HIGH CURRENT SRF CAVITY DESIGN FOR SPL AND ERHIC*

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Abstract

A high current five-cell Nb superconducting cavity, called BNL3 cavity, was optimized and designed for the SPL and eRHIC. For the fundamental mode, the optimization process aimed at maximizing the R/Q of the fundamental mode and the geometry factor G under an acceptable RF field ratio level of B_{peak}/E_{acc} and E_{peak}/E_{acc}. For higher order modes, the optimization is to lower $(R/Q)Q_{ext}$ for dipole and quadrupole modes to suppress the beam-break-up (BBU). To extract the HOM power out of the cavity, the BNL3 cavity employs a larger beam pipe, allowing the propagation of HOMs, but not the fundamental mode. Six HOM couplers (three at each end) are used to extract large HOM power. To avoid the cross-talk between cavities, tapers are employed between the cavities. This paper presents the design of the BNL3 cavity, end groups and BBU simulation results.

INTRODUCTION

The BNL3 cavity is designed to serve as a universal, high-performance accelerating cavity dedicated for high average current superconducting RF linacs and ERLs. The optimization of performance parameters, such as the cryogenic loading or peak-surface-fields, is common to all superconducting RF linear accelerators. However, the damping of HOMs is crucial for high average current machines, such as at the SPL, ESS or eRHIC. eRHIC will be used as the basis for illustrating performance of the BNL3 cavity.

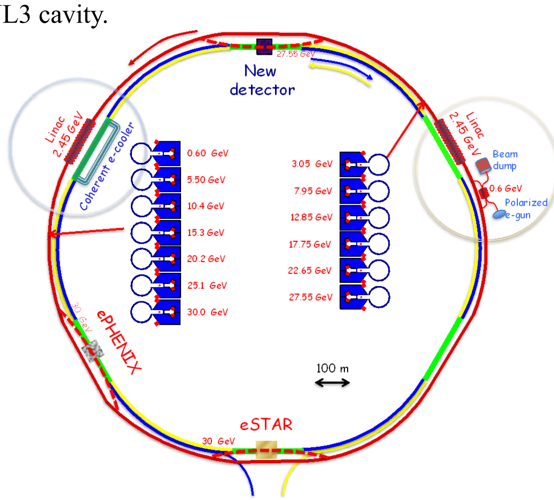

Figure 1: Schematic of eRHIC.

Figure 1 shows the schematic of the proposed ERL-based, all-in RHIC tunnel, 30 × 325 GeV, high energy and high luminosity eRHIC collider at Brookhaven National Laboratory [1]. eRHIC would employ 224 five-cell superconducting cavities in two linacs (located in two of RHIC's straight sections) to accelerate the 3.5 nC bunches in 50 mA electron current to 30 GeV of the six-pass ERL. Table 1 lists some beam parameters of the eRHIC project. The energy of the electron beam will be recovered back into the 5-cell SC cavities after the collisions and enable CW mode operation. One of the key requirements for the BNL3 cavity is to strongly damp the higher order modes, especially the high R/Q dipole and quadrupole modes.

Table 1: Some Beam Parameters of eRHIC

Parameters	eRHIC
Bunch change [nC]	3.5
Beam current [mA]	50
RMS Bunch Length [mm]	2
Number of passes	6
Beam energy [GeV]	5-30

CAVITY SHAPE AND MONOPLOLE MODES

Fundamental Mode

The BNL3 cavity [2] was optimized to minimize B_{peak}/E_{acc} and maximize R/Q for the fundamental mode. More importantly, the cavity shape was optimized for damping of HOMs effectively to satisfy requirements of high current ERL facilities. The optimized parameters for the elliptical cavity include the equator radius and profile, the iris radius, and the aspect ratio of the iris ellipse. The half-cell length depends on the cavity's fundamental resonant frequency f and electron beam velocity β, $L = \beta c/2f$ (where c is the speed of light). A large iris radius of $R_{iris} = 7.2$ cm was chosen to increase the cell-to-cell coupling, with a coupling factor of 3.02%. To allow propagation of HOMs into the enlarged beam tube, the iris radius of the end cups is 7.8 cm. The larger beam tube radius was selected to be 11 cm, allowing the propagation of all HOMs, but not the fundamental mode. To reduce the cross-talk phenomena between neighbouring cavities in a string, the enlarged beam tubes are tapered at both ends to the same radius as the end cup iris. Figure 2 shows the final design of the 5-cell BNL3 cavity in Superfish output. Table 2 compares the fundamental mode RF parameters of BNL3 cavity with BNL1, the cavity currently in use for the BNL ERL prototype [3]. From Table 2, it is evident that the BNL3 cavity shows great improvement in surface fields B_{peak}/E_{acc} or E_{peak}/E_{acc}, and 25% increase of R/Q.

