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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.

Superconducting Accelerators for High-Power X-ray production

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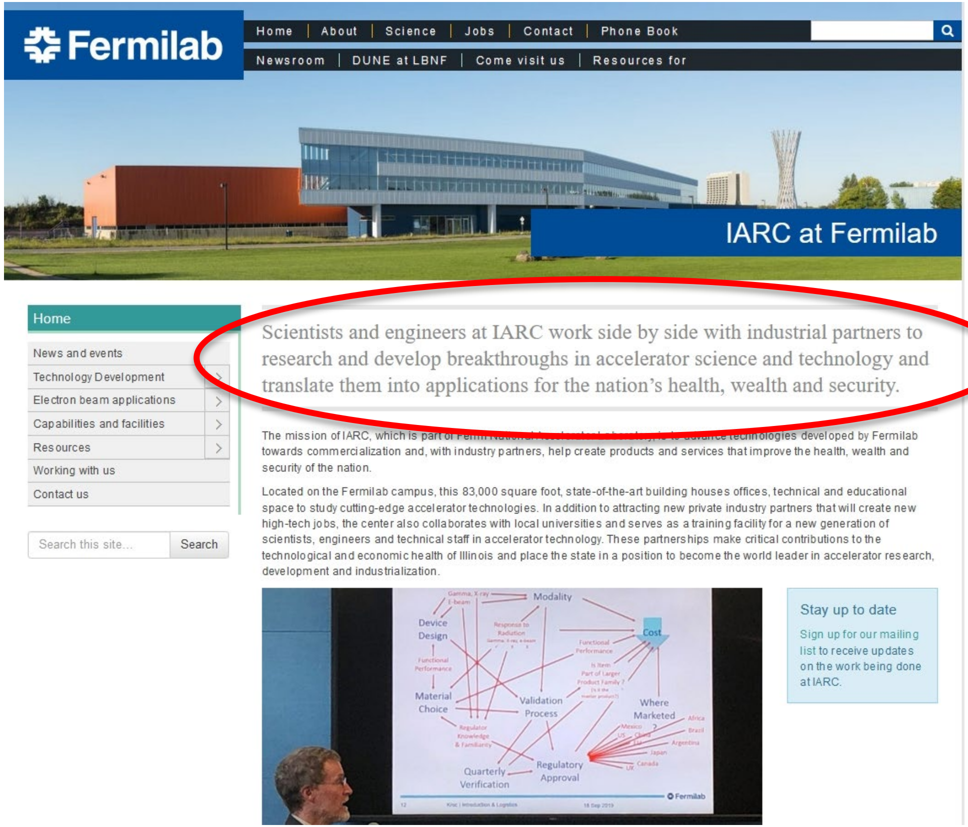
Virtual Technical Meeting on the Recent Development of Radiation Generators for Industrial Applications

29 September 2021

Fermi National Accelerator Laboratory

- National Laboratory: Funded by the Department of Energy (OHEP)
- Mission: High Energy Physics Research (Discovery Science)
- To carry out that mission Fermilab designs, builds, & operates: High Energy, High Power (MW), High reliability Accelerators
- 6800 acre (2750 ha) site, ~$360M/yr budget, Staff of 1700, > 2200 users
- 350 Accelerator Scientists and Engineers + 300 technical staff (+ANL)
- Largest collection of Accelerator Experts in the world
- Broad skills in accelerator design, simulation, fabrication, integration & test
- Also well versed in industry/university partnerships

IARC @ Fermilab



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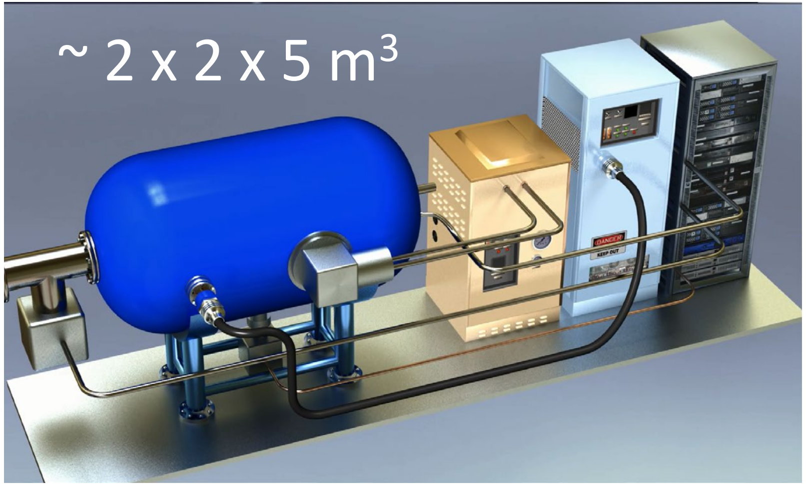
Motivation for focus on medical device sterilization

Approx 50% of single use medical devices are sterilized with gamma rays from decay of Co-60

- Worldwide, 400 MCi of 600 MCi permitted
- Medical Device industry growing at 7% per annum
- Cobalt production is behind market demand by 5%
- Sterilization capacity shortages are looming

  BPSA is aggressively pursuing X-ray by end of 2022
- Radioisotope security concerns

250 kW Industrial SRF accelerator – under development



- Energy: ~ 10 MeV
- Power: 250 KW
- Turn-key operation

- High reliability
- Low cost
- Small: Cryostat
  - ~ 0.7 m dia
  - ~ 1.5 m long

- Modified existing 650 MHz cavity
- Magnetron RF source and commercial Cryo-cooler
- Modular design scales to MW class industrial applications

- Total weight 3000-5000 lbs → viable for mobile applications
- Mobile platform enables many new applications
- Environmental applications

