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DEVELOPMENT OF LOW-FREQUENCY SUPERCONDUCTING CAVITIES FOR HIGH ENERGY PHOTON SOURCE

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Abstract

A low-frequency superconducting cavity is one of the most critical devices in the High Energy Photon Source (HEPS), a 6 GeV diffraction-limited synchrotron light source under construction in Beijing. A higher-order-mode (HOM) damped 166.6 MHz β=1 quarter-wave superconducting cavity, first of its kind in the world, has been designed by the Institute of High Energy Physics. Compact structure, excellent electromagnetic and mechanical properties and manufacturability were realized. An enlarged beam pipe was proposed allowing HOMs to propagate out of the cavity and be subsequently damped by a toroidal beamline HOM absorber at room temperature. Mounted with a forward power coupler, a tuner, two thermal break beam tubes, a collimating taper transition, two gate valves and some shielded bellows, the jacketed cavity was then assembled into a cryomodule. Two cryomodules were later required to fit into HEPS straight sections with a length limitation of 6 meters, which posed a significant challenge for the design of the cavity string. The success of the horizontal test also verifies the design of the cavity string. This article presents the design, fabrication, post-processing, system integration, and cryogenic tests of the first HOM-damped compact 166.6 MHz superconducting cavity module.

INTRODUCTION

High energy photon source (HEPS) is a diffraction-limited synchrotron light source designed by the Institute of High Energy Physics [1]. It is a 6 GeV kilometer-scale light source. The construction of HEPS began at Beijing in Jun 2019 and is expected to be completed in 2025. Five 166.6 MHz superconducting rf (srf) cavities will be installed in the storage ring as main accelerating cavities. The frequency of 166 MHz was chosen to implement a novel beam injection scheme proposed by physics [2], while compromising with the kicker technology [3]. The main parameters of HEPS are listed in Table 1.

Table 1: Main Parameters of the HEPS [4]

Parameter	**Value**	**Unit**
Circumference	1360.4	m
Beam energy	6	GeV
Beam current	200	mA
Total energy loss per turn	4.14	MeV
Total power loss to radiation	828	kW
Forward RF frequency	166.6	MHz
Total RF voltage (main)	5.16	MV
3^{rd} harmonic RF frequency	499.8	MHz
Total RF voltage (HC)	0.91	MV
Transmitter power per rf station	260	kW

A proof-of-principle (PoP) cavity has been successfully developed in HEPS-Test Facility (HEPS-TF) project [5, 6]. A HOM-damped 166.6 MHz β=1 quarter-wave superconducting cavity was proposed for HEPS storage ring [4, 7]. Mounted with a forward power coupler (FPC), a tuner, two thermal break beam tubes, a HOM absorber, a collimating taper transition, two gate valves and some shielded bellows, the jacketed cavity was then assembled into a cryomodule. In this paper, the design, fabrication, post-processing, system integration, and cryogenic tests of the first HOM-damped 166.6 MHz cavity module were introduced in detail.

DESIGN OF THE CAVITY STRING

Layout of the Cavity String

A total of four layouts for the cavity string were analyzed and finally layout1 was chosen as the baseline scheme [8], as shown in Fig. 1. The total loss factor of this setup was calculated to be 5.2 V/pC. Synchrotron light can be nicely collimated, producing sufficient shadow for downstream components.

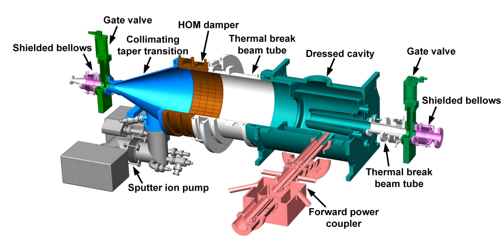

Figure 1: The 166 MHz cavity string.

Component Design of Cavity String

The Jacketed Cavity The jacketed 166 MHz cavity was fabricated by Beijing HE-Racing Technology Co., Ltd. There are 44 individual components. Grade-2 titanium was chosen to join the jacket and the NbTi flanges by using electron beam welding. The inlet flange was located at the bottom of the vessel and the feed pipe with a diameter of 8 mm guides the liquid helium into the LHe vessel. The outlet of the gas helium with a diameter of 160 mm was traditionally located on the top of the vessel. The welded cavity with helium jacket dressed are shown in Fig. 2.

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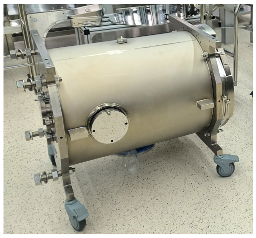

Figure 2: The jacketed 166.6 MHz srf cavity.

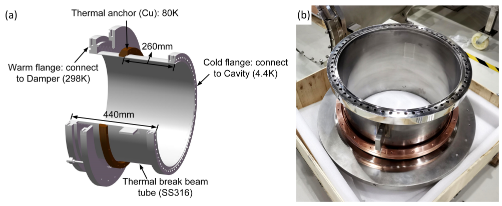

Figure 3: (a) Model and (b) fabricated thermal break beam tube.

