

DRAMATICALLY REDUCING BEAM LOSSES AT BNL 200 MeV H- LINAC*

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Abstract

The Brookhaven National Laboratory (BNL) 200 MeV Drift Tube Linac (DTL) operates at 6.67 Hz, delivering H⁻ beams for both the polarized proton program at RHIC and isotope production at BLIP. Over the past two decades, targeted upgrades—especially within the low-energy and medium-energy beam transport (LEBT and MEBT) sections—have dramatically enhanced linac performance. Beam transmission for high-current isotope production has improved by more than 100%, while transverse emittance has been halved for polarized proton operation. Moreover, beam losses have been reduced by three orders of magnitude, significantly lowering radiation levels and enabling higher current delivery. These upgrades translate into increased beam intensity to BLIP and superior quality and stability to RHIC, marking a transformative step for the linac's long-term operational reliability and scientific output.

INTRODUCTION

The Brookhaven National Laboratory (BNL) 200 MeV Drift Tube Linac (DTL) has been in continuous operation since its commissioning in November 1970. Originally designed for 100 mA peak current, 200 μ s pulse lengths, and 10 Hz repetition rate, the linac has undergone extensive upgrades over five decades to meet the evolving demands of the BNL accelerator complex. [1] Today, the linac delivers H⁻ beams at 6.67 Hz and 200 MeV in support of two primary programs: the polarized proton program at the Relativistic Heavy Ion Collider (RHIC) and the Brookhaven Linac Isotope Production (BLIP) facility. These programs impose distinct operational requirements: **RHIC Program:** 200 MeV energy, \sim 400 μ A current, 300 μ s pulse length; primary goals are to maximize polarization and minimize transverse emittance. **BLIP Program:** 66- 200 MeV energy range, \sim 600 μ s pulse length, beam current up to 60 mA; emphasis is on uniform beam delivery to the target with minimal beam losses. This paper highlights the beam loss performance of the linac, emphasizing recent upgrades that have enabled high-current, low-loss operation critical for both scientific research and medical isotope production.

BNL 200 MeV LINAC HISTORY

Initially designed for 100 mA proton beams with low emittance, early designs used a 750 keV C-W pre-injector and an 8.5 m beamline with eight triplets and two bunchers.

Particle simulations revealed that matching and quadrupole focusing were critical in limiting emittance growth, primarily occurring in the first tank (10 MeV). Capture efficiency was \sim 65-70%. [2,].

In 1982 switching to H⁻ operation increased the intensity in the AGS, while decreasing the linac output.

With the RFQ integration in 1989, the new LEBT and 7 m MEBT introduced choppers, diagnostics, and dipoles for polarized beam handling. However, beam quality suffered due to constraints on longitudinal beam size, which expanded to $\pm 120^\circ$ near the bunchers. This led to sensitivity to RF amplitude/phase at 200 MeV, although no clear transmission improvement was observed. [3, 4]

The 1996 linac RF and power systems were upgraded to 7.5 Hz, 550 μ s pulses [5]. The LEBT was shortened, and solenoids repositioned to better match into the RFQ. These changes improved RFQ transmission by 10% and reduced emittance by 20%. To address MEBT matching issues, a PMQ was added at the RFQ flange. Combined with repositioned diagnostics and quadrupoles, this led to 50% better transmission and 45% lower emittance, though Tank 1 still exhibited \sim 40% beam losses [6].

In 2000, the OPPIS polarized source was integrated, and the MEBT dipole replaced with a spin rotator [7]. In 2008, a major reconfiguration reduced MEBT to 70 cm and adjusted the LEBT to \sim 4.5 m [8]. This included collimators, choppers, neutralization via Xe gas, and additional steerers and solenoids. Resulting losses dropped to \sim 30-35%, and transverse emittance was reduced by 65% [9].

A 2010 redesign shifted the high-intensity source upstream with a 45° bend. The new 2 m LEBT included two solenoids, quadrupoles, steerers, a dipole, and a chopper. Transmission improved by 30%, raising BLIP average current from 80 to 110 μ A [10, 11]. A second source was added in 2019 at -45° [12].

