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DESIGN OPTIMIZATION OF THE 166-MHz AND 500-MHz FUNDAMENTAL POWER COUPLERS FOR SUPERCONDUCTING RF CAVITIES AT HIGH ENERGY PHOTON SOURCE

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Abstract

Five 166-MHz quarter-wave β=1 cavities have been chosen for the fundamental srf system while two 500-MHz single-cell elliptical cavities for the third-harmonic system for High Energy Photon Source (HEPS). Each cavity will be equipped with one fundamental power coupler (FPC) capable of delivering 250-kW continuous-wave rf power. For the 166-MHz FPC, two prototypes were developed and excellent performances were demonstrated in the high-power operations. However, the inner air part was observed to be warmer than predictions. Therefore, an innovative cooling scheme was adopted. In addition, the Nb extension tube at the coupler port has been elongated to solve the overheating in the cavity–coupler interface region. Concerning the 500-MHz FPC, several improvements were proposed according to decades of operation experience of the BEPCII srf system. First, a doorknob adopting WR1800 instead of WR1500 waveguide was chosen to better match the operating frequency; Second, the window position was optimized to ensure multipacting-free on the window; Third, the cryogenic heat load was estimated carefully to obtain an optimum helium gas cooling. The main parameters and the design optimizations of the 166-MHz and 500-MHz FPCs 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]. In order to accommodate the on-axis accumulation injection scheme conceived for the future, a double-frequency rf system has been adopted with 166.6 MHz as the fundamental and 499.8 MHz as the active third harmonic [3]. Five 166-MHz quarter-wave β=1 superconducting cavities (SCC) have been chosen for the fundamental while two 500-MHz single-cell elliptical superconducting cavities for the third-harmonic system [4]. Each cavity is equipped with one fundamental power coupler (FPC) capable of delivering 250-kW continuous-wave rf power, as shown in Fig. 1. The main parameters of the cavities and their FPCs are listed in Table.1. The high-power grading, strong coupling, reasonable cryogenic heat loads and large design margins are the challenges of developing the two FPCs.

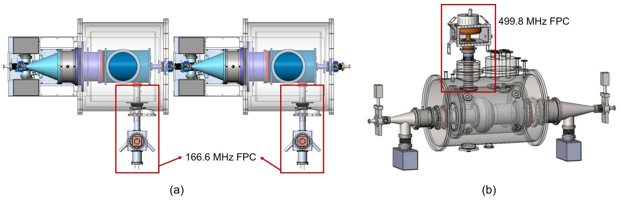

Figure 1: The general layout of the 166.6 MHz (a) and 499.8 MHz (b) cavity system for HEPS.

For the 166.6 MHz FPC, a compact geometric size to enable a clean assembly and protecting the ceramic window from bombardments by the cavity field emission induced electrons are two additional challenges. Two prototypes were developed and excellent performances were demonstrated in the high-power operations. However, the inner air part was observed to be warmer than predictions. Therefore, an innovative cooling scheme inspired by jet impingement was adopted in the formal coupler design. In addition, during the proof-of-principle (PoP) cavity horizontal test, an overheating in the cavity-coupler interface region was observed and analyzed. Then solution of elongating the niobium extension tube at the coupler port have been included in the formal coupler design.

Concerning the 500-MHz FPC, several improvements were proposed according to decades of operation experience of the BEPCII srf system. First, a doorknob adopting WR1800 instead of WR1500 waveguide was chosen to better match the operating frequency; Second, the window position was optimized to ensure multipacting-free on the window; Third, the cryogenic heat load was estimated carefully to obtain an optimum helium gas cooling.

The details of the design optimizations of the two FPCs will be presented in the following sections.

166.6 MHz FPC

Air Cooling Improvement

Two 166.6 MHz prototype FPCs were fabricated and high power tested [5]. The rf conditioning was conducted initially on a room-temperature test bench shown in Fig. 2(a) in travelling-wave mode. The rf power were kept at 50 kW cw for more than 1 h, and both couplers showed excellent rf, vacuum, and thermal performances, as shown in Fig. 2 (b). However, a higher temperature rise was measured to be 1.5 °C for the inner conductor of the T-box for every 10 kW of power ramping, which almost doubled the simulated value of 0.8 °C/kW.

