HIGH CURRENT ERHIC CAVITY DESIGN AND HOM DAMPING SCHEME *

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Abstract

A 5-cell 422 MHz SRF cavity, BNL4 cavity, was designed for the FFAG lattice based eRHIC, which is a high current (up to 50 mA), multi-pass (up to 16 passes) ERL. Compared with a 704 MHz SRF linac for conventional lattice eRHIC design, the 422 MHz SRF linac is chosen not only for better beam dynamics performance but also for lower linac cost. As FFAG based high luminosity eRHIC is a high current multi-pass ERL machine, it requires extremely good HOM damping to increase BBU threshold current and minimize the HOM power caused cryogenic load. So, HOM damping capability was the main concern for this cavity design. A HOM damping scheme with six coaxial-line HOM couplers and three waveguide couplers was proposed to damp the high-power, full-spectrum (up to 30 GHz) HOMs in the linac. The operation requirement for BNL4 cavity is $Q_0 = 5\times10^{10}$ at a gradient of 18.5 MV/m. As there is no experience in making such a big/heavy cavity and there is no available facility to handle a 5-cell 422 MHz cavity, a 3-cell prototype cavity is ordered to study the cavity's fabrication, processing and testing. This paper will present the design of the 5-cell 422 MHz cavity, progress on the 3-cell BNL4 prototype cavity and the progress of its HOM damping studies.

INTRODUCTION

The Collider-Accelerator Department at BNL proposed a FFAG lattice based electron-ion collider, eRHIC [1], which will use 42 5-cell 422 MHz SRF cavities as the main linac. Compared with the previous conventional lattice eRHIC design using a 704 MHz SRF linac, the 422 MHz SRF linac allows higher Beam-Break-Up (BBU) threshold current, longer bunches, lower energy loss and energy spread, higher beam polarization, easier path length control, lower transient effect, higher cavity quality factor, higher RF power efficiency and lower HOM power [2]. The 5-cell 422 MHz BNL4 cavity is an evolution design of the 5-cell 704 MHz BNL3 cavity [3,4,5]. BNL4 was designed to reduce both loss factor of monopole HOMs (HOM power) and impedance of the dipole HOMs, while maintaining similar performance of the fundamental mode. The operation requirement of BNL4 cavity is 18.5 MV/m with Q_0 @ 5×10^{10}. A 3-cell prototype cavity is undergoing fabrication to demonstrate and study this performance. This paper addresses the design of BNL4 cavity, with comparison of BNL3 cavity.

To reach full luminosity of eRHIC at intermediate energies, about 7 kW HOM power per BNL4 cavity should be damped, with 72 % of the HOM power below 5 GHz and the rest 28 % HOM power is between 5 GHz to 30 GHz. It is a big challenge to develop such a high power, full spectrum HOM damping scheme. A concept design of such HOM damping scheme is addressed in the paper.

422 MHZ 5-CELL BNL4 CAVITY DESIGN

Fundamental Mode

The same as 704 MHz BNL3 cavity, the 5-cell 422 MHz BNL4 cavity, employs a concept of using a large beam tube to propagate all HOMs but its end cells have irises that improve the confinement of the fundamental mode inside the structure. To reduce the cross-talk between neighboring cavities, tapered sections to a reduced diameter beam pipe are added on both sides of the cavity. Figure 1 (top) shows Superfish model of the BNL4 cavity. The field profile of the fundamental mode by Superfish is shown in Figure 1 (bottom). The fundamental mode's performance of the BNL3 and BNL4 cavities is listed in Table 1.

