Development of fundamental power coupler for C-ADS superconducting elliptical cavities *

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Abstract: 5-cell elliptical cavities have been selected for the main linac of the China Accelerator Driven sub-critical System (C-ADS) in the medium energy section. According to the design, each cavity should be driven with radio frequency (RF) energy up to 150 kW by a fundamental power coupler (FPC). As the cavities work with high quality factor and high accelerating gradient, the coupler should keep the cavity from contamination in the assembly procedure. To fulfil the requirements, a single-window coaxial type coupler was designed with the capabilities of handling high RF power, class 10 clean room assembly, and heat load control. This paper presents the coupler design and gives details of RF design, heat load optimization and thermal analysis as well as multipacting simulations. In addition, a primary high power test has been performed and is described in this paper.

Keywords: superconducting elliptical cavity, fundamental power coupler, high power, clean assembly, heat load

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1 Introduction

The China Accelerator Driven sub-critical System (C-ADS) project is a continuous wave (CW) proton linac consisting of two injector sections and one main linac. In the main linac, 650 MHz β=0.63 and β=0.82 5-cell elliptical superconducting cavities are applied to accelerate the beam current from an energy of about 180 MeV up to 1.5 GeV [1]. These cavities have been designed to work at a high quality factor of $1\times10^{10}$and a high accelerating gradient of 15 MV/m with a beam current of 10 mA [2]. To sufficiently drive each cavity, a fundamental power coupler (FPC) with the capability of delivering 150 kW RF power in CW mode is required.

The requirements of high quality factor and high working gradient of the cavities requires that the coupler design should enable clean assembly procedures to minimize the risk of contaminating the superconducting cavity (SC) [3]. One approach to satisfy this demand is double-window design such as TTF III couplers [4]. With the double-window couplers currently used worldwide, however, use of a cold window limits the power handling capability [5–7]. Another approach is a single-window design with the vacuum section of the coupler short enough to facilitate clean assembly, taking the design of the SNS SC coupler as an example [8]. However, the operating power of the SNS coupler was 53 kW on average and the highest power recorded for this kind of coupler is 125 kW, CW, for the BNL SRF Gun Coupler in tests [9, 10]. Since a coupler serves as a temperature bridge from room temperature to cryogenic temperatures, a short vacuum section and relatively high RF heating in proportion to RF power would result in excessive heat load. For C-ADS, however, where hundreds of FPCs are needed, very small heat loss is desired in the design to minimize operating costs [11]. The main challenge is to design a coupler which enables clean assembly, high power handling and low heat load simultaneously.

A coaxial type single-window FPC design was selected. Table 1 shows the main parameters of the cavities and the FPC. The design of the coupler was derived from the 500 MHz FPC for the BEPCII SC cavity, on account of its simple structure and its capability of operating with high RF power [12]. The main dimensions were rescaled to 650 MHz; some components were redesigned based on the clean assembly procedures and cooling considerations. To minimize the coupler's contribution to the overall heat load of the cryostat, the coupler outer conductor is copper-plated, double-walled and cooled by helium gas. Thorough and careful simulations are carried out to optimize the RF structures and heat load, decide cooling design and predict multipact-

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ing activities. A prototype was fabricated and a primary power test was accomplished. The details of simulations and power conditioning are presented in this paper.

Table 1. Main parameters of the cavity and FPC.

parameter	value
frequency/MHz	650
working gradient/MV/m	15
Q_0 (elliptical 082)	1×10^{10}
R/Q (elliptical 082)/Ω	514.6
beam current/mA	10
peak RF power/kW	150, CW mode
coupling type	Antenna
coaxial line impedance/Ω	50

2 RF structure design

The FPC model is based on a 50 Ω coaxial line, including a coaxial planar window, a doorknob transition, an air side coaxial line and a vacuum side coaxial line, as shown in Fig. 1.

