FEASIBILITY STUDY OF IN SITU THERMAL MONITORING OF STRIPPER FOILS IN THE J-PARC RCS.

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Abstract

Stripper foils in high-intensity proton accelerators experience significant thermal loads during beam irradiation, leading to deformation, degradation, and reduced lifetimes. In the J-PARC Rapid Cycling Synchrotron (RCS), a carbon stripper foil is irradiated by a 400-MeV injecting H^- beam and the circulating proton beam, and simulations predict temperatures of up to about 1000 °C. Direct installation of an infrared (IR) camera near the foil is not feasible due to high radiation levels, so remote temperature monitoring is required. The RCS currently uses a long-distance optical system with sapphire lenses to monitor foil motion. Sapphire lenses transmit poorly in the infrared, making conventional IR thermography impractical. To overcome this, we propose a near-infrared (NIR) camera compatible with the existing optical path. To test feasibility, a test stand using an electron-beam irradiation device is being built to simulate localized foil heating. The preliminary design, expected performance, and current status of the test stand are presented. This study provides a foundation for in situ thermal diagnostics of stripper foils in the J-PARC RCS.

INTRODUCTION

The J-PARC 3-GeV Rapid Cycling Synchrotron (RCS) employs a charge-exchange multi-turn injection system using carbon stripper foils to achieve high-intensity beams with a design output of 1 MW [1]. Following the initial 1-MW-equivalent beam extraction in 2015 [2], continuous 1-MW user operation was achieved in April 2024 [3]. This confirmed that the charge-exchange foil, a key technology for high-intensity beams, operates stably at 1 MW.

Meanwhile, J-PARC is exploring further beam intensity upgrades, including shortening the repetition cycle of the Main Ring (MR) [4] and constructing a Second Target Station for the Materials and Life Science Experimental Facility (MLF) [5]. To meet these future requirements, the RCS is expected to exceed 1 MW of output.

A critical challenge for the stripper foil during such upgrades is the temperature rise and the resulting reduction in lifetime due to increased beam irradiation. In particular, excessive temperature increase may accelerate foil degradation through carbon sublimation under vacuum conditions. Accordingly, thermal analyses were performed using the ANSYS code to evaluate the foil temperature at higher beam intensities. Furthermore, to establish a temperature-monitoring system, we are developing an offline test bench featuring an electron-beam foil-heating system. This paper reports on the thermal analysis of the stripper foil for 1.5-MW beam operation and on the development of a test bench for measuring foil temperature.

FOIL HEATING SIMULATION

Analytical Model

Simulations of the temperature rise in the stripper foil due to beam irradiation in the RCS were calculated using the ANSYS computational code. The stripper foil, fabricated by the arc discharge method, has an amorphous structure, and its exact physical properties are not yet known. Therefore, the physical properties used in the calculations were based on graphite, with a density of 2.25 g/cm^3. Since the emissivity is expected to be in the range of 0.7 to 0.9, calculations were performed using two values, 0.5 and 1.0, and the results were evaluated to determine whether they fell within that range. Additionally, the foil thickness was set to 1.5 μm, and the computational mesh size to 1 mm × 1 mm area.

The simulation employed two operating conditions: current simultaneous operation of the 1-MW MLF and the 0.8-MW MR, and standalone operation of the planned 1.5-MW MLF upgrade. The stripper foil is irradiated by both the H^- beam injected from the Linac and the H^+ beam circulating in the RCS during the injection period. Furthermore, because the painting conditions vary with each operation, it is extremely difficult to simulate the entire irradiation process. Therefore, we first calculate the particle distribution that hits the foil during the injection period using a separate multi-particle beam-tracking simulation and then set the heat input conditions assuming uniform incidence over the injection period (i.e., the macro-beam width injected from the linac).

Current Simultaneous Operation of 1-MW MLF and 0.8-MW MR

First, we performed a temperature-rise simulation under the current simultaneous operating conditions. The analysis model is summarized in Fig. 1. The foil width was 20 mm, as specified in the initial design. The Accelerator operating cycle is 2.48 seconds, during which 58 shots are supplied to the MLF and 4 shots to the MR. The beam conditions for each destination are shown in Table 1. The results of the calculation of the particle distribution hitting the foil under these conditions are summarized in Fig. 2. The transverse beam painting area for the MLF is set to be large; thus, the irradiated area of the circulating beam

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spreads out from the injected beam spot. As a result, the number of foil-hit particles is concentrated at the spot. However, for the MR, which has a narrow painting area, the number of foil-hit particles around the injection spot increases significantly. This suggests that the MR has a higher probability of a temperature increase than the MLF, despite its lower power output.

Analytical calculations were performed over 7.44 seconds, equivalent to three accelerator operating cycles. The time evolution of the maximum temperature on the foil is shown in Fig. 3. The maximum temperature depends on the beam destinations and repeats the same pattern along the operating cycle. At the MLF, it is 630 °C when assuming an emissivity of 0.5 or 532 °C when assuming an emissivity of 1.0. On the other hand, the value is 1083 °C for an emissivity of 0.5 and 948 °C for an emissivity of 1.0 at the MR.

