FERMILAB-SLIDES-20-115-DI-LDRD-TD

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

Conduction-cooled Nb_3Sn SRF at Fermilab

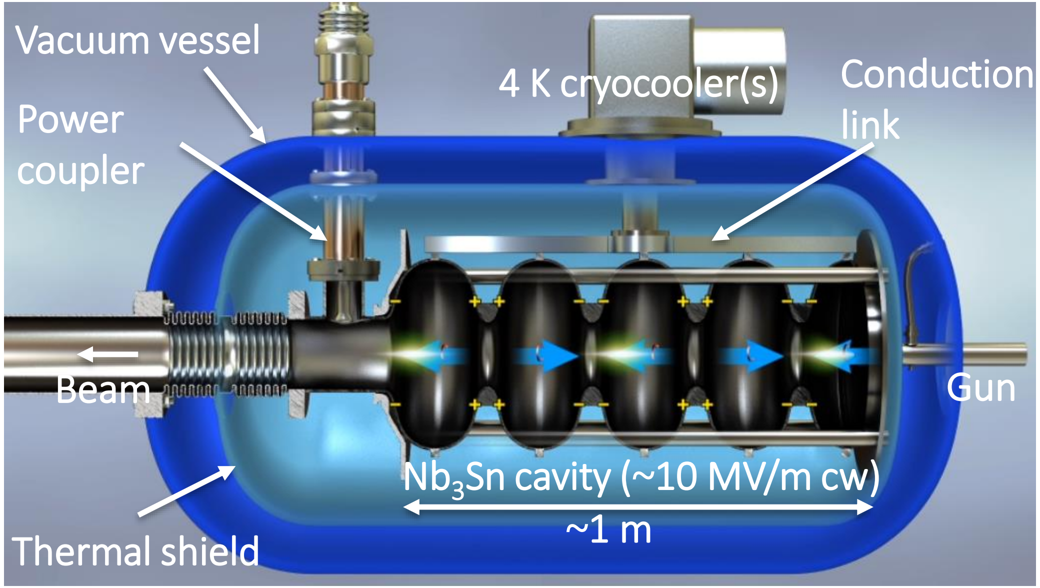
Vision: Develop compact, turnkey e-beam source for environmental and industrial applications (~10 MeV, >>100 kW)

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)

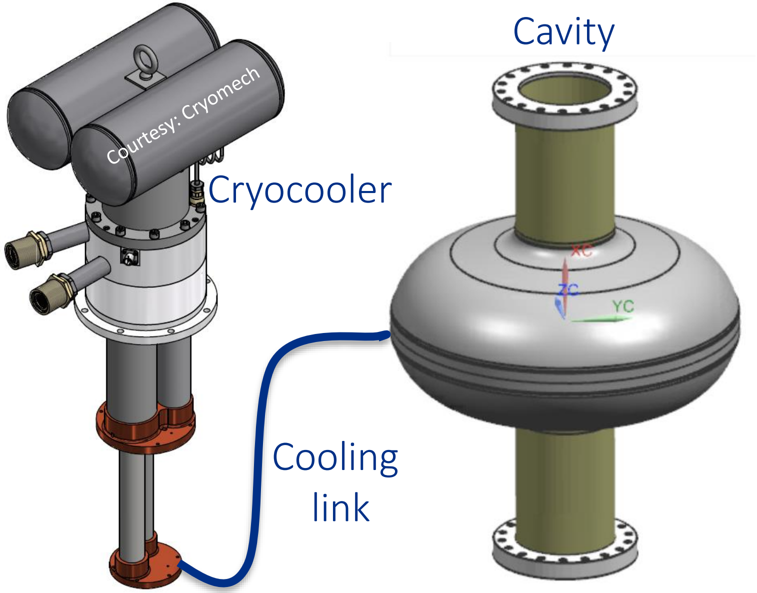
Conduction cooled Nb_3Sn SRF development

(Fermilab LDRD 2016-2019)

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

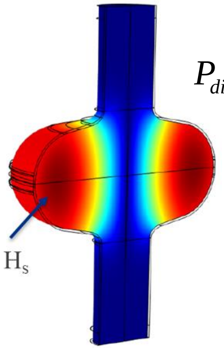
Our choice:

