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R&D STUDIES ON A 177.6 MHz 1:4 SCALE BOAT SHAPE PROTOTYPE RF CAVITY FOR THE 2 GeV CW FFA*

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Abstract

A proton circular accelerator complex composed of a 100 MeV separated radial sector cyclotron, an 800 MeV separated spiral sector cyclotron and a 2 GeV FFA was proposed and is being studied at CIAE. To satisfy the beam dynamics requirements of the FFA, NC RF cavity with high Q and R will be adopted. It is found that the boat shape cavity is the most promising candidate. Therefore, R&D on a 177.6 MHz 1:4 scale boat shape prototype cavity is being carried out to study all aspects of developing such a high-power cavity. In this scenario, self-consistent multi-physics coupled simulation study with ANSYS HFSS and Workbench was carried out. This paper describes the method to deal with a mechanical model including hundreds of bodies in the FEM analysis and shows the simulation results. In addition, the manufacturing technology and some testing results are also presented.

INTRODUCTION

CIAE has committed to the development of cyclotrons and constructed series of cyclotrons toward higher beam energy and intensity with a compact size. In recent years, the proton beam accelerator with ~GeV energy and ~MW power is being pursued, the purpose is to expand the application scopes of the proton accelerator in the fields of the fundamental physics, the nuclear industry, the home security, etc. In this situation, a proton circular accelerator complex was proposed and is being studied at CIAE [1]. The design goal is to extract a 2 GeV, 6 MW CW proton beam.

For the 2 GeV FFA, NC RF cavities will be applied to boost the proton beam energy from 800 MeV to 2 GeV. Due to the heavy beam loading, development of the NC high power waveguide type RF cavity with high Q and R is extremely important, which is unquestionably beneficial for the energy efficiency enhancement. Four geometries (i.e., rectangular, omega, racetrack, and boat) of the waveguide-type RF cavities were investigated extensively [2], it was found that the boat shape RF cavity has the highest Q and R, and is the most promising candidate.

In order to master the key technology of developing such a high-power RF cavity, R&D on a 177.6 MHz 1:4 scale boat shape prototype cavity is being carried out. For this cavity, ~100 kW RF power dissipated on the copper cavity walls needs to be brought away by the cooling water, ±170 kHz tuning range needs to be reached by deforming the RF cavity walls with the electrical cylinders. To make sure the mechanical design can meet the design demands, self-consistent multi-physics coupled simulation study (i.e., RF-thermal-structural-RF analysis) with ANSYS [3] was carried out, the optimized design results were obtained. Afterwards, the prototype cavity was fabricated by using technologies of the stamping forming, the vacuum EBW, etc. Cold test is being performed; hot test is being prepared and will be done in the very near future.

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CAVITY AND COUPLER'S RF DESIGN

Figure 1 shows the RF design of the cavity and coupler. The calculated unloaded Q of the cavity is ~43500; the maximum and minimum shunt impedances along the midplane of the rectangular beam aperture (1 m × 0.03 m) are 7.61 MΩ and 3.79 MΩ, respectively. The accelerating gap length is 0.2 m. The scale of the cavity itself is 2 m×0.5 m×0.8 m. In the realistic cavity, two identical couplers are arranged; one is for RF power coupling, another is connected with a high-power RF load to simulate the beam loading. The calculated maximum β of the coupler is ~2.6.

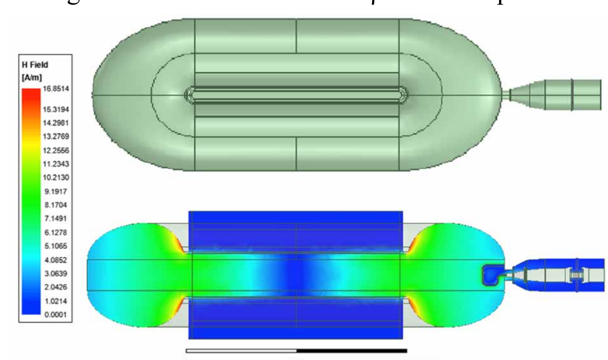

Figure 1: RF design of the cavity and coupler.

MULTI-PHYSICS ANALYSIS

Figure 2 shows the workflow and ANSYS Project Schematic giving the data linkage between the Geometry, the HFSS Design, the Static-State Thermal and the Static Structural. The bodies of the SolidWorks mechanical model imported into the Geometry can be divided into two types, namely the metal and the nonmetal ones. Each body should be named or numbered correctly in the Geometry to avoid unpredictable errors. In the HFSS Design, since only the nonmetal bodies and the metal bodies related to the RF fields are useful for the RF field calculation, all the other metal bodies can be set as Non Model to make the

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simulation executable and more efficient. To evaluate the structural deformation effect on the RF field, the Enable Stress Feedback option should be turned on and correct Model bodies must be selected. The calculated total power dissipation on the cavity walls should be scaled to the design value (e.g., ~100 kW) and is transferred to the Steady-State Thermal to serve as the heat flux. With the similar method described in [4], the thermal convection coefficient on the cooling water pipe's surface can be calculated by using the empirical formulae [5]. The calculated temperature distribution on the given model can be transferred to the Static Structural as one of the loads. In the Static Structural, by applying additionally the other loads (i.e., the earth gravity, the atmosphere pressure, the pushing or pulling forces of the cylinders, etc.) and the Degree of Freedom (DOF) constraints at the same time, the deformation and the Equivalent Stress distribution on the model can be simulated and fed back to the HFSS Design by turning Export After Solve on, then the RF performance of the cavity can be re-evaluated. By iterating the above process several times, a stable solution can be acquired, however for most cases one or two iterations is enough.

