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MANUFACTURING THE HARMONIC KICKER CAVITY PROTOTYPE FOR THE ELECTRON-ION COLLIDER*

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Abstract

High-bunch-frequency beam-separation schemes, such as the injection scheme proposed for the Rapid Cycling Synchrotron at the Electron-Ion Collider, demand rise and fall times an order of magnitude below what can realistically be accomplished with a stripline kicker. Nanosecond-time-scale kick waveforms can instead be obtained by Fourier synthesis in a harmonically resonant quarter-wave radio-frequency cavity which is optimized for high shunt impedance. Originally developed for the Jefferson Lab Electron-Ion Collider (JLEIC) Circulator Cooler Ring, a hypothetical 11-pass ring driven by an energy-recovery linac at Jefferson Lab, our high-power prototype of such a harmonic kicker cavity, which operates at five modes at the same time, will demonstrate the viability of this concept with a beam test at Jefferson Lab. As the geometry of the cavity, tight mechanical tolerances, and number of ports complicate the design and manufacturing process, special care must be given to the order of the manufacturing steps. We present our experiences with the manufacturability of the present design, lessons learned, and first RF test results from the prototype.

BACKGROUND

In January of 2020, the U.S. Department of Energy (DOE) chose Brookhaven National Laboratory (BNL) as the site for building an Electron-Ion Collider (EIC) over the competing Jefferson Lab Electron-Ion Collider (JLEIC), creating a new partnership between the two labs [1]. The Harmonic Kicker cavity was originally intended for the JLEIC Circulator Cooler Ring (CCR), a hypothetical 11-pass ring driven by an energy-recovery linac at Jefferson Lab [2], but is now envisioned with BNL as a potential injection device for their Rapid Cycling Synchrotron (RCS) [3].

The JLEIC cavity is a harmonically resonant quarter-wave radio-frequency cavity driven with the Fourier synthesis of odd multiples (1, 3, 5, 7, and 9) of its designed fundamental resonant frequency, which is the frequency between the injected and extracted bunches in and out of the CCR. In principle, this Fourier synthesis produces a narrow pulse, as shown in Fig. 1, that will kick every eleventh electron bunch without disturbing intermediate bunches [4].

The first prototype cavity was a simplified half-scale version with a fundamental resonant frequency of 95.26 MHz and was built and tested at Jefferson Lab in 2016 [5]. Presently, a high-power, water-cooled, vacuum-compatible JLEIC prototype with a fundamental resonant frequency of 86.6 MHz is nearly complete and will undergo a beam test at Jefferson Lab's Upgraded Injector Test Facility (UITF) by mid-October. The properties of this final JLEIC version of this cavity give rise to a multitude of challenges that have complicated the design and manufacturing processes as outlined in the following sections.

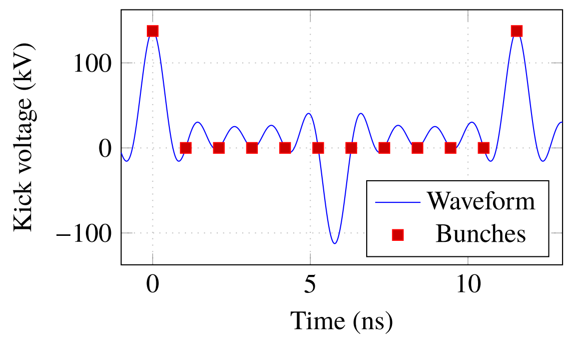

Figure 1: Kick action only on bunches at a bunch frequency equal to the fundamental of the kick waveform, $f_{HK} = 86.6$ MHz; in this example, all 11 buckets are filled at a bunch frequency of $11 f_{HK} = 952.6$ MHz.

