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Cryocooler conduction-cooled Nb_3Sn SRF at Fermilab

Ram C. Dhuley on behalf of the APS-TD/IARC conduction-cooled SRF team

Nb_3SnSRF'20, Cornell University, 13 November 2020

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Conduction-cooled Nb_3Sn SRF at Fermilab

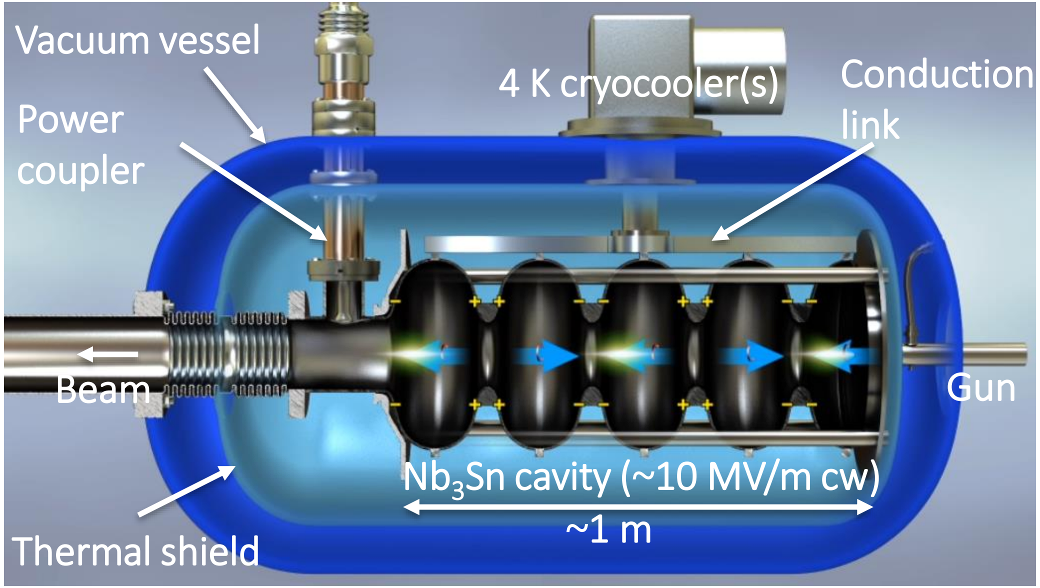
Vision: Develop compact, turnkey e-beam source for environmental and industrial applications (~10 MeV, >>100 kW)

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

Pathway: Nb_3Sn SRF cavities

- cw operation enables high average beam power
- 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



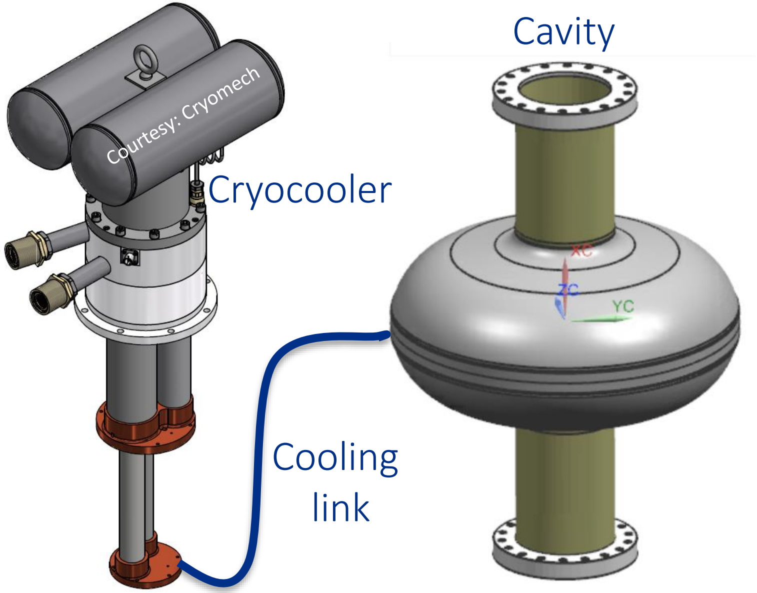
Outline

- Development of a conduction-cooled Nb_3Sn SRF cavity and gradient demonstration
  - Fermilab LDRD (2016-2019)
- Studies of accelerator design based on conduction cooler Nb_3Sn SRF
  - DOE HEP Accelerator Stewardship (2015- present)
- Prototype cryogen-free SRF electron accelerator development
  - US Army Corps of Engineers/EDRC; NNSA (2017 – present)

