BNL-96800-2012-CP

Development of fundamental power coupler for high current superconducting RF cavity

Puneet Jain[1], S. Belomestnykh[1, 2], I. Ben-Zvi[1, 2], W. Xu[2]

[1]Physics & Astronomy Department, Stony Brook University, Stony Brook, NY 117943

[2]Collider-Accelerator Department, Brookhaven National Laboratory, Upton, NY 11973

Presented at the International Particle Accelerator Conference 2012 (IPAC'12)
New Orleans, LA
May 20-25, 2012

Collider-Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy
DOE Office of Science

DISCLAIMER

DEVELOPMENT OF FUNDAMENTAL POWER COUPLER FOR HIGH CURRENT SUPERCONDUCTING RF CAVITY*

Puneet Jain[#1], Sergey Belomestnykh[1,2], Ilan Ben-Zvi[1,2], Wencan Xu[2]
[1)] Department of Physics and Astronomy, Stony Brook University, NY 11794, USA
[2)] Collider-Accelerator Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Abstract

Brookhaven National Laboratory took a project of developing a 704 MHz five-cell superconducting RF cavity for high-current linacs, including Energy Recovery Linac (ERL) for planned electron-hadron collider eRHIC. The cavity will be fed by a high-power RF amplifier using a coaxial Fundamental Power Coupler (FPC), which delivers 20 kW of CW RF power to the cavity. The design of FPC is one of the important aspects as one has to take into account the heat losses dissipated on the surface of the conductor by RF fields along with that of the static heat load. Using a simple simulation model we show the temperature profile and the heat load dissipated along the coupler length. To minimize the heat load on FPC near the cavity end, a thermal intercept is required at an appropriate location on FPC. A 10 K intercept was chosen and its location optimized with our simulation code. The requirement on the helium gas flow rate for the effective heat removal from the thermal intercept is also discussed.

INTRODUCTION

The ERL R&D program is being pursued by the Collider-Accelerator Department at BNL for future electron-hadron/heavy ion collider eRHIC [1] and coherent electron cooling [2]. The requirements of the high current, high brightness and high charge linac structures led to the design of a 704 MHz five-cell cavity [3]. Such a cavity will be fed by a high-power RF amplifier through a coaxial FPC, which shall deliver 20 kW of CW RF power to it. Apart from that FPC also interconnects different temperature layers in the accelerating module.

One of the requirements for cavity to perform at its rated specifications is to minimize heat losses in the cryostat from FPC end. This motivated us to do a systematic study on thermal calculations for FPC. As a first step, we have simulated thermal behaviour of the cold outer conductor under 50 kW of RF power in traveling wave. In the following sections we discuss the simulation model, and, the results on temperature and heat load distribution along the coupler with an optimized location of a thermal intercept.

SIMULATION MODEL

The simulation model consists of 26.8 cm long co-axial coupler. The inner conductor (IC) is a copper (Cu) rod of 3.28 cm diameter. The outer conductor (OC) is 1.5 mm thick stainless steel (SS) tube of 7.57 cm inner diameter. The skin depth (δ_s) of Cu at 704 MHz is approximately 2.5 μm. A 15 μm thick Cu coating on the inner surface of SS, which is equivalent to 6 δ_s, was chosen in our model. One end of the OC, which is near the cavity, is kept at 5 K, while the other end at 300 K. The IC is water cooled. The 50 kW of transmitted RF power dissipates heat on both conductors. Since this study is to explore the need of a thermal intercept placed over the OC, we therefore considered only the OC for thermal calculations. The model was simplified by considering the heat flow only along the coupler length thereby treating it as a 1-D heat transfer problem.

1-D model of heat transfer by conduction

The basic equation in 1-D, which governs the transfer of heat in a solid, is given by the equation,

$$\frac{\partial}{\partial x}\left(\lambda(T)A\frac{\partial T}{\partial x}\right) + P'_{RF}(T) = \rho C\frac{\partial T}{\partial \tau}\ , \qquad (1)$$

where λ, A, ρ and C are the thermal conductivity, cross-section area, mass density and specific heat of the material respectively. $P'_{RF}(T)$, the heat source term, refers to the rate of heat loss per unit length due to RF power. In the eq. (1) T represents the temperature variable and τ, the time variable.

Under steady-state condition, the time-dependent term at the right hand side of eq. (1) vanishes. The 1-D heat equation, to be solved numerically, therefore reduces to

$$\frac{d^2T(x)}{dx^2} = -\frac{1}{K(T(x))}\left[\frac{dK(T(x))}{dx}\frac{dT(x)}{dx} + P'_{RF}(T)\right], \quad (2)$$

where K(T(x)) is defined as λ(T)A. The OC can be treated as a parallel combination of SS+Cu, thus the equivalent thermal resistance gives an expression for K(T(x)) as

$$K\big(T(x)\big) = \{\lambda_{Cu}(T).A_{Cu}\} + \{\lambda_{SS}(T).A_{SS}\}. \qquad (3)$$

The second-order differential equation (eq. (2)) was solved numerically with the boundary conditions: T(x=0) =5 K and T(x=26.8cm) =300 K. Initially we started with a temperature distribution under static heat load and iterated it until the distribution converged. Simulations revealed

*This work is supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. DOE and by the DOE grants DE-SC0002496 to Stony Brook University.