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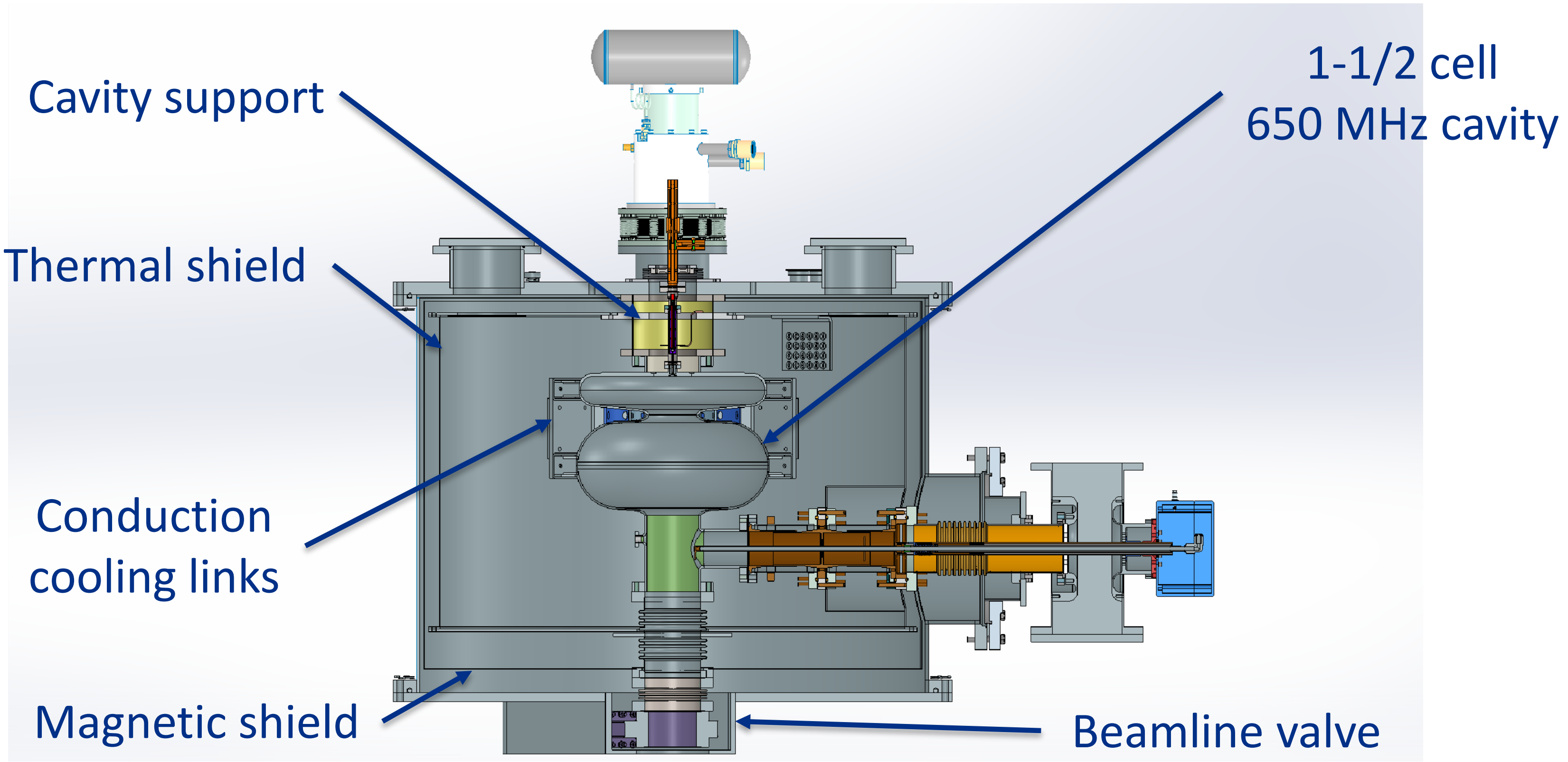
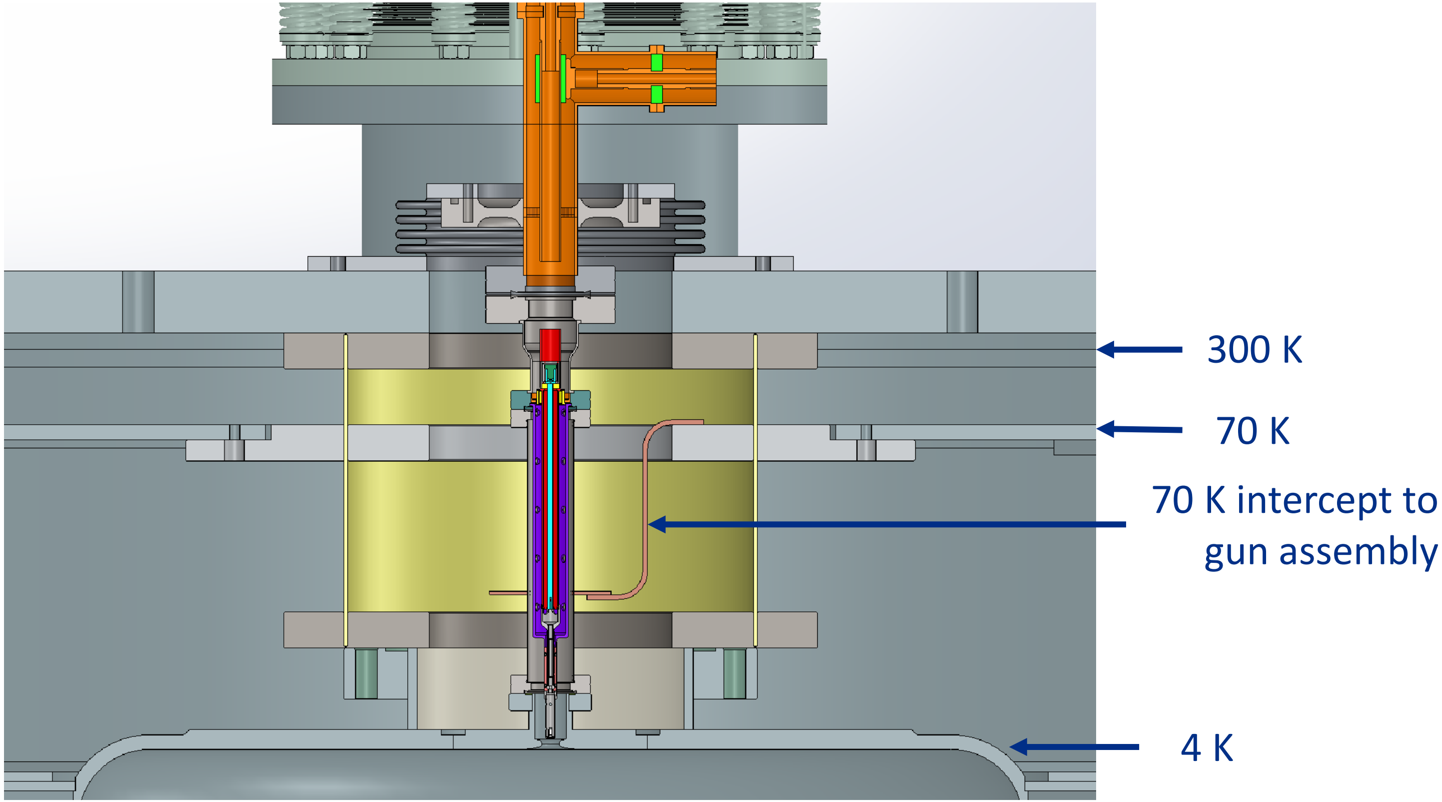
20 kW prototype



