SECOND HARMONIC CAVITY DESIGN FOR SYNCHROTRON RADIATION ENERGY COMPENSATOR IN eRHIC PROJECT

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Abstract

eRHIC project requires construction of a FFAG ring to accelerate electrons and connect to the existing ion ring of Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. This new ring will have the same radius as the RHIC ring. Synchrotron radiation lost in the electron ring should be compensated by a CW superconducting radio frequency (SRF) cavity. Here we propose an 845 MHz single cell harmonic cavity. This cavity will experience a high average current (~0.7 A) passing through it. With this consideration, this cavity design requires optimization to reduce higher order mode power. On the other hand, the cavity will operate at relatively high gradient up to 18 MV/m. Current design requires fundamental couplers to handle 400 kW forward RF power and HOM couplers to extract 2.5 kW HOM power.

INTRODUCTION

eRHIC project is based on a superconducting Energy Recover Linac (ERL). This linac will be built on top of the current RHIC ring. Electrons will be accelerated a certain numbers of passes to reach the final energy to collide with heavy ion beam. Then bunches will be decelerated to pass their energy back to SRF cavities [1]. The accelerating and decelerating electron bunches cruise co-linearly inside SRF cavities in the circulating ring. They will lose energy due to synchrotron radiation. This energy loss would cause phase changes and reduce the energy recovery rate. Second harmonic cavity is needed to accelerate both accelerating and decelerating electron bunches. High gradient operation at high beam loading is required from these cavities. As they will be part of the ERL, they should not produce much wake field power.

CAVITY DESIGN

By designing the second harmonic cavity as a single cell cavity, we can avoid the trapped modes as shown in multi-cell cavity. The maximum power of synchrotron radiation is around 2.4 MW. If we plan to use six single cell cavities, each cavity would deliver 400 kW CW power to the beam. The cavity's fundamental frequency is 844 MHz. and these cavities will operate at a gradient of 18.1 MV/m in high gradient mode and at 9.1 MV/m in high current mode. Thus, the Fundamental Power Coupler (FPC) is retractable. These six cavities will be put in between the two linacs housing fundamental cavities· The total length occupied by the SRF linac is 120 meter, and the affordable length for each second harmonic cavity is 88 cm.

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Cavity Design without Couplers

The cavity shape is optimized using 2D code Superfish while its loss factor and impedance are calculated with 2D code ABCI [2]. In Figure 1, 8 major parameters can be optimized to reach the specification. The beam pipe radius is 80 mm, which is also the beam pipe radius of the main ERL cavities. The radius of middle ellipse is critical for peak electric field. The iris radius *r* and radius of top ellipse are critical for the *R/Q* of the fundamental mode and the taper angle is critical for the loss factor.

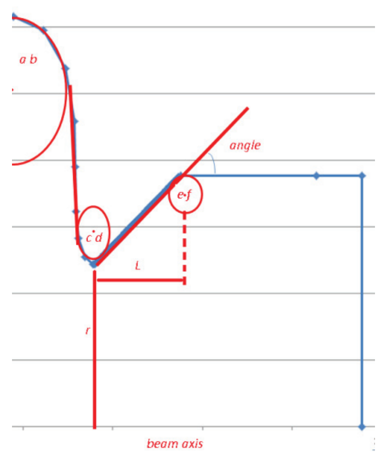

Figure 1: Optimization parameters of the harmonic cavity.

The iris should set a cut-off frequency higher than 844 MHz but the first HOM mode should leak out of the cavity. A large iris radius will reduce *R/Q* of the fundamental mode. Therefore, a taper design will be essential for maintaining high *R/Q* while allowing the first HOM mode to propagate. That determines *r* to be 71 mm.

The taper structure is used to minimize *R/Q* of HOMs, especially the first few modes. An analytical formula for taper's loss factor indicates that a longer taper will generate lower loss factor than a shorter taper [3]. However, due to limited space available for these cavities, we limited the taper length to 20 cm.

The *H* field at both ends should be limited to 100 A/m because of thermal consideration. It also defines the total length of the cavity. The *E* field pattern of the fundamental mode is shown in Figure 2. At both ends of the beam pipe, the *H* field is less than 100A/m at a gradient of 18 MV/m.

