MULTIPHYSICS DESIGN AND HIGH-POWER CONDITIONING STAND FOR THE STCF TM020 CAVITY POWER COUPLER*

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Abstract

For the TM020 cavity used for collider ring beam energy replenishment in the proposed Super Tau-Charm Facility (STCF) project, a waveguide-type power coupler capable of handling CW 300 kW power has been adopted. The power coupler assembly comprises a cavity-welded waveguide coupling port, an online adjustable movable tuner, a 90° waveguide bend, an RF window and a stepped waveguide transition. This paper systematically presents the Multiphysics design of these components. Furthermore, the high-power test configurations for both the RF window and the power coupler are detailed.

INTRODUCTION

The Super Tau-Charm Facility (STCF), which has officially released its Accelerator Conceptual Design Report (CDR), is a proposed next-generation electron-positron collider designed for unprecedented luminosity [1]. To compensate for severe synchrotron radiation losses, several TM020 radio-frequency (RF) cavities are utilized to continuously replenish the storage ring energy. Acting as the critical bridge between the atmospheric power transmission system and the ultra-high vacuum cavity, a high-power waveguide-type coupler has been specifically developed.

Table 1: Parameters of the power coupler

Parameter	Design
Frequency	499.7 MHz
Type	Online adjustable, Waveguide
Number of couplers per cavity	1
Max CW RF power	300 kW
Coupling coefficient	1~6
Tuner insertion depth	0~67 mm
Ultimate vacuum	<5e-7 Pa

The design parameters of the power coupler are shown in Table 1. Since multiphysics design of the waveguide coupling port has been detailed in our previous study [2], this paper mainly focuses on the Multiphysics design of the remaining sub-assemblies and the overall coupler integration. Additionally, the high-power testing setup of the power coupler is designed and performed.

POWER COUPLER DESIGN

To minimize the weight and maintain a compact structure, waveguide size the same as half-height WR1500 waveguide is adopted for the coupler section. Furthermore, given its multifunctional requirements, the coupler is divided into several sub-assemblies to facilitate manufacturing, operation, and maintenance. The specific functions of these components are introduced as follows:

Waveguide Coupling Port Assembly: As the critical component for achieving waveguide-to-cavity coupling, it is welded directly to the cavity to form an integrated unit. Meanwhile, a mounting port is configured on its broad wall to accommodate the movable tuner.

Movable Tuner: This component enables the online adjustment of the coupling coefficient.

90° Waveguide Bend: This assembly provides ports for vacuum pumping and monitoring while simultaneously redirecting the RF power transmission.

RF Window: This is the core component responsible for maintaining vacuum isolation while ensuring reliable high-power transmission.

Stepped Waveguide Transition: This component acts as an adapter, bridging the half-height WR1500 waveguide of the coupler section with the standard WR1800 waveguide utilized in the main transmission system.

The whole assembly of the cavity with power coupler is shown in Figure 1. The commercial software CST and ANSYS are used in the development of the power coupler [3, 4]. As the multiphysics analysis of the Waveguide Coupling Port Assembly have been introduced detailly in ref [2], we will describe the design of the remain components in the follow.

Moveable Tuner

The moveable tuner as shown in Figure 2 employs a choke structure to eliminate direct physical contact between the tuning rod and the external mounting structure. Correspondingly, a mounting port for this movable tuner is configured on the waveguide coupling port assembly.

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Actuated by a remotely operated motor, the tuning rod features a tuning range of 0 to 67 mm relative to the broad wall of the waveguide. The moveable tuner underlying principle relies on a half-wavelength transformation to minimize the complex impedance between the tuning rod and the broad wall of the waveguide. To minimum the temperature rise, three water cooling channels are used. One channel is used to cooling the tuning road, the other two channels are set on the mounting port and the shell of the moveable tuner respectively.

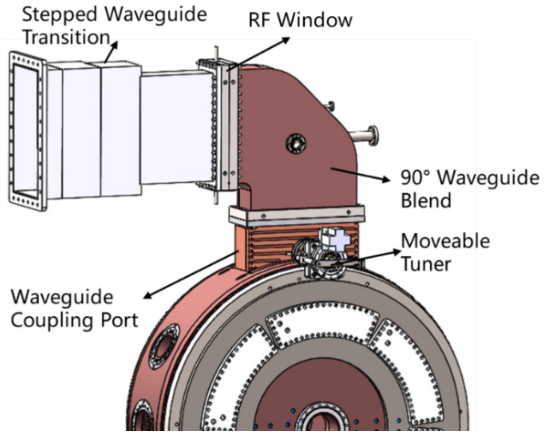

Figure 1: View of the power coupler assembly.

