COMSOL Multiphysics Application to Open Up a New Way of Cooling Superconducting RF Cavities

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Introduction

Q: What is SRF and why we need it?

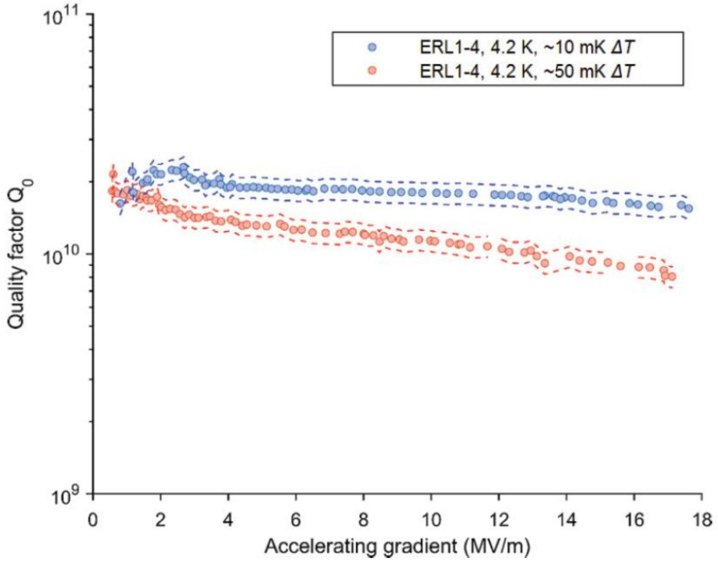
A: SRF stands for Superconducting RF. Conventional RF particle accelerators employ normal conducting copper cavities which are excited by RF fields to accelerate charged particles. They work in pulse mode because they will be overheated and melted in CW mode. Superconducting cavities made from pure Niobium are cooled to cryogenic temperatures (2K) where they loose almost all Ohmic losses, from mili-Ohm level at room temperature down to nano-Ohm level. Quality factor increases up to hundreds of billions (10^{11}). With such low losses they can work in CW mode.

Q: Why not to use just SRF?

A: One kilo-Watt of power from the outlet is required to remove one Watt from 2K for a big cryo-plant, and even more for less efficient smaller ones. So SRF gives a possibility to operate RF particle accelerators in CW mode which is beneficial for some applications and found its niche mostly in national labs. The reason is one need to cool down SRF cavities by liquid helium which require a cryo-plant – not quite a user-friendly device.

Q: But how to use SRF for industry?

A: The world is always changing and looks like we are now ready to move to industrial application of SRF. Recent discoveries with Nb3Sn made it possible (see figure on the right). Nb3Sn has 20 times lower losses and can work at 4K. Luckily, there are several commercially available free of liquid helium cryo-coolers which can provide 2W cooling capacity at 4K and cool cavities conductively. The last problem is to connect them together.



Q vs Eacc (@4.2K) experimental plot for single cell Nb3SN cavity for Cornell ERL (1.3GHz). (Courtesy of S.Posen).

The first approach on conduction cooling

Fermilab

- **Approach:**
- Connect cryo-cooler to the cavity through high conductive links (pure aluminum 5N)
- Connection with cavity through bolt joint. Aluminum studs are welded to cavity.
- Contact thermal resistance is measured.
- **Question:**
- Will this be enough to cool the cavity?
- **Way to resolve:**
- Comsol Multiphysics simulations.

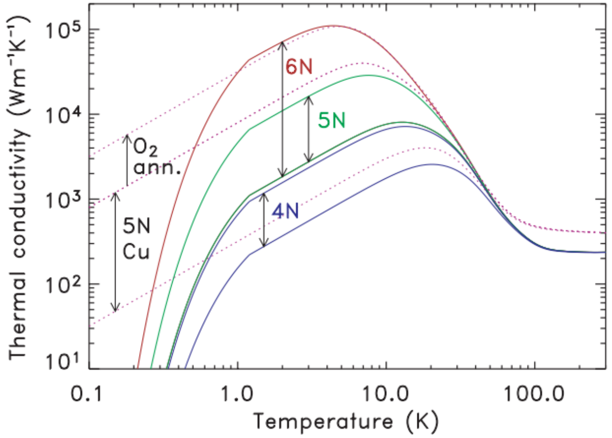


Fig.1. Thermal conductivity of Aluminum

[A.L. Woodcraft / Cryogenics 45 (2005) 626–636]

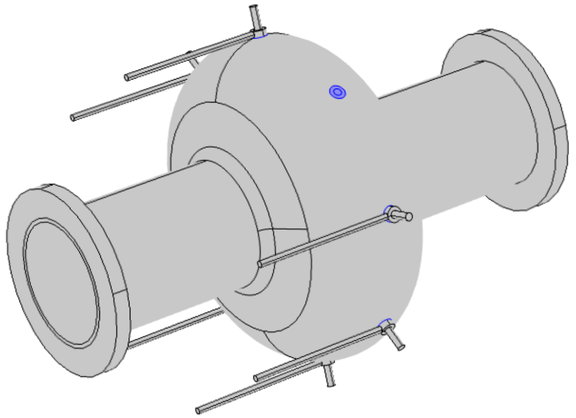
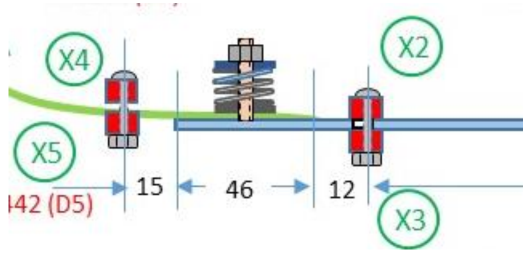


Fig. 2. Single cell cavity 3D model with cooling studs on the equator



Contact – 2 washers of 31 mm diam →7,5 cm2.

Spring load – 70 lb/inch (17.86 kg/m)

Fig. 3. AL and Nb strips connection. (Courtesy of O. Prokofiev).

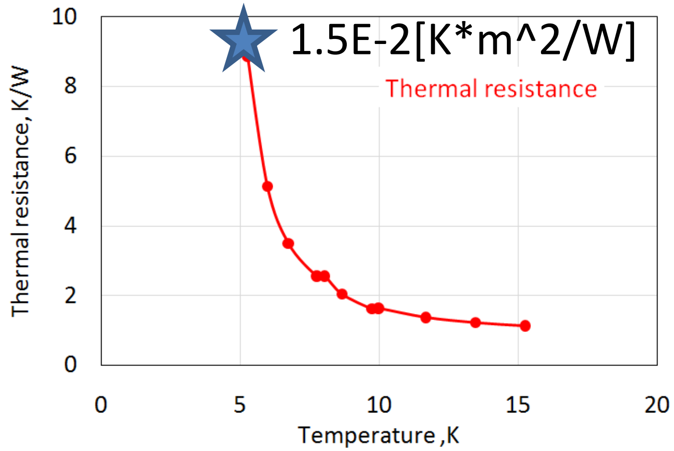


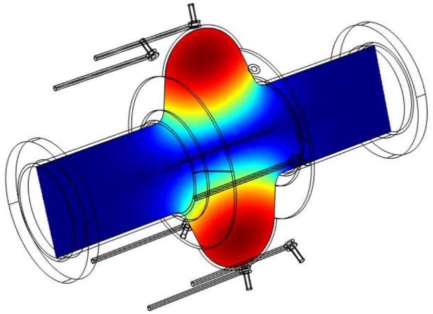
Fig. 4. Thermal contact resistance data from Fermilab experiment. (Courtesy of O. Prokofiev).