Integrated electron gun – no LEBT



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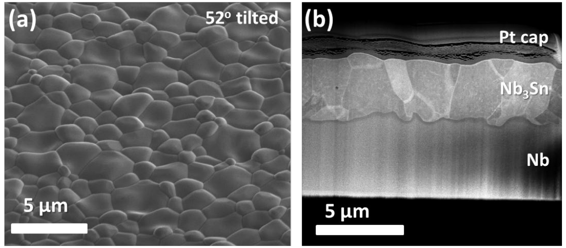
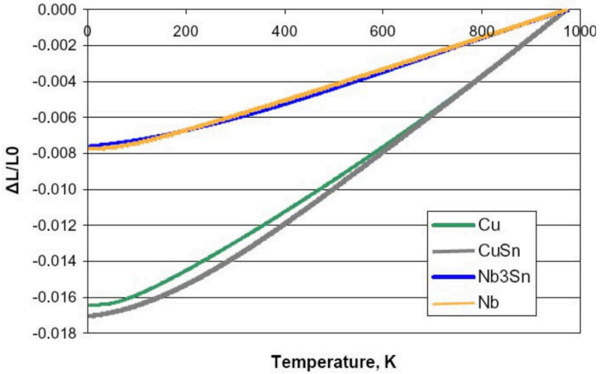
Nb_3Sn – Raises the critical temperature, T_c

- Sn vapor evaporated onto Nb cavity surface, Sn reacts with Nb to form Nb_3Sn at elevated temperatures
- Reasons for choosing vapor diffusion:
  - **Only process** shown to produce Nb_3Sn SRF cavities with high Q_0 at E_{acc} >1 MV/m
  - Extremely close match of **thermal expansion coefficient**: avoid delamination
  - High temperatures ~1100 C: low T_c Nb-Sn phases not thermodynamically stable
  - Strict control of impurities – **no copper involved**
  - Can achieve very **clean grain boundaries**
  - Relatively **smooth surface** to avoid field enhancement

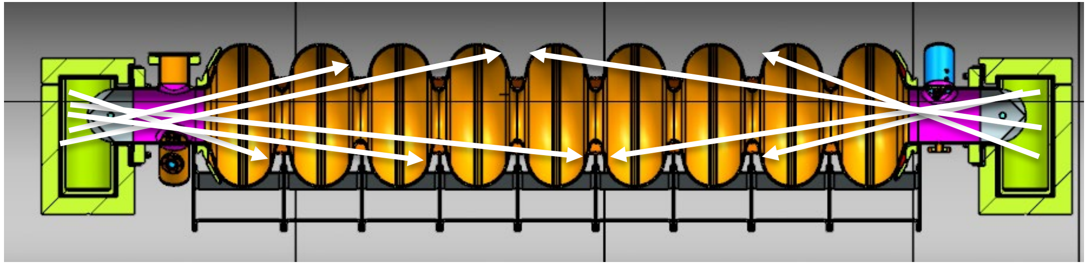


SEM images of Nb_3Sn film coated on Nb: a) surface, b) cross section

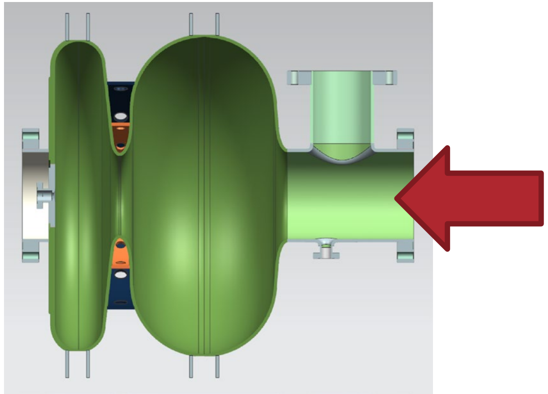


Close match of CTE between Nb and Nb_3Sn for strong bond at cryogenic temperatures

