CHARACTERIZATION OF THE FOUR-QUADRANT X-BAND CAVITY PROTOTYPE FOR THE ASTERIX PROJECT.

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Abstract

The ASTERIX project, hosted by the INFN–LNF, seeks to achieve the first demonstration of a practical, meter-scale X-band RF accelerating structure suitable for operational linear accelerators (>100 MV/m accelerating gradient). The goal is to produce innovative RF structures to qualify as part of the world-wide scientific collaboration (SLAC/CERN/INFN-LNF/KEK/Tsinghua) for R&D in the accelerator development and high-power testing of innovative cavities with high gradients. The structure is composed of four-quadrants ("open-type"), made of hard copper, joined and vacuum sealed by using TIG welding ("braze-free" technique) through a cost-effective and robust manufacturing. The full-structure RF design, in single-bunch operation mode, was carried out with the 3D numerical simulation codes Ansys HFSS and CST Microwave Studio. In this paper, we report on the engineering of the full-structure prototype optimized for low RF power measurements and initial mechanical tests in order to validate the quadrant straightness and alignment, the TIG welding process, the vacuum tightness; etc. The prototype was fabricated with lower precision of geometric dimensions and more relaxed mechanical tolerances.

INTRODUCTION

This research is conducted within an international collaboration involving SLAC National Accelerator Laboratory, CERN, INFN-LNF, KEK, and Tsinghua University, focused on the development of advanced X-band (11–12 GHz) accelerating structures for next-generation particle accelerators [1-8]. The study investigates hard-copper accelerating structures, which demonstrate improved high-gradient performance compared with conventional soft-copper designs [9], and explores innovative geometries such as open-type cavities together with braze-free assembly techniques, including TIG welding. The main goal is the realization of compact accelerating structures capable of operating above 100 MV/m for applications in research facilities [10-13], industrial systems, and medical accelerators, including EuPRAXIA@SPARC_LAB [14,15].

This paper presents the initial results obtained for the fabrication of the braze-free cavity in single-bunch operating mode to be TIG welded.

ACCELERATING STRUCTURE DESIGN

The RF design was developed for the single-bunch operating case with a gap of 1 mm, while the iris aperture was fixed at 3.5 mm throughout the structure, as shown in Figure 1 (design details can be found in [16-18]). To ensure high efficiency for the full 1-meter-long accelerating structure, composed of 120 cells, the disk thickness was set to 2 mm, resulting in an RF pulse length of 123 ns and a required input power of 77 MW.

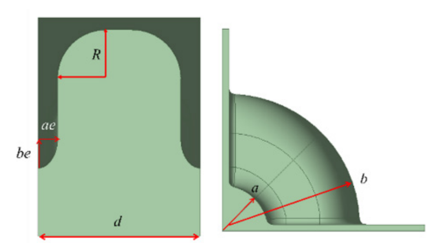

Figure 1. The geometry of the quadrant cell with gap size of 1mm.

The cavity geometry was carefully optimized in order to improve RF performance and mitigate surface field effects. In particular, the rounding applied on the cavity top increases both the shunt impedance and the quality factor by approximately 10%, while the elliptical chamfer introduced at the iris was optimized to minimize the peak surface electric fields. In addition, a 0.5 mm rounding at the

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gap was adopted to reduce the enhancement of the surface magnetic field. The complete RF optimization of the meter-long four-quadrant constant-impedance accelerating structure was carried out using the CST electromagnetic simulation code (see Figure 2). The final design achieves an average accelerating gradient of 100 MV/m with an input RF power of 77 MW.

After careful optimizations, the parameters of the full structure are listed in Table 1.