In order to reduce the temperature rise of the inner T-box, an innovative cooling scheme inspired by jet impingement

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Table 1: Main parameters of the cavities and FPCs for HEPS

Parameter	**Fundamental**	**Third-harmonic**
Beam energy [GeV]	6	
Beam current [mA]	200	
Rf Frequency [MHz]	166.6	499.8
Cavity type	Quarter-wave Beta=1 SCC	single-cell elliptical SCC
R/Q (=V_c^2/ωU) [Ω]	136	95
Maximum rf power per FPC [kW]	200, cw	220, cw
Qext	$5{\times}10^4$	$8{\times}10^4$
FPC type	Coaxial, single window	
Window type	Coaxial disk, with choke	
Coupling type	Electric	

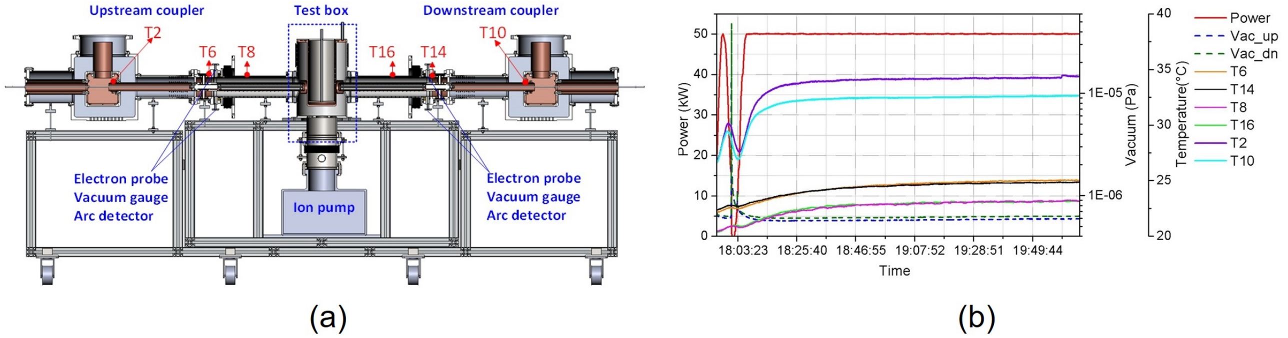

Figure 2: (a) The prototype 166.6 MHz FPC installed on the high-power test bench. "Tx" in red stands for temperature sensors. (b) Results during power keep at cw 50 kW in standing wave mode.

was developed. Fig. 3 shows the original (a) and improved (b) air-cooling scheme of the inner conductor of the air part. As can be seen, the direction of the air-cooling passage in the new design is exactly reversed to the original one, which makes the "fresh" airflow firstly reaching the inner conductor of the coaxial line with the largest power density. In addition, the outer conductor full of small holes is surrounded by an added outer cylinder equipped with two air inlet ports. The outer cylinder can also serve as a microwave shielding. Benefiting from the impinging airflow produced by the small holes, the efficiency of the heat exchange shall be signifi-cantly improved. This was verified by an rf-fluid-thermal simulation using ANSYS Workbench software suite [6] . Figs. 4 and 5 shows the velocity of the airflow and the temperature distribution of the air part before(a) and after(b) improved respectively, with cw 200 kW rf power passing through in traveling wave mode. The simulated maximum air velocity was increased from 33 m/s to 62 m/s under the forced air-cooling with flow rate of 100 l/min. Accordingly, the predicted temperature rise at the inner conductor of the coaxial line was decreased from 89 K to 10 K, with ambient temperature of 300 K.

