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NORMAL-CONDUCTING 5-CELL CAVITIES FOR HEPS BOOSTER RF SYSTEM

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Abstract

The booster ring of High Energy Photon Source is responsible for ramping the beam energy from 500 MeV to 6 GeV. Six 5-cell copper cavities of PETRA-type were chosen to provide a total accelerating voltage of 8 MV. To fulfill the specific requirements of the HEPS booster, several modifications were made to the original design by Research Instruments (RI). Six cavities manufactured by RI have been delivered to HEPS and high-power tested successively from April to December 2022. Cavities were tested up to a maximum RF power of CW 120 kW, which is the reliable capability of the power coupler specified by RI. Power-keeping at the maximum RF power was conducted subsequently, with an average time of 100 hours. Finally, in order to verify the performance during real operation, the ramped run was conducted according to the pre-defined curve required by the physics design at a repetition rate of 1 Hz, with all control loops closed (cavity frequency loop, cavity field amplitude/phase loop, amplifier amplitude/phase loop). Details on the design modifications, the low-power test, the high-power conditioning and the ramped commissioning are presented in this paper.

INTRODUCTION

High Energy Photon Source (HEPS) is a 6 GeV diffraction-limited synchrotron light source currently under construction in Beijing [1, 2], which consists of a linear accelerator, a booster ring and a storage ring. The booster ring with a circumference of 454 m is responsible for ramping up the beam energy from 500 MeV to 6 GeV. The requirements and main parameters for the HEPS booster RF system are listed in Table 1 [3, 4]. Six normal-conducting cavities of 499.8 MHz were adopted to provide a total accelerating voltage of 8 MV. Each cavity will be operated at 1.35 MV with a dissipated power of 61 kW on the copper surface while providing 9 kW to the electron beam. The optimum coupling factor of the cavity power coupler is set to 1.17.

Six 5-cell copper cavities of PETRA-type manufactured by RI Research Instruments GmbH (RI) have been successfully tested at IHEP from April to December 2022. Details on the design modifications, the low-power test, the high-power conditioning and the ramped commissioning are presented in this paper.

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Table 1: Requirements and Parameters for HEPS Booster RF System ("T-tuning" stands for temperature tuning."NCC" stands for normal-conducting cavity.)

Parameter	Value	Unit
Circumference	454.066	m
RF frequency	499.8	MHz
Total energy loss	4.02	MeV
Total RF voltage	8	MV
Number of cavities	6	
Cavity type	5-cell NCC	
RF voltage per cavity	1.35	MV
R_{sh} per cavity (V^2/2P)	15	MΩ
Q_0	>29000	
Loaded Q	13364	
Beam power per cavity	9	kW
Wall loss per cavity	61	kW
Nominal power per cavity	70	kW
Coupling factor	1.17	

DESIGN OPTIMIZATION

The five-cell copper cavity of PETRA-type was chosen considering the high level of technology readiness and years of operational experiences at various accelerator facilities. To fulfill the specific requirements of the HEPS booster, several modifications were made to the original design from RI. Firstly, a synchrotron light collimator, made of copper with water cooling, was added to the downstream beam tube. The beam tube diameter was tapered from the original 61.2 mm to 51 mm to create a shadow to properly prevent direct SR irradiation. Secondly, a viewport was added on the opposite side of the power coupler to mount an arc detector and a camera following the DESY design. The original port was enlarged from CF40 to CF63 and was aligned to be concentric with the power coupler port. To facilitate the cavity alignment, additional fiducial points were added and the two all-metal gate valves on both ends were rotated. Finally, the position of the vacuum gauges and pickup ports were adjusted accordingly. Fig. 1 shows the layout of the optimized normal-conducting 5-cell cavities for the HEPS booster.

LOW-POWER TEST

To measure the cavity RF parameters of the quality factor Q0, resonant frequency, passband frequencies, coupling factors and the frequency tuning range, low-power tests (LPT) were conducted firstly as-received and subsequently before the high-power test (HPT) by using two-port methods [5].

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Table 2: Main Results of Low-power Tests During the Site Acceptance Test

Cavity No.	As-received (Cavity status: N2-filled)				Before high power test (Cavity status: Vacuum)			
	Envir.	Freq. (MHz)	Q_0	β	Envir.	Freq. (MHz)	Q_0	β
CAV01	21.6°C, 26.1%	500.68	30244	1.11	25.3°C, 36.5%	499.80	28558	1.15
CAV02	24.4°C, 59.4%	499.71	27585	1.24	25.2°C, 60.5%	499.86	27600	1.22
CAV03	25.0°C, 28.7%	499.72	28125	1.01	30.0°C, 39.2%	499.80	28280	1.21
CAV04	19.6°C, 31%	499.80	28782	2.20	18.2°C, 25%	499.80	28211	2.14
CAV05	26.3°C, 57.3%	499.69	28269	0.5	21.0°C, 25.8%	499.80	29237	1.93
CAV06	19.6°C, 31.0%	499.78	28694	2.11	18.3°C, 34.0%	499.80	28231	2.07