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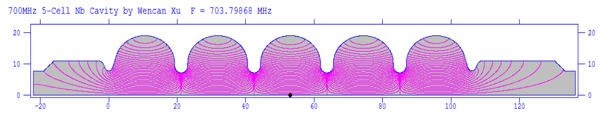

Figure 2: eRHIC cavity design.

Table 2: RF Parameters of the BNL3 and BNLI Cavities

Parameters	**BNLI**	**BNL3**
Frequency [MHz]	704	703.79
Number of cells	5	5
Geometry factor [Ω]	225	283
(R/Q)/Cavity [Ω]	404	506.3
E_{peak}/E_{acc}	1.97	2.46
B_{peak}/E_{acc} [mT/MV/m]	5.78	4.27
Coupling factor [%]	3.00	3.02

Monopole Modes

The 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:

$$P_{ave} = kI_bQ_b \tag{1}$$

The loss factor of the BNL3 cavity was calculated with ABCI [4] to be 3.6 V/pC for a Gaussian bunch of 2 mm RMS bunch length. With the parameters from Table 1, the average value of monopole mode HOM power in one BNL3 cavity is 630 W per pass. Given that the eRHIC ERL will have six acceleration passes and six deceleration passes, the HOM power load generated in each cavity is of the order of 7.5 kW, which presents a big challenge for removing it out of the cryostat.

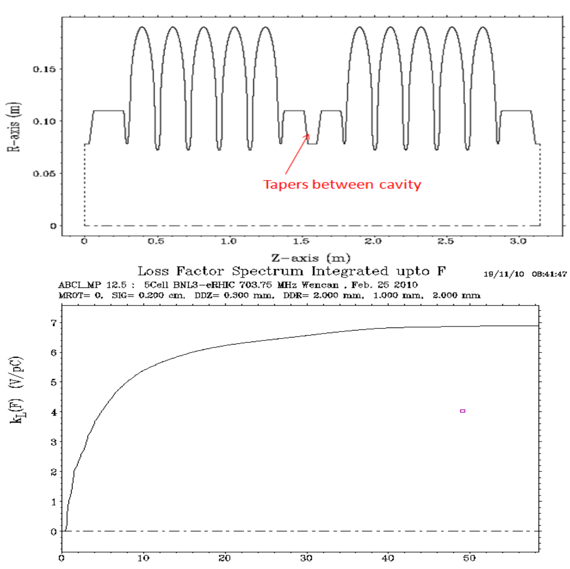

Figure 3: ABCI model of two cavities connected with taper (above) and loss factor spectrum (below).

Impact of Tapers

As it is described above, there is a taper at each end of the cavity to reduce the cross-talk between cavities. However, one may worry that the taper may increase the loss factor. In order to verify the taper impact, the loss factor with and without taper was calculated using ABCI. Figure 3 (top) shows the models in ABCI with taper, and the integrated loss factor spectrum for a Gaussian bunch of 2 mm RMS bunch length is shown in Figure 3 (bottom). The loss factor was calculated to be 7.01 V/pC. To compare the cavities connected without taper, an ABCI model was built for two cavities connected by a straight beam pipe, which is shown in Figure 4 (top). Figure 4 (bottom) shows the integrated loss factor spectrum for this model. The loss factor was found to be 6.97 V/pC. The results show that the symmetrical taper transition between cavities does not increase the loss factor, which can be explained with the analysis by L. Palumbo [5].

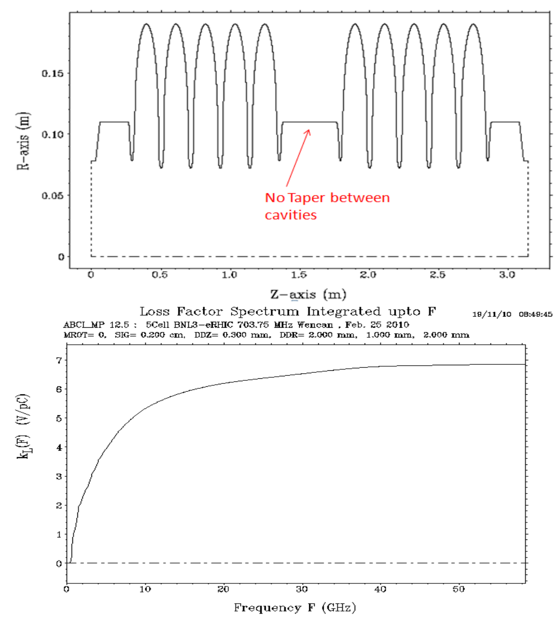

Figure 4: ABCI model of two cavities connected without taper (above) and loss factor spectrum (below).