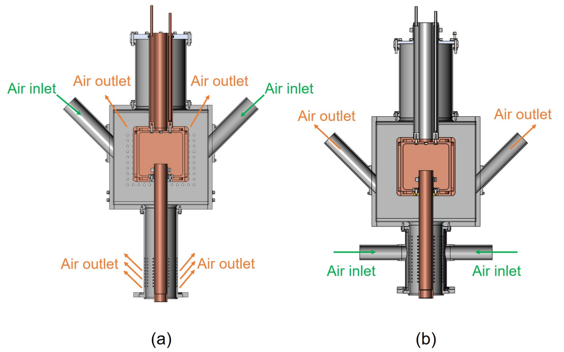

Figure 3: The air cooling scheme of the inner conductor of the air part: (a) original; (b) improved.

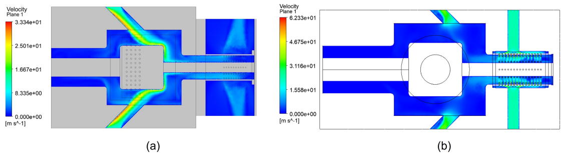

Figure 4: The velocity of the cooling air: (a) original; (b) improved.

Solution to Overheating at Cavity-coupler Interface

One prototype FPC was later integrated with the PoP cavity and attended the cavity system horizontal test, as shown in Fig. 6. However, significant degradation of the quality factor of the cavity system has been observed. Further analysis based on experiments and simulations were carried out to find the additional dynamic heat loss. Evidence from tem-

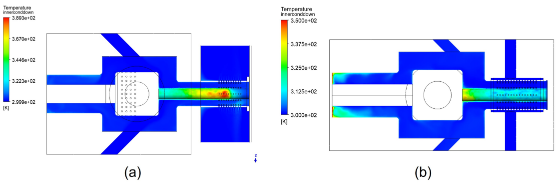

Figure 5: The temperature of the air part: (a) original; (b) improved.

perature sensor readout and heat loss measurement results suggested an overheating in the cavity–coupler interface region causing a "thermal runaway" and eventually quenching the cavity at its design voltage. A comprehensive thermal management scheme has thus been proposed, consisting of an elongated Nb extension tube at the coupler port and an optimized cooling for the power coupler. The height of the coupler port "H" has finally been chosen to be 120 mm to compromise the competing demands of a longer Nb extension tube to reduce heating and reasonable size of the helium jacket. The simulated temperature distributions of the Nb extension tube with original height "H"= 80 mm and the improved height "H"=120 mm at 1.5 MV with a helium gas flow rate of 0.04 g/s are shown in Fig. 7(a) and (b) respectively. As can be seen, the predicted maximum temperature decreased from 11.4 K to 4.8 K. The solution has been included in the design of the 166.6-MHz higher-order-mode (HOM) damped cavity for the HEPS. More details about the analysis and solution to the overheating can be found in [7].

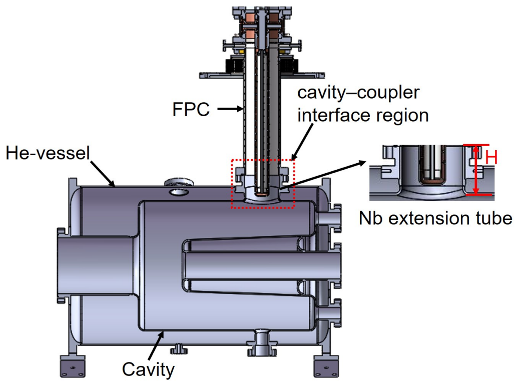

Figure 6: The dressed 166.6 MHz PoP cavity.

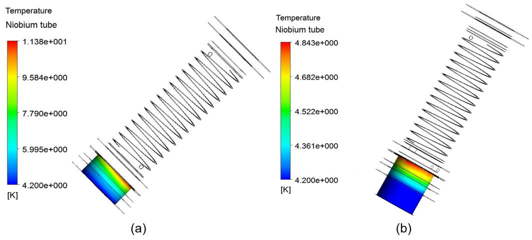

Figure 7: Temperature distributions of the Nb extension tube with the height "H"=80 mm (a) and "H"=120 mm (b) at 1.5 MV with a helium gas flow rate of 0.04 g/s.

