EXPERIMENTAL RESULT OF HIGH-POWER TRANSMISSION THROUGH 1.3 GHZ CERL INJECTOR PROTOTYPE COUPLER *

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Abstract

To get the experience of power transmission through high-power coupler, experiments were conducted at cERL test facility of KEK. The transmission of high power, up to 20 kW in CW mode at the frequency of 1.3 GHz, was achieved with the cERL injector coupler's prototype. The result of the RF tests showed that while transferring 20 kW power in CW operation, the temperature rise at some parts of the coupler is substantial, and a maximum temperature of 183^0C was observed at the inner conductor of the coupler. To realize the transmission of higher power levels in CW operation, the modifications in the existing coupler design by introduction of some cooling mechanisms or a new coupler design is essential. RF simulations of the coupler test stand were also performed and compared with measured S parameter results. The results of the RF test are discussed and future plan of the modification for the new design is presented in this paper.

INTRODUCTION

Nowadays, the efforts to develop a 100 kW class high-power input coupler for a 1.3 GHz Nb_3Sn cavity-based accelerator, are underway at KEK. Currently, KEK has a state-of-the-art input coupler i.e., the cERL injector coupler which can transfer 20-30 kW power in CW operation to the niobium cavity-based accelerators is available. However, since Nb_3Sn cavities are required to be cooled via cryocoolers at 4K, this prerequisite necessitates a new and innovative design for the input coupler.

In the series of development of this new coupler design, it is essential to understand the limitations of the current design. The high-power RF test of the cERL injector prototype coupler was planned to realize these constraints for the power transfer beyond the established range of 20-30 kW. This aims to identify opportunities for potential modifications in the geometry or a new idea for future coupler development.

Table 1 outlines the principal characteristics of the cERL injector coupler [1, 2].

EXPERIMENTAL CONFIGURATION

For this RF test, the coupler test stand was assembled in the cERL facility of KEK. This particular coupler test stand had undergone prior exposure to 1.3 GHz RF power at levels up to 30 kW during continuous wave (CW) operation. For the present investigation, the same methodology was replicated. However, additional temperature sensors were affixed to the inner conductors at locations anticipated to experience higher temperature conditions. The details of the experimental arrangement, the result of the RF test, and the future plan for the forthcoming design are discussed in this paper.

Table 1: Main Specifications of cERL Injector Coupler

Parameter	Specification
Central Frequency	1.3 GHz
Conditioning power at test stand	40 kW, CW
Operational power at cryomodule	10 kW, CW
Q_{ext}	10^6
Coupler type	Coaxial, Fixed
Number of ceramic window	1
RF window type	Disk

Coupler Assembly

In preparation for the high-power test, the coupler's elements such as the inner conductor, outer conductor, and doorknob were assembled. Given that the cold segment of the coupler had already been assembled within the controlled environment of a clean room, only the warm part needed to be assembled again. Figure 1 shows the cERL injector prototype test stand after assembly at cERL facility of KEK.

Figure 1: cERL injector prototype coupler test stand.

The S parameter for the coupler test stand was measured by network analyzer and compared with the simulated S parameter result. Figure 2 shows the comparison between

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measured and simulated S parameters. For measured data, the central frequency of first peak was 1.289 GHz having bandwidth of 4 MHz and for second peak, central frequency is 1.301 GHz having bandwidth of 2 MHz whereas for simulated case, the central frequency of first peak is 1.291 GHz having bandwidth of 3 MHz and for second peak, central frequency was 1.306 GHz having bandwidth of 2 MHz. Here bandwidth was calculated for S parameter (S11) below -20 dB. Evidently, the measured S-parameter findings exhibit favorable concurrence with the simulated S-parameter values, manifesting a frequency deviation of approximately 5 MHz.

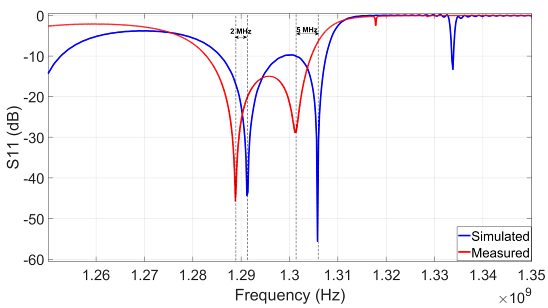

Figure 2: Comparison of simulated and measured S parameter.

