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DESIGN OF A THIRD HARMONIC CAVITY WITH LOW R/Q FOR THE ESR IN BNL EIC*

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Abstract

For the electron Storage Ring (ESR) of Brookhaven National Lab Electron Ion Collider (BNL EIC), beam loading is a great concern due to the high beam current together with abortion gap, especially for harmonic cavities due to higher operational frequency. There were attempts to use feedback/feedforward control, using multiple cavities with counter-phasing [1]. A straightforward way to lower beam loading effect is to design a cavity with low *R/Q*. In this paper, we show such a design for the 3rd harmonic cavity for BNL EIC ESR.

INTRODUCTION

In the BNL EIC ESR, counter-phasing was studied to be used to fight against beam loading of the 1st harmonic and possible 3rd harmonic accelerating cavities. There are drawbacks of using this technique, such as higher RF power, higher power dissipation on cryo system, limited working conditions, etc. A better way to ease the beam loading effect, is to design a cavity with lower *R/Q* while maintaining the other RF parameters. In this paper, we describe cavity designs with effective length longer than half of the working mode's wavelength, and with large beampipes that connected to the cavity with chokes, so that peak fields can be controlled at certain cavity voltage while *R/Q* can be lowered, and higher order modes (HOMs) can be damped using beampipe absorber. We also present the multipacting analysis, as well as a special fundamental power coupler (FPC) design.

CAVITY DESIGN

We start from the design in the pre-conceptual design report (pCDR) [2] see Fig. 1. It is a 1-cell elliptical cavity with λ/2 cavity length, with λ the wavelength of the working mode with resonance frequency f_0. Two half-cells of this cavity are identical, with the iris of each half choked and connected to the enlarged beam pipe using a taper. An FPC port is located on the right side of the cavity. SiC absorbers are used on both sides as HOM absorbers. There will be 5 cavities in the ESR providing up to 7.8 MV accelerating voltage. Each cavity is designed to provide 1.6 MV. Some of the RF parameters of this cavity are shown in Table 1. The *R/Q* of the pCDR design is 51.5 Ω, with all impedances in circuit definition in this paper, and the design goal is to lower it to 1/3 of the original value.

There are two convenient approaches to achieve a lower *R/Q*: enlarged beampipe diameter, and a cavity either longer or shorter than λ/2. With enlarged beampipe or shorter cavity, however, normally has enhanced peak electric field E_{pk} and peak magnetic field B_{pk} while maintaining its accelerating voltage V_{acc}. For a longer cavity, the lowest HOM frequency will be closer to, or even smaller than the working mode frequency at 1.7736 GHz. We explore the possibility of the cavity design with longer length together with large beampipe in this paper.

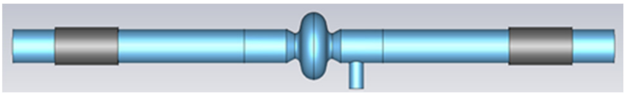

Figure 1: pCDR design of the 3rd harmonic cavity. It is a 1-cell λ/2 elliptical cavity, with an FPC port on the right side and two SiC HOM absorbers on the beampipes.

Table 1. RF parameters of the 3rd harmonic cavity of BNL EIC ESR at 1.7736 GHz. Peak fields are normalized to 1.6 MV accelerating voltage.

	pCDR design	Design goal	New 1-cell design	New 2-cell design
R/Q [Ω]	51.5	17.0	20.7	15.9
B_{pk} [mT]	82.4	80.0	115.6	81.0
E_{pk} [MV/m]	37.4	40.0	19.1	24.3

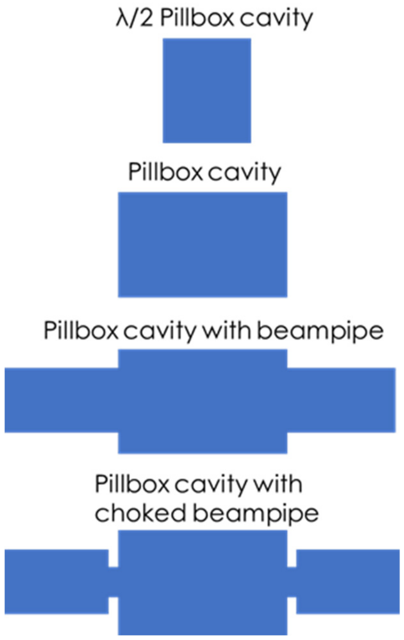

Figure 2: Design towards a longer cavity with low R/Q.

The design should adopt a simple damping scheme that is able to handle high HOM power. There are three candidates: 1, beampipe absorber, as shown in pCDR; 2, on cell damping with rectangular or ridged waveguide; and 3,

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hook or loop coupler with high pass or band pass filter. Option 2 is better suited for cavity design with small beampipe and high *R/Q*, and the design is complex. Option 3 is also complex and is not a good option for HOM power in tens of kW range. In this design option 1 is used.

