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BEAM LOSS IN THE FIRST SEGMENT OF THE FRIB LINAC*

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Abstract

Beam loss in accelerators is an unavoidable and often unwanted reality, but it is not without its use. Information from beam loss can be leveraged to optimize the tune and improve beam quality, in addition to monitoring for machine fault and failure conditions. The folded geometry at the Facility for Rare Isotope Beams (FRIB) presents a unique challenge in the detection of radiative losses, resulting in the introduction of non-traditional measurement schemes. In addition to neutron detectors and pressurized ionization chambers, FRIB will utilize halo ring monitors, fast thermometry within the cryomodules, and differential beam-current measurements. This paper will present an analysis of beam-loss measurements from commissioning the first segment of the FRIB accelerator, and a discussion of ways to evaluate and monitor the health of the beam loss monitoring system.

INTRODUCTION

Beam loss is an expected and unavoidable consequence of accelerating ions in any accelerator facility. Such losses occur throughout the linear accelerator (linac) as an unwanted consequence to beam transport, as well as intentionally at fixed locations where beam scraping and filtering occurs to improve beam quality, e.g. size, energy spread, or isotopic composition. Both of these types of loss create a background to normal beam operation. Small losses play a crucial role during linac commissioning stages. In addition, failure of accelerator components (magnets, etc.) will cause unexpected, and often large, losses.

Slow Versus Fast Losses

Machine background losses typically change very gradually. In contrast, losses from part failure arise quickly and are often large – enough so to cause significant machine damage. The techniques for monitoring or detecting these losses are different due to their time-scale and magnitude.

With small losses, the risk of immediate damage is absent, so we have the benefit of time with which to detect the loss and correct the issue, provided we have sufficient sensitivity. With large losses, the risk of immediate damage is great, but the magnitude of the loss makes it easier and faster to identify.

Machine Protection

Machine protection is a primary motivation for beam-loss monitoring. It's true that radiation damage is unavoidable, due to ever-present background. However, monitoring losses will allow operators to correct beam tunes to minimize such background radiation and maximize the lifetime of the machine. In addition, misdirected beam, e.g. due to magnet failure, requires fast identification of large losses to prevent immediate damage.

Beam losses deposit energy (heat) into the surrounding material. The resulting increase in temperature can be disastrous in the cryogenic areas of the accelerator, and can lead to dangerous quenching of the superconducting magnets.

FRIB is somewhat unusual in that the loss limits, shown in Table 1, are set primarily by the allowable heat load and machine degradation, rather than activation of machine parts.

Table 1: Loss Limits for the FRIB Linac

Beam Loss (W/m)	Stop beam?	Response Time
P < 1	No	≥ 1 sec
1 ≤ P < 10	Yes	1 sec (slow)
P ≥ 10	Yes	< 15 µs (fast)

CHALLENGES FOR FRIB

FRIB faces several challenges in the detection of beam losses in the linear accelerator (linac). FRIB linac is designed for a beam power of up to 400 kW. Such a high beam intensity means significant damage is possible quickly, making prompt detection of beam losses crucial. Magnet quenching can occur due to heating of irradiated superconducting components.

Due to the folded "paper clip" shape of the FRIB linac, we expect that background radiation from the high-energy linac segment (LS3) will swamp the detectors at the adjacent lowest-energy segment (LS1). Shielding of the beamline and superconducting cavities will help reduce this so-called radiation cross-talk, however it will still limit the effectiveness of radiation measurements in monitoring beam losses in LS1. Calculations indicate that only 1.5% of dose detected at LS1 is from LS1 losses, and cross talk from LS3 dominates low-energy half of LS2 [1].

DEVICES AND DISTRIBUTION

The most effective detection methods will differ for each section of the accelerator, as well as for fast and slow beam losses. The choice of detector is guided by the energy of the beam, the radiation type and magnitude, and the expected background. Table 2 shows the primary, secondary, and tertiary detection methods for fast and slow losses in each area.

Radiation

Radiation cross-talk limits the usefulness of standard radiation detectors. However there are several locations where these play an important role. Ionization chambers (IC) will be used primarily in the folding segments, near

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Table 2: Distribution of Fast (~35 µs) and Slow (~100 ms) Beam Loss Monitors in FRIB Linac

	LS1	FS1	LS2 low energy	LS2 high energy	FS2	LS3	BDS
Fast Primary	DBCM	DBCM	DBCM	DBCM	DBCM	DBCM	DBCM
Fast Secondary	HMR	BLM	BLM	BLM	BLM	BLM	BLM
Slow Primary	HMR/Temp	BLM	BLM	BLM	BLM	BLM	BLM
Slow Secondary	HMR/Temp		Temp	DBCM	DBCM	DBCM	DBCM

beam dumps and after the stripper. The FRIB ion chambers have a cylindrical geometry with a parallel plate electrode structure. They are mounted in pairs below the beamline, and operated at pressures up to 15 atm, depending on the desired sensitivity. In addition there will be neutron detectors (ND), especially around the cryomodules (CM). The FRIB neutron detectors are moderator-type, slow-neutron detectors, with a measureable neutron-energy range of 1-5 MeV. These detectors come equipped with an internal LED for testing purposes.