Coupler Baking

Subsequent to the S-parameter assessment, the coupler's warm part was disassembled, and the cold part was baked with ribbon heaters. The configuration for the coupler baking procedure is illustrated in Fig. 3. The surface temperature of the coupler was incrementally elevated, reaching a range of 100-120°C. After baking, the warm part was reassembled.

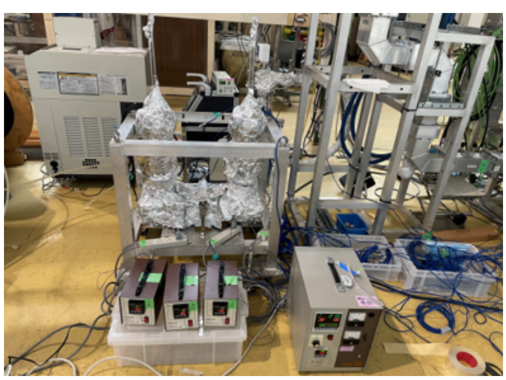

Figure 3: Configuration for the coupler baking process.

Connection of the sensors and chiller

A total of 17 thermocouples were affixed to the coupler test stand based on the magnetic field profile evaluated by the CST simulations. Figure 4 shows the location of the thermocouples along with the magnetic field profile. Additionally, to avoid any potential failure resulting from discharges at the RF window, three Arc sensors were installed.

The vacuum system was installed to actively evacuate the coupler test stand. The chiller system was connected to the water cooling channels which cooled down the coupler's antenna during power transmission.

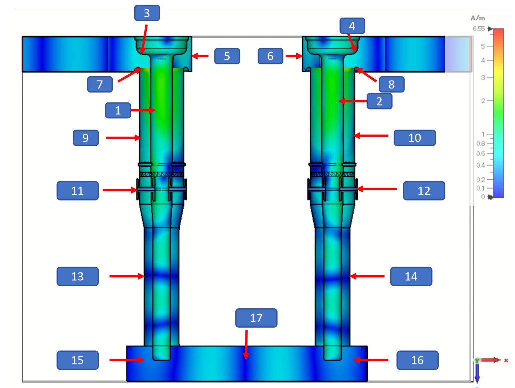

Figure 4: Arrangement of temperature sensors relative to the magnetic field profile.

Final Setup

Figure 5 provides an illustrative depiction of the arrangement of the coupler test stand for the RF power test. In this setup, a 30 kW, 1.3 GHz RF power source – specifically an Inductive Output Tube (IOT) – transmit the power to the upstream coupler. The transmitted power from the downstream coupler is judiciously absorbed by a dummy load.

The DC power supply was connected to the interlock system which further controls the operation of the IOT. Finally, the interlock levels were set for vacuum conditions, power parameters, arc occurrences, and water flow, collectively safeguarding the coupler from any potential failures.

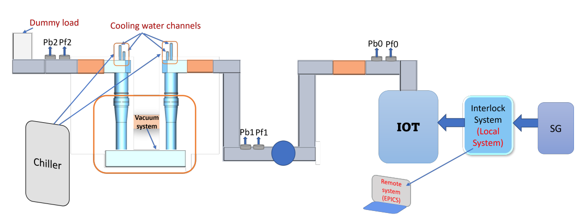

Figure 5: Schematic depiction of the coupler test stand interconnected with IOT and dummy Load. [Pf and Pb indicate forward and backward power respectively; (Pf_0, Pb_0) signifies output power from IOT, (Pf_1, Pb_1) designates input power to the upstream coupler, and (Pf_2, Pb_2) represents transmitted power from the downstream coupler.]

RESULT OF HIGH POWER TEST

The high-power test procedure commenced by subjecting the coupler test stand to pulsed operation. The pulses were 30 μs, 100 μs, 300 μs, 1 ms (1% duty), 5 ms (2.5% duty), 10 ms (5% duty), 50 ms (25% duty), for power level up to 25 kW. Subsequently, the RF test was performed in CW operation, spanning power levels of 5 kW, 10 kW, 15 kW, and 20 kW. Figure 6 shows the variation in the vacuum level with input and transmitted power during CW operation.

