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DESIGN AND PROTOTYPING OF THE ELECTRON ION COLLIDER ELECTRON STORAGE RING 591 MHZ ELLIPTICAL SRF CAVITY*

J. Guo†, Z. Conway, A. Fuller, J. Henry, J. Matalevich, R. A. Rimmer, D. Savransky
JLAB, Newport News, VA 23606, USA
D. Holmes, W. Xu, A. Zaltsman, BNL, Upton, NY, USA

Abstract

The Electron Ion Collider (EIC) is a new nuclear physics research facility to be constructed at Brookhaven Lab (BNL). It consists a few accelerator complexes, each requires some SRF and/or RF cavities to be newly built or modified. Among them, the electron storage ring's (ESR) 591 MHz fundamental RF system is one of the most challenging. This 17 cavities system will handle a variable beam current of up to 2.5 A, and replenish up to 10 MW of beam power losses from both synchrotron radiation (SR) and high-order modes (HOM). In this paper, we will report the progress of the ongoing prototyping of this cavity and the design of the cavity string.

EIC ESR RF SYSTEM

EIC ESR is a high current electron storage ring required to operate at a wide range of beam energy (5-18 GeV) and beam current (0.23-2.5 A average, with one abort gap) [1, 2]. The RF system is required to provide up to 10 MW beam power for the electron beam to replenish the synchrotron radiation and HOM losses, to be implemented with 17 single cell 591 MHz SRF elliptical cavities.

The wide range of operating beam energy results in large variation of system voltage, beam current and synchrotron phase. If all cavities operate at the same synchrotron phase, a factor of 10-20 tuning range in external quality factor (Qext) is required to minimize the reflected RF power and suppress the Robinson instability of the beam. In [4, 5] we have presented a Qext tuner design, and discussed the alternative to operate some cavities in reversed a.k.a. defocusing phase for low energy cases. The reversed phase operation (RPO) can increase the voltage of each cavity while keeping the vector sum of voltage the same, reducing the required range of Qext variation. Transient beam loading effects induced by the abort gap in the ring can also be mitigated by the higher stored energy in the RPO, in combination with a low R/Q design. This concept has been demonstrated at SuperKEKB [3]. With RPO, it's possible to operate the ESR cavities with a fixed Qext of ~2×10^5, while the reflected RF power is tolerable.

One ESR cavity will have two fundamental power couplers (FPC), each powered by a 200 kW SSA, to be installed in the initial phase. The Qext of the cavities can be fixed at 2×10^5 without RPO in this phase. The SSAs will be upgrade to 400 kW later to provide the full beam power. Recently the decision was made that the same cavity will be also used in the hadron storage ring (HSR), with single FPC and one smaller SSA.

EIC ESR CAVITY STRING RF DESIGN

The ESR cavity chose an asymmetric design, as shown in Fig. 1. The gate valves were chosen with 75 mm radius, the largest available that's possible to fit in the space through the cryomodule's vacuum vessel. The left side of the cavity has a 137 mm beampipe and tapers to 75 mm, while the radius of the beampipe on the right side is 75 mm without tapering. The large beampipe helps to lower the fundamental mode R/Q to 38 Ω (circuit definition) as well as to damp the lowest dipole HOMs with a beamline absorber (BLA). The pair of coaxial FPCs are installed on the small beampipe side, providing more room for the FPC warm to cold transition, which is constrained by the transverse size of the cryomodule. The nominal maximum voltage of each ESR cavity is 4 MV, and the gradient is 15.8 MV/m. Two single-cavity cryomodules will be arranged in one straight between two quadrupole magnets.

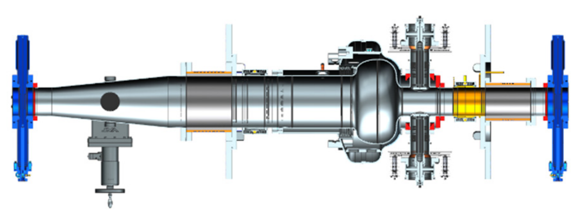

Figure 1: ESR cavity string, cut view from top.

HOM analysis and BLA development

Each ESR cavity will use two BLAs to damp the HOM, as shown in Fig 1 and 2. The BLA uses a cylindrical warm SiC absorber flush to the inner radius of the beampipe, with the shrink-fit technique similar to the BLAs used in APS-Upgrade [6]. A prototype with inner radius of 154 mm was developed at BNL and high power tested recently [7, 8], surviving the loss density of 0.44 W/mm^2 and failed at 0.64 W/mm^2. The exact failure threshold is to be determined. The design of the 75 mm and 137 mm radius versions will be scaled from the prototype.