Temperature

Stray beam will impart energy to the surrounding walls, increasing the temperature. This signature of beam loss does not suffer from cross-talk issues, as the effect is localized. Within the CM in each segment, we use resistance temperature detectors (RTD) to monitor heat deposited by beam losses. These are crucial for preventing quenching of the superconducting elements. These are located on the BPM flanges between solenoids within the CM.

Beam Halo

Between cryomodules, we will have halo monitor rings (HMR) to detect halos of poorly focused beams. Such beams will cause losses in locations where the aperture narrows. HMRs measure a current due to beam ions impacting the ring, and are particularly useful in tuning.

Beam Current

Beam current monitors (BCM) are already planned to be used in many areas of the accelerator. Differential (DBCM) data from these can help identify beam losses, which will be evidenced by an unexpected drop in beam current from one device to the next. They are only sensitive to large changes in current, however they are distributed widely throughout the accelerator.

Additional Dual-Use Options

Other diagnostic devices within the linac can serve a dual use. Beam position monitors (BPMs) in particular can be coupled either with DBCM data to increase network density and reduce response time, or with beam orbit data from the machine protection system (MPS) to detect faults with small fractional fast beam loss.

PERFORMANCE

Commissioning the first segment of the FRIB linac in March and April of 2019 provided the opportunity to evaluate the performance of the beam-loss monitoring devices installed in this section. During commissioning, beams of argon, krypton, neon, and xenon were accelerated through the first 15 cryomodules to energies of up to 20.3 MeV/nucleon and deposited in one of two beam dumps in the first folding section.

While much of the commissioning was done at very low beam intensities, tests also were run at higher duty factors. During such runs, concurrent detection of beam loss was seen from several different loss monitors. Figure 1 shows the measured response for runs with a beam duty factor (DF) of 2.5% and 10%.

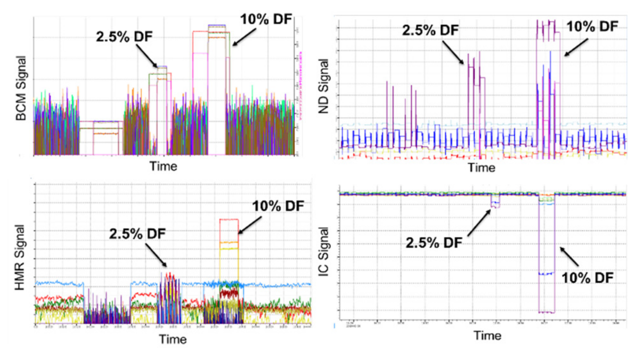

Figure 1: Concurrent detection of beam loss on BCMs, HMRs, NDs, and ICs for tests with DF of 2.5% and 10%.

The ICs only saw losses from the high-power tests, of which there were five. During these tests, beam was directed to FS1b, the second (high-power) beam dump in the folding section. The highest losses were seen on the ICs directly below this beam dump, however losses were also detectable on the devices below FS1a (low-power) beam dump, as well as after the carbon stripper. Figure 2 shows the measured IC signal as a function of beam power for these three locations. One device at each location was operated at a higher pressure (solid lines), while the second of the pair was operated at a lower pressure (dotted lines). The ratio of signals in the high and low pressure devices was consistent with the ratio of the pressures.

The NDs are sensitive to smaller losses, and were useful during lower duty-factor runs. In addition, one of the NDs (D2076) measured losses due to the use of an adjacent wire scanner profile monitor (PM). Figure 3 shows this detector's response and the corresponding beam duty factor. A small signal (<0.01 µA) is seen during times with a duty factor of 0.025%. Larger spikes are seen corresponding to the PM measurements (dots).

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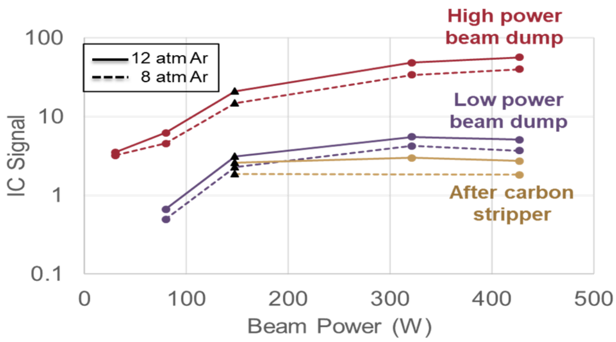

Figure 2: Ion chamber signal as a function of beam power. Beam was directed to the high-power beam dump.

