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CAVITY AND CRYOMODULE DEVELOPMENTS FOR EIC *

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Abstract

The EIC is a major new project under construction at BNL in partnership with JLab. It relies upon a number of new SRF cavities at 197 MHz, 394 MHz, 591 MHz and 1773 MHz to pre-bunch, accelerate, cool and crab the stored beams. R&D is focusing on the 591 MHz elliptical cavity and 197 MHz crab cavity first as these are the most challenging. Preliminary designs of these cavities are presented along with an R&D status report. To avoid developing multiple different cryostats a modular approach is adopted using a high degree of commonality of parts and systems. This approach may be easily adapted to other frequencies and applications.

OVERVIEW OF SRF SYSTEMS FOR EIC

The electron ion collider (EIC) [1], is a complex machine incorporating many of the challenges of e+e- factories, hadron-hadron colliders and even light sources. The complex consists of a hadron injector complex and storage ring based on upgrades to the RHIC facility, a new high-current electron storage ring and an RCS as a full energy injector. Most of the existing RF systems for RHIC will be retained or repurposed however new 591 MHz SRF bunching systems will be needed in both collider rings to attain the short bunches needed for high luminosity. In the high-current ESR these will be heavily HOM-damped single-cell cavities similar to those used in the B-factories, with high power beam line absorbers (BLAs). Table 1 lists the high level parameters for the ESR. Dual 400 kW fundamental power couplers will be used on each cavity. In the HSR the current is 0.75 A so multi-cell cavities can be used and the required voltage is about 20 MV. One or two 5-cell cavities can fulfil these requirements. Although HOM power will be lower than the ESR good damping is still required and the impedance of same-passband modes must be carefully managed. In the CDR a scaled version of a previous 5-cell cavity was assumed. Similar 5-cell cavities can be used in the RCS and in the ERL for strong hadron cooling (SHC). 1773 MHz harmonic cavities are needed to linearize the cooler linac and 197 MHz buncher cavities are needed in the injector. A low energy pre-cooler ERL is also proposed that would use 197 MHz accelerating cavities. The other major SRF system in EIC is the crabbing cavities for the interaction point (IP). Because of the large crossing angle a high crabbing voltage is needed. Due to the long bunch length in the hadron ring 197 MHz cavities are chosen with 394 MHz harmonic cavities to maintain a linear crab kick along the bunch length. The shorter bunch length in the ESR allows single 394 MHz crabbing systems to be used. Given the large number of systems to be developed a modular cryostat approach with a high degree of commonality of components is being followed to minimize design effort and speed up development.

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R&D PRIORITIES

Four items were chosen for early R&D based on risk; the 591 MHz ESR single cell, the 197 MHz crab cavity, the 400 kW FPC and the high power BLA. One prototype of each cavity will be built and tested and small batches of FPC's and BLA's will be built and evaluated. The other cavity types are assumed to be lower risk or can be developed by extrapolating from these designs, e.g. the 394 MHz crab cavity can be developed using lessons learned from the 197 MHz prototype and the 5-cell 591 MHz cavities can be developed from the single cell.

591 MHz ESR 1-CELL CAVITY

The CDR describes a symmetric 1-cell cavity using two large beam pipe absorbers, developed from an earlier 2-cell design in the pre-CDR. see Fig. 1. The number of cavities is determined by the peak voltage needed to maintain adequate bucket height at 18 GeV and the amount of coupler power needed to replace synchrotron radiation and other losses, see Table 1.

The high average current and naturally short bunch length lead to high HOM power of >40 kW per cavity. Up to 10 MW of beam power must be supplied and symmetric dual 400 kW FPC's will be fitted to each of the 17 single-cell cavities.

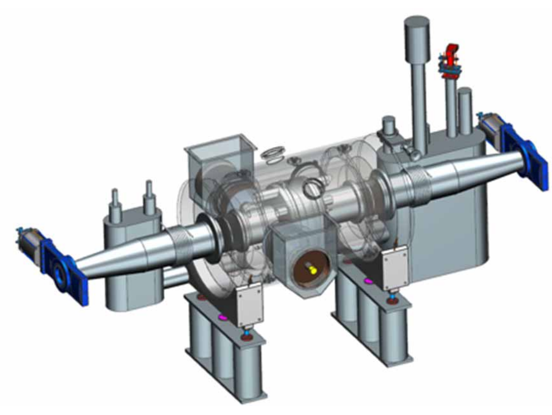

Figure 1: Symmetric single cell 591 MHz SRF cryomodule with two large warm BLA's and tapers in the CDR.

