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Progress on a conduction cooled SRF cryomodule at Fermilab

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(with contributions from Fermilab AD/ME, APS-TD/SRF, and IARC@Fermilab)

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Work group 3, TTC 2022 Aomori, Japan

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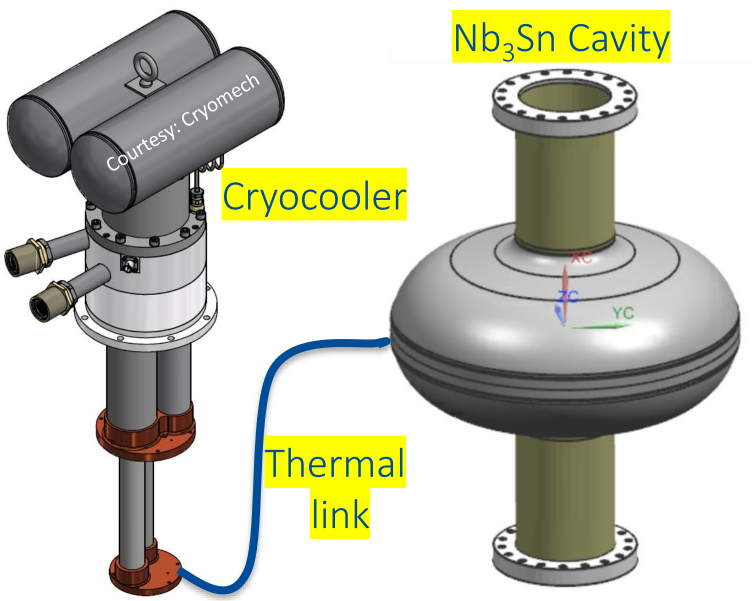
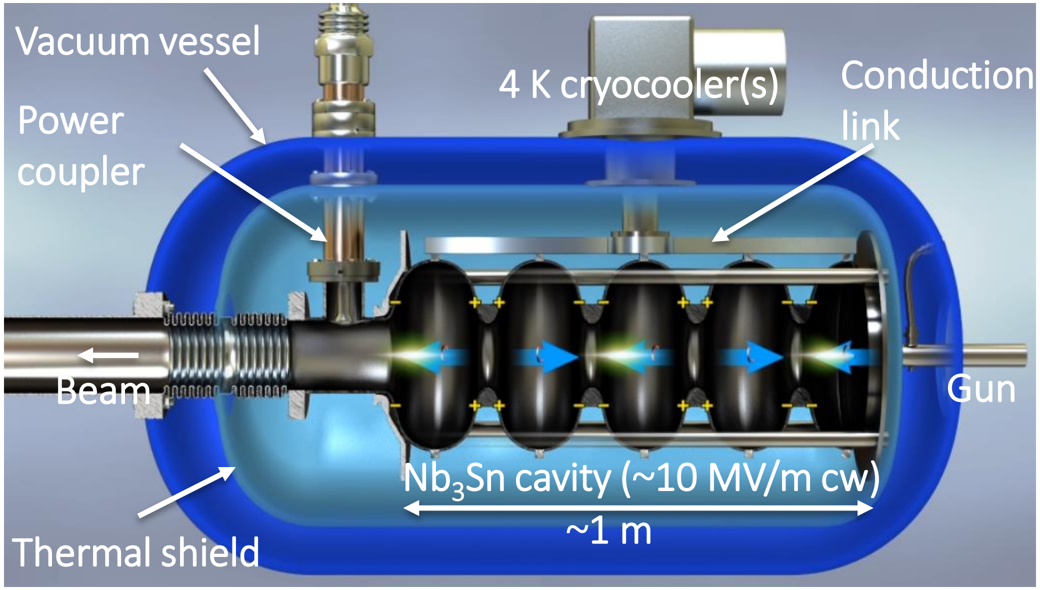
Cryocooler conduction cooled SRF

- Helium liquefier → Closed cycle cryocooler ->> reliable cryosystem
- Liquid helium bath → Conduction links ->> simpler cryomodule
- Simpler and more reliable cryosystem makes the SRF technology attractive for building compact accelerators for industrial applications

Concept of cryocooler conduction cooled SRF



Rendering of a compact, conduction cooled SRF accelerator for industrial applications



