ISBN: 978-3-95450-219-6 ISSN: 2226-0366 doi: 10.18429/JACoW-LINAC2024-THPB073

EFFECTIVE THERMAL LOAD MITIGATION IN CERL INJECTOR COUPLER THROUGH WARM SECTION MODIFICATION

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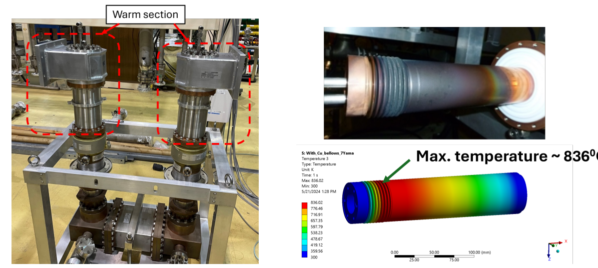
Abstract

The prototype of cERL (compact ERL) injector coupler experienced excessive thermal load during high power transmission in continuous wave (CW) mode operation. Hence, some modifications has been introduced in the warm sections of the coupler which includes a scheme for active water cooling for the inner and outer conductors. The material of the warm inner conductor was also replaced from copper coated stainless steel to pure oxygen-free copper. The high power test results with modified warm section shows effective thermal load mitigation. For the unmodified coupler, the warm inner conductor's temperature reached 183°C at 27 kW power level, while for the modified coupler with active water cooling, this temperature was mere 25°C. Due to the conduction cooling effect from the modified warm inner and outer conductor, the temperature rise of the entire coupler was suppressed. Furthermore, high power test was conducted using the forced convection cooling by a fan which additionally suppressed the temperature rise of the entire coupler components. The results demonstrate the effectiveness of the implemented modifications and suggests that the 100 kW class high power transmission in CW mode could be possible.

INTRODUCTION

In superconducting radio-frequency (SRF) accelerators, input couplers transfer power from the source to the SRF cavities. The SRF cavities have the ability to accelerate high-power beams in continuous wave (CW) mode. However, during power transmission, the coupler's components experience excessive thermal loads, leading to potential damage. Essentially, the configuration of accelerator to generate high current beams is constrained by the power transfer capability of the input coupler rather than the SRF cavities.

This problem was notably encountered by the cERL injector coupler's test stand during 100 kW power transmission in CW mode for one minute, about 15 years ago [1]. The cERL injector coupler, designed for power transmission in L-band SRF cavities, achieved power transfer up to 30 - 40 kW in CW mode at the test stand (Fig. 1(a)) [2]. However, while transferring 100 kW power for a minute, the coupler's warm inner conductor was burned due to excessive thermal load. The temperature measurement of the warm inner conductor shows that maximum temperature reached about 180^{0}C during RF transmission of 20 kW in CW mode [3]. The ANSYS



((a)) ((b))

Figure 1: (a) cERL injector coupler test stand and (b) burned warm inner conductor by 100 kW RF transmission and temperature profile by ANSYS thermal simulation.

thermal simulation of the warm inner conductor also suggests that the expected maximum temperature near bellows will be around 836^{0}C for 100 kW power transmission. The temperature profile by ANSYS simulation and the burned inner conductor are shown in the Fig. 1(b). To address this issue, some modifications were introduced in the coupler's warm section. The high-power test with modified components were performed with and without fan. The following sections highlight the implemented modifications and the results of high power test.

MODIFICATIONS IN CERL INJECTOR COUPLER

The warm inner and outer conductor of the cERL injector coupler were fabricated from stainless steel with 20 µm copper coating. This design exhibited poor thermal conductivity, leading to overheating and subsequent burning of the warm inner conductor. Additionally, substantial temperature rise was observed in the outer conductor and other components.

To address these thermal issues, modifications were implemented in the warm section of the cERL injector coupler. The revised components are as follows:

- **Warm inner conductor**: The inner conductor was re-fabricated using oxygen-free copper, which significantly improves thermal conductivity. Figure 2(a) illustrates the modified inner conductor, which includes integrated water cooling channels. These channels allow chilled water from the chiller to circulate through the space adjacent to the bellows.
- **Warm outer conductor**: The outer conductor was re-fabricated with added jacket on it's outer surface. This jacket is designed to be filled with chilled water, as depicted in Fig. 2(b).

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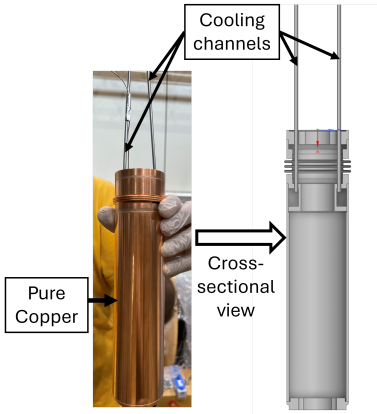

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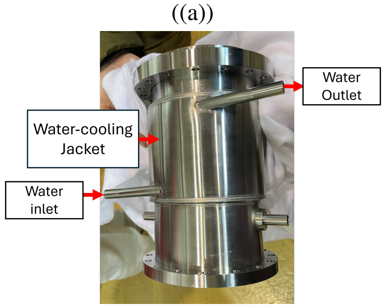

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Figure 2: (a) Modified warm inner conductor and it's cross-sectional view and (b) modified warm outer conductor.

