CRYOGENIC THERMOMETERS AS SLOW BEAM LOSS DETECTORS*

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Abstract

Due to the folded geometry of the linac, beam loss monitoring at the Facility for Rare Isotope Beams (FRIB) [1], especially for small losses, is extremely challenging in the low energy section of the linac. Fast detection is not required for slow/small beam losses, and we therefore propose thermometers installed in the cryomodules at potential hot spots, such as the locations upstream of solenoids. Cryogenic thermometry tests were implemented in the ReA6 cryomodule with heaters and RTD thermometers. The preliminary study shows that the 10 mK signal resolution of thermometers corresponds to ~5 mW heat power in 100 seconds, or ~1 W heat power in 10 seconds, which is sufficient to satisfy the requirement for small beam loss at FRIB.

INTRODUCTION

The unique paper-clip geometry of the FRIB linac leads to radiation cross-talk between the low-energy segment and the adjacent high-energy segment. This creates a background which can obscure beam losses, especially small losses in the low-energy segment. Ion chambers, proposed for beam-loss detection in the high-energy sections, are not suitable for the low-energy sections due to this radiation cross-talk and also the x-ray background from field emission in the RF cavities. Neutron detection in these areas is similarly affected.

In this paper, we investigate the suitability of cryogenic thermometers as a tool to measure small beam losses in which prompt detection is not critical (also referred to as "slow" losses). The first section analyzes potential beam-loss hot spots in the FRIB cryomodules. The next section describes the simulation of thermal sensitivity and response time at possible thermometer locations. The final section presents the results of cryogenic thermometry tests implemented in the ReA6 cryomodule.

LOSS HOT SPOTS IN CRYOMODULES

Beam Loss Simulation

The most probable cause of beam loss at FRIB is the failure of solenoids or cavities. Three classes of beam loss were simulated using the code IMPACT [2]:

- 1 of 69 solenoids is tripped (including 69 cases);
- 1 of 332 cavities tripped (including 332 cases);
- 2 of 332 cavities tripped randomly (including 170 cases).

A summary of the beam-loss simulation results is shown in Fig. 1. The largest peaks in power loss occur at positions 284 m and 446 m, corresponding to the second and third Folding Segments of the FRIB linac. The large beam loss in these locations is due to cavity failure. To protect the cryomodules from damage, however, we are more interested in detecting small losses which may occur over a long period time. These occur mainly in the lower-energy Linac Segments 1 and 2, as shown in Fig. 2.

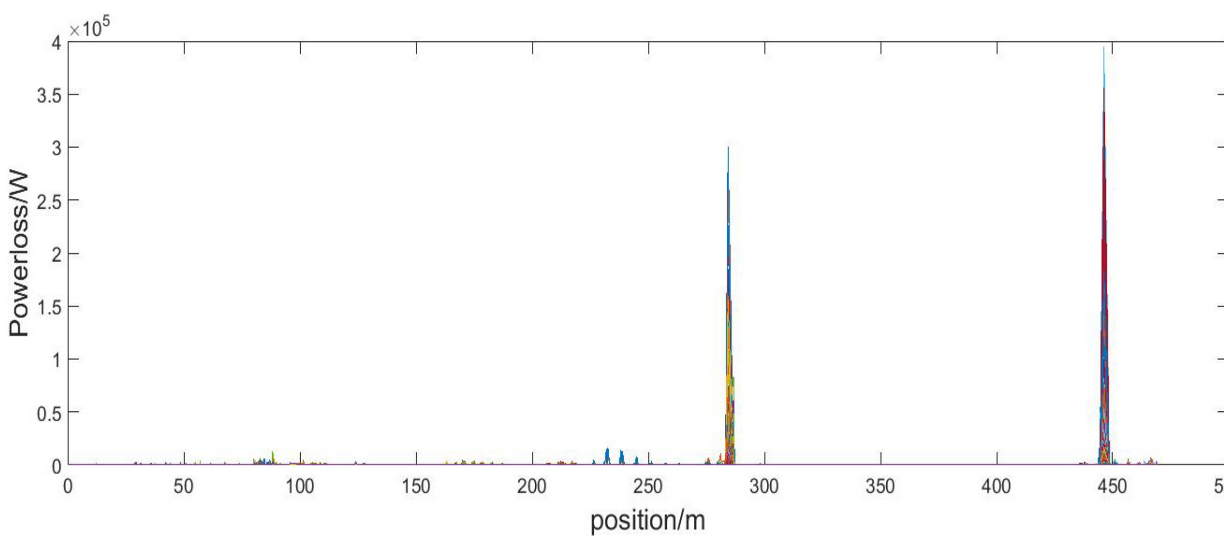

Figure 1: Summary of beam-loss results from IMPACT simulations. The corresponding FRIB linac segments are: Segment 1 = 0 - 126.5, Segment 2 = 136.5 m - 283.3 m, Segment 3 = 301.5 m - 443.7 m.

