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FIRST COAXIAL HOM COUPLER PROTOTYPES AND RF MEASUREMENTS ON A COPPER CAVITY FOR THE PERLE PROJECT

C. Barbagallo*[1], P. Duchesne, W. Kaabi, G. Olivier, G. Olry, S. Roset, F. Zomer[1]
Laboratoire de Physique des 2 Infinis Irène Joliot-Curie (IJCLab), Orsay, France
J. Henry, S. A. Overstreet, G.-T. Park, R. A. Rimmer, H. Wang
Jefferson Lab, Newport News, USA
S. Barrière, S. Clement, R. Gérard, F. Gerigk, P. Maurin, CERN, Geneva, Switzerland
[1]also at The Paris-Saclay University, Gif-sur-Yvette, France

Abstract

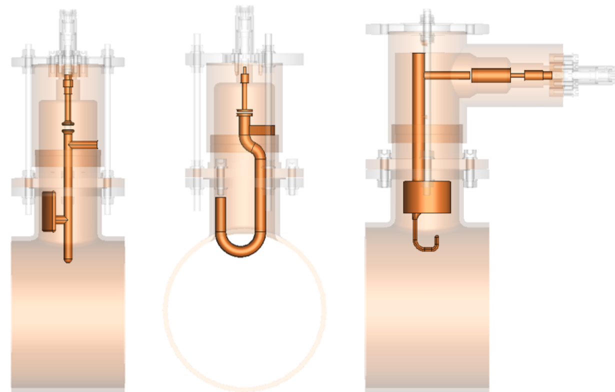
The PERLE (Powerful Energy Recovery Linac for Experiments) project relies on superconducting RF (SRF) cavities to reach its goals. The installation of coaxial couplers on the cutoff tubes of SRF cavities is foreseen for damping cavity's Higher Order Modes (HOMs). The prototyping and fabrication of 3D-printed HOM couplers for the PERLE cavity have recently started in collaboration with JLab and CERN. This paper provides an overview of the design of the fabricated HOM couplers and the first RF measurements of the cavity's HOMs performed at warm on an 801.58 MHz 2-cell copper cavity to validate coupler design performances. Measured cavity data is also compared to eigenmode simulations to confirm simulated results and see to what extent any reduction in damping can be predicted.

INTRODUCTION

The PERLE accelerator [1] comprises two 82 MeV superconducting linacs, each consisting of four 5-cell elliptical Nb cavities ($\beta = 1$), capable of operating at 801.58 MHz in continuous-wave (CW) mode [2]. The installation of coaxial-type HOM couplers is being considered to mitigate the beam-induced HOMs effect. After optimizing the RF transmission of the Probe, Hook, and DQW HOM couplers based on the HOM spectrum of the 5-cell PERLE cavity (as presented in [3]), we demonstrated in our previous work (ref. [4]) that these coupler designs fulfill regenerative beam breakup (BBU) and fundamental mode (FM) RF-heating requirements. Consequently, prototypes of each coupler were fabricated, as illustrated in Fig. 1, to validate their performance on an 801.58 MHz two-cell PERLE-type OFHC (Oxygen-free High Thermal Conductivity) copper cavity since the 5-cell copper cavity was still under fabrication at Jefferson Lab during the measurement campaign. This decision was based on the assumption that the frequency spectrum of a 5-cell cavity is sufficiently similar to that of a 2-cell cavity.

In the following, we will discuss the fabrication technique employed for the HOM coupler prototypes. Then, we will present external quality factor (Q_{ext}) measurements for FM and trapped high R/Q HOMs, which are the most critical, to evaluate whether our measurement setup is appropriate for verifying the simulated eigenmode CST [5] results.

* carmelo.barbagallo@ijclab.in2p3.fr



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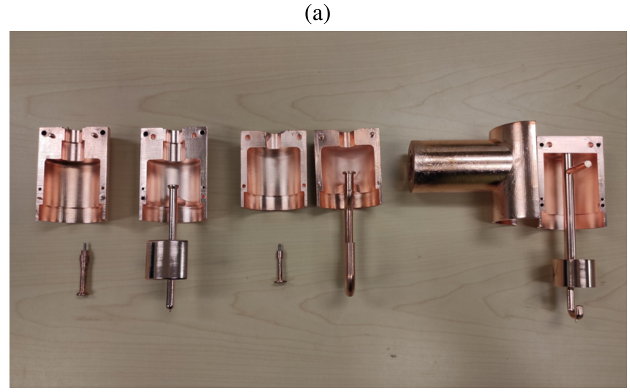

(b)

Figure 1: Mechanical design (a) and 3D-printed plastic and copper-coated prototypes (b) of the Probe, Hook, and DQW HOM couplers (from left to right).