These upgrades yielded a 25% reduction in RHIC emittance at collision energy and widespread loss reduction. Figure 1 shows the present layout of the LEBT and MEBT, two unpolarized and polarized source sending beam to single RFQ. source can be change at rate of 10 Hz.

Now linac is delivering the highest average current to BLIP while maintaining minimum losses since it was built in 1970. Figure 2 summarizes maximum average intensity of the BNL H⁻ linac over 55 years.

Figure 3 shows a comparison of the beam footprint at the BLIP target before and after the upgrade after 2010. Radiation due to beam losses has been reduced everywhere, compared to before the upgrade.

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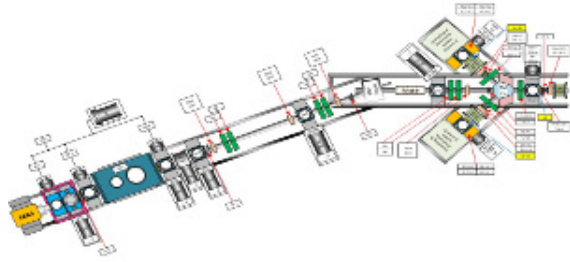


Figure 1: LEBT and MEBT in 2018, two unpolarized and polarized source sending beam to single RFQ. source can be change at rate of 10 Hz.

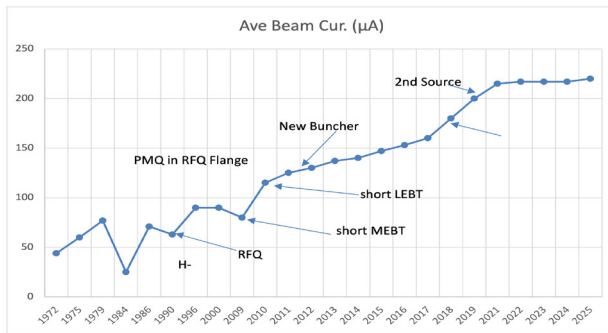


Figure 2: Maximum average intensity of the BLIP 200 MeV linac.

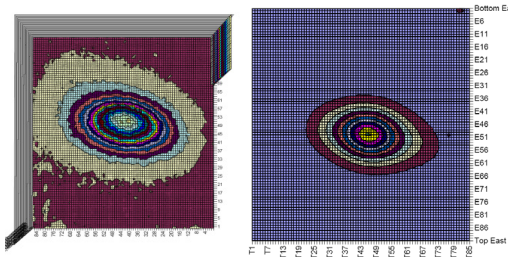


Figure 3: Beam footprint at the BLIP target (left), before and (right), after reconfiguration of LEBT/MEBT in 2010 showing the same number of contours.

BEAM LOSSES IN THE BNL LINAC

Beam losses in the BNL H^- linac can be categorized into two primary types: **Continuous losses:** These include mechanisms such as residual gas stripping, intra-beam stripping (IBSt), magnetic field stripping, photodetachment, and beam halo/tail losses. **Occasional losses:** These are caused by equipment failures, such as RF system faults or ion source issues.

Continuous Losses

There are several continuous beam loss mechanisms of interest in high-intensity H^- linacs:

(a) Beam Halo and Tail Losses: Historically, beam halo and tail have been major contributors to beam loss in the BNL linac. This is due to technological constraints and mismatched beam injection into the DTL, often resulting

from the varying demands of different operational programs.

(b) Residual Gas Stripping: Beam losses occur due to single-electron ($H^- \rightarrow H^0$) or double-electron ($H^- \rightarrow H^+$) stripping through interactions with residual gas molecules. These cross sections scale inversely with the square of the beam velocity ($\sim 1/\beta^2$) [13]. At BNL, residual gas stripping is currently the dominant beam loss mechanism. The cross section for double stripping is about 4% of the single-stripping cross section.

