PROGRESS ON LOW-LEVEL RF QUALIFICATION OF A 3D-PRINTED 704.4 MHz CH CAVITY

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Abstract

Additive manufacturing enables compact accelerating structures with complex internal features such as integrated cooling channels. Within the Resonators Additively Constructed for Experiments project at GSI, a 3D-printed 704.4 MHz CH cavity was developed as a compact high-frequency H-mode prototype. This paper reports on the progress from the first low-level radio-frequency (RF) characterization to the modified, copper-plated and retuned cavity configuration. Initial measurements showed a resonance frequency below the target value and an asymmetric field distribution, attributed to the initial cavity geometry, preliminary contact conditions and the capacitive coupling scheme.

Based on these findings, the cavity configuration was refined by replacing the capacitive coupling with an inductive loop and adding four static tuners. After these modifications, the field asymmetry was reduced and the cavity frequency could be adjusted to the design value of 704.4 MHz. The dynamic tuners provided a measured tuning range from 701.9 MHz to 706.3 MHz. Together with the quality-factor evaluation and computed-tomography inspection of the integrated cooling channels, these results confirm the successful low-level RF and manufacturing qualification toward future high-power operation.

INTRODUCTION

Metal additive manufacturing (MAM) is a promising route for normal-conducting accelerator components because it enables compact geometries and internal cooling structures that cannot easily be realized by conventional manufacturing. For high-frequency H-mode cavities, this design freedom is particularly attractive, since small cavity dimensions, high radio-frequency (RF) power density and tight mechanical tolerances have to be combined. The increased RF power density makes the removal of local thermal losses more challenging and motivates cooling channels placed close to the thermally loaded regions. At the same time, the RF performance remains sensitive to dimensional accuracy, electrical contact conditions and surface quality.

The present work builds on an earlier study of a compact 704.4 MHz CH-cavity concept with seven accelerating gaps and integrated cooling channels [1], which forms the basis of the current Resonators Additively Constructed for Experiments (RACE) test-cavity development at GSI. The broader RACERS initiative, Research on Additive Construction for Efficient Resonating Structures, provides the framework for several MAM-based accelerator and storage-ring R&D activities at GSI and was recently summarized in Ref. [2]. Following this prototype stage, the present contribution reports on the subsequent development and low-level RF qualification of the updated modular test cavity, see Fig. 1. The work includes retuning of the RF structure, improvement of the coupling scheme and inspection of the integrated cooling channels.

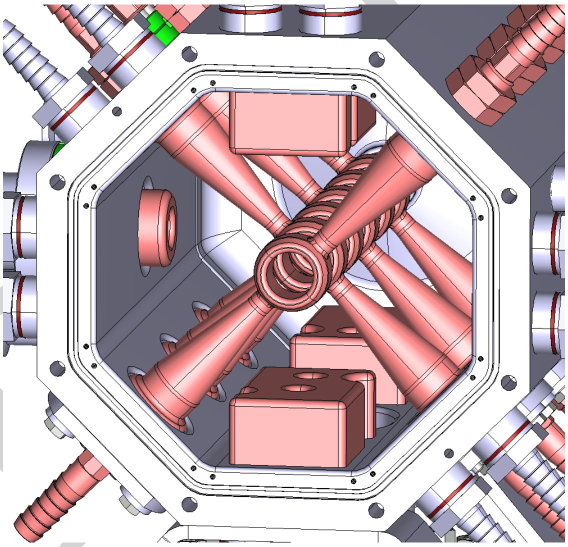

Figure 1: Additively manufactured 704.4 MHz CH cavity after the final mechanical modifications.

INITIAL RF CHARACTERIZATION

The first low-level RF characterization was performed before copper plating and before the final mechanical modifications of the cavity. In this diagnostic configuration, the cavity was excited by capacitive input and pickup antennas, while the mountable electrodes were installed with preliminary contact conditions. The dynamic tuners were already available and were used to investigate the frequency response of the cavity.

The measured resonance frequency was significantly below the design value of 704.4 MHz. Depending on the dynamic tuner positions, the resonance frequency was found between approximately 676 MHz and 680.5 MHz. At a nominal dynamic tuner position of 12 mm, a frequency of 678.8 MHz was measured. The dominant contribution to this frequency offset was identified as the larger inner tank radius used in the initial cavity geometry. An additional

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contribution was associated with the preliminary contact conditions of the mountable electrodes.

The first bead-pull measurement also showed an asymmetric longitudinal field distribution, as shown in Fig. 2. This asymmetry was mainly attributed to the capacitive excitation scheme and was further influenced by the preliminary contact configuration of the mountable electrodes. The initial RF and bead-pull measurements therefore served as a diagnostic reference for the subsequent modification of the coupling and tuning concept.

