Field-Emission Electron Source Embedded in a Field-Enhanced Conduction-Cooled Superconducting RF Cavity

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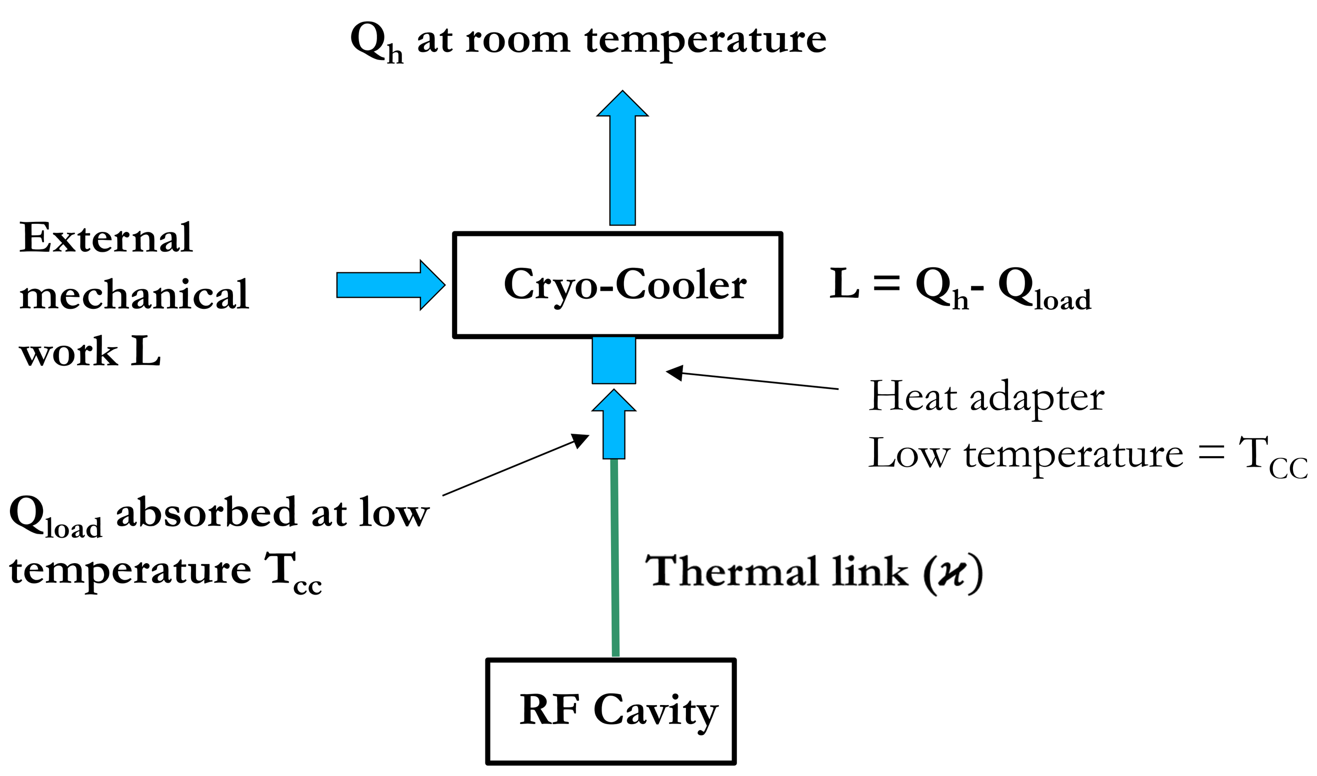
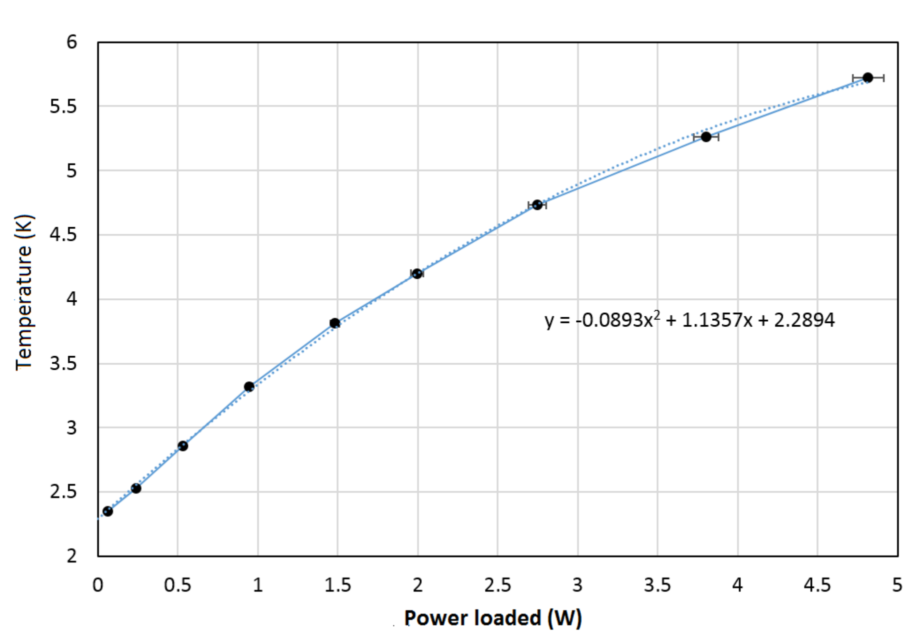
ABSTRACT