A discharge event happened at the 20 kW power level – a rapid escalation in the vacuum level beyond the interlock threshold, prompting an automatic shutdown of the RF power.

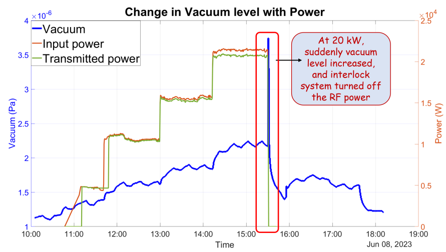

Figure 6: Fluctuations in vacuum level relative to input and transmitted power during CW operation.

At each power increment during CW operation, sufficient waiting time was allocated to observe the attainment of temperature saturation. The temperature profile at distinct locations within the coupler test stand has been represented in Fig. 7, with the input power.

Furthermore, Figure 8 presents the peak temperature reached at each specific location when operating at the 20 kW power level during CW operation. The maximum temperature was observed at the warm part of the upstream coupler i.e., 183^{0}C was at the inner conductor of the warm part of the upstream coupler, whereas at the inner conductor of downstream coupler, the maximum temperature was 152^{0}C.

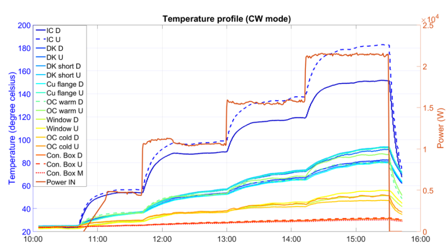

Figure 7: Temperature profile at distinct locations of the coupler with input power. [IC: Inner conductor, DK: Doorknob, OC: Outer conductor, U: upstream, D: Downstream]

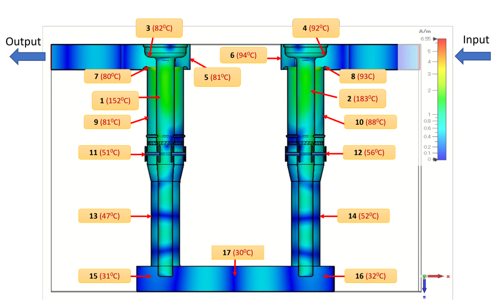

Figure 8: Maxmium temperature at distinct locations at 20 kW power in CW operation.

Figure 9 indicated that the temperature rise exhibits a linear correlation with the increase in power level, remaining consistent until 20 kW during CW operation. This pattern serves as a significant indication, underscoring that extending to the 100 kW level could result in a temperature ascent of approximately 800°C at the inner conductor. This, in turn, could lead to the burned down of the coupler components under the influence of RF power.

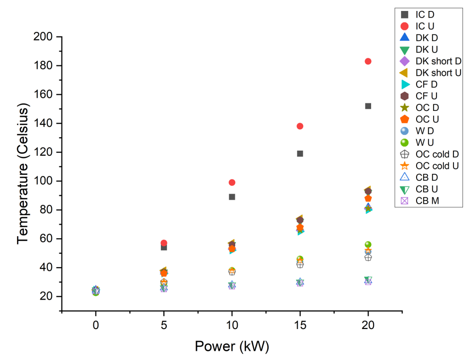

Figure 9: Saturated temperature at distinct location with power level. [IC: Inner conductor, DK: Doorknob, OC: Outer conductor, U: upstream, D: Downstream]

By following the preceding RF test, it was interesting to see the effectiveness of enforced conventional air cooling. Therefore, a fan was introduced to facilitate the cooling process during the transmission of 15 kW power in CW operation as shown in Fig. 10. This experimental setup aimed to validate the potency of the cooling condition.

Subsequently, Fig. 11 shows the trend of the temperature with and without the fan operation. The temperature difference with and without fan operation was 19°C a the inner conductor and 27°C at the outer conductor of the upstream coupler and this clarify that the cooling was effective even at the inner conductor.