- 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

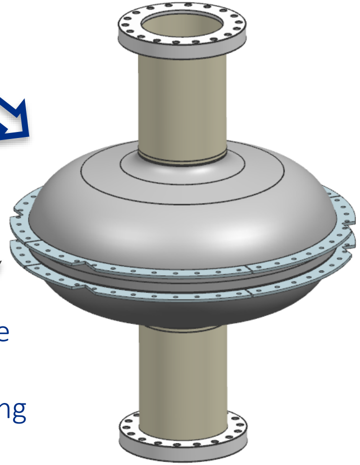


Cavity preparation for conduction link attachment

Conceptualization of conduction cooling



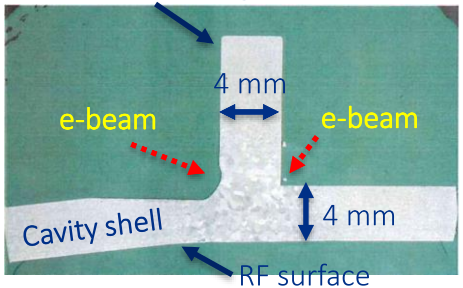
$$P_{diss} = \frac{1}{2} R_s \oint |H_s|^2 ds$$



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

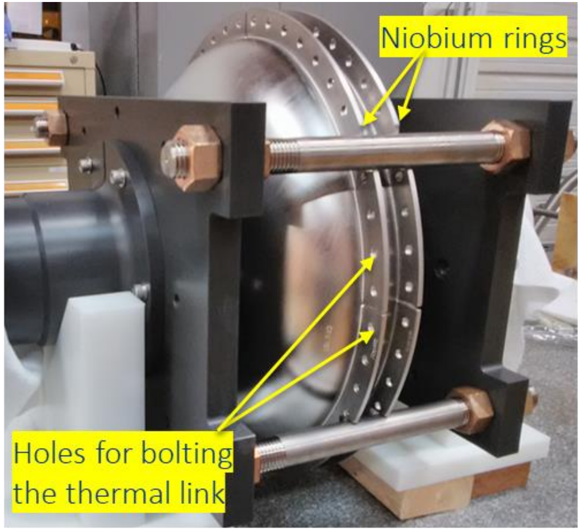
Development of conduction cooling

E-beam weld recipe development
- Full penetration
- Avoid weld beads on the RF surface



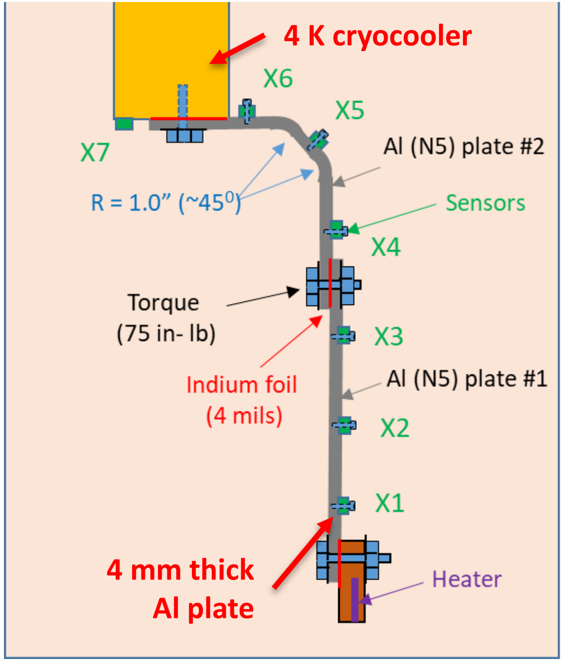
Courtesy: C. Grimm (Fermilab)