Conduction cooled Nb_3Sn SRF development

(Fermilab LDRD 2016-2019)

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

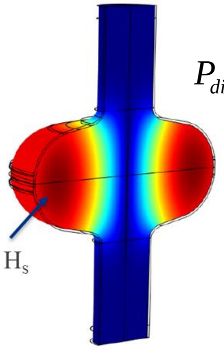


Our choice:

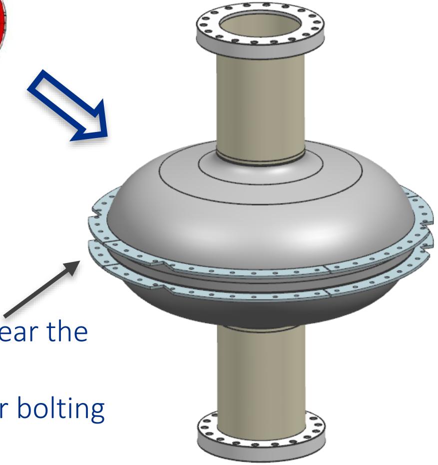
- Single cell 650 MHz, Nb_3Sn coated niobium cavity
- Cryomech PT420 cryocooler (2 W @ 4.2 K with 55 W @ 45 K)
- High purity aluminum for the conduction cooling link

Cavity preparation for conduction link attachment

Conceptualization of conduction cooling



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

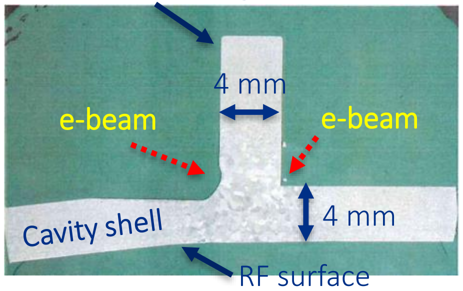


- Weld Nb rings near the equator
- Provide holes for bolting the thermal link

Development of conduction cooling

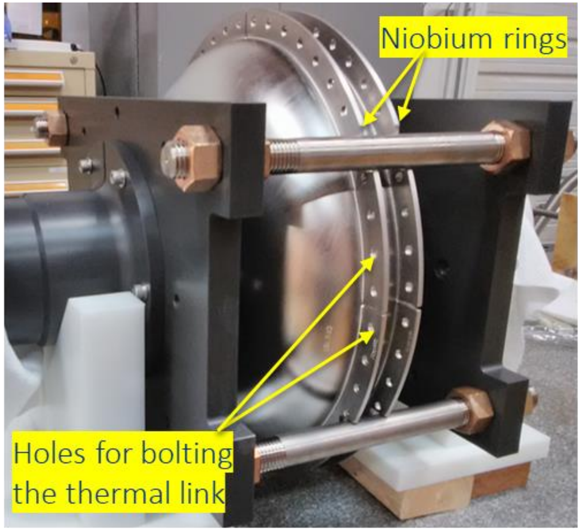
E-beam weld recipe development

- Full penetration
- Avoid weld beads on the RF surface



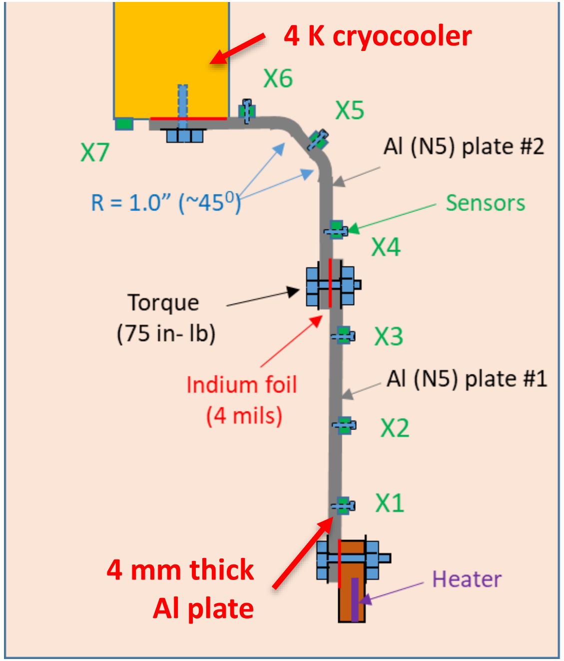
Courtesy: C. Grimm (Fermilab)