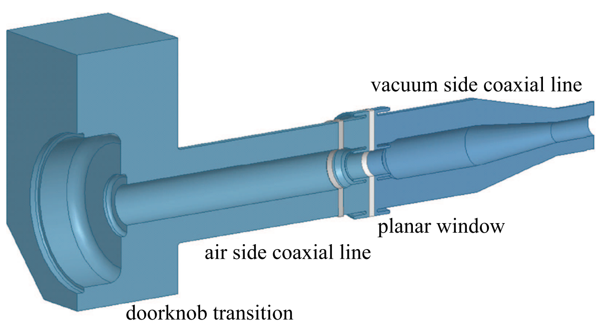

Fig. 1. (color online) FPC electromagnetic model.

The RF window is a critical component of the FPC. It works as a vacuum barrier for the cavity while letting the RF power go through. The window is made of 97.6% Al_2O_3. To adequately handle high RF power, the window has a big diameter of 171 mm, brazed to a specially designed choke structure. The choke mainly contributes to impedance-matching of the window. Meanwhile, it weakens local electric field on the ceramic-copper weld joints, which may be dangerous when exposed to high intensity electric field, and presumably reduces the risk of multipacting. As shown in Fig. 2, the electric field on the ceramic surface around the choke area is lower than for the window with no choke. Specifically, on the surface of the inner conductor to the ceramic weld joint, the electric field is 23.5 % lower.

A doorknob configuration is used for the transition from the WR1500 waveguide, which connects to the klystron, to the coaxial line of the coupler. The RF performance of the doorknob is sensitive to its dimensions. In order to achieve good impedance matching, the dimensions of the doorknob were optimized, including the seat height (H), seat diameter (D), and the distance from the seat to the shot circuit (L), as shown in Fig. 3.

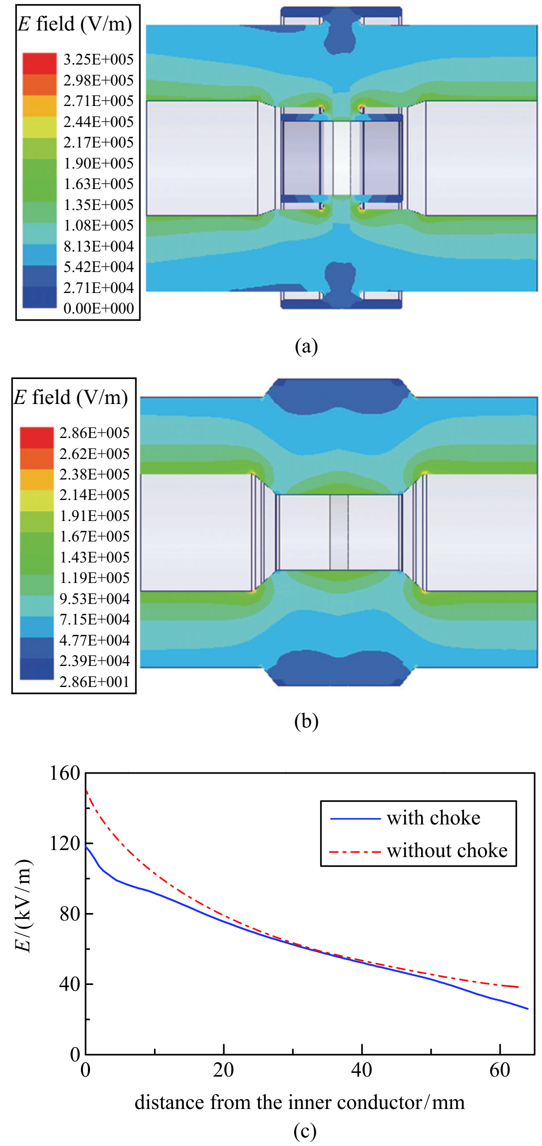

Fig. 2. (color online) The complex electric field contour of the window as 150 kW RF power goes through: (a) window with choke structure; (b) window without choke structure. (c) The complex electric field on the surface of the ceramic in these two cases.

Further simulations of the integrated coupler have been carried out. Fig. 4 shows the calculated S11 curve of the whole coupler. The S11 is about −46 dB at the working frequency, 650 MHz. The bandwidth is about 50 MHz at S11= −25 dB.

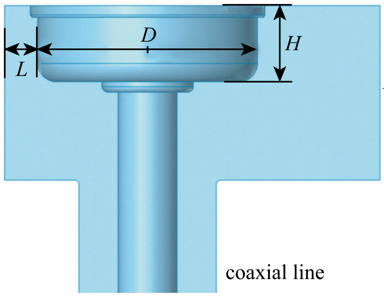

Fig. 3. (color online) Model of the doorknob and its optimization dimensions.

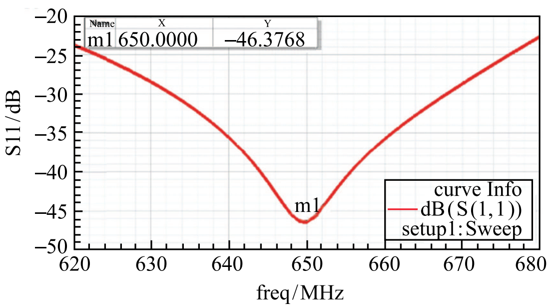

Fig. 4. (color online) Calculated S11 curve of the FPC (S11= −46 dB at 650 MHz, relative permittivity of ceramic= 9.2).

3 Heat load optimization

As the FPC acts as a thermal transition between the room-temperature RF transmission system and the SC cryogenic environment, the coupler leads to static and dynamic heat load to the cavity and the cryogenic systems. For high power couplers, joule heat due to RF loss makes the dynamic heat load considerable; meanwhile, the shorted vacuum section of the outer conductor (to enable clean assembly with the cavity) greatly increases the static heat load. Therefore, reducing the coupler's contribution to the heat load to a reasonably low level becomes a big challenge.

In order to decrease RF losses, the stainless steel outer conductor is copper plated. The thickness of the copper plating, which has a major influence on the static heat load, was selected carefully. The copper plating should be thick enough to reduce RF dissipation while minimizing the increase in thermal conduction and static heat load. Based on simulations and the copper plating technology, the thickness of the copper plating layer was chosen as 10 um, about three RF skin depths.

Then, cooling of the outer conductor was optimized carefully. Methods of cooling by thermo-anchors and helium gas were explored. In the case of thermo-anchor cooling, two thermo-anchors at 5 K and 80 K respectively were attached to the outer conductor. Analysis was performed to optimize the location of the anchors to minimize total cryogenic load. The heat loads of the coupler are listed in Table 2. Obviously, the heat loads do not fit well with the cryogenic requirement. Therefore, helium gas cooling was selected. As shown in Fig. 5, the outer conductor was a double-wall stainless steel tube with a spiral flow passage inside. 5 K helium gas flows in the tube near the cold flange, spirals up and flows out close to the bottom of the RF window at 300 K. According to calculations, a flow rate of 0.05 g/s for helium gas is adequate. Correspondingly, the heat load of the FPC is less than 4 W (scaling to heat load at 5 K), smaller than the average heat loss of C-ADS CM1 FPCs [13].

Table 2. Heat flow at thermos-anchors for the coupler model with a 5 K and an 80 K anchor.

heat load type	heat load/W
2 K heat load	0.61
5 K heat load	4.57
80 K heat load	13.27

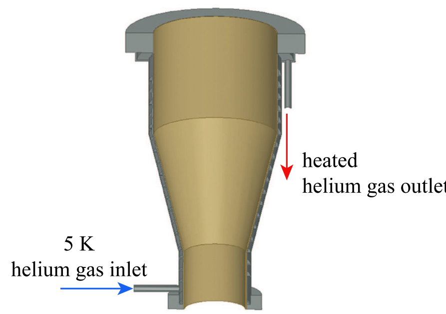

Fig. 5. (color online) The helium cooling outer conductor.

4 Thermal design

For FPCs working at high RF power, sufficient cooling is indispensable to control the heat due to ohmic dissipation of RF power in the walls of the coupler. Aiming to ensure that the coupler is adequately cooled, thermal analysis was performed for each component of the FPC.

The atmospheric components of the FPC, including the doorknob and the air side coaxial line, were both cooled by air flow, while the coaxial line was cooled in a special way. The outer conductor was machined with several rows of air outlets at the end nearest the window. Therefore, the cold air which comes into the doorknob can flow in the coaxial line and cool both the inner and outer conductor.

The oxygen-free copper inner conductor on the vacuum side was water cooled. Water enters through a tube which extends to the end of the inner conductor and flows along the internal wall of the inner conductor all the way up to the top of the window, taking away all the RF loss on the vacuum side inner conductor, a big fraction of dielectric loss in the ceramic and a part of RF loss on the air side inner conductor. To keep the cooling water temperature rise less than 1 ℃(entering at 25 ℃) with 150 kW RF power passing through, a flow rate of 2.5 l/min is required. As Fig. 6 shown, with air and water cooling, the highest temperature appears in the middle of the air side inner conductor or in the center of the ceramic. The highest temperature does not exceed 37 ℃.

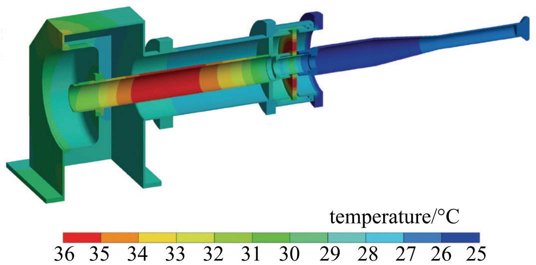

Fig. 6. (color online) Temperature contour of the FPC's air side conponents with 150 kW RF power passing through in traveling wave mode.

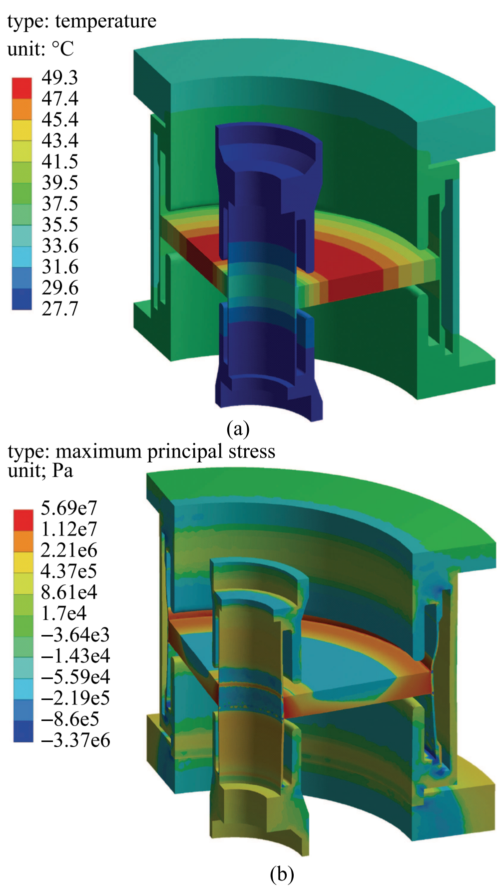

Fig. 7. (color online) (a) Temperature contour of the window assembly with 300 kW RF power. (b) The corresponding maximum principal stress contour of the window assembly.

The RF window is the most fragile component of the coupler, as it is prone to high stresses due to thermal expansion and contraction. Thermal analysis and mechanical stress analysis were performed for the window under 300 kW (twice the operational RF power). As Fig. 7 shows, the maximum temperature is 49.6 ℃, located in the center of the ceramic, and the maximum stress is 56.9 MPa, appearing on the edges of the ceramic-copper weld joints. The maximum stress is less than one fifth of the flexural strength of the ceramic.

5 Multipacting simulations

Multipacting simulations for the FPC were performed with MultiPac 2.1, an electron trajectory tracking code with a 2D FEM field solver [14]. The analysis was carried out for the vacuum side coaxial line and window structure respectively.

In the simulations, the RF power was swept from 1 kW to 150 kW with full reflection at different reflection phases and different emitting phases of the initial electrons. The simulation results of the coaxial line, as Fig. 8 shows, reveal that nearly all of the free electrons disappear after 20 impacts, and the final residual electrons are fewer than the initial electrons at each power level below 150 kW. The simulation results of the window at different reflection phases are similar to those of the coaxial line. These simulations indicate that there is no hard multipacting barrier under 150 kW power for the FPC.

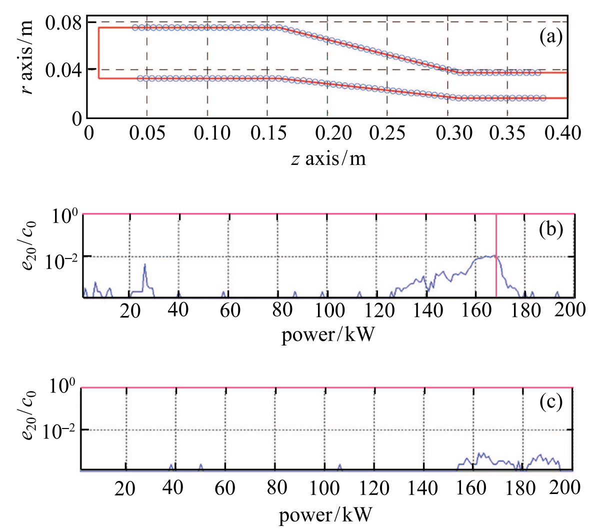

Fig. 8. (color online) (a) 2D model of the coaxial line with a taper for multipacting simulation in MultiPac 2.1. The circles represent the initial electrons. (b) Enhanced electron counter function in the coaxial line with an electric wall at the right-hand end of the model. (c) Enhanced electron counter function in the coaxial line with a magnetic wall at the right-hand end of the model. Note that multipacting occurs only when the enhanced counter function is greater than one.

6 High power conditioning

One FPC was successfully manufactured, and tested with a 500 MHz klystron as the 650 MHz power source was not ready yet. To get 500 MHz RF power going through the FPC with little reflection, the original doorknob was replaced with a doorknob from a BEPCII coupler [12]. In the test stand, the FPC was mounted on a connecting waveguide with an already conditioned BEPCII coupler. FR power came through the FPC upstream, went to the BEPCII coupler through the connecting waveguide and finally, was absorbed by a terminating load which connected to the downstream coupler. The conditioning stand is shown in Fig. 9.

The conditioning was started after a high temperature baking of the test stand for about 51 hours. Pulsed and CW conditioning methods were applied in turn. During the RF processing, the ARC signal, electron signal, vacuum and temperature of the couplers were monitored and interlocked with the power to prevent damage of the couplers. As shown in Fig. 10, after five days of conditioning, the target power of the traveling wave, 150 kW in CW mode, was reached. No unexpected temperature rise was observed in the FPC components in the test. The highest temperature on the window was recorded as 32.3 ℃, after continuous 150 kW conditioning for more than thirty minutes.