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Table 1: ESR RF Requirements

V (MV)	I (A)	No. cavities	Beam Power (MW)	Coup. power (kW)	HOM power (kW)
68	2.5	17	10	400	>40

RF Design

The cavity is a low R/Q design to minimize beam gap transients and overall impedance. The large beam pipes needed for HOM damping must be tapered down to fit through the straight section quadrupole magnets. 150mm ID shielded gate valves are chosen to isolate each module. The CDR assumes one cavity per cryomodule as in KEK-B and other rings. Since the CDR a more compact design with one large and one small beam pipe has been developed, Fig. 2, eliminating one taper and one large BLA. This asymmetric design is about 25% shorter, and has 11% lower loss factor, although the power in the one remaining large BLA is increased by 13%. A comparison of the two designs is given in Table 2. Both cavities meet the requirements for longitudinal impedance less than 1.53 kΩ-GHz and transverse impedance less than 0.71 MΩ/m per cavity for 17 cavities.

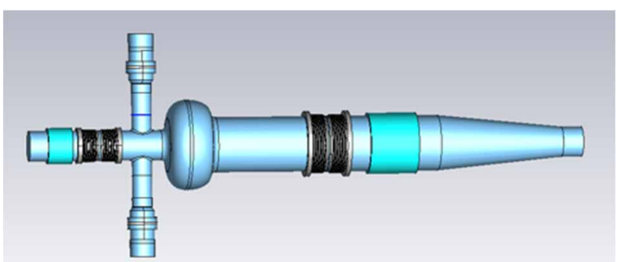

Figure 2: New asymmetric 591 MHz 1-cell SRF cavity with one large and one small BLA. About 64% of the HOM power goes to the large BLA, 28% to the small one and 8% exits the beam pipes.

Table 2: Basic ESR Cavity Design Parameters

Parameter	Sym.	Asym.
R/Q (circuit definition, Ω)	37	38
Epk/Eacc	2.13	2.01
Bpk/Eacc (mT/MV/m)	4.87	4.87
G (Ohms)	293	307
FPC tip penetration at Qext=3.5E5	1mm	3mm
Approx. total length (Gate valve to gate valve)	3.75m	2.8m

Figures 3 and 4 show the longitudinal and transverse impedance spectra of the asymmetric cavity. Coupled-bunch feedback systems will give additional margin on top of this.

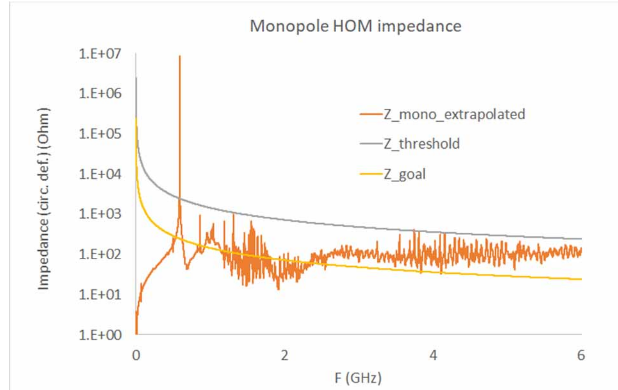

Figure 3: Monopole impedance of asymmetric 591 MHz SRF cavity.

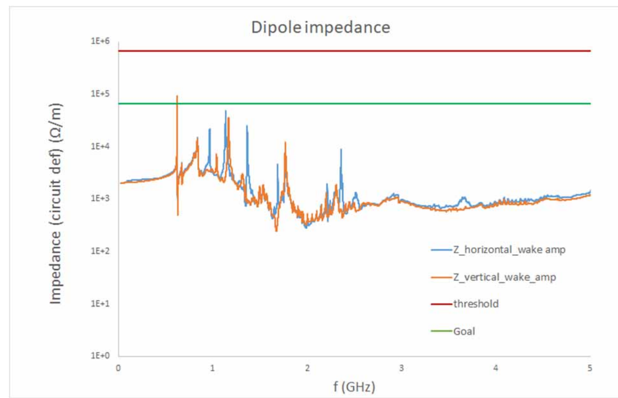

Figure 4: Dipole impedance of asymmetric 591 MHz SRF cavity.