Ring-welded single cell 650 MHz cavity



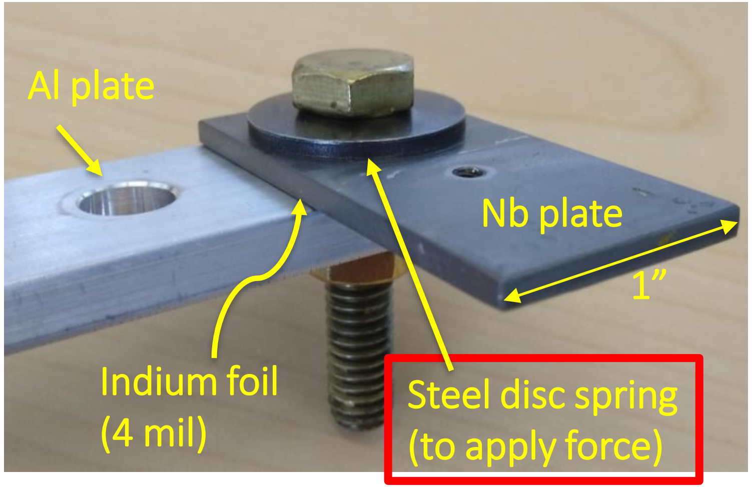
Thermal characterization of the conduction link

5N aluminum samples



Courtesy: O. Prokofiev (Fermilab)

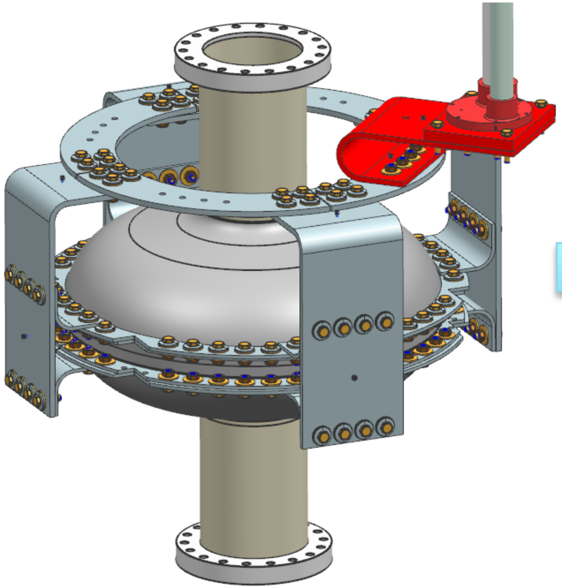
Nb-Al bolted contacts



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

Conduction link design and performance verification

Al conduction link bolted to the Nb rings around the cavity

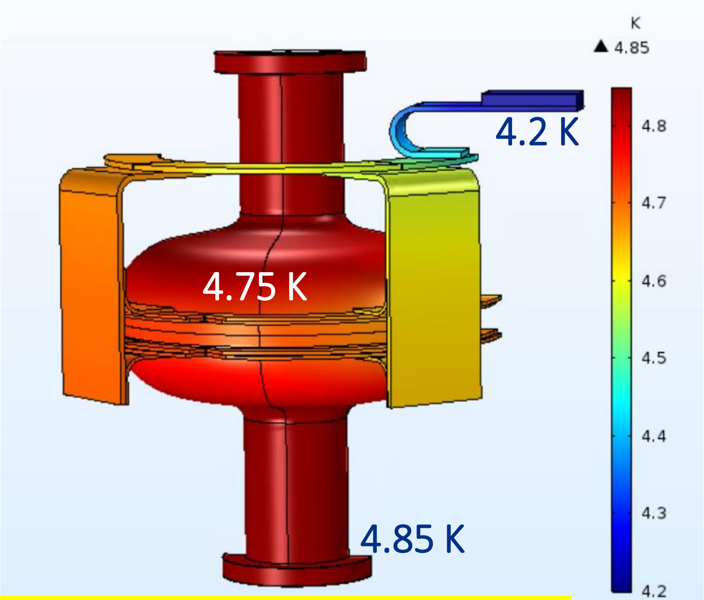


Nb_3Sn surface resistance (BCS from SRIMP + 10 nΩ)

