EXPLORING CAUSES OF BEAM LOSS AT CEBAF

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Abstract

At Jefferson Lab, the Continuous Electron Beam Accelerator (CEBAF) features a unique design with two linear accelerators and two arc sections allowing for multiple turns of the electron beam, as well as four experimental end stations. This topology leads to increased beam losses, especially in the spreader and recombiner regions connecting the arcs to the linacs and in the extraction regions connecting the experimental end stations to the accelerator. These losses result in equipment activation and operational interruptions. Recent upgrades to the facility's diagnostic systems, including the addition of xenon ion chambers, have provided higher-resolution data regarding these loss events. Building on this improved observational capability, we are developing a simulation framework using optics codes and the Geant4-based BDSIM to model beam extinction and halo formation in these regions. This work aims to correlate simulation results with experimental data to isolate the causes of beam loss and inform future machine tuning strategies. We present a summary of conclusions drawn from recent operational studies and outline a plan to model the beam loss and validate the simulations.

INTRODUCTION

Beam loss is a persistent concern for accelerator operations. It presents an operational and environmental hazard through the creation of activated materials. Beam loss damages the accelerator components and nearby equipment, necessitating repairs. Significant beam loss results in accelerator "trips" that force a shutdown, complicating ongoing operations and experiments. Therefore, the minimization of beam loss is a high priority for all accelerator facilities, including the Continuous Electron Beam Accelerator (CEBAF) [1]. In this paper, the success of recent improvements in monitoring beam loss will first be reported. Then, persisting issues in beam loss monitoring will be highlighted. Finally, potential improvements to beam loss monitoring at CEBAF will be proposed.

SUCCESSES

One source of improvement in beam loss monitoring (BLM) is in the addition of xenon ion chambers (IDX). Similar to the neutron dose rate meters (NDX) installed in CEBAF, IDX instead monitor ionizing radiation [2]. In the 2022-2023 run, there were just under 40 000 BLM fast shut down (FSD) trips across the 278 days of operation located in the extractor region [3, 4]. With the addition of 4 IDX in the region where beam is deflected for extraction to a hall rather than continued recirculation, the 2023-2024 run reported around 9000 BLM FSD trips instead, conservatively reducing the number of BLM FSD trips by a factor of four after accounting for the different beam energies between each run [3, 4]. This reduction was largely driven by the IDX monitors allowing operators to distinguish exactly which pass needed steering attention. Table 1 provides a comparison between the trips before the addition of the IDX monitors and after at three specific locations [4].

Table 1: Change in Trip Number Before and After IDX Installation

BLM Monitor	**2022–2023**	**2023–2024**
ILM7S01	2885	1283
ILM4E02	1140	270
ILM4E08	12305	963

While this is not a rigorous comparison, as there are a multitude of confounding factors that would appear in the comparison between two runs a year apart, there is a clear significant improvement. Moreover, in the 2024 scheduled accelerator maintenance (SAM), an additional 4 IDX units were installed in the northeast spreader region, which unveiled more causes of beam trips and revealed orbit drift in low-current runs [3, 4].

Additionally, beamline monitors and beam cavity monitors (BCMs) have been used successfully to perform both real-time and offline diagnostics. First, specific beamline monitors are more useful in minimizing beam loss due to monitor degradation [5]. Unlike legacy photomultiplier tubes (PMTs) whose glass darkens over time with high exposure, the IDX monitors provide a much more stable baseline. Moreover, some legacy monitors have high baseline noise during beam off operations [5], and therefore can be misleading during diagnostics without prior knowledge. For instance, legacy spreader BLMs often see field emission background from the C100 cryomodules [1], whereas the xenon-filled IDXs are largely immune to this. Figure 1 shows how different BLM monitors have different inherent noises.

With the increasing familiarity and notation of troublesome monitors, more accurate diagnostics have been made [5]. BCMs have also been used to correct beam currents in experimental halls [6]. With Gaussian fits and linear regressions, successive analyses of recorded loss signals to Hall A and C currents were able to reduce the average instantaneous loss to 24 nA with a standard deviation of around 250 nA [6].

