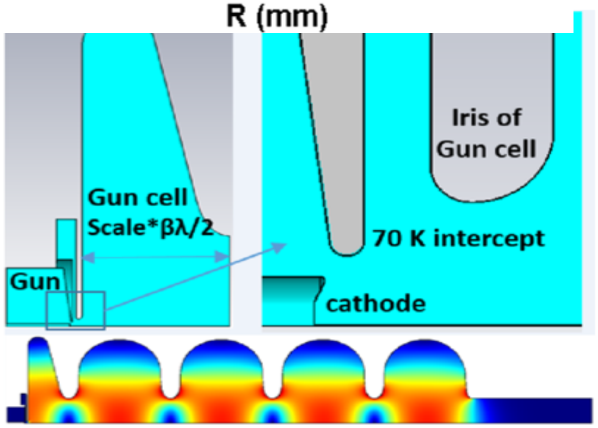
Two PIP-II couplers are under production.

Beam Physics: Simulated Integrated Electron Gun

Reduces size and complexity

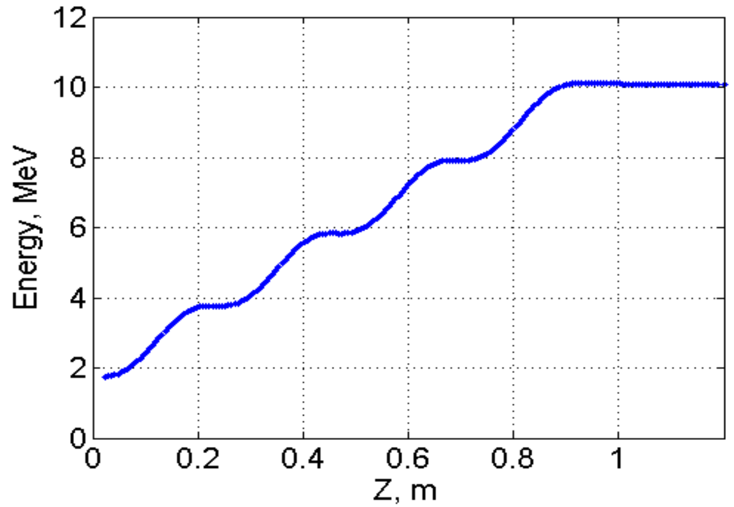


	Value
Electron energy	9 MeV±5%
Current modulation range	0.1 μA - 1 mA
Beam loss at 4K	<0.5 W
Cathode backward bombardment	<1 W
Cathode blackbody radiation	< 200 mW