HOM COUPLER PROTOTYPING

To evaluate in a design phase HOM coupler transmission behavior via low-power RF measurements at room temperature, expensive Nb coupler fabrication can be avoided. A potential cost-saving and time-efficient technique currently under development at CERN involves 3D-printing HOM couplers using epoxy and copper-coating the surface via electroplating to impart necessary electrical characteristics.

3D Printing for HOM Coupler Fabrication

The CERN Polymerlab team employed the Viper si2 SLA© (Stereolithography) rapid prototyping machine to 3D print HOM couplers using both Accura© 25 [6] and Accura©

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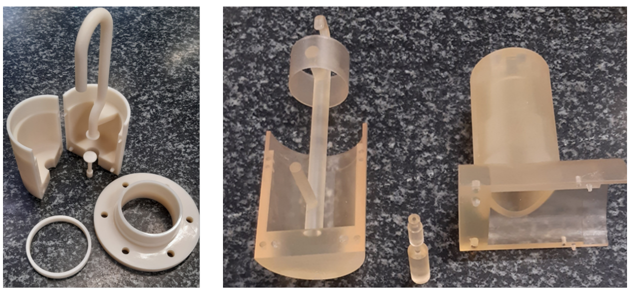
48 HTR (High-Heat-Resistant) [7] epoxy (see Fig. 2.). Accura 25 (white) has greater flexibility and lower stiffness but also exhibits lower tensile strength and deflection temperature at high pressure. Accura 48 HTR (transparent) has higher strength, stiffness, and thermal stability, making it a more robust material for 3D printing and better suited for electroplating. After the 3D printing, the coupler components are cleaned using a solvent and cured for 15 minutes in an ultraviolet (UV) oven. This ensures complete resin polymerization and consequently amplifies their mechanical properties and durability.



(a) (b)

Figure 2: 3D-printed Accura 25 Hook coupler (a) and Accura 48 HTR DQW coupler (b).

Copper-Coating of HOM Couplers

After surface preparation, the HOM couplers were electroplated with copper in a bright acid copper bath. To improve copper adhesion during coating, a light corundum-based sandblasting treatment was applied to the printed parts at a pressure of 3 bars, followed by degreasing using an NGL 17-40-type detergent to remove any blasting residue. The prepared components were then immersed in a carbon-based bath to allow negatively charged carbon particles to create a substrate for copper coating [8]. Figure 1(b) illustrates the 3D-printed epoxy and copper-coated Probe, Hook, and DQW HOMs couplers. Our goal was to achieve a 30 µm copper substrate covering the entire surface. Due to the limitations of the used technique, we could not fully control the homogeneity of the deposit throughout the process, resulting in an estimated average coating thickness of 50 µm for the entire part, except at the electrical contact points where it can reach up to 200 µm.

To ensure HOM coupler transmission was not affected by geometric variations, we set a minimum feasible tolerance of ±0.5 mm for the entire coupler surface, except for the regions influencing the notch frequency, where the tolerance was established at ±0.25 mm. 3D-scanning measurements were carried-ou to asses the deviation between the 3D-CAD step file and printed copper-coated HOM couplers. To provide an illustrative example, we present the results of the metrological analysis for the Hook coupler only (see Fig. 3) [9]. The tolerances are within the set range for most of the coupler surfaces. However, a lack of material ranging from 1.074 to 1.197 mm in the radial direction was detected in the lower-curved part of the antenna, which may be due to the high shrinkage of Accura 25 and can impact the magnetic field coupling. In addition, excess material ranging from 0.815 to 0.968 mm was found on both sides of the small straight part of the antenna, which can potentially affect the electric coupling, including the notch frequency of the Hook coupler.

