BEAM LOSS MONITOR SYSTEM FOR THE LOW-ENERGY HEAVY-ION FRIB ACCELERATOR

Z. Liu, T. Russo, R. Webber, Y. Yamazaki and Y. Zhang,
Facility for Rare Isotope Beams (FRIB), Michigan State University, East Lansing, MI 48824, USA

Abstract

Radiation transport simulations reveal shortcomings in the use of ion chambers for the detection of beam losses in low-energy, heavy-ion accelerators like FRIB. Radiation cross-talk effects due to the specific FRIB paper-clip geometry complicate locating specific points of beam loss. We describe an economical and robust solution that complements ionization chambers. A specifically designed device, the halo monitor ring (HMR), is implemented upstream of each cryomodule to detect beam loss directly. Together with fast response neutron scintillators, the new integrated BLM system satisfies both machine protection and sensitivity requirements.

INTRODUCTION

Traditional BLM system for proton accelerators mainly consists of ionization chambers and scintillation detectors such as neutron detectors. This combination is usually not sufficient to protect low-energy high-power proton / heavy ion machines due to: 1) low radiation level from beam loss, 2) significant X-ray background near high-gradient superconducting RF cavities, and 3) poor loss localization with neutron detectors.

FRIB, as one of the many examples, faces even more challenges on machine protection. It is designed to accelerate all stable ions with beam power up to 400 kW and energies from 0.2–1 GeV/u [1], with a three folded superconducting driver linac as shown in Fig. 1. Such a folded geometry brings additional difficulties with heavy radiation projected from high energy segments [2]. Moreover, the limited design margin of FRIB cryogenic heat load requires average beam loss lower than 1W/m, which corresponds to a radiation level that is totally overwhelmed by the SRF cavity X-ray background.

This paper presents a solution for this problem, which replaces ion chambers at FRIB cold area with a specifically designed device named "Halo Monitor Ring", and neutron detectors are planned as background detectors to make BLM system a complete coverage for the low energy part.

INEFFICIENT RADIATION DETECTORS

Figure 2 shows the gamma radiation at 30 cm away from a cryomodule for different ion energies, in the form of instantaneous dose (rad/hr) deposited in an ion chamber there. The heaviest ion 238U and lightest 18O are compared with a proton beam, each normalized to 1W/m. A pencil beam with 3mrad angle of divergence was uniformly distributed along one linac segment (150 m); hence every macro-particle hits the beam pipe.

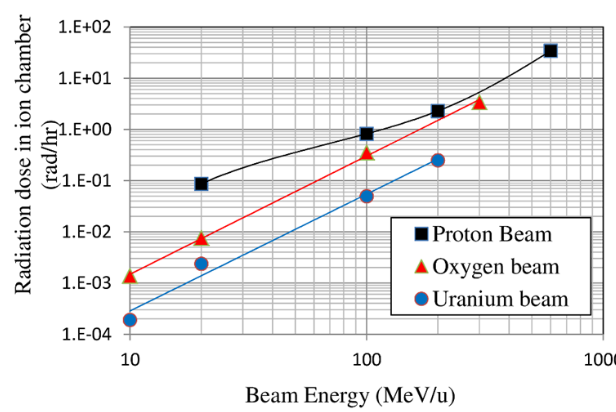

Figure 2: Instant gamma ray dose (rad/hr). Loss is normalized to 150W/150m. Proton is listed as reference.