Challenge of Closed Structure

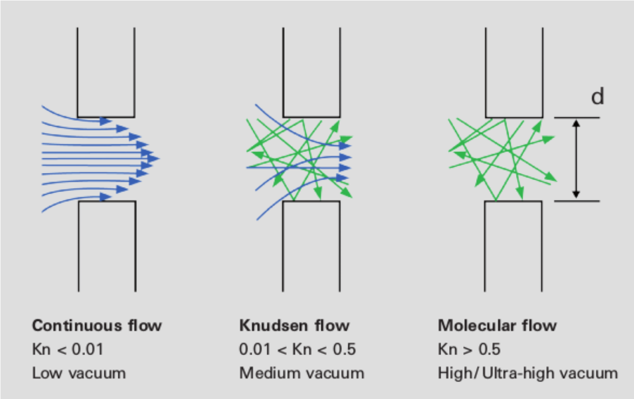


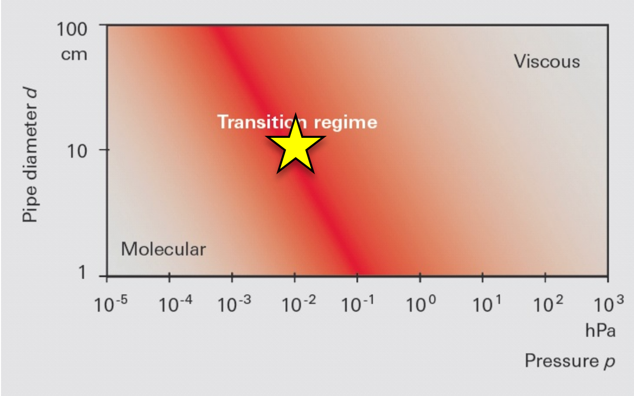
Good performance already: 9-cell 1.3 GHz, open on both sides



This project: 1.5-cell 650 MHz, open on one side

- Sn vapor flow is below viscous regime – line-of-sight is a factor
- High performance coatings in complex 9-cell cavity give hope for 1.5 cell

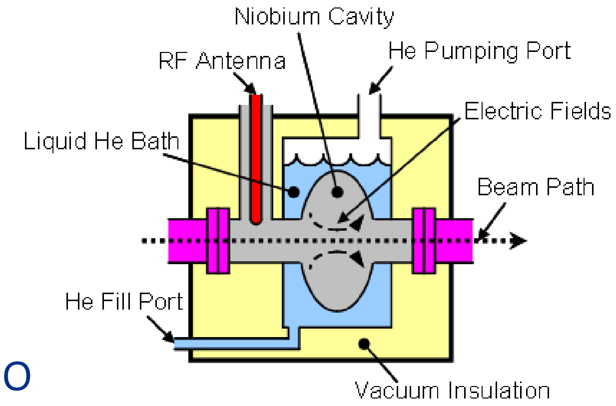


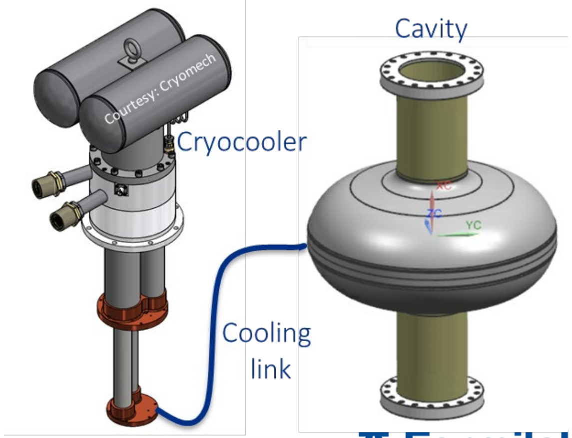


https://www.pfeiffer-vacuum.com/en/know-how/introduction-to-vacuum-technology/fundamentals/types-of-flow/

What is a conduction-cooled SRF cavity?

- SRF cavities require cooling near 4 Kelvin to operate in the superconducting state. The cooling is traditionally provided by liquid helium.
- The 20 kW accelerator will be the first ever to use an SRF cavity without liquid helium
- Cavity is cooled *via* thermal conduction using:
  - High thermal conductivity link
  - Mechanical 4 K cryocoolers

