Operation regime analysis of conduction cooled cavities through multi-physics simulation*

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Abstract

Euclid Techlabs in collaboration with Fermilab IARC (Batavia, IL) is developing industrial superconducting 10MeV electron linac [1, 2]. Cryocoolers are to be used for cooling instead of liquid helium bath to simplify the linac infrastructure [3]. The cavity linked to commercially available cryo-cooler cold head [4, 5] through highly conductive aluminium (AL) strips. However, this solution raises a problem of contact thermal resistance. This paper shows some results of Comsol multyphysics simulations of the cavity cooling by AL strips. Some insight was obtained on the acceptable range of contact resistance. Operation regimes were obtained at different accelerating gradients and cavity temperatures. The results of simulation are presented and discussed.

INTRODUCTION

Recent discoveries in the SRF community that nitrogen doped and Nb_3Sn coated bulk niobium cavities drastically increase the quality factor and, therefore, decrease the RF heating of cavity walls. The most interesting innovation is an approach based on Nb_3Sn because it allows cavity operation at 4.5K, with dissipation equivalent to that of bulk niobium cavities at 2 K.

A quality factor of $\sim 2 \cdot 10^{10}$ was demonstrated at 4.5K in a single cell cavity coated with Nb_3Sn [6]. This is equivalent to a total RF heating of 5W in 9-cell Tesla cavity at 10 MV/m which can be removed by commercially available cryocoolers [4, 5], providing that Nb_3Sn coating of multi-cell cavities can be demonstrated and a high thermal conductance scheme is designed to connect the cavity to the cryocooler

A commercially available cryocooler from can remove around 2W at 4.5K. It is much simpler than liquid helium refrigerators and does not require a dedicated person to operate and maintain. It also occupies much less space which is an important for industrial applications. Preliminary 3D model of compact SRF accelerator is depicted on figure 1. Industrial SRF accelerator complex contain a cryostat with an SRF cavity, cryocooler, RF feeding module and control system rack. All of these can be fitted in 2x2x5 m^3 dimensions. The use of conduction cooling drastically simplifies cryostat requirements as soon as a thermal shielding from room temperature and vacuum are required only. Dissipated RF losses in the cavity removed by the cryocooler cold head which is connected to the cavity through high thermal conductive aluminium (AL) strips.

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In this contribution, we present preliminary thermal and RF simulation results of a conduction cooled RF excited superconducting accelerator cavity.

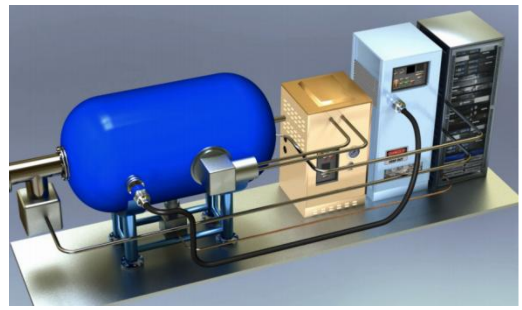


Figure 1: Compact SRF industrial accelerator model with the sizes 2x2x5 m^3.

ALUMINUM STRIPS CONTACT TO THE CAVITY

The initial idea to connect the cryocooler cold head to the cavity via high purity aluminum (AL) strips or rods was based on welded studs to the cavity outer surface in the equator region (see inset of Fig. 2). AL strips are pressed against the cavity outer surface at the locations of the welded studs. Welded studs had rather low ultimate stress value and could demonstrate contact resistance as low as 10^{-2} $K \cdot m^2/W$ because the resistance is inversely proportional to the applied force.

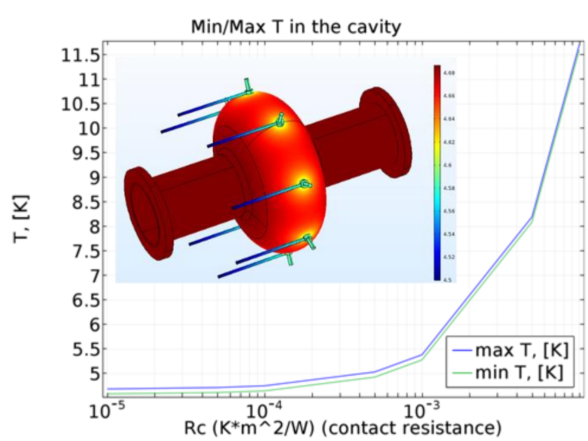


Figure 2: Cavity temperature vs thermal contact resistance between the cavity surface and AL rods. Insert shows temperature distribution in 3D model.

3D Finite Element Modelling (FEM) using Comsol was performed to investigate the influence of contact resistance on SRF conduction cooled cavity performance. A model of 1.3GHz elliptical cavity was used in the studies.