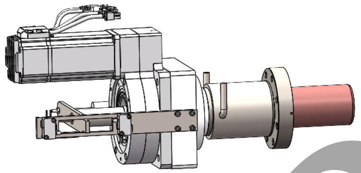

Figure 2: Mechanical design of the moveable tuner.

90° Waveguide Bend

Primarily, the 90° waveguide bend serves to redirect the power transmission. To maintain the vacuum integrity within the coupler, this component is equipped with three CF 35 flange ports and one CF16 flange port. An arc detector probe will be mounted on the CF16 flange port to protect the ceramic window. Among the CF35 flange ports, one is dedicated to vacuum monitoring equipment, another featuring an extended tube is utilized for mounting a getter pump, while the third is reserved as a spare.

The electromagnetic simulation is executed in CST Studio and the field distribution corresponding to 0.5 W incident power is shown in Figure 3. The S11 parameter is optimized to -94.6 dB at 499.7 MHz and a -35 dB bandwidth of 63 MHz is obtained.

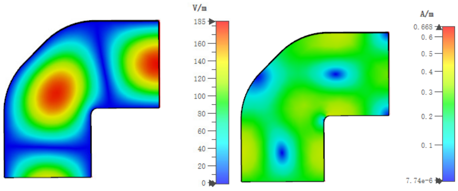

Figure 3: Electromagnetic field distribution: a). E-field (left); b). H-field (right).

Multiphysics simulations are performed in ANSYS Studio. Figure 4 show the simulation model for thermal and mechanical analysis. The main body of the 90° waveguide bend is fabricated from oxygen-free copper, while the connecting flanges at both sides are made of 316L stainless steel. During the simulation, the background temperature is set to 25 ℃. As can be seen in Figure 4-5, the maximum temperature rise is about 17.641 ℃ when an RF power of CW 300 kW is transmitted through. Correspondingly, the max equivalent stress and total deformation is respectively 133.29 MPa and 0.16629 mm. The peak stress is concentrated at the bottom of the stainless-steel flange, which is attributed to the fixed constraint applied there. As for the copper main body, the max stress is below 60 MPa. Significant deformation occurs at the exterior bend of the waveguide due to thermal expansion, whereas the deformation in the central region is induced by vacuum pumping. Overall, as evidenced by the simulation results above, the proposed design entirely satisfies the stringent operational requirements.

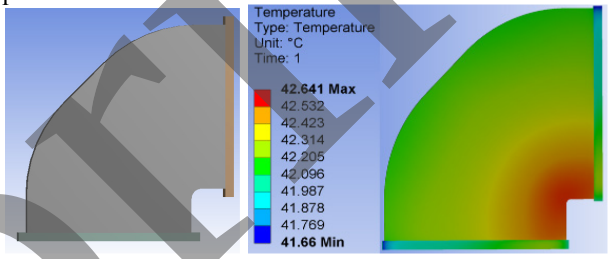

Figure 4: The thermal and mechanical simulation model (left) and the temperature distribution under a transmitted power of CW 300 kW (right).

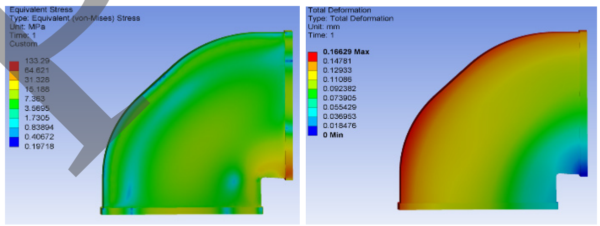

Figure 5: The corresponding stress distribution (left) and deformation distribution of this component (right).

RF Window

The RF window serves as a critical component of the coupler. Considering both fabrication cost and structural compactness, a rectangular geometry is selected for the RF window. The metallized AL-995 alumina ceramic from Morgan is utilized as the dielectric material. During the assembly process, the ceramic is first brazed to the peripheral window frame, and the resulting sub-assembly is subsequently joined to the water-cooling jacket via electron-beam welding.

The S11 parameter of the RF window is finally optimized to -66.7 dB at a frequency of 499.7 MHz. Furthermore, the maximum electric field in the RF window is approximately 0.62 MV/m when a peak power of 300 kW is transmitted. The electromagnetic simulations results are shown in Figure 6. Following the electromagnetic design, multipacting (MP) simulations are carried out. To suppress MP, the vacuum side of the RF window is sputtered with 5nm TiN. As shown in Figure 7, the SEY within the RF window is strictly less than 1, confirming the complete absence of MP.

