DESIGN, FABRICATION, AND TEST OF A TM_{020}-MODE CAVITY WITH ELLIPTICAL CHOKE FOR SUPER TAU-CHARM FACILITY

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Abstract

An improved TM_{020}-mode RF cavity has been developed for the collider rings of the Super Tau-Charm Facility (STCF). By utilizing a higher TM_{020}-mode for beam acceleration, this cavity has a lower $R/Q = 83.5\ \Omega$ and a higher unloaded $Q = 61300$, compared with conventional TM_{010}-mode cavities. These characteristics help reduce the required detuning frequency and significantly suppress coupled-bunch instabilities (CBIs) driven by the accelerating mode. The optimized cavity operates at 499.7 MHz and provides an effective accelerating voltage $V_a = 0.6$ MV. An elliptical choke is employed to reduce leakage power, achieving less than 2% power loss in the accelerating mode. In addition, harmful parasitic modes other than the TM_{020}-mode are effectively suppressed by positioning the elliptical choke at the magnetic node of the operating mode. After fabrication, the cavity prototype was precisely tuned, and low-power RF measurements were performed. The measured results show good agreement with the simulations, confirming the performance of the improved TM_{020}-mode cavity.

INTRODUCTION

Radiofrequency (RF) cavities are widely used in accelerator facilities to transfer power to the beam, accelerate charged particles, and compensate for synchrotron radiation losses, such as synchrotron radiation sources [1–3] and colliders [4–5]. Over the past two decades, with the continuous development of high-energy physics, a next-generation Tau-Charm factory, namely the Super Tau-Charm Facility (STCF), has been actively promoted by the particle physics community in China [6]. The STCF aims to address fundamental questions such as the nature of color confinement and the origin of matter-antimatter asymmetry. The primary design goals of the STCF are a center-of-mass energy ranging from 2 to 7 GeV and a peak luminosity exceeding 5 × 1034 cm−2 s−1. The STCF project is currently under development with an extensive R&D program including the RF system. Normal-conducting (NC) cavities have been chosen as the primary technical route to support high circulating currents (≈ 2 A) due to their structural simplicity and relatively low construction and maintenance costs. These cavities are designed to provide strong suppression of higher-order modes (HOMs) and are equipped with high-power RF couplers. To meet the physics requirements of the collider rings, the RF system must provide a total accelerating voltage of 6 MV and a beam power of 3 MW for each ring. This will be achieved by installing 12-15 cavities in each ring, each delivering an accelerating voltage of 0.5 MV and a beam power of 250 kW to the beam.

The TM_{020}-mode normal-conducting (NC) cavity has been selected as one of the primary candidates for the STCF collider ring RF system because of its favourable performance in high-current storage rings. This cavity type was initially proposed by researchers at KEK and RIKEN and has been successfully commissioned for the Nano-Terasu storage ring [7]. Compared to conventional TM010- mode cavities, the TM_{020}-mode cavity exhibits a higher unloaded quality factor Q_0 and a lower R/Q [8]. These characteristics effectively reduce the required detuning frequency and significantly suppress coupled-bunch instabilities (CBIs) driven by the accelerating mode. Furthermore, the symmetric electromagnetic field distribution of the TM_{020}-mode enables ferrite absorbers to be directly embedded into coaxial slots inside the cavity, as shown in Figure 1. This damping scheme not only strongly suppresses harmful parasitic modes without significantly affecting the accelerating TM_{020}-mode, but also reduces the longitudinal space required by the cavity, making the structure extremely compact.

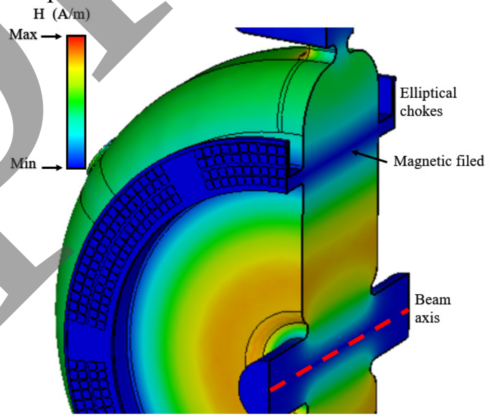

Figure 1: Electromagnetic field distribution of the TM_{020}-mode and location of the choke structure.

In our previous research, the leakage of the accelerating mode caused by the introduction of the input coupler and other components was successfully addressed by employing elliptical chokes and symmetrically arranged frequency tuners [9]. Following the completion of the RF optimization, comprehensive multi-physics analyses, including thermal and mechanical simulations, were conducted to design an effective cooling system. The prototype cavity was fabricated by Lanzhou Ion Therapy Co., Ltd. However, for this type of TM_{020}-mode cavity, experimental verification after fabrication is particularly important because its RF performance is highly sensitive to practical factors such as machining accuracy, brazing deformation, assembly conditions, tuner perturbations. Therefore, low-power RF measurements are indispensable for evaluating the resonant frequency, quality factor, tuning characteristics of the fabricated cavity, as well as validating the consistency between the experimental behavior and the design model.