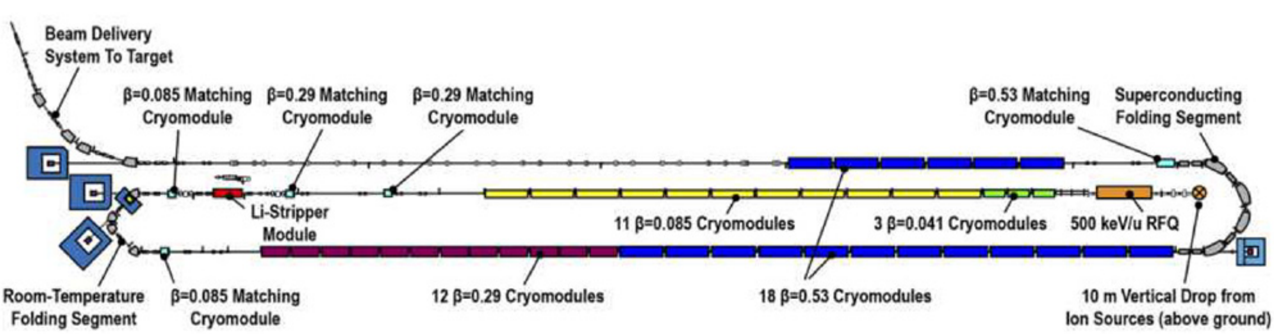

Figure 1: Schematic layout of FRIB driver linac. The specific energy for 238U is 0.5-17 MeV/u at LS1, 17 - 150 MeV/u at LS2, and 150 MeV -200 MeV/u at LS3.

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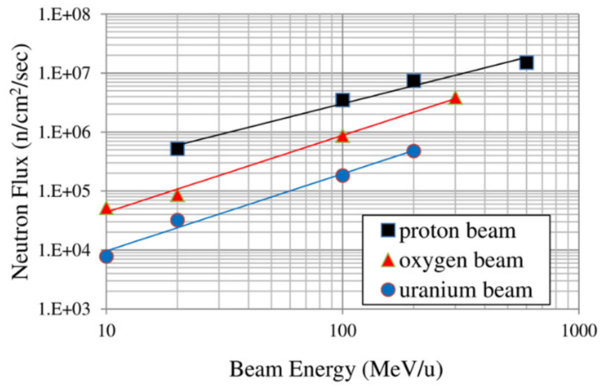

Figure 3: Neutron Flux (n/cm2/sec). Loss is normalized to 150W/150m.

Although highly sensitive ion chambers can have a wide dynamic range from 10^{-6} to 10 rad/hr, Figure 2 indicates two major obstacles to the use of ion chambers at FRIB:

1) Losses in the high energy segment of the FRIB linac would result in significant radiation at the low energy segments. As the distances from LS3 to LS1 is ~ 4 m compared with 30cm ion chamber location, the 1/r spatial dependence implies 1/13 of the LS3 loss appearing as a radiation background at LS1. Considering the 238U energy range in the three segments, the radiation cross-talk from LS3 can overshadow the whole of LS1 and first half of LS2.

2) The X-ray background from a superconducting cavity has been measured to be 10 rem/hr at 1 m from the β = 0.053 Half-Wave Resonator (HWR) in a Dewar test [3]. Approximately 60% of this radiation will be transmitted through a 0.75 inch steel vacuum vessel, giving an X-ray background of ~6 rem/hr or 6 rad/hr outside the cryomodule. Radiation from chronic low-level beam loss is overwhelmed by the X-ray background. According to Fig. 2, ion chambers for high beta cryomodules might work with X-ray background subtraction, but not for low beta cryomodules.

Figure 3 shows that secondary neutron fluxes, another source of beam loss detection, are significant for heavy ions. However, the neutron signal also experiences strong radiation cross-talk and therefore only provide large-area background information during normal operation.

These difficulty naturally encourage other methods to to detect primary lost particles rather than radiation detectors. Halo Monitor Ring (HMR), as one directly measuring method, is specifically developed for low-energy heavy-ion accelerators.

HALO MONITOR RING

The HMR is a fixed, circular, large aperture, niobium collimator installed on the diagnostics box wall upstream of each cryomodule. It intercepts charged particles outside its aperture and outputs an electrical current signal. The HMR avoids the strong radiation cross talk problems suffered by ion chambers and neutron detectors and, as shown in Table 1, produces larger signals for both slow and fast losses.

Table 1: Comparison of HMR and Ion Chamber Signals

Loss Mode	Loss Source Location	Loss Level (W/m)	Ion Chamber Signal (pA)[a]	HMR signal (nA)[c]
Slow loss	LS1	1	0.003	72
	LS2	1	0.3	29
	LS3	1	4.2	9
Fast loss	3rd β=0.29 cavity[b]	~1300 (in ~15m)	~7.0	29×10^3

Table 1 compares the HMR to an ion chamber for different loss modes and levels. For a 1W/m uniform loss, a typical LS1 HMR (ID 22 mm, OD 50 mm) will intercept at least 5W of beam halo, assuming 3 mrad halo divergences (RMS divergence at LS1 is 1 mrad). The HMR has obvious advantages for both loss modes, especially in the low energy sections. Its signal is significantly larger than that from an ion chamber and it is insensitive to radiation cross talk.

