# STUDY OF A DUAL-FEED TM020-MODE CAVITY FOR THE SUPER TAU-CHARM FACILITY*

Li Sun[1], Yelong Wei[†1], Zhicheng Huang[1], Yihao Zhang[1], Zexin Cao[1], Chengzhe Wang[1]
[1]National Synchrotron Radiation Laboratory
[1]University of Science and Technology of China, Hefei, China

*Abstract*

Radio frequency (RF) cavities play an important role in the ring RF systems of accelerator facilities by replenishing the beam energy lost to synchrotron radiation. Compared to the $\mathrm{TM}_{010}$-mode RF cavity, the $\mathrm{TM}_{020}$-mode cavity exhibits a higher quality factor helping with efficiency and lower characteristic impedance, which reduces transient beam loading effects. However, the leakage of the operating mode and input coupler power capacity under high beam current remain critical issues for the $\mathrm{TM}_{020}$-mode cavity. This paper proposes elliptical choke geometry for coaxial slot and dual-feed input couplers to reduce field asymmetry and thermal load for a normal-conducting $\mathrm{TM}_{020}$-mode cavity. Electromagnetic simulations confirm excellent RF performance, demonstrating a cavity voltage of > 500 kV, an unloaded quality factor of > 60000, and operating-mode leakage suppressed to < 1%. Overall, the proposed dual-feed cavity with elliptical choke meets the demanding power, stability, and reliability requirements of next-generation high-current ring RF systems.

## INTRODUCTION

As a key platform for next-generation frontier particle physics research, the Super Tau-Charm Facility (STCF) imposes unprecedented demands on beam performance, particularly in terms of ultrahigh luminosity and operation under high-current conditions [1]. In such facilities, the RF system serves not merely as an energy-replenishing unit but as a core subsystem that critically determines beam stability, lifetime, and ultimate luminosity [2]. Due to its intrinsic R/Q, the $\mathrm{TM}_{020}$-mode cavity would be helpful to suppress transients beam loading effects under the high-current scenarios envisioned for STCF. Therefore, a TM020-mode normal-conducting (NC) cavity has been selected as a candidate for the RF system of STCF [3–6].

This study aims to develop a high-performance and highly reliable $\mathrm{TM}_{020}$-mode cavity suitable for the STCF project. An innovative design integrating an elliptical coaxial-slot cavity with a symmetrical dual-feed waveguide-type strongly rounded input coupler is proposed. This design incorporates a waveguide-type input coupler with large rounded corners to mitigate localized heating at the coupling iris under high power, and integrates a symmetric configuration with elliptical coaxial slots to suppress field leakage [7].

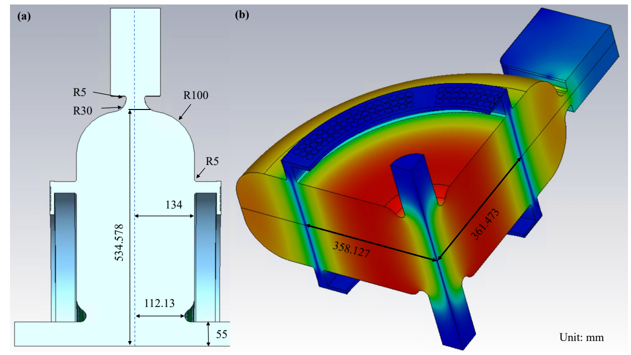


Figure 1: (a) Corresponding geometric structure and parameters with strongly rounded coupling iris, input coupler and elliptical choke-type coaxial-slot. (b) Magnetic field distribution of operation mode.

## CAVITY DESIGN

Based on the physics design goals of the STCF project, such as its wide energy range (2–7 GeV) and high peak luminosity ($> 0.5 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$), the key parameters of the electron storage ring relevant to the RF system are summarized in the Tab. 1. Under the requirement of a 2 A high beam current, a single ring rf system must provide at least 6 MV of accelerating cavity voltage and 3 MW of beam power.

The vacuum model of the main structure, which consists of one main cavity, two waveguide-type input couplers, two parasitic mode absorber structures, and four frequency tuners (temporarily excluding vacuum ports and pick-up ports). The cavity frequency is primarily determined by the equatorial radius of the main cavity body, while the $R/Q$, $E_\mathrm{p}/E_\mathrm{acc}$, and $H_\mathrm{p}/E_\mathrm{acc}$ are mainly governed by the nose-cone curvature. The unloaded quality factor $Q_0$ is largely influenced by the chamfer design on both sides of the main cavity body and the geometry of the coaxial-slot structure. Additionally, the beam-pipe diameter significantly affects both $R/Q$ and $Q_0$, a smaller diameter leads to higher values of these parameters. To balance the requirements for $R/Q$ and $Q_0$ while mitigating coupled-bunch instability (which favors a lower $R/Q$), the beam-pipe radius has been set to 55 mm. The nose cone incorporates optimized top and bottom chamfers to reduce the surface peak electric field, thereby preventing breakdown. The nose-cone design adopts a 30° angle complemented by a 30 mm top chamfer. The corresponding geometric parameters are illustrated in Fig. 1.