Mechanical Design

Although large the ESR cavity can withstand atmospheric pressure without external support and once in the helium vessel with tuner fitted will be able to withstand maximum over-pressure of 2.2 atmospheres warm. Tables 2 and 3 show the mechanical properties of the bare cavity. Figures 5 and 6 show ANSYS simulations of the tuning force and pressure analysis, as shown also in Table 4. Stiffeners will be added to control Lorentz force detuning and pressure sensitivity as needed. Vertical test results will be available in time to influence the first article cavity and cryostat.

Table 3: Mechanical Properties of Bare 591 MHz cavity

Tuning Sensitivity (KHz/mm)	Stiffness (N/mm)	Elastic tuning range (mm)	Force to Yield (N)
447.05	14,258	0.435	6,200

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Table 4: Pressure sensitivity of warm cavity with both ends constrained, no stiffeners.

Pressure (atm), 295.15K	Pressure sensitivity (Hz/atm)	Stress (MPa)	Safe?
1	12,028	19.97	Yes
2	12,003	39.94	Yes
3	11,979	59.91	No

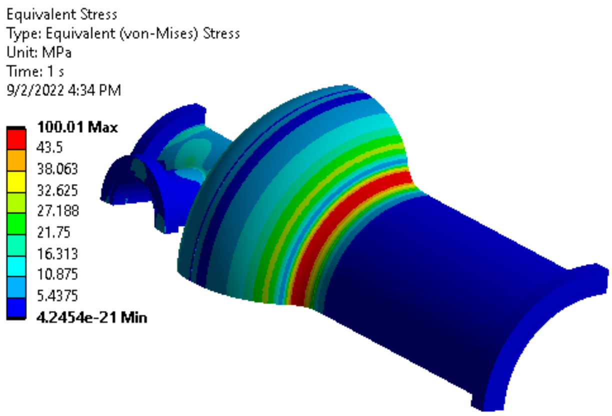

Figure 5. Tuning deformation of 591 MHz 1-cell cavity.

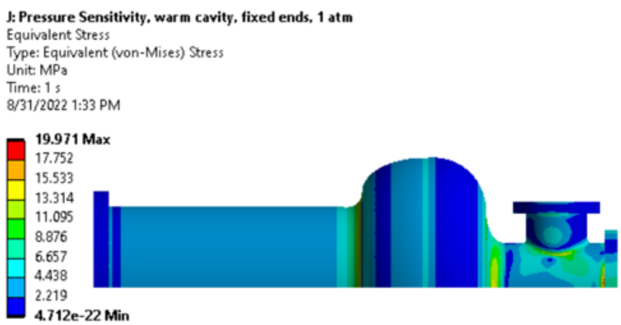

Figure 6. Pressure sensitivity of warm cavity with both ends constrained, no stiffeners.

Thermal Design

Initial thermal analysis, Fig. 7, shows that the 400 kW FPC can be integrated into the cryostat using a helium gas cooled connection similar to the SNS cryostat. The coupler port location is chosen to allow the lowest Q_{ext} foreseen in any operating scenario to be achieved. The FPC will be fixed but will have a range of Q_{ext} adjustment by stub tuners in the external circuit. Fig. 8 shows the proposed fabrication scheme which follows conventional SRF construction practices. Subject to final design review it is intended to start prototyping the bare cavity in the near future.

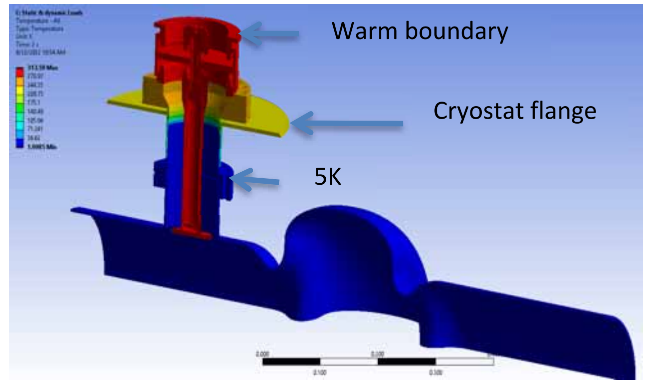

Figure 7: Preliminary thermal analysis of FPC cold to warm transition.