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

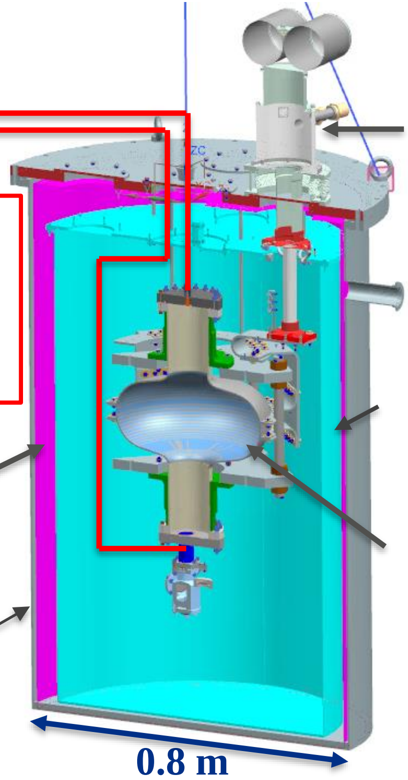
R.C. Dhuley *et al.*, ***IOP Conf. Ser.: Mat. Sci. Eng.***, 2020. https://doi.org/10.1088/1757-899X/755/1/012136

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)

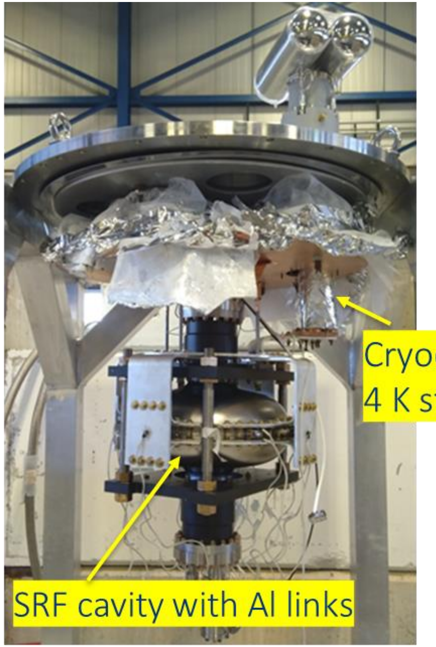
Vacuum vessel



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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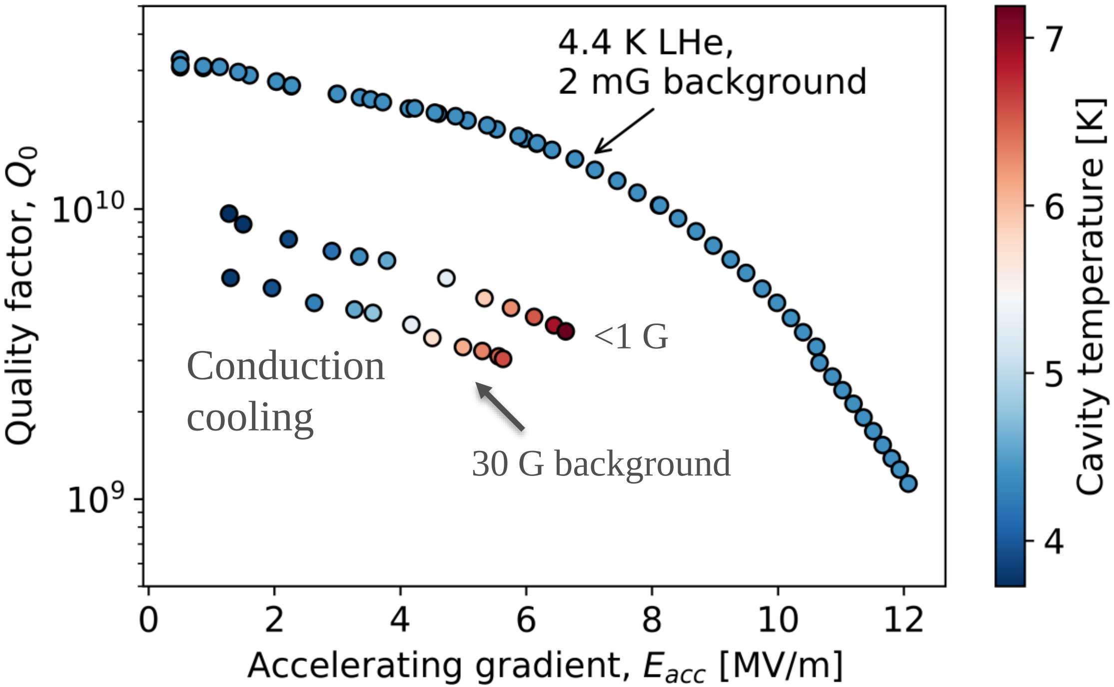
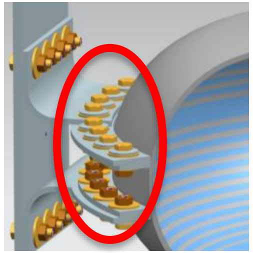
First results for the conduction-cooled Nb_3Sn cavity