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† wylong@ustc.edu.cn

Table 1: Collider ring physics parameters.

| Parameter | Value1 | Value2 | Value3 | Value4 | Units |
|---|---|---|---|---|---|
| Circumference, $C$ | | 825.524 | | | m |
| Revolution frequency, $f_{\text{rev}}$ | | 363.15 | | | kHz |
| Beam energy, $E_0$ | 1 | 1.5 | 2 | 3.5 | GeV |
| Beam current, $I_b$ | 1 | 1.5 | 2 | 2 | A |
| Momentum compaction, $\alpha_p$ | 13.36 | 13.9 | 14.07 | 14.3 | 1E-4 |
| Synchrotron tune, $\nu_z$ | 0.0147 | 0.0173 | 0.0193 | 0.0228 | - |
| Damping time, $\tau_{x,\ y,\ z}$ | 43.79/43.79/21.89 | 26.56/26.56/13.28 | 17.69/17.69/8.85 | 12.9/12.9/6.45 | ms |
| Energy loss per turn, $U_0$ | 125.77 | 311 | 622.6 | 1494 | keV |
| RF voltage, $V_{\text{RF}}$ | 0.75 | 1.5 | 2.5 | 6 | MV |
| Synchronous phase, $\phi_s$ | 166 | 170 | 168 | 166 | deg |
| Natural bunch length, $\sigma_z$ | 6.96 | 7.38 | 7.55 | 8.26 | mm |
| Charge per bunch, $q$ | 3.34 | 6.25 | 8.34 | 8.34 | nC |

As illustrated in Fig. 1(a), the external part of the input coupler is a half WR1800 rectangular waveguide (457.2 mm×114.3 mm). The coupling iris is a rectangular aperture with dimensions of 110.543 mm×41.794 mm×35 mm. The upper and lower edges of the aperture are chamfered with optimized radii of 5 mm and 30 mm, respectively, to maintain an appropriate local magnetic field distribution. Simultaneously, the input coupling coefficient $\beta$ corresponds to near-critical coupling ($\beta \approx 1$).

The presence of two waveguide-type coupling irises, four frequency tuner ports, and additional ports on the cavity stretch the originally circular magnetic field nodes of the $\text{TM}_{020}$ mode. An elliptical coaxial slot is employed to better conform to this perturbed field distribution. As illustrated in Fig. 1(b), the elliptical slot has major and minor axes of 361.493 mm and 358.127 mm after optimization, respectively, with its center remaining on the beam z-axis. The absorber elements are fabricated from R1500-type ferrite, a material known for its effective electromagnetic absorption across a broad frequency range from 100 MHz to 10 GHz. Each ferrite tile measures 16 mm×16 mm×2 mm and is arranged with a 60° angular spacing in the damping structure.

Based on the three-stage design approach described above, the resulting RF parameters of the cavity are summarized in Tab. 2.

Table 2: Optimized $\text{TM}_{020}$-mode cavity RF parameters.

| Parameter | Value | Unit |
|---|---|---|
| Operation frequency, $f_0$ | 499.7 | MHz |
| Unloaded quality factor, $Q_0$ | 61512 | - |
| Shunt impedance, $R_a$ | 5.35 | MΩ |
| Characteristic impedance, $R/Q$ | 87.12 | Ω |
| Cavity voltage, $V_c$ (@50 kW) | 517 | kV |
| $E_p/E_{acc}$ | 2.9 | - |
| $H_p/E_{acc}$ | 2.9 | mA/V |
| Leakage rate, $\eta$ | 0.517 | % |

The dimensions, tuning range, and impact on the cavity's radio-frequency (RF) parameters are the primary considerations in the design of a frequency tuner. The required tuning range is typically determined by taking into account both beam-loading effects and the frequency shifts resulting from thermal deformation of the cavity. The physical size and insertion depth of the tuner influence the performance of the operating mode. For simplicity, the steady-state formula eq. 1 is used to calculate the frequency shift caused by the beam loading effect.

$$df_{\text{beam}} \approx -\frac{I_b \sin(\phi_s) R/Q}{2V_c} f_0. \tag{1}$$

Based on the data in Tab. 1, the maximum frequency shift is obtained as -21 kHz. Considering the frequency shifts induced by multi-bunch effects, parasitic mode influences, thermal effects, and others, we set the tuning target at 200 kHz.