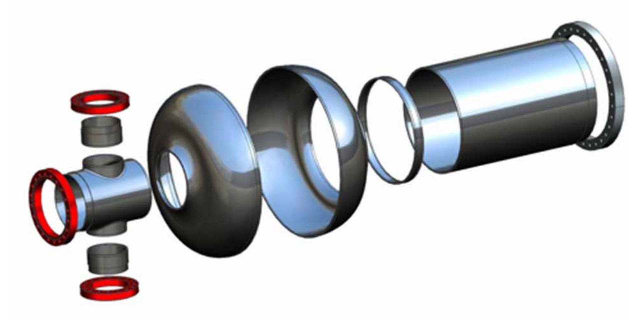

Figure 8: Fabrication model of the 591 MHz 1-cell SRF prototype cavity.

197 MHz CRAB CAVITY

The crab cavity systems for EIC are very challenging, combining low frequency, high gradient and high HOM power. Hence the 197 MHz crab was chosen for early R&D and prototyping. Both RFD and DQW designs were evaluated based on prior experience with the cavities for LHC. Both designs met requirements. The RFD design was selected for EIC as the fabrication plan was slightly further advanced. Table 5 shows the high level parameters. Because of the high hadron energy and the large crossing angle almost 34 MV of installed voltage is needed, with four cavities each side of each IP. The cavity qualification will include margin to be able to run with one cavity off. Second harmonic 394 MHz cavities are needed to linearize the crab kick over the long hadron bunches. The ESR having lower energy electrons can get by with a single 394 MHz cavity each side of each IP, but the higher current makes the HOM damping even more demanding. The impedance budget allows for a future second IP.

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Table 5: Crab Cavity RF Requirements

	V_t (MV)		No. Cavities per IP	
system	HSR	ESR	HSR	ESR
197 MHz	33.8	-	8	-
394 MHz	4.75	2.9	4	2

RF Design

The 197 MHz RFD cavity is optimized to minimize peak surface fields and most multipacting barriers by careful choice of dimensions. The poles will be held fixed in operation to avoid variability in multipole components and tuning will be made via the side walls. The cavity will have compact "dog-bone" waveguide HOM dampers on the end caps to un-trap all harmful HOMs. Four identical ports will be used, two vertical and two horizontal, to maintain symmetry, see Fig. 9. In the 197 MHz cavity one vertical and one horizontal port will be terminated by broad-band HOM absorbers. The other horizontal port will accommodate the FPC and the remaining vertical port will house the field probe. Two options are under consideration for the absorbers, internal waveguide types, Fig. 10 and external loads with a cold coax to waveguide transition inside the module, Fig. 11. Both options meet the stringent HOM damping requirements and the module length is the same in each case. A selection will be made at a later date based on cost and manufacturability. The choice is independent of the cavity prototyping since the ports are the same in either case. Figures 12 and 13 show the transverse and longitudinal impedances of the cavity and Figs. 14 and 15 show the two module options. Figure 16 shows an early concept of the 394 MHz crab cavity that must handle the higher HOM power of the ESR. In this concept all four ports are terminated to share the HOM power between more loads.

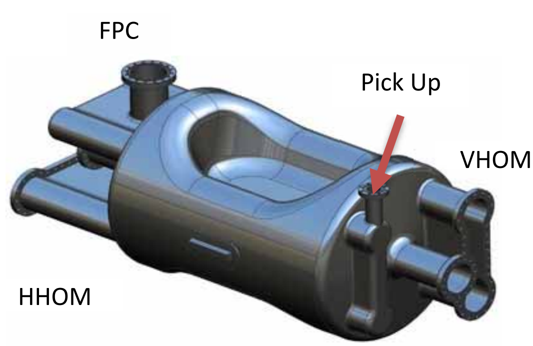

Figure 9: 197 MHz RFD type crab cavity.