(c) Intra-Beam Stripping (IBSt): IBSt occurs when H^- ions lose electrons through Coulomb interactions with neighboring particles in the beam [14]. This results in H^0 or H^+ formation, leading to unconfined particle losses. The IBSt loss rate is proportional to the square of the beam density. In the BNL linac, IBSt-related losses are approximately an order of magnitude lower than those from residual gas stripping.

(d) H^+ Capture and Acceleration: H^+ ions formed through double-stripping events can be captured and accelerated along with the intended H^- beam. This mechanism contributes beam losses that are two orders of magnitude lower than residual gas stripping in the BNL linac [15].

(e) Magnetic Field Stripping: In the rest frame of the H^- ion, magnetic fields are Lorentz-transformed into electric fields. At high enough field strengths, these can strip electrons. However, for the BNL linac, this effect is negligible, with estimated fractional losses on the order of 10^{-13} per meter [16].

(f) Photodetachment: Black-body radiation can also induce electron stripping, though this mechanism is insignificant at the beam energies used in current H^- linacs [17].

Occasional Losses

RF system failures account for more than 95% of beam trips and require continuous monitoring. The remaining trips are typically attributed to ion source faults.

BEAM LOSS MITIGATION

Beam Halo and Tail

Lattice Modifications An ideal match between the RFQ and DTL could have been achieved using a $5\beta\lambda$ -long FODO lattice, with quadrupole spacing of approximately $1\beta\lambda$ and at least two bunchers [9]. However, requirements for beam chopping and polarized beam injection necessitated a triplet lattice configuration. This mismatch primarily impacted the longitudinal plane in the MEBT, while the transverse plane was adequately tuneable through independently adjustable DTL quadrupoles [18].

Both RFQ and DTL use FODO lattices with $\beta\lambda \approx 6$ cm and short focusing periods of 6-12 cm. In contrast, the MEBT incorporated drift spaces 15-20 times longer to accommodate chopper, dipole, and diagnostics, expanding the aperture from ~ 1 cm (RFQ) to ~ 10 cm (MEBT), and then contracting to 2 cm (DTL).

Longitudinal mismatch was exacerbated by limited focusing from only three unequally spaced bunchers. The bunch length grew more rapidly than the transverse beam

size, due to longer longitudinal focusing periods and non-linear sinusoidal restoring forces, which caused beam losses at higher energies [8]. Additional mismatches existed between DTL tanks due to 0.6-1 m drift introducing discontinuities in longitudinal focusing. Modern linacs effects by adjusting the synchronous phase of cells at tank boundaries [19]. Cumulative upgrades to the LEBT and MEBT have reduced DTL beam losses to a few percent.

Collimation To reduce beam halo entering the DTL, a graphite collimator (0.8×1.6 cm) was installed at the DTL entrance (see Fig. 4).

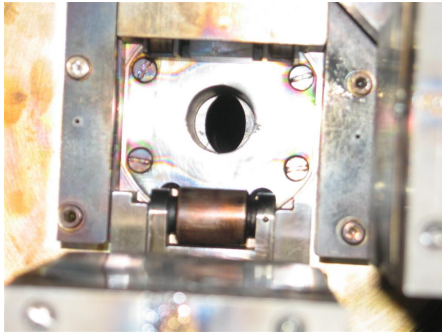


Figure 4: Graphite collimator AT entrance of the Tank1.

Beam Tuning

Implementation of new neutron loss monitors and iterative simulations using live lattice parameters further reduced beam losses to the 10^{-5} level. Currently, the dominant loss mechanism is H^- stripping due to residual gas. Figure 5 shows emittance reduction in PARMILA simulations using operational lattice settings.