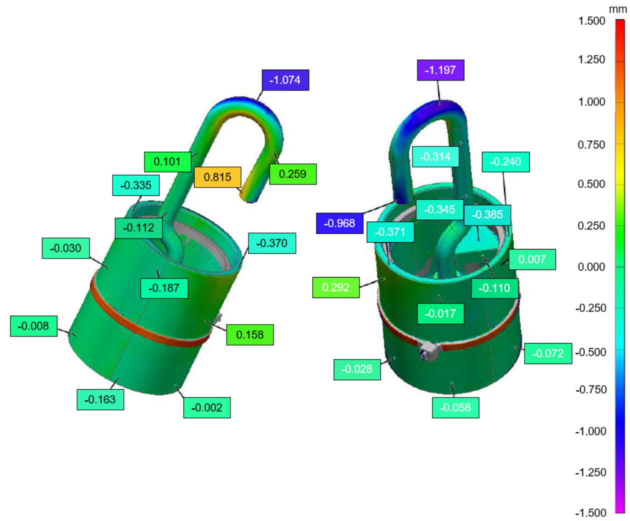


Figure 3: 3D-scanning measurements for the Accura 25 Hook coupler (HookV01).

HOM COUPLER RF MEASUREMENTS

This section presents several Q_{ext} measurements for FM and the most problematic parasite modes for the PERLE type-cavity, which include the first monopole (TM_{011}) and the first two dipole mode (TE_{111} and TM_{110}) passbands, and compare them with simulations. The Hook, Probe, and DQW coupler prototype measurements were conducted at Jefferson Lab on a 2-cell 801.58 MHz Cu cavity at low power and room temperature. The setup is shown in Fig. 4.

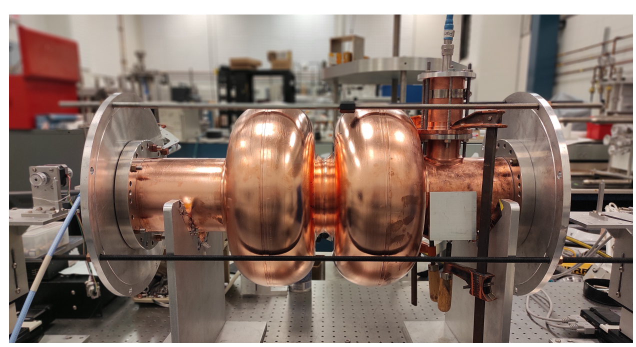


Figure 4: HOM coupler prototype on the right-hand beam pipe of a 2-cell Cu PERLE-type cavity. The reference antenna is on the opposite side of the cavity (not shown).

The RF transmission was measured from an input, or reference, antenna at the beam pipe port to the HOM coupler port. A penetration depth of 20 mm for the coupler

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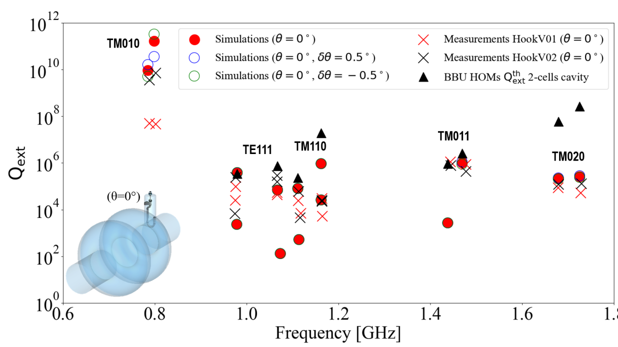
antenna into the cutoff tube was used for all three couplers. The designed couplers were equipped with a rotating flange enabling the investigation of damping performance for different orientations of the coupling antenna. The procedure to measure Q_{ext} for FM and HOMs involves the following steps [10, 11]: (i) Measuring the loaded quality factor Q_l by S_{21} transmission. (ii) Measuring the coupling factor β_1 and β_2 for the antennas from the measured S_{11} and S_{22}. The coupling factor β is calculated from the measured S_{11} using the formula $\beta = \frac{1 \pm |S_{11}|}{1 \mp |S_{11}|}$, where the upper sign corresponds to over-coupling and the lower sign to under-coupling. (iii) Evaluating the intrinsic quality factor $Q_0 = Q_l(1 + \beta_1 + \beta_2)$. (iv) Determining $Q_{\text{ext}} = Q_0/\beta$. Figure 5 shows the results for suitable coupler orientations for efficient HOM damping. The study found that simulated eigenmode CST results agree with measurements for the studied configurations.