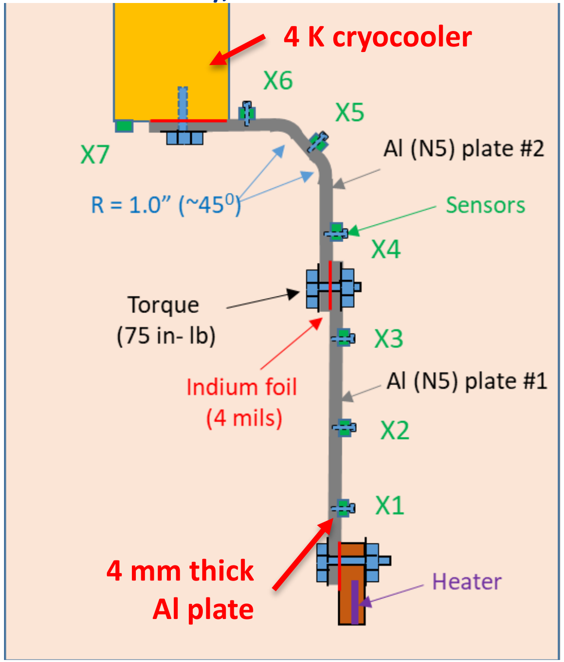


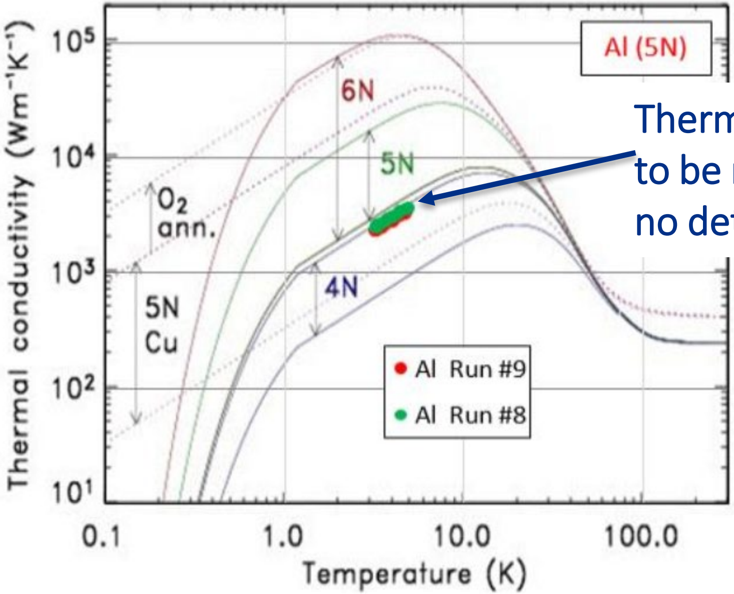


Characterization of link thermal conductor

5N purity aluminum is chosen as the thermal link material

Setup for measuring 4 K thermal conductivity, contact resistance



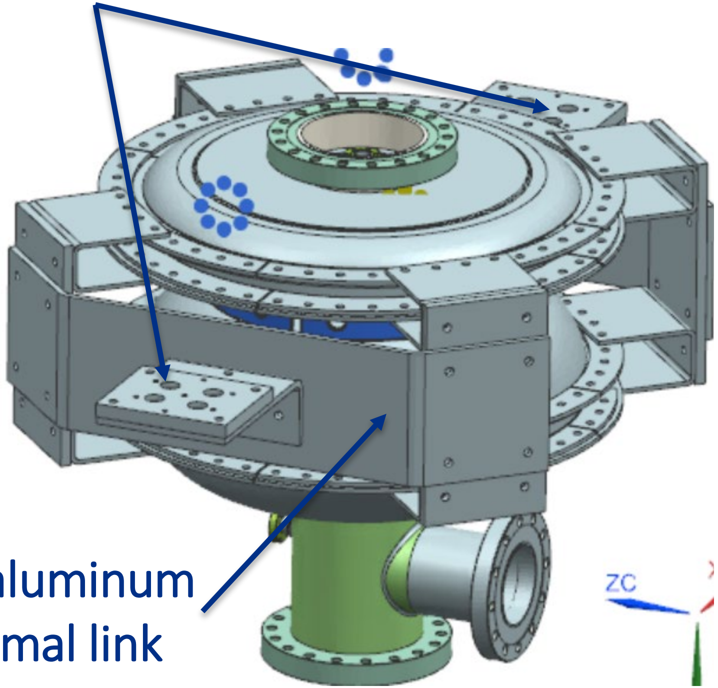


Thermal conductivity found to be near the lower band of 5N, no deterioration from bending

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

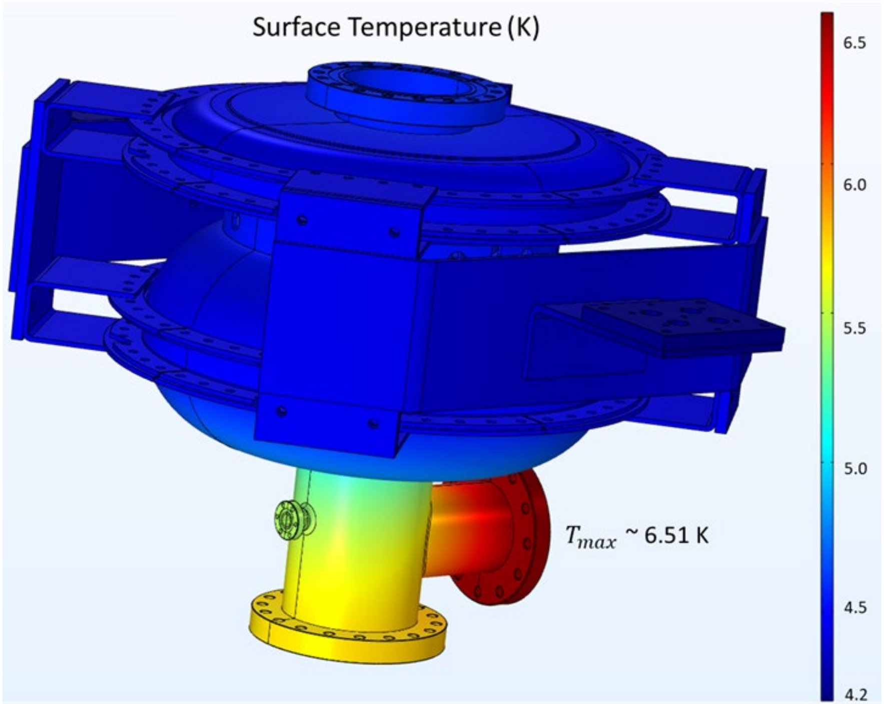
Thermal link design for the 1.5-cell cavity

