INPUT RF COUPLER DESIGN FOR ENERGY COMPENSATOR CAVITY IN eRHIC*

Chen Xu, Steven Bellavia, Ilan Ben-Zvi[1], Michael Blaskiewicz, Yue Hao Kevin Smith
Roberto Than, Alex Zaltsman
Brookhaven National Laboratory, Upton, New York, USA
[1]also at Stony Brook University, Stony Brook, New York, USA

Abstract

This report gives a detail design of a 1.3 GHz input coupler for second harmonic cavity for eRHIC project. This coupler is designed to transmit 200KW CW RF to the cavity to compensate the synchrotron radiation loss. This report includes RF and thermal simulation for this design.

INTRODUCTION

High current accelerator always requires high RF power to accelerate the charge particles. The coaxial couplers are preferable in some case because of the compact size. The compact size will introduce low static loss when the transmission RF power is small. [1] However, the coaxial antenna has an inner conductor which is hard to cool in a superconducting cyromodule system. [2,3] On the other hand, the outer conductor is easy to cool by different thermal anchors. The distribution of the dynamic RF loss on inner and outer conductor are inverse proportional to the radius ratio in TEM mode operation. Increasing the coaxial impedance by reducing the radius can reduce the total dynamic loss of the TEM coupler system, but it makes the inner conductor cooling harder. Meanwhile, the inner conductor has higher dynamical loss and hard to cool, the inner conductor operation temperature is usually more than 300K when water cooling is inside. The conflict is that the surface resistance reduces with lower temperatures. Because of the better cooling capability, the dynamic loss from the outer conductor reduce more dynamic loss. Thus, it will make the whole coupler system dynamic loss smaller. Moreover, reducing the dynamic loss of the inner conductor can help reduce the black body radiation. In this paper, we studied a coaxial coupler at 1.3GHz and explored the capability of the RF delivery with a optimized water cooling scheme.

FUNDIMENTAL COUPLER

The electromagnetic fields of a TEM coaxial coupler have a rotation symmetry; thus the H field are uniform on both surfaces. The loss on inner and outer conductor is inversely proportional to the radius ratio. [1] With a coax line with inner conductor and outer conductor radii a and b, we can get characteristic impedance Z, the attenuation coefficient α, and Peak electric field of this structure in the following equation:

$$Z = \frac{1}{2\pi}\sqrt{\frac{\mu}{\varepsilon}}\ln\frac{b}{a} \approx 60\Omega\ln\frac{b}{a}$$

$$\alpha = \frac{R_s}{2\eta}\frac{a^{-1}+b^{-1}}{\ln\frac{b}{a}}$$

$$E_{peak} = \sqrt{\frac{\eta P_{in}}{\pi a^2 \ln\frac{b}{a}}}$$

The RF dissipated power can be enhanced when the surface resistance changes with the changes on local surface temperature. (RRR) The high RRR suggests that the inner conductor temperature increase, the RF loss increases as well. When outer conductor temperature anchored, the RF loss from outer conductor might well controlled. Meanwhile, the thermal conductivity also changes with different temperatures. This positive thermal feedback model could further increase the RF from inner conductor where the cooling is weak. The cooling system are mostly limited by the water cooling capability. When designing the RF couplers, those factors must be considered. This study includes simulation with the thermal feedback model and iterations. We implement our Multiphysics simulations by ACE3P software [4].

Let us talk about the limited capability of water cooling. Inside of the inner conductor, the chill water is flowed. With a certain flow rate and piping dimension, the convection coefficient between the inner conductor and water is 300W/m2/K. This value limits the thermal transfer between the interface and defines the temperature gap between this metal and water interface. At a certain stage, nucleate boiling vaporization is formed: The bubbles will be developed if the surface is hotter than the boiling temperature of the liquid. In this case, a bubble film is developed on the surfaces, it would further reduce the heat transfer convection coefficient and makes the heat transfer worst. This could cause thermal run-away and it defines the capability of the couplers. In this study, we simulate the maximum of the power L band couplers that are used in the CERL and bERLinPro projects. This is the state-of-the art high power coupler and its design capacity if 115kW CW at 1.3GHz.

THERMAL SIMULATION

In the Fig. 1, we plotted the coupler geometry when no RF is transmitted. Here we describe the geometry and boundary setups for this coupler. Thin film Cu plating on stainless steel are used on both inner and outer conductors to reduce RF loss and conduct heat loads. Theoretically,

---

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S.Department of Energy.

the film would be preferably thin to reduce the static loss. In this simulation, the thickness of Cu film on the inner and outer conductors are 10 µm. The outer conductor should be cooled with the thermal anchors at different temperatures. Meanwhile, we also made some optimizations, including:

1. Reducing inner conductor radius from 15.5mm to 13mm. That suggests that we increase the impedance from 61Ω to 71Ω to reduce the total dynamic loss.
2. Improved thermal simulation by a detailed water cooling design and optimize the locations of the thermal anchors to improved thermal conditions to increase the power handling capacity.