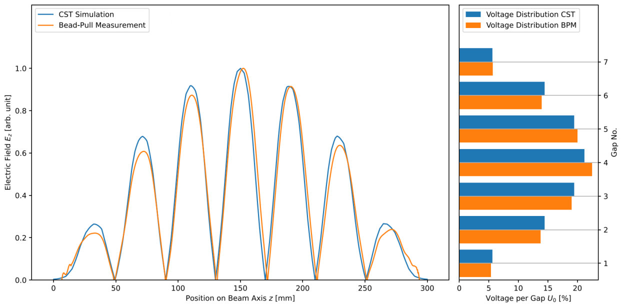


Figure 2: Initial bead-pull measurement of the unplated cavity with capacitive coupling compared with the CST simulation. The measured field profile and the derived gap-voltage distribution show an asymmetric deviation from the expected distribution.

CAVITY MODIFICATIONS AND RETUNING

The modification strategy was derived directly from the initial low-level RF measurement campaign. Capacitive RF excitation was replaced by an inductive loop coupler to reduce the field perturbation and to provide a more suitable coupling scheme for subsequent RF studies. In addition, four static tuners were implemented to compensate the frequency deficit and to shift the accessible tuning range toward the design frequency.

Prior to copper plating, a test measurement was performed to verify the modified cavity configuration. As shown in Fig. 3, the static tuners shifted the cavity into the required frequency region. At the nominal dynamic tuner position of 12 mm, the design frequency of 704.4 MHz was reached, with the dynamic tuners providing a measured range from 701.9 MHz to 706.3 MHz.

After this successful verification, the stainless-steel cavity tank was copper plated to improve the RF surface conductivity, increase the quality factor and reduce ohmic RF losses. The cavity was then reassembled for renewed low-level RF, bead-pull and quality-factor measurements.

RF AND FIELD RESULTS

After copper plating and reassembly, the RF characterization focused on operation at the design frequency, quality-factor evaluation and the resulting field distribution. A representative S-parameter measurement with inductive loop coupling is shown in Fig. 4. The resonance frequency was measured at 704.43 MHz. From the 3 dB bandwidth of the S_{12} transmission response, a loaded quality factor of $Q_\mathrm{L} \approx 2.48 \times 10^3$ was obtained using

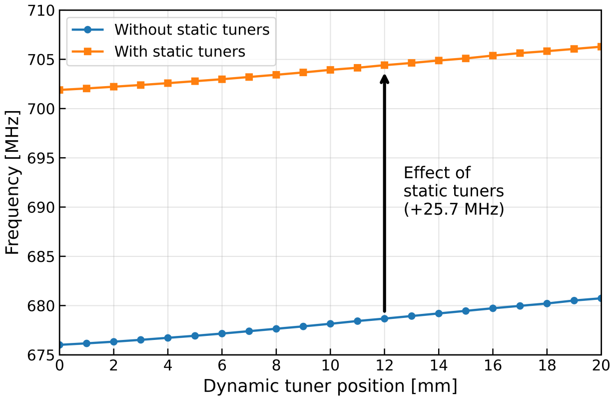


Figure 3: Measured resonance frequency as a function of dynamic tuner position without and with static tuners. At the nominal tuner position of 12 mm, the static tuners shift the resonance by about 25.7 MHz and bring the cavity to the design frequency of 704.4 MHz.

$$Q_\mathrm{L} = \frac{f_0}{\Delta f_\mathrm{3dB}}. \tag{1}$$

Using the effective coupling factors $\beta_\mathrm{in} \approx 1.1$ and $\beta_\mathrm{p} \approx 0.12$, the unloaded quality factor was estimated according to

$$Q_0 = Q_\mathrm{L} \left(1 + \beta_\mathrm{in} + \beta_\mathrm{p}\right). \tag{2}$$

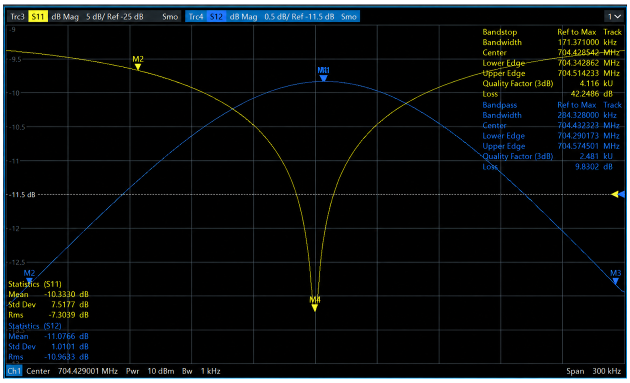
This results in $Q_0 \approx 5.5{\times}10^3$, a clear improvement compared with the earlier unplated diagnostic configuration, for which $Q_\mathrm{L} \approx 320$ and $Q_0 \approx 650$ were estimated.

The longitudinal field distribution was evaluated by a new bead-pull measurement after the coupling modification and copper plating. As shown in Fig. 5, the measured field profile is in good agreement with the CST simulation. The derived gap-voltage distribution confirms that the asymmetry observed in the initial capacitive-coupling setup was reduced. Small remaining deviations are attributed to tuner settings and to the reproducibility of the electrode contact.

CT INSPECTION OF THE COOLING CHANNELS

The integrated cooling channels are a key feature of the additively manufactured cavity concept, since they enable cooling close to thermally loaded regions. To assess the manufacturing quality of the internal channel geometry, computed tomography (CT) was performed on a representative mountable electrode.