Some Concerns about HMR

To consider the HMR a promising device for a superconducting linac, we take FRIB as an example to investigate some potential operational consequences, such as sputtering, thermal damage, outgassing, electron cloud, and secondary losses resulting from edge ionization.

Sputtering might cause damage to HMR itself as well as contamination to the nearby cavity. It is a long-term effect and only slow losses needs to be considered. Assuming 5W beam halo intercepted as a tube volume (ID 28mm, OD 30mm, L 5mm), the time to sputter all the Nb atoms can be calculated as

$$t = \frac{N_{Nb}}{Y \times N_{ion}} \quad (1)$$

where N_{Nb} is the number of Nb atoms in the small tube volume, Y is the sputtering yield from SRIM [4] code, and is the number of ion particles corresponding to 5W loss. According to Fig. 4, sputtering is not a problem for the HMR itself.

Sputtering will contaminate a nearby cavity if the Nb film accumulates to 40nm on the cavity wall, which is the London penetration depth. As a first order estimation, we assume the sputtered Nb atom scattering uniformly from the center of HMR. Equation (2) gives the rate of sputtered atoms attached to the entrance of cavity per cm^2, where the accumulation density should be the largest.

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$$n = \frac{N_{ion} \times Y}{4\pi L^2} \times \sin(\theta) \approx \frac{N_{ion} \times Y}{4\pi L^2} \times \frac{r}{L} \quad (2)$$

where L is the distance between HMR and nearest cavity (~50 cm), r is half of the cavity aperture (~2cm), and θ is the angle between sputtered atom and beam pipe. To accumulate a 40nm layer, the equation predicts that it takes at least ~2×10^8 hours (thousands of years) for 0.5 MeV/u 238U and even longer for higher energies.

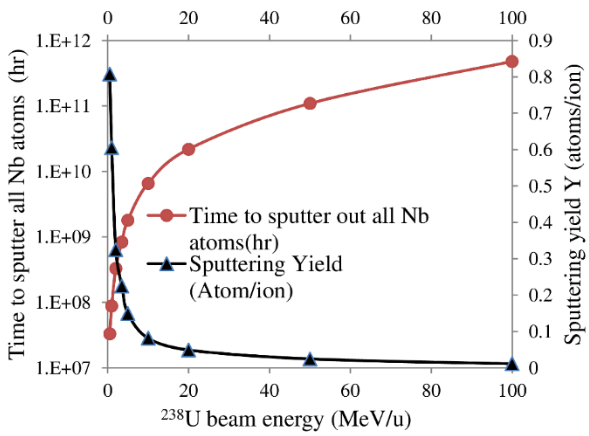

Figure 4: Estimation of damage time to HMR by slow loss induced sputtering. Damage time (red circles) is calculated by Equation (2) in unit of hours.

Edge Ionization Estimation

Ions grazing the edge of HMR could generate secondary loss due to ionization. This is discovered in AGS which lead to a vacuum pipe crack [5]. To investigate this potential hazard at FRIB, we use GEANT4 and IMPACT to simulate secondary losses by a HMR, especially for the continuous primary beam loss ≤ 1W/m. As shown in Table 2, these secondary losses are not significant. But the simulation reveals some hot spots such as bending magnets, which encourage planning of secondary collimators there.

Table 2: Secondary Loss Induced by HSR Edge Ionization

HMR Location	HMR Edge Thickness (mm)	^{238}U Energy MeV/u	Particles Grazing Edge [a] (W)	Scattering after Grazing (W)
End of LS1	5	17	0.10	9×10^{-4}
Mid of LS2	15	100	0.14	0.07
End of LS2	30	150	0.15	0.09

SUMMARY

We quantitatively presented the difficulties to use customary ion chambers to detect beam losses at a low-energy heavy-ion accelerator, while the special three folded structure of FRIB leads to a strong radiation cross-talk effect that adds additional obstacles to use radiation detectors. Hence we develop HMR upstream of each cryomodule to detect beam losses directly. To complete the detection coverage, twenty-four neutron detectors, arranged uniformly in the accelerator enclosure, are planned for measurement of radiation background. Movable ion chambers will only be used in the high energy sections of the machine and in areas that are designed to experience high beam power deposition, such as the stripping area and beam dumps.

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