Thermal link design for conduction cooling of SRF cavities using cryocoolers

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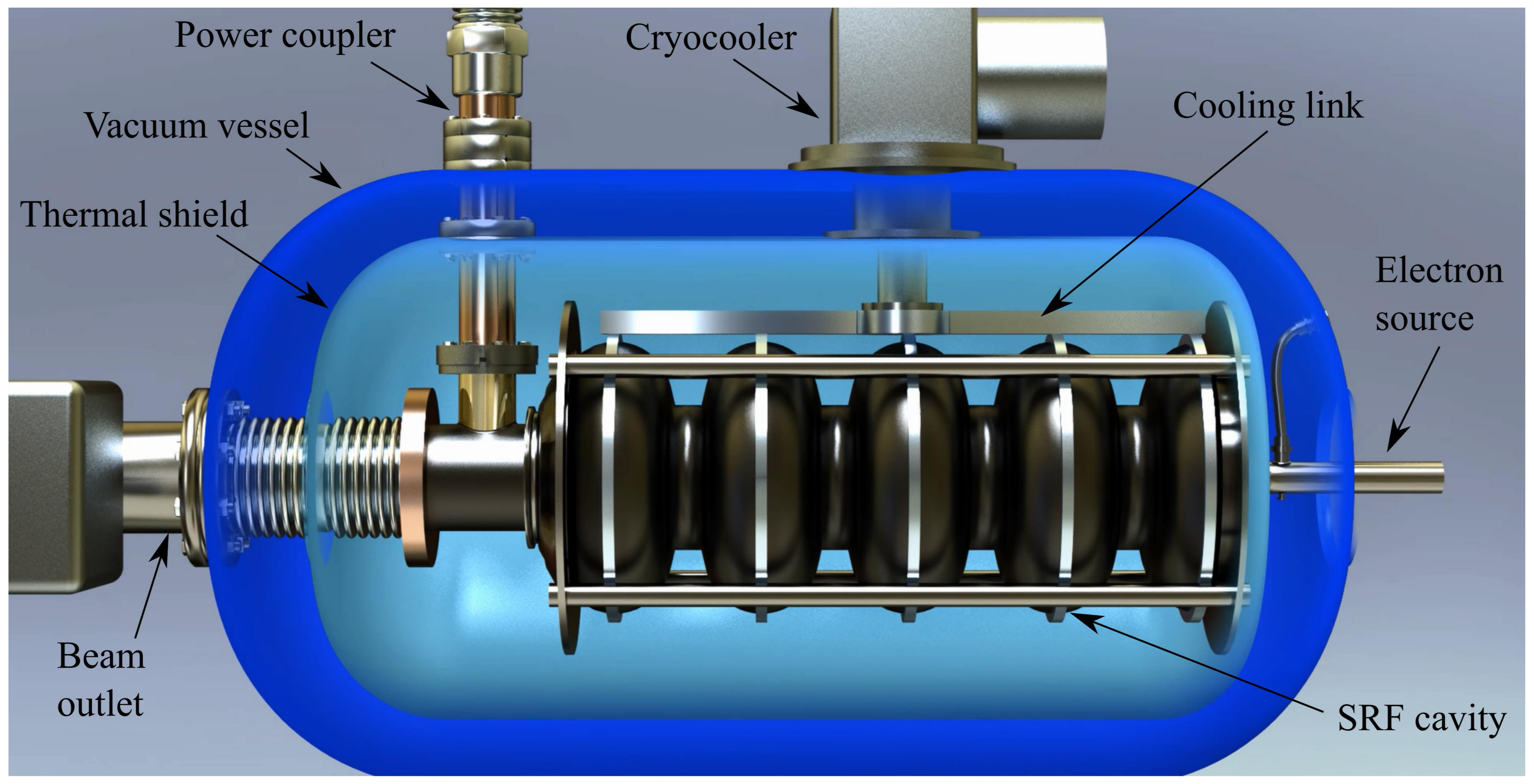
The opportunity

A completely cryogen-free superconducting radio frequency (SRF) accelerator can be developed by conductively cooling Nb_3Sn coated niobium cavities using regenerative cryocoolers. The accelerator can serve as a compact, mobile source of high average power electron beams for a number of industrial applications [1].