Quality factor of $2 \cdot 10^{10}$ was used as was obtained during the experiment at Cornell with a niobium cavity covered by Nb_3Sn [6]. Accelerating gradient is 10MV/m which corresponds to 0.55W of dissipated power in the single cell cavity. The cavity connection to the cryocooler is emulated by constant temperature boundary condition and is equal to 4.5 K. Thermal conductivity of Nb around 0.1 kW/m/K and Al (5N) of 3 kW/m/K were used and can be found in [7] and [8] respectively. The results of the simulation are presented on figure 2. The cavity temperature is strongly dependent on the contact resistance as one can see from Fig. 3. It is obvious that the first generation AL strip contact through the welded studs cannot provide stable operation because of high contact resistance of 10^{-2} $K \cdot m^2/W$. New types of connections were investigated. The experimental data of contact resistance is presented on figure 3 and discussed in further detail in [9].

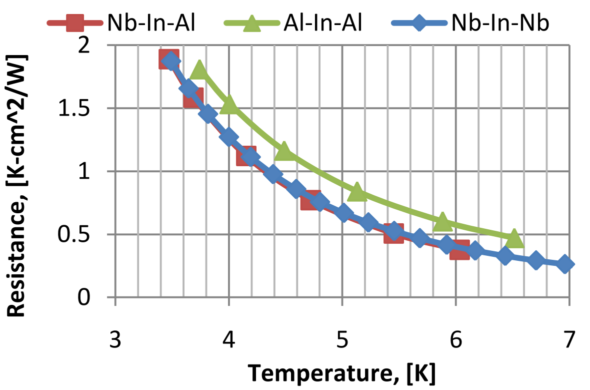


Figure 3: Thermal contact resistance vs temperature (Nb – niobium, In – indium, AL –aluminium).

It is remarkable to emphasize that contact resistance of Nb to Al was lowered by two orders of magnitude when a thin layer of indium was placed in between. Contact resistance was decreased significantly down to 10^{-5} $K \cdot m^2/W$ level. This type of connection was used for stable operation regime analysis.

650MHZ CAVITY STABLE REGIMES

650 MHz cavity is one of the candidates for conduction cooled industrial SRF accelerator. Fermilab has two types of 650 MHz cavities developed for PIP-II project, low-beta (0.61) and high beta (0.92) [10]. A 3D model of high beta single cell cavity was changed to beta=1 and used for coupled simulations. RF parameters of the cavity can be found in Table 1.

Table 1. 650MHz beta=1 cavity parameters.

beta	1
Rs, [nΩ]	10
Eacc, MV/m	10
Pd, [W]	1.33
W, [J]	8.67
F0, [MHz]	647.18
Q0	2.66E10
G, [Ω]	265.8
Epk/Eacc, [(MV/m)]/(MV/m)]	1.67
Bpk/Eacc, [mT/(MV/m)]	3.65
R/Q, [Ω]	150.9
L_cell, [m]	0.2311

R_{BCS} can be found using online calculator based on J. Halbritter FORTRAN-Program for the computation of the surface impedance of superconductors [11]. The following NB_3Sn properties for R_{BCS} were used: operating frequency F=650 MHz, critical temperature T_c=18 K, $\Delta/k \cdot T_c = 2.4$, London penetration depth λ_L=885 A, intrinsic coherence length ξ_0=110 A, RRR=0.4 [12]. The calculated surface resistance for Nb_3Sn at 650MHz can be found on figure 4.

