FERMILAB-SLIDES-20-018-DI-LDRD-TD

Cryocooler conduction-cooled SRF cavities for particle accelerators

Ram C. Dhuley

Cockcroft Institute Seminar, 08 September 2020

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Superconducting radiofrequency (SRF) technology has revolutionized particle accelerators for science

SRF benefits for large scientific machines

- High wall-plug efficiency
- High average beam power

Breakthroughs continue to ensue

- Niobium cavities achieve >50 MV/m in 2 K liquid helium
- Nb_3Sn cavities attain >20 MV/m in 4.5 K liquid helium

Fermilab

SRF for
basic science

⇒

SRF for
industry & society

- SRF relevant Industrial applications of particle accelerators?
- How to make SRF suitable for industrial settings?

IARC at Fermilab

IARC's mission: Partner with industry to exploit technology developed in the pursuit of science to create the next generation of industrial accelerators, products, and new applications.

Partners

- MWRD of Greater Chicago
- US Army Corps of Engineers (ERDC)
- Northern Illinois University
- Euclid Beamlabs
- General Atomics

In-house facilities

- Several 4 K cryocoolers, cryogenic test stands, 500 W LHe refrigerator
- LLRF system, solid state RF power source (20 kW)
- 9 MeV, 1 kW electron accelerator (A2D2)

Contact

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https://iarc.fnal.gov/

Outline

- Industrial applications and scope of SRF accelerators
- Cryocooler conduction-cooled SRF cavities
  - Development at Fermilab
  - First results
  - Ongoing R&D
- Fermilab's conduction-cooled SRF accelerator program
- New R&D facilitated by cryocooler-cooled SRF
- Summary and outlook

Industrial applications and scope of SRF accelerators

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:

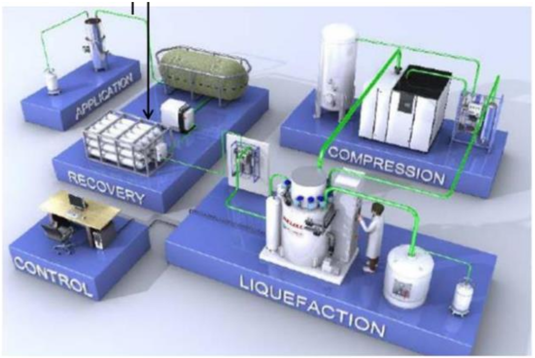
- Low capital and operating expense
- Robust, reliable, turnkey operation

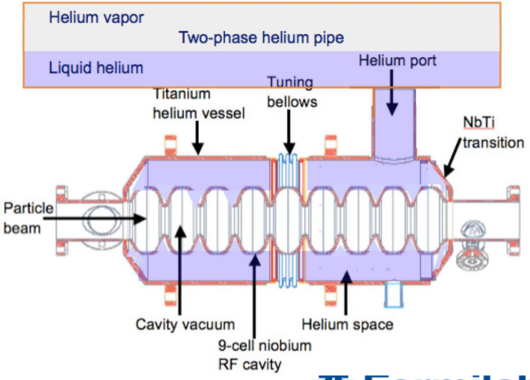
http://accelconf.web.cern.ch/AccelConf/napac2016/talks/thb3io02_talk.pdf

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!





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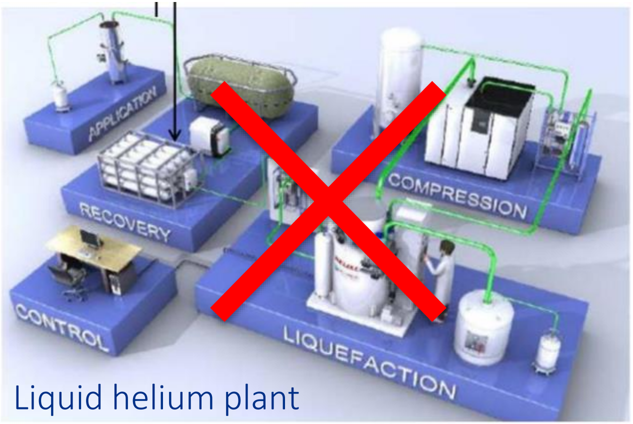
Simplifying SRF cryogenics for industrial settings

Nb$_3$Sn cavity dissipates ~6-8 W @ ~4.5 K

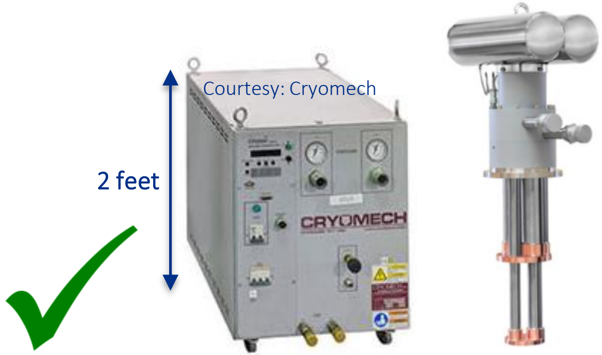
(1 m x 10 MV/m cw; 650 MHz/1.3 GHz)

Use commercial, off-the-shelf 4 K cryocoolers

(helium plant not required)



Liquid helium plant



Compressor Cryocooler

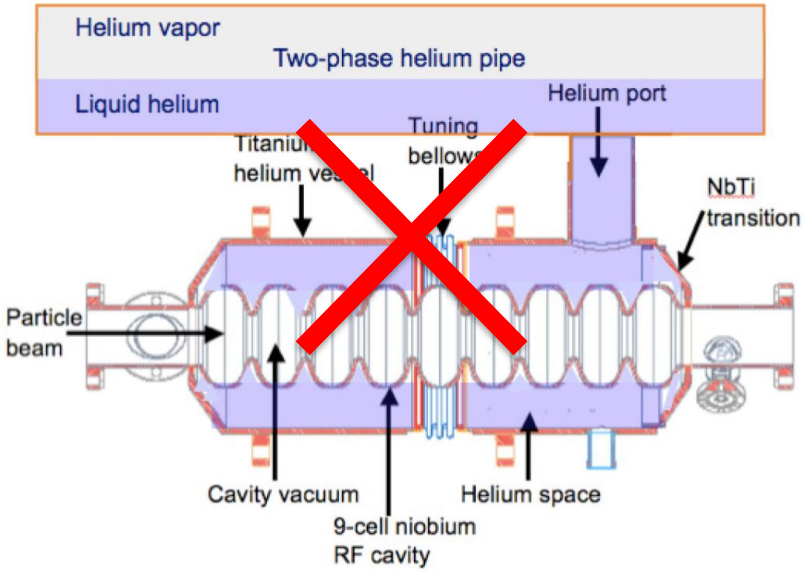
Cryocoolers offer

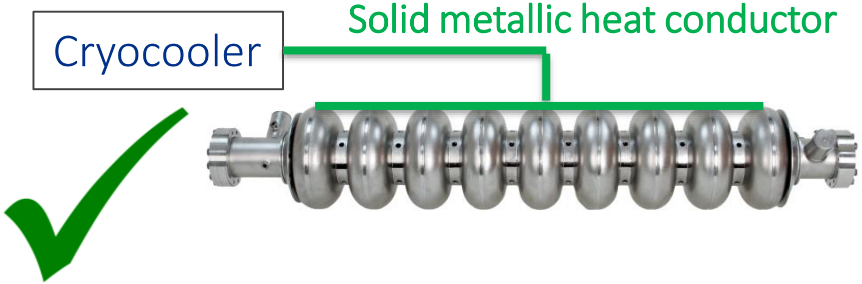
- Closed cycle cooling at ~45 K and ~4 K
- Compact, small footprint
- Reliability (MTBM > 2 years non-stop operation)
- Turnkey operation (no trained operator needed, turn ON/OFF with push of a button)

