DIGITAL TWIN DEVELOPMENT FOR THE NASA SPACE RADIATION LABORATORY*

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Abstract

The NASA Space Radiation Laboratory (NSRL) at Brookhaven National Laboratory simulates the galactic cosmic ray space radiation environment by delivering high energy heavy ions and protons to the NSRL Target Room for radiobiology studies and microelectronics testing. The AGS Booster synchrotron delivers beams to the NSRL beamline via resonant slow extraction. NSRL tuning is difficult due to the non-linearity from slow extraction and octupoles, and the beam shape is optimized empirically by operators. To streamline and improve NSRL operations, we develop a real-time digital twin for the beam line, starting from the extraction bumps in the Booster and extending all the way to the targets. This digital twin allows users to both load live settings from the real system to the online model, and to send model suggested settings to the real machine. We demonstrate that an accurate digital twin can improve operations at the NSRL beam line.

INTRODUCTION

The NASA Space Radiation Laboratory (NSRL) facility at Brookhaven National Laboratory (BNL) is designed to study the radiation effects of a wide variety of heavy ion species over different beam intensities and energies. Figure 1 shows the NSRL acceleration chain. The beam is first injected into the AGS Booster synchrotron via one of three transfer lines: LINAC to Booster (LtB), EBIS to Booster (EtB), or TVdG to Booster (TtB). In the Booster, the beam is accelerated to kinetic energies ranging from 50 to 2500 MeV/n (MeV per nucleon) and then extracted to the NSRL beam line using resonant slow extraction [1].

In this work, we present the development and operational application of a digital twin (DT) framework for the NASA Space Radiation Laboratory (NSRL) facility at Brookhaven National Laboratory. The framework combines physics-based accelerator models with live machine data to support beam diagnostics, interpretation, and tuning. The implementation centers on three principal elements: the Booster extraction system, the NSRL beam line optics, and the integration of these models within a control-oriented DT architecture that enables virtual diagnostics and model-guided operation.

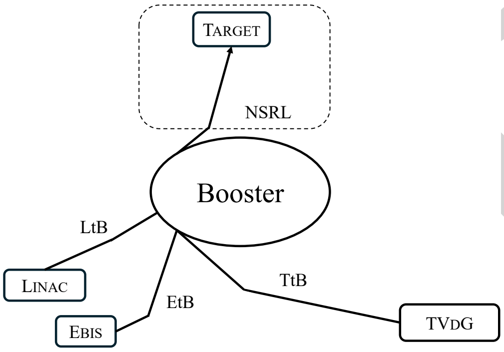

Figure 1: Schematic layout of the NSRL line, the AGS Booster, and the three injector lines (LINAC, EBIS, and TVdG). Adapted from [1].

DIGITAL TWIN ARCHITECTURE

A digital twin is defined as "a set of virtual information constructs that mimics the structure, context, and behavior of a natural, engineered, or social system (or system-of-systems), is dynamically updated with data from its physical twin, has a predictive capability, and informs decisions that realize value" [2]. Two-way interaction between virtual and physical systems is widely regarded as a defining characteristic of a digital twin framework.

In accelerator applications, we adopt the following definitions:

- Virtual Accelerator (VA): A model-based representation of a physical accelerator constructed from simulations, surrogate models, or appropriate simplifications suitable for describing the machine state [3].
- Digital Shadow: A VA that remains continuously synchronized with the physical accelerator, but does not control machine settings.
- Digital Twin: A VA that is continuously synchronized with the physical system with bidirectional interaction.

Figure 2 illustrates how a VA-based digital twin framework integrates into the operational workflow of a particle accelerator. In this work, the virtual accelerator underlying the DT is based on nonlinear, multi-particle tracking implemented in Bmad [4] and SciBmad [5]. The DT systems described in this paper operate in two modes, as shown in Fig. 3. In monitor mode, the system functions as a Digital Shadow, providing continuous virtual diagnostics without altering machine settings. In control mode, the DT supports model-based evaluation of machine configurations, control studies, and software validation workflows. This frame-

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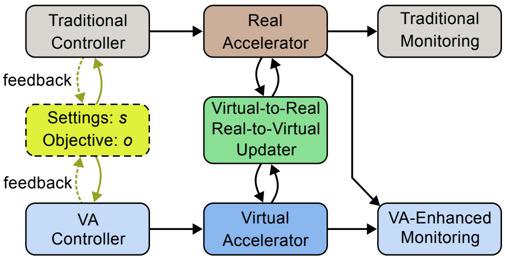


Figure 2: Digital twin workflow for particle accelerator operation enhanced by virtual accelerator. Adapted from [3].