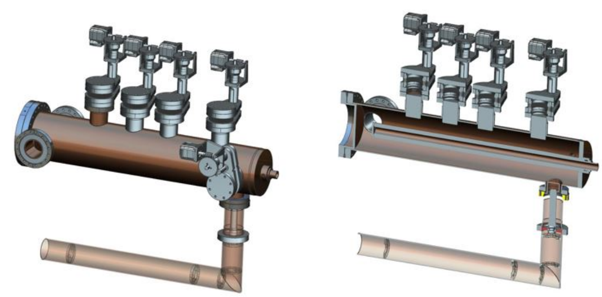

Figure 2: The original model of the JLEIC high-power kicker cavity.

KICKER CAVITY DESIGN EVOLUTION

Even at first glance, the early model of the JLEIC high-power kicker cavity in Fig. 2 looks like the complicated machine that it is. Its field defined by the coaxial geometry of the body and the inner conductor combined, it relies on concentricity and imposes tight tolerances on the components and their respective joints. One can easily imagine how this deceivingly simple model might rapidly evolve to the models shown in Fig. 3 after the start of fabrication. The

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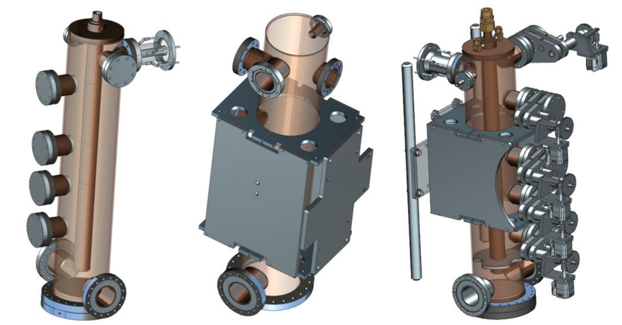

Figure 3: The evolution of the JLEIC high-power kicker cavity since the start of fabrication.

Figure 4: The kicker cavity after all the ports have been vacuum brazed in the body.

design evolution is from the left to right in Fig. 3, and the models are oriented with the beam-pipe end on the bottom, as it is intended to be installed on the UITF beam line for testing.

The leftmost model is the cavity during its RF testing phase. The cavity is equipped with five prototype aluminum plungers which are fixed at 15 mm into the cavity and a prototype coupler port.

Each sub-assembly on the cavity was vacuum-brazed into the body as seen in Fig. 4, at temperatures that inevitably annealed the copper, forcing us to improve our design. The central model in Fig. 3 is the cavity during its trimming phase. For trimming the body of the cavity, we needed to design special side plates to accommodate reference points when the cavity is mounted onto the machine for repeatability of the cuts into the body. The rightmost model in Fig. 3 shows the cavity in its final assembly phase, equipped with body support structures as well as two rods for our back-tech to transport the cavity for installation onto the beam-line.

There are two other sub-components that deserve mentioning: the tuner assemblies and the inner conductor. There are five total automated tuner assemblies: four on top and one hanging perpendicular to these assemblies on the cavity. Mounted on bellows, the plungers are driven in and out

Figure 5: Inner conductor assembly.

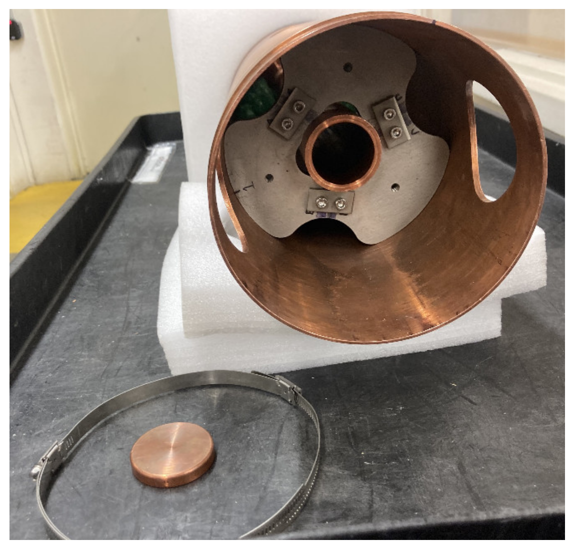

Figure 6: A SS support to center the inner conductor in the body.

of their respective ports by stepper motors, controlling the resonant frequency of all five modes in conjunction in a five-dimensional control loop. Then there is the inner conductor, which is the only part of the cavity that is designed to be water-cooled. There is another copper rod inside the inner conductor rod which has water channels machined down the length of the tube to allow water to exit the assembly. The assembly is shown in Fig. 5.