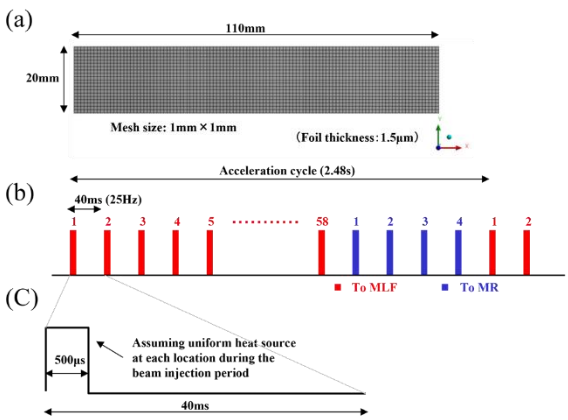

Figure 1: Analytical model for simultaneous operation of MLF (1MW) and MR (0.8MW). (a) Foil size, (b) Beam operation cycle, (c) Heat input conditions.

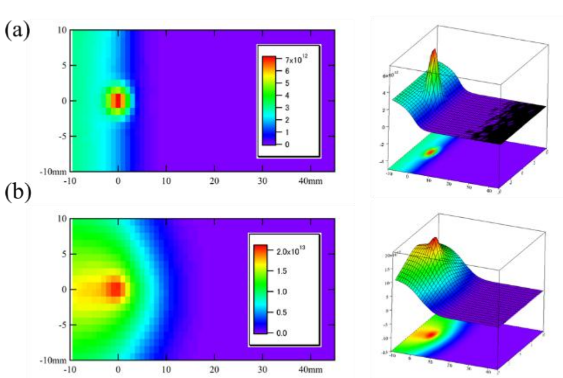

Figure 2: Distribution of foil-hit particle at (a) 1-MW MLF, and (b) 0.8-MW MR.

Table 1: Current beam operating conditions

Beam destination	Peak current	Macro width	Chop width	Paint condition
MLF	50 mA	500 μs	456 ns	200π -Anti.
MR	50 mA	500 μs	440 ns	50π-Corr.

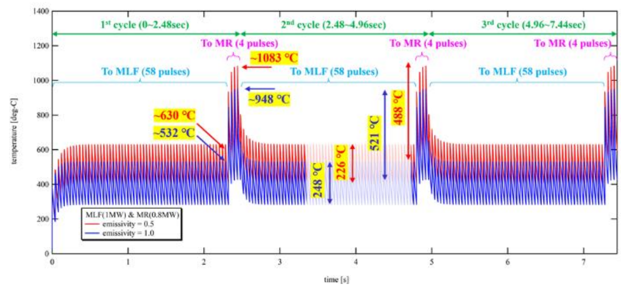

Figure 3: Time evolution of the maximum temperature on the foil for simultaneous operation of the MLF and the MR.

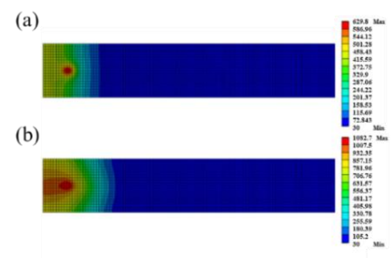

Figure 4: Two-dimensional temperature map on the foil for the simultaneous operation of the MLF and the MR.

Fig. 4 shows the two-dimensional temperature map on the foil after beam irradiation for the 58th pulses of the MLF (a) and the 4th pulses of the MR (b), which are the last pulses for each beam destination in the operating cycle. These maps are similar to the foil-hit particle distributions. Thus, a smaller painting area is disadvantageous as it leads to higher foil temperatures. On the other hand, analytical results show that even under the most severe conditions, the maximum temperature reached on the foil is 1083 °C, providing a substantial margin below the carbon sublimation region in vacuum, where rapid thermal degradation is expected.

Future Standalone 1.5-MW MLF Operation

Temperature-rise simulations were performed under operating conditions corresponding to a 1.5-MW beam from the RCS for future upgrade plans. As shown in the analytical model in Fig. 5, the foil width was set to 14 mm to minimize beam loss caused by foil scattering. Although there is currently no dedicated accelerator cycle for standalone MLF operation, we conducted a 4-second analysis (totaling 100 shots) to evaluate long-term thermal stability. The specific beam parameters are summarized in Table 2, and the resulting foil-hit particle distribution is shown in Fig. 6.

The analytical results are shown in Fig. 7. The maximum temperature saturates after approximately five shots, reaching 1,116 °C with an emissivity of 0.5 and 986 °C with an emissivity of 1.0. Fig. 8 displays the foil temperature distribution after the 100th beam pulse. Compared to the 1-MW MLF operation, the 1.5-MW case involves both higher beam intensity and a narrower painting area. Consequently, the high-temperature region has expanded, and a new peak-temperature area has formed, particularly near the foil edges. Although the maximum temperature of 1,116 °C is higher than that observed in the 0.8-MW MR operation, it remains well below the sublimation temperature of carbon in a vacuum. Therefore, even at the increased intensity of 1.5 MW, no significant reduction in foil lifetime due to sublimation is expected, and substantial foil thinning is unlikely under the present operating conditions.

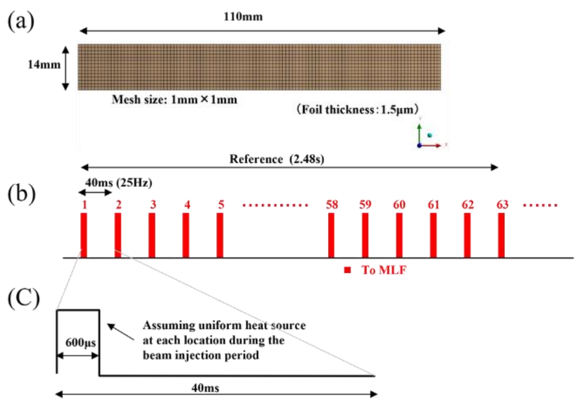

Figure 5: Analytical model for solo operation of MLF (1.5 MW). (a) Foil size, (b) Beam operation cycle, (c) Heat input conditions.

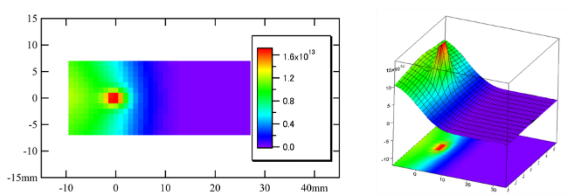

Figure 6: Distribution of foil-hit particles at 1.5-MW MLF.

Table 2: Future high-power operating conditions

Beam destination	Peak current	Macro width	Chop width	Paint condition
MLF	60 mA	600 μs	460 ns	150π-Anti.

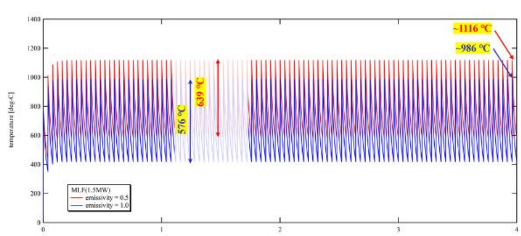

Figure 7: Time evolution of the maximum thermal point on the foil for solo operation of the 1.5-MW MLF.

Figure 8: Two-dimensional temperature map on the foil for future high-power operation of the 1.5-MW MLF.

TEMPERATURE MEASUREMENT SYSTEM FOR STRIPPER FOIL

Simulations showed that at 1.5 MW, the foil reaches approximately 1,116 °C, well below the carbon sublimation temperature. However, to account for simulation uncertainties (such as imprecise material properties and beam painting modeling), online temperature measurement is essential.

Performance Evaluation Test Bench

J-PARC RCS has a real-time foil observation system consisting of sapphire lenses and mirrors that transmit the optical image to a location far from the stripper foil, avoiding the high-radiation environment [6]. Currently, this system uses a digital camera to monitor foil motion, but switching to an infrared camera would enable measurement of the foil temperature. However, sapphire lenses transmit poorly in the infrared, making conventional IR thermography impractical. To overcome this, we propose using a near-infrared (NIR) camera compatible with the existing optical system.

For measuring temperature with an NIR camera, the emissivity setting is a critical parameter. Therefore, we are developing an offline test bench to evaluate the foil's emissivity and to calibrate the camera's temperature, as shown in Fig. 9. We are currently modifying the electron-beam irradiation system to enable foil heating. For camera calibration, the sample holder will be replaced with a carbon block equipped with a heater. Performance evaluation tests of this setup are scheduled to be conducted within 12 months.

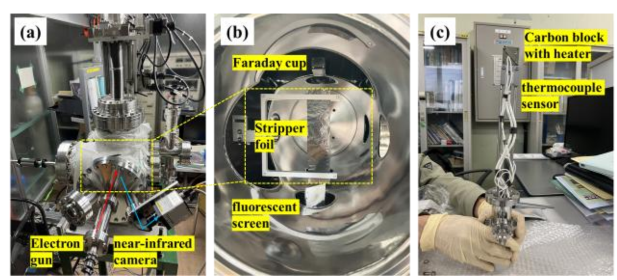

Figure 9: Test Bench for evaluation of the NIR camera. (a) Electron beam irradiation device, (b) Stripper foil, (c) carbon block with heater ribbon for thermal calibration.

CONCLUSION

J-PARC plans to increase the beam power, with the RCS aiming for an output of 1.5 MW. Thermal simulations using ANSYS showed that the maximum foil temperature reaches approximately 1116 °C even at 1.5 MW operation, remaining well below the carbon sublimation temperature in vacuum. Therefore, the current foil is expected to maintain sufficient thermal margin for future operations. On the other hand, online temperature measurement remains essential because of uncertainties in material properties and beam painting conditions. We are considering an update to the existing optical observation system to include a near-infrared camera. Accordingly, a test bench for performance evaluation and thermal calibration is currently under development.

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