We present simulations and experimental progress toward the development of a high-current electron source with the potential to deliver high charge electron bunches at GHz-level repetition rates. To achieve these goals electrons are generated through field-emission and the cathode is immersed in a conduction-cooled superconducting 650-MHz RF cavity. The field-emitters consist of microscopic silicon pyramids and have a typical enhancement factor of about 500. To trigger field-emission, the peak field inside the RF cavity of about 6 MV/m is further enhanced by placing the field-emitters on the top of a superconducting Nb rod inserted in the RF cavity. So far, we cannot control the duration of the electron bunches which is of the order of RF period. Also, the present cryocooler power of about 2~W limits the beam current to microamp level.

RF Cavity Conduction Cooling



$$Q_{load} = \varkappa \cdot (T_{cav} - T_{CC})$$



- P_{load} includes the RF cavity dissipated power (P_d) losses due to heat dissipation through equipment components ($P_{loss} \approx 0.4$ W).
- $T_{cav} \approx T_{CC} + 0.5$
- **At $T_{CC} = 4.2\ K \rightarrow P_{load} = 2.0$ W and $T_{cav} \approx 4.7\ K$**

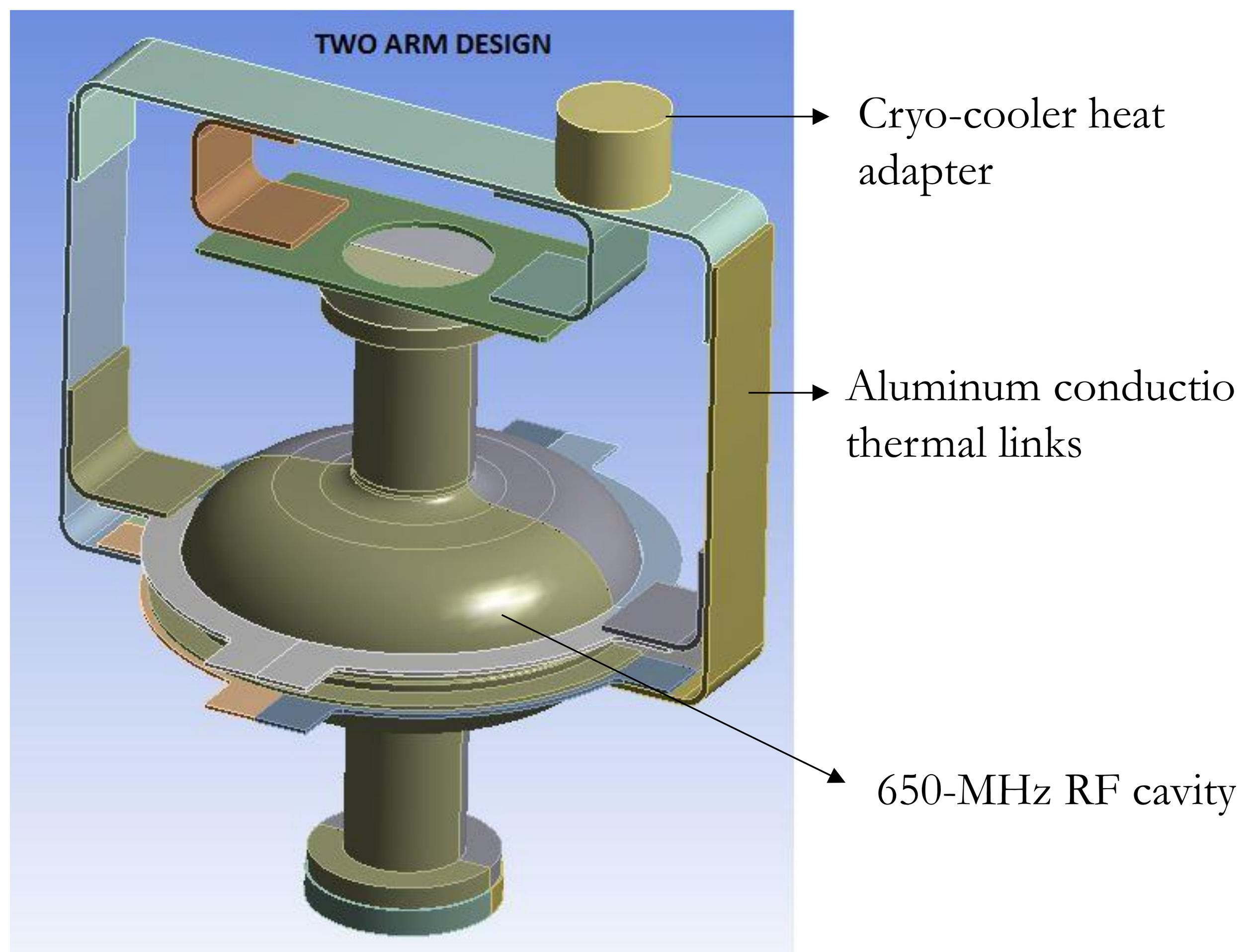
- **RF cavity made of superconducting niobium.**
- Resonance frequency: 650 MHz
- The two-arm conduction thermal link made of aluminum.

