Cryocooler conduction-cooled SRF cavities for compact particle accelerators

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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.

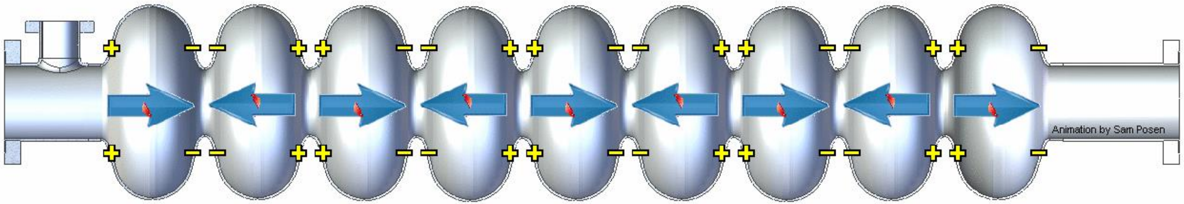
FERMILAB-SLIDES-21-121-DI-TD

Topics for today

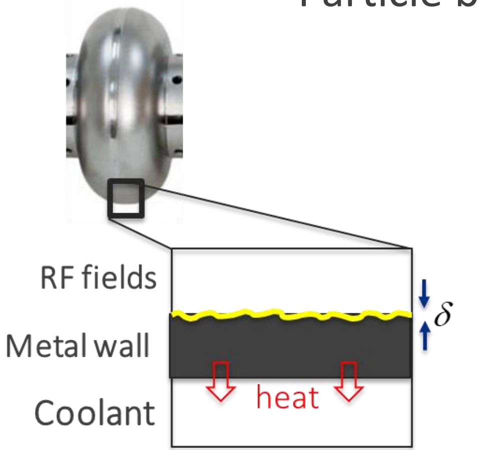
- Basics of Superconducting Radio Frequency cavities
- SRF based compact accelerators for industrial applications
- Fermilab R&D for conduction-cooled SRF cavity
- Fermilab design and development of compact SRF accelerators
- Summary and outlook

Some SRF basics

RF cavity working principle



- Metallic cells maintain a standing-wave RF field
- Particle bunches in phase with the RF field gain energy



- RF fields penetrate a penetration depth, δ in the metallic cell walls and dissipate heat in the ***surface resistance, R_s***
- A coolant on the outside extracts the heat and prevents the cavity from heating above its design temperature

RF surface resistance

Why is RF surface resistance a key parameter?

- Dissipated power in the cavity is proportional to its surface resistance
- The cost of cooling the cavity (coolant fluid, temperature, fluid pumping power, etc.) scales with dissipated power
- With hundreds of cavities in a particle accelerator, the cavity cooling cost forms a significant fraction of accelerator operating cost

Keeping low RF surface resistance is therefore necessary to reduce the accelerator operating cost.

Normal conducting vs. superconducting cavities

How does the surface resistance compare?

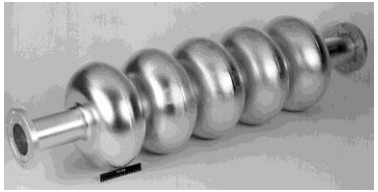
Water cooled copper cavity at room temperature

$$R_s = \frac{1}{\sigma\delta} = \sqrt{\frac{\mu_0\omega}{2\sigma}}$$

ω = angular frequency
σ = electrical conductivity

With σ ~ 5.8 x 10^7 S/m at 1.5 GHz and 300 K, we get R_s = 10 mΩ

Liquid helium cooled niobium cavity ≤ ~5 K



$$R_s = R_{BCS}(T) + R_{res}$$
$$\simeq A\frac{\omega^2}{T}\exp\left(\frac{-1.85T_c}{T}\right) + R_{res}$$

At 1.5 GHz and 2 K, and neglecting the residual R_{res}, we get R_s = 20 nΩ

Fermilab

Normal conducting vs. superconducting cavities

Ratio of surface resistance at 1.5 GHz:

$$\frac{R_s(niobium, 2K)}{R_s(copper, 300K)} = \frac{20\, n\Omega}{10\, m\Omega} \sim 10^{-6}$$

Penalty for 2 K cryogenics:

$$\eta_{Carnot} = 0.67\% \qquad \eta_{plant} \simeq 20\%$$

Even after accounting the premium for 2 K cryogenics, **SRF drives down the cooling driven operating cost by a factor ~1000 !**

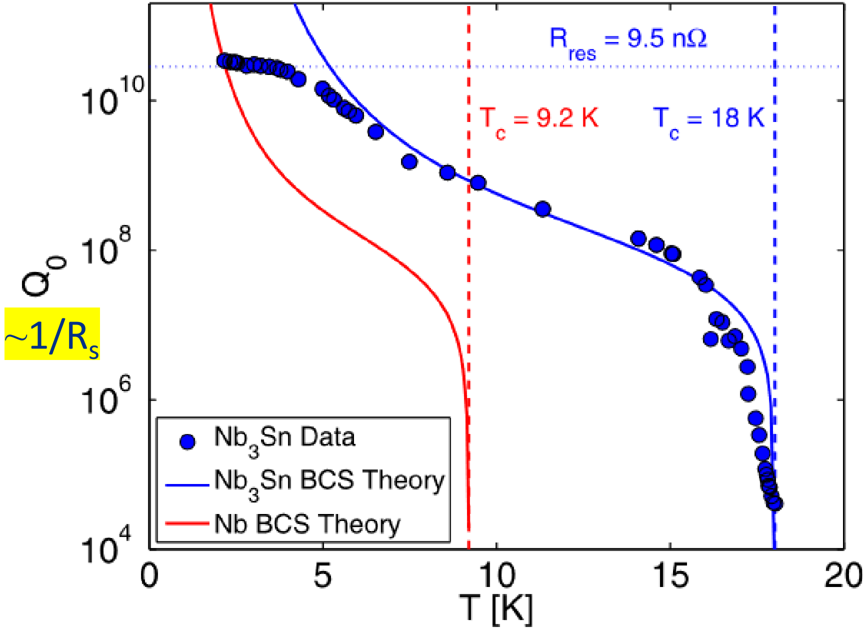
The significantly lower surface resistance in SRF also offers other benefits:

- Cavities can be operating with 100% RF duty cycle that facilitate production of high average power particle beams
- Cavities can be made with larger aperture (by relaxing shunt impedance) that reduce loss of high-power beams during transport through the cavity

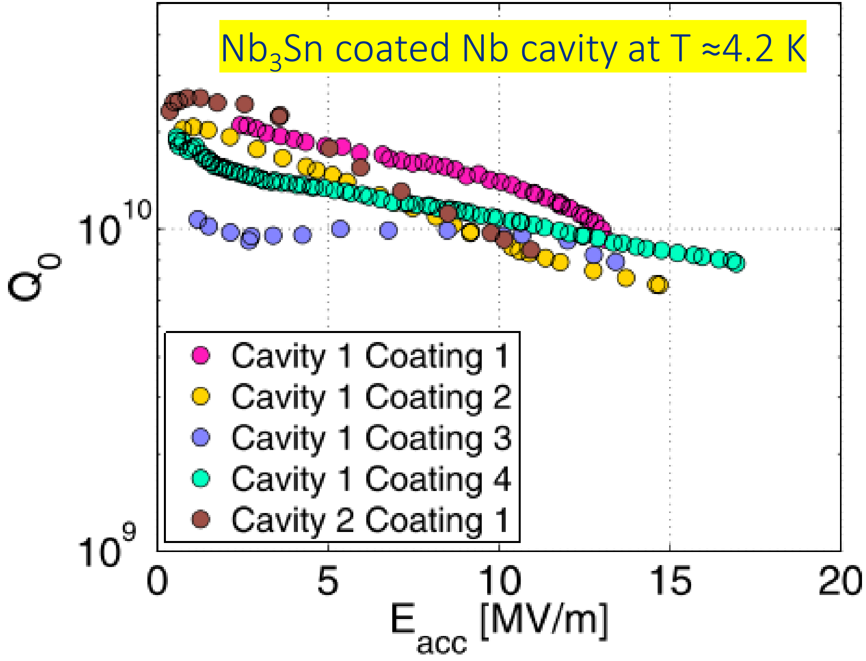
Nb_3Sn cavities further reduce the cryogenic penalty

