DEVELOPMENT OF STCF S-BAND HIGH-GRADIENT TRAVELING WAVE ACCELERATING STRUCTURES*

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Abstract

The Super Tau-Charm Facility (STCF) is a next-generation electron-positron collider project proposed in China, designed to explore frontier physics in the tau-charm energy region. The facility's accelerator is required to provide electron and positron beams with tunable energies ranging from 1.0 to 3.5 GeV. This study presents the design of a traveling-wave accelerating structure for the STCF. By optimizing the regular-cell configuration, a high shunt impedance is achieved. The peak electric field in accelerating structure is reduced by adjusting the accelerating gradient profile, and an under-coupled output coupler design is adopted to enhance the performance of the accelerating structure. The objective is to achieve an accelerating gradient of 22.5 MV/m with an input power of 45.3 MW, and to further increase the power in pursuit of high-gradient operation in the S-band.

INTRODUCTION

The Super Tau-Charm Facility (STCF), a next-generation electron-positron collider project actively promoted by the Chinese particle physics community, is designed to conduct cutting-edge scientific research in the tau-Charm energy region. Efforts are currently underway to secure support from the central government of China for its construction during the 15th Five-Year Plan period [1, 2].

The design of the STCF linac is based on single-pulse operation, leading to the choice of room-temperature traveling-wave accelerating structures and a waveguide system that incorporates pulse compressors. More specifically, the main electron linac injector will utilize 50 of these accelerating structures, each 3 meters long.In operation, a single klystron, combined with a pulse compressor, is used to drive two accelerating structures. These structures will operate at 2998.2 MHz, which corresponds to the sixth harmonic of the collider ring's frequency of 499.7 MHz.

Multipole components in couplers can lead to degradation of beam emittance, making it essential to select an appropriate coupler design that minimizes these effects [3, 4]. In this study, various coupler configurations were compared to evaluate their multipole characteristics and associated impacts. Within the context of STCF, dual-feed racetrack couplers were ultimately chosen due to their enhanced capability to suppress multipole components, thereby more effectively reducing multipole-induced effects.

Constant-impedance and constant-gradient traveling-wave accelerating structures are widely used in large-scale scientific facilities and industrial applications. However, achieving high gradients in the S-band is often limited by breakdown in individual cells. To address this, a design approach based on peak-field-balanced regular cells is proposed. By tailoring the gradient distribution along the structure, the peak electric field in each cell is equalized. This enables an average gradient of 22.5 MV/m to be achieved in the S-band with an input power of 45.3 MW, while also offering the potential for further enhancement to higher gradient levels.

This paper describes the design of a 3-meter traveling wave accelerating structure for STCF and presents its corresponding parameters. A brief comparison of multipole components arising from different coupler designs is provided, along with an overview of the cooling scheme considerations for the STCF traveling wave structure.

STRUCTURE DESIGN

To accelerate the electron beam to the design energy, the S-band traveling wave accelerating structure operating in the $2\pi/3$ mode will be employed. The operating temperature of the structure is set to 30°C. Dual-feed racetrack couplers are adopted, along with a regular cell design featuring a modified gradient distribution. This accelerating structure requires tuning, and a schematic of the cell and coupler designs is shown in Fig. 1.

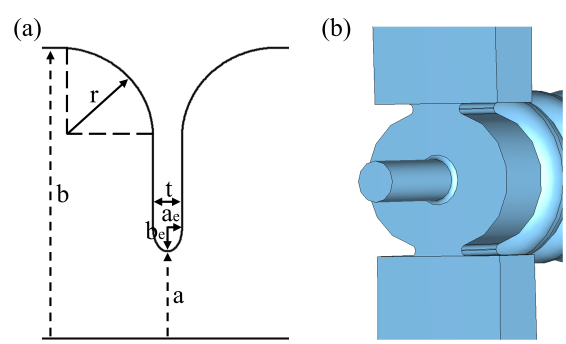

Figure 1: Schematic diagrams of the STCF traveling wave accelerating structure: (a) single cell, (b) coupler (not to scale).