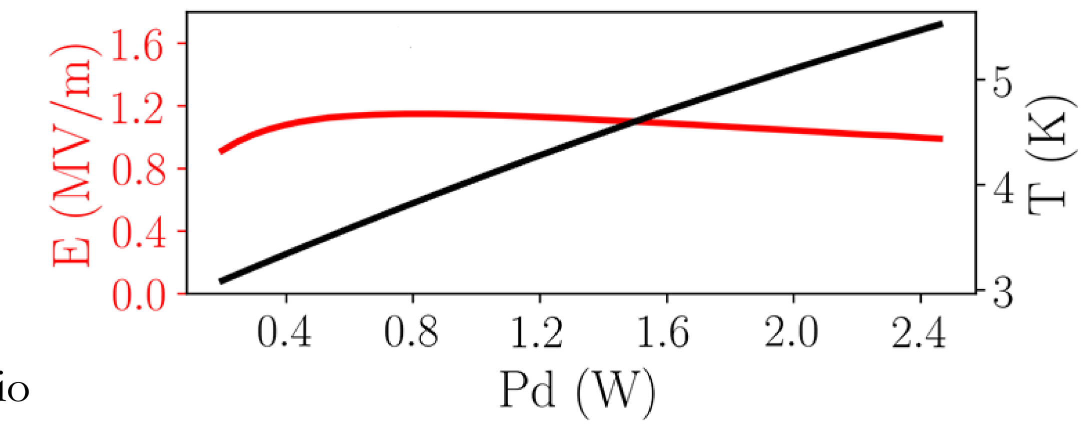
To evaluate fields inside the RF cavity

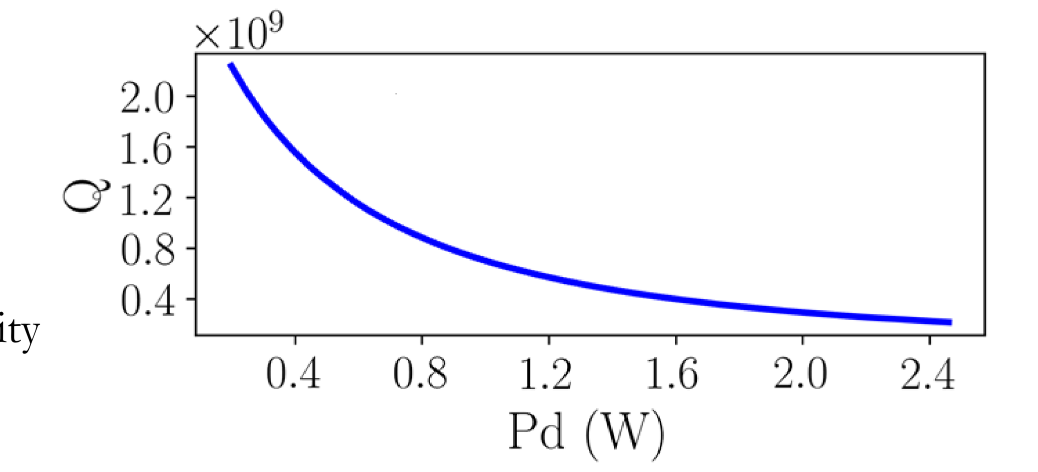
$$P_d = \frac{(V_{acc})^2}{(R/Q)Q} = \frac{(V_{acc})^2 \cdot R_s}{G}$$

$$V_{acc} = E_{av} \cdot L_{cav}$$

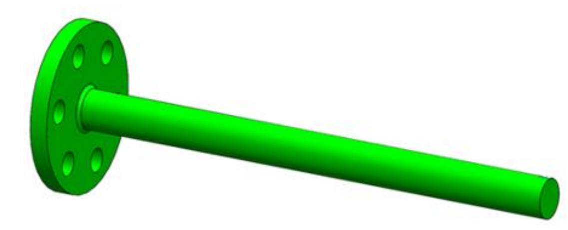
- $L_{cav} = 0.56$ m
- R/Q and G depend on cavity geometry
- Surface resistance R_s depend on cavity temperature $T_{cav.}$