499.8 MHz FPC

WR1800 Waveguide Doorknob Design

The design of the HEPS 499.8 MHz FPC was derived from KEKB 508 MHz FPC [8] and BEPCII 500 MHz FPC [9]. In order to better match the operating frequency, the RF power distributions are realized by EIA standard WR1800 waveguide for HEPS storage ring third-harmonic HPRF system [10]. Thus, the doorknob of the FPC, acting as a transition between the waveguide of the transmission line and the coaxial section of the coupler was redesigned based on WR1800 size instead of WR1500 used by KEKB and BEPCII FPC. The dimensions shown in Fig. 8(a) were optimized carefully and a minimum reflection at the nominal frequency was achieved finally. This was shown in Fig. 8(b).

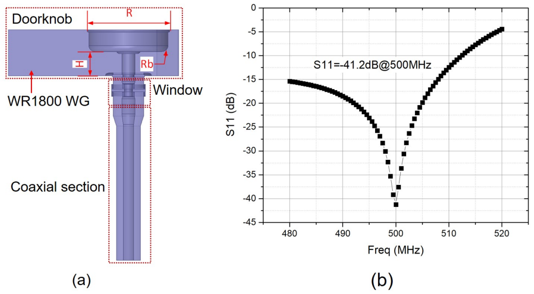

Figure 8: (a)The rf model of HEPS 499.8 MHz FPC; (b)The optimized transmission performance.

Multipacting Prediction and Window Position Optimization

Multipacting may deteriorate the performance of a FPC and, if left unchecked, may cause the window crack consequently breaking the vacuum of the srf cavity with disastrous consequences [11]. Therefore, it is important to eliminate those hard multipacting barriers at the nominal power level by optimizing the rf geometry in the design stage.

Multipacting simulations were carried out by using CST Microwave Studio and Particle Studio software [12]. Multipacting predictions of the window and the coaxial section in traveling wave mode were conducted initially. The results shown in Fig. 9(a) indicate that the hard multipacting band between 60 kW and 150 kW, located at the rf window. And there is no hard multipacting barrier in the coaxial section, as shown in Fig. 9(b).

Multipacting simulation of the rf window during the cavity system horizontal test was subsequently carried out by using the rf model shown in Fig.9(a). To the obtain the real rf-field within the FPC, two-port method was used with the Qext of the port 2 equal to the quality factor of the unloaded cavity during the horizontal test. The multipacting band of the rf window under different accelerating voltages was simulated. Hard multipating barriers were found above the accelerating voltage of 2.0 MV in current window position with "D"=961.5 mm. Further simulation has been performed by changing the window position. Taking into account to

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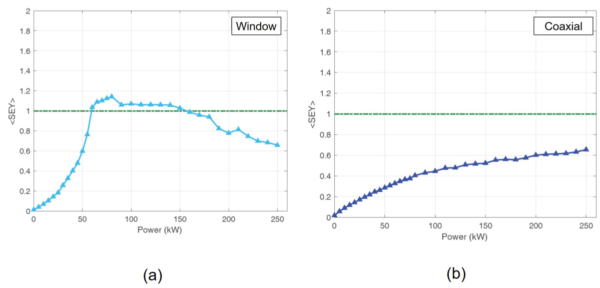
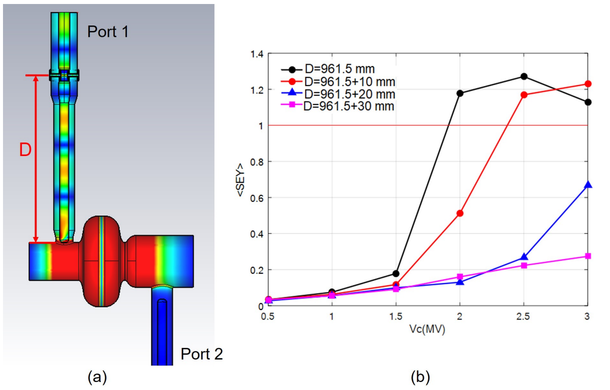
avoid increasing the cryogenic heat load, the window was moved far away from the cavity. A 20 mm movement of "D" is sufficient to realize multipacting-free of the window during the horizontal test with the accelerating voltage below 3.0 MV. These are shown in Fig. 10(b).