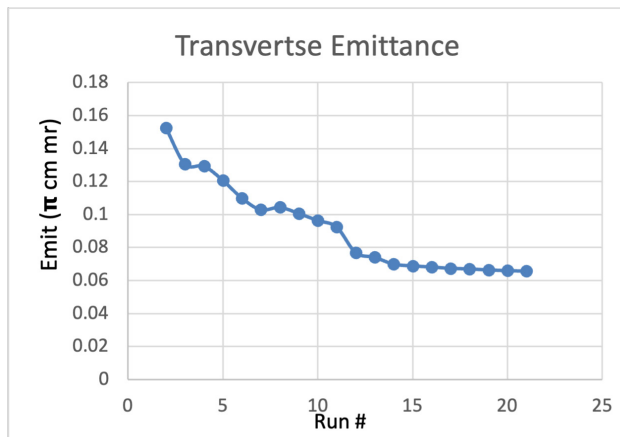


Figure 5: Emittance reduction in PARMILA simulations using iterative operational lattice settings.

Gas Stripping of H^-

To mitigate beam loss from residual gas stripping, all 50-year-old ion pumps in the linac were replaced in 2020 with new ion pumps integrated with NEG pumps and modern control systems. This improved base pressure to $\sim 1 \times 10^{-7}$ Torr.

Doubly Stripped H^+

H^- ions can convert to protons via two mechanisms: (1) direct double electron stripping ($H^- \rightarrow H^+$) and (2) a two-step process: (a) $H^- \rightarrow H^0$ followed by (b) $H^0 \rightarrow H^+$. Counterintuitively, the proton fraction scales approximately as x^2 , where x is pressure. Most protons are generated in the LEBT, where the pressure ($\sim 3 \times 10^{-6}$ Torr) enhances beam pulse shaping and current. Protons formed in the low-energy section are captured 180° out of phase in the RFQ and accelerated to full energy. After exiting the 200 MeV DTL, they are bent in the opposite direction of the H^- beam by the first bending magnet (BM1). The estimated H^+ fraction reaching BM1 is $\sim 1.7 \times 10^{-7}$, while linac losses due to this process are two orders of magnitude lower. In 2018, a vacuum leak was attributed to these protons [15]. As shown in Fig. 6, a new vacuum chamber will be installed in the next run with proton beam dump which will be able to measure the intensity of doubly stripped proton.

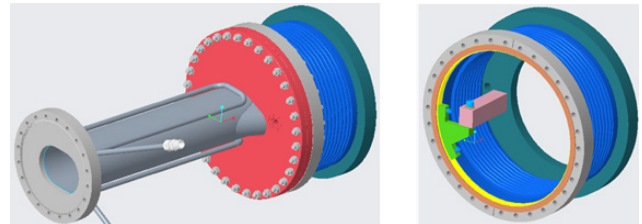


Figure 6: Model of the BM1 vacuum chamber with bellow containing doubly stripped proton dump.

Equipment Failure

To mitigate RF-related beam trips, the following system upgrades were made: (a) Replacement of 5 kW peak power amplifiers with solid-state units, (b) pressurized coax, (c) Migration from TTL/analogue to digital low-level RF (LLRF) controls, (d) Integration of pulsing logic, RF malfunction diagnostics, tank and timing control, (e) Implementation of real-time fault warnings and automated system recovery, (f) New timing system, (g) Vacuum ion pump replacement.

DISCUSSION

The primary beam losses in the BNL linac were historically due to mismatched injection conditions, largely driven by changes in front-end technologies (e.g., from Cockcroft-Walton to RFQ) and varying demands from user programs. These mismatches were corrected through a series of upgrades: 1970: Linac commission, 1977: 5 Hz Operation, 1984: switch to H^- , 1986: add polarized H^- source, 1989: RFQ installation, 1996: Shortened LEBT, 6.67 Hz Operation, 2000: Addition of the polarized OPPIS source, 2008: Shortened MEBT and Xe-based H^- space-charge neutralization [20], 2009: Further shortened LEBT, 2012: New MEBT buncher, 2018: Second high-intensity ion source, 2023: High-power supply upgrade for the MEBT buncher.

These cumulative modifications have reduced continuous beam losses in the linac to the percent level. Further reduction was achieved through installation of highly

sensitive neutron loss monitors and iterative beam simulations using real-time lattice data. Current beam losses are on the order of 10^{-5} , primarily attributed to residual gas stripping.

Figure 7 shows the beam power delivered to BLIP, illustrating nearly an order-of-magnitude increase over prior years.