Rendering of a cryogen-free SRF electron beam accelerator based on conduction cooling by a two-stage 4 K cryocooler. All cryogenic components are enclosed in a vacuum vessel. Cryocooler Stage I cools the thermal shield to ≈50 K while Stage II maintains the SRF cavity at ≈4 K.

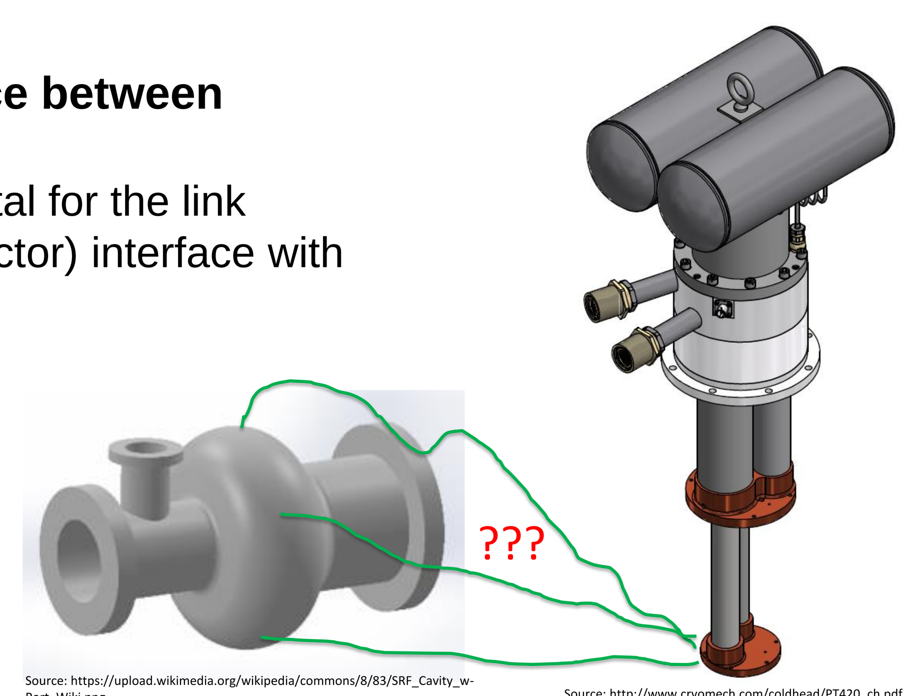
Challenge: design of link to achieve good thermal contact between cavity and cryocooler

Minimize the temperature difference between cavity and cryocooler

- choose high thermal conductivity metal for the link
- design link-cavity (metal-superconductor) interface with low thermal contact resistance

Devise a practical method of attaching thermal link to the cavity

- anchor the link near the cell equator (elliptical surface) where most RF heat is dissipated



Design challenge: connecting the cavity and cryocooler with a high thermal conductance link

Present work

We have designed a thermal link for cooling SRF cavities with the following:

- 4.5-cell 650 MHz and 9.cell 1.3 GHz (each nearly a meter long)
- Nb_3Sn coated RF surface
- beam energy of 10 MeV (average accelerating gradient of 10 MV/m).