Simplifying SRF cryogenics for industrial settings

Remove cavity dissipation *with* thermal conduction (conduction cooling)

(conventional liquid helium bath not required)



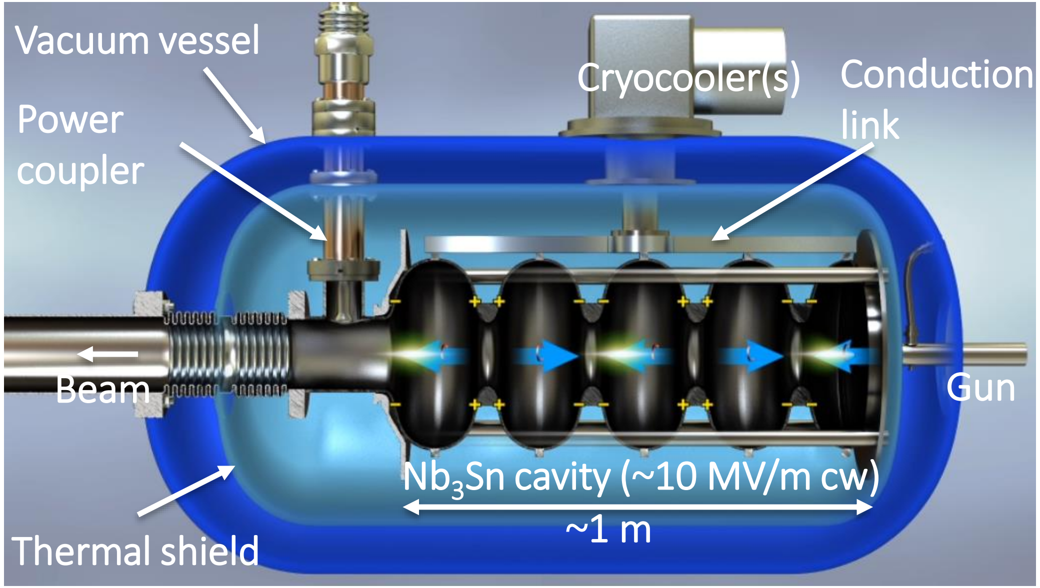


Absence of cryogenic liquids

- Compact, simplified construction
- No pressure vessel safety concerns
- Facilitates deployment in remote locations

Concept of a cryocooler conduction-cooled SRF accelerator

R.D. Kephart, *SRF2015*, 2015. https://accelconf.web.cern.ch/srf2015/papers/frba03.pdf
Patents: US10390419B2, US10070509B2, US9642239B2



All cryogenics integrated into the module

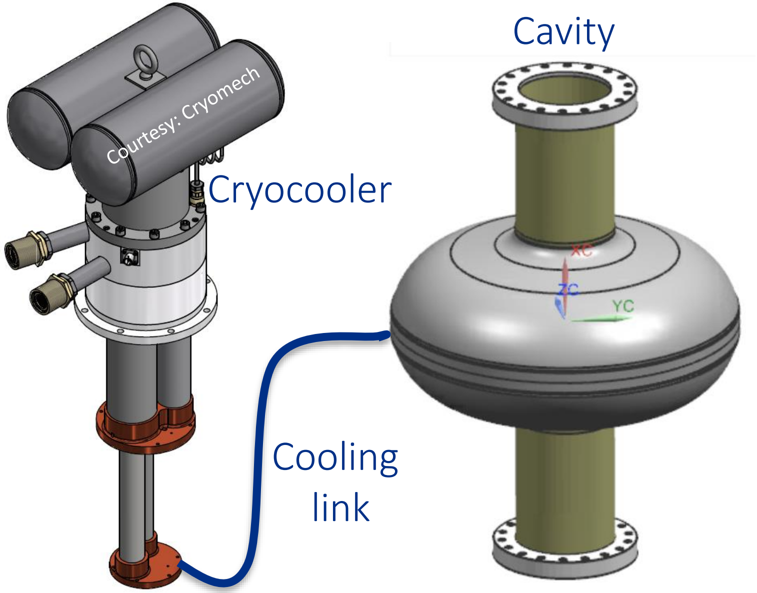
- Cryocooler 4 K stage cools the SRF cavity
- Cryocooler 45 K stage cools thermal shield/intercept
- Enclosed in a simple vacuum vessel

Conduction-cooled SRF cavity development at Fermilab

Goal: To demonstrate 10 MV/m cw on an SRF cavity with cryocooler conduction-cooling

Our choices:

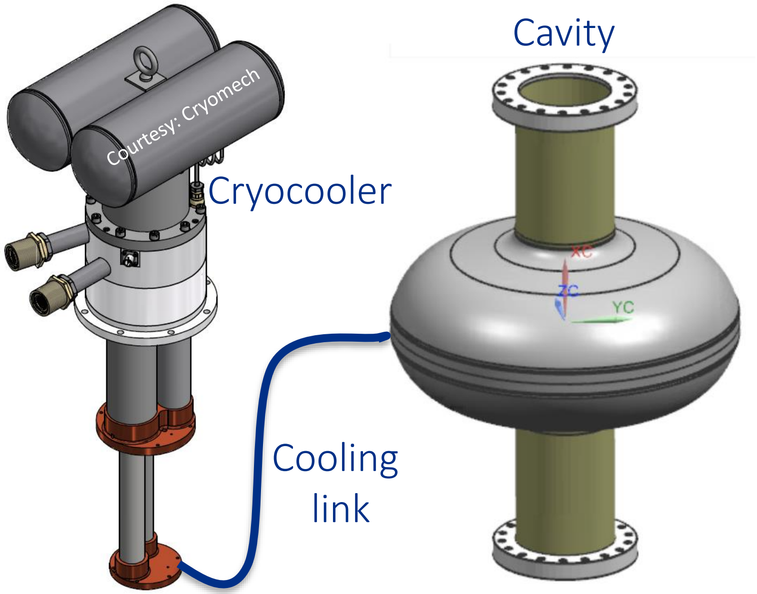
- Single cell 650 MHz, Nb_3Sn coated niobium cavity
- Cryomech PT420 cryocooler (2 W @ 4.2 K with 55 W @ 45 K)
- High purity aluminum for the conduction cooling link



Goal: To demonstrate 10 MV/m cw on an SRF cavity with cryocooler conduction-cooling