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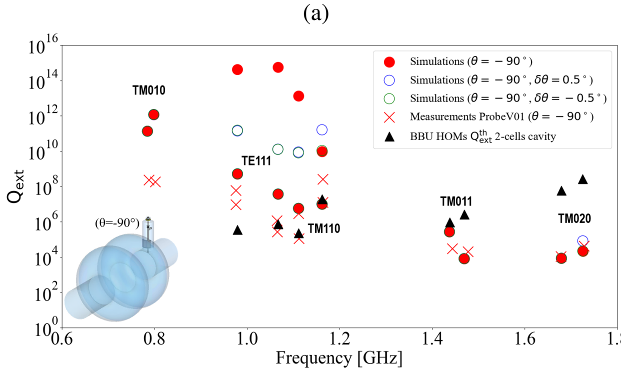

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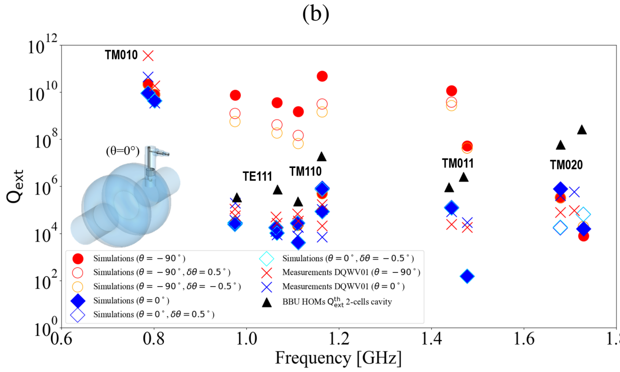

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Figure 5: Measured and simulated Q_{ext} for FM and trapped high R/Q HOMs, using one Hook (a), Probe (b) or DQW (c) coupler on a 2-cell 801.58 MHz Cu cavity.

However, significant deviations were observed for certain modes, particularly for one of the two polarizations of dipole modes. This could be due to various reasons: (i) The orientation of the coupler plays a crucial role, as a slight tilt $\delta\theta$ (for example 0.5°) can result in a significant impact on either the magnetic or electric coupling to the antenna, leading to a considerable change in Q_{ext} for certain coupler directions. (ii) Measurements of S_{11}, or S_{22}, for modes with weak coupling to the antennas can lead to measurement inaccuracy. Only in a few cases, we succeeded in measuring the two polarizations of dipole modes separately. (iii) Cavity imperfections and weak RF contact in the clamped assembly can also be sources of error. In addition, in this configuration with a single coupler, only one polarization is effectively attenuated. To damp the other polarization, an additional coupler could be installed on the opposite side of the cavity.

The built couplers demonstrated satisfactory performance in rejecting the FM and damping HOMs within BBU requirements. Specifically, it has been observed that the second version of the fabricated Hook coupler (ref. HookV02) exhibits superior performance compared to its predecessor (ref. HookV01). This improvement may be attributed to the more precise alignment of the antenna to the coupler shell and a reduction in both shrinkage and excess material on the coupler surface. Our investigation suggests that the Probe coupler can efficiently damp monopole modes, while the Hook coupler shows promising results in damping dipole modes. On the other hand, the DQW coupler is the most effective solution for attenuating both monopole and dipole HOMs.

CONCLUSION

In this paper, we conducted RF measurements of coaxial HOM coupler prototypes installed on an 801.58 MHz 2-cell OFHC Cu cavity designed for R&D bench measurements for the PERLE project. Our study has successfully demonstrated the potential of using 3D-printed epoxy copper-coated coaxial HOM couplers to facilitate the design process and verify transmission behavior. Simulated eigenmode results obtained from CST agree with the measurements for the analyzed configurations. The DQW coupler was found to be particularly effective in damping both dipole and monopole modes. Future tests on the 5-cell copper cavity with various coupler schemes (for instance, 4 DQW couplers) are planned to confirm if their measured damping performance meets the BBU requirements. Further RF heating studies are needed to determine if active cooling is required for the Nb version of the couplers that are intended to be installed on the Nb 5-cell PERLE cavity.

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