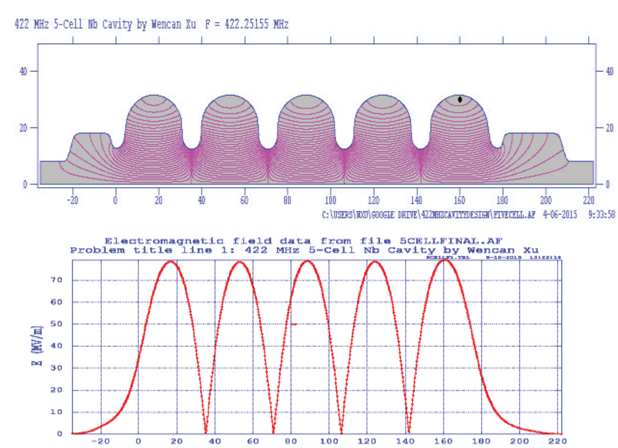

Figure 1: BNL4 cavity configuration (top) and fundamental mode field profile (bottom).

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Table 1: RF Parameters of the BNL3 and BNLI Cavities

Parameters	BNL3	BNL4
Frequency [MHz]	703.79	422
Number of cells	5	5
Geometry factor [Ω]	283	273
(R/Q)/Cavity [Ω]	506.3	503
Epeak/Eacc	2.46	2.27
Bpeak/Eacc [mT/MV/m]	4.27	4.42
Coupling factor [%]	3.0	2.8
Loss factor [V/pC]	2.28	1.93

Monopole Modes and HOM Power

Except for the consideration of dipole HOMs and fundamental mode's performance, BNL4 cavity was design to reduce the loss factor. It turned out that the BNL4 cavity's loss factor is reduced by 15 % as compared to BNL3 cavity scaled to the same frequency. The loss factors with and w/o fundamental mode are calculated by ABCI [6] and shown in Figure 2 for the eRHIC electron beam's bunch length of 4mm RMS.

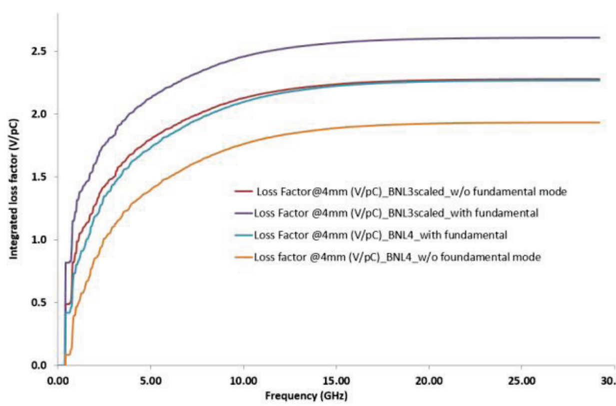

Figure 2: Integrated loss factors of the BNL4 cavity and the BNL3_scale cavity, for the rms bunch length of 4 mm.

An average monopole mode HOM power in a cavity is proportional to the bunch charge Q_b, beam current I_b, and the longitudinal loss factor k_p:

$$P_{ave} = k_{\square} I_b Q_b \qquad (1)$$

The loss factor of the BNL4 cavity was calculated with ABCI to be 1.93 V/pC for a Gaussian bunch of 4 mm RMS bunch length, which reduced from 2.28 V/pC for BNL3 caviy scaled to 422 MHz. With eRHIC beam parameters (7 passes, 50 mA ERL, 5.3 nC per bunch) for an intermediate energy, where HOM damping is the limitation of the luminosity, an average value of monopole mode HOM power in one BNL4 cavity is 7 kW per cavity. This presents a big challenge for removing it out of the cryostat and it has to be damped outside the cryomodule.

Transversal Beam-Break-Up (BBU)

The FFAG lattice based eRHIC design is a multi-pass (up to 16), high current ERL design. One important concern for the linac cavity design is to increase the beam break up (BBU) threshold current. The transverse BBU threshold beam current depends mainly on the strength of dipole HOMs. It is clear from the BBU formula [7] that a small $(R/Q)_d\, Q_{ext}$ can increase the threshold current. The shunt impedance of the HOMs, which together with the R/Q values determines the minimum required Q factors. Figure 3 shows the estimated (worst-case) impedance limit as black line set by the BBU for the maximum M_{12} value of the arcs for eRHIC, which is 150 m. Comparing the simulated impedances with the worst-case limit, the designed cavity's HOM impedance is well below the BBU limit.