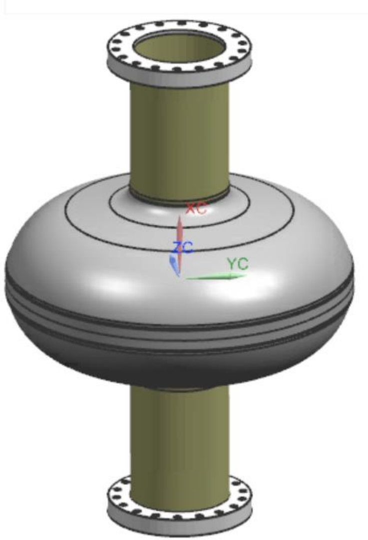
Technical challenges:

- Preparing the cavity for conduction cooling
- Managing thermal resistance (contact and bulk)
- Magnetic shielding of the cavity



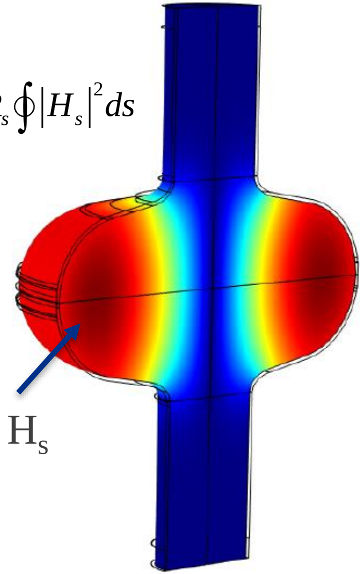
Cavity preparation for thermal link attachment

Need a thermal link attachment point on the niobium cavity shell

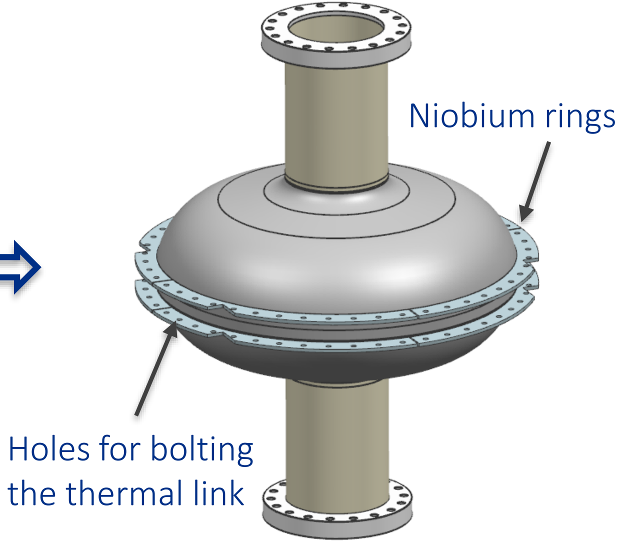


Dissipation is prominent near the equator

$$P_{diss} = \frac{1}{2} R_s \oint |H_s|^2 ds$$



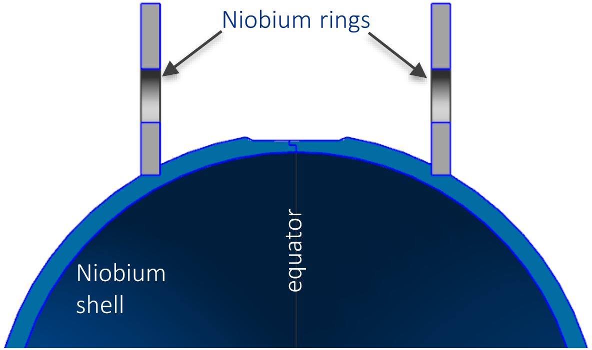
Solution: E-beam weld niobium cooling rings near the equator



Cavity preparation for thermal link attachment

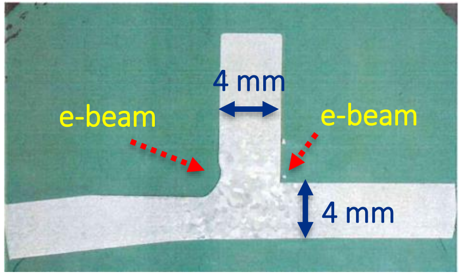
R.C. Dhuley, Provisional Patent **63/023,811**

Joint design for e-beam welding

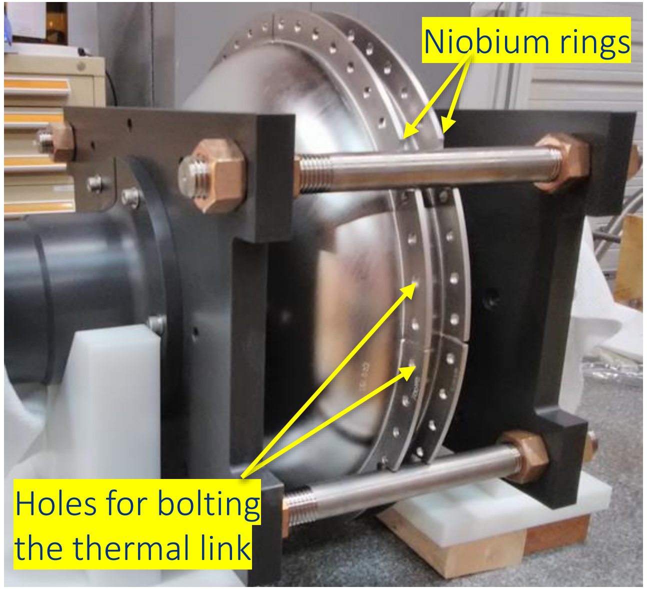


Weld development

- Full penetration for thermal conductivity
- Avoid weld beads on the RF surface



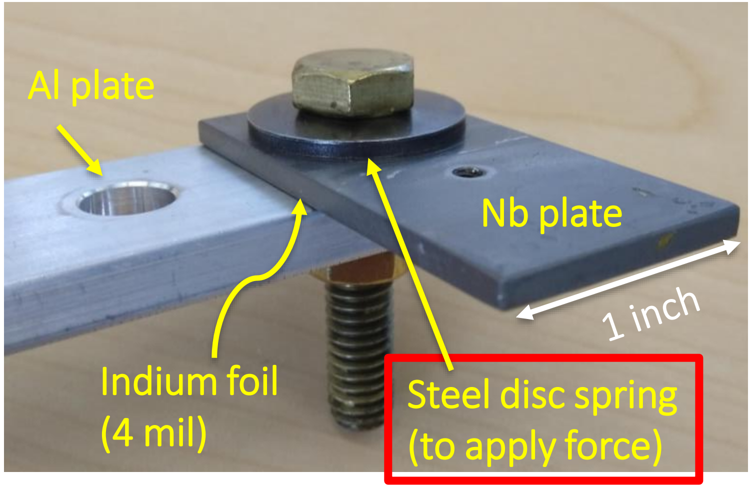
Single cell cavity ready for conduction cooling