Nb_3Sn cavities operate at ~4 K with performance similar to niobium cavities at 2 K

- These are bulk niobium cavities with a few micron layer of Nb_3Sn on the RF surface



S. Posen et al., Appl. Phys. Lett. 106, 082601 (2015)



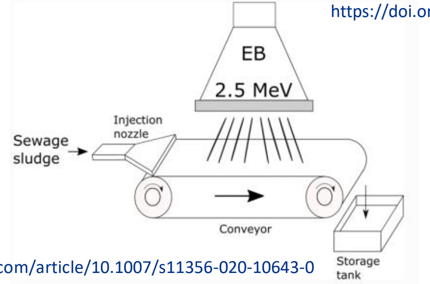
S. Posen et al., Appl. Phys. Lett. 106, 082601 (2015)

SRF accelerators – applications landscape

Current usage dominated by basic research needs: colliders, FELs, proton and neutron sources

Potential industrial applications: e-beam radiation treatment of flue gases, municipal/industrial wastewater, sewage

https://doi.org/10.1016/j.radphyschem.2012.01.030



https://link.springer.com/article/10.1007/s11356-020-10643-0

Tailoring SRF for industrial applications

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:

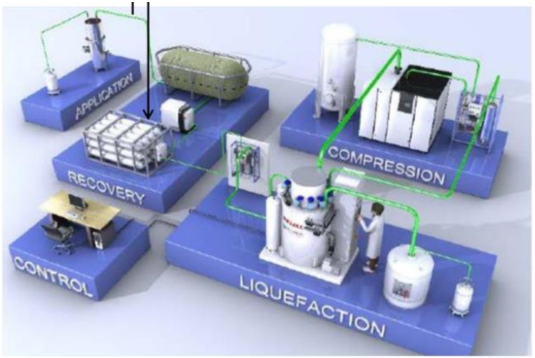
- Low capital and operating expense
- Robust, reliable, turnkey operation

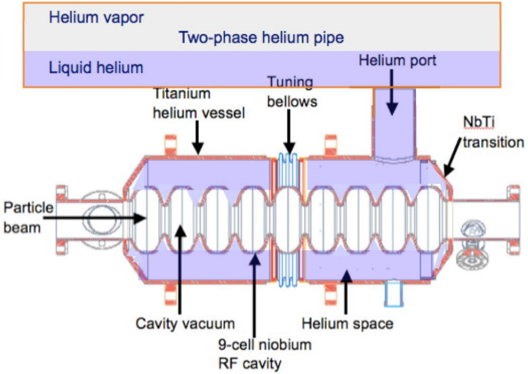
http://accelconf.web.cern.ch/AccelConf/napac2016/talks/thb3io02_talk.pdf

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!

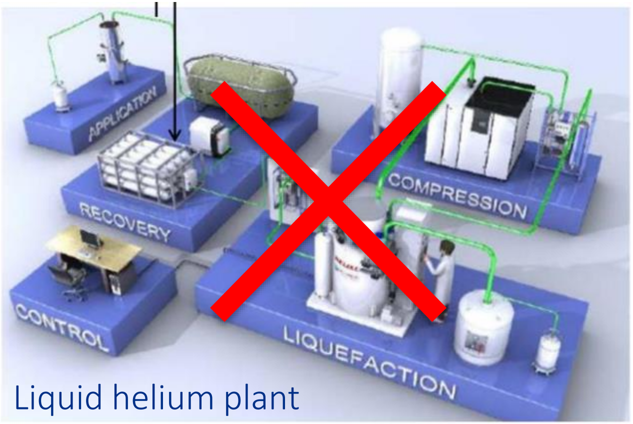




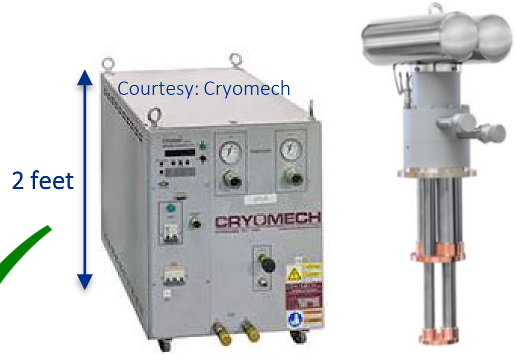
Simplifying SRF cryogenics for industrial settings

Nb_3Sn cavity with 10 MeV 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

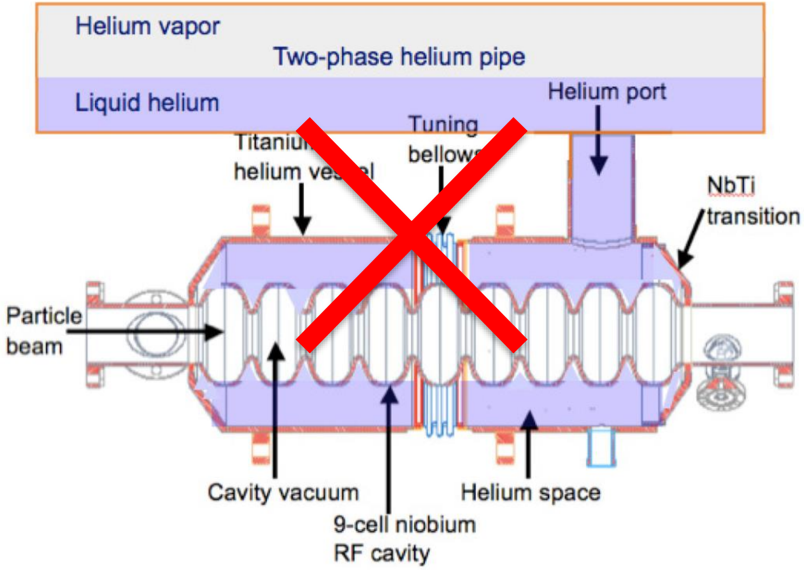
Cryocoolers offer

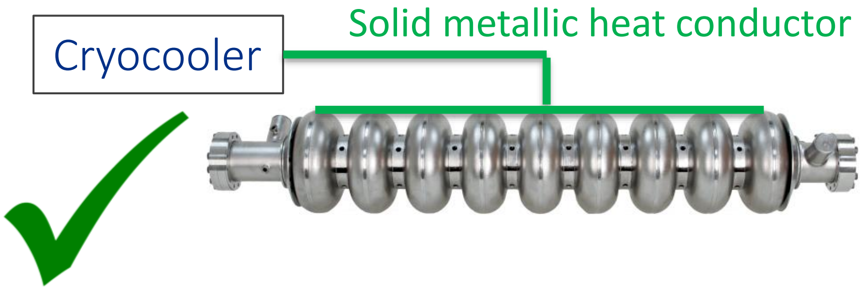
- Closed cycle cooling at ~45 K and ~4 K
- Compact, small footprint
- Reliability (MTBM > 2 years non-stop operation)
- Turnkey operation (no trained operator needed, turn ON/OFF with push of a button)