This paper presents the design, fabrication, and low-power RF measurement of a TM_{020}-mode cavity with elliptical chokes. Section II briefly introduces the cavity design and fabrication. Section III presents the low-power RF measurement and tuner measurement results. Section IV summarizes the paper.

CAVITY DESIGN AND FABRICATION

The proposed TM_{020}-mode cavity was designed to meet the requirements of the high-current STCF collider rings. The primary goal is to provide the required accelerating voltage while effectively suppressing harmful parasitic modes, including the TM_{010}-mode and HOMs. The RF structure consists of the cavity body with elliptical chokes, three frequency tuners, and an input coupler, as shown in Figure 2.

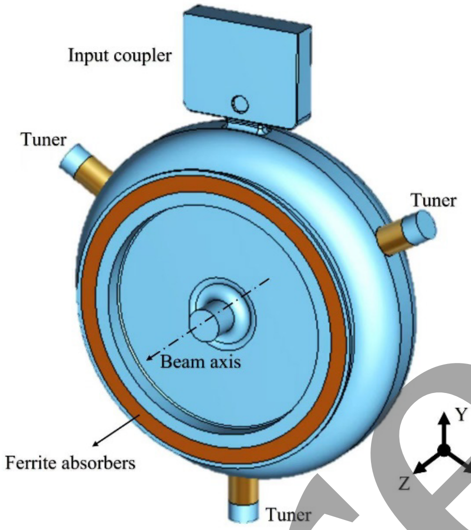

Figure 2: Three-dimensional view of the TM_{020}-mode cavity, including the cavity body with elliptical chokes, the input coupler, and the three frequency tuners.

The beam-pipe diameter was set to 120 mm, corresponding to cutoff frequencies of 1.46 GHz for the TE11 mode and 1.91 GHz for the TM01-mode. This choice is favorable for the propagation and damping of harmful parasitic modes. A pair of elliptical chokes was incorporated into the cavity wall and located near the magnetic-field nodes of the TM_{020}-mode, as shown in Fig. 1. The chokes strongly reflect the accelerating mode while allowing parasitic modes to propagate toward the ferrite absorbers. The optimized cavity operates at 499.7 MHz with an unloaded quality factor $Q_0$of 61300, an R/Q of 83.5 Ω, and a shunt impedance of 5.12 MΩ. The main RF parameters are summarized in Table 1.

Table 1. RF Parameters of the Optimized Cavity

RF parameters	
Working mode	TM_{020}
Frequency [MHz]	499.7
Unloaded quality factor Q_0	61300
Shunt impedance R [MΩ]	5.12
R/Q [Ω]	83.5
$\mathrm{E}_{\mathrm{peak}}/\mathrm{E}_{\mathrm{acc}}$	3.01
$\mathrm{B}_{\mathrm{peak}}/\mathrm{E}_{\mathrm{acc}}$ [mA/V]	2.96

To compensate for frequency shifts caused by fabrication tolerances and thermal expansion, three frequency tuners were symmetrically installed on the cavity equator at 120° intervals. This configuration was adopted to minimize field deformation and suppress accelerating-mode leakage during tuning. Simulation results show that the required tuning range of ±200 kHz can be covered while keeping the accelerating-mode leakage below 5%.

The prototype cavity was fabricated after the RF optimization and thermomechanical design. The cavity body and nose-cone plates were made of oxygen-free high-conductivity copper, while stainless-steel flanges were used for vacuum sealing and external connections. To compensate for possible frequency deviations caused by fabrication errors, a machining allowance of 5 mm was initially reserved on the machining faces of the nose-cone plates, as shown in Figure 3. These faces were incrementally machined according to intermediate frequency measurements, providing a practical method for resonant-frequency calibration before final assembly. Simulations show that removing 1 mm from these faces decreases the resonant frequency by approximately 250 kHz; therefore, the total frequency correction range is about -1250 kHz.

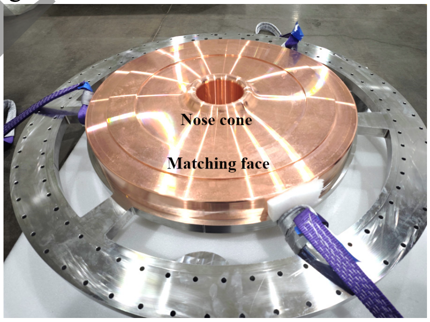

Figure 3: Machining face on the nose cone plate for resonant frequency calibration.

The effects of vacuum loading and thermal deformation were also considered in the final frequency setting, which were expected to decrease the resonant frequency by about 200 kHz during operation. To reduce the required tuner insertion and the corresponding tuner-induced leakage, a 1 mm allowance was finally retained on the machining faces of the nose-cone plates. As a result, the cold-cavity design frequency was set to 499.95 MHz. The completed prototype is shown in Figure 4.

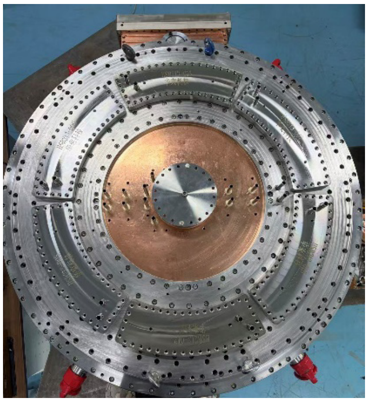

Figure 4: The completed prototype of TM_{020}-mode cavity.