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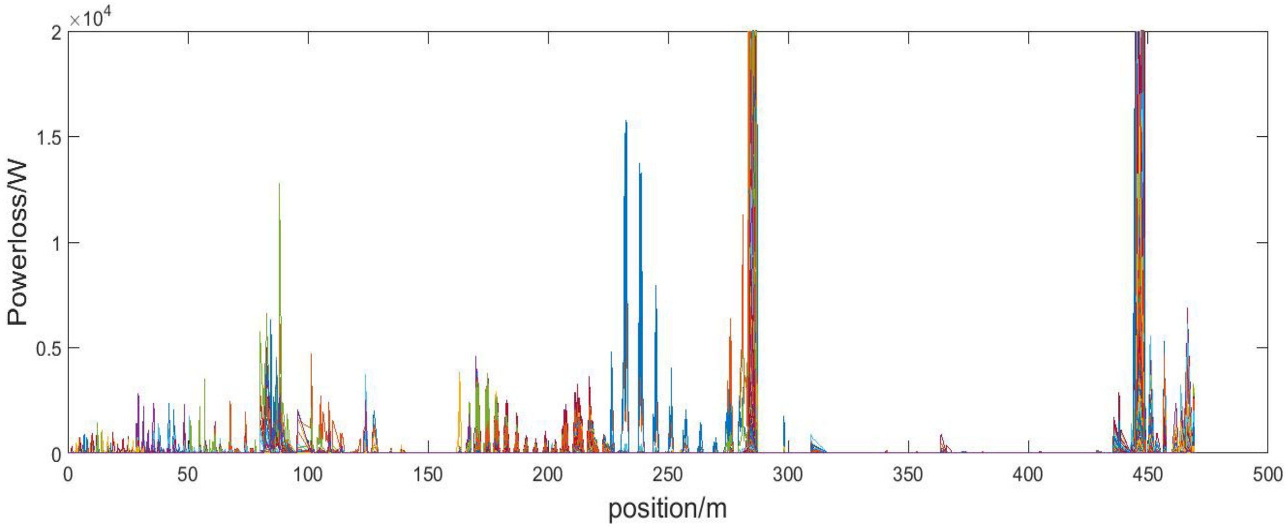

Figure 2: Close-up of small losses occurring in Segments 1 and 2 of the FRIB linac.

Slow-Loss Hot Spots

Since the cryogenic thermometers will be used to detect slow/small beam losses, they will be distributed mainly in Linac Segments 1 and 2, and possibly in a few of the potential beam loss positions in segment 3.

Almost 90% of the beam loss occurs in either the cavities (70.24% of total beam loss inside cryomodule), the drift spaces before solenoid (12.36%), or the solenoids (6.84%). Beam loss inside a cavity or solenoid cannot be measured directly by temperature sensors because they are inside helium jackets. Therefore, we plan to install thermometers close to the solenoids in the drift space before and after.

SIMULATION OF THERMAL SENSITIVITY AND RESPONSE TIME

A cavity and a solenoid are connected by a flexible coupling (bellows), providing a short section of drift space between them. To decide the attachment point for the thermometers, a simulation of sensitivity and response time was performed. For the simulation, sensors were placed on both bellows flanges and the bellows wall, as shown in Fig. 3.

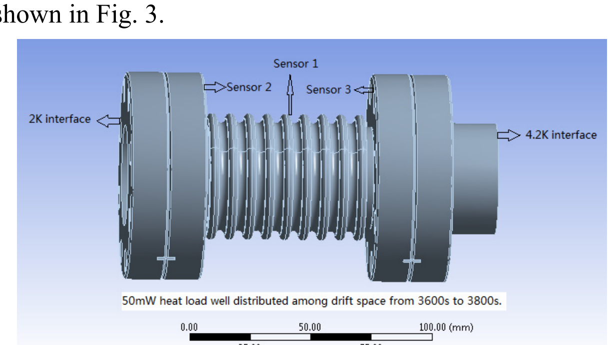

Figure 3: Thermal simulation for the drift space between cavity and solenoid. Left bellows flange is connected to the cavity flange (2K interface), right one is connected to the solenoid flange (4.2K interface). There is 50 mW heat load well-distributed among the drift space from 3600s to 3800s during the simulation.