Longitudinal Beam-Break-Up

A similar formula for longitudinal BBU was derived by [8], ideally, R_{56} =0, there is not longitudinal BBU threshold current limitation. However, in reality, R_{56} is not always to be 0. In Figure 4, shows the impedance requirement for the longitudinal BBU estimation, which uses a conservative R_{56} = 10 cm. With this conservative estimation, the cavity HOM damping capability is way below the requirement of eRHIC.

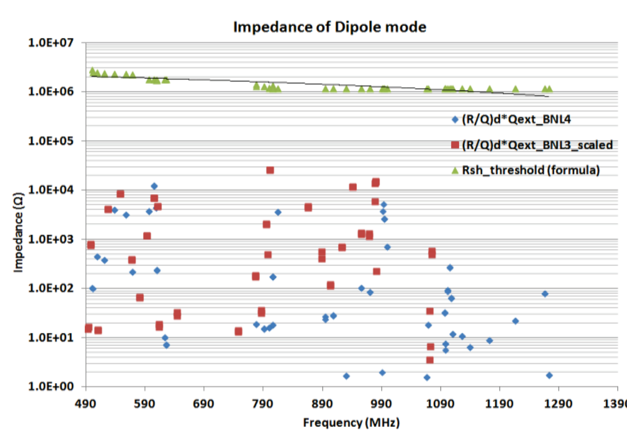

Figure 3: Impedances of dipole HOMs. eRHIC requirements (green triangles and the black line), BNL3 (blue diamond) and BNL4 (red square) cavities' dipole HOM damping capability.

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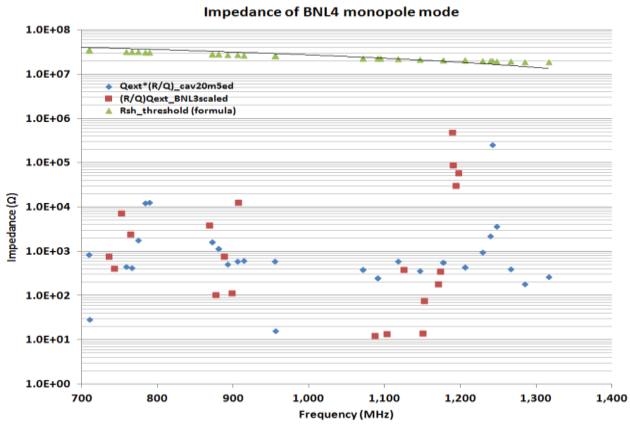

Figure 4: Impedances of monopole HOMs. eRHIC requirements (green triangles and the black line), BNL3 (blue diamond) and BNL4 (red square) cavities' monopole HOM damping capability.

Mechanical Design and Prototype Cavity

In eRHIC design, the electron beams will collide with different proton energy from 40 GeV to 250 GeV, which corresponds to a frequency shift up to 113.2 kHz for 422 MHz cavity. ANSYS simulation shows that the cavity's tuning sensitivity is 55 kH/mm, so the tuning range requirement for BNL4 cavity is 2.05 mm. With a 3.2 mm thickness of Nb sheet, the cavity can be tuned up to 2.8mm without exceeding the yield strength of Nb: 7000 psi. In the prototype cavity, we use 4 mm thickness for the Nb sheets. Figure 5 shows the 3-cell prototype cavity, which will be made by RI [9]. The prototype cavity is fabricated to study cavity's performance ($Q0=5\times10^{10}$ at 18.5 MV/m), with different surface treatment. It will also be used for HOM damping study as well.