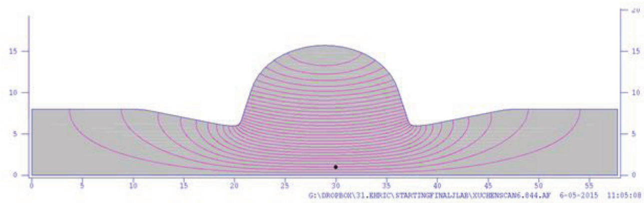

Figure 2: *E* field pattern from Superfish.

Table 1 compares parameters of the BNL4 cavity (5-cell main linac cavity) and the second harmonic cavity.

Table 1: Parameters of the eRHIC ERL Cavities

Parameters	BNL4	Second harmonic cavity
Frequency [MHz]	422.2	844
Geometry factor	273	293.8
(*R/Q*)/cell [Ω/cell]	100.6	81
Epeak/Eacc	2.27	2.83
Bpeak/Eacc [mT/MV/m]	4.42	4.513
Total length(cm)	270	70
First HOM frequency (MHz)	498	976
Longitude loss factor	2.2	0.546

The cavity loss factor calculated for a 4 mm (rms) long bunch is 0.546 V/pC. This loss factor includes the fundamental mode loss factor, which is 0.11 V/pC. 46% of the HOM power is attributed to modes with frequencies beyond 5 GHz.

Setting up the two beam pipe absorbing boundary conditions, we obtained the *R/Q* and external *Q* of the cavity. The shunt impedance is a product of these two parameters and is shown in Figure 3.The most dangerous mode is the first dipole pair.

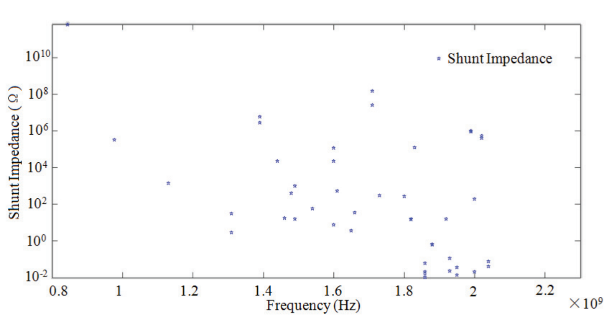

Figure 3: Shunt impedance of the cavity HOMs.

Simple formulae to calculate beam break-up (BBU) current threshold are used, and these formulae are appropriate for single mode and multiple pass scenario [4]. In this approximation, we used the following eRHIC lattice parameters: $T_{12} = 150$ m and $R_{56} = 10$ cm. We assumed that bunch passes the cavities for 12 times, and bunch arrives on crest of each HOM to obtain the worst BBU threshold current for each HOM. We found that the dangerous mode (first dipole pair) has the threshold beam current of more than 1 A.

Cavity Design with Couplers

The cavity will operate at different gradients depending on the beam current and number of ERL passes. Regardless of the gradients, 400 kW RF power will be delivered to the beam. Thus, for the given *R/Q*, the external *Q* of the FPCs will be in a range from 6×10^4 to 1.5×10^5. It would be ideal to put the FPCs near the cavity. However, putting the FPCs on the taper would complicate the helium jacket design. Thus, the nearest location is the rim of the long taper. We plan to put three HOM coaxial couplers 120 degrees apart on the other side of taper rim of cavity. Figure 4 illustrates the couplers' setup.

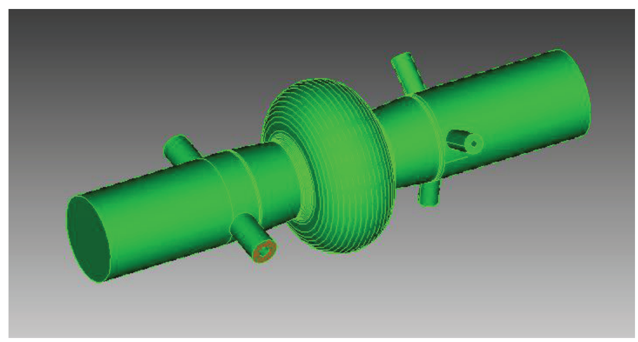

Figure 4: The cavity with the FPCs and HOM couplers.