Conduction cooled SRF R&D at Fermilab

- Development and performance testing of cryocooler conduction-cooled SRF cavities (2018-22)
  - Demonstrated 10 MV/m cw on a single-cell 650 MHz Nb_3Sn cavity conduction cooled by a Cryomech PT420 cryocooler
  - https://doi.org/10.1088/1757-899X/1240/1/012147 and https://doi.org/10.1088/1361-6668/ab82f0
- Design studies of high average power e-beam accelerators (2019-22)
  - Designed a 10 MeV, 1000 kW avg. power e-beam conduction cooled SRF accelerator for wastewater treatment
  - https://doi.org/10.1103/PhysRevAccelBeams.25.041601
- e-beam SRF accelerator development (2021–ongoing)
  - **Build and operate a 1.6 MeV, 20 kW e-beam machine <this talk>**
  - Build a 8 MeV, 20 kW e-beam machine for mobile applications <J. Thangaraj talk; WG3 today 2:17 PM>

e-beam SRF accelerator development

- Motivation – Development of an alternative to Co-60 radiation sources for the medical devices sterilization industry
- e-beam based X-ray sources is an attractive alternative
  - ~15 kW X-rays provide comparable radiation dose to ~1 MCi of Co-60
  - 150-200 kW e-beam is needed to produce 15-20 kW X-rays!
- The high average-power e-beam requirement can be realized *via* cw operation of an SRF accelerator
- Fermilab's staged approach
  - Build components, integrate, and operate a 1.6 MeV, 20 kW e-beam machine
    - Integrated thermionic electron gun
    - Cryocooler conduction-cooled Nb_3Sn SRF cavity
    - Low heat leak power coupler
    - Low heat leak and magnetically shielded cryostat
    - Solid state RF power source
    - Beam delivery
  - Use experience and lessons learnt to build 8 MeV, 200 kW e-beam machine to produce X-rays for the medical devices sterilization industry

1.6 MeV, 20 kW conduction-cooled SRF accelerator cryostat

Cryocoolers
(Two thermal stages – 4 K, 45 K)

Thermionic electron source
(integrated with the cavity)

Vacuum vessel

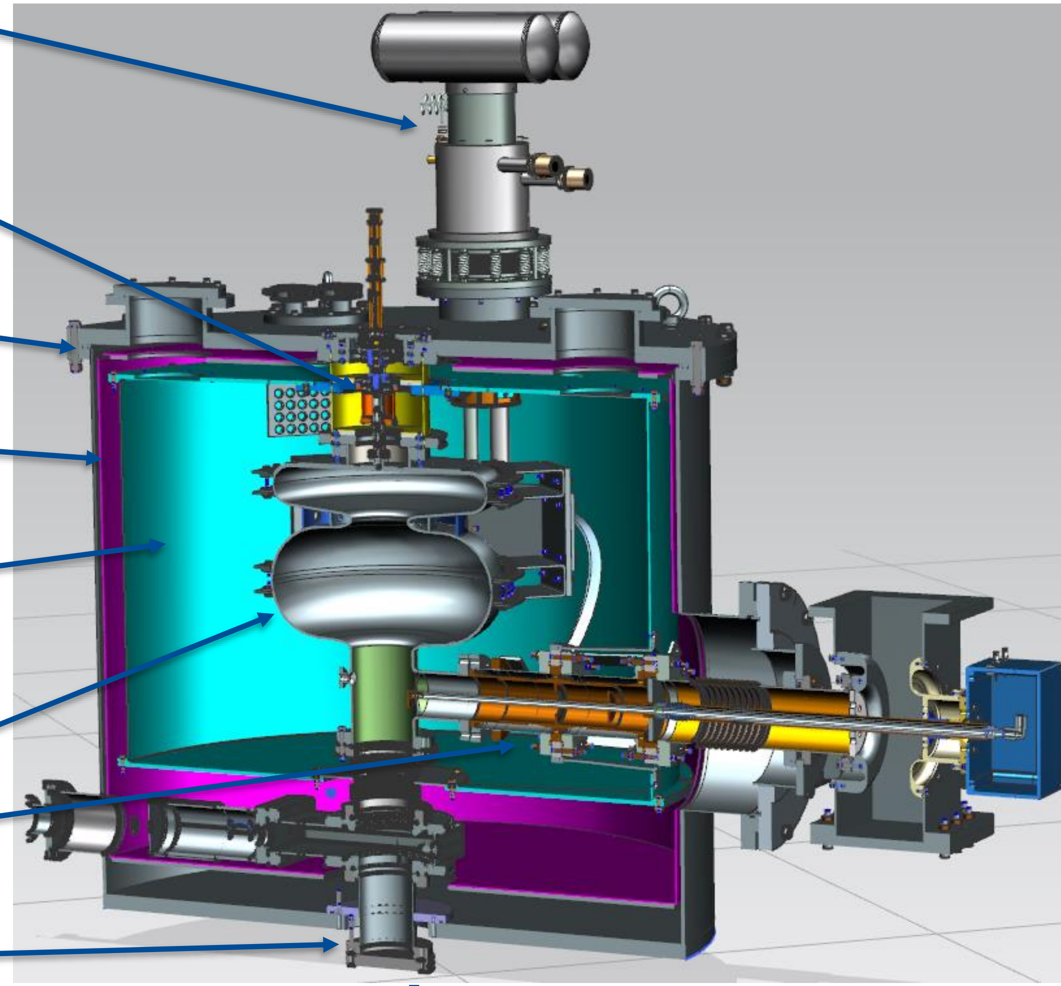
Magnetic shield
(single layer, room T)