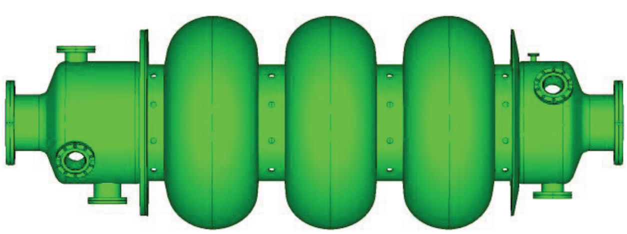

Figure 5: 3-cell prototype of the BNL4 cavity.

HOM DAMPING SCHEME

HOM damping can be separated operationally into three steps: 1) HOMs propagate out of the cavity's cells and travel to the location of HOM couplers; 2) The HOM couplers pick up the HOM fields but reject the fundamental mode; 3) The HOM power is transmitted out of the SRF cavity or cryomodule. *The first step* was accomplished in the cavity design (as shown in Figure 3 and 4): all of the dipole modes have external quality factors (Q's) lower than 2.5×10^4 and all of the monopole modes have external Q's below 1.7×10^4. *The second step*, to damp the full HOM spectrum (as shown in Figure 3, the eRHIC beam can excite HOMs up to 30 GHz), will employ two types of HOM couplers as shown in Figure 6: six coaxial-line HOM couplers located on the enlarged beam pipes at both ends of the cavity for HOMs with frequency < 5 GHz (which accounts for 72% of the HOM power) and three waveguides located at the end of the cavity for HOMs with frequency > 5 GHz (which account for 28% of the HOM power). *The third step* is to divert and absorb the HOM power generated inside the cavity outside the cryomodule. A crucial component in achieving *the third step* is an RF window, which isolates the cavity vacuum from outside components, but at the same time transmits all HOM power through it. It is very important to design a high power, broadband, low loss, and reliable RF window. Also, thermal design has to be carried out carefully to reduce heat load on the cryomodule, when delivering the HOM power outside.

We are making a lot R&D effort on design of the high power, full spectrum HOM damper. The prototypes of these couplers and RF windows will be tested at room temperature and low temperature with the prototype 3-cell Nb cavity.

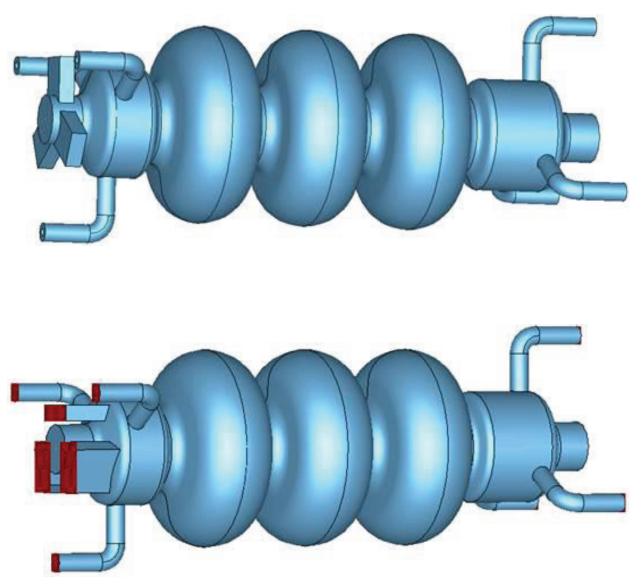

Figure 6: Two potential HOM damping schemes.

CONCLUSION

A 5-cell 422 MHz BNL4 cavity is developed for the FFAG lattice based eRHIC design, with consideration to the reduction of the loss factor (HOM power) and dipole and monopole HOM impedance for higher BBU threshold current. This cavity's performance will be demonstrated with a 3-cell Nb prototype Nb cavity, a contract for which has been rewarded to RI. The eRHIC electron beams can excite up to 7 kW HOM power per cavity, which has to be damped outside the cryomodule. A concept design with six coaxial HOM dampers for lower frequency and three waveguide HOM damper for high frequency HOMs is under study.

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