Multipole Components

For the STCF accelerating structure, three typical coupler designs were developed to investigate the impact of multipole components. These include a dual-feed racetrack

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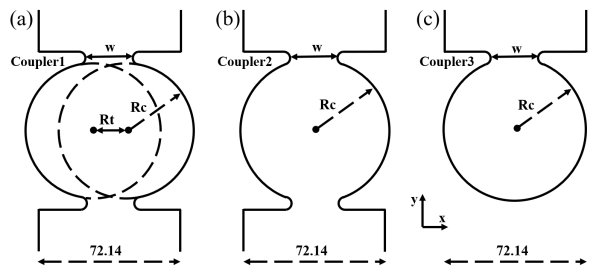

Figure 2: Schematic diagrams of three typical coupler designs.

coupler, a dual-feed coupler, and a single-feed coupler, each optimized as illustrated in Fig. 2. The dual-feed racetrack coupler employs a cavity geometry formed by two circles with offset centers. This configuration is specifically designed to suppress the dipole and quadrupole components introduced by the input and output couplers.

Multipole components under different coupler designs were extracted using fast Fourier transform analysis [4]. The extracted multipole components are shown in Fig. 3. The results clearly show that the single-feed structure exhibits a pronounced dipole component. In the dual-feed structure, the dipole component is significantly reduced, but a notable quadrupole component remains. In contrast, the dual-feed racetrack structure effectively minimizes both dipole and quadrupole components. Consequently, the dual-feed racetrack coupler is adopted for the traveling wave accelerating structure in STCF.

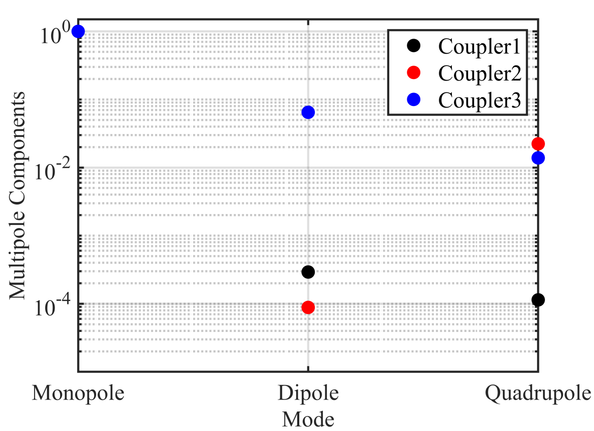

Figure 3: Multipole components for the three optimized typical coupler designs.

Regular Cells

The individual cell was optimized using the electromagnetic simulation software. The design method for the regular cell is as described in the reference [5, 6]. By rounding the cell edges with a radius of $r = 13$ mm, the quality factor was improved and the shunt impedance was further increased. The single cell peak surface field was reduced by employing an elliptically shaped iris. Based on these considerations, an elliptical chamfer with an aspect ratio $a_e/b_e = 0.6$ was adopted for the structure.

Table 1: Parameters of Accelerating Structure in STCF Main Electron Linac Injector

Parameters	**Unit**	**Value**
Frequency	MHz	2998.2
Average gradient	MV/m	22.5
Unloaded gradient	MV/m	20.99–26.48
Cell number		90+2
Input power	MW	45.37
Iris aperture, 2a	mm	25.31–18.77
Quality factor		15510–15401
Shunt impedance	MΩ/m	63.41–74.58
Disk thickness	mm	4
Group velocity, v_g/c		0.0264–0.0098
Filling time	µs	0.57
Peak-to-average ratio		2.15–1.80
Peak field strength	MV/m	44.59–47.70
Total length	mm	3165

To optimize the peak field in the regular cells, a scheme involving the modification of the individual cell gradient was applied to the current design. The gradient settings and the corresponding peak-to-average ratio for an average gradient of 22.5 MV/m are plotted in Fig. 4. The parameters of the STCF traveling wave accelerating structure's regular cells are listed in Table 1.

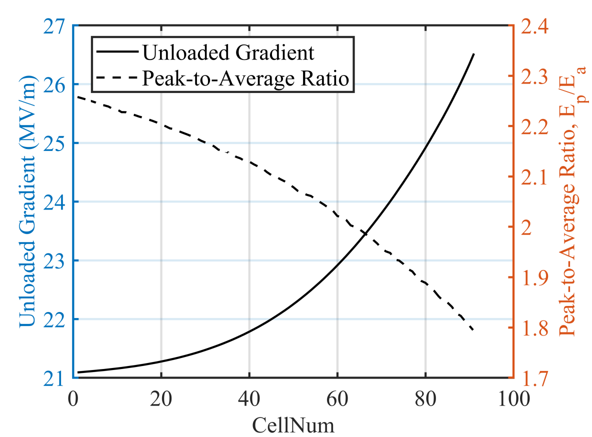

Figure 4: Variation of unloaded gradient (left) and peak-to-average ratio (right) with cell number.