The selected cryocooler is Cryomech PT420 (capacity 2 W @ 4.2 K)

The thermal link is made of high purity (5N) aluminum

Method of determining the required link thermal conductance

Step 1: Determine required number of cryocoolers

Cavity parameters:

Parameter	650 MHz	1.3 GHz
G [Ω]	265	270
R/Q [Ω], per cell	150	115
L_{acc} [m], per cell	0.231	0.115
R_{res} [nΩ] for Nb_3Sn	10	
$R_{BCS}(T)$ for Nb_3Sn	Calculated using SRIMP [2]	
Estimated dissipation at 5 K [W], per cell (total)	**1.72 (7.8)**	**0.86 (7.8)**

Cryocooler capacity: $Q_c[W] = 0.24T_c^2 - 0.56T_c + 0.12$ (2.4 < T_c [K] < 5.8)

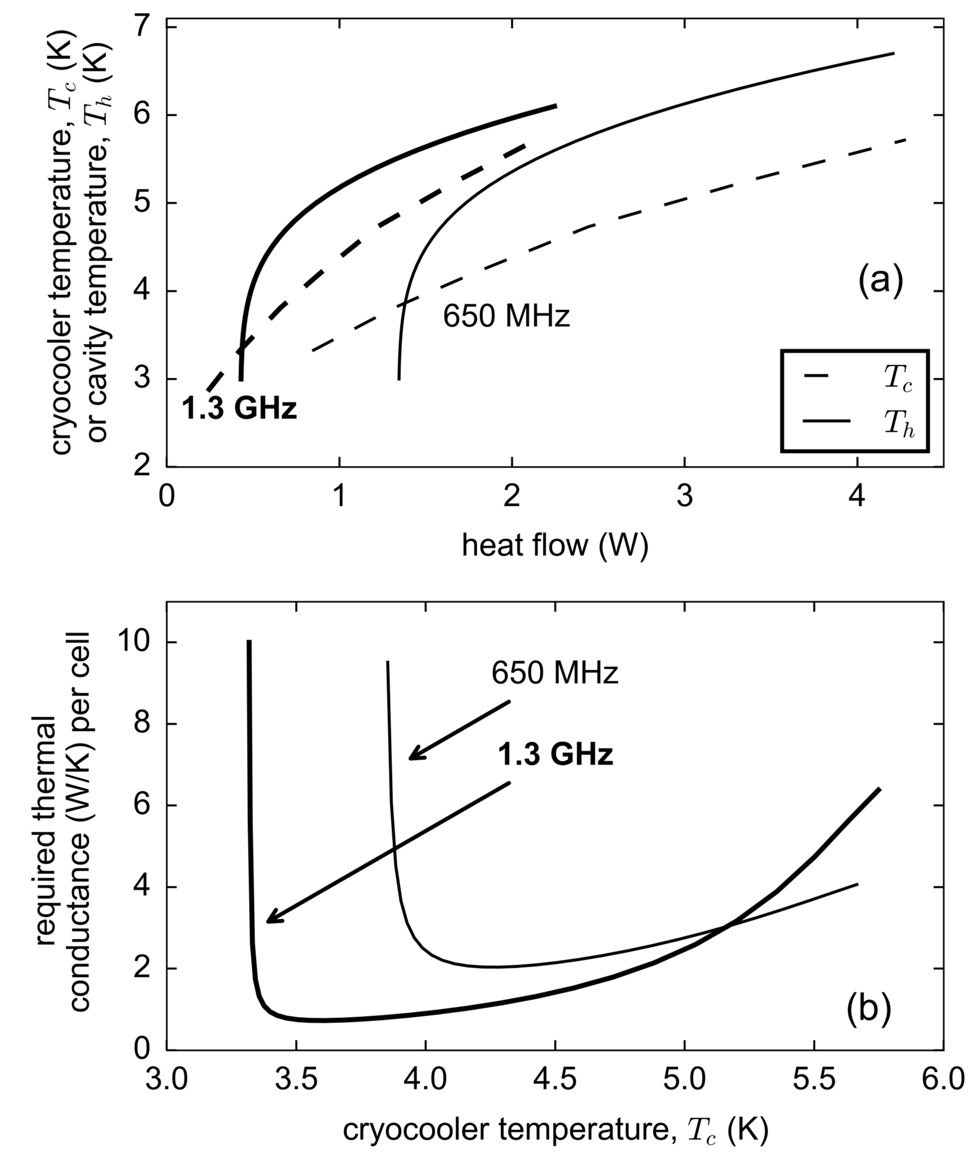
- need **four cryocoolers** for the multi-cell cavities