2 x cryocooler mounting pads



5N aluminum thermal link

FEA verification of thermal link performance



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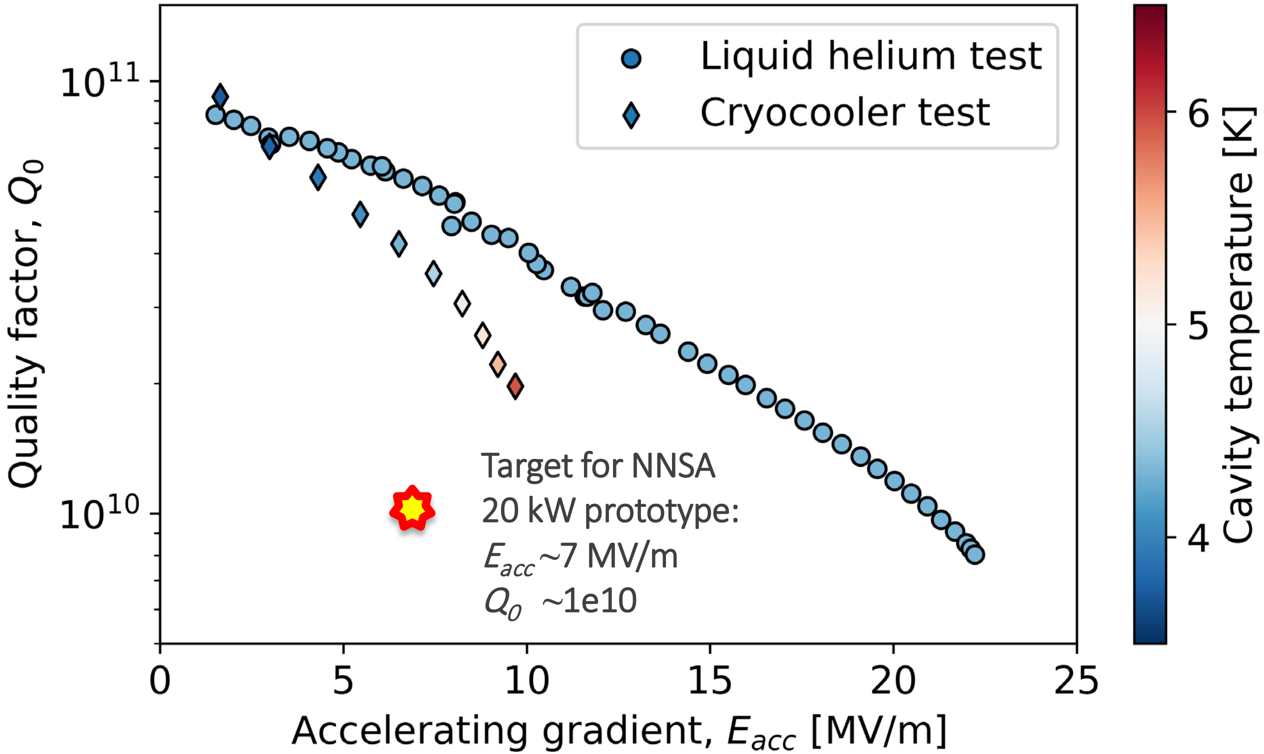
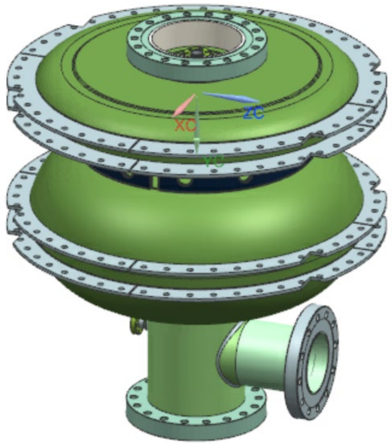
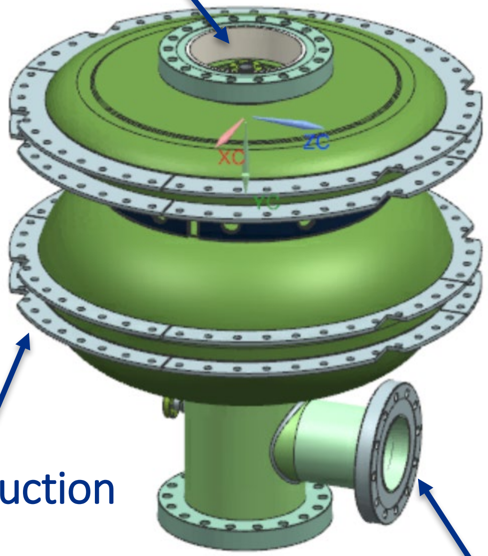
Specifications for the 1.5-cell cavity





1.5-cell cavity expected heat load



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

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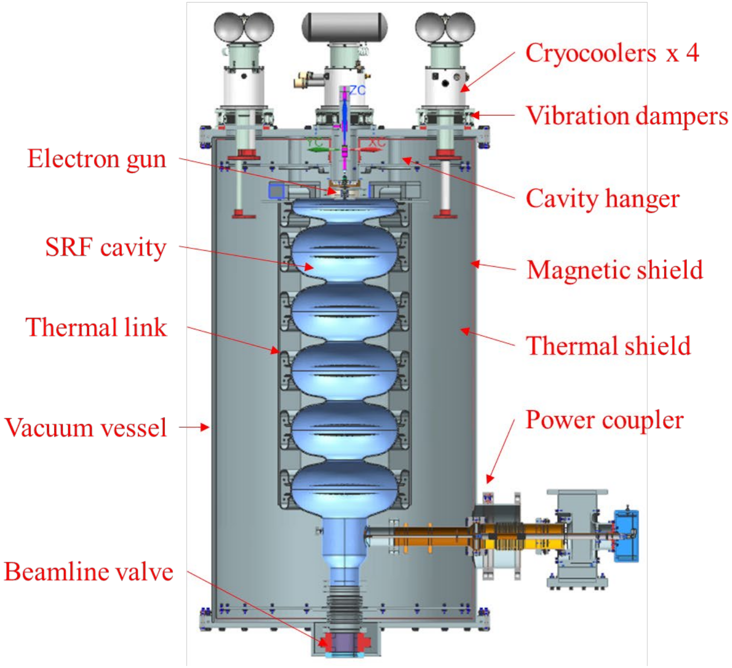
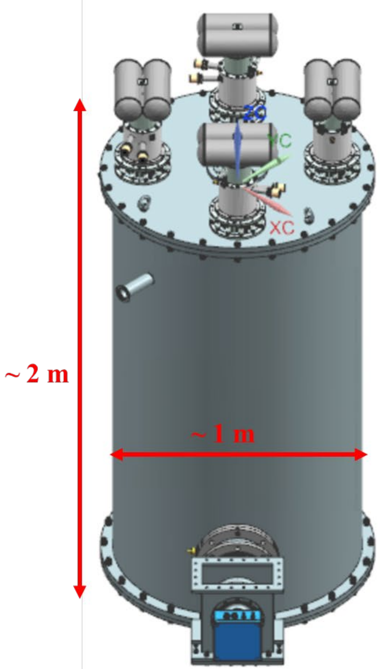
Estimated heat loads to ~50 K