Simulation procedure

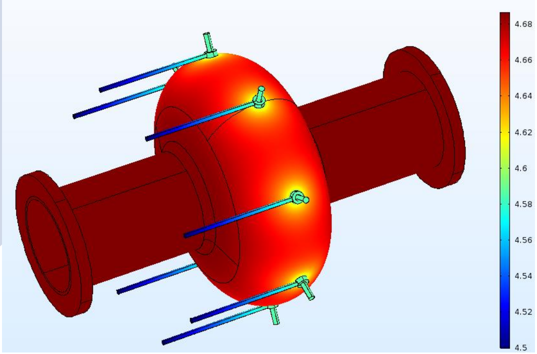
RF

Generate heat load map for thermal

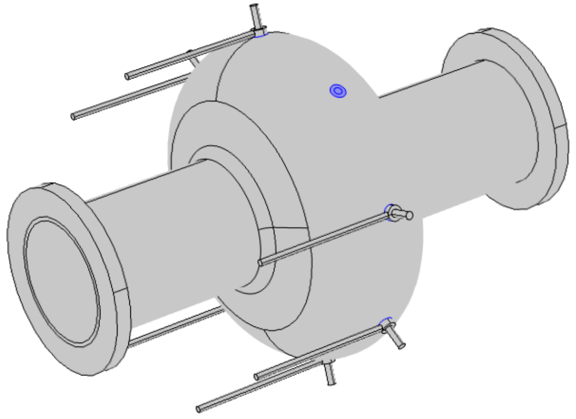
Thermal



$$P_d = \frac{1}{2} \cdot R_s \cdot \int (H_\tau)^2 \cdot dS$$



Eigenmode solver of Radio Frequency module



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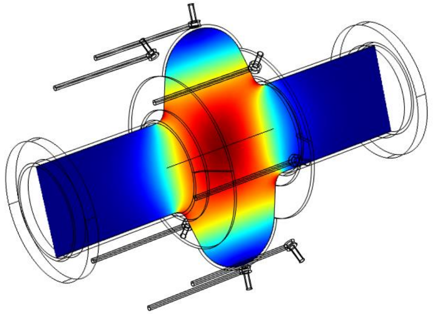


Fig.2. Electric field distribution in the cavity.

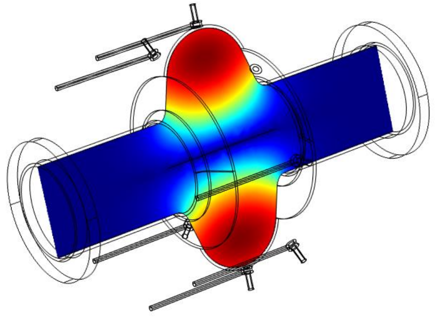


Fig.3. Magnetic field distribution in the cavity.

- Electromagnetic fields are found for a certain mode (TM010)

- The fields are scaled for the certain accelerating gradient

$$V_{acc} = \int E_z(0,0,z) \cdot \exp\left(ik \cdot z / \beta \right) \cdot dz$$

- RF losses map is transferred to the next thermal study.

$$P_d = 1/2 \cdot R_s \cdot \int (H_\tau)^2 \cdot dS$$

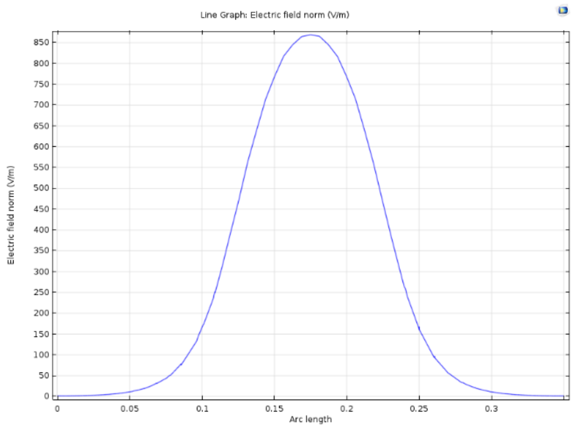


Fig.4. Electric field along the cavity axis

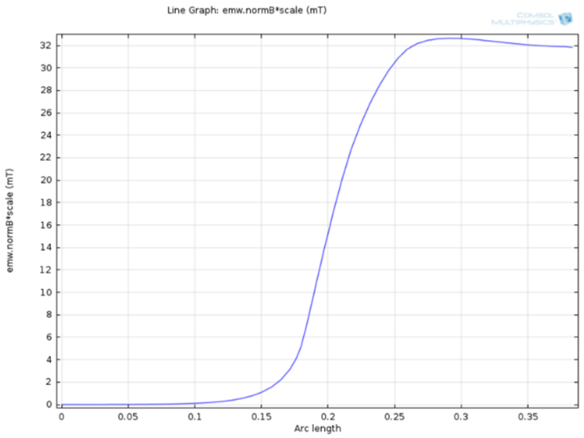
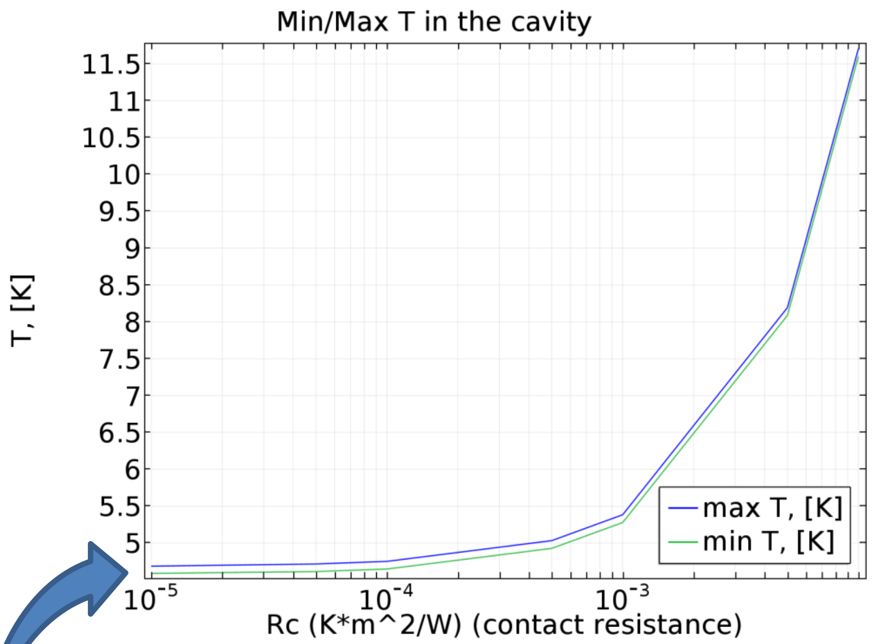
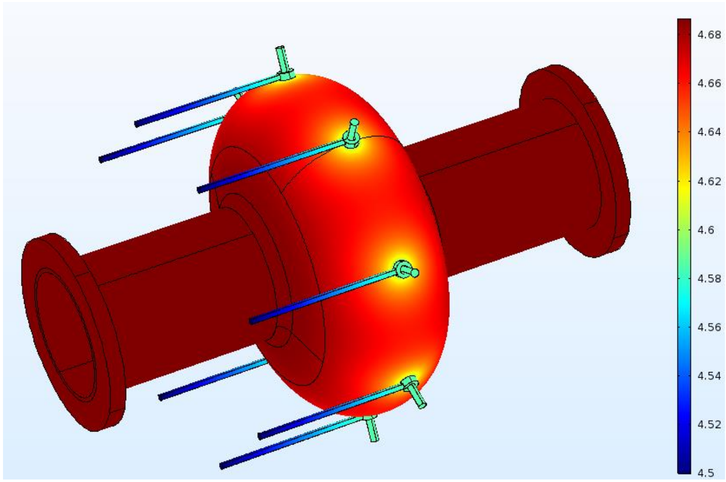