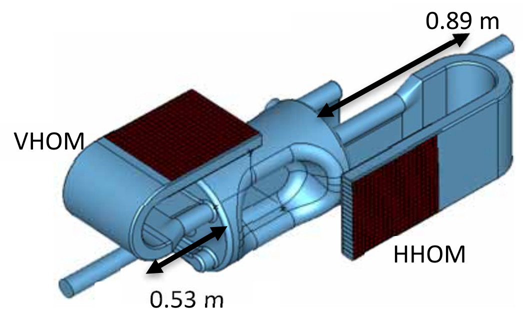

Figure 10: RFD with waveguide HOM absorbers.

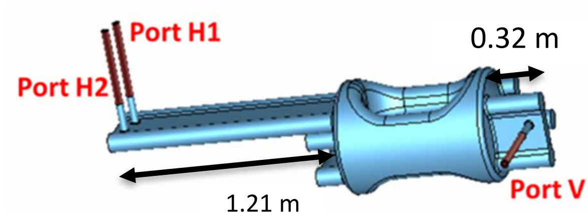

Figure 11: Crab cavity with coaxial HOMs.

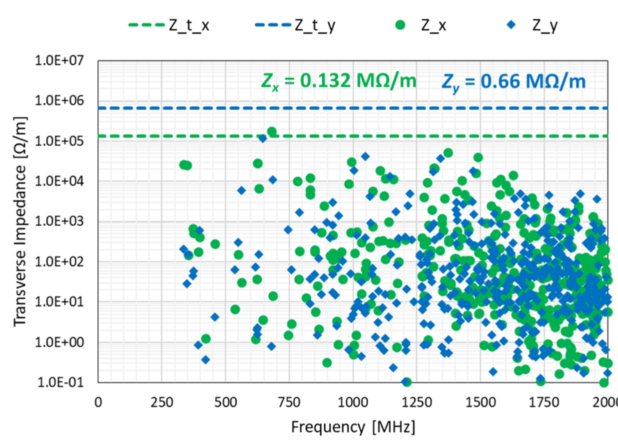

Figure 12: Transverse impedance of modes in the 197 MHz crab cavity.

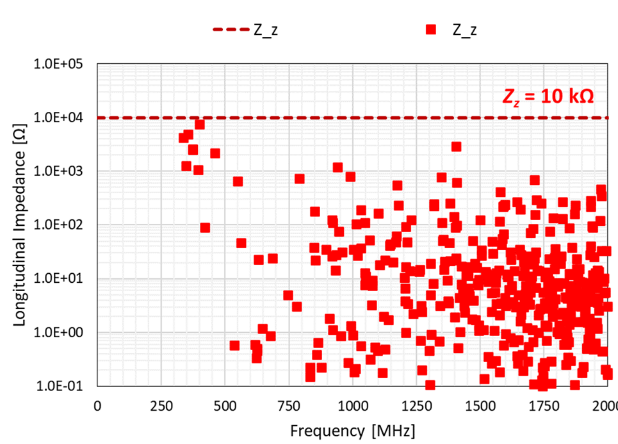

Figure 13: Longitudinal impedance of modes in the 197 MHz crab cavity.

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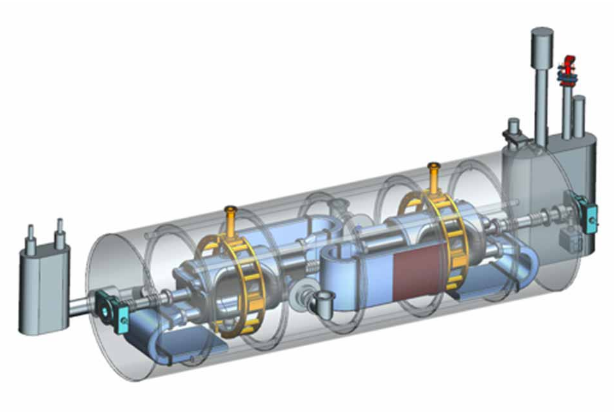

Figure 14: 197 MHz crab cavity cryomodule with internal waveguide HOM loads.