Characterization of thermal resistance

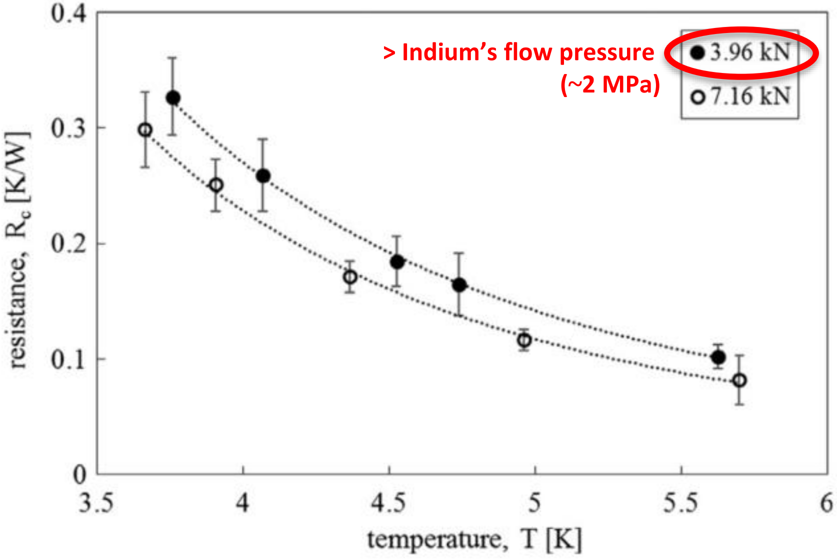
1. Cavity-link (niobium-aluminum) bolted thermal contacts

Test joint details



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

Joint thermal resistance

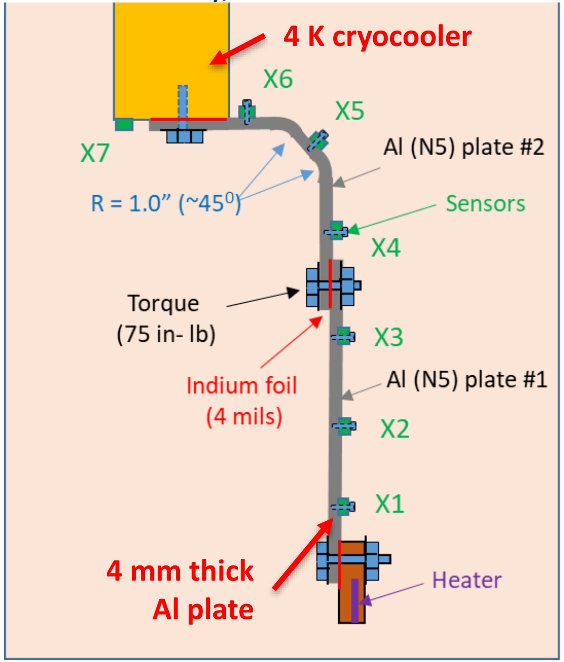


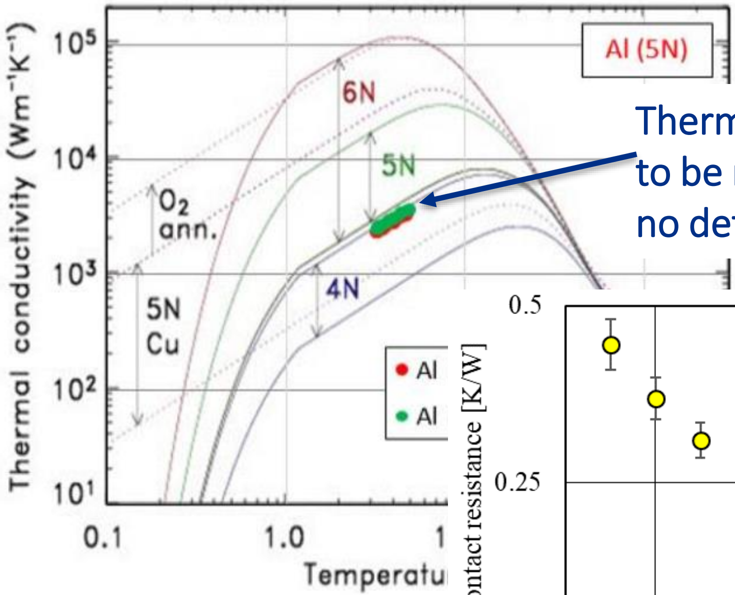
Selected design: 4 mil indium, ~4 kN force

Characterization of thermal resistance

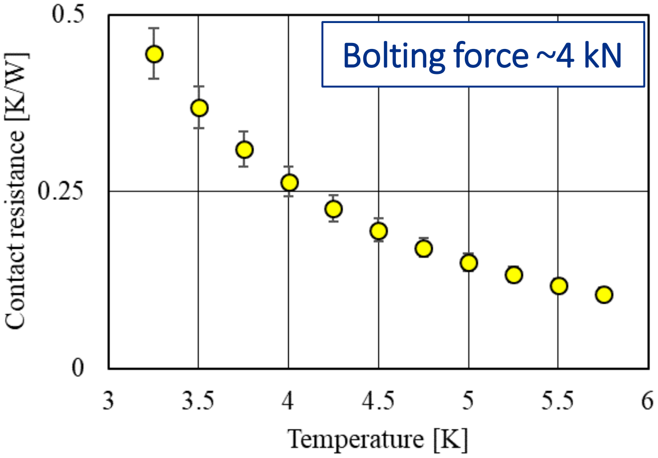
2. Thermal characterization of high purity aluminum

Setup for measuring 4 K thermal conductivity, contact resistance





Thermal conductivity found to be near the lower band of 5N, no deterioration from bending

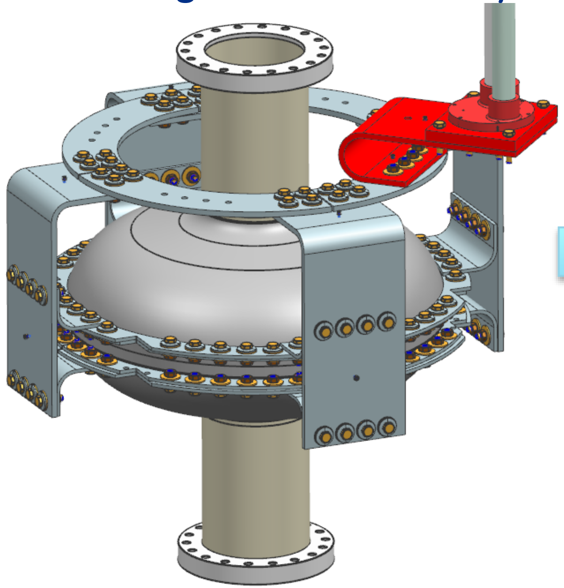


Fermilab

Design of the conduction link design

3. Mechanical design; verification *via* multiphysics simulations

Al conduction link bolted to the Nb rings around the cavity

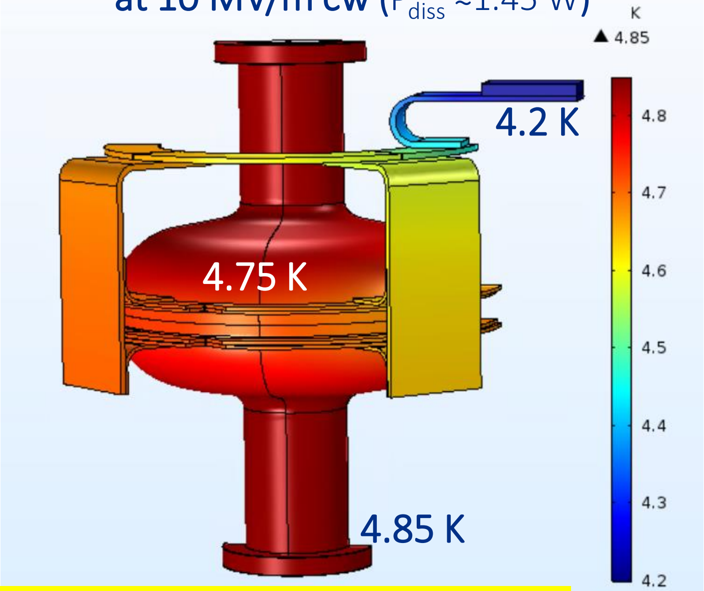


Nb_3Sn surface resistance (BCS from SRIMP + 10 nΩ)