EXPERIMENTAL SETUP

The cERL injector coupler test bench consists of two couplers connected via a box as shown in Fig. 1(a). The warm inner and outer conductors of the downstream coupler was replaced by the modified ones. The RF power from a 30 kW IOT power source was transferred to the upstream coupler and then transmitted through the downstream coupler to be absorbed by a dummy load as shown in the schematic Fig. 3 of the experimental setup . Power measurements were taken at three locations: at the output of the IOT (Pf0, Pb0), at the upstream coupler's input (Pf1, Pb1), and at downstream coupler's output (Pf2, Pb2) where Pf denotes forward power and Pb denotes backward power. A chiller provided cooled water during power transmission for the active cooling of modified inner and outer conductors in downstream coupler and for the antenna of both the couplers, with a flow rate of 1 L/min per component. A total of 17 temperature sensors monitored the coupler test bench, while an additional temperature sensor was attached to the water outlet pipe of the chiller. The setup also includes three arc sensors (two arc sensor are located at the vacuum side of the RF window and one at the upstream coupler's doorknob) and two cameras (to monitor the ceramic window).

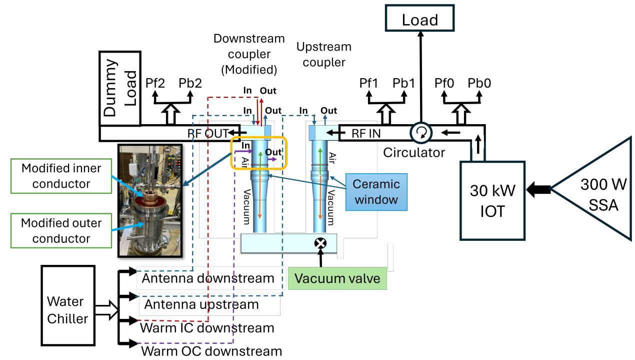

Figure 3: Schematic of the experimental setup with unmodified upstream coupler and actively cooled modified downstream coupler connected via a box. Here IC: Inner conductor, OC: Outer conductor.

HIGH POWER TRANSMISSION TEST

Procedure of High-power Test

The high-power transmission test was conducted in continuous wave (CW) mode. The power level (Pf0) was increased from 5 kW to 27 kW. The input power level (Pf1,Pb1) and output power level (Pf2,Pb2) were recorded by USB power meter as shown in Fig. 4. Each power level was maintained for 45 to 60 minutes to reach temperature stabilization. Similarly, a high-power test was conducted with forced convection air cooling facilitated by a fan and increasing the power from 5 kW to 25 kW in CW mode.

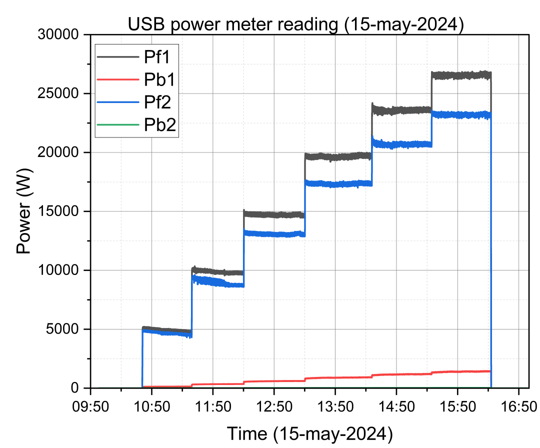

Figure 4: Input (or transmitted) and reflected power with time.

Results of High-Power Test

Figure 5 compares the temperature profiles of the upstream (unmodified) and downstream (modified) coupler's inner (Fig. 5(a)) and outer conductor (Fig. 5(b)) and Fig. 6 presents the temperature profile at each temperature sensor location at the power level of 27 kW in CW mode. The unmodified inner conductor (sensor 1) reached 183°C, while