(a) (b)

Figure 9: Multipacting simulation results in traveling wave mode: (a) window; (b) coaxial section.



(a) (b)

Figure 10: Multipacting simulation of the rf window during the cavity system horizontal test: (a) rf simulation model and the rf-field. (b) the predicted hard multipacting barriers.

Cryogenic Heat Load Estimation

Since the FPC acting as a thermal bridge between room and cryogenic temperatures, the cryogenic heat load to helium bath needs to be minimized with appropriate cooling scheme. An rf-fluid-thermal coupled simulation was carried out as cw rf power of 250 kW passing through the coupler under different inlet pressures of the helium gas indicating as pressure-drop. The simulation results are listed in Table. 2. As the pressure-drop decreased from 1000 to 300 Pa, the helium gas flow rate reduces accordingly; and the average temperature of the helium gas at the outlet increases significantly. However, the heat load at 4.2 K is almost the same, which indicates that the cooling is sufficient to take away the static and dynamic heat loss to 4.2 K through the power coupler. It needs to be noted that the calculated rf dissipation on the outer conductor immersed in the helium bath of 0.814 W is added in the simulated heat load at 4.2 K directly.

The velocity of the helium gas flow is shown in Fig. 11(a). The pressure-drop has a great influence on the helium flow velocity at the outlet. When the pressure-drop decreases from 1000 Pa to 300 Pa, the average velocity decreases by about 29%. Fig. 11(b) shows the temperature distribution of the entire outer conductor. Here the pressure-drop is chosen as 500 Pa.

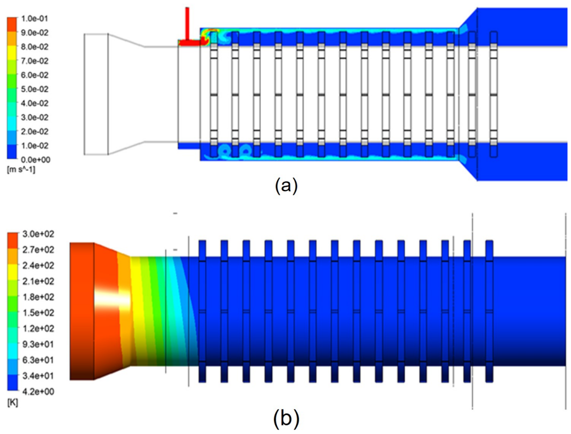


Figure 11: The rf-fluid-thermal simulation results with the pressure-drop of 500 Pa : (a) The velocity of the helium gas flow; (b) The temperature distribution of the entire outer conductor.

FINAL REMARKS

The formal FPCs for both 166.6 MHz and 499.8 MHz superconducting cavities at HEPS has been designed. A series of improvements have been included in the formals design. For the 166.6 MHz FPC, a new innovative cooling scheme using the jet impingement structures and making the inlet and outlet reversed was adopted and proved effective to reduce the temperature of the inner conductor close to the window significantly by the simulation. In addition, a 40 mm elongation of the niobium extension tube at the coupler port has been applied to solve the observed quality factor degradation of the PoP cavity system attributed to the overheating occurring at the cavity-coupler interface region. Concerning the 499.8 MHz FPC, the doorknob was redesigned based on WR1800 size to achieve a better frequency matching and a minimum reflection at the nominal operation frequency. Multipacting predictions at different operation conditions were conducted. The window position was optimized to ensure multipacting-free on the window with the window moved far away from the cavity 20 mm. In further, the cryogenic heat load was estimated carefully to obtain an optimum helium gas cooling.

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Table 2: The Results of the Cryotenic Heat Load Calculation under Different Pressure-drops

Value	Pressure-drop(Pa)		
	1000	500	300
Helium gas flow rate [kg/s]	1.62E-3	9.78E-4	6.54E-4
Temp. of the outlet helium gas [K]	8.9	12.1	16.1
Rf dissipation [W]	43.3	44.5	45.3
Heat load at 4.2 K [W]	0.91	0.91	0.92

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