By putting open boundary conditions on all couplers ports and beam pipes, we calculated the shunt impedance of the cavity when the *Qe* of the FPCs is 6×10^4. After adapt the shunt impedence into the formulaes,we obtained the BBU current threshold in Figure 5.

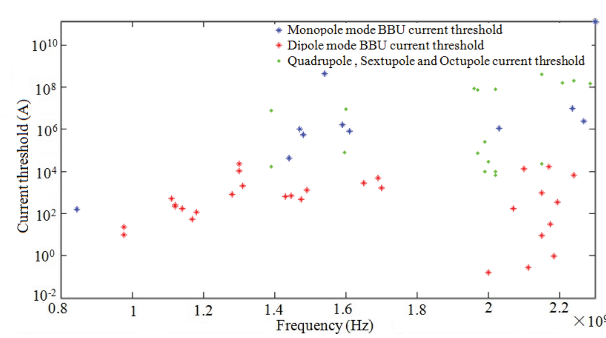

Figure 5: The BBU current threshold for different modes.

Several dipole modes have threshold less than 0.1 A, which is below the eRHIC's 0.7 A beam current. Meanwhile, the FPCs are deeply inserted into the beam pipe. In a further study of the mode patterns, we found that those dipole modes are introduced by the FPCs and have very high shunt impedances.

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FPC Optimizations

The requirement of high coupling of the FPCs and low loss factor prompted a global optimization of the FPCs and the cavity. There are two tentative solutions to improve the FPC coupler.

1. Reduce the taper length on the FPC side.
2. Optimize the FPC coupler tip shape.

One can reduce the length of the taper to obtain better coupling at the expense of increasing loss factor. One can reduce the taper length only at the FPC side and keep the taper length on the HOMs side unchanged. The relation of the increasing loss factor and reduction of taper length are shown in Figure 6. We reduced the FPC side taper length to 60% of the length on the HOM side.

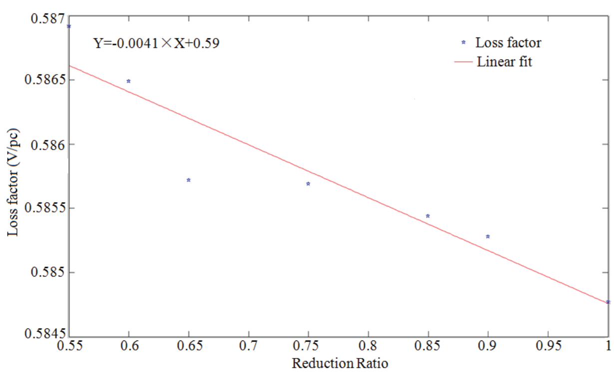

Figure 6: The relation of loss factor and FPC side taper length.

On the other hand, the tip shape of the FPC is also optimized. We increased the coaxial line characteristic impedance from 50 Ω to 60 Ω. A "pringle chip" shape tip is adapted to improve the coupling.[5] The relation of the external Q and insertion length is illustrated in Figure 7. By using this coupler, the coupling increases by 20%, compared to the flat top FPC.

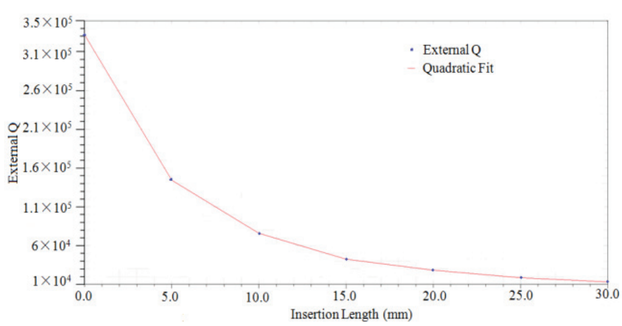

Figure 7: The external Q changes with the FPC insertion length.