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/

Fermilab

Ongoing work to reach 10 MV/m

1) Reduce background magnetic field

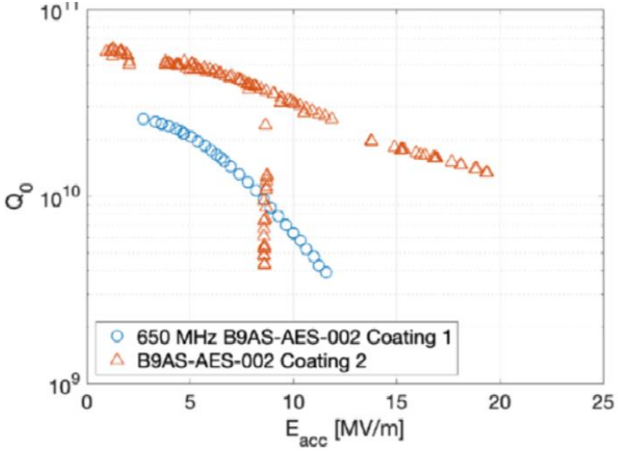
Steel (magnetic)

Beryllium copper (non-magnetic)

2) Cryocooler cycling for uniform cooldown across Nb_3Sn Tc

3) Re-coat cavity with improved Nb_3Sn recipe

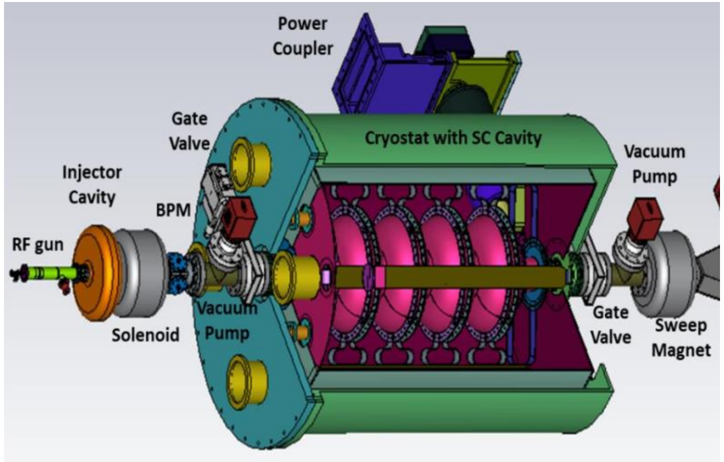
S. Posen *et al.*, https://accelconf.web.cern.ch/srf2019/papers/thfub1.pdf



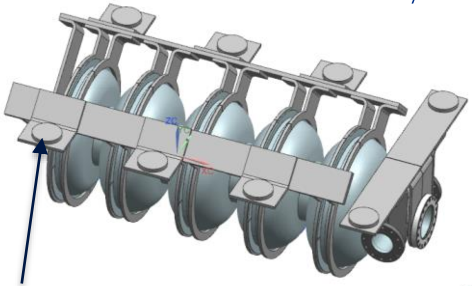
Design of a 10 MeV, 1000 kW (100 mA) module