- Surface resistance determined by solving the BCS equation.
- Dissipated power P_d as well as reflected and transmitted powers can be measured.
- RF cavity quality factor can be measured from P_d decay time.







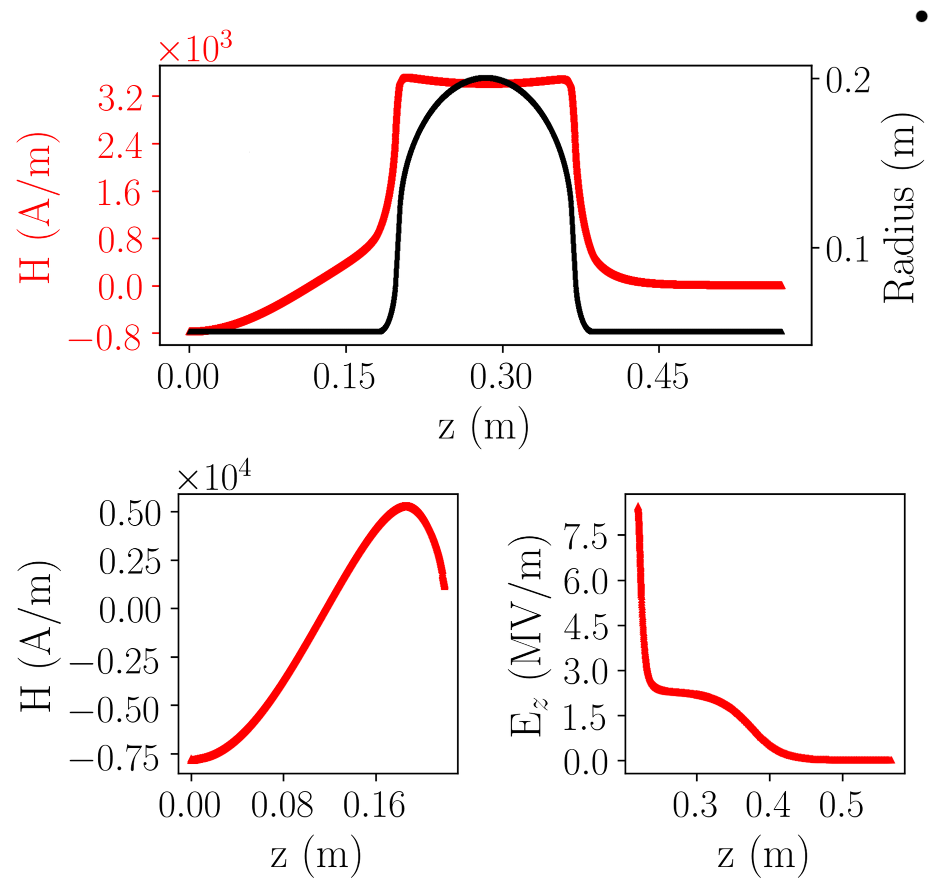
Niobium superconducting rod attached to flange inserted in the RF cavity