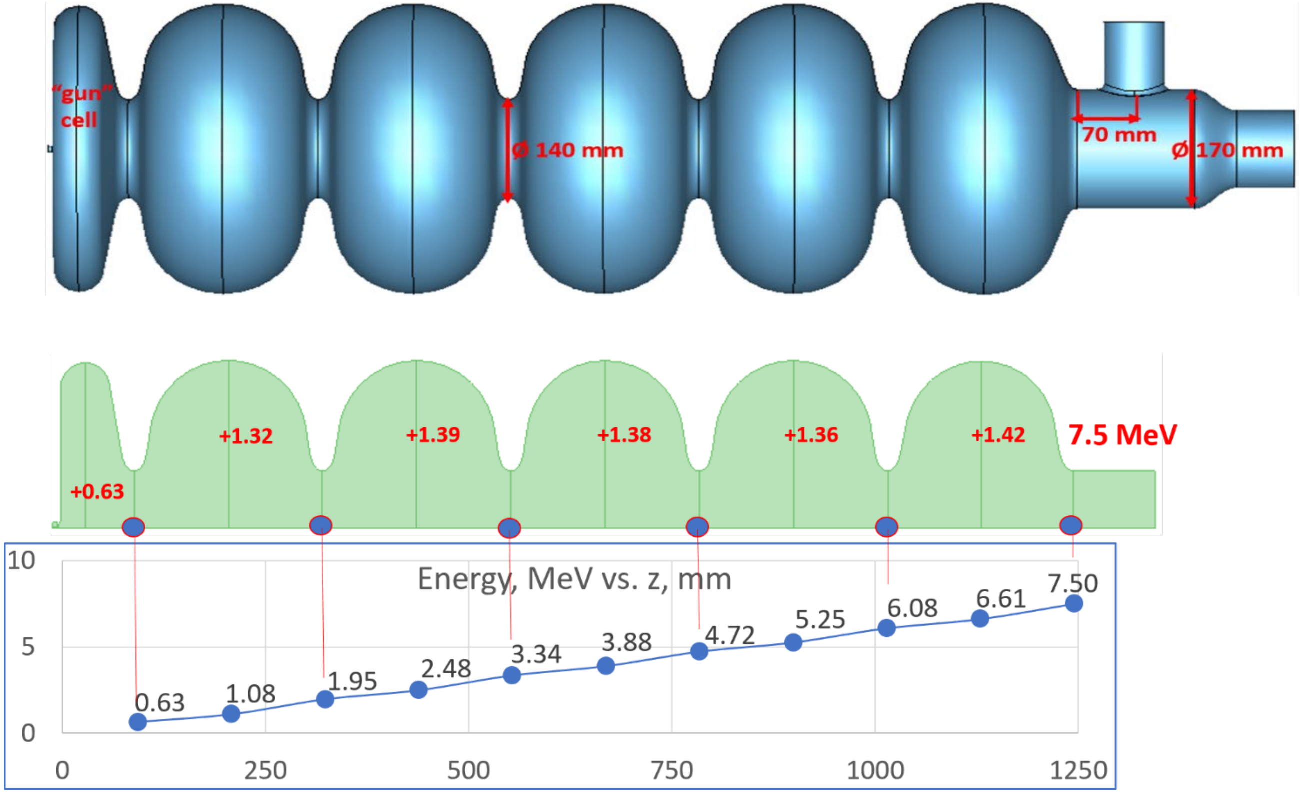
Heat source	Heat load (W)
Radiation and residual gas conduction	5.6
Gun static heat leak	0.4
Conduction through cavity supports	3.0
Cold to warm transition bellows	6.2
Coupler static + dynamic at 20 kW CW	5.0
Total	**20.2**