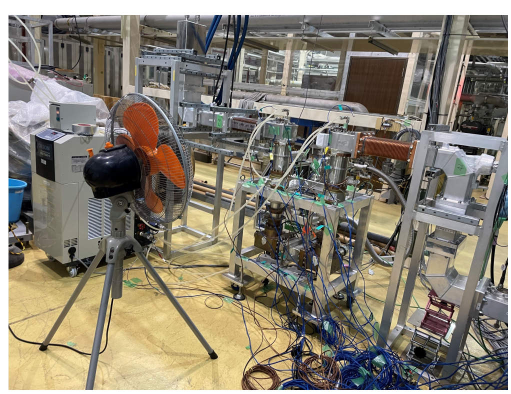

Figure 10: Configuration of coupler test stand incorporating cooling fan system.

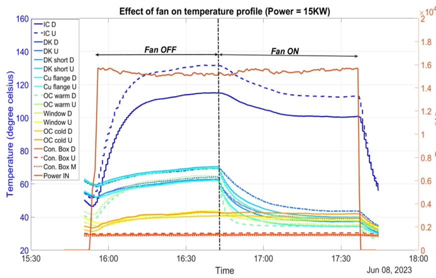

Figure 11: Temperature profile with and without fan operation during 15 kW CW RF transmission. [IC: Inner conductor, DK: Doorknob, OC: Outer conductor, U: upstream, D: Downstream]

FUTURE PLAN

To actualize power transmission reaching up to 100 kW for the Nb_3Sn cavity-based accelerator system, a strategic roadmap has been devised to address two primary challenges:

- **Mitigating Heat Load through Superconducting Coating:** To mitigate the heat load exerted on the cavity, the plan is to apply the coating of a superconducting material, specifically MgB_2 (T_c = 39K), onto the RF surface of the cold segment's outer conductor. and maintaining the temperature of this region below 30K. Visual representation of this plan is furnished in Fig. 12.

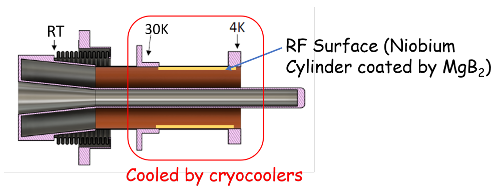

Figure 12: Schematic to illustrate the coupler's outer conductor coated by superconducting material MgB_2 to mitigate heat load to the Nb_3Sn cavity.

- **Enhancing Cooling Efficiency:** A concurrent initiative involves a more comprehensive redesign of the warm portion's inner and outer conductor. This redesign entails augmenting the dimensions to accommodate an increased number of water cooling channels. Additionally, a cooling jacket for the outer conductor is proposed to further enhance heat dissipation efficiency. Figure 13 shows the schematic model for this plan.

Through these strategic interventions, it is envisaged that the envisaged power transmission threshold of 100 kW can be achieved with an advanced thermal management approach, ultimately advancing the capabilities of the Nb_3Sn cavity-based accelerator system.

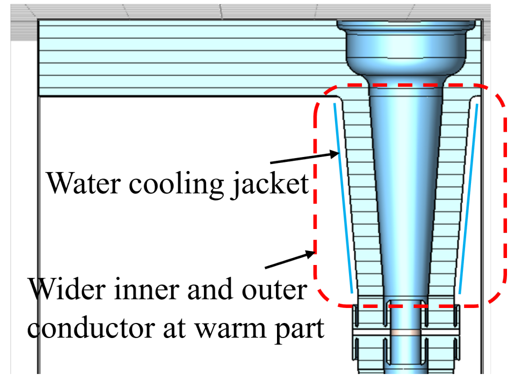

Figure 13: Schematic model to effectively cool the outer and inner conductor of warm part.

SUMMARY

The RF power test of the prototype cERL injector coupler was conducted in pulse and continuous wave (CW) operation in KEK's cERL facility. Temperature rises linearly with the power level where the peak temperature of 183°C was observed at the inner conductor of the warm part of the coupler during 20kW CW operation. Extrapolating from the observed linearity, it can be inferred that this inner conductor could potentially reach temperatures nearing 800°C during 100 kW CW operation. This substantial temperature rise serves as a limiting factor, effectively restricting power transmission capabilities beyond the 20 kW.

A more sophisticated thermal design, coupled with a robust cooling strategy, becomes a paramount necessity in order to surmount this temperature-related constraint. This endeavor seeks to devise an approach that can effectively address thermal challenges, thereby unlocking the potential to extend the power transfer threshold up to the envisaged 100 kW mark.

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