DIPOLE MODES AND DAMPING

Dipole Modes and BBU Threshold

The transverse loss factor was calculated to be 3.1 V/pC/m using ABCI. In an Energy Recovery Linac, the electron beam goes through the same RF cavities more than once. The return of the electron beam can induce beam-break up (BBU), mainly depending on the characteristics of the dipole HOMs in the cavities. Assuming that HOMs behave independently and do not interfere with each other, the threshold current in the presence of a single HOM can be approximated as [6]

$$I_{\rm th} = \frac{2pc}{Q_{\rm b}k(R_{\rm d}/Q)Q_{\rm ext}M_{12}\sin(\omega T_{\rm r})} \tag{2}$$

where p is the beam momentum, c is the speed of light, k is the higher-order-mode's wave number, R_d/Q is the shunt impedance and Q_{ext} is the quality factor, M12 is the transport matrix parameter, and T_r is the bunch return time. From the threshold current formula (2), it is clear that a small R_d/Q and/or Q_{ext} can increase the threshold current. A smaller Q_{ext} means shorter damping time and larger current needed to deposit enough energy to disturb the beam.

HOM Damping

For damping HOMs in the BNL3 cavity, we developed a new two-stage HOM coupler [7]. To simulate effectiveness of the damping, we put two azimuthally spaced by 120° HOM couplers at each end of the cavity with a rotational offset of 60° between the pairs, as shown in Figure 5. The Q_{ext} of HOMs were calculated with CST Microwave Studio [8]. The result of HOM damping for dipole modes is shown in Figure 6. The Q_{ext} for most of higher order modes is below 10^4, except for four modes with resonant frequencies around 1.6 GHz. Fortunately, R/Qs of these modes are low, of the order of 0.1 Ohm. The final design will have three HOM couplers (azimuthally spaced by 120°) at each end of the cavity with 60° rotation between them in order to reduce power propagation through each HOM coupler.

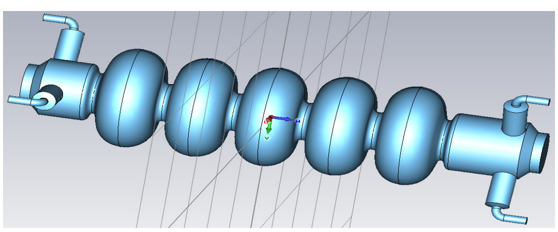

Figure 5: Cavity with two-stage HOM couplers.

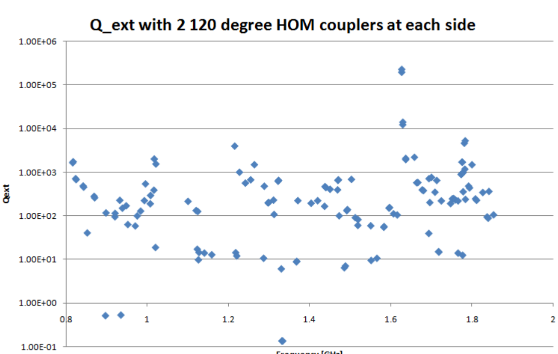

Figure 6: Q_{ext} of dipole HOMs.

MECHANICAL DESIGN

The cavity mechanical analysis and design was carried out at AES [9]. Figure 7 shows the layout of the cavity, which includes three HOM couplers at each side of cavity, a fundamental power coupler on the long beam pipe and a pick up probe on the short beam pipe. Table 3 lists operational characteristics of the cavity. A copper prototype will be fabricated to check the frequency tuning, field flatness, HOM spectrum and HOM damping, before Nb cavity is fabricated.

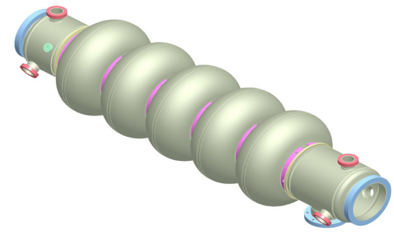

Figure 7: Layout of BNL3 cavity.

Table 3: Operational Characteristics of BNL3 Cavity

Parameters	Results
Frequency tuner sensitivity [kHz/mm]	157.5
Tuning range [kHz]	+/-700
Frequency tuning sensitivity [kHz/lbf]	0.160
Lorentz detuning coefficient [Hz/(MV/m)^2]	1.36
Helium pressure sensitivity [Hz/mbar]	26
First mechanical mode [Hz]	162
Calculated Q_0 @ 25 MV/m	2.0×10^{10}

SUMMARY AND CONCLUSIONS

The 5-cell BNL3 cavity is designed with low surface field ratio B_{peak}/E_{acc}, high (R/Q)Q and high cell-to-cell coupling. Tapers at each end of the cavity are used to reduce the cross-talk between cavities. We verified that the tapers between two cavities have negligible effect on the loss factor. Simulations show that with the enlarged beam pipe, optimized cavity shape and two HOM couplers at each end of the cavity, HOMs are well damped. The final design of the cavity will have three HOM couplers at each end. This configuration will be tested on the prototype cavity.

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