RF + thermal simulations

Thermal conductivities, contact resistance, cryocooler capacity

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

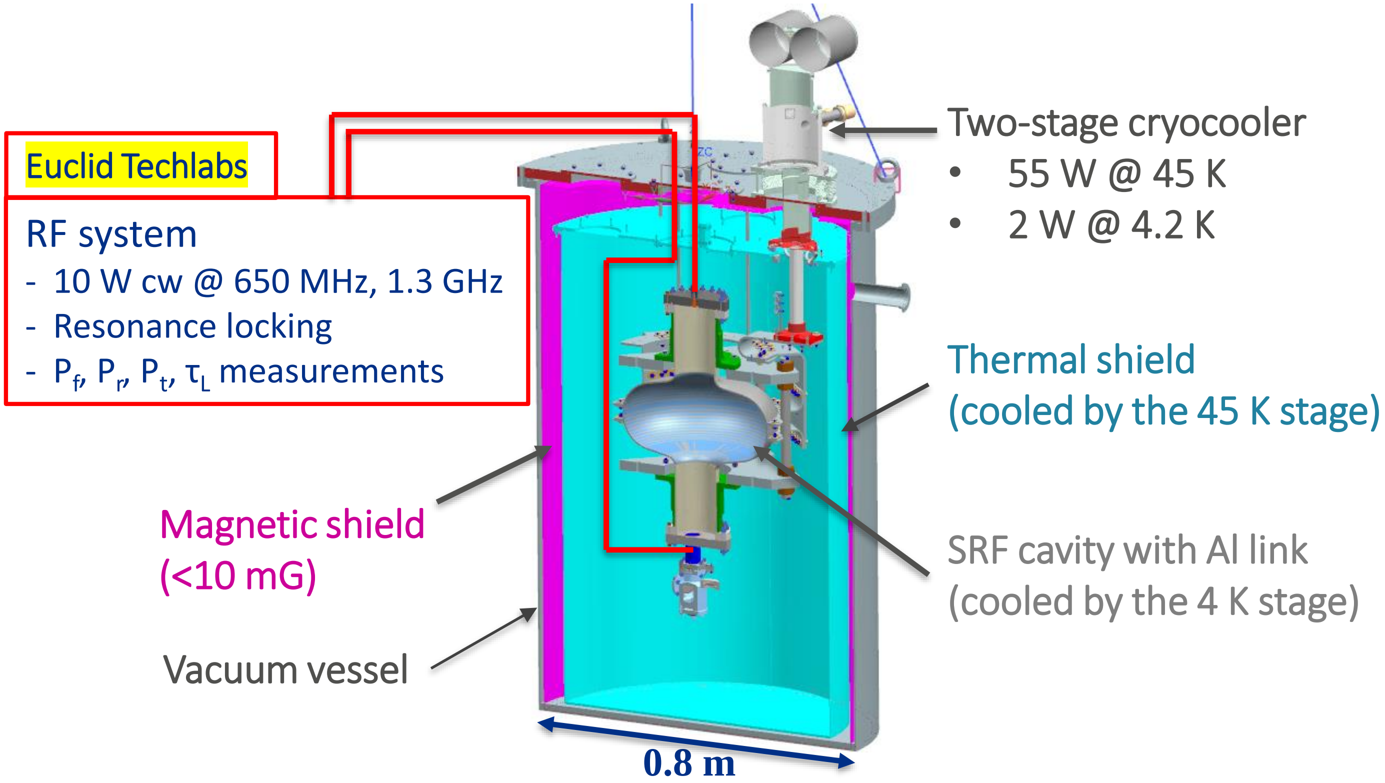


Simulated conductance ($P_{diss}/\Delta T$) ≈ 2.6 W/K

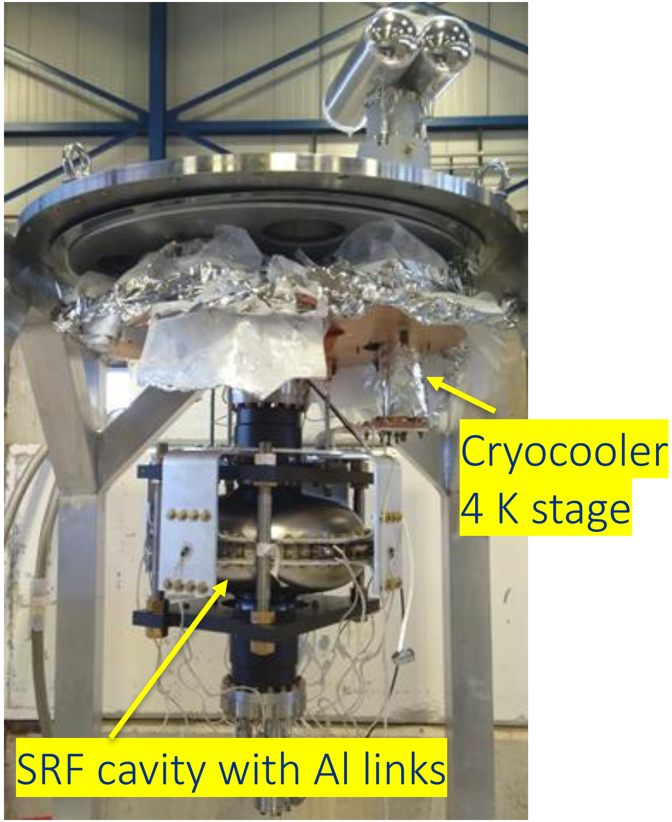
J. Thompson and R.C. Dhuley, 2019. https://doi.org/10.2172/1546003
R.C. Dhuley *et al.*, ***IEEE Trans. Appl. Supercond.***, 2019. https://doi.org/10.1109/TASC.2019.2901252