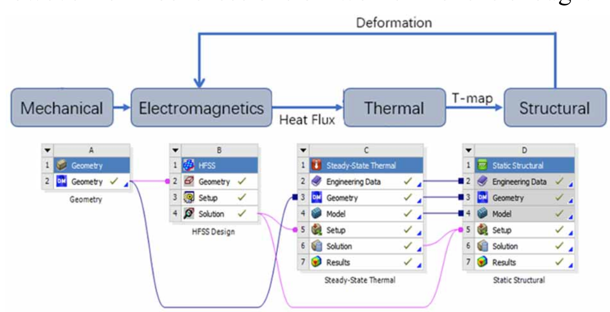

Figure 2: Workflow and ANSYS Project Schematic.

Figure 3 shows the SolidWorks [6] mechanical model of the cavity assembly with a scale of 2.4 m×1.4 m×2.5 m. In the multi-physics analysis, the electrical cylinders were excluded to facilitate the simulation. However, there are still ~280 bodies to be played.

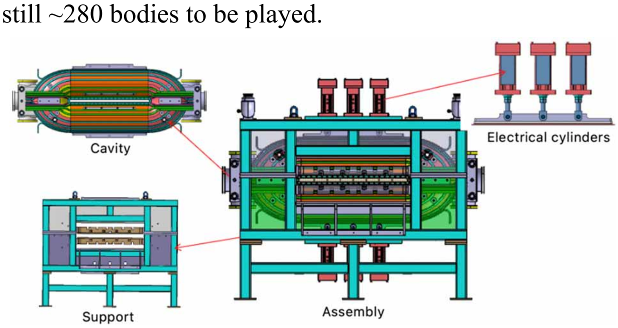

Figure 3: SolidWorks model of the cavity assembly.

The temperature distribution on the prototype cavity's copper walls is shown in Fig. 4. By applying 52 cooling pipes with 8 mm × 8 mm section size, the water temperature rise is 3.58°C at 2 m/s water velocity. With 35°C cooling water, the maximum temperature rise is ~42°C and locates at the left and right sides of the rectangular nose cones.

The simulated deformation and the equivalent stress distribution in the Static Structural with the earth gravity, the ~100 kW RF heating, the atmosphere pressure and the 14000 N pushing force (28000 N in total for both the upper and lower sides) applied are shown in Figs. 5 and 6, respectively. For this case, the cavity frequency is tuned by +176 kHz with a maximum deformation of 2.96 mm. Similar results can be obtained for the case of tuning the frequency by -164 kHz with 30000 N pulling force (60000 N in total) and a maximum deformation of 2.64 mm. The 16000 N force difference (32000 N in total) between the pushing and pulling cases is used to withstand the atmosphere pressure. The maximum secondary equivalent stress for both the pushing and pulling cases are ~187 MPa.

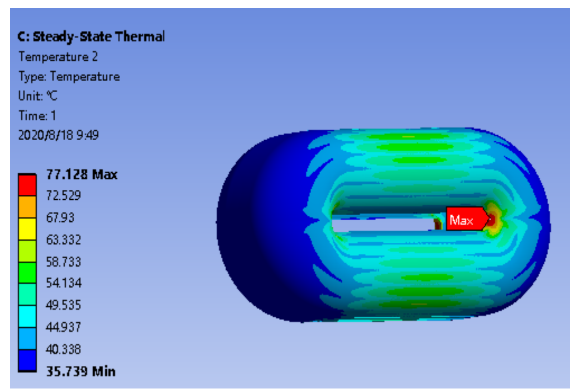

Figure 4: Temperature distribution on the cavity walls.

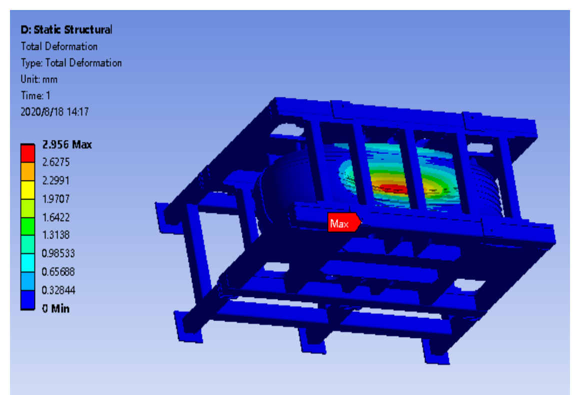

Figure 5: Deformation for +176 kHz frequency tuning.