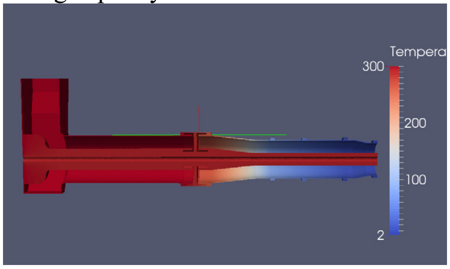

Figure 1: The temperature profile @ 0kW: Static loss.

We summarised the static loss to the thermal anchors in Table 1. The RF loss to 2K is ~ 0.26W. The major thermal transportation occurs between the chill water and 300K anchor.

Table 1: The Statics Loss

Statics loss (w)				
2k	5k	80k	300k	Water Cool
0.264	1.841	8.434	-35.909	25.370

Temperatures profiles along the couplers when transmitted RF power is 115kW and 200kW in Fig. 2. The peak temperature is slightly higher than Jlab results for the bERLinPro. Reasons for differences: 1. RRR. 2. Loss tangent at window. 3. The coupling strength with the cavity.

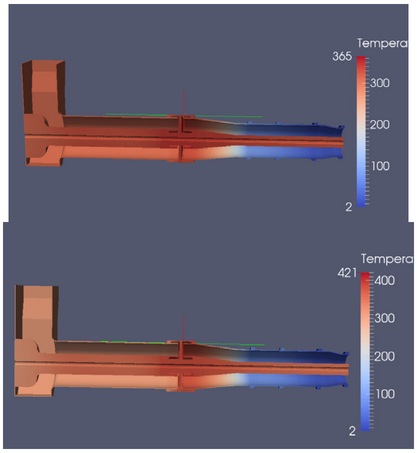

Figure 2: The temperature profile @ 115kW and 200kW: Static loss.

At 115kW, the max temperature occurs at the windows near the inner conductor and it is less than 100K increase. At 200kW, the max temperature occurs at the windows near the inner conductor and it is larger than 100K increase. Both cases use the thermal conductivity of 300W/m2/K. To transmit RF power at 200kW, this conductivity needs to be optimized.

DISCUSSION

Now we take a closer look at the inner conductor.

1. For a laminar flow heat transfer, Reynold number is less than 2000, h is given at about 300 W/K/m2. (by Jlab)
2. Presuming the maximum temperature gap is 100K, we obtain a surface heat flux density limit of Q=3x104 W/m2.
3. Now we estimate the small pipe surface area. For a small water pipe with 1cm radius, the perimeter is 0.0628m. Thus, the maximum 1D line power density, which is the water-cooling capability, is 1.88KW/m. (over-estimated)
4. For example, our coupler length is around 0.75m, maximum water capability is 1410W, which is higher than current power.
5. Current results show more than 373K@200kW, because the H field enhancement and cause local heating at windows choke.

We optimize the supply water pipe thick in Fig. 3. The mechanical hold is also considered. The figure shows a water supply and return pipes. The thin return pipe could offer a laminar flow with thermal coefficient more than 2000 W/m2/K. In this case, with a uniform 1000W RF loss (presume 1D uniform distribution), the water temperature increase will be ~ 7.92K.

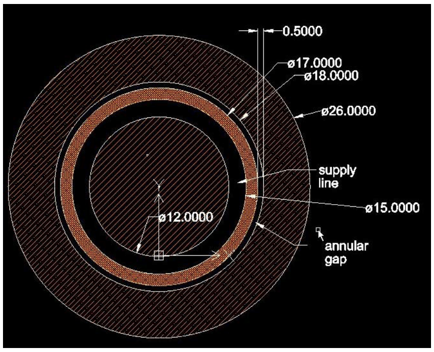

Figure 3: The chill water pipes inside of the inner conductor.

We will estimate the RF capacity with the optimized cooling scheme. We plotted the temperature profiles at different RF power levels in Fig. 4. The transmitted RF power are 115 kW, 200 kW and 300kW. Temperature is below 373K when input power is 200kW in this case. More the thermal anchors locations could be optimized to further reduce the peak temperature. At 300 kW level, the peak temperature reaches more than 100C and suggests that the capacity of this couplers is less than 300kW.