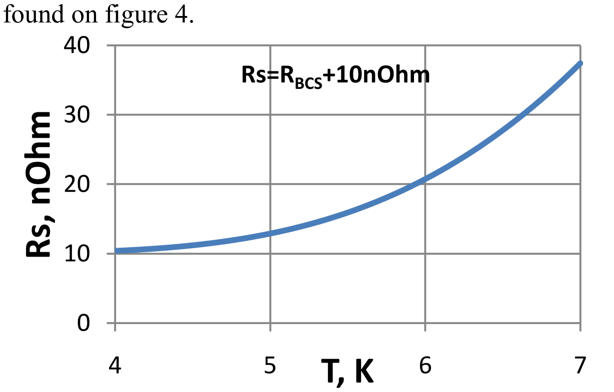
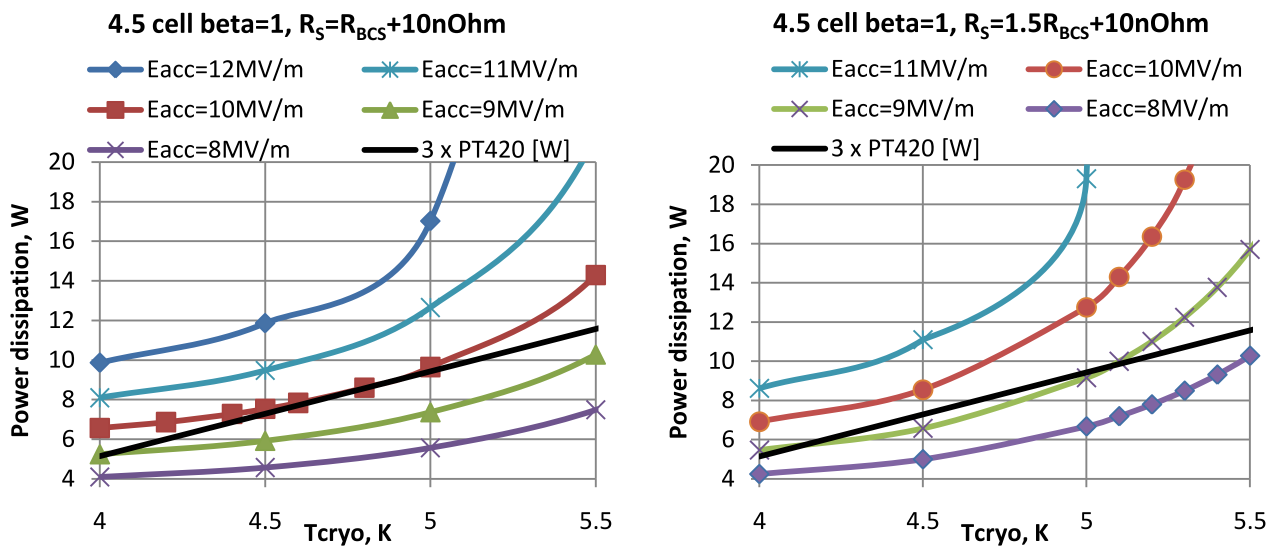


Figure 4: Nb_3Sn surface resistance at 650MHz used in simulations.

Temperature dependent electrical surface resistance shown on figure 4 was used in simulations. Residual resistance was assumed to be 10 nOhm following the data in [4].

Magnetic field distribution from electromagnetic module of Comsol was used for surface losses as an input for thermal module. Temperature of the cryocooler cold head depends on the power flow and because of that it was swept to determine stable regime of operation of SRF cavity. Total RF power dissipation was extracted from the converged thermal solution. Total losses were then scaled to 4.5 cell cavity which is one of the possible designs of standalone full size cavity for e^- acceleration with integrated gun. The results are presented on figure 6. The black curve on the in figure 5 (a) and (b) is obtained by extrapolating the Cryomech PT420 capacity map available from the vendor [3] scaled for 3 cryocoolers. Accelerating gradients from 8 MV/m to 12 MV/m were investigated. The stable point of operation corresponds to the point where power dissipation in the cavity crosses cryocooler capacity for the first time (on the left). The second point of crossing is unstable and may lead to thermal run-away.



a b

Figure 5: Power dissipation plots in 650MHz cavity vs cryocooler cold head temperature for a): $R_S=R_{BCS}+R_{RES}$ and b): $R_S=1.5 \cdot R_{BCS}+R_{RES}$. PT420 - cryocooler capacity.

Adding more power for example from any static heat load move the power disipation curve up such that unstable and stable point move towards each other. Once they meet there is only one point of the cavity operation but it became unstable now. There is only a small stable region for 10MV/m as one can see from figure 5(a) if only 3 cryocoolers are employed. Lower gradients show some excess of cryocooler capacity and are stable. Additional cryocoller is required for reliable cavity operation higher than 10 MV/m. Stable operation signifficantly depends on surface resistance. 50% and 100% higher BCS resistance were investigated. We were able to find stable operation for the first case (see fig. 5b) but there was none for the second.

CONCLUSION

3D simulations revealed a need of thermal contact resistance improvement to successfully cool the 1.3 GHz SRF cavity by conduction cooling. Values less than 10^{-5} $K \cdot m^2/W$ were obtained during the experiments.
Stable operation regions of 650 MHz cavity were simulated for gradients from 8 to 12MV/m and $R_S=R_{BCS}+R_{RES}$. Stable operation regions were obtained for gradients from 8 to 10MV/m.
The biggest temperature drop was observed in aluminium strips. Thicker strips might decrease the drop and stabilize the cavity. Initial results show that high conductivity aluminum strips can extract the heat out and operate a properly coated Nb3Sn cavity at practical gradients. Efforts are underway for practical design of the conduction cooling network of high purity aluminum.

ACKNOLEGEMENT

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