Ring-welded single cell 650 MHz cavity



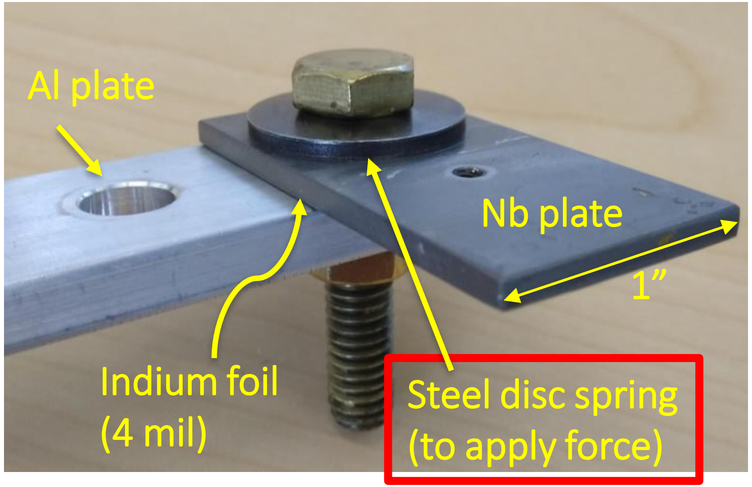
Thermal characterization of the conduction link

5N aluminum samples



Courtesy: O. Prokofiev (Fermilab)

Nb-Al bolted contacts



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

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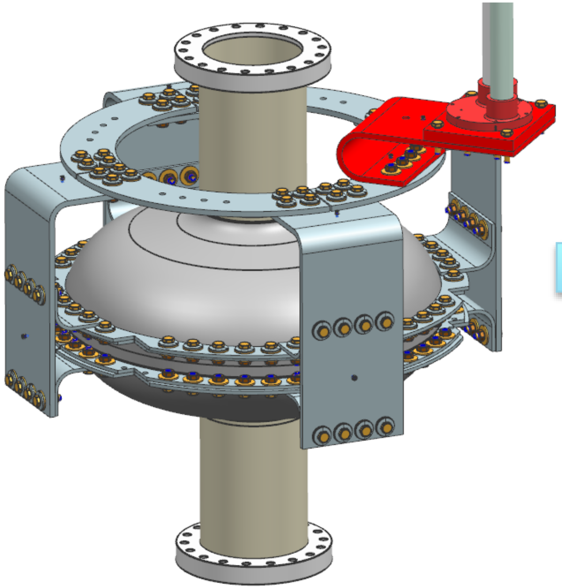
Conduction link design and performance verification

Al conduction link bolted to the Nb rings around the cavity

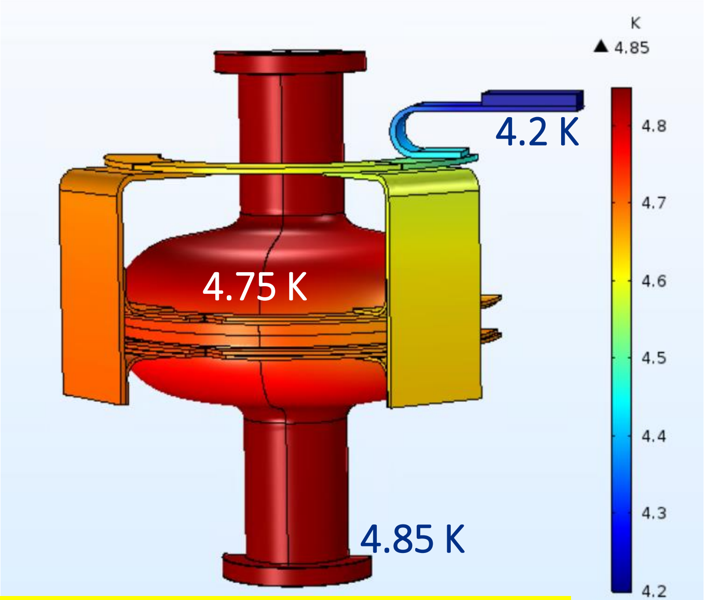


Nb_3Sn surface resistance (BCS from SRIMP + 10 nΩ)