ISBN 978-3-95450-182-3

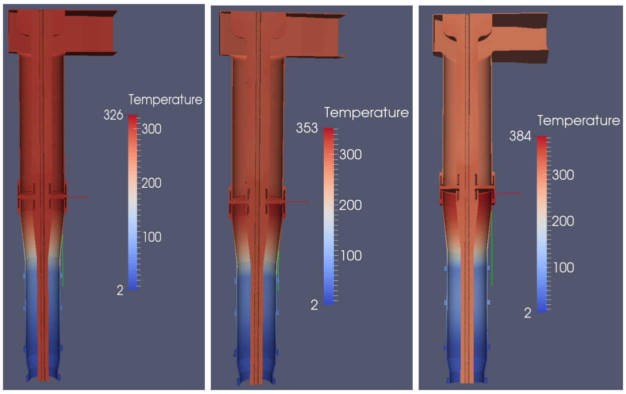

Figure 4: The temperature profile at different RF levels.

We also estimated the thermal loads to different thermal anchors and summarized them in the Table 2. The dynamic loss at 2K anchor is just above 1W at 300kW.

Table 2: The Dynamic Loss at Different RF Levels

Dynamic loss (w)	**TEM (115kW)**	**TEM (200 kW)**	**TEM (300 kW)**
2K	0.656	0.871	1.093
5K	3.027	3.426	5.220
80K	16.482	23.260	32.275
300K	185.765	338.436	518.060
Water	272.926	464.325	750.525
Total	478.856	830.317	1309.173

We plotted the peak temperature as function of the RF power in Fig. 5. We interpolated that the transmitted RF power is around 260kW when the peak temperature is 100C. Therefore, we conclude the capacity of this RF coupler is 260 kW.

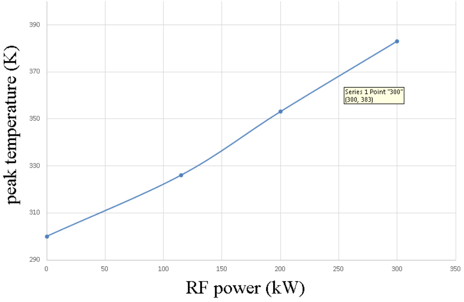

Figure 5: The interpolation of the coupler RF capacity.

COUPLING TO THE CAVITY

We equipped the couplers to the single cell cavity that is designed for the synchrotron radiation compensator for eRHIC machine [5] in Fig 6. This cavity was designed to minimize the loss factor by using a long taper beam pipe. This dual coupler system could offer around 500kW RF power for the heavy beam load cavity.

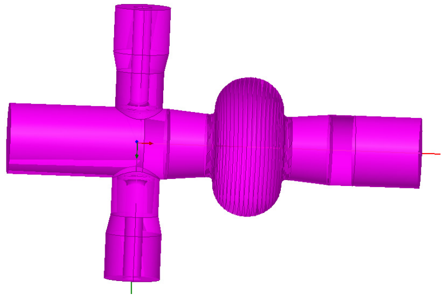

Figure 6: The single cell cavity with two FPC.

The external q should be adjustable for different operational modes. The couplers insertion length can be adjusted to achieve qe changes from 1x10^5 to 1x10^7 as shown in the Fig. 7.

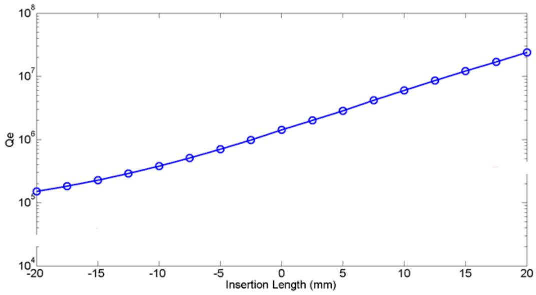

Figure 7: Qe changing range with different insertion length of these fundamental couplers.

CONCLUSION

In this study, we have developed a high power FPC for the eRHIC synchrotron radiation compensation cavity. The RF and thermal calculations are better than other state-of-the-art devices. The coupler is capable of handling 260kW, as needed for eRHIC.

REFERENCES

[1] V. Veshcherevich *et al.*, “Design of high power input coupler”, in *Proc. SRF2005*, pp.590-592.

[2] E. Kako *et al.*, "High power tests of CW input couplers for cerl injector cryomodule", in *Proc. IPAC'12*, New Orleans, Louisiana, USA, p. 2230 .

[3] V.F. Khan *et al.*, "High power RF input couplers and test stand for the bERLinPro project", in *Proc. IPAC’14*, pp.2487-2489.

[4] K. Ko *et al.*, “Advances in parallel electromagnetic codes for accelerator science and development”, in *Proc. LINAC’10*, Tsukuba, Japan, FR101.

[5] C. Xu *et al.*, “Second harmonic cavity design for synchrotron radiation energy compensator in eRHIC project”, in Proc. SRF2015,Whistler, Canada, pp.1052-1055.