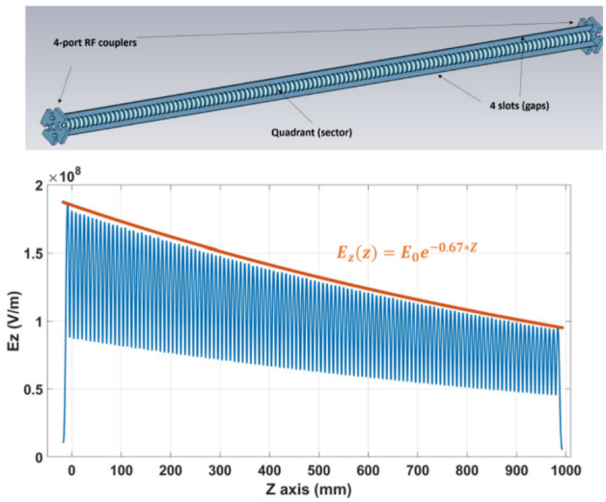

Figure 2: Top, full 1m long four-quadrant structure; bottom, on-axis electric field profile.

Table 1: Parameters of the Full Structure

Parameter	Value
Frequency [GHz]	11.994
Gradient [MV/m]	100
Input power [MW]	77
Operating mode [rad]	2π/3
Cell length [mm]	8.333
Cell Number	120
Full structure length [m]	1
Disk thickness [mm]	2
Quality factor	6931
Iris radius [mm]	3.5
Shunt impedance [MΩ/m]	97.3
Group velocity [c%]	0.027
Filling time [ns]	123
Attenuation factor	0.6545
Peak S_c [W/μm^2]	8.8
Pulse Heating [K]	24.6
E_p [MV/m]	245

MECHANICAL PROTOYPE

During the first year of the project, we have developed the mechanical drawings and engineering of the full-scale structure (given in Figure 3), without RF power couplers, in order to perform the following tests:

- TIG welding process,
- structure straightness and quadrant alignment,
- vacuum performance.

The final CAD model of the prototype including tuning pins, alignment pins, welding teeth, central pumping port and secondary vacuum chambers is shown in Figure 3.

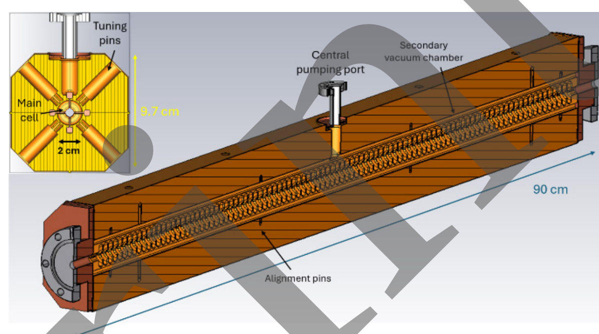

Figure 3: Final CAD model of the prototype.

The machining process of the mechanical prototype has recently started and it is in-progress. The four quadrants are fabricated inside a CNC milling machine which can host the whole parts:

- Machine Model: Doosan DNM 750L
- Precision for the prototype <0.05mm
- Roughness for the prototype <1 Ra

In Figures 4 and 5, one quadrant is shown on a granite table for inspection using a coordinate measuring machine (CMM).

Figure 4: One quadrant after machining.

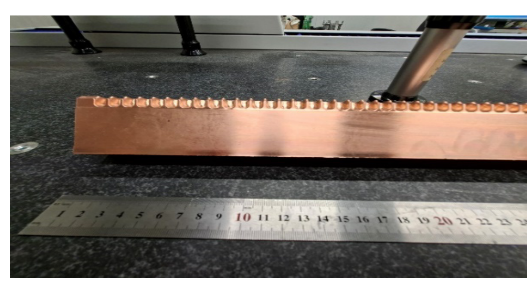

Figure 5: Close-up of one quadrant after machining. The single cells are visible.

CONCLUSIONS

The RF and mechanical design of the ASTERIX four-quadrant X-band accelerating structure for single-bunch operation has been presented. The optimized 1 m long constant-impedance structure achieves an average accelerating gradient of 100 MV/m with 77 MW input power. In parallel, a full-scale mechanical prototype has been developed to validate the hard-copper manufacturing approach. The prototype quadrants will be soon joined by using the TIG welding process. The TIG-welded prototype will be used to verify machining tolerances, alignment, straightness, and vacuum performance.

Future activities will include the design of TIG-welded RF structures for high-power testing in the following years of the project.

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