The cavity needs to handle up to 2.5 A beam current with bunches of 7 mm long and 27.6 nC charge, repeating at 98.5 MHz. The BLAs will absorb not only the HOM power excited in the cavity, but also excited within the BLA. With the comparably small radius, the self-heating of the 75 mm radius BLA can reach 0.26 W/mm^2 with the 2.5 A beam current. In the previous design iteration, the length of the 75 mm radius BLA was set at 120 mm, sufficient to damp

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† jguo@jlab.org

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the cavity monopole and dipole modes impedance below the design goal [4]. However, the power flow monitor in the short range wakefield simulation showed that this BLA will have a heat load of up to 26.5 kW or 0.47 W/mm^2, a level that's close to the failure threshold. The latest design extended the BLA to 240 mm long. Figure 2 showed the results of a simulation of the two cavities system with 240 mm long small BLA, reducing the total loss density to 0.36 W/mm^2, and the left half of the BLA will have slightly higher loss density of 0.38 W/mm^2, while the total HOM loss per cavity increases from 61 kW to 72 kW.

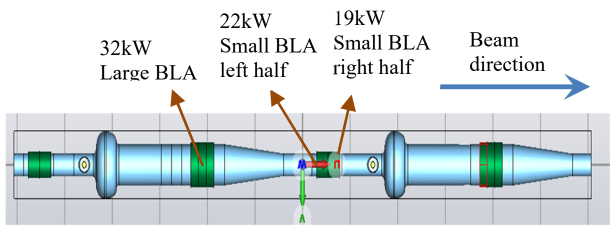

Figure 2: HOM loss power flow monitored in two BLAs of two cavities, 7 mm 27.6 nC bunches, 2.5 A average current.

With the design of cavity string components maturing, more iterations of long range wakefield simulation are needed to update the HOM impedance estimate. However, with a longer 75 mm radius BLA, the results are not expected to be worse.

RF Shielded Bellows for Warm-to-Cold (WTC) Transition

The ESR 591 MHz cryomodule requires a pair of WTC bellows in the beampipe to provide thermal isolation between the cavity and the vacuum vessel, as well as the mechanical compliance due to cavity tuning, cryomodule cool down, and assembly/fabrication tolerance. The bellows need to be RF-shielded from the wakefield of the high current beam with different bunch fill patterns of 98.5 MHz (1160 bunches), 49.3 MHz (580 bunches) and 24.6 MHz (290 bunches). The RF-shield can't have sliding contacts due to cleanliness requirements in the SRF section, making the design more challenging. A choke shielded design was chosen, and two versions with different beampipe radii (75 mm and 137 mm) are under development. The design concept may also be applied to other parts of the EIC, like the warm bellows in the ESR SRF sections.

The choke shielded bellow design for ESR was inspired by the BESSY VSR cold bellow, which has been tested with up to 400 mA beam current at room temperature [9]. Figure 3 shows the concept of the ESR shielded WTC bellow. It is shielded with a labyrinth like choke, which also separates the warm and cold sections. The assembly is water cooled on the warm side, 4 K trace cooled on the cold side, with a 50 K intercept in the middle of two bellow sections. The choke will be made of copper, however a stainless steel cylinder can be brazed to the warm choke, and help to concentrate the loss on the warm side, reducing the cold side loss and cryogenic load.

The main concern for this design is the monopole modes trapped in the quasi coaxial structure behind the shield, which may generate significant heat load when the bellow is deformed and one or more modes hit the beam excitation line. Modes above the cut-off of the beampipe will be well damped by the BLAs, the total HOM heat will be significantly reduced in case of hitting resonance, and mostly absorbed in the BLAs.

The shielded bellows are optimized so that most of the monopole modes are expelled above the beampipe cut-off. For both the 75 mm and 137 mm radius versions there is only one trapped monopole mode. This mode is tuned to a frequency away from excitation lines in the multiples of 24.6 MHz. Lower frequency helps to lower the heating. This mode's H-field is concentrated on the warm side, as shown in Fig. 4, which also reduces the cryogenic load. The R/Q of this mode is around 3 Ω (circuit definition) in the 137 mm radius bellow, with small variation depending on the deformation. The 137 mm radius bellow can be compressed/stretched by a total of 12 mm with a frequency range of 14 MHz around 260 MHz, far enough from the excitation lines of 246.3 MHz and 270.9 MHz. Deformation in other dimensions may contribute to the frequency change, but expected to be a much smaller extent. For the 75 mm radius bellow, the allowable range of longitudinal deformation is much smaller due to the higher cutoff and trapped mode frequency, only around 3 mm. The 75 mm radius bellow also has smaller compliance range requirements, with very small cool down contraction and no deformation due to tuning.

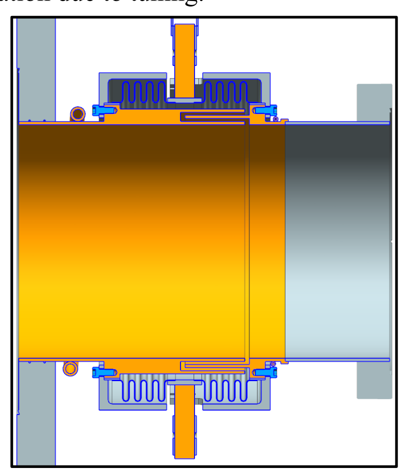

Figure 3: EIC ESR choke shielded WTC bellow.