Using cylindrical cavity without beampipe as an example, with TM_{010} the working mode at f_0, all HOMs in TM configuration (longitudinal HOMs) have frequencies higher than f_0, and longitudinal HOM with the lowest frequency is TM_{011} for cavity with length $\geq \lambda/2$. For the transverse HOMs in TE configuration, the TE_{111} mode has the lowest resonant frequency, and with cavity length increasing from $\lambda/2$, its frequency starts to come closer to, and might be even lower than f_0. See Fig. 2, for a $\lambda/2$ pillbox cavity, the frequency of TM_{011} mode is $\sqrt{2}f_0$, and for TE_{111} it is $1.26f_0$. With cavity length increases to λ, these two values change to $\sqrt{5}/2f_0$ and $0.914f_0$, respectively. While taking the beampipe into account, please note the cutoff frequency of TE_{11} is lower than that of TM_{01} in a beampipe, thus with a reasonable big opening, TE_{111} can leak out of the cavity, even with its frequency closer to or lower than f_0. Such a beampipe can also be used to extract TM_{011} mode. There are also drawbacks of using large beampipe, the frequencies of these two HOMs will be lowered with larger beampipe, causing them difficult to leak out, and the *R/Q* of the working mode will also be lowered and causing higher B_{pk} at certain V_{acc}. Similar to the pCDR design, choking the beampipe is a solution, see the bottom plot of Fig. 2. with the cost of increasing external quality factor Q_{ext} of the HOMs. With a cavity length at 0.7λ, and beampipe radius of 0.8R, with R the cavity radius, and iris radius of 0.4R, the R/Q of this cavity can be suppressed to 21.5 Ω, with 106.9 mT B_{pk} and 46.6 MV/m E_{pk} at 1.6 MV V_{acc}. A more realistic elliptical design is shown in the top of Fig. 3, with cavity further lengthened to 0.8λ. The RF parameters of this 1-cell cavity is shown in Table 1. Please note with an elliptical shape, it has a lower E_{pk} while comparing with the pillbox design due to the elimination of sharp edges on the iris, and it has a higher B_{pk} since the magnetic field is more concentrated to the center of the cavity. In short, stretching the 3^{rd} harmonic cavity design in pCDR to a longer version can lower the *R/Q*.

The above design has a B_{pk} higher than 80 mT with 1.6 MV V_{acc} thus further optimization is needed. One might consider using more cavities to provide a total 7.8 MV per turn, with each cavity provides less V_{acc} so that $B_{pk} < 80$ mT and a lower number of total *R/Q* per turn can be achieved. Optimizer is used trying to find a design with minimum $A = R/Q \times B_{pk}$ at 1.6 MV V_{acc} and working frequency. Simulation results reveal that the longer the cavity, the smaller the *R/Q* and *A*. It is possible to use more longer cavities to reduce the total *R/Q*. This, however, is not a good solution while considering the number of cryomodules, which is a direct reflection of the cost. A multicell cavity design is a better solution to reduce the number of cryomodules that required. Since beampipe absorbers are used, 2-cell design becomes a reasonable solution, cavity design with cells more than 2 might bring trapped modes within cells, and it is possible to optimize a 2-cell design using either 0 mode or π mode. Another way to lower the B_{pk} at 1.6 MV is to fine tune the shape of the straight section, the location that has high magnetic field, of the 1-cell design. It is also considered that while lengthen the cavity, instead of squeezing the end plates, we squeeze the center of the cavity to slightly increase the *R/Q* so that a lower B_{pk} can be achieved at 1.6 MV. These three methods result the same cavity geometry, as shown in Fig. 3. During optimization, if π mode is used, the field pattern in this 2-cell cavity is similar to the TM_{011} mode in a 1-cell cavity, and the benefit of using 2-cell is that it is possible to adjust the frequency of the 0 mode while maintaining the frequency of the π mode. We choose 0 mode for further optimization and get a 2-cell cavity with each cell 0.9λ in length, 0.54R radius for both end iris and center iris, and 0.85R beampipe radius. RF parameters of this 2-cell design is shown in Table 1. The electric field of the working mode in this design is shown in the bottom plot of Fig. 3.

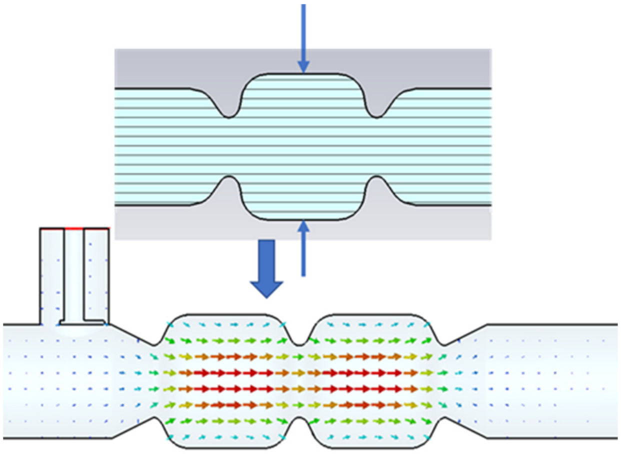

Figure 3: Long elliptical choked cavity, with the top 1-cell design and the bottom 2-cell design. The bottom plot also shows the electric field of the working mode with FPC on the left.