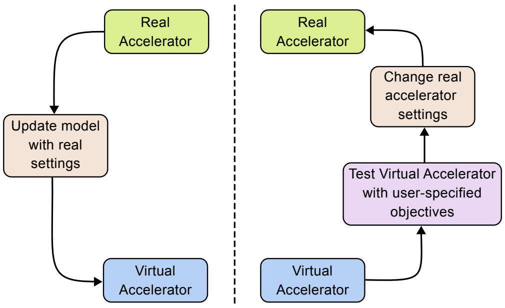


Figure 3: Two modes of a digital twin system: monitor mode or digital shadow (left), and control mode (right). Adapted from [3].

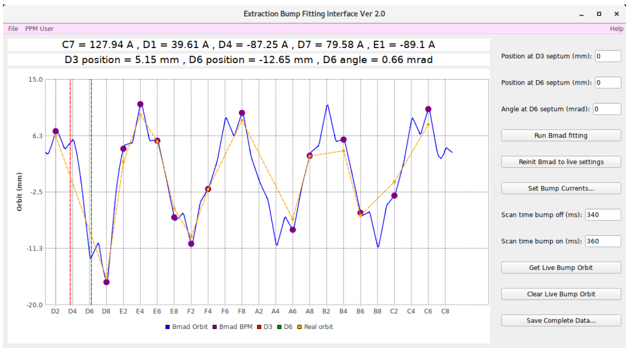
work allows models traditionally used for offline analysis to function as persistent operational tools, supporting machine studies and tuning activities without requiring specialized modeling expertise or dedicated beam time.

BOOSTER EXTRACTION BUMPS

Beam is extracted from the Booster to the NSRL beam line via resonant slow extraction. During the extraction process, the Booster equilibrium orbit is locally distorted to bring the coasting beam closer to the D3 and D6 septa without striking other apertures. This local orbit distortion (bump) is produced by exciting the back-leg windings of five Booster dipole magnets located at C7, D1, D4, D7, and E1 [6].

The Booster extraction regime operates under significant diagnostic and timing constraints, making routine model-based bump optimization historically unavailable. Therefore, we developed a digital twin application to facilitate tuning the five bump magnets. Upon launch, the interface reads the beam parameters and the five bump magnet currents from the live machine and loads them into the model, providing a virtual diagnostic of the real-time differential bump orbits. Figure 4 shows the DT GUI displaying the operational extraction bump for 1 GeV/n protons.

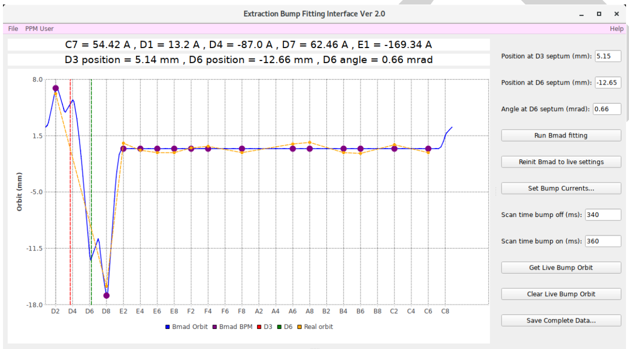
The DT application parametrizes the extraction bump using three user-defined constraints: the horizontal position at D3, and the horizontal position and angle at D6. From these constraints, the required kicks of the five bump magnets are obtained by solving the linear closed-orbit response of the lattice. If the user is satisfied with the optimized orbit, the model-suggested currents can be applied to the real machine.



C7 = 127.94 A , D1 = 39.61 A , D4 = -87.25 A , D7 = 79.58 A , E1 = -89.1 A
D3 position = 5.15 mm , D6 position = -12.65 mm , D6 angle = 0.66 mrad

Position at D3 septum (mm): 0
Position at D6 septum (mm): 0
Angle at D6 septum (mrad): 0
Scan time bump off (ms): 340
Scan time bump on (ms): 360

Figure 4: Digital twin interface used during live extraction tuning, showing model-predicted orbit responses (blue) and measured bump residuals (orange) used to guide operator adjustments.