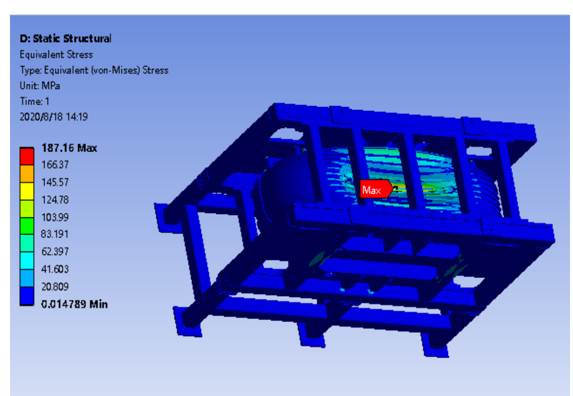

Figure 6: Stress for +176 kHz frequency tuning.

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CAVITY FABRICATION AND COLD TEST

By evaluating the maximum primary (<68 MPa at here) and the secondary stresses (~187 MPa at here) of the mechanical model with ANSYS and considering the application of the stamping forming technology in the cavity fabrication, half-hard (Y/2) 6 mm thick copper plate (~220 MPa tensile strength, ~103 MPa yield strength and ~65% extensibility) was selected as the cavity wall's raw material.

Due to the cavity's irregular shape, it is very important to control the distortion during the manufacturing and accurately determine the position during the welding. Special tooling and welding process were designed. Especially, EBW was fully adopted to weld all the copper cavity walls together. Figure 7 shows the detailed mechanical fabrication process. Most of the parts of the copper cavity were formed by the stamping forming. Due to the existence of the spring back phenomena and the difficulty to find an accurate reference for the wire-electrode cutting, additional CNC machining was applied. Finally, all the dimension errors were compensated by fine finishing the rectangular nosecone according to the measurement during the cavity pre-assembling process. All of the water-cooling pipes were attached to the outer cavity wall by soldering. The Q and resonant frequency were checked frequently to make sure the fabrication is going on the right way and the cavity's performance consistent with the RF design.

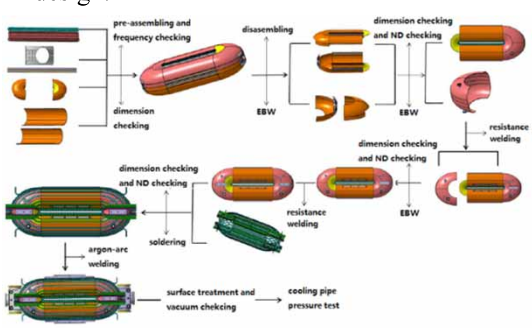

Figure 7: Cavity's mechanical fabrication process.

Figure 8: One of the two half-cavities and the surface roughness measurement.

Figure 8 shows one of the two half-cavities after the all-manual polishing and the measurement of the surface roughness, which is better than 0.1 µm. Mirror surface effect has been obtained. Figure 9 shows the cavity outside look after the soldering of all the cooling pipes. Figure 10 shows the cavity inside and the cavity assembly at the installation site of CIAE. Figure 11 shows the coupler and the Q measurement results. For the coupler, forced air cooling is used for the ceramic window, while water cooling for the coupling loop, the inner and outer conductors. For the Q measurement, two small loop probes with very small βs were used, indicates the unloaded Q is higher than 42314.3, which is ~97% of the design goal. The measured tuning range is ±180 kHz with maximum deformations of ±2.5 mm.

Figure 9: Cavity outside look after the soldering of all the cooling pipes.

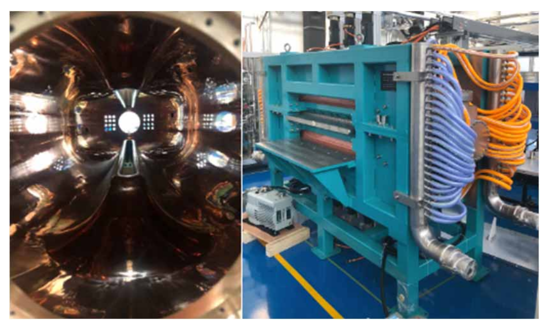

Figure 10: Cavity inside and the cavity assembly at the installation site of CIAE.

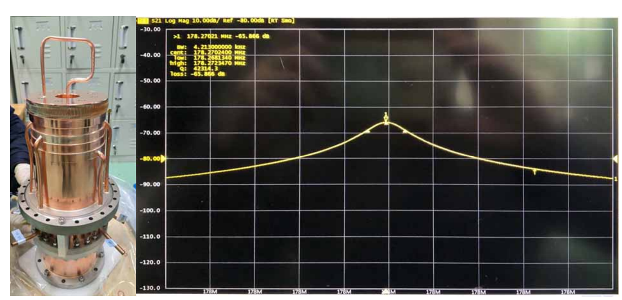

Figure 11: Cavity coupler and Q measurement.

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SUMMARY

A 177.6 MHz 1:4 scale boat shape prototype cavity has been fabricated with satisfied cold testing results. The hot test is being prepared recently and will be launched in the very near future.

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