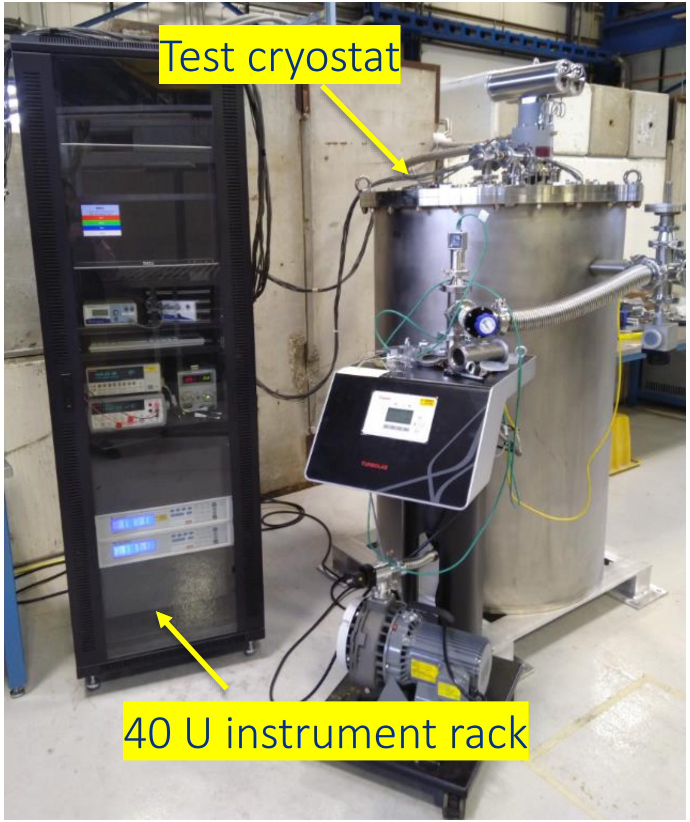
Conduction-cooled SRF cavity measurement setup at Fermilab

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



Conduction-cooled SRF cavity measurement setup at Fermilab





Cavity processing and test sequence

Niobium cavity with conduction rings

⇩ RF check, bulk EP, 800 ^{0}C bake, light EP, HPR

2 K VTS test of niobium cavity (check 10 MV/m cw)

⇩

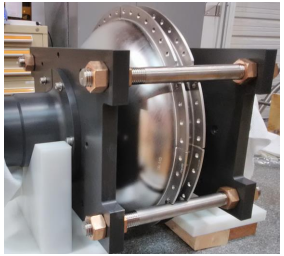
Coat with Nb_3Sn

⇩

4.4 K VTS test of Nb_3Sn cavity (baseline test)

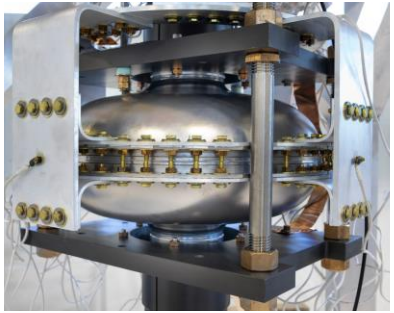
⇩ Warm-up, connect thermal link

Conduction-cooled tests of Nb_3Sn cavity



Cavity as received from vendor

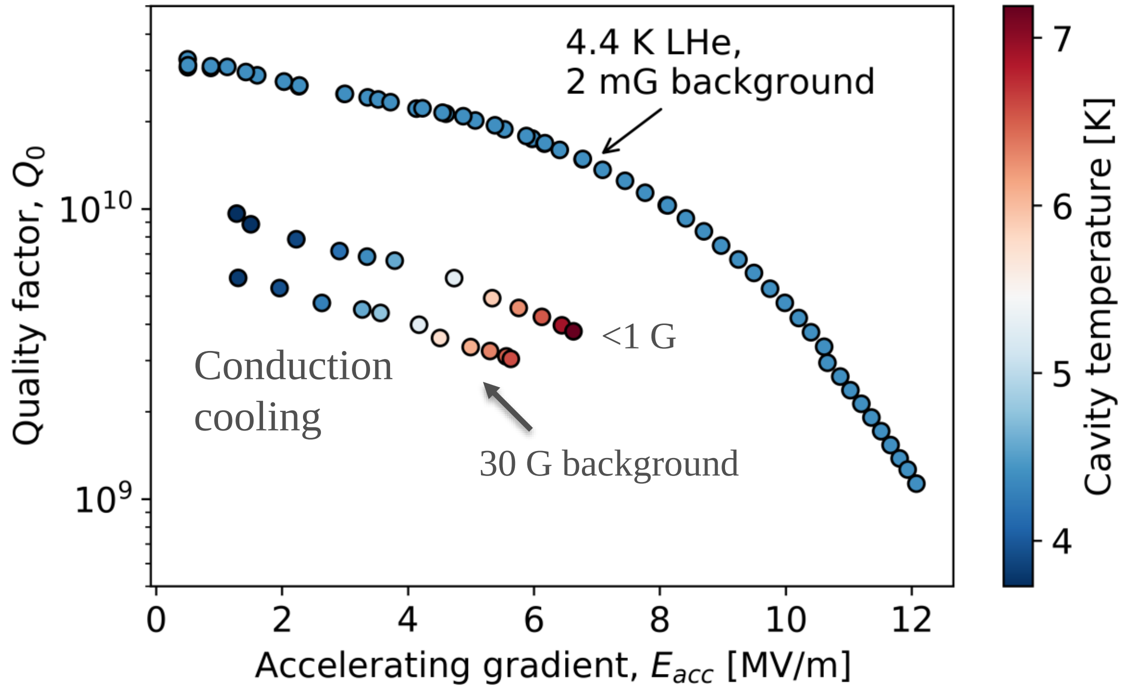
Cavity on HPR tool



Cavity dressed with Al link

First results for the conduction-cooled Nb_3Sn cavity

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



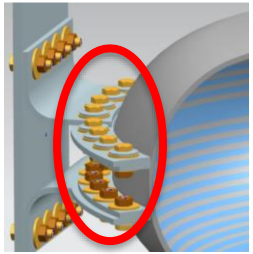
(max. E_{acc} limited by RF power)

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

Ongoing research to reach 10 MV/m

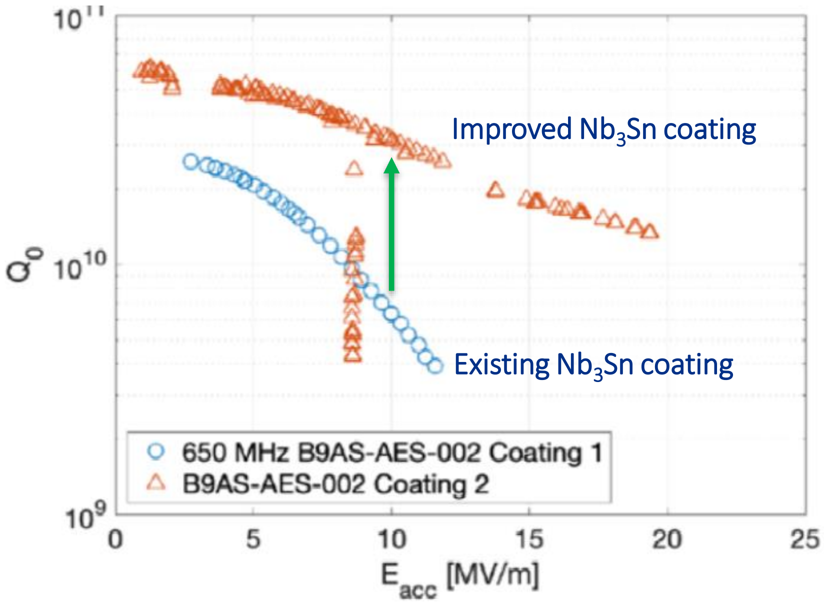
1. Improve magnetic hygiene to reduce trapped flux