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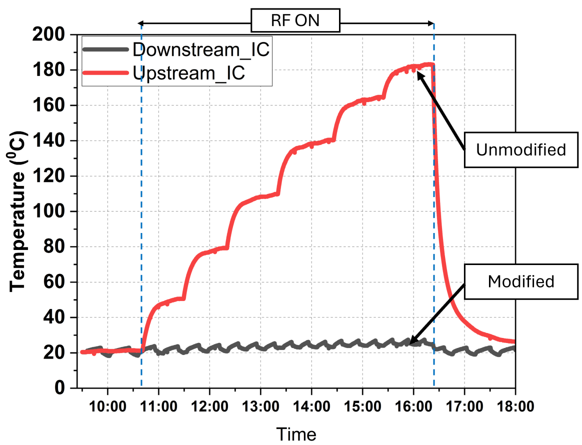
the modified inner conductor with active water cooling (sensor 2) only reached 25°C. Similarly, the unmodified outer conductor (sensor 10) reached 85°C, whereas the modified outer conductor with active water cooling (sensor 9) reached only 27°C. These results underscore the effectiveness of the modifications in the suppression of the temperature rise during power transmission. Additionally, the comparison at the upstream and downstream coupler's doorknob (sensors 3 and 4), short position (sensors 5 and 6), and RF window (sensors 11 and 12) further demonstrate the effective temperature suppression due to the conduction cooling from the water-cooled modified components.



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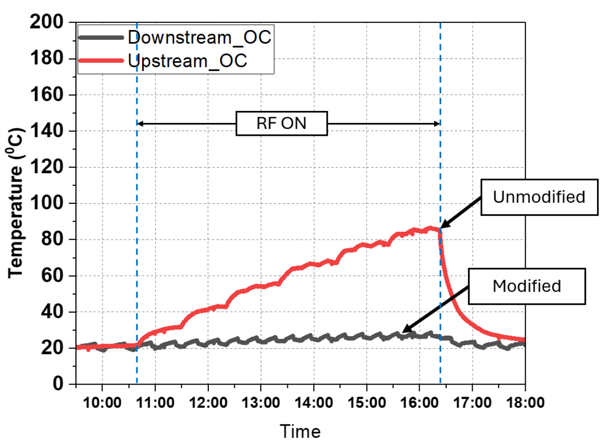

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Figure 5: (a) Temperature profile of unmodified and modified inner conductor and (b) temperature profile of unmodified and modified outer conductor, under power test.

To further suppress the thermal load at the doorknob, waveguide, and RF window, a fan was used to provide forced convection cooling during the RF transmission. Figure 7 illustrates the temperature profiles of all the sensors during the RF transmission test with and without a fan. The fan effectively mitigated the temperature rise across the coupler

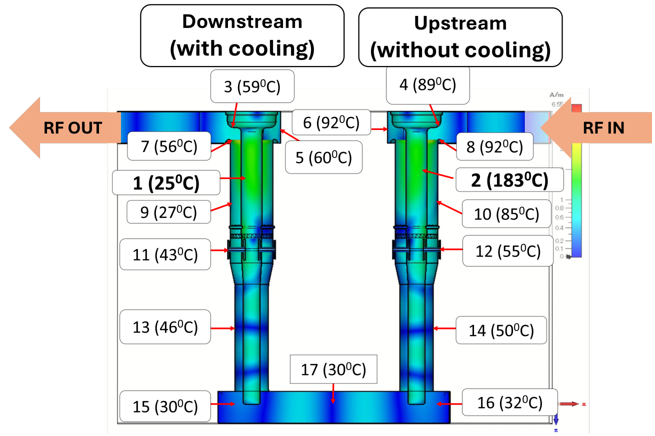

Figure 6: Temperature profile at power level 27 kW.

test stand. With active water cooling along with forced convection cooling by the fan during high-power transmission, the maximum temperature rise was suppressed to less than 22^{0}C.

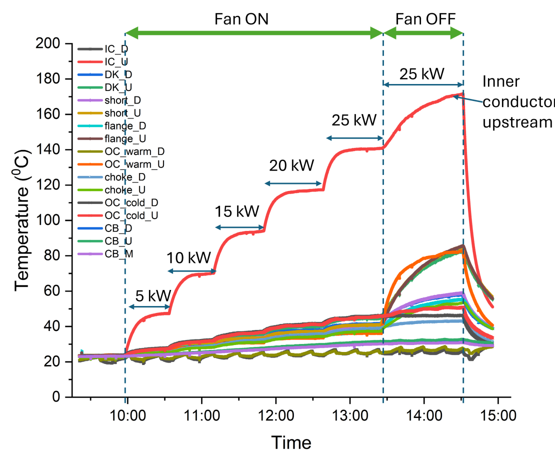

Figure 7: Measured temperature profile during RF transmission with fan (here at time 13:30, fan was turned off which led to increase in the temperature at all locations).

CONCLUSION

Modifications to the warm section of the cERL injector coupler were successfully implemented, and high-power transmission tests were conducted in continuous wave (CW) mode up to 27 kW. The high-power transmission tests demonstrated that modifications to the cERL injector coupler significantly improved thermal management. Additionally, high power test conducted with a fan further improved cooling efficiency. With these enhancements, it is anticipated that the cERL injector coupler can support RF power transmission up to 100 kW in CW mode.

ACKNOWLEDGEMENTS

Author would like to acknowledge the support of Tetsuya Michikawa (Tonichi-giken), Hiromitsu Nakajima (KEK) and Hiroki Yamada (NAT).

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