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

Fermilab

Fermilab vision for SRF industrial accelerators

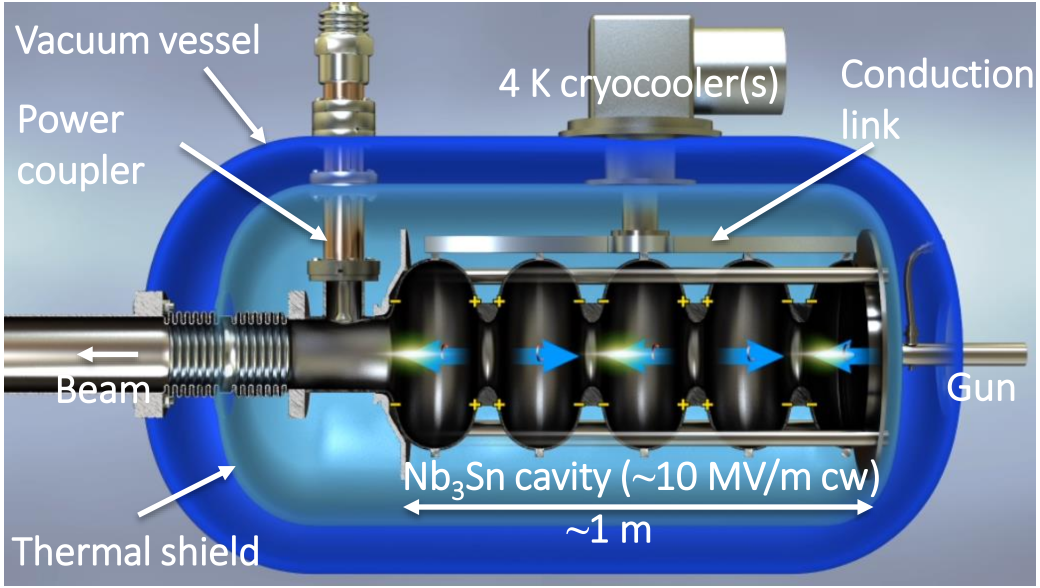
Vision: Develop compact, turnkey e-beam source for environmental and industrial applications (~10 MeV, >>100 kW)

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

Pathway: Nb_3Sn SRF cavities

- cw operation enables high average beam power
- Low Rs (high Q_0) @ >4 K allows conduction-cooling using 4 K closed-cycle cryocoolers

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



Fermilab

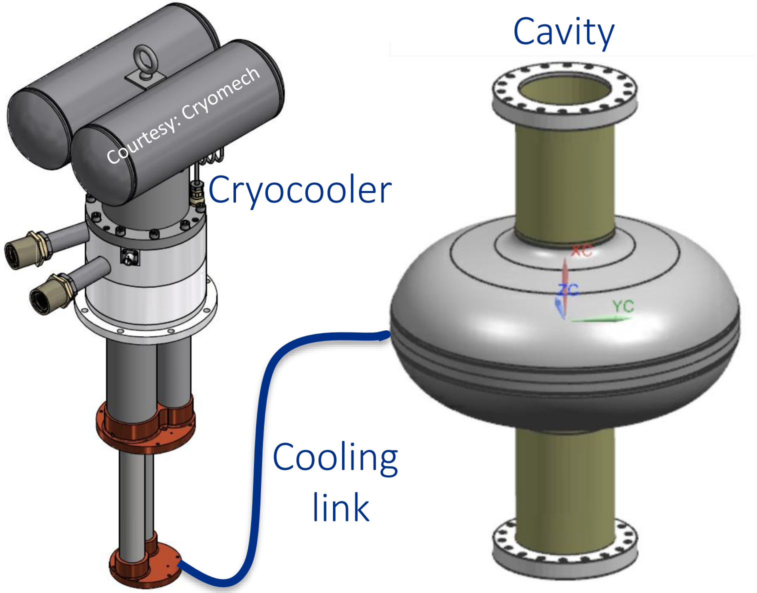
Fermilab R&D for a conduction-cooled SRF cavity

Conduction cooled Nb_3Sn SRF development

Goal: demonstrate 10 MV/m cw on an Nb_3Sn cavity with cryocooler conduction cooling

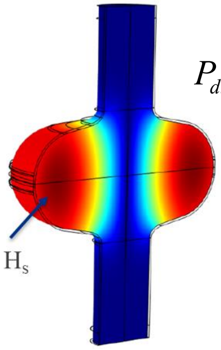
Our choice:

- ➢ 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

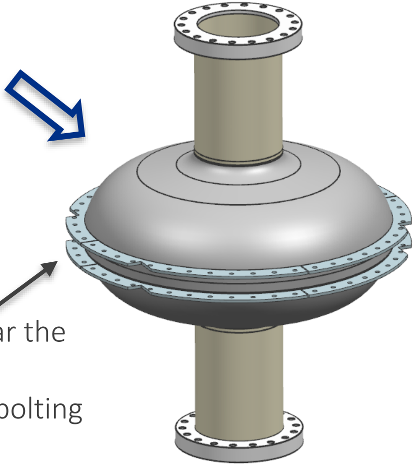


Cavity preparation for conduction link attachment

Conceptualization of conduction cooling



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

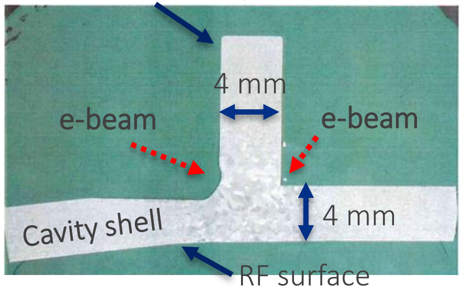


- Weld Nb rings near the equator
- Provide holes for bolting the thermal link

Development of conduction cooling

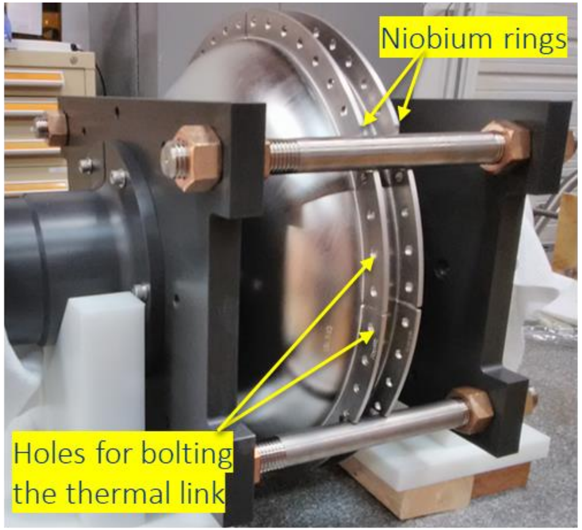
E-beam weld recipe development

- Full penetration
- Avoid weld beads on the RF surface



Courtesy: C. Grimm (Fermilab)