Thermal shield
(conduction cooled to the 45 K stage)

1.5-cell Nb_3Sn cavity (650 MHz)
(conduction cooled to the 4 K stage)

Power coupler

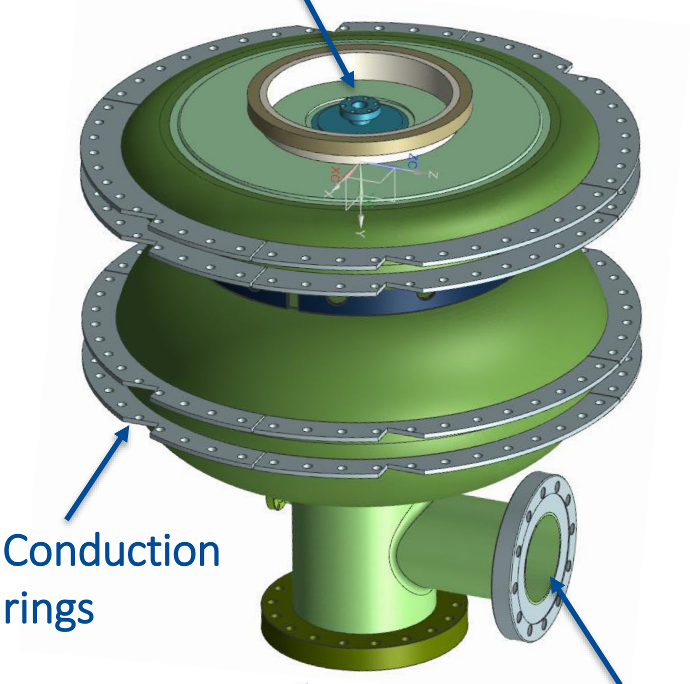
Beam outlet



~1 m diameter

Component details

SRF cavity and heat load estimation



Heat load at ~5 Kelvin	Value [W]
RF dissipation in cavity (with Q_0 = 1e10)	1.46
Gun static heat leak	0.08
Cathode radiation to cavity (temp = 1373 K)	0.22
Conduction through cavity supports	0.1
Conduction through outlet beam pipe	0.1
Thermal radiation to cavity from thermal shield	0.1
Thermal radiation to cavity through beam pipe window	0.24
Beam loss (1e-6 of 20 kW = 0.02 W)	0.02
Coupler static + dynamic at 20 kW cw	1.0
Total	3.5

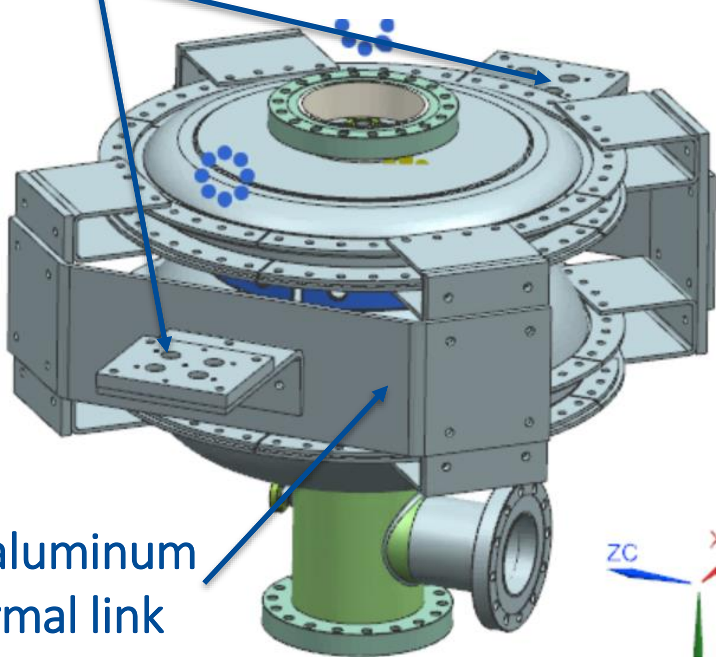
Manageable with 2x Cryomech PT420 coolers