- ✓ 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

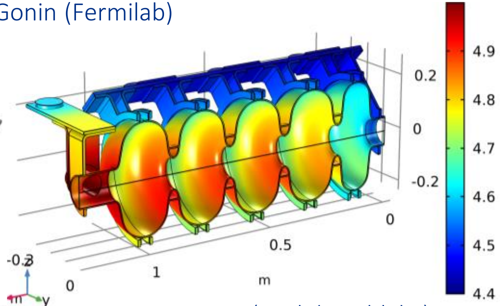
- Cryostat design and integration (thermal and magnetic shield, vacuum vessel, couplers)
- Cost assessment



Courtesy : I. Gonin (Fermilab)



8 x PT420 mounting pads



Courtesy : R. Kostin (Euclid Techlabs)

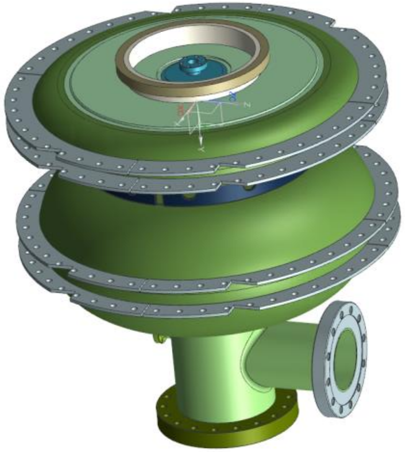
Prototype cryogen-free SRF electron accelerator development

(US Army Corps of Engineers/ERDC; NNSA)

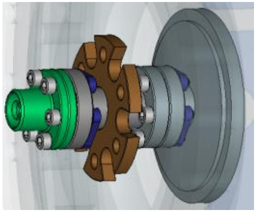
Goal: Component production, integration, and demo of a 1.6 MeV, 20 kW accelerator

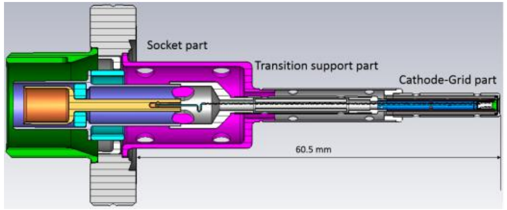
(precursor to the 7-10 MeV, 200-250 kW module for pavement reconstruction, medical device sterilization)

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



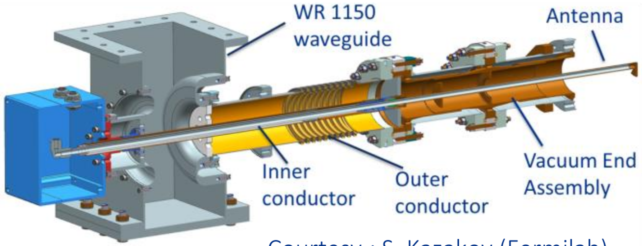
Integrated thermionic cathode





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

Low heat leak coupler (<1 W)



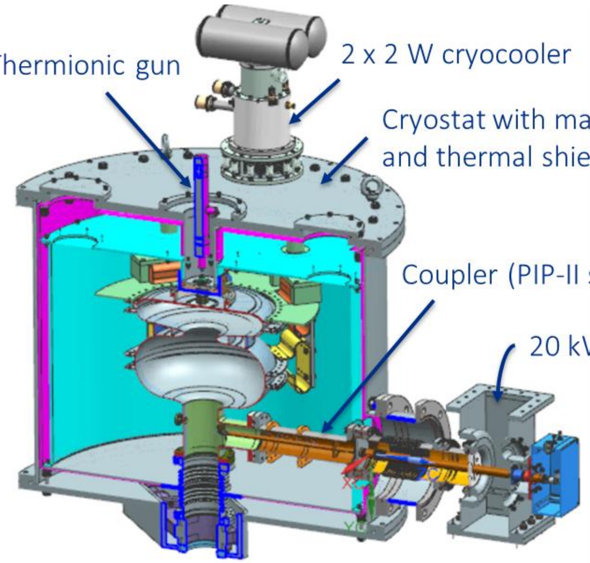
Courtesy : S. Kazakov (Fermilab)

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)