FPC, HOM AND MULTIPACTING

For a cavity with a large beampipe, it is not easy to achieve enough FPC coupling coefficient. Electric coupler with an endplate larger than the inner conductor of the coax is normally used, and sometimes a special shape endplate needs to be used to get enough coupling [3]. For a beampipe with 0.85R, it is even more difficult. A new design with endplate nonconcentric to the inner conductor is used, shown on the left of bottom plot in Fig. 3 to achieve 5.9e4 FPC Q_{ext} with 72 mm ID FPC port.

The longitudinal HOM impedance budget is 26 kΩ-GHz and for the transverse it is 12 MΩ/m for the whole ESR with 6 3^{rd} harmonic cavities. Per cavity it is 4.3 kΩ-GHz longitudinal and 2 MΩ/m transverse. The longitudinal and transverse HOM impedance spectrum are shown in Fig. 4 Most of the HOMs are within the budget, except two longitudinal modes, with a TM_{011} mode at 2.315 GHz with 230 loaded Q and 25.0 Ω *R/Q*, and a TM_{021} mode at 4.332 GHz with 16000 loaded Q and 1.2 Ω *R/Q*. Further optimization is needed to lower these two values within impedance budget.

With *R/Q* 1/3 of the pCDR design, the dynamic power dissipation to the cryo system will be elevated. One advantage of the 2-cell design is that it has a high geometry factor at 393 Ω, 1.46 times of the value in the pCDR design. In this case the dynamic power dissipation is twice of the pCDR design.

Multipacting simulation is also done using FishPact, a 2D simulation tool based on SuperFish for cylindrical symmetric resonator [4]. There is some enhancement in the number of secondary electrons at low field, around 0.4 MV. And by increasing the impact number from 20 to 40, the final impact energy drops from 367 eV to 11 eV, and the enhanced counter function drops from 673 to 0. Conclusion can be made that some secondary electrons can be generated at this field level, however, multipacting will not happen. This conclusion is cross checked using ACE3p [5] that showing the most persistent multipactor survived 34 RF cycles at around 0.4 MV. Please note the FPC is not included in this multipacting simulation and further study is needed.

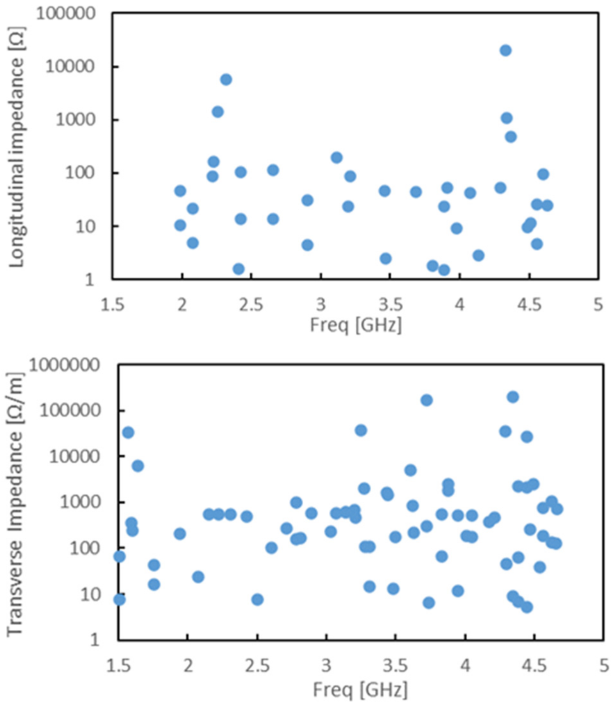

Figure 4: Longitudinal (top) and transverse (bottom) HOM impedance in the 2-cell design.

CONCLUSION

For the BNL EIC ESR 3rd harmonic cavity, starting from the pCDR design, we show a 1-cell design of choked cavity that is longer than λ/2 with large beampipe to achieve a lower R/Q while trying to maintain the peak fields at certain cavity voltage. Further optimization showed that 0 mode of the fundamental mode in a 2-cell design give a better result, with R/Q less than 1/3 of the value in pCDR design, and B_{pk} at 81.0 mT, E_{pk} at 24.3 MV/m at 1.6 MV cavity voltage. HOMs in the 2-cell cavity are simulated with encouraging results, with further optimization needed for two longitudinal modes. Based on simulation, multipacting is not a concern in this design given the cavity surface being properly treated. A special FPC design with electrical endplate nonconcentric to the inner conductor is used to achieve low coupling coefficient for a cavity with large beampipes. Similar idea can also be applied to ESR fundamental cavity at 591 MHz to lower the R/Q. It differs from the 3rd harmonic cavity with an upper limit on the beampipe diameter due to the difficulty in vacuum sealing, thus posing limitations on the lowest R/Q that can be achieved.

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