LOW-POWER RF MEASUREMENT

Low-power RF measurements were performed to verify the resonant frequency, unloaded quality factor Q, and tuning characteristics of the fabricated TM_{020}-mode cavity. For this type of cavity, experimental verification is important because the resonant frequency and field distribution are sensitive to machining accuracy, brazing deformation, assembly conditions, and tuner perturbations.

Measurement Setup and Frequency Correction

The low-power measurements were performed using a Vector Network Analyzer (VNA, Keysight) to characterize the RF properties of the prototype. The cavity was placed in a temperature-controlled laboratory (20℃ 83300Pa, and 18% relative humidity). To excite the TM_{020}-mode, two small inductive loop probes were inserted into the iris ports to measure the transmission coefficient (S21), as shown in Figure 5.

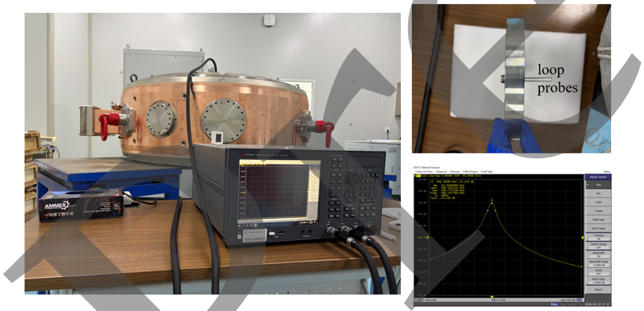

Figure 5: Low-power measurement setup for the TM_{020}-mode cavity, including the VNA, inductive loop probes, and the measured S_{21} response.

Since the electromagnetic simulations were conducted in a vacuum environment, the resonant frequency measured in air (f_{air}) must be corrected to the vacuum frequency (f_{vac}) using the relationship $f_{vac} = f_{air} \times \sqrt{\varepsilon_r}$. To ensure precision, the relative permittivity of air ($\sqrt{\varepsilon_r}$) was determined by a conversion program that integrates the measured ambient temperature, atmospheric pressure, and humidity. Based on these specific conditions, an $\sqrt{\varepsilon_r}$ of 1.00014 was applied, resulting in a positive frequency shift to compensate for the dielectric effect of the air medium.

RF Measurement Results

After frequency correction from air to vacuum, the resonant frequency of the TM_{020}-mode was measured to be 499.85 MHz. The unloaded quality factor Q_0 was approximately 52,500 which is about 85% of the simulated value, mainly due to fabrication and surface-loss effects. The measured frequency and Q_0 are in reasonable agreement with the simulation results, confirming that the fabricated cavity meets the RF design expectations.

Tuner Measurement

Tuner measurements were performed to evaluate the frequency tuning capability of the fabricated cavity. The three tuners were inserted symmetrically into the cavity, and the resonant frequency and unloaded quality factor of the TM_{020}-mode were recorded as functions of the tuner insertion depth, as shown in Figure 6.

As expected, increasing the tuner insertion depth resulted in a positive shift of the resonant frequency. A decrease in Q_0 was also observed during the tuning process, mainly due to field distortion induced by tuner insertion. Nevertheless, the measured Q_0 remained sufficiently high over the required tuning range, confirming that the three-tuner symmetric configuration provides adequate frequency tuning while limiting tuner-induced leakage.

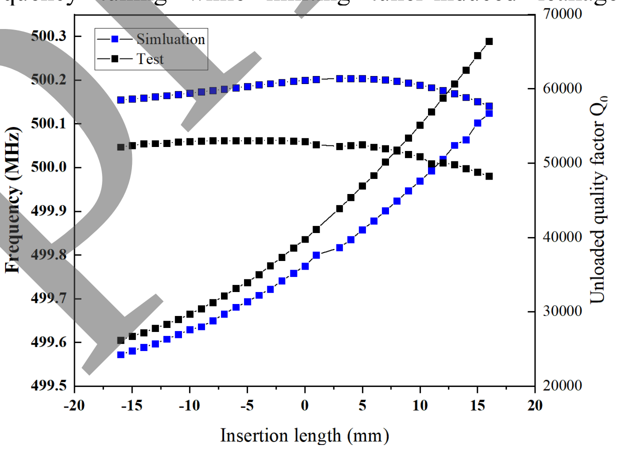

Figure 6: Measured resonant frequency and unloaded quality factor of the TM_{020}-mode as functions of tuner insertion depth.

SUMMARY

A prototype TM_{020}-mode cavity with elliptical chokes was fabricated and measured at low RF power for the STCF collider rings. After frequency correction from air to vacuum, the measured TM_{020}-mode frequency was 499.88 MHz, and the unloaded quality factor was approximately 52,500. Tuner measurements confirmed that the required frequency range can be covered while maintaining acceptable RF performance. These results verify the fabrication feasibility and low-power RF performance of the proposed cavity, providing a basis for future high-power tests.

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