[#]Puneet.Jain@stonybrook.edu

that ten iterations were sufficient to get a steady state temperature distribution. For accuracy, a step size of 0.1 mm was chosen in simulations.

At low temperatures copper exhibits anomalous skin effect and it was incorporated in our model to calculate the loss term $P'_{RF}(T)$. The temperature dependent thermal conductivities of SS and Cu, and the temperature dependent surface resistivity of Cu were taken from the published literature [4].

Simulation results without heat intercept

The temperature distribution along the coupler length is shown in figure 1. The difference in the two curves is due to the additional heat source owing to ohmic losses on the copper surface by RF fields.

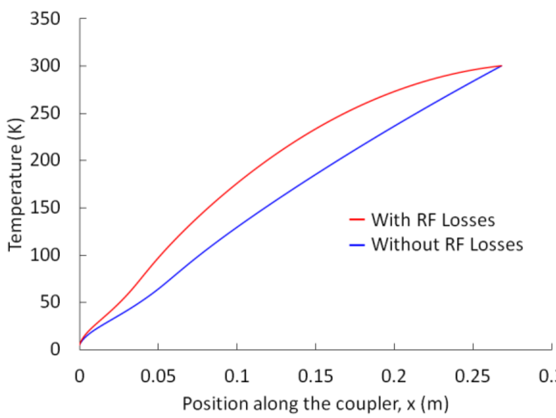

Fig. 1: Temperature profile along the coupler.

The conductive heat load due to temperature gradient is given by

$$\dot{Q} = -K(T)\frac{\partial T}{\partial x}. \tag{4}$$

Figure 2 shows a static heat load of 6.2 W and a distribution of heat load in presence of RF generated heat source term.

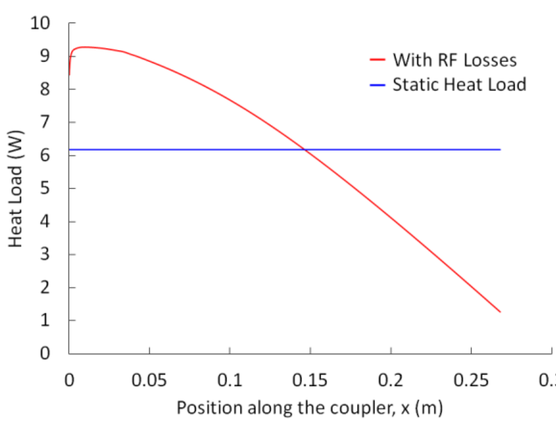

Fig. 2: Heat load along the coupler.

A dip in the heat load near x=0, observed in RF losses case, is due to the numerical glitch as there is no sink in the simulation model to dissipate the heat load.

THERMAL INTERCEPT

Result from figure 2 shows that heat of 9.1 W flows to the coupler end near the cavity. In order to minimize this heat load, a thermal intercept of 10 K is introduced.

Point-like thermal intercept

For actual design of thermal intercept, we first modelled a point-like intercept in our simulation. The position of thermal intercept was optimized to minimize the heat load from FPC to the cavity end. Our simulation result, shown in figure 3a, suggests that the location of thermal intercept should be at 6.7 cm down the coupler from the cavity end.

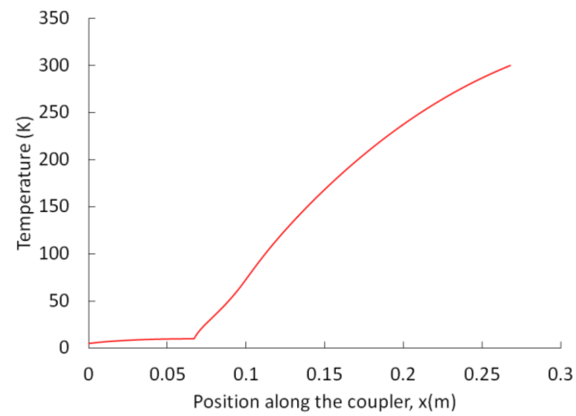

Fig. 3a: Temperature profile along the coupler with a point-like thermal intercept of 10 K at 6.7 cm.

Figure 3b shows that a heat load of less than 0.4 W is dissipated at x = 0 with a point-like thermal intercept of 10 K at 6.7 cm.