For unforeseen reasons, this evolution and most of the other complications was fueled primarily by the fact that we were forced to change our Electron-Beam Welding (EBW) plans to accommodate brazing all ports and sub-assemblies to the cavity. The alloy needed to braze the ports into the body required temperatures that inevitably annealed the body

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Table 1: Trimming Steps – All Frequencies in MHz

step	f_1	f_3	f_5	f_7	f_9
initial	86.257	258.024	432.223	603.296	776.994
1	86.411	259.050	431.905	604.610	778.186
2	86.514	259.361	432.445	605.376	778.865
3	86.611	259.649	432.894	606.042	779.016
final	86.611	259.689	433.014	606.181	777.566
target	86.588	259.774	432.956	606.138	779.319

of the cavity; and so, SS rounding clamps and backing plates were added to keep the body as round as possible during its transportation and fabrication. A special SS support had to be designed to hold the inner conductor center in the cavity during transportation (shown in Fig. 6).

TRIMMING AND RF TESTING RESULTS

The trimming steps are listed in Table 1. There are three locations that are reserved for trimming: the open end of the body, the end cap of the inner conductor, and the copper portion of the top-hat flange that protrudes inside the cavity towards the inner conductor. The initial measurements were done before any trimming. The first trim was a 2 mm cut into the body, the second trim was a 1 mm cut on inner conductor cap and on the body, and the third trim was a 1 mm cut into the body and a 1.2 mm cut on the inner conductor cap. The final RF measurement was done after the inner conductor cap was welded onto the inner conductor assembly.

LATEST DEVELOPMENTS AND NEXT CHALLENGES

Despite significant design and manufacturing challenges, we were recently able to progress to the final assembly stage of this cavity. The joining of the inner conductor assembly to the body of the cavity was complicated by the fact that, because the ports had been brazed into that end of the cavity at 700 °C, we could not find a lower-temperature brazing alloy to buy off the shelf for the final joint of this assembly. Instead, the joint was performed with a special soldering alloy, S-Bond 220 [6], which is designed for a bonding temperature of about 250 °C. Figure 7 shows the soldering of the inner conductor assembly to the body of the cavity with S-Bond 220.

The next fabrication challenge will be the cleaning of the kicker cavity to remove the oxidation of the copper, especially on the inside of the cavity. Figure 8 shows the body of the cavity being cleaned with a micro90 detergent. The SS fixture in Figure 6 will be in place anytime that the cavity needs to be turned on its side and so is blocking access to the inside of the cavity. The cavity must remain vertical during the cleaning and the SS fixture inserted before tuning the cavity as it dries. After the cleaning of the cavity is successful, the cavity will undergo further RF tests in preparation for the upcoming beam test.

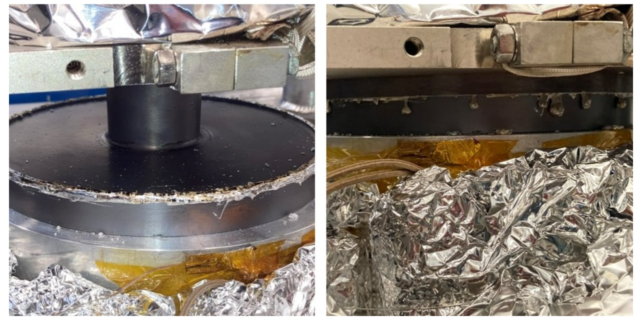

Figure 7: S-Bond 220 soldering of the kicker cavity body and the inner conductor assembly.

Figure 8: Micro90 detergent cleaning of the body.

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