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Design and RF Conditioning of Superconducting Fundamental Power Coupler for the High-Energy Linear Accelerator at RAON

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1. Introduction

Superconducting Radio-Frequency (SRF) fundamental power couplers (FPCs) play a critical role in delivering high RF power from the source to the cavity, impacting accelerator performance and reliability. The SRF cavities in the low-energy section of RAON linear accelerator (linac) currently operate with a maximum input RF power of 4 kW. To accelerate heavy-ion beams up to 200 MeV/u, a high-energy linac section is under development, requiring up to 7 kW of continuous-wave (CW) input forward power through the FPC. To meet this requirement, high-power FPCs optimized for CW operation are being developed and tested, with a target external quality factor (Qext) of approximately 4E6 for the high-energy section. The present design represents the highest-specification SRF power coupler developed domestically in Korea in terms of operating frequency and power. Extensive room-temperature RF conditioning tests were conducted to validate power handling capability, thermal stability, and long-term operational robustness. The RF tests were performed under full-reflection conditions, sustaining a maximum CW 7 kW input power. This paper presents the latest design features and RF conditioning results of the FPC intended for application in the high-energy section of RAON.

2. Design Specification

The front section of the high-energy linac at RAON is currently under development based on a balloon-shaped type-1 single spoke resonator (SSR1) cavity [1,2]. The SSR1 cavity operates at 325 MHz and is designed to provide an accelerating gradient of approximately 8 MV/m. The fundamental power coupler (FPC) integrated into the SSR1 cryomodule must reliably deliver high RF power under beam-loading conditions. The detailed RF specifications of the FPC, including operating frequency, input power, and coupling requirements, are summarized in Table I.

Figure 1 shows the 3D design configuration of the FPC [3]. The coupler features a single ceramic window and three diagnostic ports for monitoring vacuum level, electron current, and Arc discharges caused by multipacting (MP).

Table I: RF specification of FPC for RAON SSR1 cryomodule

Parameter	Value
Operating Frequency	325 MHz
Operating Power	7 kW (with beam loading)
Qext	4E6
Impedance	90 Ω (Vacuum side), 50 Ω (Air side)

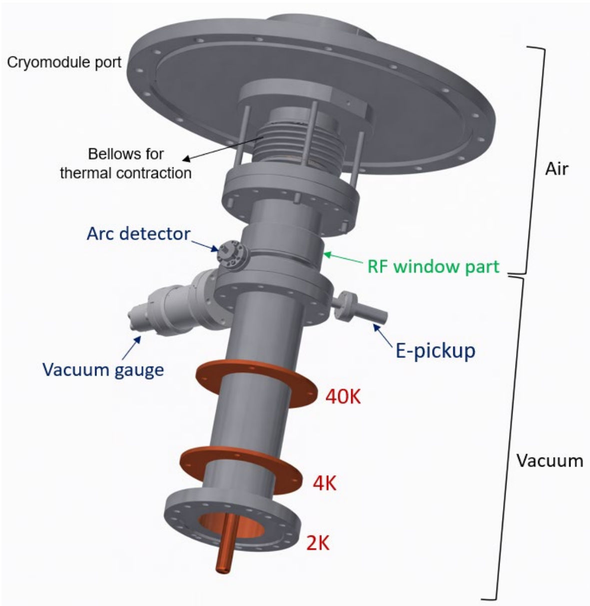

Fig. 1. FPC design for RAON SSR1 cryomodule. There are two thermal intercepts (4K, 40K) and three diagnostic ports (Vacuum gauge, Arc detector, E-pickup).

3. High Power RF Test and Results

3.1 Test Procedure and setup

Figure 2 shows the 325 MHz test bench assembled with two FPCs. Vacuum pump station is pumping out the vacuum from the test cavity. The RF signal, generated by a signal generator and amplified by a solid-state power amplifier (SSPA), is delivered to FPC1 via a transmission line. The RF power passes through the test cavity and is transmitted to FPC2. The forward and reflected powers are monitored by directional couplers located upstream and downstream of the test bench, respectively. Under this test bench conditions, the measured resonant frequency was 325.71 MHz with S11 of -28 dB and S21 of -0.085 dB, which were consistent with the CST simulation results.

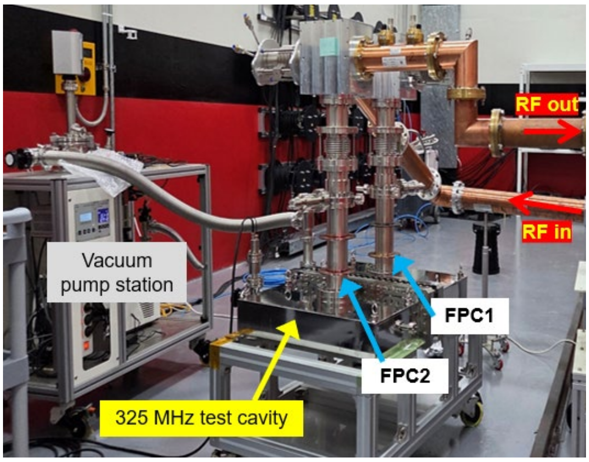

Fig. 2. 325 MHz Test bench assembled with two FPCs, RF waveguides and vacuum pump station.

The test procedure was conducted as follows:

1. Traveling-wave mode (RF output power terminated in a dummy load).
   - Pulse to CW up to 7kW average power.
   - Pulse (up to 30% of duty) reaching a peak power of 18kW (limited by SSPA).
2. Standing-wave mode (full-reflection, RF phase is adjusted using a movable short).
   - Pulse to CW up to 7kW average power.
   - Repeat at different RF phase (in 6 steps).

3.2 Test Results

The results of the standing-wave test at 7 kW CW forward power are summarized in Fig. 3 as a function of the adjusted RF phase. The maximum temperature of the RF windows in FPC1 and FPC2, as well as the test cavity, strongly depend on the reflection phase. Severe MP was observed in FPC2 at lower phase regions (0°–45°), leading to significant and non-linear temperature rise along with occasional interlock trips. In this region, strong MP persisted even after long-time conditioning.

In contrast, stable CW operation was achieved in higher phase regions (90°–120°), where MP activity was significantly reduced. Under these conditions, we could sustain 7 kW to the FPCs for about 8 hours. The temperature increased approximately linearly with the forward input power, indicating dielectric-loss-dominated heating behavior. The vacuum level remained below 1e-6 mbar throughout the test.

To mitigate the MP, the application of a DC-bias is strongly recommended. We plan to apply a DC voltage through the inner conductor of the FPC to evaluate the effectiveness of MP suppression for future linac operation.

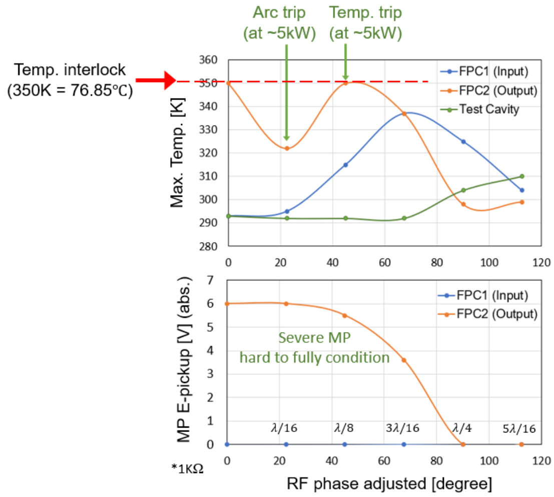

Fig. 3. Summary of RF test results performed in Standing-wave mode (full-reflection) with CW 7kW forward power. (Upper) Maximum temperature at RF windows (FPC1, 2) and test cavity, (Lower) MP-induced electric current (converted to voltage) as a function of the RF phase.

Conclusions

In this work, a high-power fundamental power coupler for the high-energy section of RAON has been designed and experimentally validated under 7 kW continuous-wave operation. The standing-wave tests demonstrated strong phase dependence of MP and thermal behavior, with stable operation achieved at higher RF phase regions. Severe MP and non-linear temperature rise were observed at lower phase regions, highlighting the importance of MP mitigation strategies. Future work will focus on implementing DC bias to suppress MP and ensure reliable operation in the cryomodule environment.

Acknowledgement

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