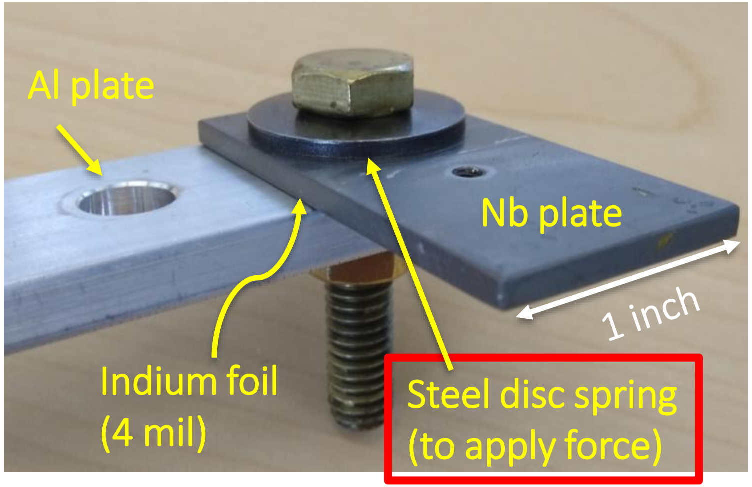
Ring-welded single cell 650 MHz cavity



Characterization of thermal resistance

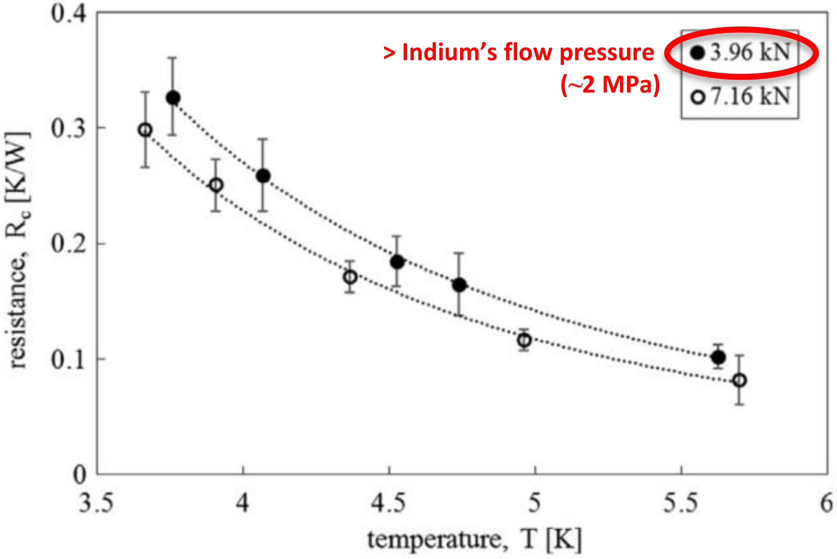
1. Cavity-link (niobium-aluminum) bolted thermal contacts

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

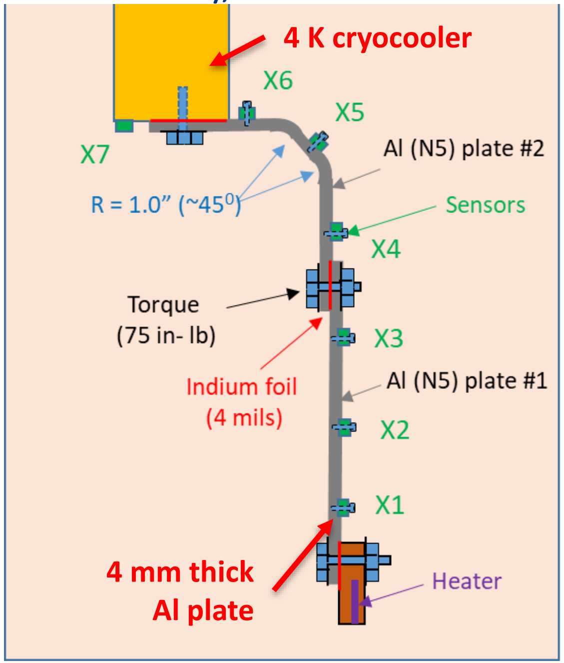


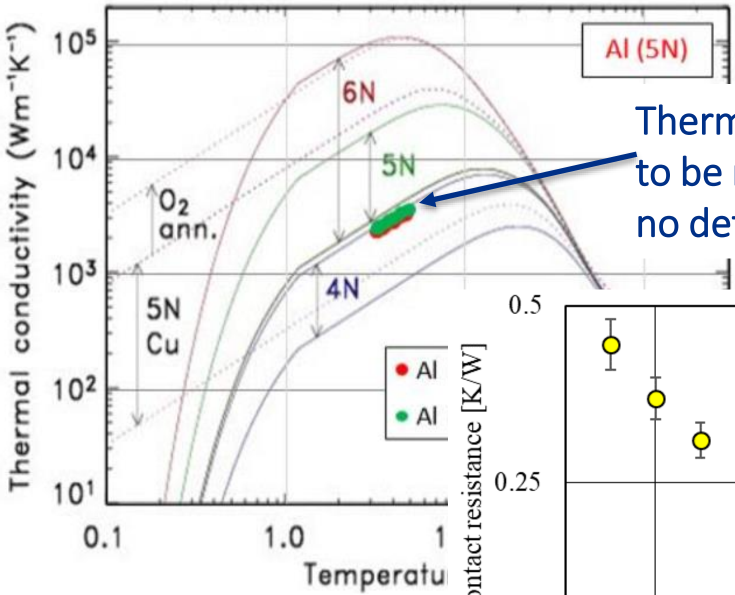
Selected design: 4 mil indium, ~4 kN force

Characterization of thermal resistance

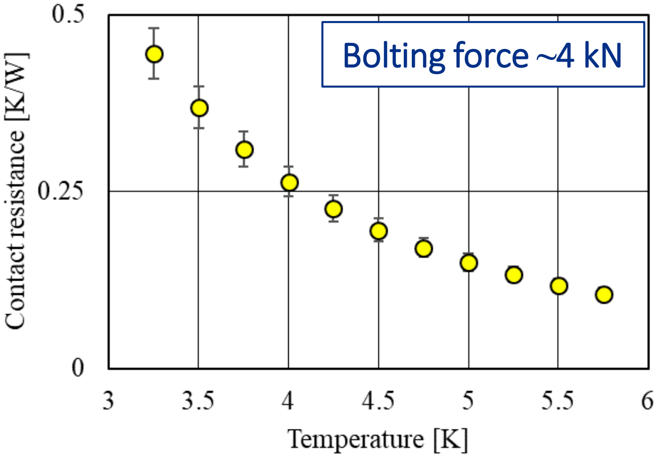
2. Thermal characterization of high purity aluminum

Setup for measuring 4 K thermal conductivity, contact resistance



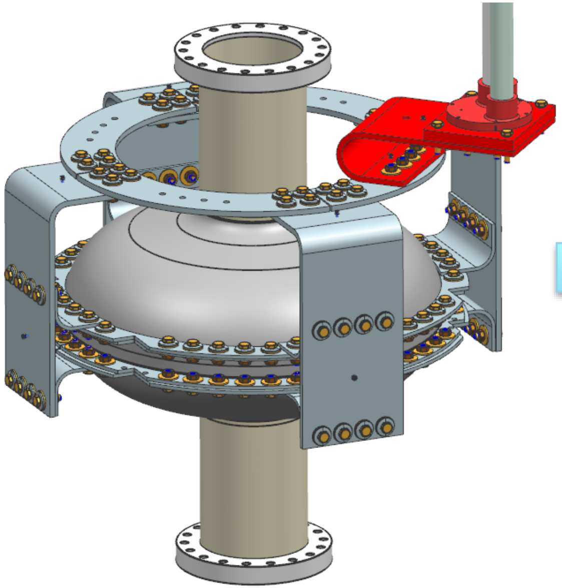


Thermal conductivity found to be near the lower band of 5N, no deterioration from bending



Conduction link design and performance verification

Al conduction link bolted to the Nb rings around the cavity

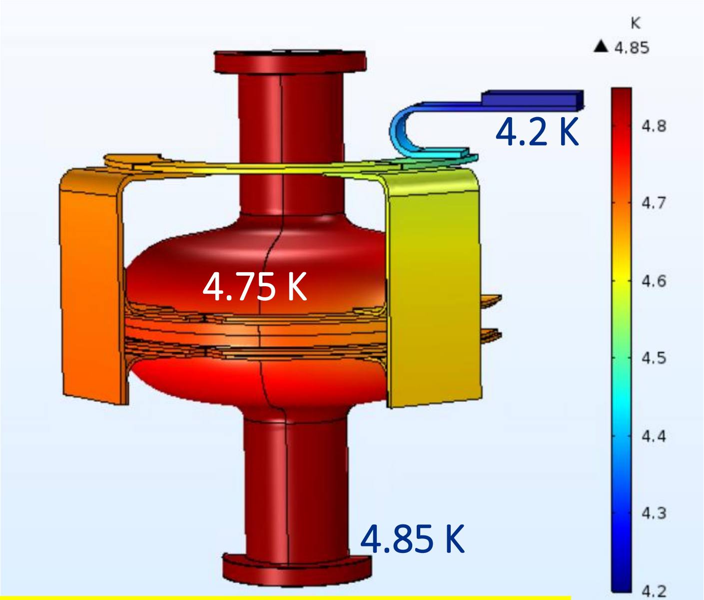


Nb_3Sn surface resistance (BCS from SRIMP + 10 nΩ)