Steel (magnetic)

Beryllium copper (non-magnetic)

2. Flux expulsion by slow/fast cooldown using cryocooler

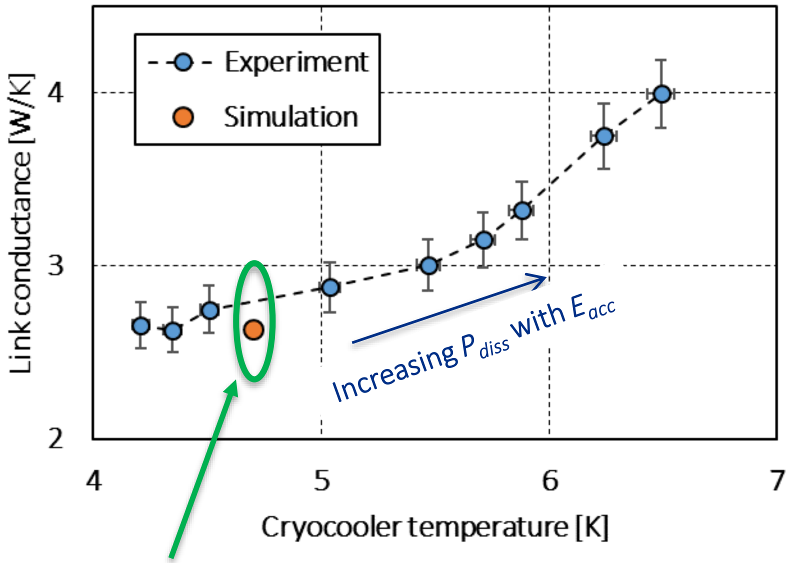
3. Improve Nb_3Sn coating recipe



S. Posen *et al.*, https://accelconf.web.cern.ch/srf2019/papers/thfub1.pdf

Conduction link performance, cavity thermal stability

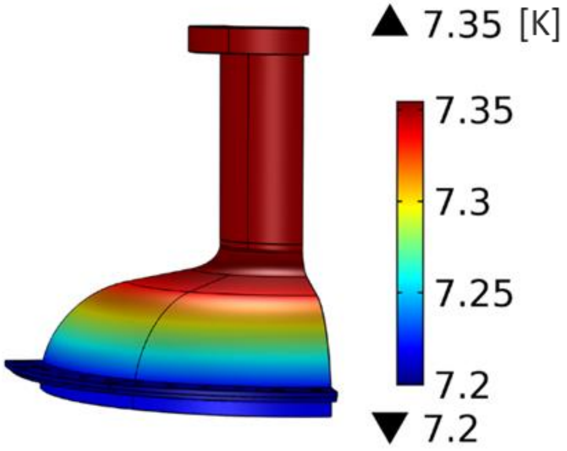
Comparison of measured and simulated link thermal conductance



Good match!

Computed cavity surface temperature at steady state with 6.6 MV/m cw

- Ring temperature = 7.2 K (boundary condition)
- RF dissipation = 4 W (boundary condition)



Courtesy : R. Kostin (Euclid Techlabs)

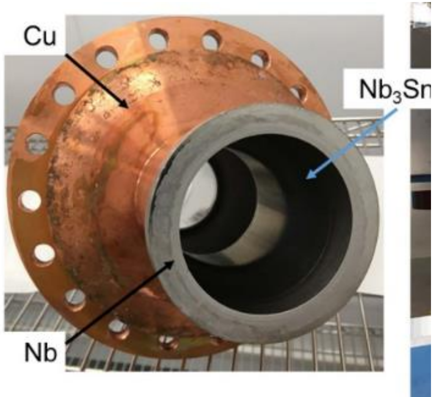
- $\Delta T_{spatial}$ <0.15 K
- T_{max} < 9 K

A new frontier in SRF is simplifying the cooling methods!