Fig.5. Magnetic field along the cavity axis

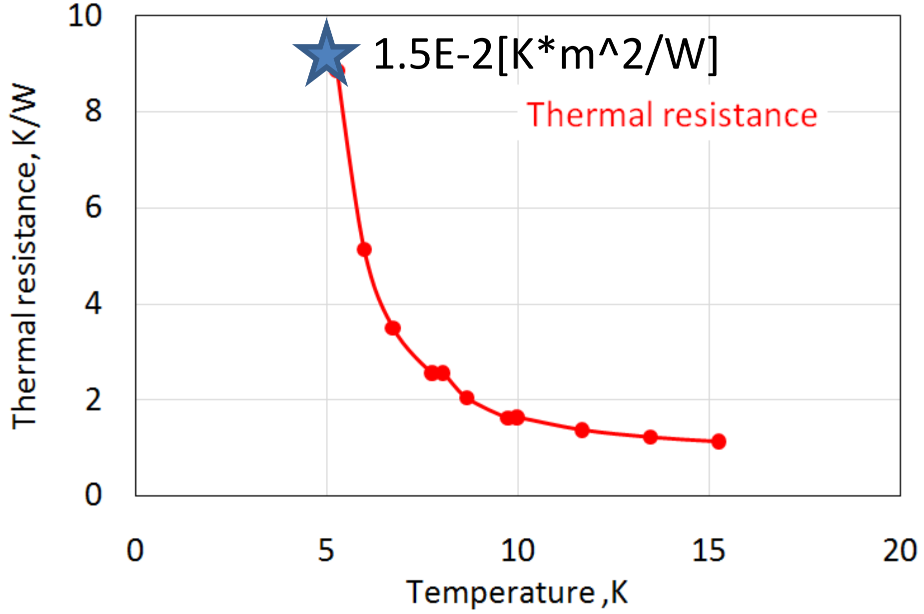
Thermal simulation of Heat Transfer Module



1.5E-2[W/m^2/K]



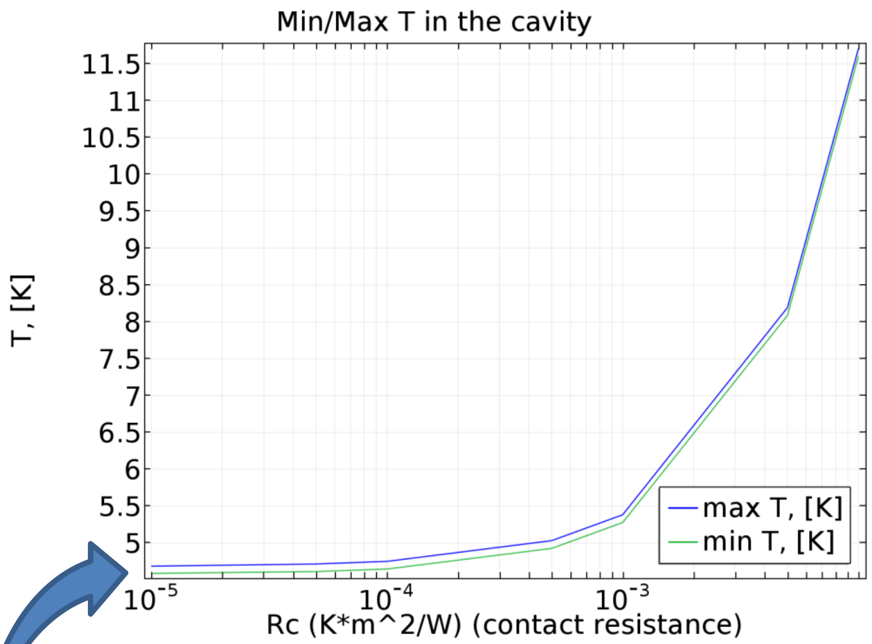
Temperature distribution in K.

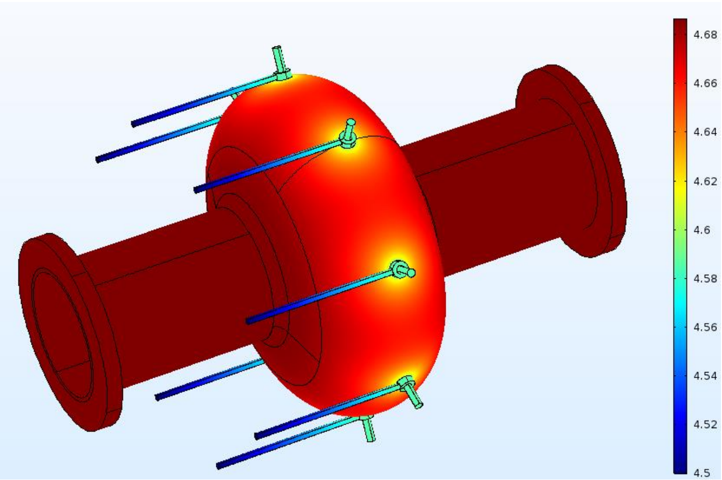


Thermal contact resistance data from Fermilab experiment. (Courtesy of O. Prokofiev).

- The maximum thermal contact resistance of 1.5E-2 [m^2*K/W] was reached limited by the holding force
- At least 1E-4 is required

Conclusions on the 1-st generation design



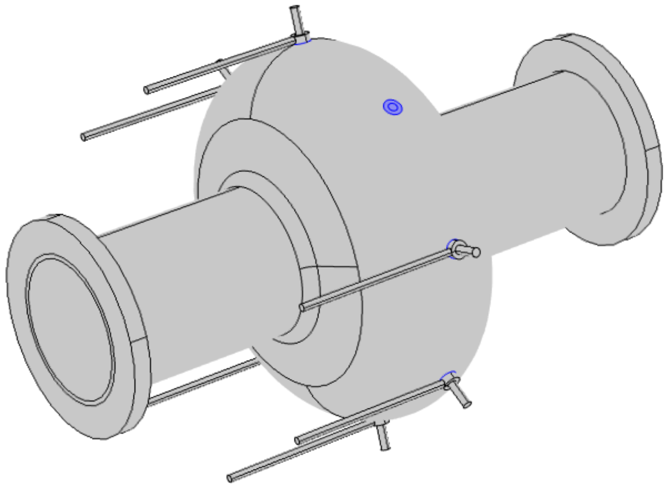


Temperature distribution in K.

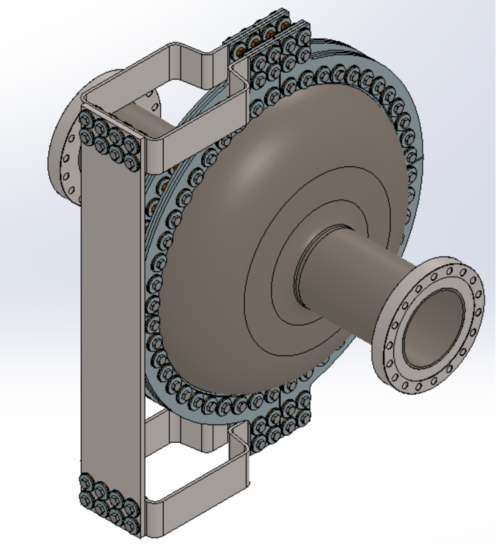
1.5E-2[W/m^2/K]

- Strong dependence of cavity temperature on contact resistance is observed. Contact resistance should be smaller than $Rc=10^{-4}$ [m^2*K/W] in order to get the temperature in the cavity below 4.8 [K] for the investigated geometry.
- Contact resistance, taken from experiment, of $Rc=10^{-2}$ [m^2*K/W] will lead cavity to quench.
- This contact resistance is the maximum achievable value for the first generation design limited by the applied force.
- A new conduction cooling design is required and was proposed.