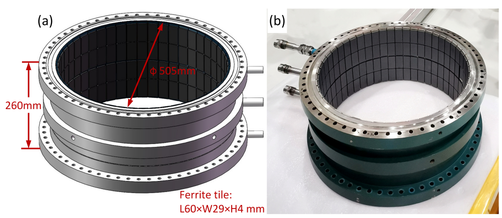

Figure 4: (a) Model and (b) fabricated HOM absorber.

Thermal Break Beam Tube The thermal break beam tube is a transition from 4 K at the cavity beam pipe to the room temperature outside the cryomodule. A thermal anchor at 80 K was added to reduce the cryogenic heat load. To minimize the heat load of 4.2 K, the thermal anchor position and tube thickness were optimized to be 260 mm and 2.5 mm, respectively. The total length of the thermal break tube was determined to be 440 mm to increase the temperature of warm flange higher than the dew point of 14°C (287 K). And the static heat load of 4.2 K and 80 K was reduced to 6.2 W and 87 W, respectively. The thermal break tube were shown in Fig. 3.

HOM Absorber The HOM absorber was made of 200 ferrite tiles, as shown in Fig. 4. Each ferrite tile was brazed to the copper base and water cooling channels were designed with a cooling capability of 10 kW rf power. The impedance of M2 was calculated to be $1.29 \times 10^4\ \Omega$, marginally exceeding the most stringent damping requirement of $1.14 \times 10^4\ \Omega$. The impedances of all other HOMs are below the threshold. The mechanical and thermal performances were also examined and acceptable for operation.

Collimating Taper Transition The transition from the cavity aperture of 505 mm to 63 mm of the interconnecting section is realized by a taper structure. After the beam comes out of the last bending magnet, it transverses a drift distance and then enters the cavity. Therefore, collimating is required

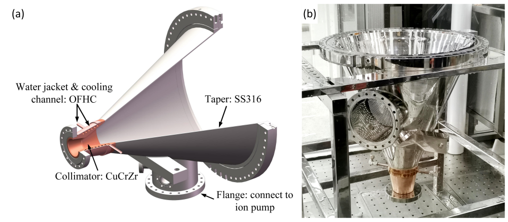

Figure 5: (a) Model and (b) fabricated collimating taper transition.

to create shadows for the downstream components like cavities, gate valves and shielded bellows. The well designed collimators were simple, compact, sufficiently cooled, and with large tolerances, as shown in Fig. 5. The higher temperature of 64°C observed on the spot of the direct light incidence, meeting the HEPS requirement.

Shielded bellows A rf-shielded bellows was designed to compensate for the longitudinal length variations from manufacturing, installation, cavity shrinkage during cooldown, tuner movement and so on. The maximum compression displacement is ±15 mm with a total length of 66 mm of the bellows.

ASSEMBLY AND HORIZONTAL TEST

Assembly

The assembly of the 166 MHz cavity string and the cryomodule was performed at the Platform of Advanced Photon Source Technology (PAPS), as shown in Fig. 6. The jacketed cavity, two thermal break beam tubes and a collimating taper transition were high-pressure rinsed by ultrapure water. The HOM absorber was cleaned with alcohol while the gate valves were purged by nitrogen until the particle count was reduced to 0. Next, the cavity string without ion pump were assembled in a class 10 clean room. After a slow pumping, a leak check of the cavity string was performed. Then, the cavity string was transferred outside the clean room. The HOM absorber was 150 °C baked for 86 h, and the cavity was subsequently 120 °C baked for 48 h while the other components were kept below 110 °C in experiment hall. Next, the position of the string was collimated, after which the temperature sensors and cables were placed. After that, the cavity string was pushed into the cryomodule for cryogenic pipeline connection and magnetic shield installation. Then, the cavity string and cryomodule were integrated successfully. Because the sputter ion pump was too large, it couldn't be integrated with the cavity string until the cryomodule endplates were installed. A movable clean room was built, and the assembly of the ion pump and cavity string was completed in the class 100 movable clean room. Next, the cryomodule was pushed out and the tuner was equipped on the cryomodule endplate in the experiment hall. At last, the cryomodule was transported to a horizontal test stand and connected to a distribution valve box, high-power transmission line, FPC, rf cables, etc.