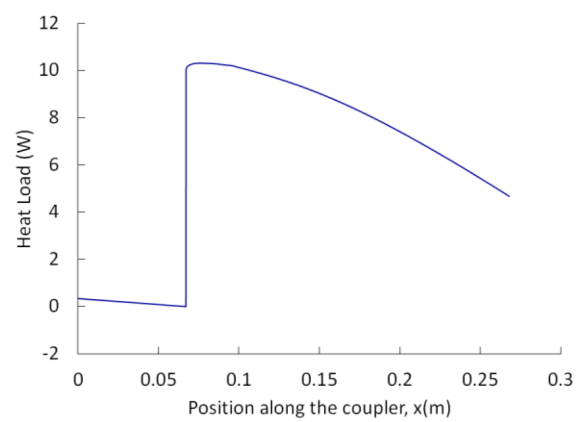

Fig. 3b: Heat load along the coupler with a point-like thermal intercept of 10 K at 6.7 cm.

Real heat intercept

The heat load plot (figure 3b) shows that a power of 10.4 W is dissipated at a point-like thermal intercept. The copper coated surface is not smooth in general which results in an additional power loss. We added 20% to the simulated heat load at the thermal intercept. Thus a heat load of 12.5 W is to be removed from the surface of the thermal intercept of a chosen length. The heat is carried away by helium gas. Assuming that the temperature of helium gas at the inlet is 6 K and that at the outlet is 10 K, the mass flow rate of helium gas is given by

$$\dot{m} = \frac{\dot{Q}}{C_p.\Delta T_{gas}} = \frac{12.5\ W}{5.2\ J/(g.K).(10-6)K} = 0.6\ g/s. \quad (5)$$

If the heat removal coefficient (h) between the conductor wall and the helium gas be taken as 160 W/(m^2-K), the temperature difference ΔT between the wall and gas as 4 K, then the required length of the thermal intercept is given by

$$l = \frac{\dot{Q}}{h.\pi D.\Delta T} \cong 8\ cm, \quad (6)$$

where D is the outer diameter of OC. The simulation result of temperature distribution along the coupler with an 8 cm long thermal intercept and 0.6 g/s mass flow rate of helium gas is shown in figure 4a. The thermal gradient of helium gas along the intercept length was assumed to be constant in our simulation model.

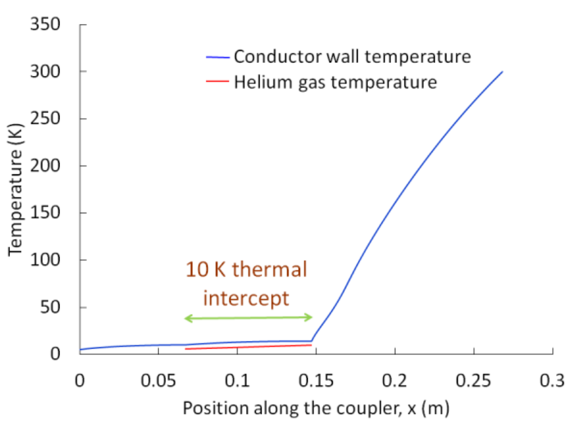

Fig. 4a: Temperature profile along the coupler with an 8cm long thermal intercept of 10 K at 6.7 cm.

The heat load distribution along the coupler with this intercept is shown in figure 4b. The heat load at the cavity end remains below 0.4 W.

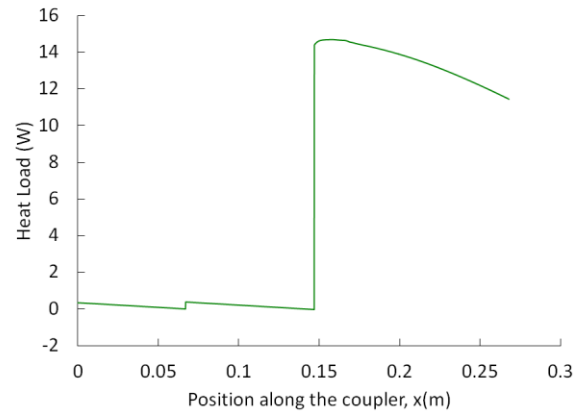

Fig. 4b: Heat load along the coupler with an 8cm long thermal intercept of 10 K at 6.7 cm.

CONCLUSION

The thermal calculations of temperature and heat load distributions on FPC are well understood by our simplified simulation model. The requirements on the helium gas flow rate and heat removal coefficient are moderate and can be easily achieved. A detailed analysis of the thermal calculations in 2-D is in progress.

REFERENCES

[1] http://www.bnl.gov/cad/eRhic/eRHIC_ZDR.asp

[2] Vladimir N. Litvinenko, "Coherent electron cooling-perfect tool for high luminosity RHIC and eRHIC," http://www.cad.bnl.gov/MAC/MAC_08/PDF/15_VL_CAD_MAC_February_2008.pdf

[3] Ilan Ben-Zvi et al., "R&D towards cooling of the RHIC collider," Nucl. Instrum. Methods Phys. Res., Sec. A 532 (2004) 177.

[4] Dohlus M., Kostin D.Möller W.-D., "Tesla RF power Coupler Thermal Calculations", Proc. of LINAC 2004 Lübeck, Germany.