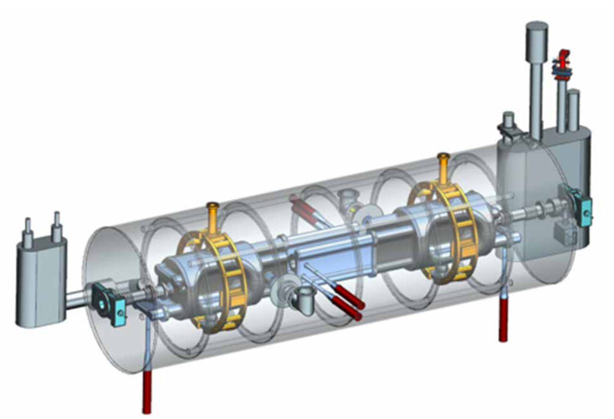

Figure 15: 197 MHz crab cavity cryomodule with exteral coaxial HOM loads.

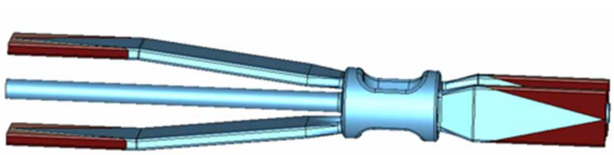

Figure 16: Simulation model of 394 MHz crab cavity concept with 4 HOM absorbers to handle the increased power of the ESR. In practice the waveguides would be folded similarly to the 197 MHz cavity.

Mechanical Design

The 197 MHz crab cavity is very large and cannot withstand significant external pressure without additional support. An external frame will be used to maintain the pole separation and fix the tuner mounts during handling and leak checking and the end caps will be constrained longitudinally against external pressure. For the bare cavity prototype this cage will also support the cavity during processing and vertical testing. For the production cavities this function will be incorporated into the helium vessel design. Detailed mechanical analysis of the cavity and cage are ongoing.

The fabrication of the cavity is complicated by the shape and size of the parts. It will not be possible to deep draw the poles in one step so the poles will be fabricated from sub-assemblies and joined to the "saddle" part of the body by e-beam welding. Side plates that also incorporate the tuner mounts will join the poles together to form the central barrel of the cavity. The end caps will be assembled from pressed dishes, dog bone waveguides and beam tubes. At this stage all surfaces are accessible for trimming and mechanical polishing if needed. The final joins will be circumferential full-penetration e-beam welds between the end caps and the body. Figure 17 shows the high level assemblies. Details of the sub-assembly fabrications are still being developed. Subject to design review, fabrication of the prototype 197 MHz crab cavity will begin in the near future.

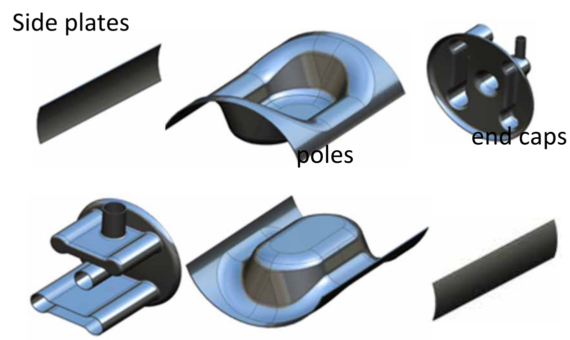

Figure 17. Major high-level subassemblies of the 197 MHz crab cavity prototype. Each assembly will be made from several smaller parts.

FPC AND BLA

The 400 kW FPC and high power beamline absorbers are critical components and therefore chosen for early R&D. The FPC [3], has gone through one design iteration already based on early testing experience. The design features a robust high purity alumina ceramic, water-cooled inner and warm outer conductors, a choke design for low surface fields on the ceramic and triple joints and mechanical design capable of withstanding 10G shock loads, see figure 18 . Six next-generation couplers will now be fabricated and tested with two being aimed at the first article cryomodule. The cold to warn outer conductor transition will have helium gas cooling to minimize dynamic load to the cryogenic system.

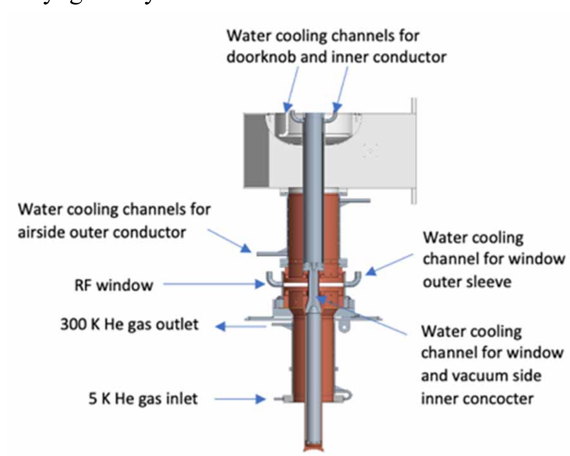

Figure18. High power FPC with water-cooled antenna and helium gas cooled cold outer conductor.