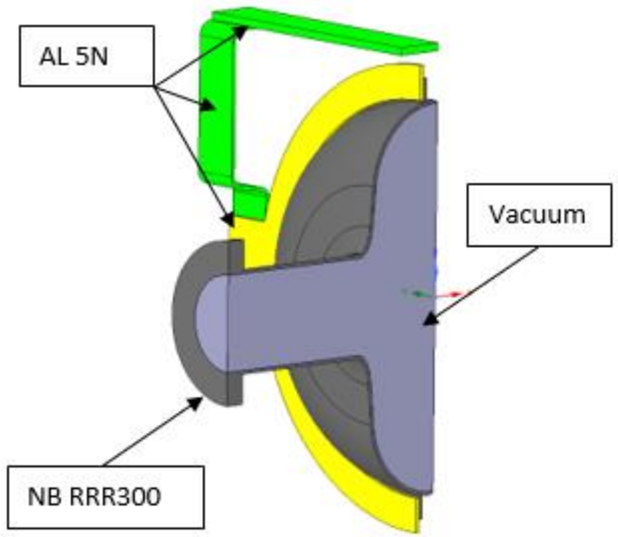
2-nd Generation of Conduction Cooling



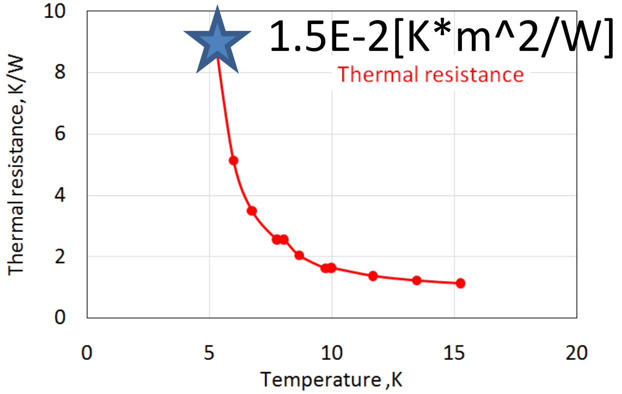
Single cell cavity 3D model with cooling studs on the equator



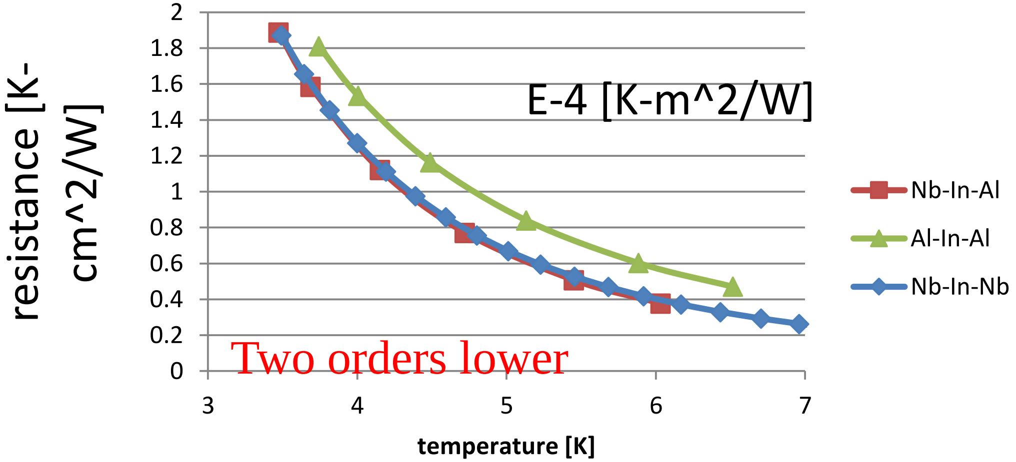
Mechanical model of conduction cooled cavity.



Simplified FEA model of conduction cooled cavity.



Thermal contact resistance data from Fermilab experiment. (Courtesy of O. Prokofiev).



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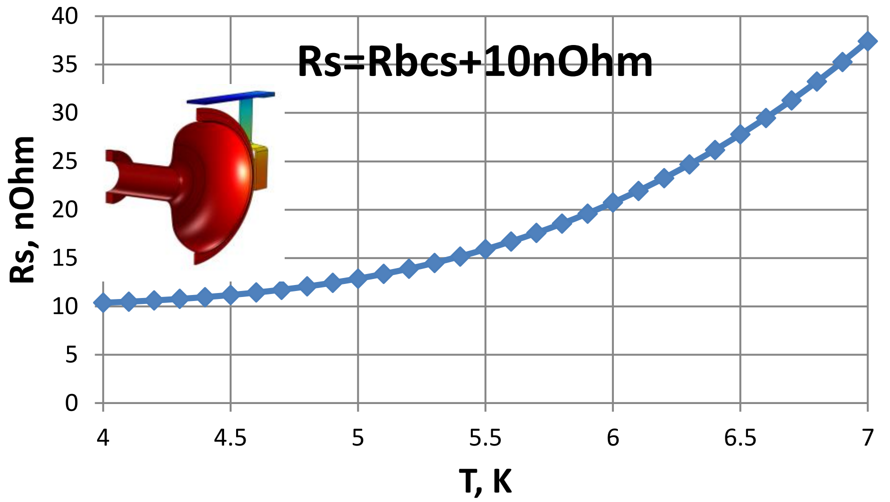
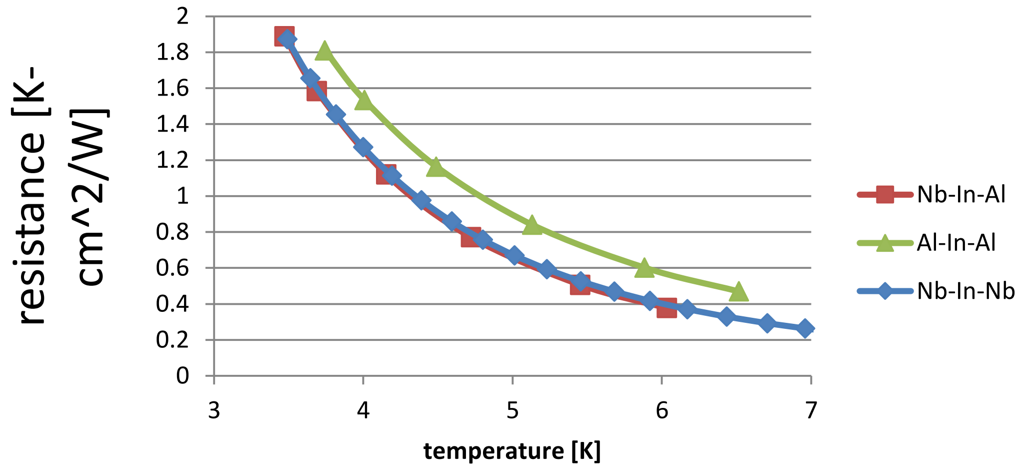
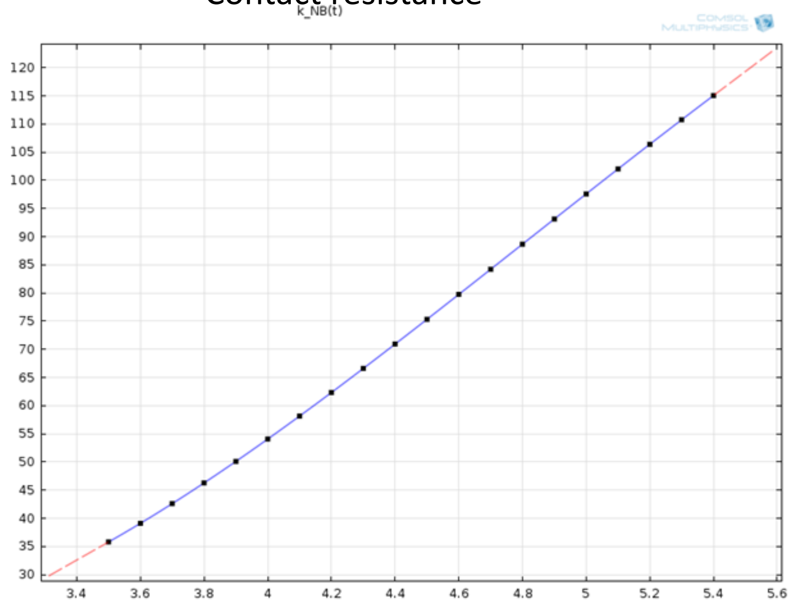
Material properties



Nb_3Sn BCS resistance plus 10nOhm residual resistance.