Component details

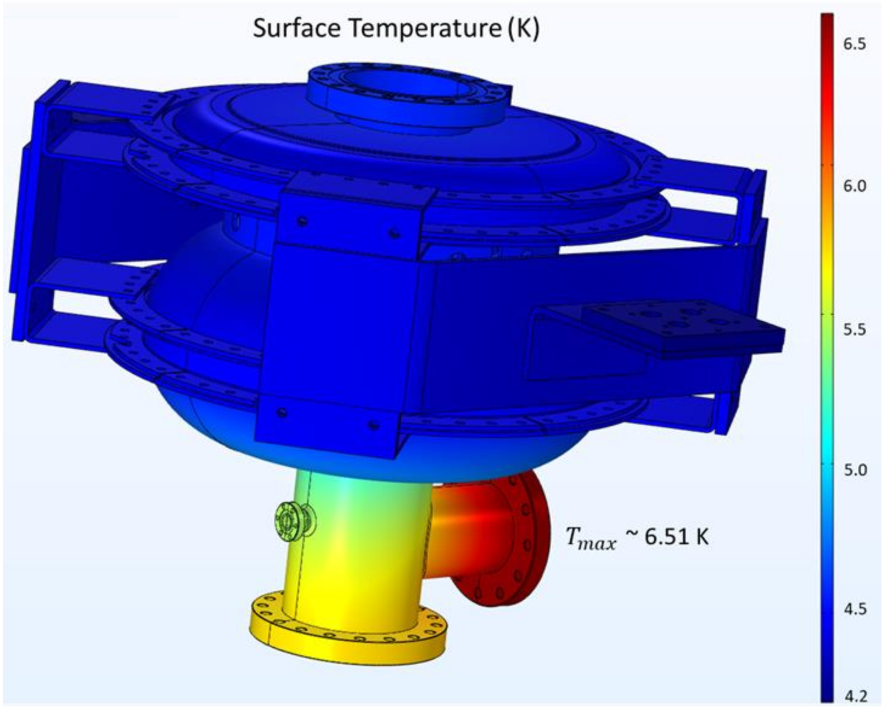
Verification of conduction cooling (RF + thermal simulation)

2 x cryocooler mounting pads

5N aluminum thermal link

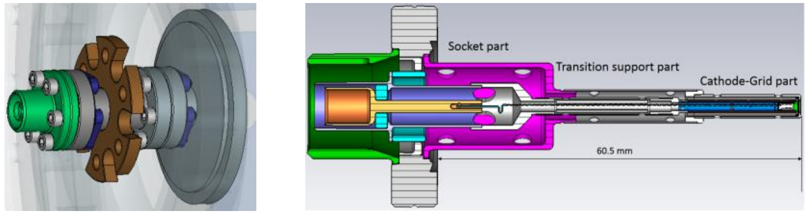


FEA verification of thermal link performance



Component details

Integrated thermionic cathode

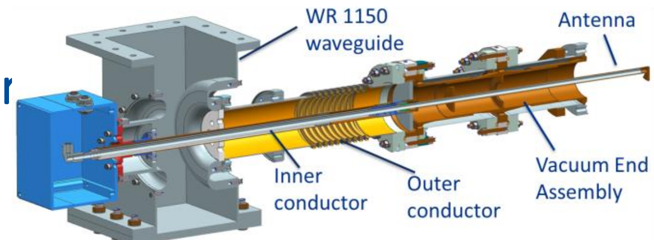


Courtesy : I. Gonin, V. Yakovlev, T. Nicol (Fermilab)

650 MHz, 20 kW solid state RF amplifiers

Courtesy : C. Edwards (Fermilab)

Low loss coupler (<1 W to 5 K)



Courtesy : S. Kazakov (Fermilab)

Cryocoolers and compressors

Courtesy : M.I. Geelhoed (Fermilab)

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Current status

- 1.5-cell SRF cavity → delivery expected in November 2022
- Power coupler → delivery expected in February 2023
- Thermionic gun → delivery expected in March 2023
- Cryostat
  - Cavity conduction links → fabricated and ready for assembly
  - Thermal shield → in procurement
  - Magnetic shield → in final design
  - Vacuum vessel → in final design
- LLRF and SSAs → at hand, to be commissioned in early 2023
- Test cave and water/electrical utilities → ready

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Funding for conduction cooled SRF demonstration

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- DOE HEP Accelerator Stewardship (R.C. Dhuley)

Funding for Nb_3Sn coating infrastructure

- Fermilab LDRD (S. Posen)
- DOE Early Career Award (S. Posen)

Funding for building the 1.6 MeV, 20 kW e-beam SRF accelerator

- US National Nuclear Security Administration (T. Kroc, R.C. Dhuley)

Thank you