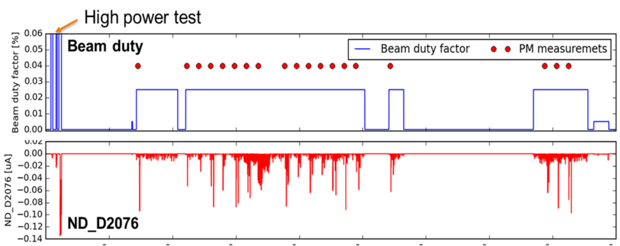

Figure 3: Neutron detector signal spikes corresponding to usage of an adjacent profile monitor (dots).

Estimate of Beam Loss

We can use the loss from PM measurements to calibrate ND D2076. The beam consisted of 50 µs pulses at 5 Hz, andt he PM has three 100 µm diameter wires passing through the beam over the course of 120 s. We can calculate the total intercepted beam is 0.5 W-sec. The average ND signal for the 19 measurements (integrated over the scan time) was -0.52 µA-sec. This gives us a calibration factor of -0.96 W/µA.

Applying this loss calibration to the high duty-factor tests, we get fractional beam losses on the order of 10^{-4}, as shown in Table 3. Similar results are obtained at low duty factor argon runs. Data from krypton beam was also examined, however a calibration was not possible since there was negligible additional signal during PM measurements.

Table 3: Estimated Beam Loss During High-Power Runs

	#1	#2	#3	#4
Beam duty [%]	10%	2.5%	99.5%	10%
Current [eµA]	34	34	3.2	3.1
Power [W]	308	74	288	28
Beam loss [mW]	47	12	76	10
Fraction	1.5e-4	1.6e-4	2.6e-4	3.6e-4

HEALTH AND MAINTENANCE

One of the health checks for the NDs is a linearity test of the photomultiplier tube (PMT). In this test, the current of the built-in LED is ramped to provide a varying light output. Figure 4 shows the detector response to one such test for the NDs in LS1. Two detectors show some non-linearity at very low LED currents/light outputs. Degradation of the linearity can indicate problems with the (PMT), and can limit the useful range of output.

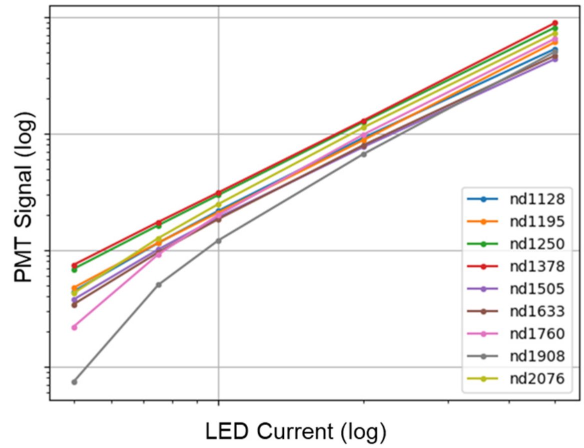

Figure 4: Neutron detector signal at a bias of -700 V, as a function of test LED current. Two detectors show non-linearity for small LED light output (current <1 µA).

The sensitivity of the ion chambers is proportional to the gas pressure, so accurately monitoring the detector pressure is important to the success of these devices. Currently, this is done manually on a monthly schedule. A pressure loss of approximately 0.5% per month has been observed. Work is underway to change implement a strain gauge pressure sensor to allow continual remote monitoring.

SUMMARY

The paper-clip geometry of the FRIB linac creates unique challenges for loss monitoring, especially in the low-energy segments. High-power beams and superconducting devices complicate matters further, and require fast response to losses. This is provided primarily by differential beam-current monitoring. Radiation cross talk can be mitigated by using novel devices and techniques, such as the halo monitoring and thermometry which are important for slow losses in LS1. Radiation monitoring devices become useful throughout the rest of the linac for slow losses.

Loss monitors in the LS1 and FS1 segments were commissioned earlier this year. HMRs performed very well, providing useful data during beam tuning. NDs saw loss at both low and high power levels. IC only responded to high-power tests, indicating that we may want to increase the pressure of the device for higher sensitivity. One ND could be calibrated using loss on PM wire. Fractional beam losses on the order of 10^{-4} were seen during both low and high power tests.

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[1] Z. Liu *et al.*, "Ion chambers and halo rings for loss detection at FRIB," in *Proc. IPAC'12*, New Orleans, LA, USA, May 2012, paper MOPPR077, pp. 969-971.