200 kW, 7.5 MeV 1st Article



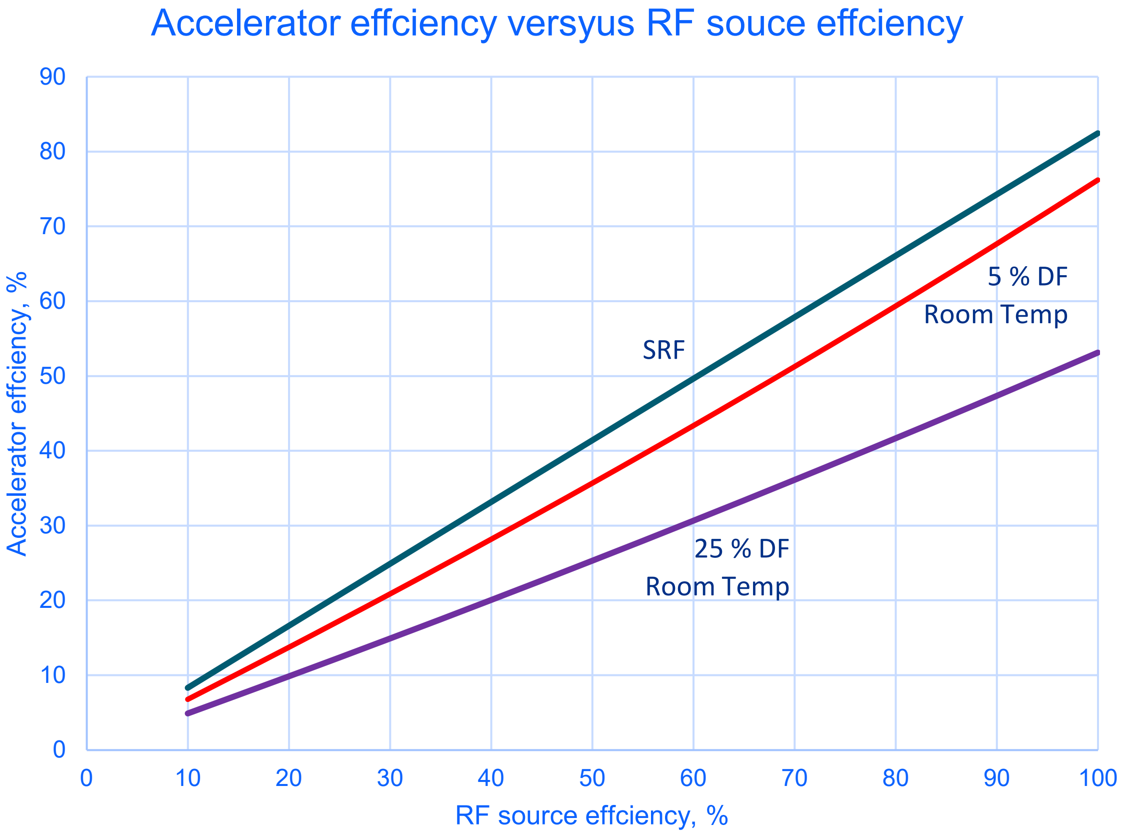


RF Design

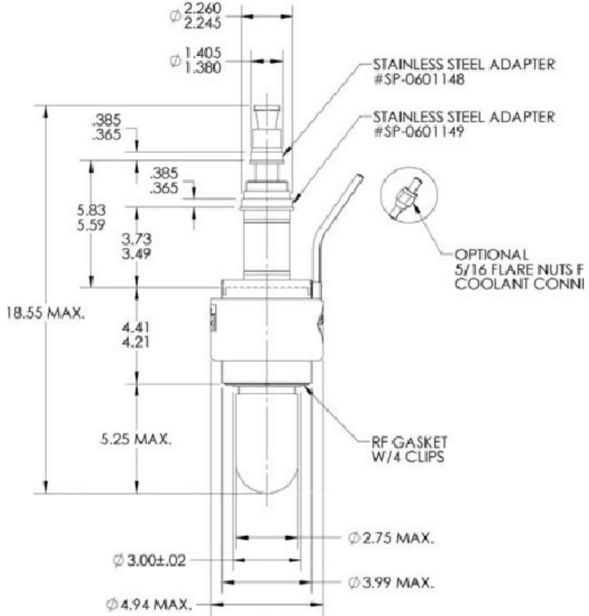


"gun" cell
Ø 140 mm
70 mm
Ø 170 mm
+0.63
+1.32
+1.39
+1.38
+1.36
+1.42
7.5 MeV
Energy, MeV vs. z, mm
0.63
1.08
1.95
2.48
3.34
3.88
4.72
5.25
6.08
6.61
7.50
10
5
0
0
250
500
750
1000
1250

Efficiency – the key to economical applications



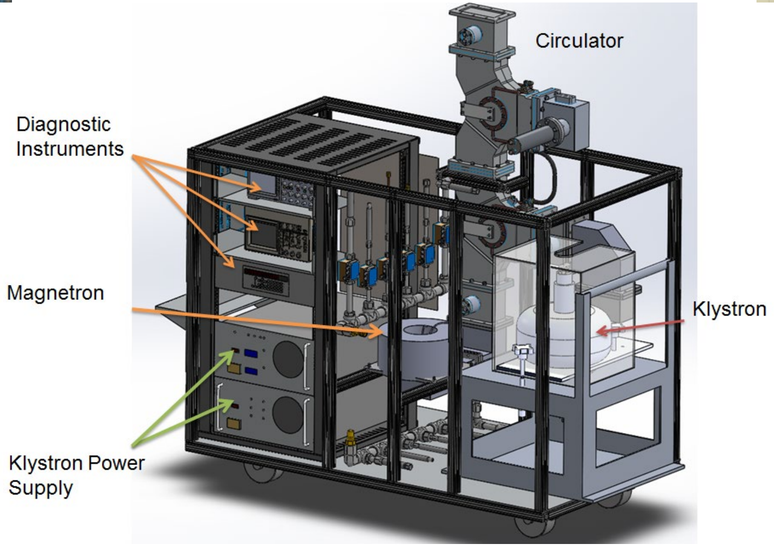
Magnetron Power for Accelerators

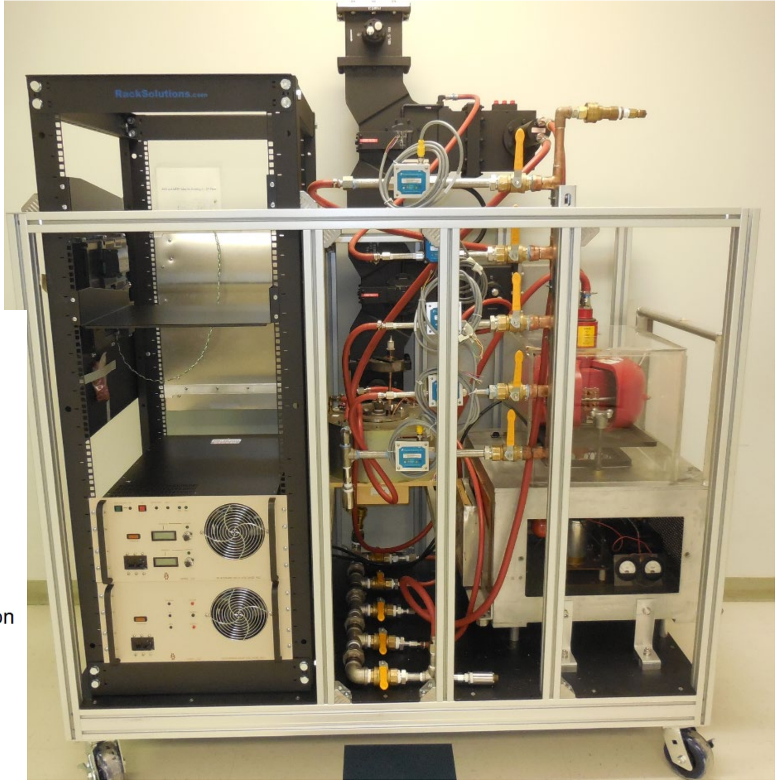


PERFORMANCE CHARACTERISTICS

Frequency	896, 911, 915, 922, 929 MHz
Power Output	100 kW
Anode Voltage	21 kV
Anode Current	6.5 A
Efficiency	86 %

Phase & Amplitude Control for Magnetron Driven Accelerators





Magnetron Performance Improvement Program

The program:

1. Use a modern 3D simulation code to understand in detail the beam dynamics of a magnetron.
2. Benchmark the code. This improved and benchmarked code will strengthen the RF industry allowing better designs of the magnetron for different applications – scientific, industrial, civil, and military.
3. Finally, it would be possible to optimize the magnetron design to improve its longevity and efficiency and optimize various operation regimes. Different options could be explored, like 2D harmonic cavities, different types of cathodes including the newly developed Nanocomposite Scandate Tungsten cathodes [12].
4. The goal would be to achieve an efficiency of more than 85% with tube lifetime of ~50,000-80,000 hours.

Thank you

Work supported by the Fermi National Accelerator Laboratory, managed and operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy.