ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA185

THE HIGH-POWER TEST OF CW 250 kW FUNDAMENTAL POWER COUPLERS FOR HEPS 166.6 MHz SUPERCONDUCTING QUARTER-WAVE BETA=1 CAVITY

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Abstract

High Energy Photon Source is a 6 GeV diffraction-limited synchrotron light source currently under construction in Beijing. To provide the required 5.2 MV of RF voltage and 850 kW of beam power, five 166.6 MHz superconducting quarter-wave beta=1 cavities have been chosen for the fundamental RF system of the storage ring. Each cavity will be equipped with one fundamental power coupler (FPC) capable of delivering over 200 kW continuous-wave (CW) RF power. Based on the test performances of two prototype couplers, formal couplers have been optimized, fabricated and high-power tested up to CW 250 kW in the traveling-wave mode and CW 100 kW in the standing-wave mode covering 16 phase points.The high-power test of the formal FPCs on the test bench is presented in this paper, focusing on the effectiveness of the modifications compared with the prototypes.

INTRODUCTION

High Energy Photon Source is a 6-GeV diffraction-limited synchrotron light source with a kilometer-scale storage ring, currently under construction in Beijing [1, 2]. In order to accommodate the on-axis accumulation injection scheme, a double-frequency RF system has been adopted with 166.6 MHz as the fundamental and 499.8 MHz as the active third harmonic [3,4]. The quarter-wave β=1 superconducting cavities (SCC) has been chosen for the fundamental RF system of the storage ring. The main parameters of the 166.6 MHz cavity and its FPC are listed in Table 1 [5]. Five 166.6 MHz cavities shall provide 5.2 MV of RF voltage and 850 kW power to the 6 Gev 200 mA electron beam. Each cavity is equipped with one FPC capable of delivering 200 kW continuous-wave RF power. For the coupler, a 50 Ω coaxial structure with single Tristan-type window (coaxial disk with choke structure) was employed. A very strong electric coupling with an external quality factor Q_{ext} of $5{\times}10^4$ is realized by positioning the coupler at the cavity wall.

Two prototype FPCs have been developed and examined with both bench-test and cavity horizontal-test [6, 7]. Based on the high-power test performances of the prototypes , a series of modifications were employed in the formal couplers. Two formals have been optimized, fabricated and high-power tested up to CW 250 kW in the traveling-wave (TW) mode and CW 100 kW in the standing-wave (SW) mode covering 16 phase points.The high-power bench-test of the formals is presented in this paper, focusing on the effectiveness of the modifications compared with the prototypes.

Table 1: Main Parameters of the 166.6 MHz Cavity and Its FPC

Parameter	Value
Beam energy	6 GeV
Beam current	200 mA
RF frequency	166.6 MHz
Cavity type	Quarter-wave β=1 SRF
R/Q ($=\lvert V_c\rvert^2/\omega U$)	136 Ω
Max. RF power per FPC	200 kW (CW)
Q_{ext}	$5{\times}10^4$
FPC type	Coaxial, single window
Window type	Coaxial disk with choke
Coupling type	Electric

MODIFICATIONS AND LAYOUT

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 every 10 kW. Thus, a new innovative cooling scheme using the jet impingement structures and making the inlet and outlet reversed was adopted [8]. Meanwhile, a 40 mm elongation of the niobium extension tube at the coupler port and an optimization of the position of the helium gas inlet for the coupler outer conductor cooling have 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. Finally, in order to accurately measure the coupler-induced heat load, several special bases were added on the outer conductor to arrange the temperature sensor. The general layout of the formal coupler is shown in Fig. 1. It consists of a coaxial section, an RF window, and a T-box transition. The manufacturing of the formals were completed at IHEP workshop in the middle of 2021, as shown in Fig. 2.

HIGH-POWER TEST

Two formal couplers have been high-power conditioned on the test bench to remove residual gases, dust, particulates by RF power; and to validate the coupler's performance. These are described in this section.

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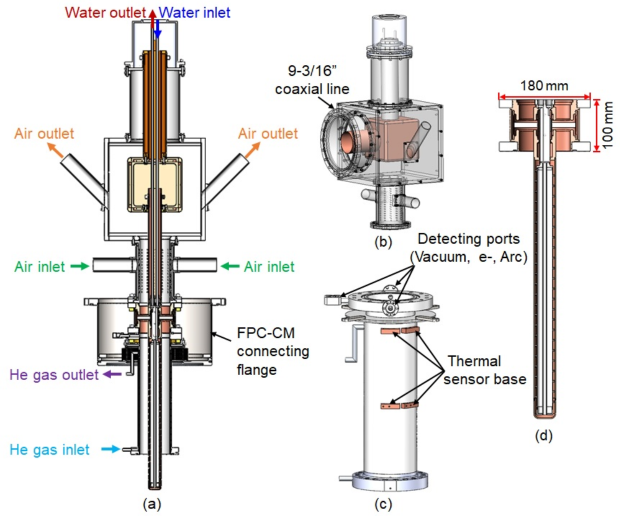

Figure 1: Layout of the coupler assembly (a) and its main components: T-box (b), coaxial section (c), RF window (d).