Combining both optimization solutions, the shunt impedances of this cavity with the FPC and HOM couplers are calculated and the BBU threshold current is shown in Figure 8. The minimum threshold of BBU current is more than 1 A. The final cavity shape is shown in Figure 9.

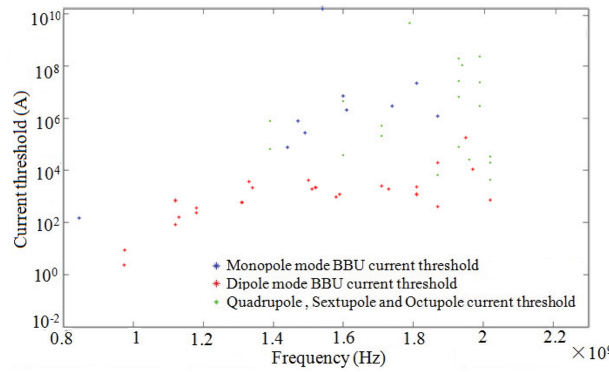

Figure 8: The BBU threshold current for the cavity with all coupler inserted. The Qe of FPC is 1.2×10^5.

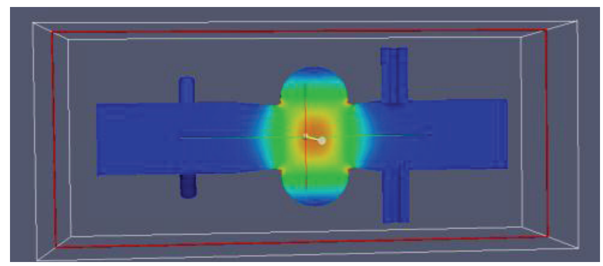

Figure 9: Fundamental mode in the harmonic cavity with couplers.

WAKE FIELD DISCUSSION

A time domain calculation was conducted to quantify coupling of all couplers. A 4 mm (rms) long and 3 nC charge bunch passes through the cavity, and the output power for each port is recorded. The energy leakage can be obtained by integrating the power from each port. A snapshot of E field pattern is illustrated in Figure 10. The FPCs are also extracting HOM energy. The integrated output energy from all ports is 3.11×10^{-6} J, while the expected energy from loss factor is 3.6×10^{-6} J. The difference would be the energy loss on the wall.

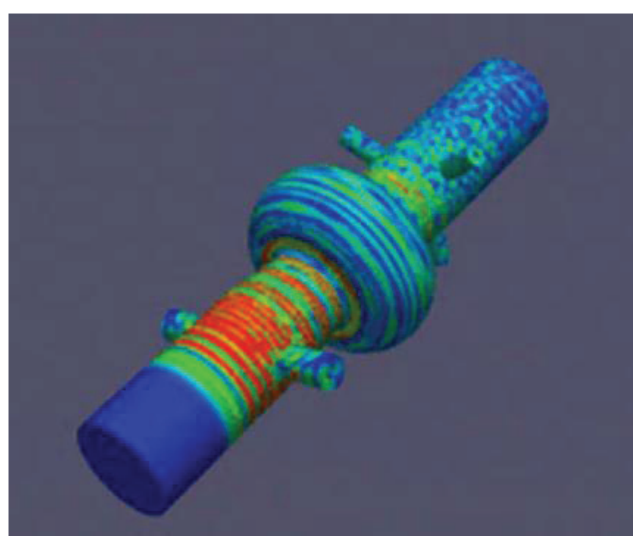

Figure 10: A snapshot of E field pattern is shown when the bunch enters the cavity on axis from upper right corner.

In this simulation, two open boundary conditions were used for beam pipe at both ends. The real boundary impedance would be an impedance of an adjacent cavity or trains of cavities. Thus, this simulation underestimates the power extraction of all couplers. A large-scale wake field simulation will be conducted on cavities cascading train in time domain.

CONCLUSION

In this paper, we report the RF optimization of the second harmonic SRF cavities for synchrotron radiation compensation. Preliminary time domain calculations are initiated. Thermal simulations and mechanical designs will follow to finalize the cavity design.

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