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The high power beam line absorber [4], follows the "shrink fit" approach used by Argonne National lab for the APS upgrade. A one-piece cylinder of silicon carbide loaded dielectric absorber is fitted inside a water cooled jacket with no water to vacuum braze joints, see figure 19. Although the HOM power is high the power density in the large ceramic is within already demonstrated limits. Two prototypes have already been successfully completed and passed outgassing and low power RF tests. High power tests using a klystron RF source are planned soon.

Figure 19. Dielectric beam line absorber with shrink-fit cooling jacket.

5-CELL AND OTHER CAVITIES

In addition to the cavities selected for early R&D several other important designs are needed. The HSR, RCS and cooler ERL all require 591 MHz 5-cell cavities. These are assumed to be developed from the ESR 1-cell and are the same in all applications, using two high power BLA's with tapers, see figure 20. While this design will likely meet all requirements for beam voltage, HOM damping etc, the BLA end groups are sized for the high current HSR and may be more than what is required in the other applications. The long end groups drive the size of the cooler ERL and in the future more compact HOM end groups could be considered for the RCS and ERL.

Other cavities needed include a 1773 MHz 5-cell cavity for linearization in the cooler. This can be similar to CEBAF multi-cell designs or scaled from the 591 MHz 5-cell cavity. The cooler injector and proposed low energy precooler will need 197 MHz quarter wave accelerating cavities. These can be conventional SRF designs except for the high power couplers and strong HOM damping needed. These cavities are not part of the early R&D program, but basic concepts are being developed for layouts, costing etc. as needed.

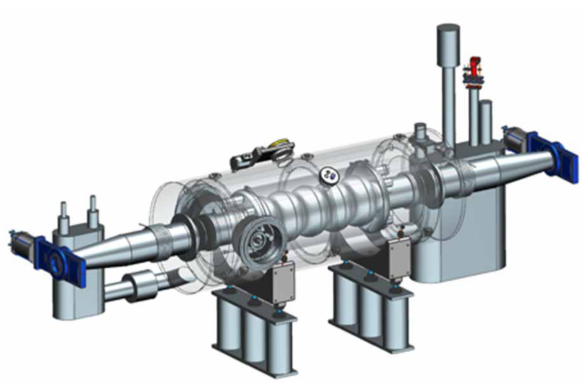

Figure 20: 5-cell cavity module for use in the HSR, RCS and cooler developed from ESR 1-cell.

MODULAR CRYOSTAT

In order to reduce costs, speed up development and provide for ease of support and maintenance a modular approach is being taken in developing the various cryomodules needed for EIC. Using standardized dimensions for vacuum vessels, helium vessels, end cans, couplers, valves etc. ensures a high degree of commonality between the modules. Differences are kept to a minimum and only when driven by requirements, such as the 197 MHz crab cavity, which is significantly bigger than all the other cavities. Even then many common components and subassemblies can be used. For simplicity and ease of integration the cryostat dimensions used for the SNS PPU, which is currently in production at JLab, were taken as the starting point. While the details of the 2 K cryogenic distribution for EIC have not been finalized we have used the SNS end cans with bayonet fittings as a basis, however these are literally "bolt-on" and can be replaced by a different interconnect scheme if necessary.

CONCLUSIONS

A variety of challenging cavities, cryomodules and ancillary components are needed for EIC. The designs from the CDR are being further developed to be ready for the TDR and CD2. The ESR 591 MHz single cell and the HSR 197 MHz crab cavities were selected for early R&D and good progress has been made on these designs. The high power FPC and BLA, which are critical components, have similarly progressed to prototyping and testing. More designs are needed but these will be developed from and informed by the early R&D models. The modular cryostat approach will speed up development, minimize total cost and design effort and allow common spares and easier support of the machine in operation.

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