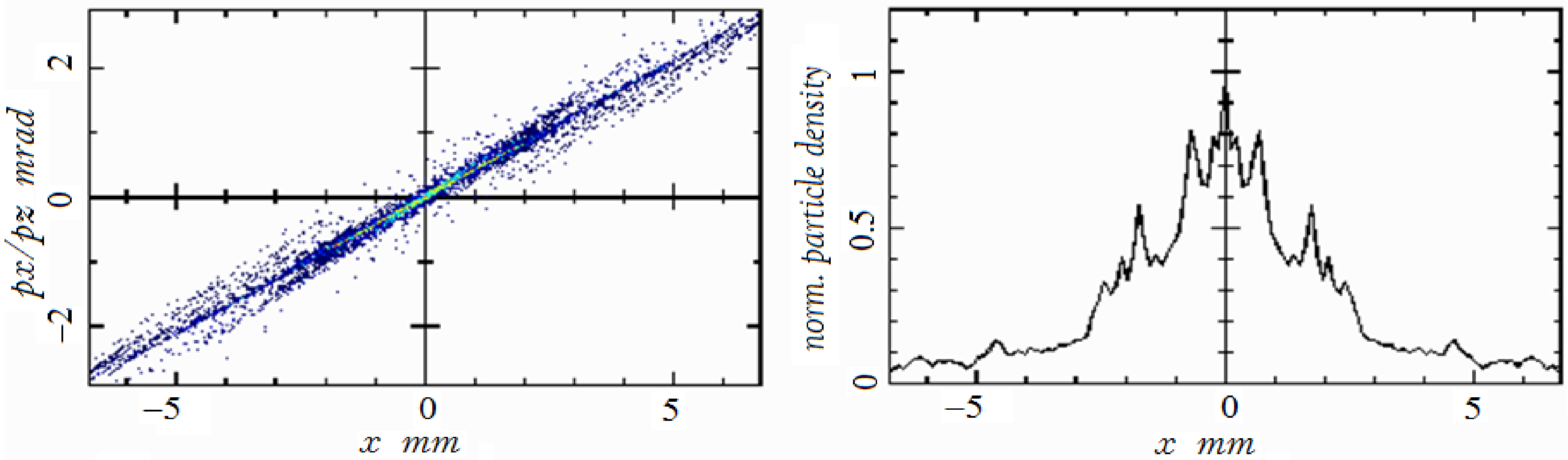


Simulations of the Cavity

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

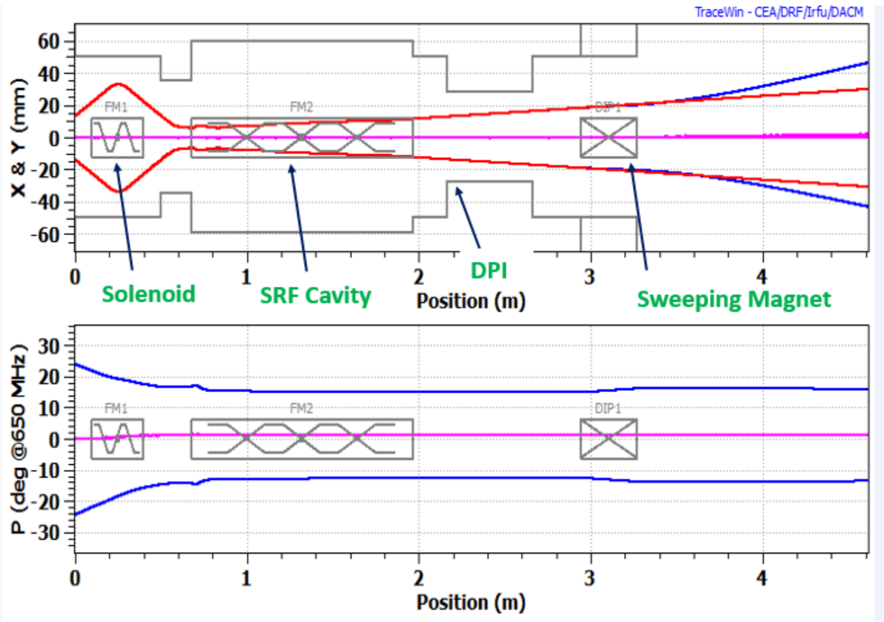


- *(Top) Bunch acceleration along the cavity (RMS energy).*
- *(Bottom Left) Transverse (x-x′) phase-space distribution.*
- *(Bottom Right) Transverse beam charge density distribution.*

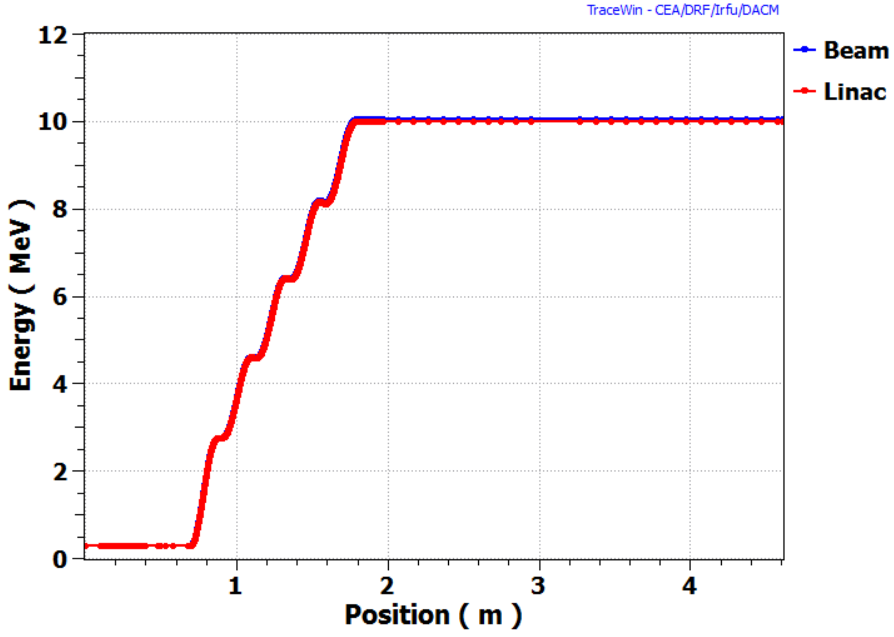


Beam Envelope Simulation from external injection (10 MW)