- Support for cathode (array of field-emitters).
- Places the cathode in a high field region.
- Enhances fields at the tip (typically by a factor of ≈ 3)

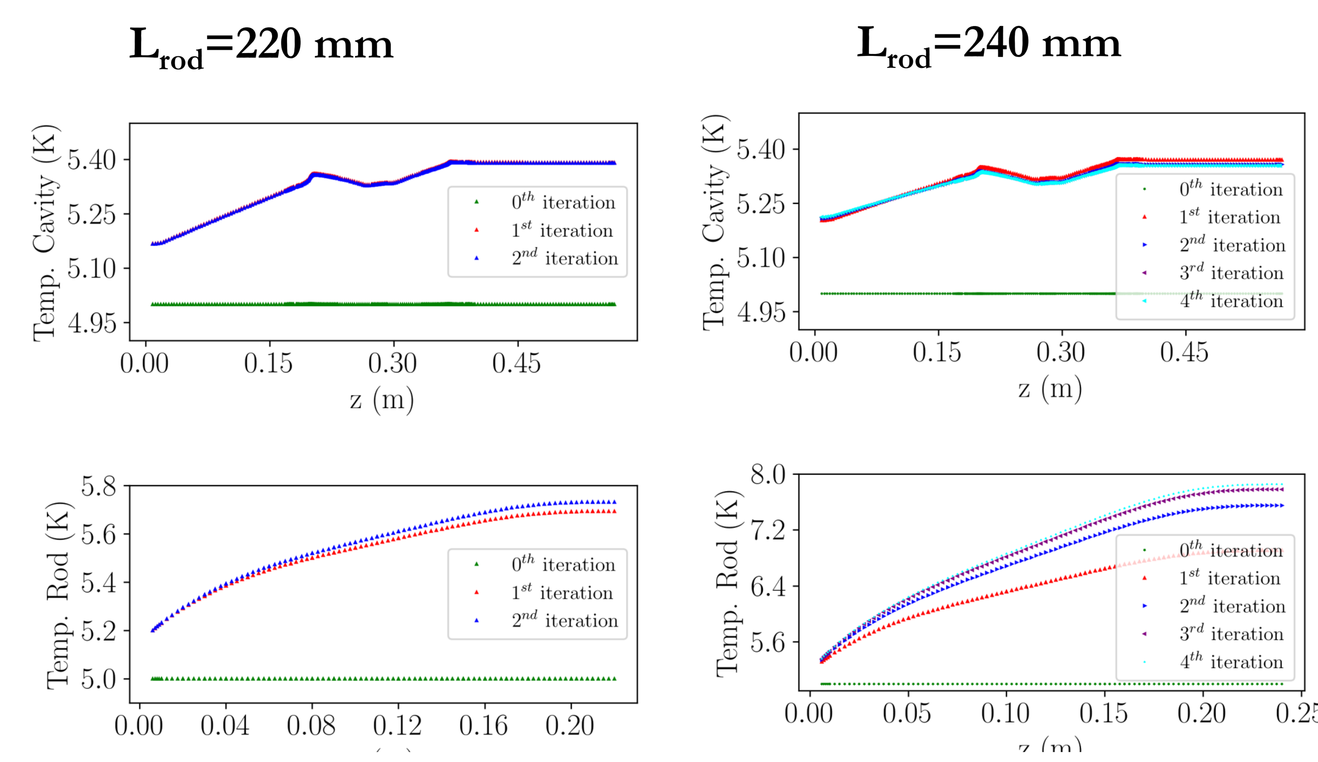
EM fields when Nb rod inserted

Superfish with corrections for surface resistance R_s calculation



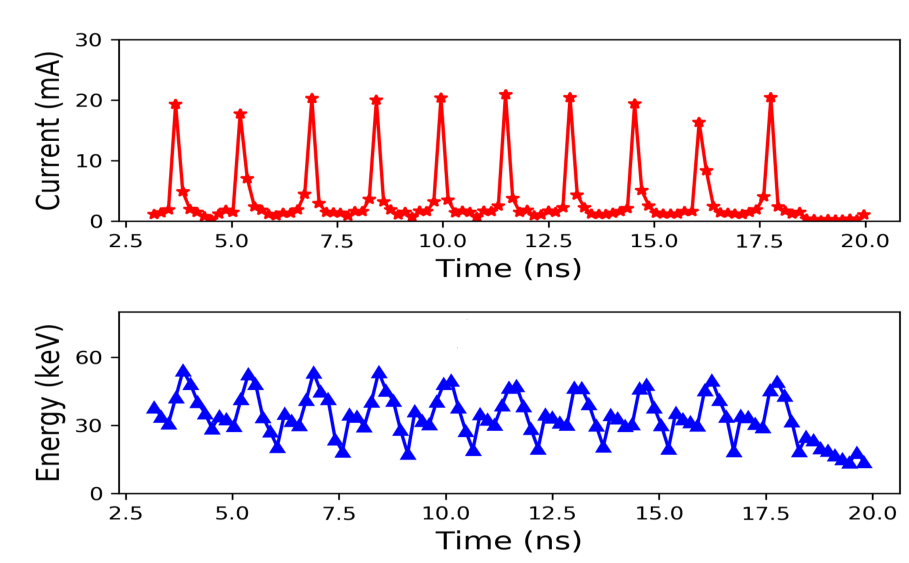
Thermal analysis

- ANSYS thermal simulation code.
- Assume temperature at cryo-cooler adapter = 4.2 K and power load 2 W
- Dissipated power distribution: $dP = \frac{R_s}{2}|H|^2 dS$ evaluated with Superfish
- Iterative process: dissipated power at step n depends on temperature at the previous step n-1.
- A few iterations are usually enough for convergence.



Field-emission cathode

- Field-emission array deposited on rod tip.
- Silicon pyramids with height ≈1 μm separated by ≈2 μm
- Estimated enhancement parameter: $\beta = 500$
- Cathode radius: 2mm
- Faraday cup at opposite end of the RF cavity
- WARP simulations: current ≈ 3 mA; KE ≈ 30 keV @ P = 2 W



Conclusions:

- Construction of a superconducting field-emission electron source cooled through thermal conduction is underway at Fermilab.
- A 650 MHZ niobium RF cavity is cooled by conduction to operate in superconducting regime.
- The cryo-cooler (Cryomech PT420) typically operates at power load of 2 W and temperature 4.2 K. Most of the power load (1.6 W) is used to cool the RF cavity.
- The input power is generated by a solid state amplifier with central frequency of 650 MHz and bandwidth of 10 MHz. The input power is limited to 5W. So far, this is the main constrain for the beam current which has to be at microamp level.
- A superconducting rod inserted in the RF cavity is used as a cathode holder.
- The cathode consists of a field emission array with enhancement factor of about 500.
- We anticipate that beam current is at microamp level, kinetic energy about 30 keV and repetition rate 650 MHz.
- Main limitations: low RF power supply (5 W) and relatively low cryo-cooler power (2W) @ T = 4.2 K

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