Step 2: Graphically solve for cavity and cryocooler temperature, considering steady state heat flow balance

$$\frac{(E_{acc}L_{acc})^2 R_s(T_h)}{(R/Q)G} = K_{link}(T_h,T_c)*(T_h-T_c) = Q_c(T_c)$$

Cavity dissipation, per cell — Heat flow through thermal link — Cryocooler capacity, per cell

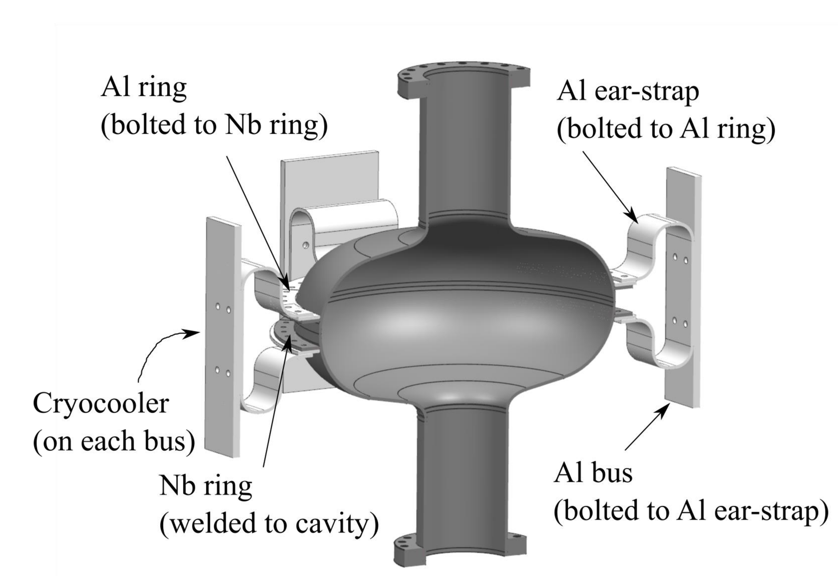
Step 3: Evaluate the required thermal conductance $K_{req} = \frac{Q_c}{T_h - T_c}$



(a) Comparison of cavity and cryocooler operating temperatures for a given heat flow and (b) Required thermal conductance between the cavity and the cryocooler for stable operation at a given T_c.

Thermal link: design and performance

Mechanical design: High purity aluminum strips bolted to niobium rings welded around cavity equator

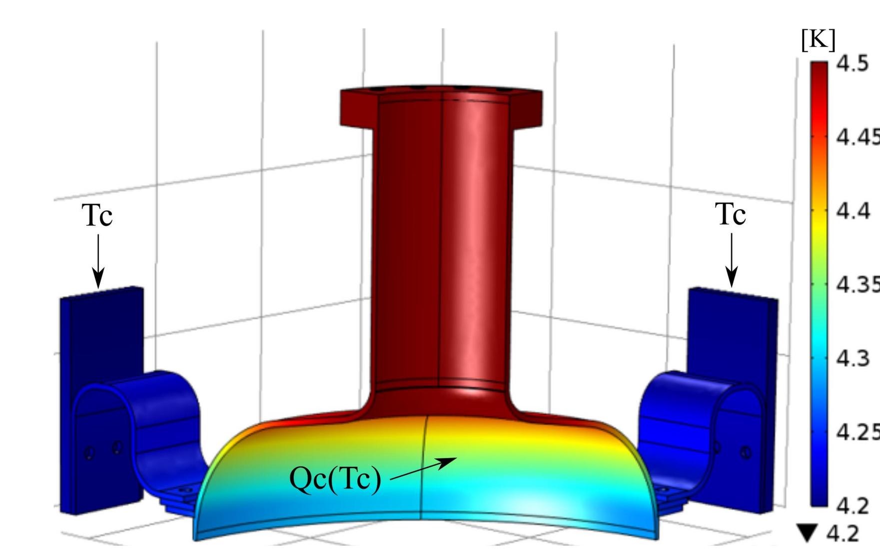


Going from the cavity to the cryocooler, the link has:

- Nb rings welded to the cavity,
- Al rings bolted to the Nb rings [3],
- Al ear-straps bolted to the Al rings, and Al bus-bars bolted to the ear-straps.