The gradient settings shown in Fig. 4 are designed to transform the peak electric field distribution in the regular cells from a decrease from the input coupler to the output coupler in the constant gradient case to a nearly uniform distribution, with a slight increase at the output coupler, in order to reduce the breakdown probability of the S-band traveling wave accelerating structure.

COOLING SCHEME

Since the traveling wave accelerating structure may operate at repetition rates of 30/90 Hz, the choice of a water cooling scheme for the traveling wave accelerating structure is crucial.

An example with the same water circuit design is simulated using COMSOL Multiphysics software to analyze the cooling effects of internal and external water cooling schemes on the traveling wave accelerating structure. Considering a klystron output power of 40 MW, a pulse width of 4 μs, waveguide loss of 0.6 dB, and neglecting pulse compressor losses, with one power source driving two accelerating structures, and repetition rates of 30 Hz and 90 Hz, the average power loss per cell is shown in Fig. 5.

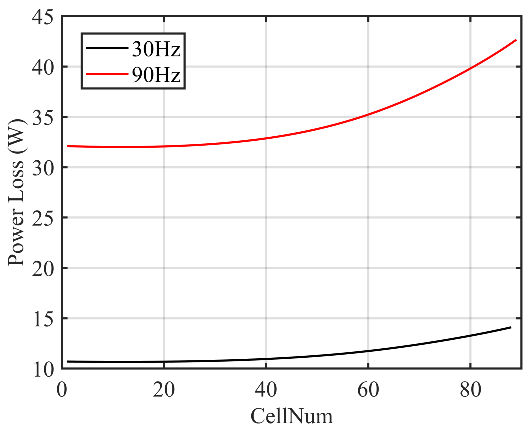

Figure 5: Average power loss at 30 Hz and 90 Hz.

Assuming that for external water cooling, the water pipe is attached to the accelerating structure wall with a width of 5 mm, the inlet temperature of the cooling water is 30 °C, the inlet flow velocity is 2.5 m/s, the heating power of the accelerating tube is assigned in five segments, and considering that the ambient temperature remains constant at 30 °C with a relative humidity of 30%, the multiphysics calculation results are shown in Fig. 6.

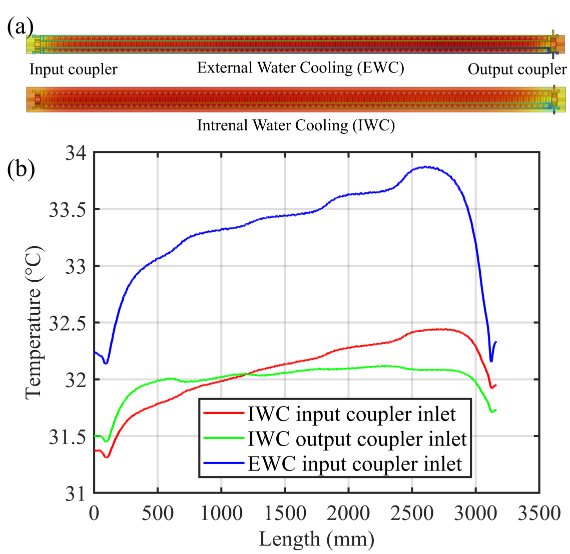

Figure 6: (a) Schematic of IWC and EWC configurations with water inlets at the output coupler side; (b) longitudinal temperature profiles at 90 Hz repetition rate for three cooling configurations, at 45 mm off-axis (near cavity wall).

The multiphysics calculation results indicate that, compared to external water cooling, internal water cooling exhibits a stronger cooling capacity under the same conditions. Due to the higher power at the tail end of the current traveling wave accelerating structure design, when the structure is divided into five segments, the tail end temperature is also higher. However, because of the superior cooling effect of internal water cooling, the front end temperature becomes lower. Therefore, it is a better choice to reverse the water inlet position and place the cooling water inlet near the output coupler.

CONCLUSION

In conclusion, this paper presents a design scheme for a constant gradient (CG) traveling wave accelerating structure tailored to the STCF project, which aims to equalize the peak electric field by varying the gradient settings, with the goal of achieving a high gradient in the S-band. It details the design parameters of the electron main linac traveling wave accelerating structure for STCF, including considerations of the multipole components in the coupler. Additionally, the effectiveness of different water cooling schemes is analyzed. For the current accelerating structure, it is recommended to position the water inlet near the output coupler. The feasibility of this design approach for equalizing the peak electric field in the traveling wave accelerating structure will be verified at the Super Tau-Charm Facility Beam Test Platform, with the expectation of achieving the targeted high gradient.

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