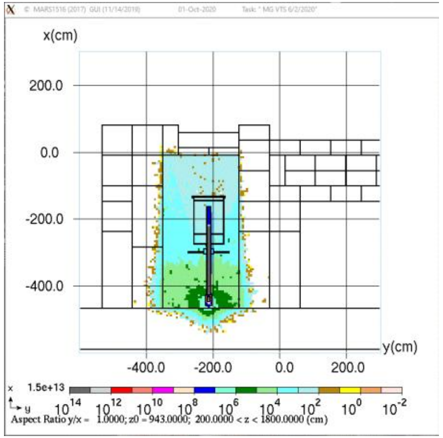
Courtesy : M.I. Geelhoed (Fermilab)

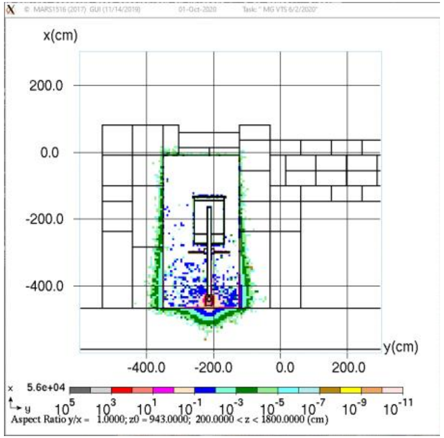
Prototype cryogen-free SRF electron accelerator development

(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

Fermilab

Acknowledgement

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- 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

U.S. DEPARTMENT OF ENERGY | Office of Science
HEP Accelerator Stewardship

euclid BEAMLABS

NNSA National Nuclear Security Administration

US Army Corps of Engineers (ERDC)

NORTHERN ILLINOIS UNIVERSITY
Northern Illinois Center for Accelerator and Detector Development

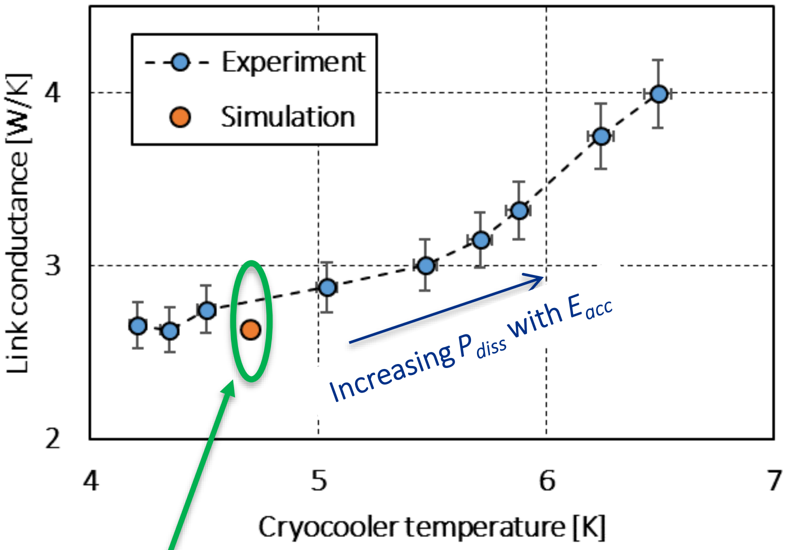
GENERAL ATOMICS

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

Thanks! Questions?

Extra: Conduction link performance, cavity thermal stability

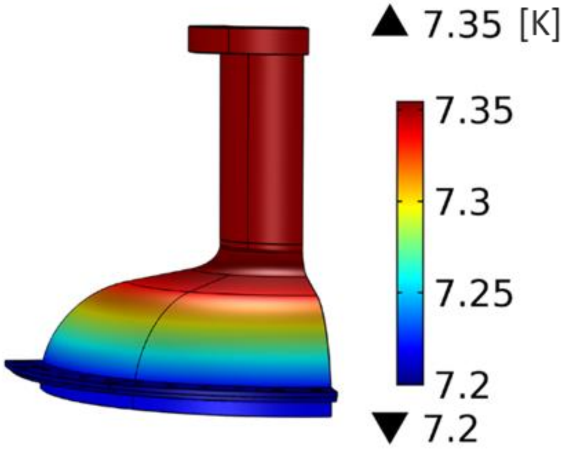
Comparison of measured and simulated link thermal conductance



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