RF + thermal simulations

Thermal conductivities, contact resistance, cryocooler capacity

FEA verification of thermal conductance of the link



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

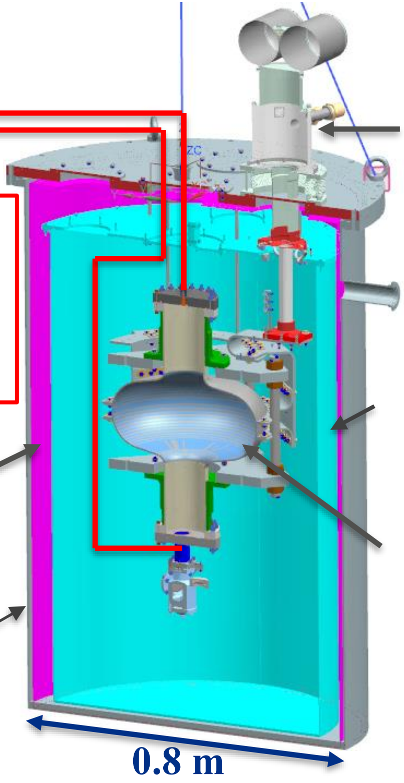
R.C. Dhuley *et al.*, ***IOP Conf. Ser.: Mat. Sci. Eng.***, 2020. https://doi.org/10.1088/1757-899X/755/1/012136

Euclid Techlabs

RF system
- 10 W cw @ 650 MHz, 1.3 GHz
- Resonance locking
- P_f, P_r, P_t, τ_L measurements

Magnetic shield (~15 mG)

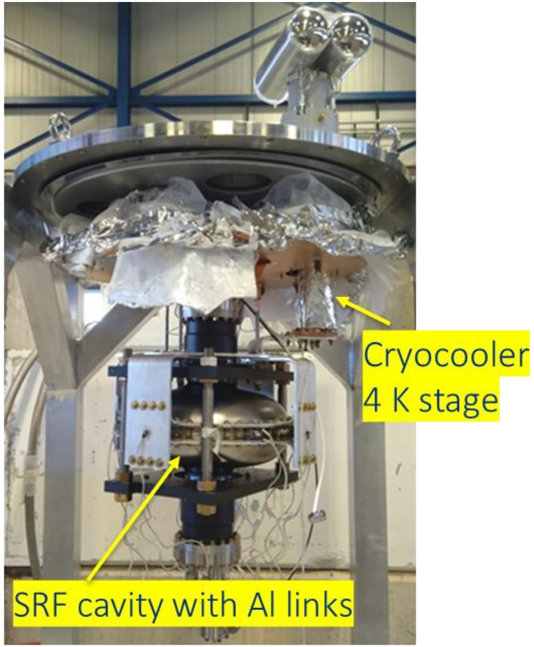
Vacuum vessel



Two-stage cryocooler
- 55 W @ 45 K
- 2 W @ 4.2 K

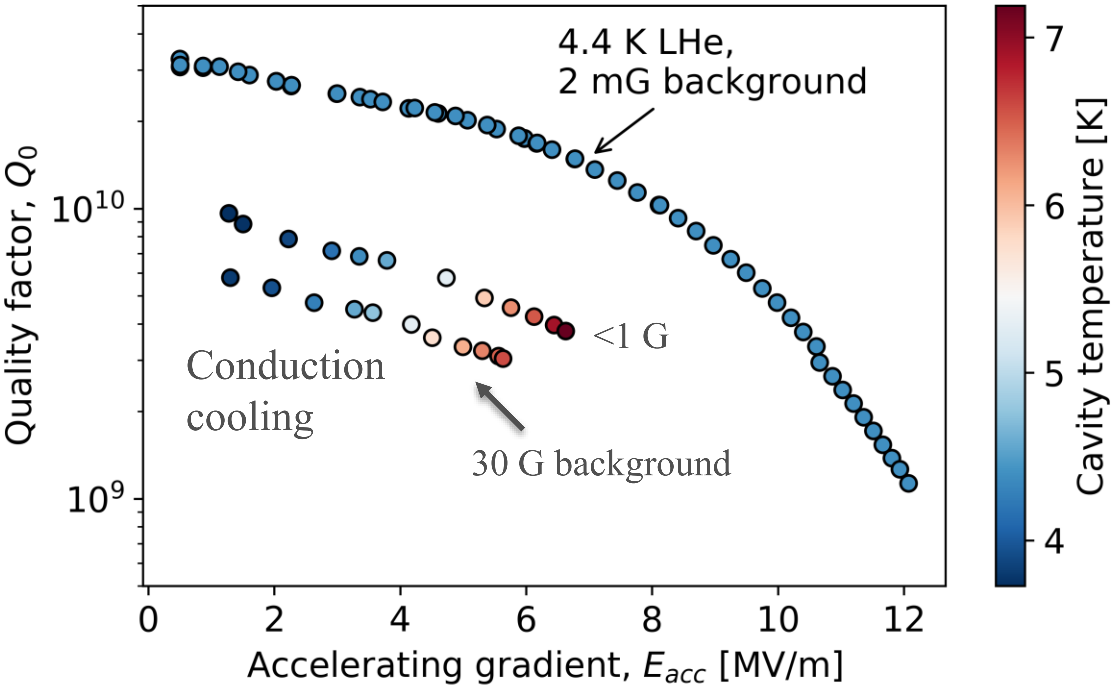
Thermal shield (cooled by the 45 K stage)

SRF cavity with Al link (cooled by the 4 K stage)

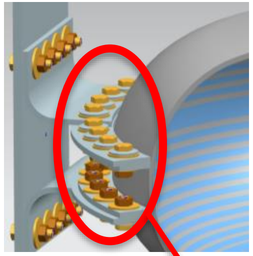


First results with the conduction-cooled Nb_3Sn cavity

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



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



disc springs ~30 G led to large flux trapping

Steel (magnetic)