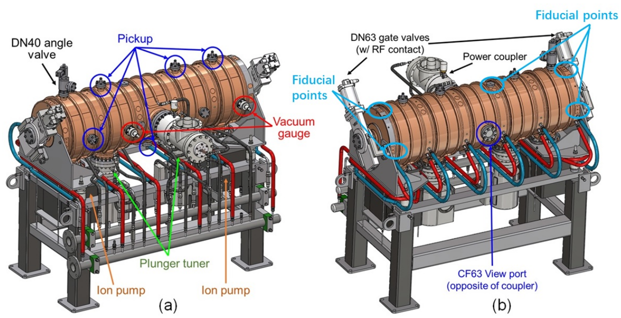

Figure 1: Layout of the normal-conducting 5-cell cavities for HEPS booster.

The former is to assess whether the performance is affected by the transportation, while the latter is to determine the RF parameters required by the accelerating voltage estimation in the following HPT. The main results from the two LPTs for each cavity are summarized in Table 2.

HIGH-POWER TEST

Setup

The setup of the high-power test system is shown in Fig. 2. The 500 MHz cavity system was connected to the 500 MHz-150 kW solid-state amplifier by WR1800 waveguides. The high vacuum pressures were maintained by two 300 l/s ion pumps installed at the bottom of the end cells. The cooling system includes water cooling for the cavity body and the vacuum part of the power coupler, as well as air cooling for the air part of the power coupler. Vacuum pressures, temperatures, flow rates and pressure of the coolants, the coupler arc, as well as the sudden-increasing reflection power were monitored and interlocked. Table 3 lists the applied threshold value of each signal during the high-power tests.

Method and Procedure

The high-power conditioning was initially conducted in pulsed mode with an increased duty factor from 0.1% to 100% by gradually increasing the pulse width. At each pulse width, the power level was increased up to the target value according to the vacuum pressure. An automatic conditioning program developed for high-power input couplers [6] was transplanted and adopted for cavity conditioning, which

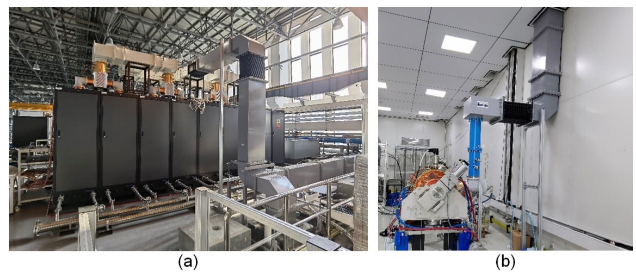

Figure 2: Setup for high-power test: (a) roof view, (b) bottom view.

Table 3: Threshold of Each Interlock Signal During HPT

Signal	Threshold value
Vacuum	<3E-5 Pa
FPC cooling air pressure	10 mbar above ambient
FPC cooling air Input Temp.	<40 °C
FPC cooling air Temp. rise	<25 °C
Cooling water Temp. rise	<15 °C
Cooling water flow	>118 l/min
Cooling air flow	>23 m^3/h
Cavity body Temp. rise	<60 °C
FPC window Temp. rise	<25 °C

considerably reduced the operator's workload and significantly increased the conditioning efficiency. The RF power can be automatically tuned up and down according to the implemented algorithms based on the predefined vacuum thresholds. The power level will be increased at a defined rate if the vacuum pressure is better than the low limit, and will remain constant if the vacuum reading is between the high limit and the low limit. Finally, the power will be decreased at a defined rate if the vacuum pressure deteriorates above the high limit. All data were recorded in an EPICS database. Then, RF power was kept at the maximum level promised by RI, with the outgassing, RF activities and temperature rise monitored closely. Finally, considering that the cavity works at a ramping mode in the actual operation, the accelerating voltage ramping experiment was carried out under a set of parameters determined by two scenarios of normal beam operation and initial vacuum cleaning. During the ramping-mode test, the frequency and amplitude-phase

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control loops of the LLRF, as well as the amplitude-phase control loop of the power amplifier were closed.

Results

It took 12 to 30 calendar days to complete the high-power test of each cavity, among which the duration of the actual conditioning time varied from 5.5 to 21 days, which was largely determined by the cavity performance. The conditioning efficiency evaluated by the effective conditioning time ratio was considerably increased as the auto-conditioning was adopted ever since the second cavity. All the cavities except for CAV06 were kept at CW 120 kW for at least 48 hours. These are shown in Fig. 3. The outgassing mainly occurred at the power level above 80 kW, as shown in Fig. 4. One special phenomenon needs to be noted: the RF power of CAV06 was limited to CW 100 kW due to serious outgassing and excessive heating at the bottom of the cavity body between cell 3 and cell 5.