Fermilab

- 650 MHz
- welded niobium rings

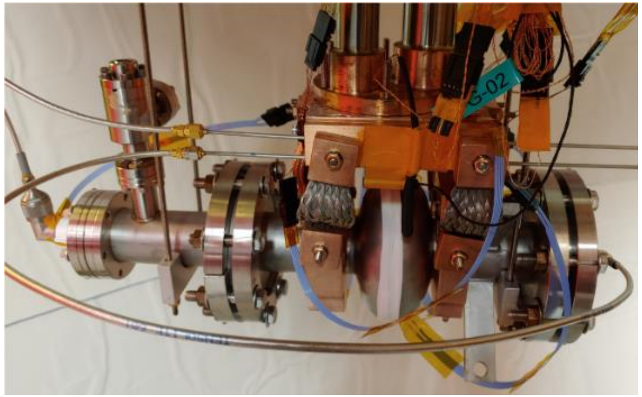
Jefferson Lab



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

- 1.5 GHz
- Cold sprayed + electrodeposited copper

Cornell University



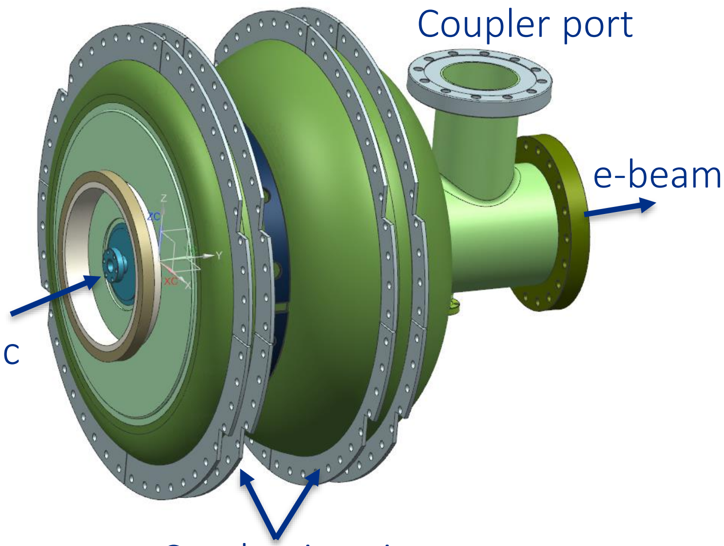
https://arxiv.org/abs/2002.11755

- 2.6 GHz
- Copper clamps

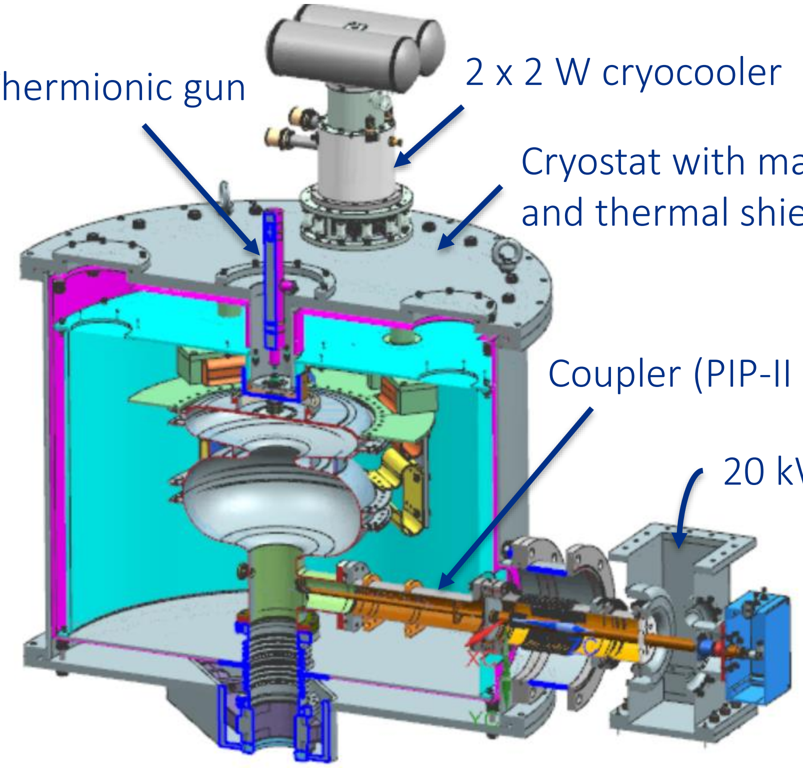
Conduction-cooled SRF accelerator program at Fermilab

Prototype electron accelerator development (1.6 MeV, 20 kW)

Supported by US Army Corps of Engineers (ERDC)



E_{acc} ≈4.7 MV/m; Cryo load ≈3.8 W @ 4.5 K



Design and economics studies of industrial scale SRF electron accelerators (10 MeV, >>100 kW)

Supported by US Dept. of Energy HEP Accelerator Stewardship Program

Phase (year) / Fermilab PI	Activity	Stewardship partner
I (2016-17) / R.D. Kephart	Conceptual design of a 250 kW and economic analysis of a 1000 kW facility	MWRD of Greater Chicago
II (2017-18) / J.C.T. Thangaraj	Conceptual design of a 1000 kW module and economic analysis of a 10000 kW facility	MWRD of Greater Chicago
III (2019-in progress) / R.C. Dhuley	Practical cryogenic design and cost analysis of a 1000 kW module	GENERAL ATOMICS

Design reports available at: https://iarc.fnal.gov/publications/

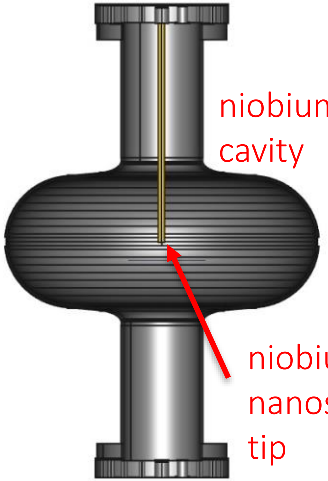
New R&D facilitated by cryocooler-cooled SRF cavities

Development of SRF based field emission sources

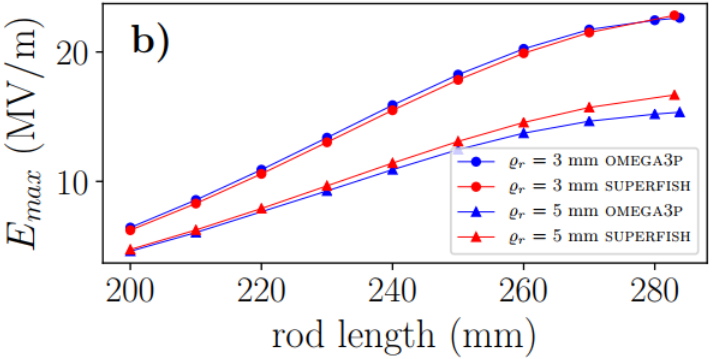
PI: Dr. Philippe Piot (NIU/Argonne National Lab.)

NIU-Fermilab collaboration

- field emission cathode with nanostructured surface located in high e-field region of an SRF cavity
- use cw operation to produce high repetition rate field emission (high I_{avg})



Cathode surface e-field
(650 MHz cavity, 1.6 W cryo-cooling)

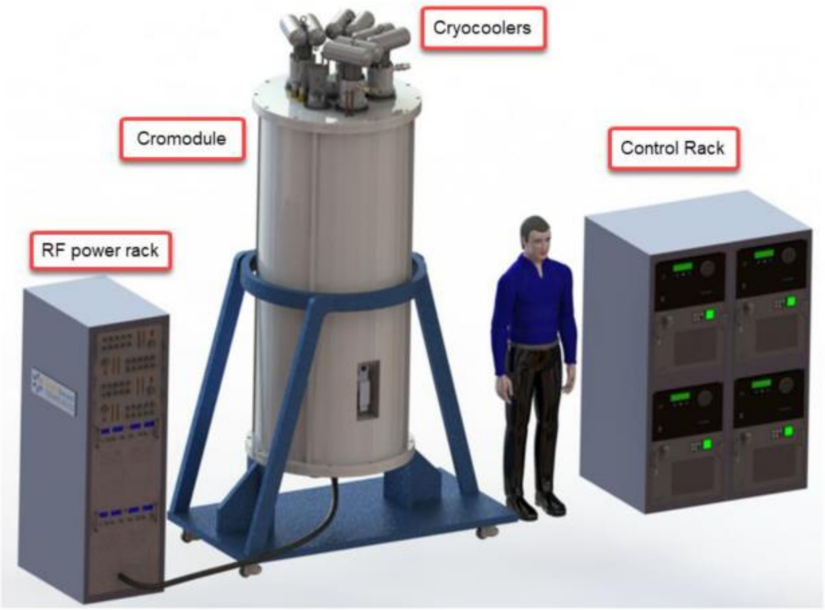


Mohsen *et al.*, http://accelconf.web.cern.ch/ipac2019/papers/tupts083.pdf

Cryocooled based standalone SRF modules

Cryocooled SRF has already been picked up by the particle accelerator industry!

S. Kutsaev *et al.*, https://ieeexplore.ieee.org/document/9119112/



A SRF QWR cooled by pulse tube coolers for beamline upgrade at Argonne Natl. Lab.

Summary and outlook

Cryocooler conduction cooling offers simple, reliable cryogenics for developing industrial SRF e-beam accelerators

Conduction-cooled SRF R&D at Fermilab

- First demonstration >6.5 MV/m cw on a 650 MHz Nb_3Sn coated cavity
- Prototype development and high-power accelerator design in progress

Access to SRF without full stack helium cryogenic systems

- University groups, industries can embark on in-house SRF R&D
- Standalone compact cryomodules for new SRF installations/upgrades

Acknowledgement

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- Accelerator design studies: **R.C. Dhuley** DOE HEP Accelerator Stewardship Award
- Conduction-cooled SRF demonstration: **J.C.T. Thangaraj**, Fermilab LDRD
- Nb_3Sn development: **S. Posen** Fermilab LDRD, **S. Posen** DOE Early Career Award
- Compact SRF accelerator development: US Army Corps of Engineers (ERDC)

HEP Accelerator Stewardship

US Army Corps of Engineers (ERDC)

NORTHERN ILLINOIS UNIVERSITY
Northern Illinois Center for Accelerator and Detector Development