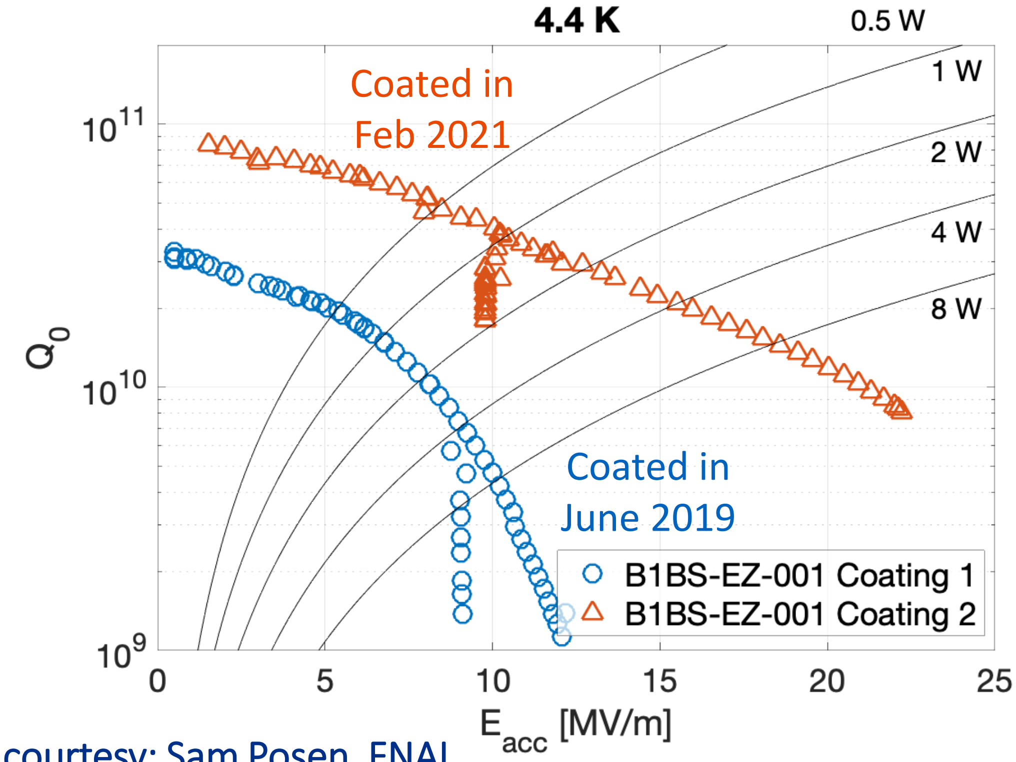
Conduction cooling with <1 G disc springs

- $Q_0 = 10^{10}$ at E_{acc} = 1 MV/m
- max E_{acc} = 6.6 MV/m

Getting to 10 MV/m cw

1) Improved Nb_3Sn coating

- Suspected cause for Q-slope degradation was thin regions (coating 1)
- Added extra $SnCl_2$ nucleation agent relative to previous coating to attempt to improve uniformity (coating 2)
- **New coating (coating 2) showed substantial improvement (over coating 1)**



Slide courtesy: Sam Posen, FNAL

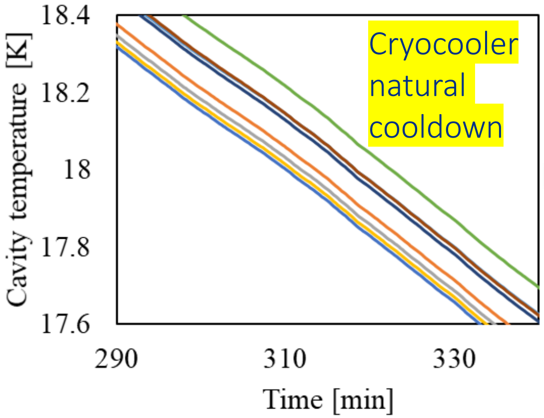
Getting to 10 MV/m cw

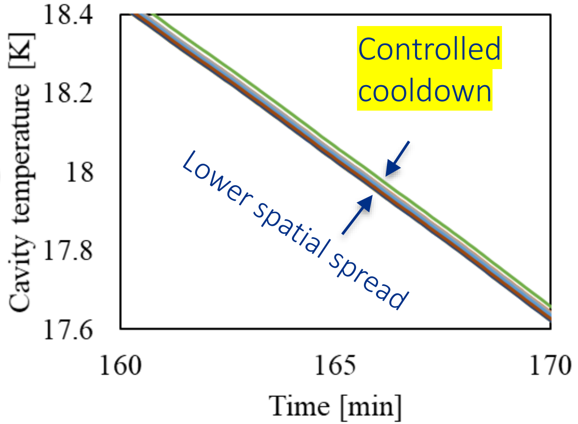
2) Improve magnetic hygiene around the cavity during cooldown (remove magnetic disc springs)

Steel (magnetic)

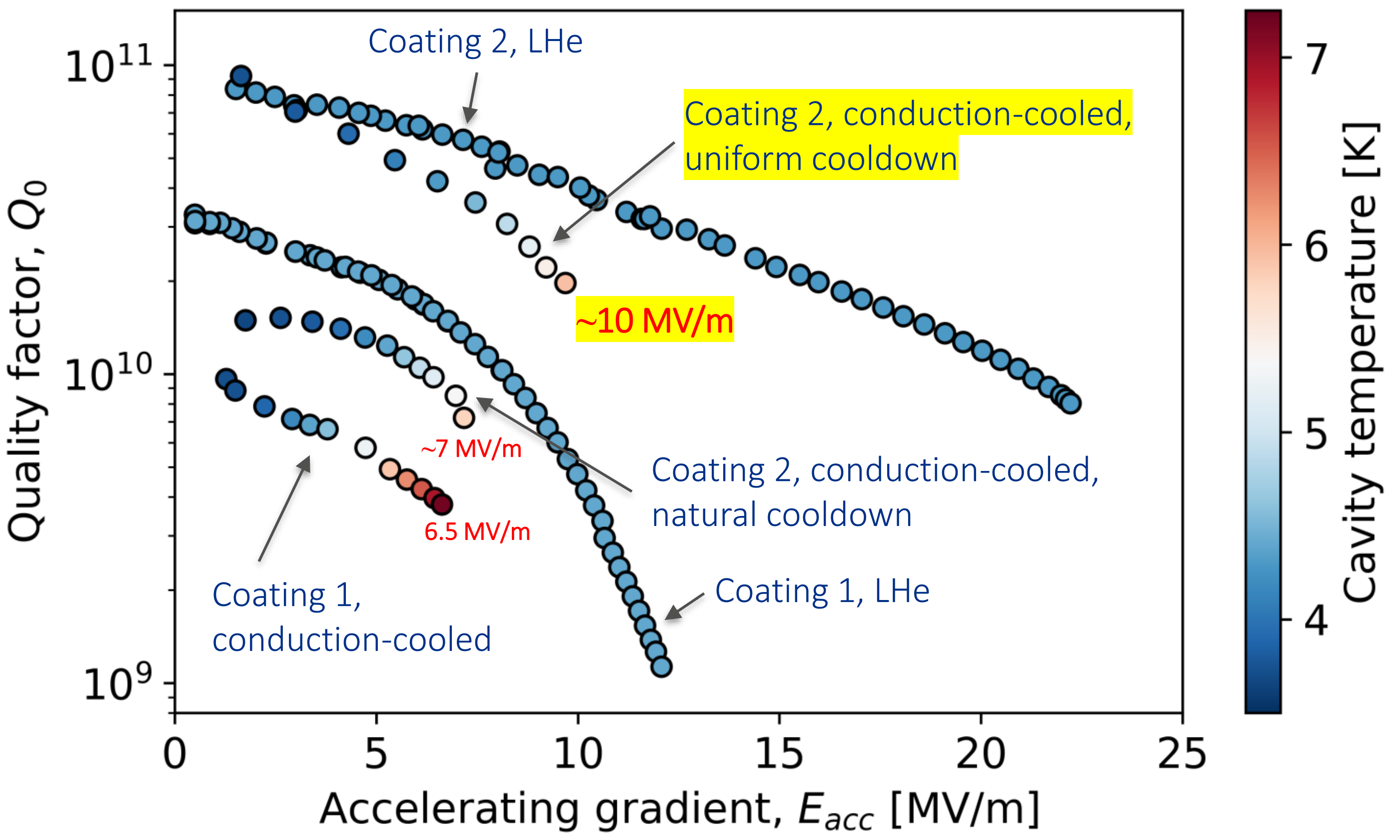
Beryllium copper (non-magnetic)

3) Controlled, spatially-uniform cooldown of the cavity across Nb_3Sn T_c = 18 K (reduces thermocurrent induced flux trapping)