Since it is difficult to attach a thermometer to the ridged surface of the bellows wall, we examined the response time at the bellows flanges. The simulation shows that the temperature rises faster for the solenoid-side flange (Fig. 4) than the cavity-side flange (Fig. 5). A 10 mK rise in temperature takes about 30 seconds at the solenoid-side flange, while it takes about 50 seconds at the cavity-side flange. Also, the temperature of the solenoid-side flange has a much higher saturation temperature than cavity-side flange. Thus, we see higher thermal sensitivity on the solenoid side.

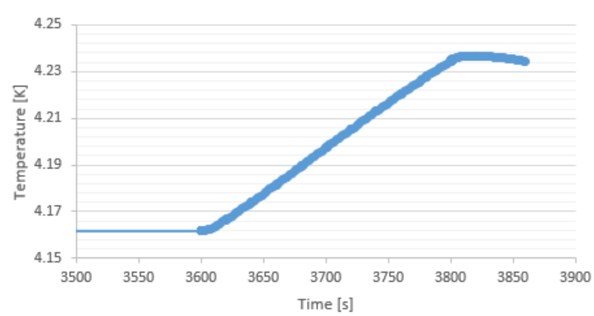

Figure 4: Solenoid-side bellows flange, Temperature vs. Time.

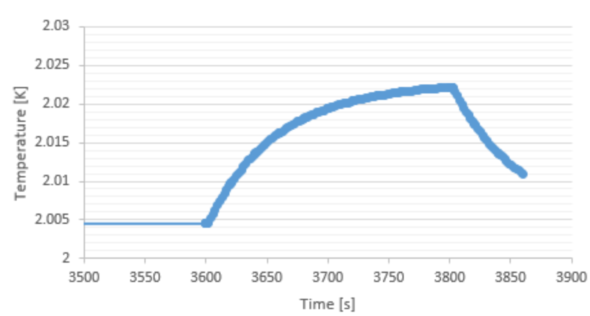

Figure 5: Cavity-side bellows flange, Temperature vs. Time.

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The simulation result is consistent over a range of heat loads from 5mW to 100mW. Based on these results, the thermometer should be attached on the bellows flange nearest the solenoid.

CRYOGENIC THERMOMETRY TESTS

A proof-of-concept test for the cryogenic thermometry was performed in the ReA6 cryomodule [3]. A 5Ω heater was used to mimic small beam loss. Three Cernox RTD sensors (TI79, TI81 and TI82) were attached near solenoid helium jacket and one (TI1) on the jacket itself (see Fig. 6). All measured signals were processed by a digital low-pass filter to reduce the white noise.

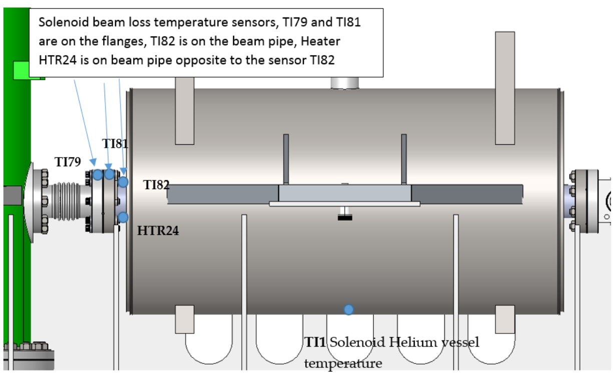

Figure 6: Schematic of thermometry test in ReA6 cryomodule. TI79, TI81, TI82 and TI1 are thermometers. HTR24 is 5 Ω heater.

The background temperature was measured by sensor TI1 in order to characterize the noise. Temperature fluctuations were about ±5 mK, and the average temperature drifted no more than a few mK over the course of the 1.5-hour test (see Fig. 7). This simple noise measurement indicates that a ΔT of 10 mK is certainly distinguishable by the Cernox sensors without "heroic" signal conditioning.

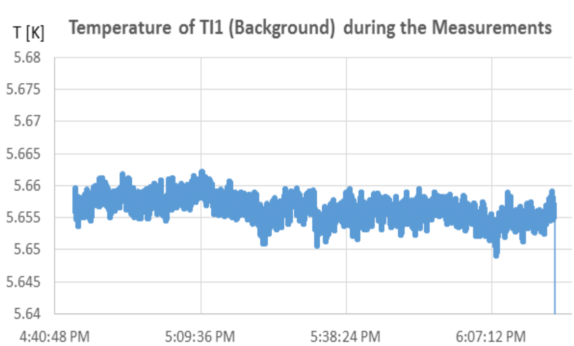

Figure 7: Background temperature fluctuation during the test, spanning about 1.5 hours. Temperature background fluctuations are about ±5 mK.