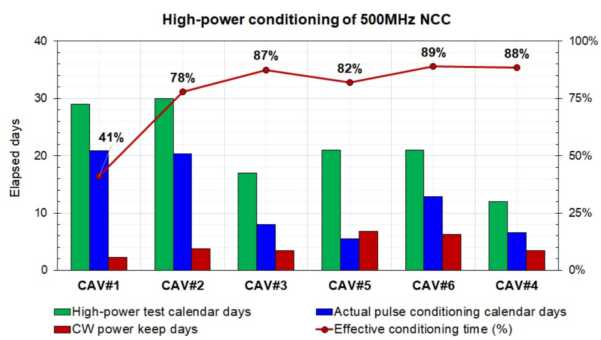

Figure 3: Statistics of the high-power tests.

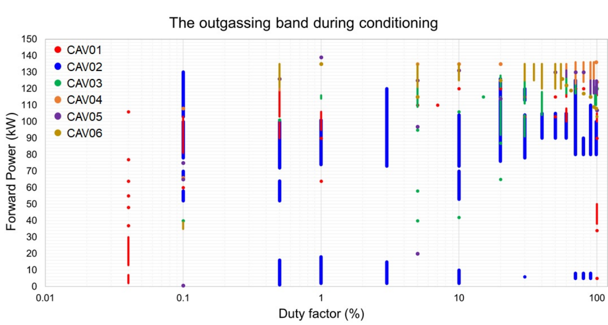

Figure 4: Outgassing bands during the high-power tests.

During the power keeping, the temperatures were measured and shown in Fig. 5. The bottom of the cavity body was observed as the hottest area for all cavities, while the heating of the other areas was different from one cavity to another. The temperature rises at both the window and the T-piece of the power coupler are the least, which indicates sufficient cooling of the coupler. In the meanwhile, the vacuum pressures of all cavities can stay at around 2E-6 Pa, except for the vacuum measured close to the beam outlet of CAV06 which may have defects.

In the final ramping experiment, the cavity voltage was changed successfully from 0.3 to 1.7 MV according to the ramping curving shown in Fig. 6, which satisfied both the normal beam operation and the initial vacuum cleaning requirements. Since a maximum ramping rate of 20 kHz was required, a total of 20000 steps was adopted for a complete ramping period of one second. In addition, the motor-driven tuner, as well as all control loops were proved to be working stably.

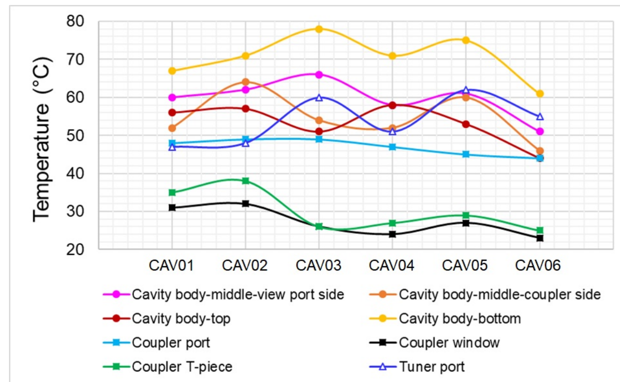

Figure 5: Temperature rise during power keeping.

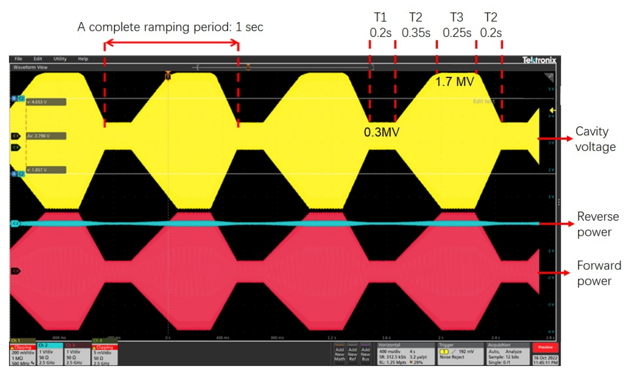

Figure 6: Cavity voltage ramping curve.

FINAL REMARKS

Six 5-cell copper cavities of PETRA-type for HEPS Booster RF system have been high power tested up to CW 120 kW at IHEP. Among them, three cavities have been installed in the tunnel in Nov. 2022. The initial commission of the first three in-tunnel cavities will start in May 2023.

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