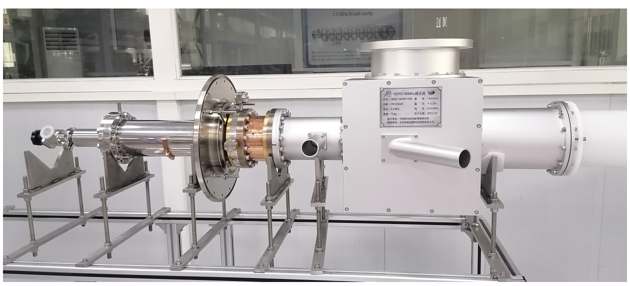

Figure 2: The fabricated formal coupler.

Preparation and Setup

The preparation, consisting of the ultra-pure water cleaning, baking, clean-assembly of the coupler, as well as the assembly of the high-power test system as shown in Fig. 3, was similar with that of the prototype couplers [6]. However, two improvements were made to improve the performances. Firstly, a specially-developed baking oven with the characteristics of vacuum pumping, temperature controlling and Nitrogen gas filling was adopted to bake the coupler-bench system to 110 °C for 112 h , which avoided the oxidization of the apperance while improving the baking effect, as shown in Fig. 4. Secondly, baking, high-power conditioning and the disassembling after test were conducted in a class-1000 clean room instead of normal experiment hall where the prototype coulers were operated, which greatly improved the cleanliness and reduced the risk of cavity contamination.

High-Power Test

The conditioning was initially conducted in a pulsed mode with a gradually increased pulse width, and eventually reached 100% duty cycle. 16 thermal couples were mounted on various locations to record temperatures of the couplers and the test-box, as shown in Fig. 5. The FPCs were protected from deteriorated vacuum, arc discharging

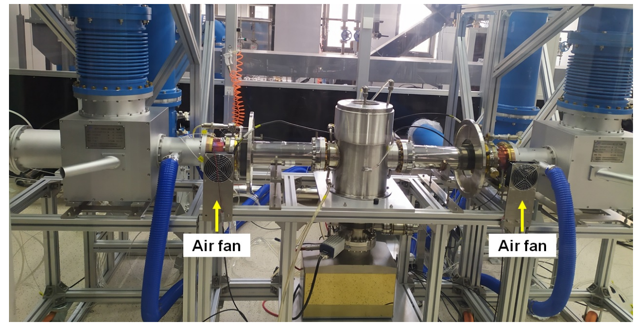

Figure 3: High-power test setup of the couplers.

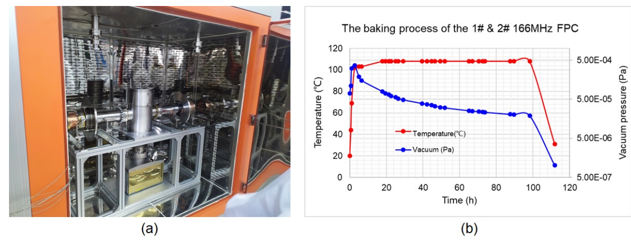

Figure 4: Baking of the couplers.

and overheating by the interlock system. Benefiting from the clean-operation in the whole process , no arc or multipacting-induced electrons were observed during the conditioning except for the conditioning with improper DC bias voltage that exciting obvious electrons.

It took approximately 100 h to reach CW 250 kW for the initial TW conditioning. Then, the RF power was kept at CW 250 kW for about 120 h, and both couplers showed excellent RF, vacuum and thermal performances, as shown in Fig. 6. Finally, the coupler was further conditioned up to CW 100 kW in standing-wave mode, with the reverse wave varied in a step of 1/16 of the 166.6 MHz wavelength (~112.5 mm). The vacuum pressures and window temperatures during SW conditioning are shown in Fig. 7.

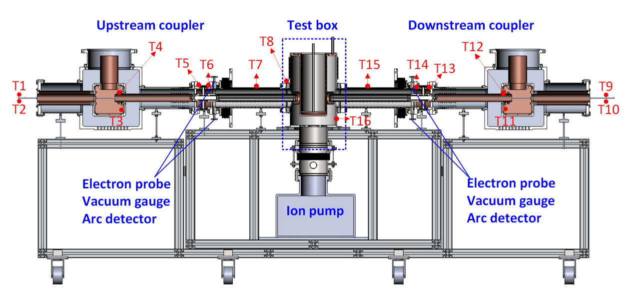

Figure 5: Temperature sensor locations.