Contact resistance



Nb RRR300 thermal conductivity as a function of T

Thermal conductivity of Aluminum strips k=3[kW/m/K]

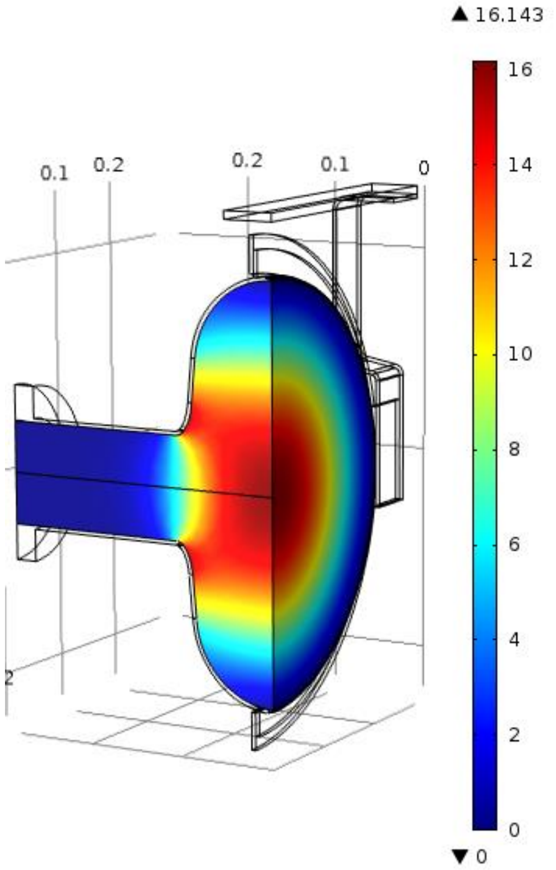
Temperature dependent material properties were used:

1. Electrical surface resistance of Nb3Sn

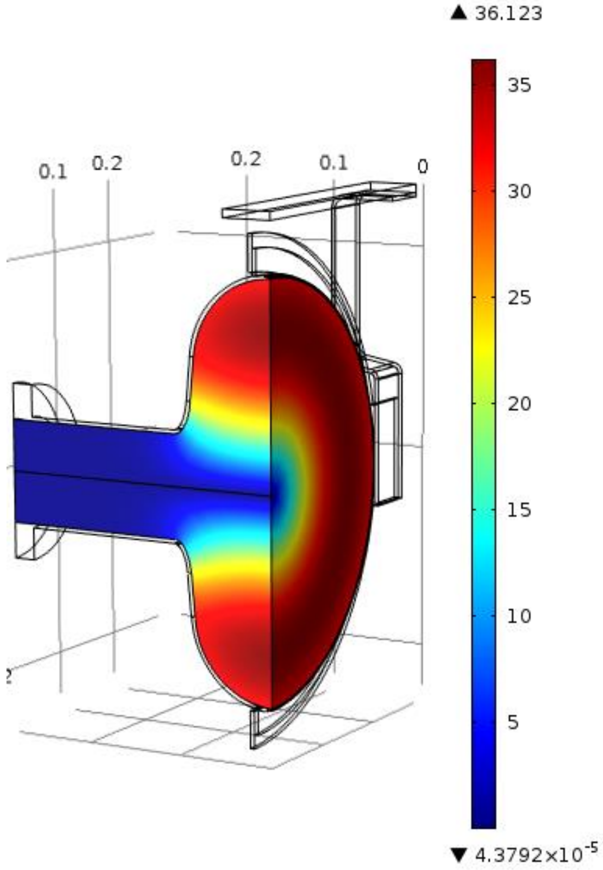
2.Temperature resistance between Aluminum to Aluminum, Aluminum to Niobium and Niobium to Niobium (welding seam).

3. Thermal conductivity of Niobium.

Eigenmode solver of Radio Frequency module



E field



B field

$$Q_0 = \frac{\omega \cdot W_s}{P_d}$$

$$R/Q = \frac{(E_{acc} \cdot L)^2}{P_d \cdot Q_0}$$

Table 1. 650MHz beta=0.9 single cell cavity parameters.

Rs, [nΩ]	10
Eacc, MV/m	10
Pd, [W]	1.05
W, [J]	6.6
F0, [MHz]	647.1
Q0	2.56E10
G, [Ω]	256.1
Epk/Eacc, [(MV/m)]/(MV/m)]	1.61
Bpk/Eacc, [mT/(MV/m)]	3.61
R/Q, [Ω]	155.4
L_cell, [m]	0.2056
Aperture, mm	100.1

$$V_{acc} = \int E_z(0,0,z) \cdot \exp\left(ik \cdot z/\beta\right) \cdot dz \qquad P_d = 1/2 \cdot R_s \cdot \int (H_\tau)^2 \cdot dS \qquad W_s = \frac{\oint \varepsilon_0 E^2 dV}{4} + \frac{\oint \mu_0 H^2 dV}{4}$$

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Thermal simulation of Heat Transfer Module

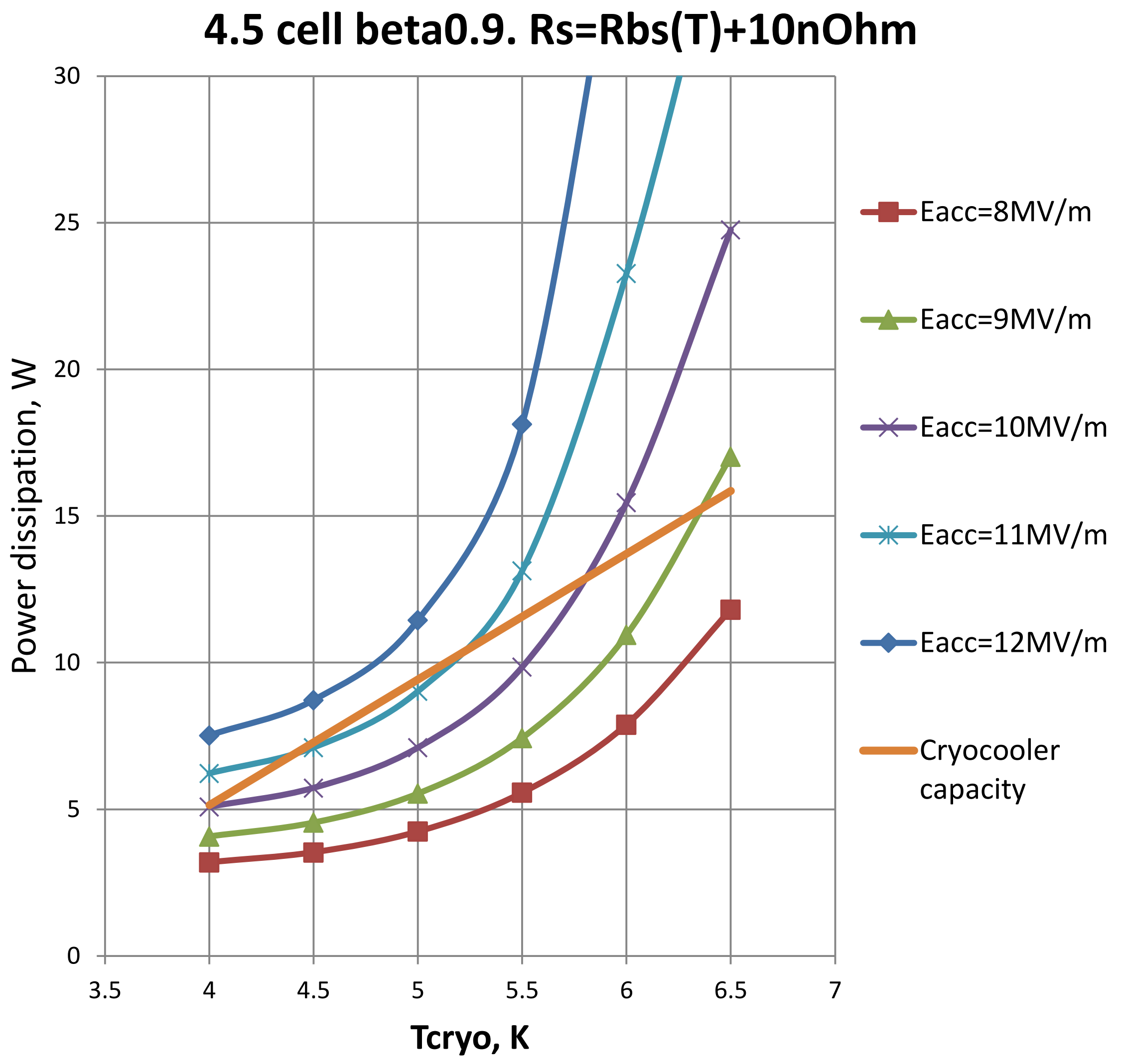


Fig.1. Dissipated power in 4.5cell beta 0.9 cavity and cryocooler capacity as a function of temperature.