Figure 6 summarizes three characteristic CT views. The cross-section confirms the presence and positioning of the parallel cooling channels, while the longitudinal and central sections show the internal channel routing through the electrode. The CT data confirm the continuity of the cooling channels and do not indicate any critical blockage or collapse of the internal structure. Thus, the inspection provides an



Bandstop	Ref to Max	Track
Bandwidth	171.371000	kHz
Center	704.428542	MHz
Lower Edge	704.342862	MHz
Upper Edge	704.514233	MHz
Quality Factor (3dB)	4.116	kU
Loss	42.2486	dB

Bandpass	Ref to Max	Track
Bandwidth	284.328000	kHz
Center	704.432323	MHz
Lower Edge	704.290173	MHz
Upper Edge	704.574501	MHz
Quality Factor (3dB)	2.481	kU
Loss	9.8302	dB

Statistics	(S11)	
Mean	-10.3330	dB
Std Dev	7.5177	dB
Rms	-7.3039	dB

Statistics	(S12)	
Mean	-11.0766	dB
Std Dev	1.0101	dB
Rms	-10.9633	dB

Ch1 Center 704.429001 MHz Pwr 10 dBm Bw 1 kHz Span 300 kHz

Figure 4: Low-level S-parameter measurement of the copper-plated cavity with inductive loop coupling. The S_{12} bandwidth corresponds to $Q_\mathrm{L} \approx 2.48 \times 10^3$. Using the measured coupling levels, an unloaded quality factor of approximately $Q_0 \approx 5.5 \times 10^3$ is estimated.

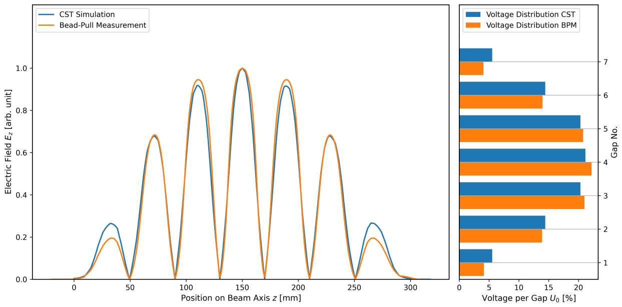


Figure 5: Bead-pull measurement of the modified and copper-plated cavity compared with the CST simulation. The longitudinal field profile and the derived gap-voltage distribution show a reduced asymmetry compared with the initial capacitive-coupling configuration.

important manufacturing verification for the modular cavity components.

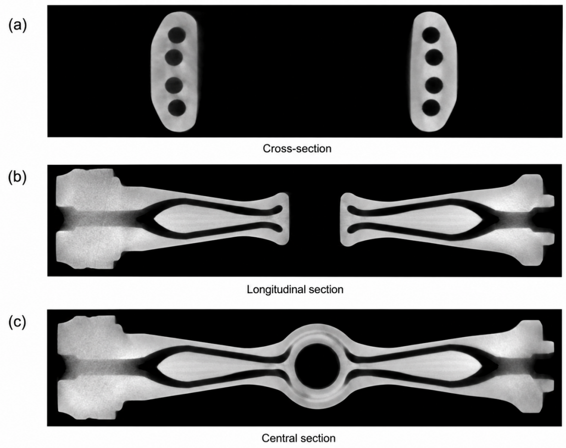


Figure 6: Computed-tomography inspection of a representative mountable electrode with integrated cooling channels: (a) cross-section, (b) longitudinal section, and (c) central section. The CT images confirm the continuity and manufacturing quality of the internal cooling-channel geometry.

CONCLUSION AND OUTLOOK

The 3D-printed 704.4 MHz CH cavity developed within the RACE project was modified, copper plated and subjected to renewed low-level RF qualification. The first measurements of the unplated and capacitively coupled cavity revealed a resonance frequency below the design value and an asymmetric field distribution. These findings were traced back to the initial cavity geometry, preliminary contact conditions of the mountable electrodes and the capacitive excitation scheme.

After implementing an inductive loop coupler and four static tuners, the cavity could be retuned to the target frequency region. At the nominal dynamic tuner position of 12 mm, the design frequency was reached, with a measured dynamic tuning range from 701.9 MHz to 706.3 MHz. For the copper-plated configuration, an unloaded quality factor of approximately $Q_0 \approx 5.5 \times 10^3$ was estimated. The bead-pull measurements confirm the improved field-distribution behaviour, while CT inspection verifies the manufacturing quality and continuity of the integrated cooling channels.

Future work will include the installation and qualification of new exchangeable electrode assemblies with optimized internal cooling channels. These components will be used for systematic tuner and coupling scans, further field-flatness optimization and a more precise determination of Q_0. The next qualification step is a full vacuum test of the assembled cavity. A preliminary vacuum test reached 3×10^{-5} mbar and confirmed the leak tightness of four electrode interfaces, while remaining leak paths were identified at two electrode sealing surfaces. In parallel, an additively manufactured inductive coupling loop will be installed to further improve the coupling performance. Subsequently, high-power RF tests with a 4 kW amplifier are planned, including monitoring of inlet and outlet water temperature and flow rate of each individual electrode cooling circuit.

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