Temperature Rise Validation Since one of the main modification is the cooling of the air part, the temperature rises during TW power-keeping were compared with those of the prototypes. The ambient temperature shown in Fig. 6 was 22 °C. Thus, the measured maximum temperature rise at the inner conductor of the T-box (T4 and T12) was reduced from 1.5 °C (prototypes) [6] to 0.6 °C (formals) for every 10 kW

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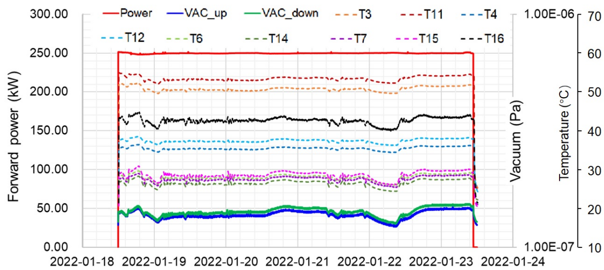

Figure 6: Vacuum and temperatures during power keep at CW 250 kW in TW mode for 120 h.

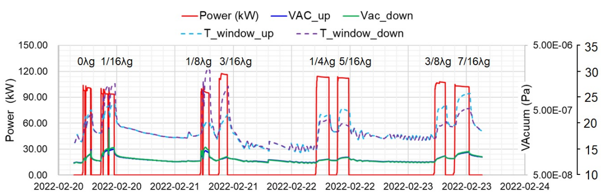

Figure 7: Vacuum and temperatures during SW aging.

of power ramping, which well validated the effectiveness of the new cooling scheme. Meanwhile, by adding two air fans shown in Fig. 3 for each window, the temperature rise at the outer conductor of the window was decreased from 0.6 °C (prototypes) [6] to 0.3 °C (formals) for every 10 kW of power ramping.

Multipacting Validation During the initial TW conditioning, multipacting was encountered between 10 kW and 50 kW of incident power, which was in good agreement with the simulations [6]. Furthermore, hard multipacting barriers were observed between 10 kW and 25 kW, which was identified by the vacuum pressure deterioration when the RF power ramping up to CW 250 kW after conditioning, as shown in Fig. 8 .

Considering the existence of the hard multipacting barriers, DC biasing was applied after initial TW conditioning. The bias voltage was scanned from 0 V to -600 V and then from 0 V to +600 V. It proved to be effective to suppress the hard multipacting with a bias voltage higher than +600 V. However, multipacing-induced outgassing was observed as the bias voltage varied between -600 V and +400 V. This can be attributed to the provoking of the new multipacting zones or insufficient suppressing of the hard multipacting barriers by applying improper bias voltages. In addition to outgassing, excessive heating of the outer conductor of both couplers was observed, with temperature increasing from ~20 °C to ~50 °C within several minutes. These are shown in Fig. 9. The multipacting-induced overheating shall be explored in the future.

FINAL REMARKS

Two formal couplers for HEPS 166.6 MHz superconducting cavity have been optimized, fabricated and high-power tested up to CW 250 kW in TW mode and CW 100 kW

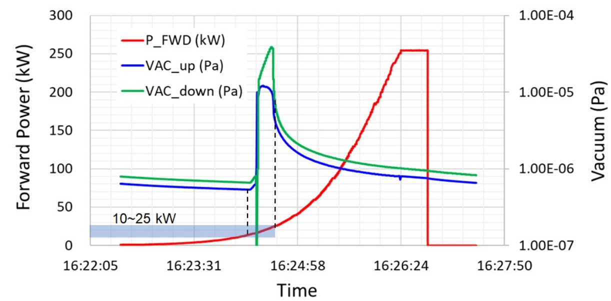

Figure 8: Hard multipacting barriers observed after initial TW conditioning.

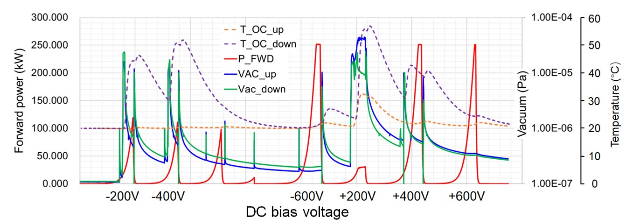

Figure 9: Test results with various DC bias voltages.

in SW mode covering 16 phase points. RF, vacuum, and thermal performances were proved to be excellent. Especially, the cooling modification of the air part was validated to be effective. Due to the low RF frequency, hard multipacting was encountered as predicted. Based on the DC bias aging experiment, bias voltage higher than + 600 V was determined for routine operation.

One formal coupler has been assembled with the higher-order-mode-damped 166.6 MHz superconducting cavities recently, and the cavity horizontal-test is scheduled for next month. Both the thermal behaviour at the cavity-coupler interface and the coupler-induced heat load will be examined carefully during the horizontal-test to verify the modifications of the coupler port.

ACKNOWLEDGEMENTS

This work was supported in part by High Energy Photon Source, a major national science and technology infrastructure in China, and in part by the National Natural Science Foundation of China under Grant 12075263.

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