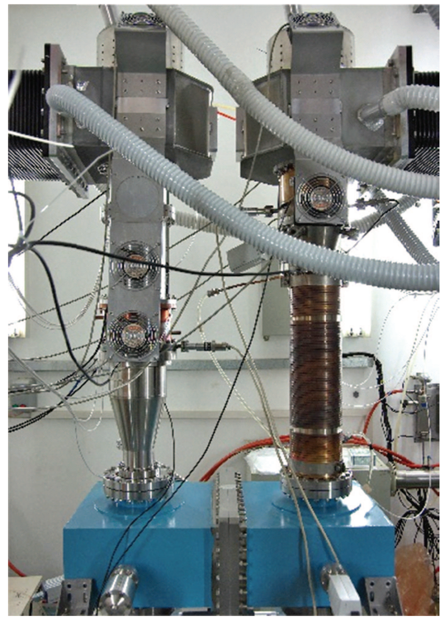

Fig. 9. (color online) Test stand used in conditioning. The left-hand coupler is the 650 MHz C-ADS FPC with the doorknob replaced, and the right-hand one is a BEPCII FPC. The two couplers were connected through a waveguide cavity.

7 Summary

A new high power coupler for 650 MHz C-ADS superconducting elliptical cavities has been designed and tested. The FPC was designed with a large-diameter planar window with choke structure to provide 150 kW of CW RF power to the cavities. The vacuum section is short to enable clean mounting with the cavity and accordingly, copper plating thickness optimization and helium gas cooling were applied to minimize the heat load.

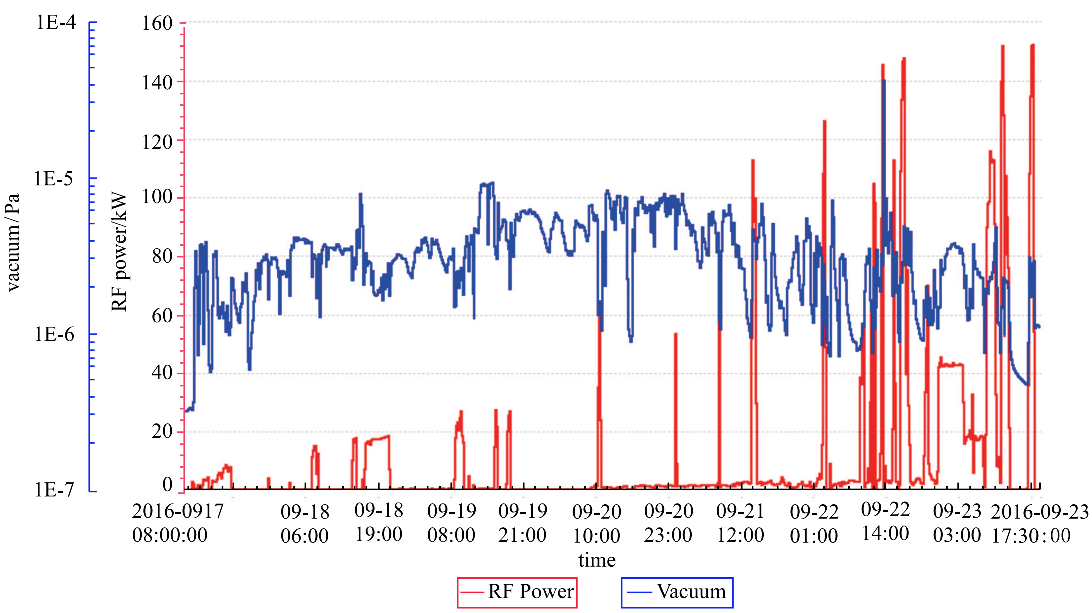

Fig. 10. (color online) Conditioning history of the FPC. Pulsed and CW conditioning methods were applied in turn in the processing. RF power of 150 kW was reached after conditioning for about 5 days.

Sufficient water and air cooling methods were adopted to cool the FPC. Multipacting simulations indicate that there is no hard multipacting barrier in the coupler. Moreover, a primary power test was finished and verifies the FPC's power handling capability. We believe that this work will provide a reference for future design of similar high power couplers which serve superconducting cavities of high quality factor and high accelerating gradient.

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