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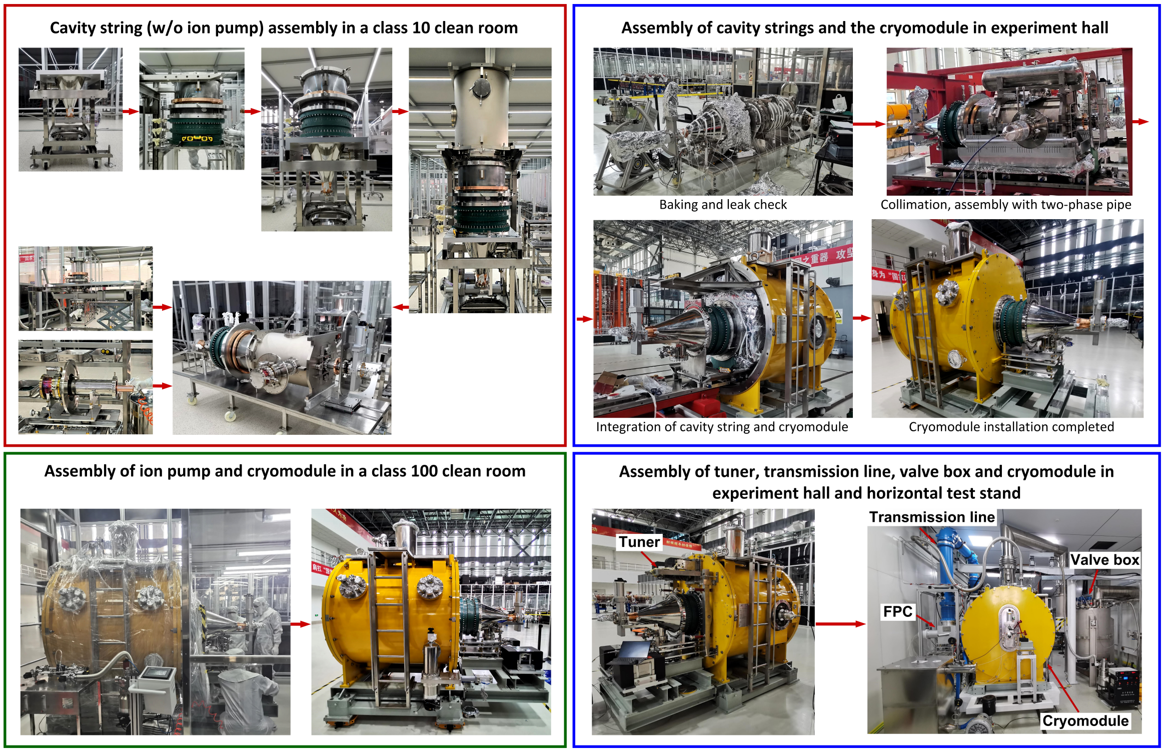

Figure 6: Assembly of the 166 MHz cavity string and the cryomodule.

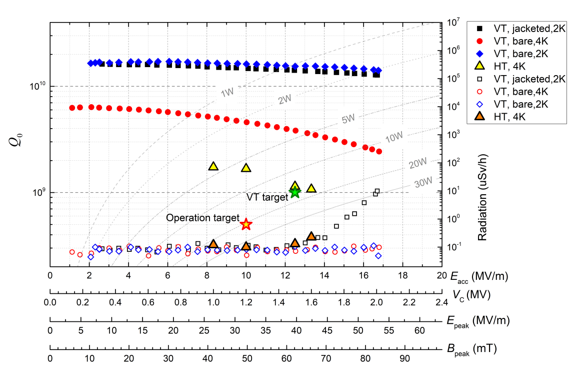

Figure 7: Quality factor and radiation level of the jacketed cavity during horizontal tests.

Horizontal Test

The cooldown process from room temperature to 4.2 K was conducted in two stages: a slow cooldown to ~40 K and a fast cooldown to 4.4 K. The former required a maximum temperature difference of less than 10 K on the cavity to reduce the risk of vacuum leak in particular on large beam pipe with a diameter of 505 mm caused by excessive stress from thermal contraction. The frequency of the cavity cooled down to 4.4 K in the cryomodule was measured to be 166.596 MHz, which was highly consistent with the design frequency. Then, the frequency was easily pulled up 4 kHz by the tuners and the target frequency of 166 MHz was achieved. This excellent consistency and accurate frequency demonstrated a successful frequency control and reliable manufacturing and post-processing methods.

The unloaded quality factor (Q_0) of the jacketed cavity was measured as a function of accelerating voltage (V_c) at 4.4 K, as shown in Fig. 7. The Q_0 at designed V_c of 1.2 MV was measured to be $1.7{\times}10^9$, greatly exceeding the operation target of $5{\times}10^8$. The dynamic heat loss at designed V_c was calculated to be 6.2 W based on the liquid level gauge. The corresponding radiation readouts are also displayed on the same plot, and no early field emission was observed.

FINAL REMARKS

The first dressed 166.6 MHz HOM-damped cavity has been designed for HEPS. The cavity string, including the jacketed cavity, a collimating taper transition, two thermal break beam tubes, a HOM absorber, a forward power coupler and a tuner were designed, fabricated, processed and assembled in a cryomodule. Horizontal tests at 4.4 K were subsequently conducted and the Q_0 greatly exceeded the long-term operation goal. After a slow cooldown process, the cavity was tuned to the operating frequency of 166.6 MHz, indicating an excellent frequency control and reliable development capabilities. The entire cavity system has been successfully verified by the horizontal test.

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