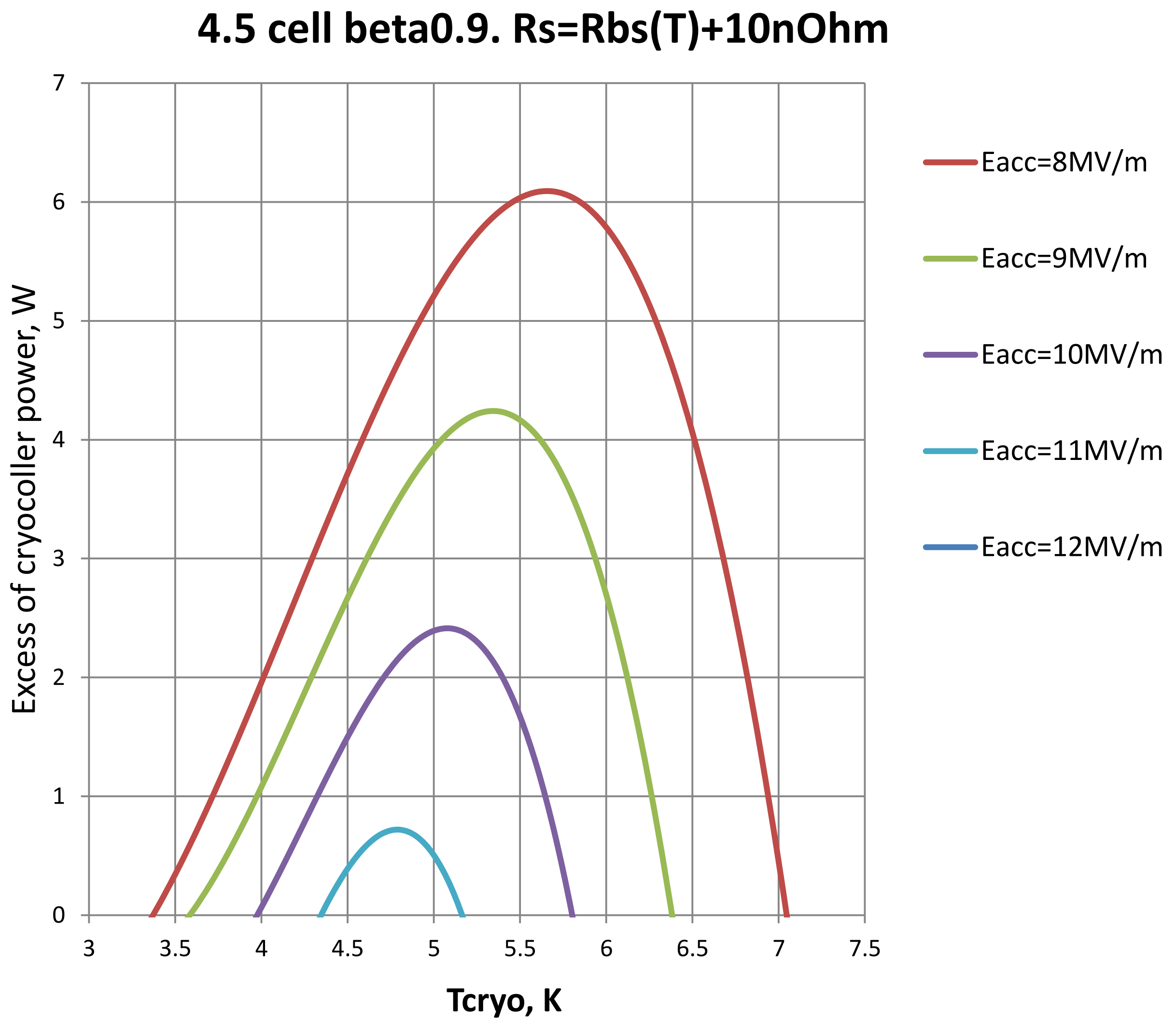
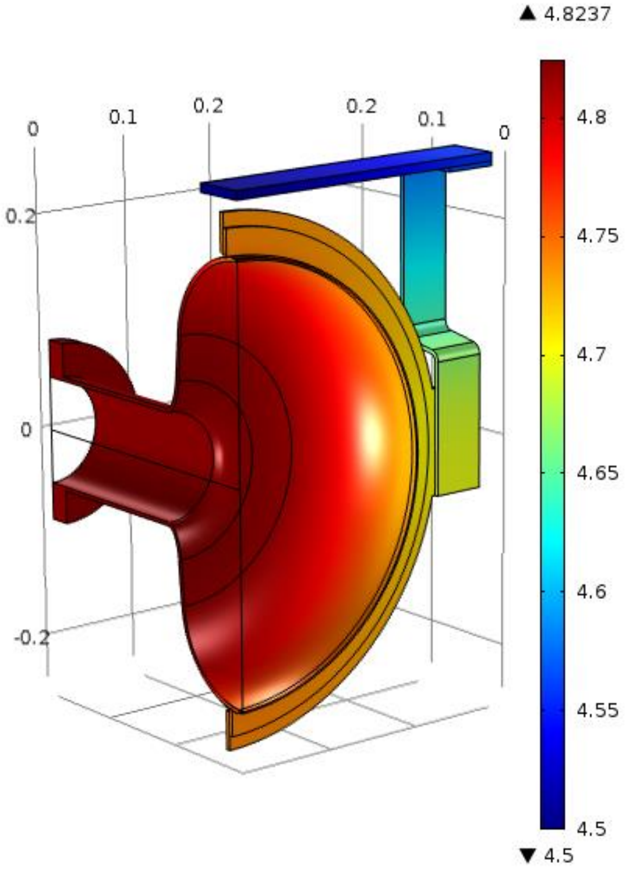


Fig.2. Excess of cryocooler power for 4.5 cell beta 0.9 cavity with Rbc+Rres and 2Rbcs+Rres (Rres=10nOhm).