C7 = 54.42 A , D1 = 13.2 A , D4 = -87.0 A , D7 = 62.46 A , E1 = -169.34 A
D3 position = 5.14 mm , D6 position = -12.66 mm , D6 angle = 0.66 mrad

Position at D3 septum (mm): 5.15
Position at D6 septum (mm): -12.65
Angle at D6 septum (mrad): 0.66
Scan time bump off (ms): 340
Scan time bump on (ms): 360

Figure 5: Digital twin interface used for Booster extraction bump tuning, illustrating the model-predicted bump orbit (blue) and the corresponding minimized residual orbit observed (orange) after applying the DT-derived settings to the machine.

Figure 5 shows the DT interface after applying the model-recommended bump settings to the machine, producing a closed bump with minimized residual orbit distortion throughout the Booster ring. Reducing unintended orbit excursions improves operational robustness by decreasing sensitivity to aperture limitations and mitigating parasitic losses outside the extraction region. In routine operation, the DT interface substantially simplifies bump tuning by providing immediate visibility into residual-orbit behavior, thereby reducing reliance on empirical trial-and-error adjustments necessitated by limited diagnostics.

NSRL BEAM LINE

The NSRL beam line consists of three dipoles (RD1–RD3) forming a 20° bend, nine quadrupoles (RQ1–RQ9), two octupoles (Oct1 and Oct2), and four in-vacuum segmented wire ionization chambers (SWICs, or “multi-wires”: MW063, MW090, MW158, and MW188), as shown in Fig. 6. It is designed to produce a 1–20 cm diameter beam spot on the target. The ion beams are stripped by foils with adjustable thickness before reaching the D6 septum. The two octupoles, located upstream of RQ5 and RQ6, transform a Gaussian-like beam distribution into a uniformly distributed rectangular cross section in both planes. Figure 7 presents the uniform beam image and its projections for 480 MeV/n iron. Beam uniformity is quantified as the root mean square

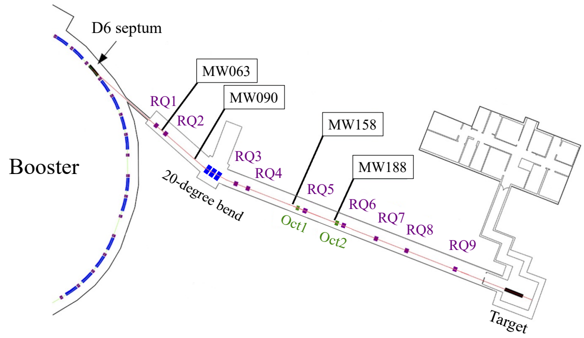


Figure 6: Schematic drawing of the NSRL beam line showing different magnet components and multi-wires. Adapted from [6].

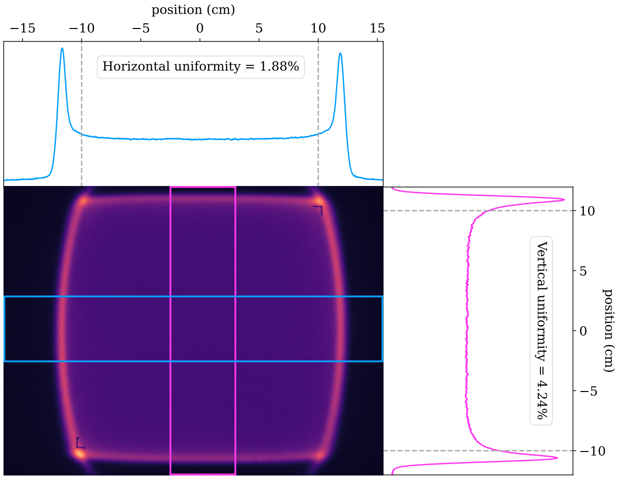
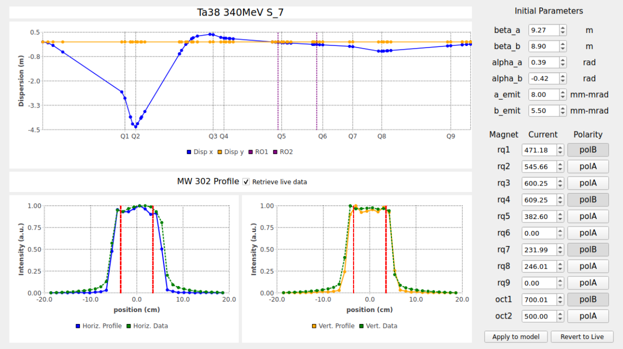


Figure 7: Two dimensional 20 × 20 cm beam image at the NSRL target. The horizontal and vertical projections of the beam distribution and the calculated uniformity are shown on the top and right sides of the image.