The step response of each sensor was recorded for heat loads from 2 mW up to 1 W. Fig. 8 shows the 4.5 mW heat load case for TI82. Sensors at the other two locations (TI81 and TI79) have similar results. The stated sensitivity of the sensor is 2 mW according to the technical specifications. However, a more reasonable lower bound for this measurement appears to be 5 mW.

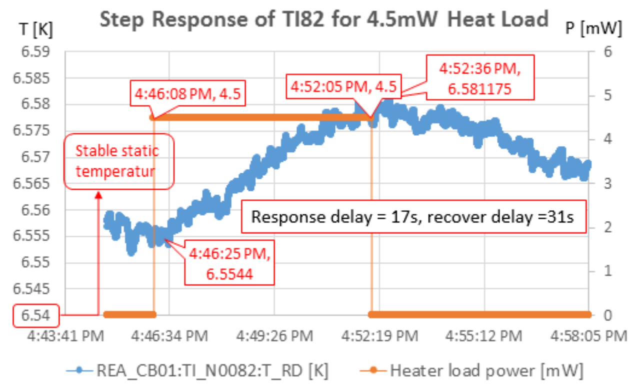

Figure 8: 4.5-mW-heat-load step response for TI82. Response delay is the time until the temperature begins to rise after heater turned on. Recover delay is the time until the temperature begins to drop after the heater is turned off.

Table 1 summarizes the measurement data for TI82 with heat loads from 2 mW to 1 W. The response time is less than 20s when heat load is > 5 mW. Since it has been indicated that the Cernox sensor can distinguish a ΔT of 10mK, we define beam loss (BL) detection time as the time for the temperature to rise 10mK after the heater is turned on. For example, if FRIB's local slow/small beam loss is 50 mW, the thermometer should detect it within 21 seconds.

Table 1: Summary of TI82 Measurement Data

Heat Load	Response Time	BL detection time
2 mW	83 s	303 s
4.5 mW	17 s	107 s
12.5 mW	14 s	50 s
32 mW	11 s	29 s
50 mW	10 s	21 s
98 mW	11 s	17 s
1013 mW	10 s	11 s

The location of the thermometers will affect the results, and this was also considered in the test. The effect is apparent in Fig. 9, which shows the results for a 50 mW heat load. The beam-loss detection time increased when the distance from thermometer to heater increased. Using the average beam-loss detection time (about 30 s), we get good agreement between our measurements and the thermal simulation for the 50 mW heat load case, which also took about 30s to rise 10 mK (Fig. 4). In summary, the thermometry measurement technique showed a 5mW lower bound for beam loss and it will detect beam loss at expected power levels (< 100mW) in the time scale of a minute.

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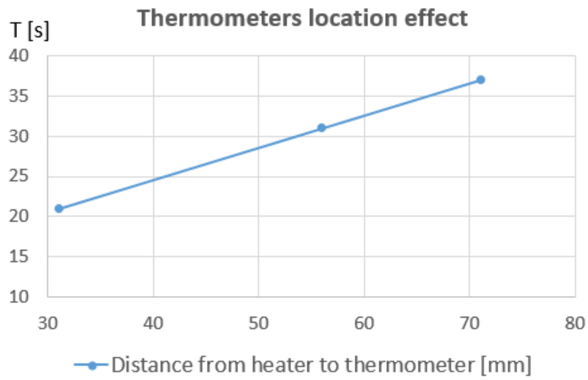

Figure 9: Beam loss detectable time vs. Distance from heater thermometer.

CONCLUSION

Slow/small beam-loss monitoring is extremely challenging in the low-energy segment of FRIB, but critical in order to protect cryomodule from degradation due to radiation damage. Thermometry has been proposed as a method for detecting these small losses without interference from radiation cross-talk. Beam-loss simulations determined that the slow-loss hot spots in the cryomodules are within the cavities and solenoids, and in the drift space before a solenoid. Thermal-sensitivity and response-time simulations were performed in order to determine the suitability of several sensor locations. A proof-of-concept test was implemented in the ReA6 cryomodule, showing a reasonable loss detection limit of 5 mW. At the power levels specified for slow losses at FRIB (< 100mW) the sensor response is less than a minute, as required for FRIB slow beam loss monitors.

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REFERENCES

[1] FRIB website: http://www.frib.msu.edu/
[2] IMPACT website: http://amac.lbl.gov/~jiqiang/IMPACT/index.html
[3] ReA6 website: https://people.nscl.msu.edu/~iwasaki/rea6.html

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