3σ beam envelopes

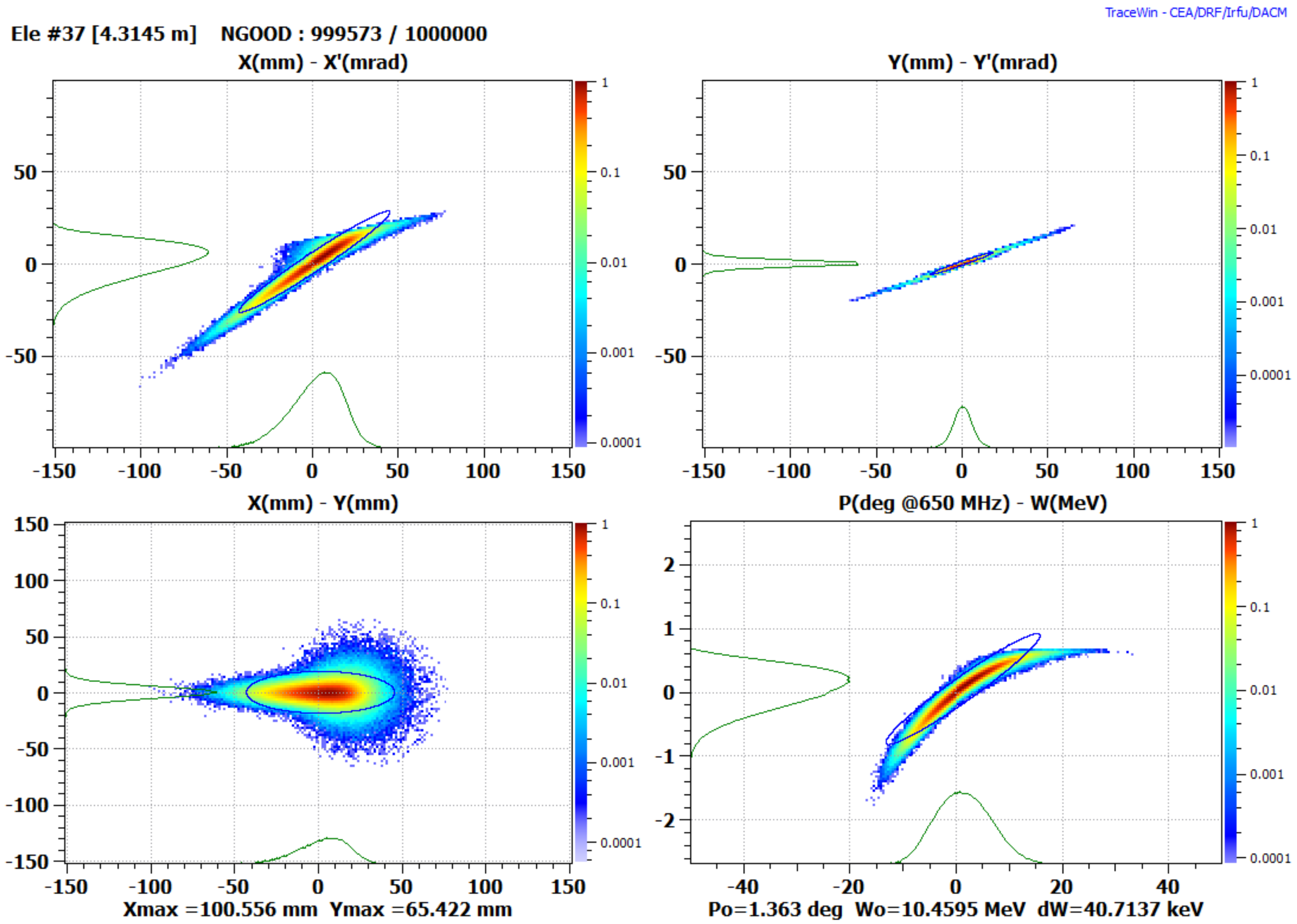


Beam Energy



- Beam dynamics 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)

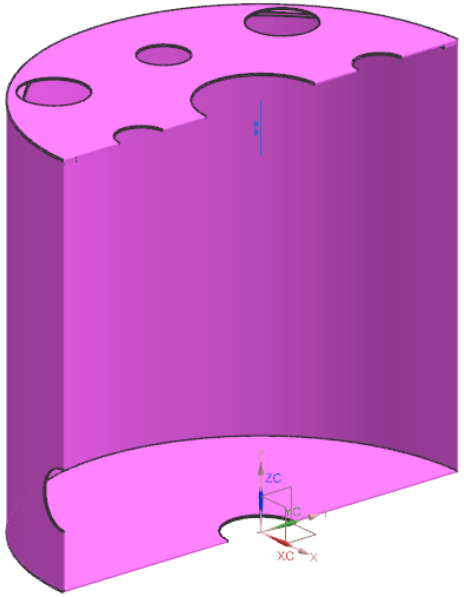


- Output beam distribution at the end of the beamline (very low losses!)