(RMS) deviation of the beam intensity within the central uniform region, with values of ≤ 5 % routinely achieved in NSRL experiments.

The DT GUI interface for the NSRL beam line provides tuning assistance and virtual diagnostics. The underlying physics model of the NSRL DT is based on the newly developed SciBmad [5], which is not only faster than traditional Bmad programs but also differentiable, a key feature for integrating machine learning techniques [7]. Upon launch, the interface reads beam parameters and magnet currents from the live machine and updates the SciBmad model accordingly, providing a virtual diagnostic of the dispersion along the NSRL line and the transverse beam profiles at the target (MW302).



Initial Parameters

beta_a 9.27 m
beta_b 8.90 m
alpha_a 0.39 rad
alpha_b -0.42 rad
a_emit 8.00 mm-mrad
b_emit 5.50 mm-mrad

Magnet	Current	Polarity
rq1	471.18	polB
rq2	545.66	polA
rq3	600.25	polA
rq4	609.25	polB
rq5	382.60	polA
rq6	0.00	polA
rq7	231.99	polB
rq8	246.01	polA
rq9	0.00	polA
oct1	700.01	polB
oct2	500.00	polA

Figure 8: NSRL line digital twin interface displaying simulated dispersion and a comparison between simulated (blue and orange) and measured (green) transfer beam profiles at the target (MW302).

Figure 8 shows the DT GUI displaying the NSRL optics and beam profiles for 340 MeV/n Tantalum. Users can retrieve live profile data from MW302 when the beam is not blocked by testing materials, enabling comparison and calibration of the simulation model's initial conditions. While operators have achieved a nearly achromatic beam line through empirical tuning, the absence of direct dispersion diagnostics made this process opaque and difficult to reproduce. The DT interface provides visibility into these hidden quantities, thus enabling more systematic and transferable tuning strategies.

Future developments will incorporate dipole correctors and trajectory reconstruction. The NSRL beam line exhibits a non-zero raw orbit whose origin is under investigation, potentially arising from alignment and geometric effects between the Booster extraction region and the transport line. Extending the DT to include orbit response and correction will improve model fidelity and enable exploration of data-intensive optimization strategies

CONCLUSION

In this work, we developed and deployed digital twin systems to support beam tuning and virtual diagnostics for the NSRL beamline. The framework integrates physics-based accelerator models with live machine settings and operator-facing interfaces, enabling a continuously synchronized representation of the accelerator. This architecture offers a scalable path toward more reproducible operation, reduced reliance on empirical procedures, and tighter integration between accelerator physics models and real-time machine control.

REFERENCES

[1] N. Tsoupas *et al.*, "Uniform beam distributions at the target of the NASA Space Radiation Laboratory's beam line", *Phys. Rev. Spec. Top. Accel. Beams*, vol. 10, no. 2, p. 024701, Feb. 2007. `doi:10.1103/PhysRevSTAB.10.024701`

[2] National Academies of Sciences, Engineering, and Medicine, *Foundational Research Gaps and Future Directions for Digital Twins*. Washington, DC: The National Academies Press, 2024. `doi:10.17226/26894`

[3] T. Miceli, A. Pathak, and A. Sauers, "Twinac: A Universal Framework for Virtual Accelerator Controls", 2025. `doi:10.48550/arXiv.2507.20493,`

[4] D. Sagan, “Bmad: A relativistic charged particle simulation library”, *Nucl. Instrum. Methods Phys. Res. A*, vol. 558, no. 1, pp. 356–359, 2006. doi:10.1016/j.nima.2005.11.001

[5] M. Signorelli, D. Sagan, G. Hoffstaetter, and J. Devlin, “SciBmad: A differentiable and high performance software library for particle accelerator design, nonlinear analysis, simulation, and machine learning”, presented at IPAC’26, Deauville, France, May 2026, paper THP5325, this conference.

[6] K. Brown *et al.*, “The NASA Space Radiation Laboratory at Brookhaven National Laboratory: Preparation and delivery of ion beams for space radiation research”, *Nucl. Instrum. Methods Phys. Res. A*, vol. 618, pp. 97–107, 2010. doi:10.1016/j.nima.2010.02.276

[7] J. Kaiser, C. Xu, A. Eichler, and A. Santamaria Garcia, “Bridging the gap between machine learning and particle accelerator physics with high-speed, differentiable simulations”, *Phys. Rev. Accel. Beams*, vol. 27, no. 5, p. 054601, May 2024. doi:10.1103/PhysRevAccelBeams.27.054601