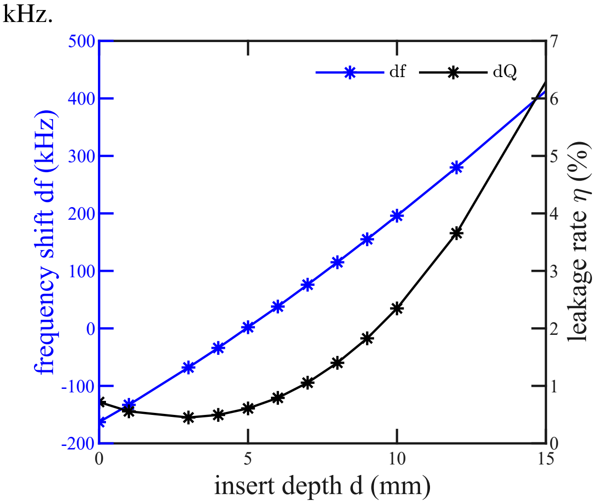


Figure 2: Impact of frequency tuner insertion $d$ on frequency shift $df$ and operation mode leakage rate $\eta$.

For the cavity, the dimensions of the cylindrical tuner, defined by its diameter $R$ and insertion depth $d$, determine the resonant frequency of the operating mode. In the $\text{TM}_{020}$-mode cavity, the insertion depth d exhibits a more significant influence on the magnetic nodes within the electromagnetic field distribution. Consequently, a careful balance must be struck between minimizing the maximum insertion depth and optimizing the tuner diameter. Through continuous optimization, we set the radius of the tuner R to 45 mm with an initial insertion depth of 5 mm. As shown in Fig. 2, within an insertion depth range of 0–9 mm, the tuning range reaches approximately ±150 kHz while maintaining a leak rate below 2%. Within this range, simulations indicate that the leakage of the operating mode remains below 2%, and the power absorption by the absorber material is kept under 1 kW, both of which fall within acceptable limits.

## WAKEFIELD IMPEDANCE

Wake impedance serves as a critical parameter for evaluating the influence of RF cavities on coupled-bunch instability. Given a determined radiation damping time, parasitic modes exceeding the instability threshold require coordinated suppression through a feedback system, which actively damps coherent bunch oscillations by driving dedicated correctors.

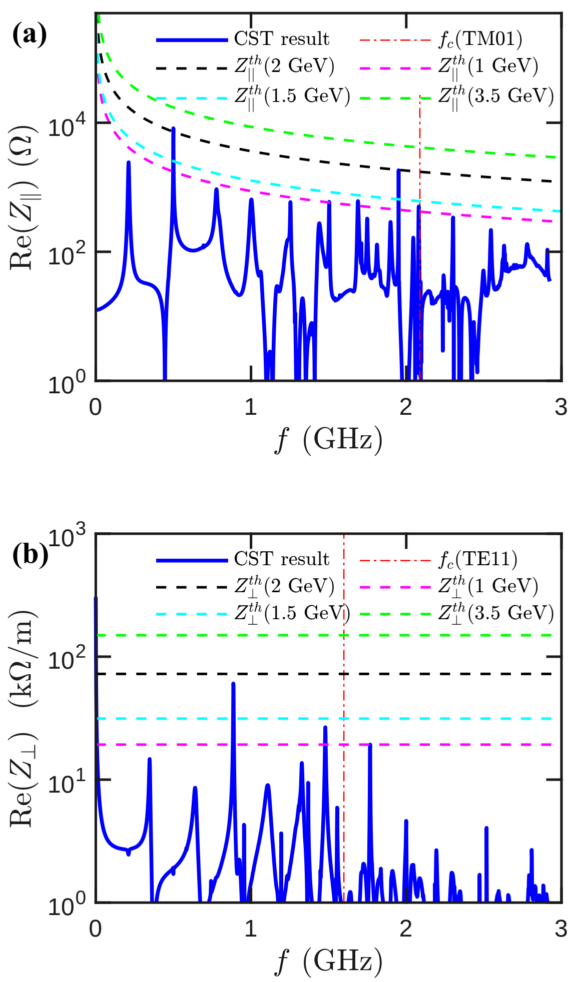


Figure 3: Wake impedance. The dashed line represents the threshold curve. (a) Longitudinal $Z_{||}$ (b) Transverse $Z_{\perp}$

The analysis in this section was performed using the wakefield solver in CST Studio Suite. In the simulation, a wakelength of 200 m was set, and sufficient attenuation of parasitic modes was accounted for in the model. Figure 3 presents the optimized longitudinal and vertical wake impedance of the cavity, where the dashed line indicates the instability threshold and the solid curve represents the simulation result. It can be observed that parasitic modes remain below the instability threshold under 2 GeV and 3.5 GeV operating conditions for single cavity. However, at beam energies of 1 GeV and 1.5 GeV, some modes exceed the threshold and would require active suppression via a bunch-by-bunch feedback system to rapidly damp its instability.

## CONCLUSION

This paper presents the design of a 500 MHz $TM_{020}$-mode cavity featuring a dual-feed input coupler to meet the high-beam-current requirements of the future Super Tau-Charm Facility (STCF) in Hefei, China. To suppress the longitudinal and transverse parasitic-mode coupling impedance, extensive iterative optimizations were performed, including the nose-cone profile and the absorber-module layout. Simulation results show an unloaded quality factor of ~61,000 and a shunt impedance of ~5.3 MΩ for such a cavity.

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