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

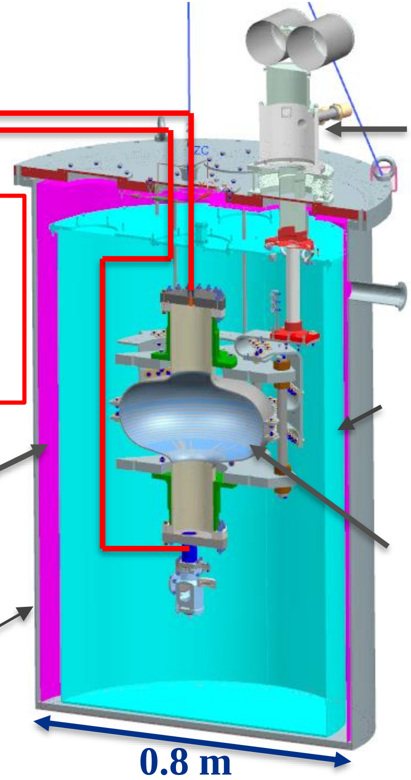
R.C. Dhuley *et al.*, ***IOP Conf. Ser.: Mat. Sci. Eng.***, 2020. https://doi.org/10.1088/1757-899X/755/1/012136

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)

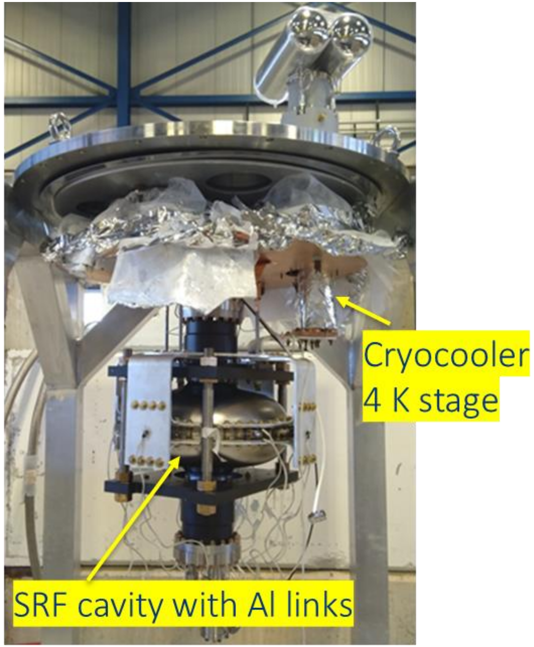
Vacuum vessel



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)



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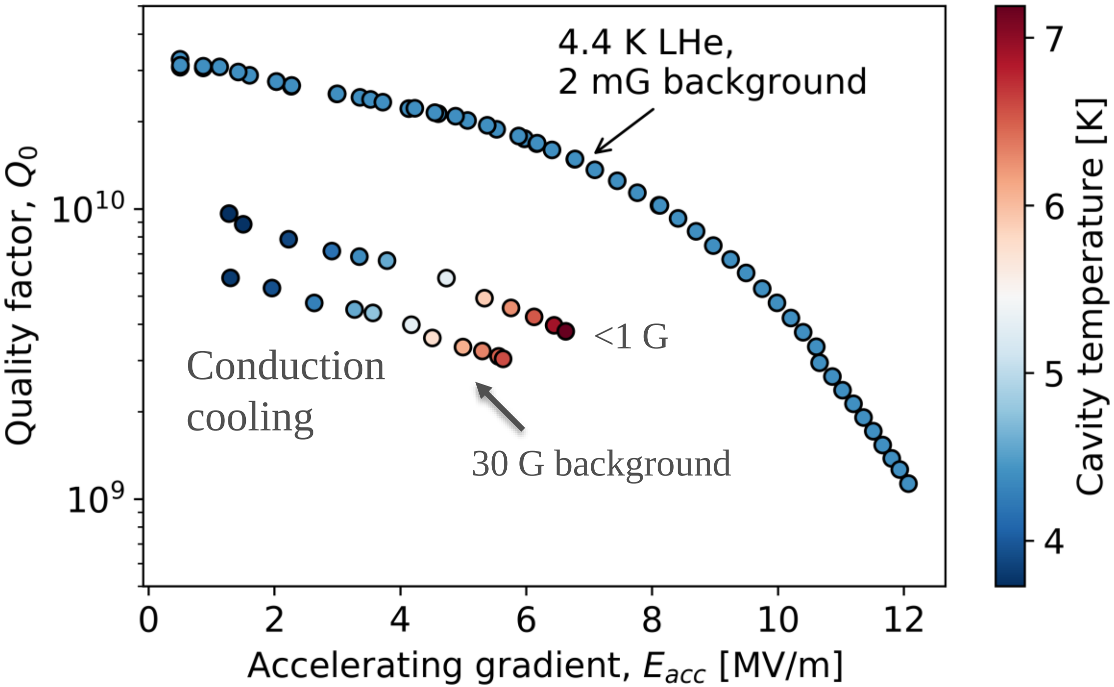
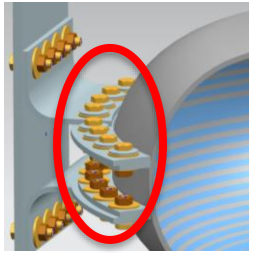
First results for the conduction-cooled Nb_3Sn cavity