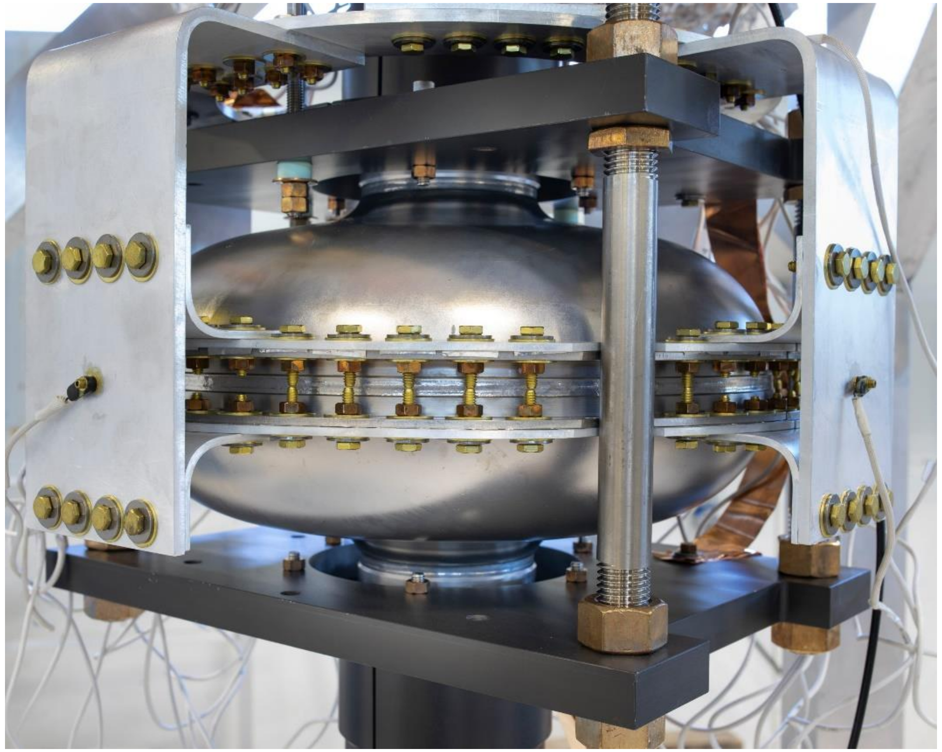
Conclusions on the 2-nd generation design

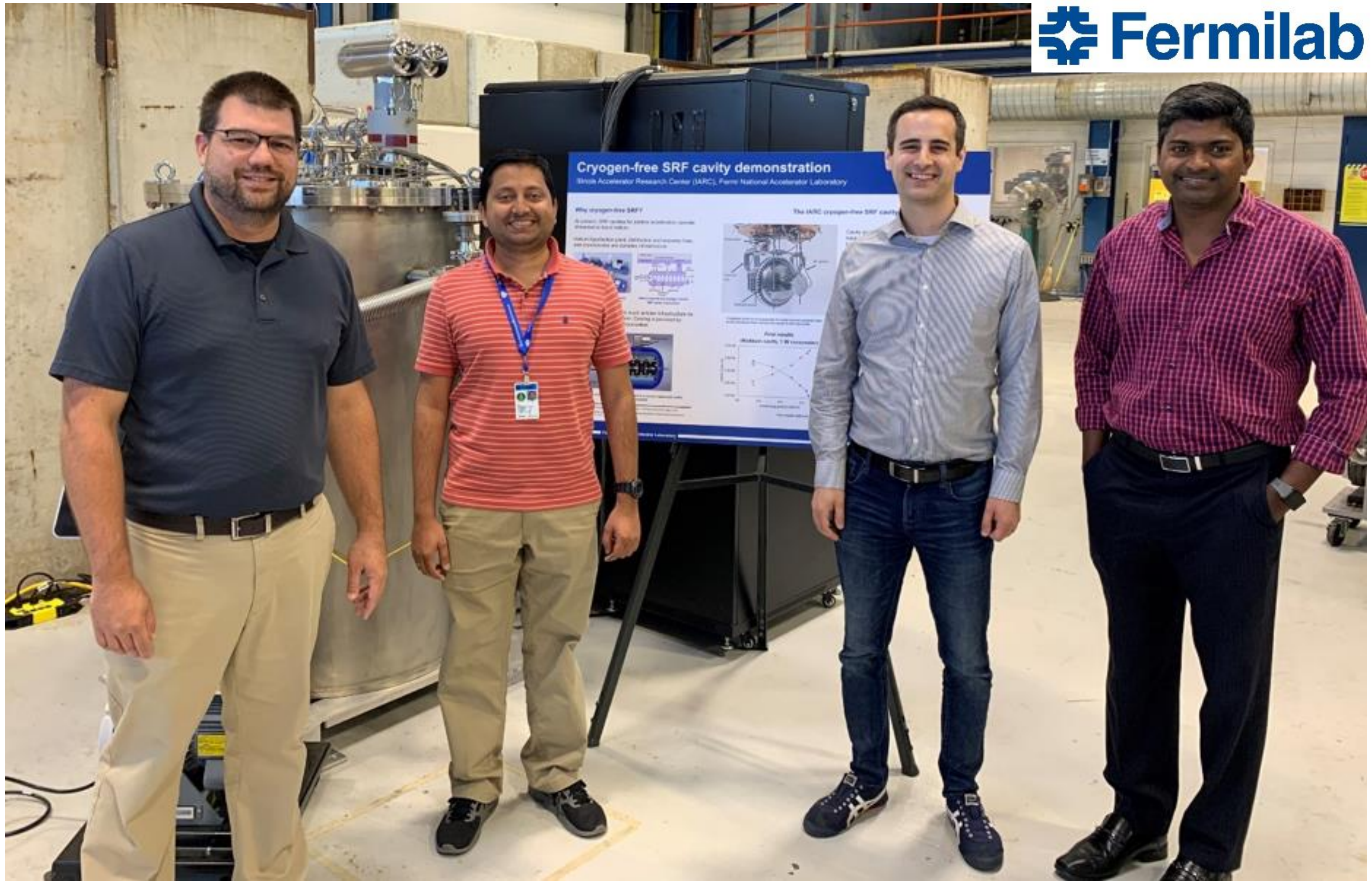


Temperature distribution in the cavity at 10[MV/m], Rs=10[nOhm]

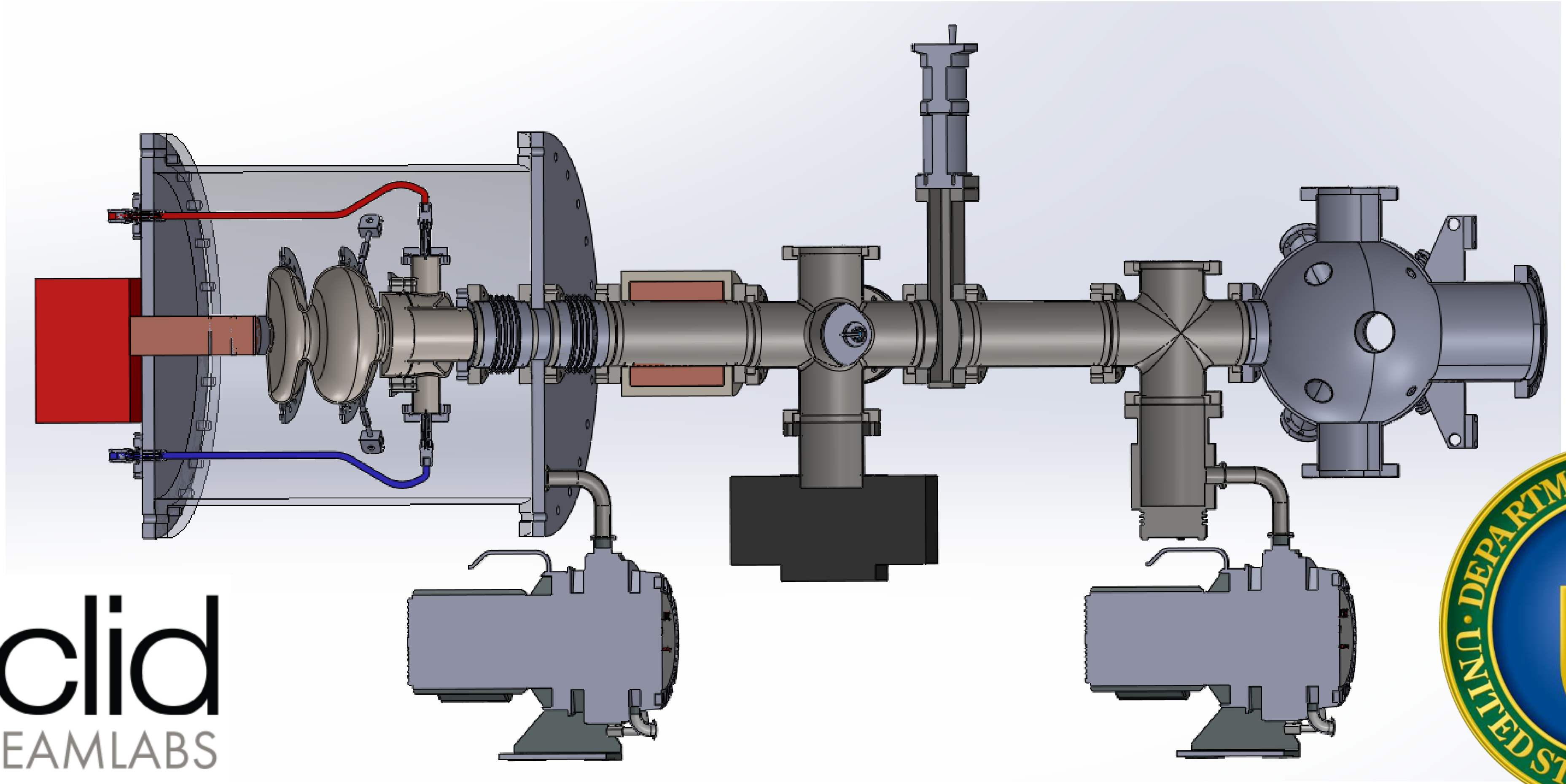
- Comsol multiphysics simulations showed encouraging results of 650 MHz cavity cooled by AL strips. Only 0.3[K] temperature rise was obtained at 10 [MV/m] and Rs=10[nOhm].
- Euclid's proposed design helped to decrease contact resistance down to the desired levels of E-4 [m^2*K/W].
- Stable operation regions were obtained for gradients from 8 to 12MV/m and Rs=Rbcs+10 nOhm. The excess of cryocoller capacity at different temperatures is also found.
- Stable operation regions were obtained for gradients from 8 to 10MV/m and Rs=1.5Rbcs+10 nOhm. The excess of cryocoller capacity at different temperatures is also found.
- **These COMSOL studies paved the way for conduction cooling technology and made possible SRF application in industry!**