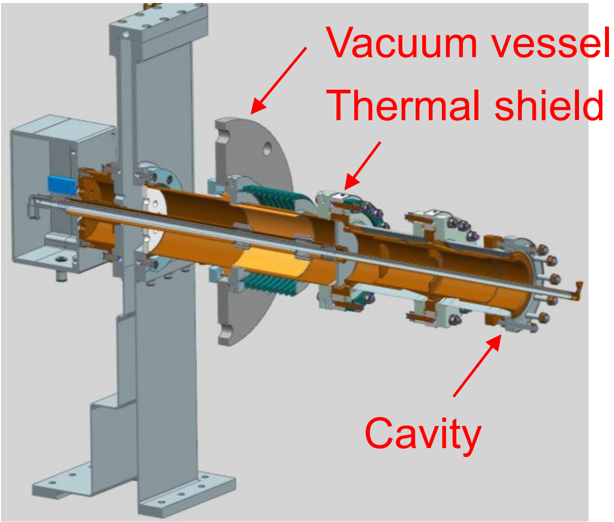
Challenges ahead…

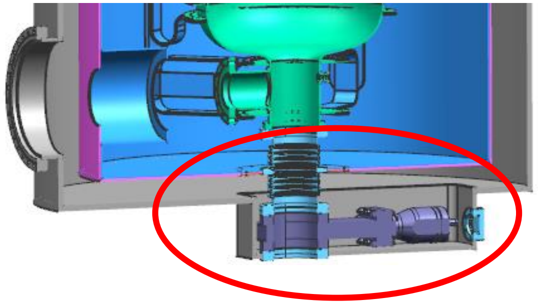
- Magnetic shield
  - ➢ SRF cavities are very sensitive to trapped magnetic fields
  - ➢ Need < few mG to keep RF heat dissipation under cryocooler budget
  - ➢ Penetrations and access ports are to be carefully designed

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



Magnetic shield with penetrations





Shut-off valve at beam outlet

Compact SRF Accelerator

Technology Summary

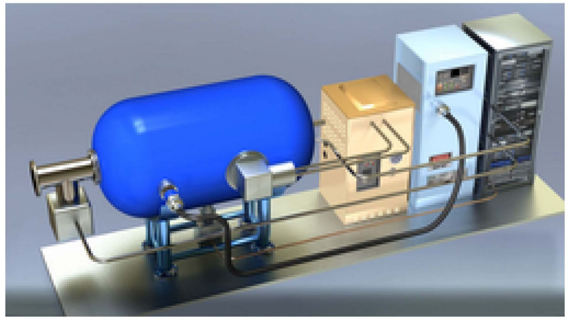
Accelerators developed for science now are used broadly for industrial, medical, and security applications. Over 30,000 accelerators touch over $500B/yr in products producing a major impact on our economy, health, and well-being. Industrial accelerators must be cost-effective, simple, versatile, efficient,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



Invention Details

Patent Status: Multiple patents pending

Contact:
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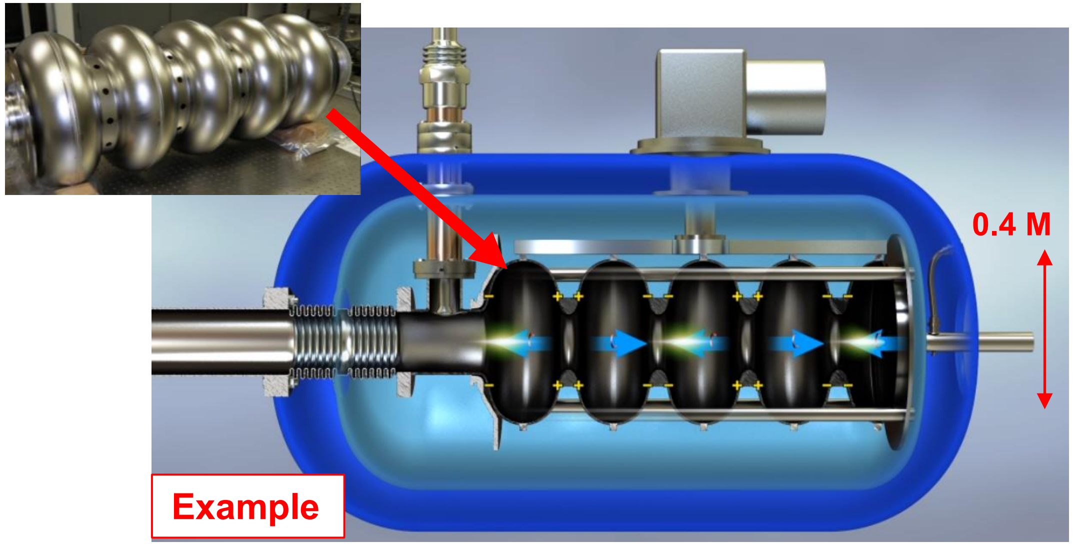
Fermilab, MS 312- PO Box 500
Batavia, IL 60510

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 thorough partnerships is building the first article of an entirely new class of industrial SRF-based electron accelerators that use no liquid cryogens

Thank you!!!