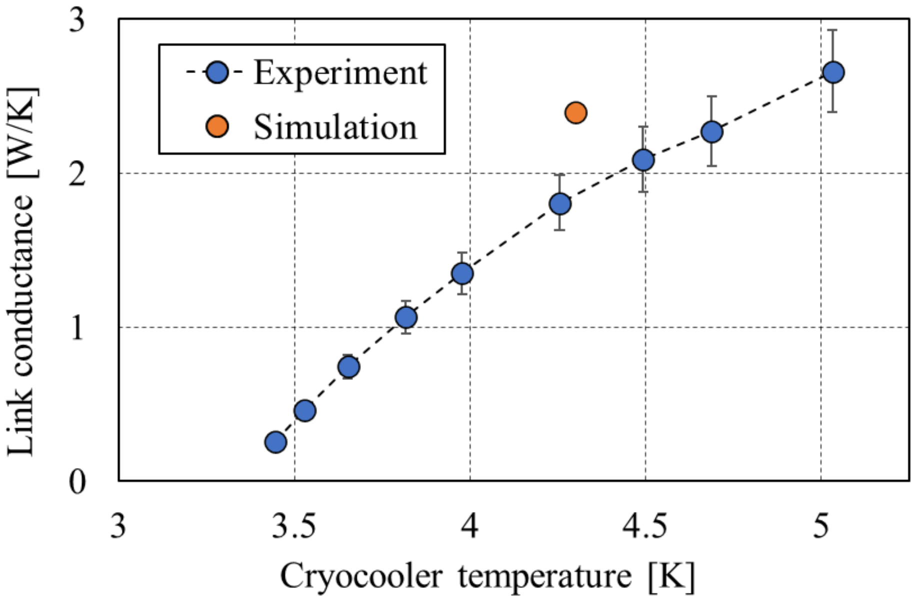


Results with new Nb_3Sn coating (R.C. Dhuley arXiv:2108.09397v1)



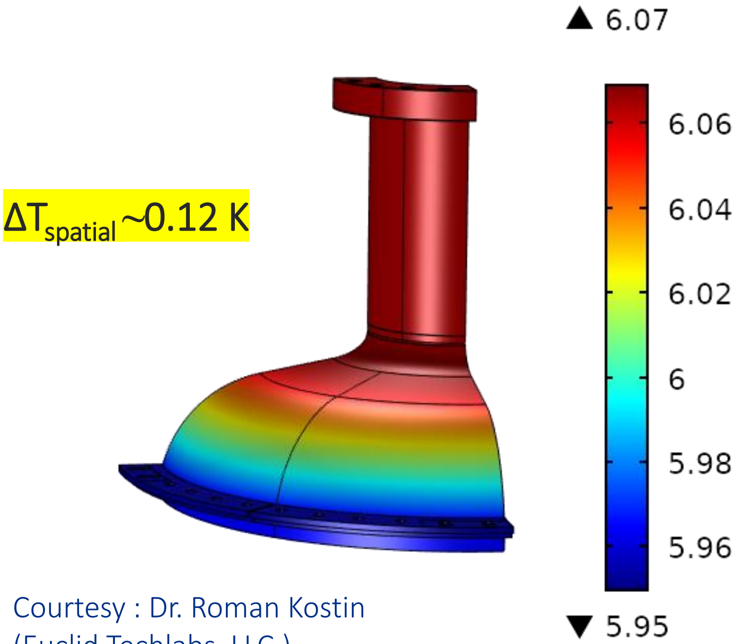
Conduction link performance, cavity thermal stability

Comparison of measured and simulated link thermal conductance



Computed cavity surface temperature at steady state with ~10 MV/m cw

- Ring temperature = 5.95 K, RF dissipation = 2.4 W



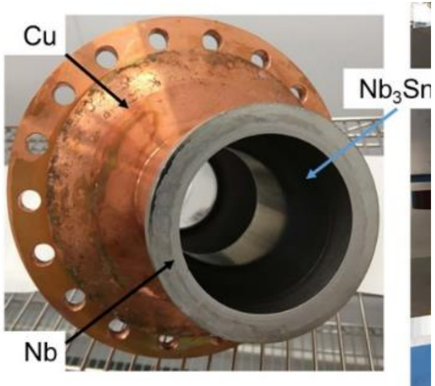
Courtesy : Dr. Roman Kostin (Euclid Techlabs, LLC.)

A new frontier in SRF is simplifying the cooling methods!

Fermilab

- 650 MHz
- welded niobium rings

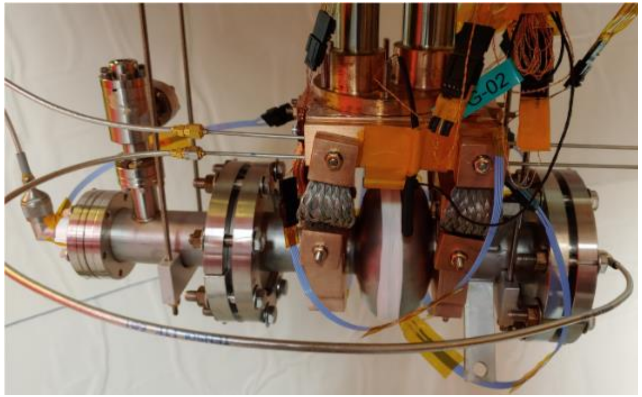
Jefferson Lab



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

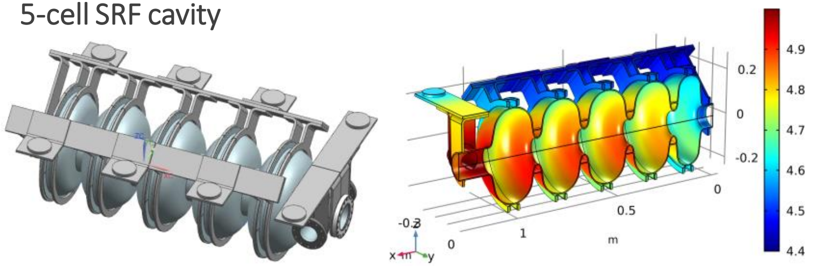
Design and development of e-beam accelerator based on conduction cooled SRF cavities

- Design studies for a 10 MeV, 1000 kW accelerator
- Prototype development of a ~1.6 MeV, ~20 kW accelerator

Design of a 10 MeV, 100 mA e-beam accelerator

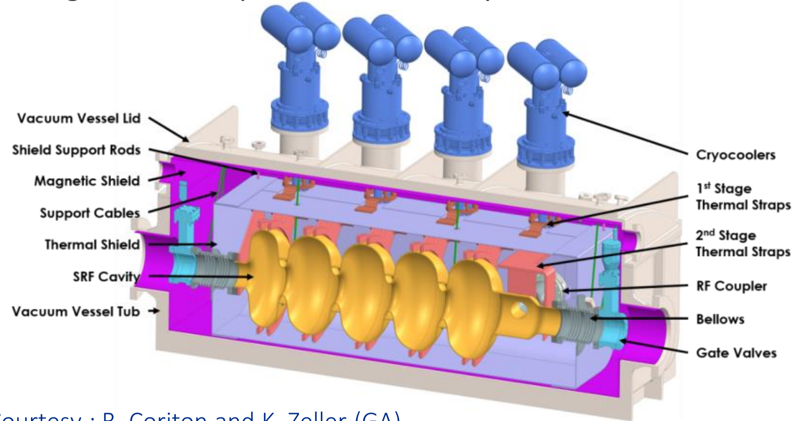
- ✓ RF design of a 5-cell 650 MHz cavity
- ✓ Beam transport simulations (external injection 300 keV → 10 MeV)
- ✓ Calculation of 4 K heat load, cryocooler selection
- ✓ Design and thermal simulations of conduction link
- ✓ Cryostat design and integration (thermal and magnetic shield, vacuum vessel, couplers)
- ✓ Cost assessment of the 10 MeV accelerating module

Design and multiphysics simulation of a conduction-cooled 5-cell SRF cavity



Courtesy : R. Kostin (Euclid Techlabs)