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

Conduction cooling with <1 G disc springs

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

E-beam accelerator design studies with conduction cooled Nb_3Sn SRF (DOE Accelerator Stewardship 2015 - present)

Phase (year) / Fermilab PI	Activity	Stewardship partner
I (2016-17) / R.D. Kephart	Conceptual design of a 250 kW and economic analysis of a 10 MeV, 1000 kW facility*	MWRD of Greater Chicago
II (2017-18) / J.C.T. Thangaraj	Conceptual design of a 10 MeV, 1000 kW module and economic analysis of a 10000 kW facility	
III (2019-in progress) / R.C. Dhuley	• Practical cryogenic design and cost analysis of a 1000 kW module • Demonstration of 10 MV/m cw	GENERAL ATOMICS

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

Ongoing work to reach 10 MV/m

1) Reduce background magnetic field

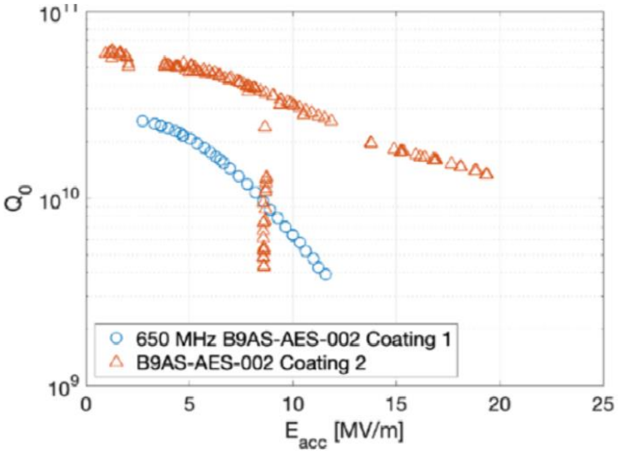
2) Cryocooler cycling for uniform cooldown across Nb_3Sn Tc

3) Re-coat cavity with improved Nb_3Sn recipe

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

Steel (magnetic)

Beryllium copper (non-magnetic)



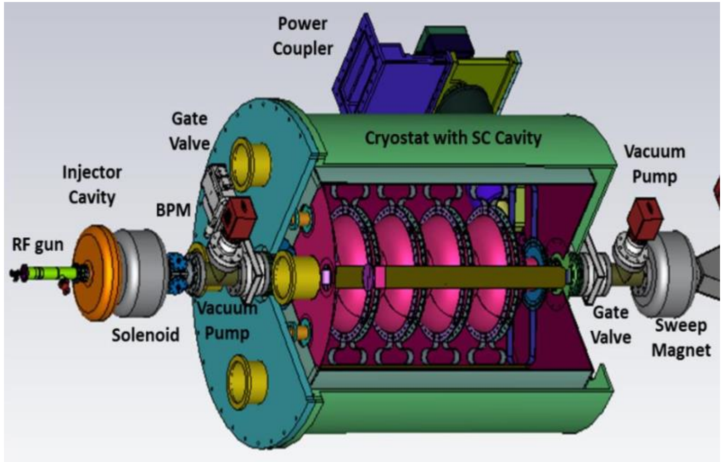
Design of a 10 MeV, 1000 kW (100 mA) module