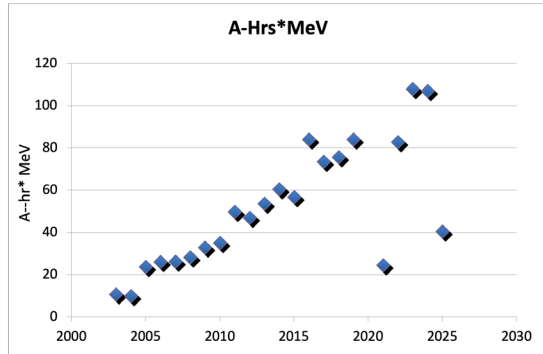


Figure 7: Beam power in unit of A-Hrs* MeV over the years.

Figure 8 presents measured residual radiation dose rate in units of mrem/h measured after four hours of beam operation. In recent years, residual radiation dose rate has remained below 1 mrem/h. Figure 9 depicts beam power lost per meter due to the residual gas tripping of the H^- along the BNL linac based on the measured pressure in the DTL Tanks. Figure 10 shows the estimated, $(0.33P_{\text{Lost}}(E-9)^{1.8}/E)$ residual dose rate in unit of mrem/h along the linac which is in excellent agreement with measured values.

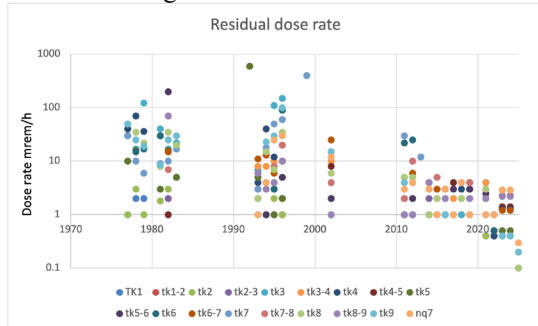


Figure 8: Residual radiation dose rate (mrem/h) measured after four hours of beam operation.

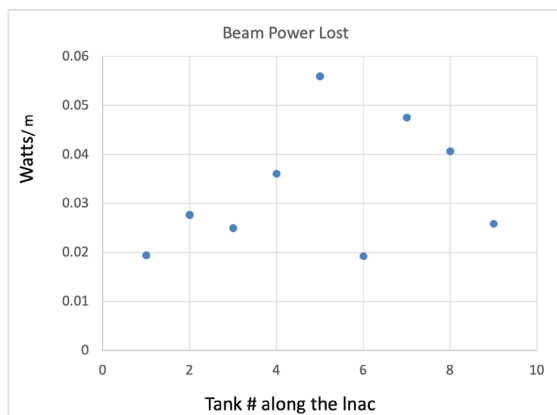


Figure 9: Beam power lost due to gas tripping of H^- along the linac.

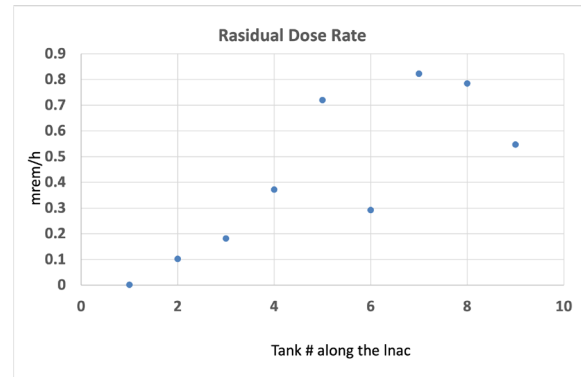


Figure 10: Calculated residual dose rate due to gas stripping of H^- along the linac.

Overall, radiation dose rates in the linac have decreased by approximately three orders of magnitude. When coupled with the increased beam power, this represents a four-order-of-magnitude reduction in fractional beam losses, achieving loss levels near 10^{-5} while maintaining linac availability above 95%.

Due to these exceptionally low radiation levels, the linac tunnel was recently reclassified from a High Radiation Area to a Radiation Area.

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