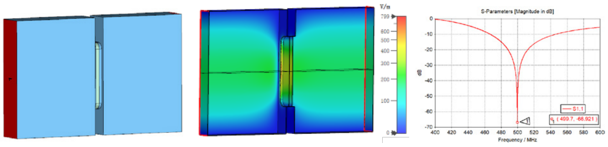

Figure 6: The electromagnetic simulation model (left), the electric field distribution with 0.5 W incident power (middle) and optimized S11 parameter (right).

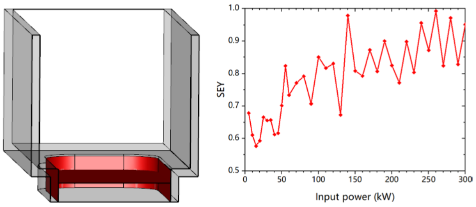

Figure 7: The MP simulation: a). Particle source (left), b). The SEY curve vs. Input power.

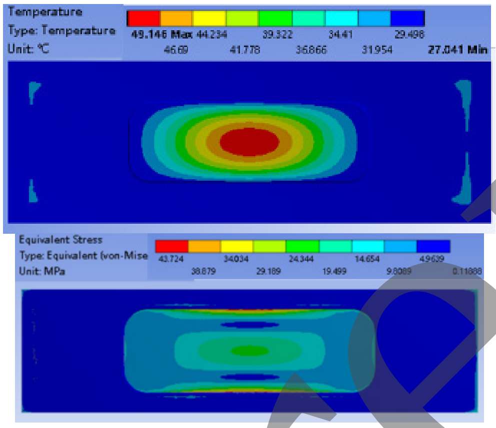

Figure 8: Thermal simulation results (up) and mechanical simulation results (down) without steel flange.

Stable operation of the RF window has always been the primary design objective, although it is influenced by various factors such as thermal gradients and actual operating conditions. To mitigate the heat generation caused by dielectric loss in the ceramic, a peripheral water-cooling jacket is employed around the window. Simulation results indicate that the maximum temperature rise of the RF window is approximately 22.1 °C, located at the center of the ceramic. Furthermore, regarding the copper and ceramic components, the maximum stress is concentrated at the braze joint between the window and the copper, reaching approximately 43.7 MPa, as shown in Figure 8. This value fully satisfies the operational requirements.

HIGH-POWER CONDITIONING SETUP

The entire coupler will undergo high-power conditioning up to a maximum CW power of 50 kW in conjunction with the cavity. The complete assembly is consistent with the configuration shown in Figure 1. As a pivotal component, the RF window requires conditioning to higher power levels; however, this is constrained by the output of the power source. Therefore, we design an RF window test bench to conduct testing in a standing-wave (SW) mode. The RF window will be tested up to more than 50 kW CW power under SW conditions to verify its performance. As shown in Figure 9, the test bench assembly consists of two stepped waveguides transition, two RF windows, and a connecting waveguide that provides necessary monitoring and vacuum pumping port for the high-power conditioning.

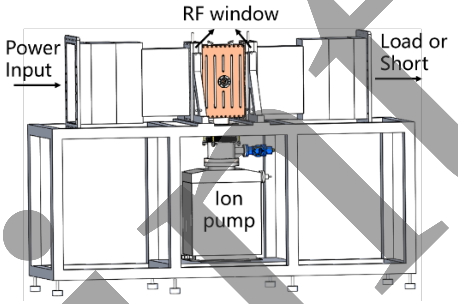

Figure 9: High-power test bench for RF window.

CONCLUSION

In this paper, the multiphysics design and analysis of the power coupler components have been presented in detail. Additionally, a dedicated high-power test bench is designed specifically for the RF window, which serves as a critical component. The simulation results demonstrate that the proposed coupler fully satisfies the operational requirements of the STCF TM020 cavity. Currently, all components are under fabrication and are scheduled to be completed by the end of June. It is anticipated that the high-power conditioning of the coupler will be finalized within this year.

REFERENCES

[1] Ai, Xiao-Cong, *et al.*, "Conceptual design report of the Super Tau-Charm Facility: The accelerator", *Nucl. Sci. Tech.*, vol. 36, no. 12 , 242, 2025.
`doi:10.1007/s41365-025-01833-x`

[2] Fan, M., Y. Wei, C. Wang, and Z. Liptak. "Design of an online adjustable waveguide coupler for the TM020-mode cavity of proposed STCF", in *Proc. IPAC'16*, May 2025, paper WEPB113, pp. 1944-1947.
`doi: 10.18429/JACoW-IPAC2025-WEPB113`

[3] CST, https://www.3ds.com

[4] ANSYS, https://www.ansys.com