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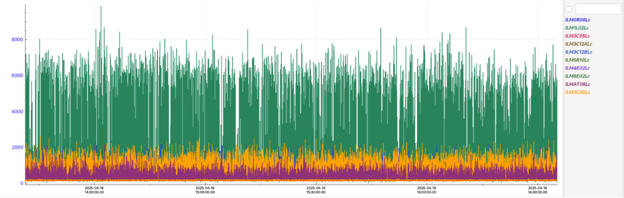

Figure 1: Signal noise amplitude from different BLM monitors measured over several hours of beam-off downtime [5]. The green monitor has much higher noise than the orange or purple monitors, thereby making it less useful for diagnostic purposes.

ONGOING ISSUES

However, despite recent successes, there remain significant issues with beam loss monitoring, the largest of which is that the placement of BLM monitors is mostly empirical [5]. While there are qualitative justifications for the current placement of monitors, such as near equipment that needs to be protected, around the arcs where beam dynamics become more complex, and in other sensitive areas, there is not a rigorous method to determine which BLM systems should be positioned and at what locations [5]. Often, the optimal detector location is dictated by the lattice optics rather than being immediately adjacent to the component needing protection. Over time, initially valid reasons for the placement of specific monitors can become outdated or forgotten, complicating troubleshooting efforts [5]. Additionally, there is currently not strict operational control over the movement of monitors, where they are sometimes displaced without notice, exacerbating the problem further [5].

Another problem is that different monitors have different diagnostic capabilities. In the least diagnostically useful case, Machine Protection System (MPS) monitors merely alert that a trip has or has not happened without any accompanying amplitude data [5]. This means operators cannot easily diagnose the very fast transient losses that frequently cause trips, forcing the control room to troubleshoot without relevant information. Others provide signals that operators must interpret individually [5]. While there has been success on this front as mentioned earlier, this process is ultimately inefficient. This is because individual monitors' signals change over time, which makes prior knowledge less useful. The main cause for this signal change is primarily due to monitor degradation, but also from changing parameters in the beamline such as element displacement and maintenance [5].

Next, due to the highly connected nature of the accelerator, the source of beam loss is not necessarily local to the source of radiation [5]. For example, regions of high activation shown in radiation maps can have many "sources" along the accelerator [7], such as a slight undocumented degradation in a bending dipole magnet or a small shift in a focusing quadrupole. These negative effects can be mitigated with a large number of monitors. However, this would entail a serious financial cost, and it does not address the core issue of small changes upstream in the accelerator resulting in significant, obscure effects downstream [5].

Finally, there is also an imbalance in regional protection. For example, there are regions that historically have high levels of activation that have not been addressed [5, 7], such as areas in the east arc. There is also the potential for overprotection in regions with more BLMs than are required, which inhibits efficient coverage of the accelerator. Additionally, moving monitors around to address this complicates diagnostic efforts in two ways. First, there is the question of where to optimally place the monitor, which is currently a problem that is only solved qualitatively and not quantitatively [5]. Second, the signal experience associated with the monitor becomes less pertinent due to the required reanalysis of the behavior at the new location [5]. There is also the issue of potentially mistaking an adequately protected region as overprotected, where the removal of a monitor might result in previously prevented damages [5]. Proper identification of the best diagnostic devices, along with the best placement, significantly affects the diagnostic web used to adjust the beam during operations [5].

POTENTIAL RESOLUTIONS

Additional IDX monitors have been acquired, and, as of Spring 2026, quadruplet groups of IDX monitors have been installed at the spreaders, recombiners, extraction, and start of the beam switch yard regions, resulting in a total of 24 IDX monitors present in the accelerator [3, 4]. This is predicted to significantly improve BLM and diagnostic abilities near known problematic regions [3, 4]. These could also enable 'Beam Loss Imaging' using 1D or 2D resistive arrays of IDX detectors to extract weighted spatial coordinates of loss events, saving on DAQ readout channels while providing better localization.

Simulations offer valuable insights into reducing accelerator beam loss. We are currently adding aperture constraints to the accelerator code ELEGANT [8] to better model regions involved in positron and degrader studies at CEBAF [4]. Incorporating realistic aperture sizes within the ELEGANT framework, coupled with optimization algorithms, will improve the accuracy of simulated beam conditions.