Accelerating gradient of 6MV/m demonstrated recently!





Current Euclid project based on conduction cooling: UED/UEM



Project is funded by Department of Energy, **Phase II** Grant #DE-SC0018621

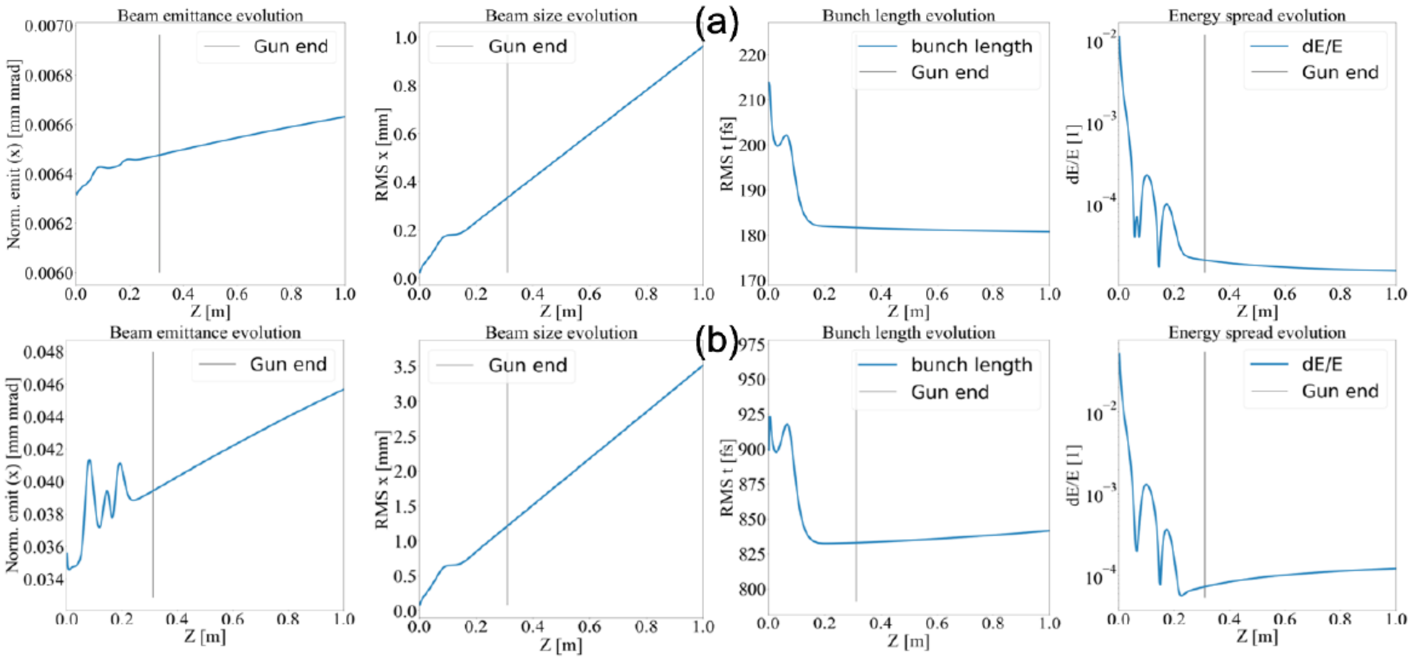
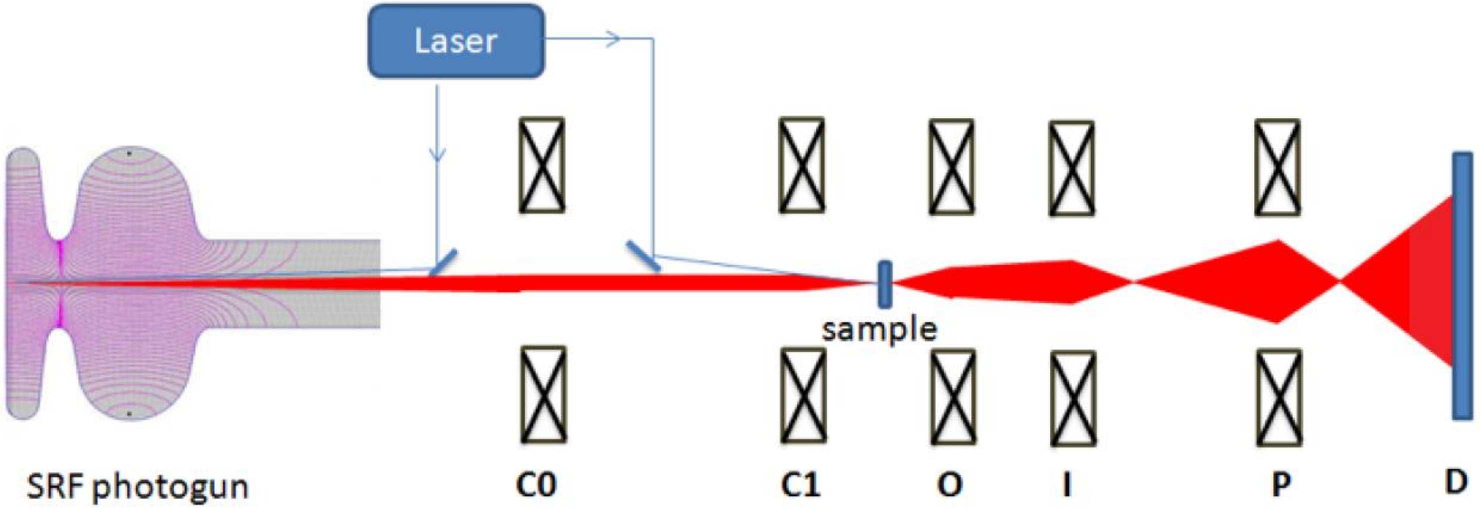


Table 1: Desired beam parameters for future UED/UEM

	UED	**UEM**
Charge	10 fC - 0.5 pC	0.5-1 pC
Bunch length	10 fs	ns - ps
Energy spread	10^{-4}	10^{-5}
Repetition rate	up to MHz	up to 100 Hz



Thank you for your attention!