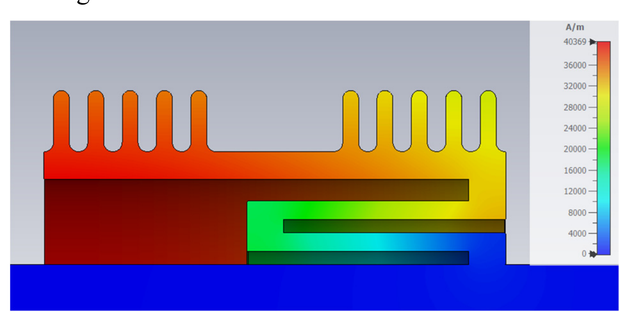

Figure 4: H-field of the trapped monopole mode (260 MHz) in the 137 mm radius shielded bellow.

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PROTOTYPE CAVITY FABRICATION

The EIC R&D effort includes to fabricate and test a functional prototype cavity, which helps to understand the fabrication process requirements, and verify the RF/thermal/mechanical design of the cavity. All subcomponents of the cavity were first test built from aluminum before being built from niobium. The prototype will be cryogenic tested at 2K in the Jefferson Lab Vertical Test Area (VTA).

This 591 MHz cavity has the largest diameter among all cavities JLab has built. In order to fabrication the cavity, it was split up into separate bodies that could be built independently and then electron beam weld (EBW) or braze together. The fabrication flow is shown in Fig. 5. The main parts are the two asymmetric half-cell, the two sized beampipes, and the FPC pipes.

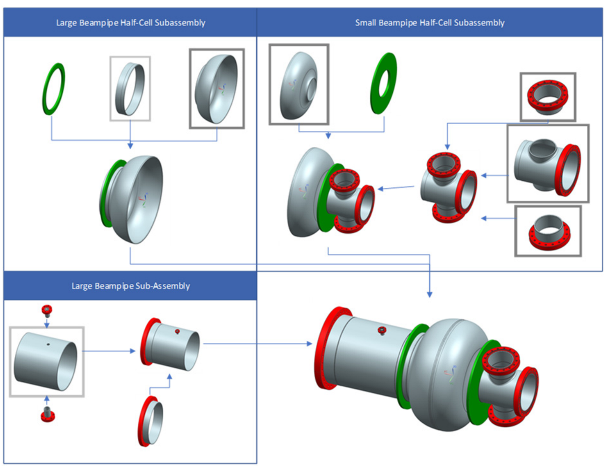

Figure 5: ESR Elliptical R&D Cavity Fabrication Plan.

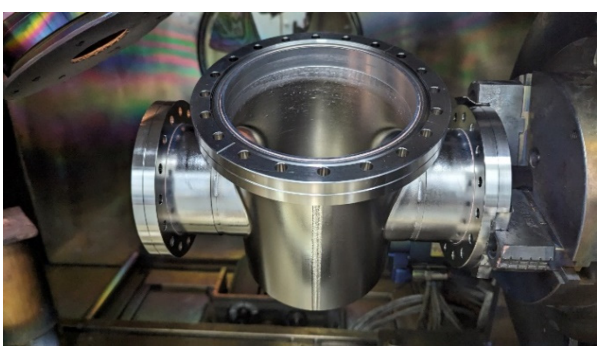

Figure 6: Niobium small beampipe subcomponent after EBW.

Figure. 7: Niobium subcomponents of the 591 MHz cavity.

The FPC ports were first pulled from the small beampipe. Due to the close radius between the small beampipe and the FPC ports (about 3:2 ratio), it's challenging to pull the port with a wall long enough to trim to flat. Two niobium FPC pipes were first brazed to the stainless steel flanges and then EBW to the small beampipe, as shown in Fig. 6. The half cells were pressed with dies designed with springback compensation. A few trimming iterations have been performed to make sure the welded cavity will have a frequency close to the recipe and require minimal plastic bench tuning. The large beampipe has been rolled and welded together. Figure 7 shows all the 4 subcomponents, and Fig. 8 shows the 4 subcomponents stacked into the cavity.

The large beampipe will be cut into three pieces soon, with one piece brazed with the flange. We will EBW the subcomponents from the small beampipe side to the large beampipe side in the near future.

Figure 8: Subcomponents stacked into the 591 MHz cavity (not welded yet).

CONCLUSION AND FUTURE WORK

We have reported the latest updates of the design and prototyping of the EIC ESR cavity and string components. Fabrication of the prototype cavity is ongoing, with all niobium pressing complete and a few weld and braze done. The remaining weld and braze is expected to be complete shortly, and on schedule for vertical testing late this summer. The RF/thermal/mechanical design and analysis/optimization of the full cavity string is also moving forward, integrating the Qext tuning network, FPCs, doorknob transitions, BLAs, shielded bellows, RF gaskets, etc. The shielded bellow designs need to be finalized.

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