- ✓ 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

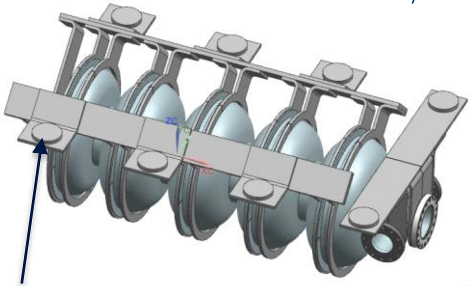
euclid BEAMLABS

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

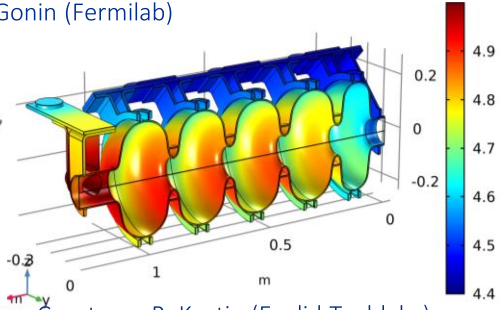
GENERAL ATOMICS



Courtesy : I. Gonin (Fermilab)



8 x PT420 mounting pads



Courtesy : R. Kostin (Euclid Techlabs)

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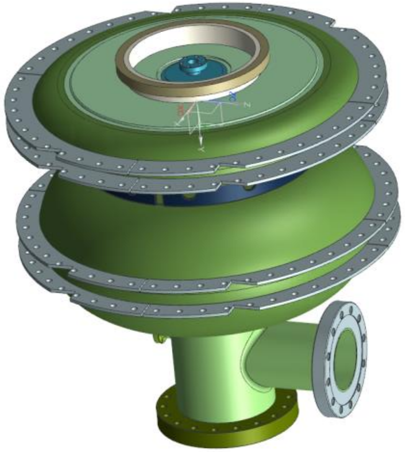
Prototype cryogen-free SRF electron accelerator development

(US Army Corps of Engineers/ERDC; NNSA)

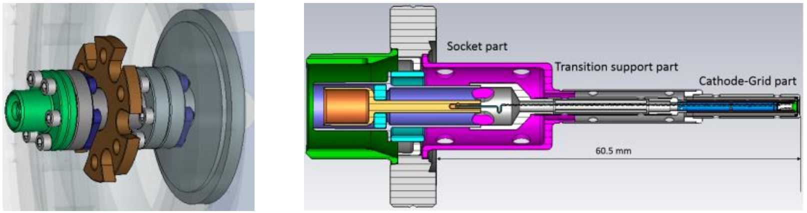
Goal: Component production, integration, and demo of a 1.6 MeV, 20 kW accelerator

(precursor to the 7-10 MeV, 200-250 kW module for pavement reconstruction, medical device sterilization)

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

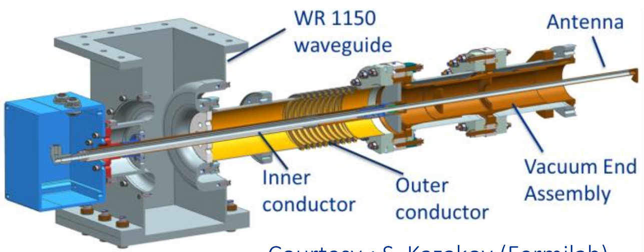


Integrated thermionic cathode



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

Low heat leak coupler (<1 W)



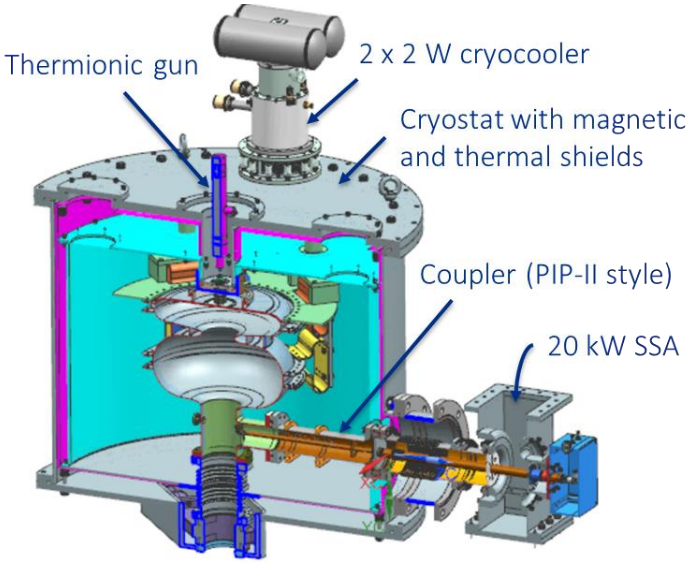
Courtesy : S. Kazakov (Fermilab)

All components are fab ready.