To further enhance these simulations, we are combining ELEGANT with Python-based multi-objective optimization frameworks, specifically utilizing the `pymoo` package [9]. As an initial test case, we optimized a simple beamline (diagrammed in Figure 2) to simultaneously minimize two objectives: the sum of the squared geometric quadrupole strengths (O_1, Equation 1) at each Q_i and the beam's radial spread (O_2, Equation 2) measured at the elements W1 and W2. In these equations, K_i is the geometric strength of quadrupole i, $N = 100$ is the number of simulated particles per bunch, and x_{ij} and y_{ij} are the transverse coordinates of particle j at element W1 or W2. The resulting Pareto front for this optimization is shown in Figure 3.

$$O_1 = \sum_{i=1}^{4}(K_i)^2, \tag{1}$$

$$O_2 = \sqrt{\sum_{j=1}^{N}(x_{1j}^2 + y_{1j}^2)} + \sqrt{\sum_{j=1}^{N}(x_{2j}^2 + y_{2j}^2)}, \tag{2}$$

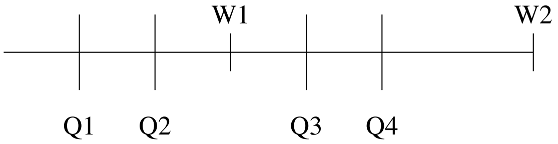

Figure 2: Abstract diagram of the test beamline. The elements Q1-Q4 represent potential focusing and defocusing quadrupoles whereas "W1" and "W2" are watch elements that record positional information of the beam bunch according to ELEGANT's lattice definitions [8].

Python (and `pymoo` specifically) was chosen over ELEGANT's built-in optimization tools because it provides greater flexibility for complex multi-objective problems. It also simplifies the integration of external accelerator codes into a single general framework. The initial objectives (O_1 and O_2) represent simplified operational priorities. First, minimizing radial spread prevents particles from striking the beam pipe; this reduces energy deposition into the accelerator superstructure, which is a significant source of beam loss. A tighter beam also generally improves experimental outcomes. Second, minimizing quadrupole strength reduces the power consumption and overall operating costs of the accelerator.

Future models could incorporate additional objectives, such as shaping the beam for specific experiments, optimally modulating the strength of accelerating elements, or minimizing generated radiation. Crucially, as this work progresses, optimized optics outputs from ELEGANT will feed directly into BDSIM [10] models of short beamline sections. This will allow us to simulate localized radiation deposition and validate our beam loss models directly against the empirical radiation maps actively being surveyed at CEBAF. By bridging ELEGANT's optics optimization with BDSIM's physical deposition tracking, as well as dedicated studies with dosimetry, we can rigorously correlate machine tuning with physical radiation reduction. Future work will focus on improving computational efficiency, testing more complex beamlines and objectives, and integrating external tracking tools into the optimization pipeline for deeper operational analyses.

CONCLUSION

In this article, first a brief description of beam loss and its negative consequences is given. Second, recent successes in tackling beam loss for the past few runs at the CEBAF accelerator at Jefferson Lab are discussed. Third, persisting issues in overcoming beam loss are highlighted, with a specific focus on how beam loss monitors play into these issues. Finally, potential solutions and improvements to the beam loss problem are provided, with a brief example for how developing computer simulation tools might be able to help future efforts. Reducing beam loss is a significant and ongoing process, but successes can pave the way for more and better experiments, lower expenses, and safer conditions for operators.

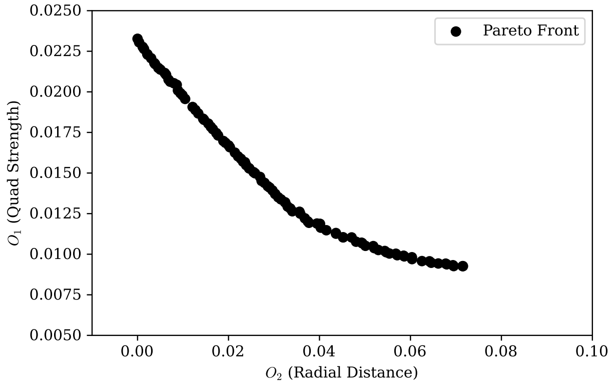

Figure 3: Pareto front of the multi-objective optimization. Solutions that populate the bottom right corner prioritize minimizing O_1, the geometric strengths of the quadrupoles, whereas solutions that populate the top left minimize O_2, the radial spread of the particles. Solutions that exist between the two extremes are more balanced with respect to optimizing both objectives.

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