Design of the complete accelerator cryomodule

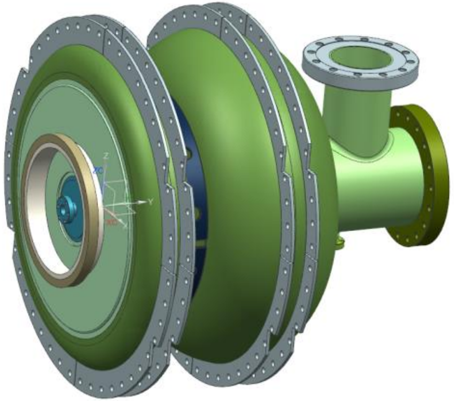


Courtesy : B. Coriton and K. Zeller (GA)

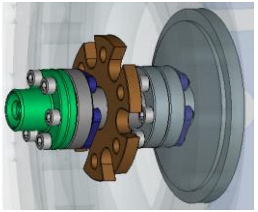
Prototype cryogen-free SRF electron accelerator development

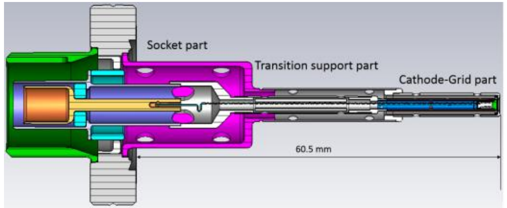
Goal: Component production, integration, and demo of a 1.6 MeV, 20 kW accelerator

650 MHz Nb_3Sn cavity
(Cryoload ≈3.8 W @ 5 K)



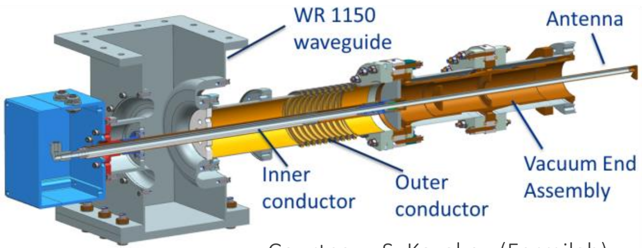
Integrated thermionic cathode





Courtesy : I. Gonin, V. Yakovlev (Fermilab)

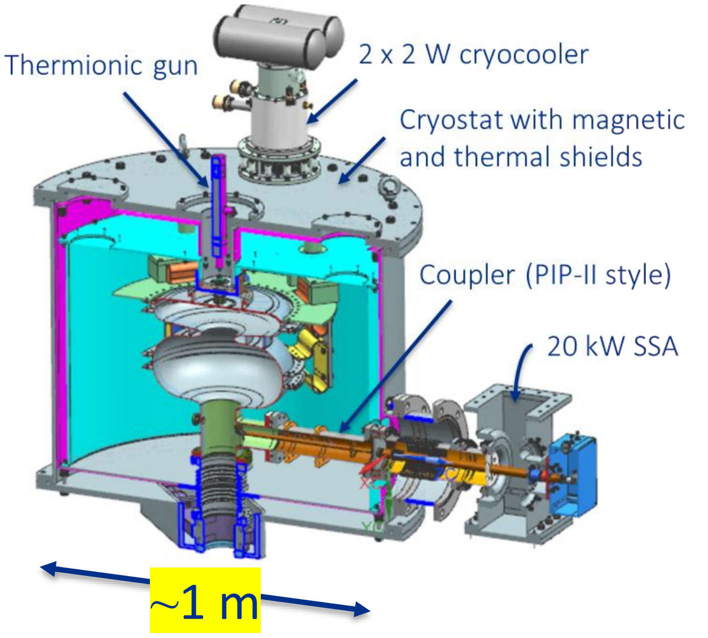
Low heat leak coupler (<1 W)



Courtesy : S. Kazakov (Fermilab)

Prototype cryogen-free SRF electron accelerator development

Cryostat assembly



20 kW Solid State RF Amplifier

Cryomech PT420 coolers

Courtesy : M.I. Geelhoed (Fermilab)

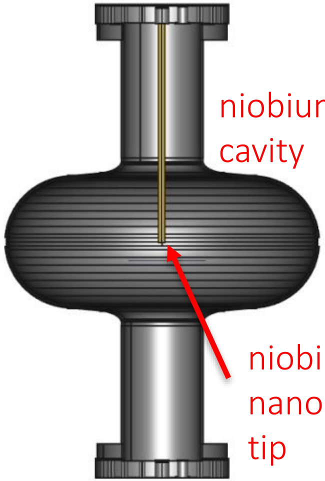
New R&D facilitated by cryocooler-cooled SRF cavities

Development of SRF based field emission sources

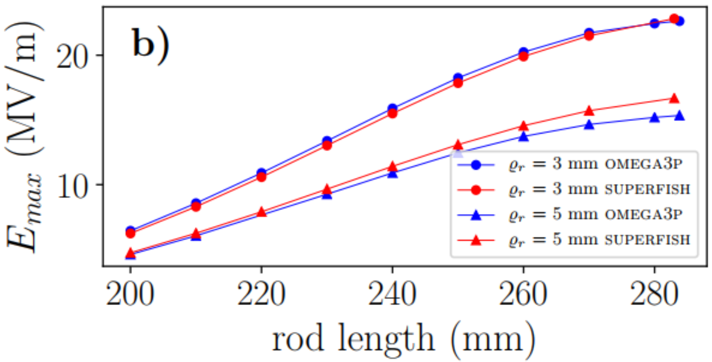
PI: Dr. Philippe Piot (NIU/Argonne National Lab.)

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)

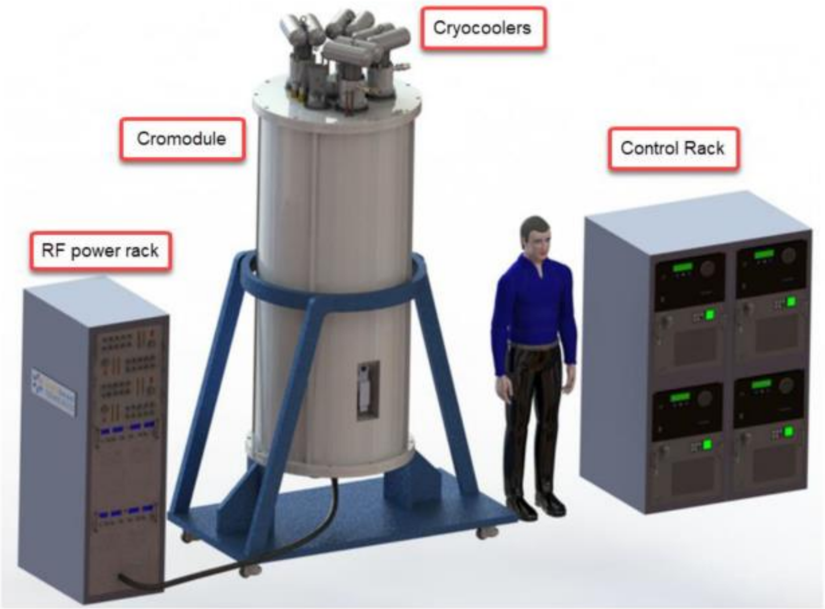


Mohsen *et al.*, https://doi.org/10.1016/j.nima.2021.165414

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 National Laboratory

Summary and outlook

- Fermilab has demonstrated 10 MV/m cw gradient with conduction-cooled SRF cavity
  - This is an enabler for high-efficiency e-beam sources for industrial uses of electron irradiation
- Design and development of prototype SRF based compact e-beam accelerators is in progress
- Conduction-cooled SRF has opened new avenues for SRF R&D
  - Universities as well as industry has already capitalized on this new opportunity

Acknowledgement

This presentation 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.

Thanks for your attention!

Questions?