The thermal link is illustrated for a single cell cavity.

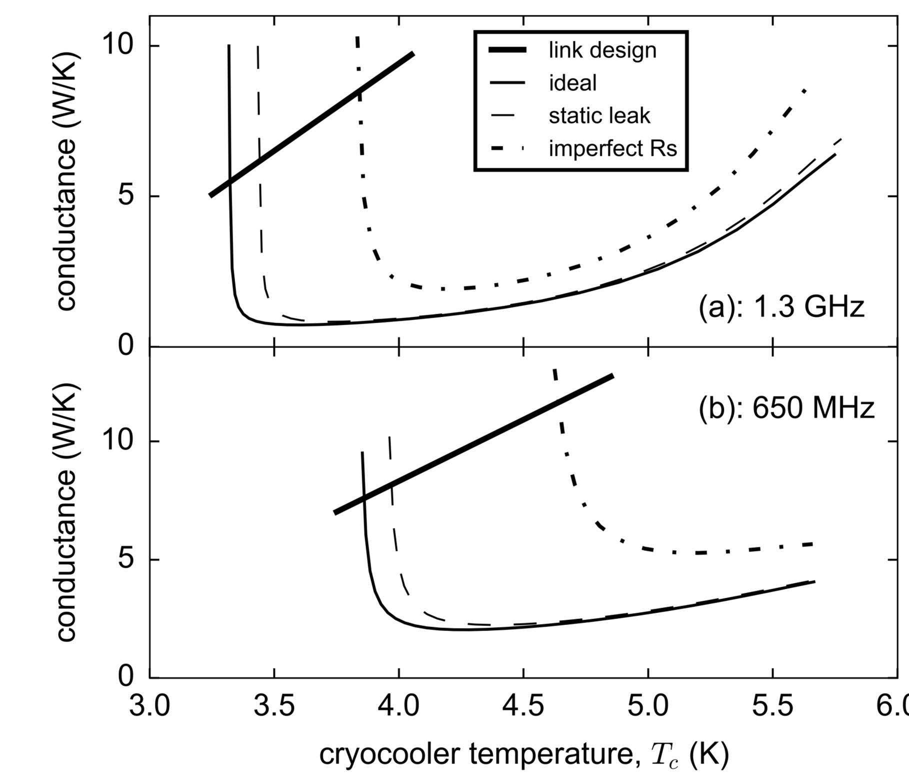
Evaluation of link thermal conductance *via* FEM simulations



Simulation geometry [4] and steady state temperature distribution of the cavity and thermal link. Boundary conditions:

- constant T_c on the Al bus,
- heat flux $Q_c(T_c)$ on the RF surface.

Sample result is shown for a 650 MHz cell and T_c = 4.2 K.



Calculated link thermal conductance (bold solid line) compared with the required conductance for the cases of:

- ideal coating with no static load,
- static load- 0.1 W for 650 MHz; 0.05 W for 1.3 GHz,
- and imperfect coating with 50% higher surface resistance.

Intersection of link conductance with the required conductance curve denotes the cryocooler operating temperature.

Takeaway

A thermal link design and analysis that will enable cryogen-free cryocooler-cooled SRF compact accelerators for industrial applications of electron beams.

References

[1] R. Kephart et al., *Proc. SRF 2015*, 1467-1773, 2015.
[2] SRIMP code, available at https://www.classe.cornell.edu/~liepe/webpage/researchsrimp.html.
[3] R. C. Dhuley et al., *Cryogenics* 93, 86-93, 2018.
[4] R. Kostin et al., *Proc. IPAC2018*, 2697-2699, 2018.

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