Prototype cryogen-free SRF electron accelerator development

(US Army Corps of Engineers/ERDC; NNSA)

Cryostat (design in progress)



20 kW SSA (to be installed)

Cryomech PT420 coolers (commissioned and installed)

Courtesy : M.I. Geelhoed (Fermilab)

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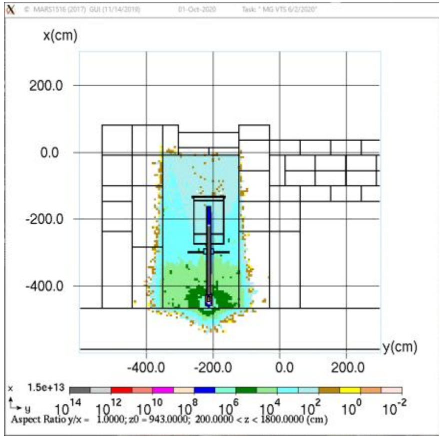
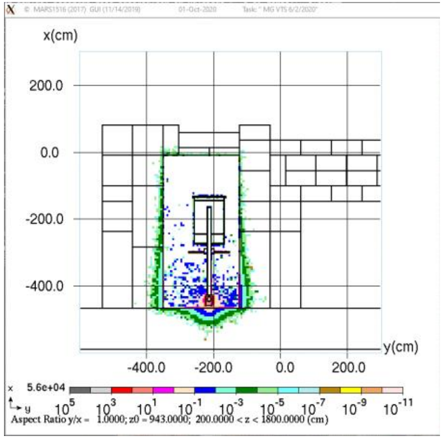
Prototype cryogen-free SRF electron accelerator development

(US Army Corps of Engineers/ERDC; NNSA)

Installation and test site is being prepared

MARS simulation for radiation shielding design





Courtesy : M.I. Geelhoed (Fermilab)

Accelerator enclosure

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.

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

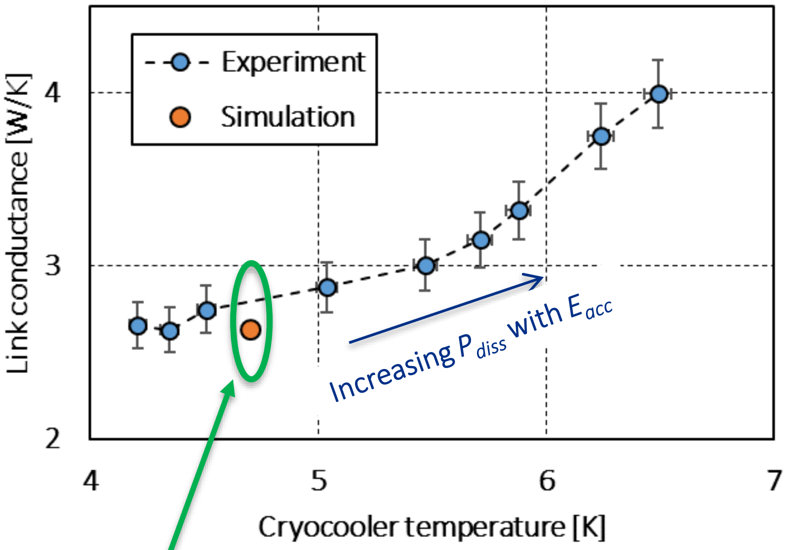
HEP Accelerator Stewardship

US Army Corps of Engineers (ERDC)

Thanks! Questions?

Extra: Conduction link performance, cavity thermal stability

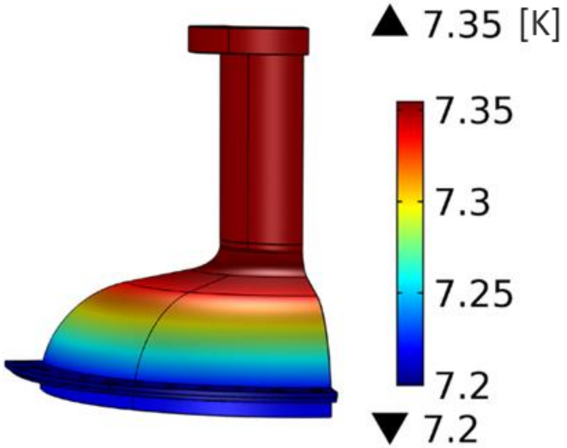
Comparison of measured and simulated link thermal conductance



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

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