BEAM PERFORMANCE OF THE POSITRON TRANSPORT LINE FOR THE CEBAF POSITRON UPGRADE*

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Abstract

The Low Energy Recirculator Facility (LERF), formerly used for the Free Electron Laser program, has been proposed as the injector site for the planned 12 GeV CEBAF positron upgrade (Ce^+BAF). The 123 MeV positron transport line from LERF to the North Linac spans 872.5 m and is designed using a combination of FODO cells and Double-Bend Achromat (DBA) arcs, keeping transverse beta functions below 130 m and horizontal dispersion within ±0.3 m. Multi-particle tracking with ELEGANT demonstrates nearly complete transmission (>99%) to the North Linac for nominal beam parameters, while spin tracking with BMAD confirms a total spin rotation of approximately 100° in good agreement with analytical predictions. A systematic 6D acceptance study for Ce^+BAF shows that transmission above 70% requires a normalized transverse emittance $\epsilon^n_{x,y} < 100$ mm·mrad, an rms bunch length $\sigma_z < 1$ mm, and an rms momentum spread $\Delta p/p < 0.5\%$.

INTRODUCTION

The CEBAF 12 GeV positron upgrade (Ce^+BAF) plans to reuse the Low Energy Recirculator Facility (LERF) building, formerly hosting the JLab FEL program, as the host for a positron source and pre-accelerator. Positrons generated on a high-Z target by an electron driver are captured and accelerated in LERF to 123 MeV [1–3]. They must then be transported from the LERF to CEBAF and injected into the final chicane dipole of the existing electron injector.

The transport line that connects LERF to CEBAF must meet two main constraints, first: it must fit within the existing CEBAF tunnel, leaving sufficient egress for personnel and maintenance, and second: it must accept a positron beam whose transverse and longitudinal emittances are roughly two orders of magnitude larger than those of the CEBAF electron beam. The same transport line is also considered to deliver 650 MeV electrons from the LERF to CEBAF for the 22 GeV FFA@CEBAF upgrade [4, 5], requiring common beamline components and demands bipolar power supplies for transporting either electrons or positrons. This contribution summarizes the optics solution adopted for this transport line, the multi-particle and spin-tracking performance, and the resulting six-dimensional acceptance limits for Ce^+BAF.

LAYOUT AND OPTICS

The 872.5 m transport line is suspended from the tunnel ceiling along the inner tunnel wall of the CEBAF ring, opposite the existing CEBAF accelerator located on the outer radius of the ring. It merges into the CEBAF accelerator at the entrance to the North Linac by mirroring the last two dipoles of the present electron injector chicane (Fig. 1). Bipolar power supplies on every dipole and quadrupole make it usable for both 123 MeV positrons and for 650 MeV electrons. The beamline consists of four functional blocks: (i) a vertical and horizontal LERF-to-South matching section that closes both transverse dispersions; (ii) a 14-cell horizontal FODO South straight optimized to minimize the quadrupole count while keeping the $|\mathrm{Tr}(M_{\mathrm{cell}})| < 2$; (iii) a 180° West arc built from Double-Bend Achromat (DBA) cells; and (iv) a NL merger that suppresses both transverse dispersions and simultaneously matches the Twiss parameters at the injector chicane for either 123 MeV positron or 650 MeV electron operation.

For the DBA cell the horizontal phase advance between the two dipole centers is set to $\mu_x = \pi$, which is the standard DBA achromat condition that simultaneously closes the horizontal dispersion and its derivative. ELEGANT [6] returns $\mu_x \approx 3.135$ rad for the cell, i.e. within 0.2% of π, confirming that the cell is achromatic to numerical precision. The full optics is shown in Fig. 2: the beta functions remain less than 130 m through the entire 872.5 m line, and the horizontal dispersion is maintained within ±0.3 m.

The dipoles are 1-m-long sector bends and the quadrupoles are 15-cm normal-conducting magnets, scaled from standard CEBAF designs [7] perform at both 123 MeV and 650 MeV. The bend apertures are 104 mm gap arc-zero dipoles with pole width of 20 cm to accommodate the sagittas for all applications in the arc, including the final vertical dipole which deflects beam to the North Linac injection point.

MULTI-PARTICLE TRACKING

Multi-particle tracking has been performed in ELEGANT with 10^4 macroparticles drawn from a non-truncated Gaussian distribution using the nominal Ce^+BAF capture parameters. The transmission from the LERF exit to the NL is 99.7%; the rms bunch length grows from 0.5 mm to 1.7 mm and the normalized transverse emittances from 31/31 to 50/34 mm·mrad in the horizontal/vertical planes. The bunch-length elongation follows from the unchirped longitudinal transfer

$$\sigma_{z,\mathrm{out}} = \sqrt{(1 + R_{56}\, h)^2 \sigma_z^2 + (R_{56}\sigma_{\delta_0})^2}, \qquad (1)$$

with $R_{56} = 0.284$ m at the NL injection point. An alternative optics solution with a smaller (and even negative) R_{56} is also

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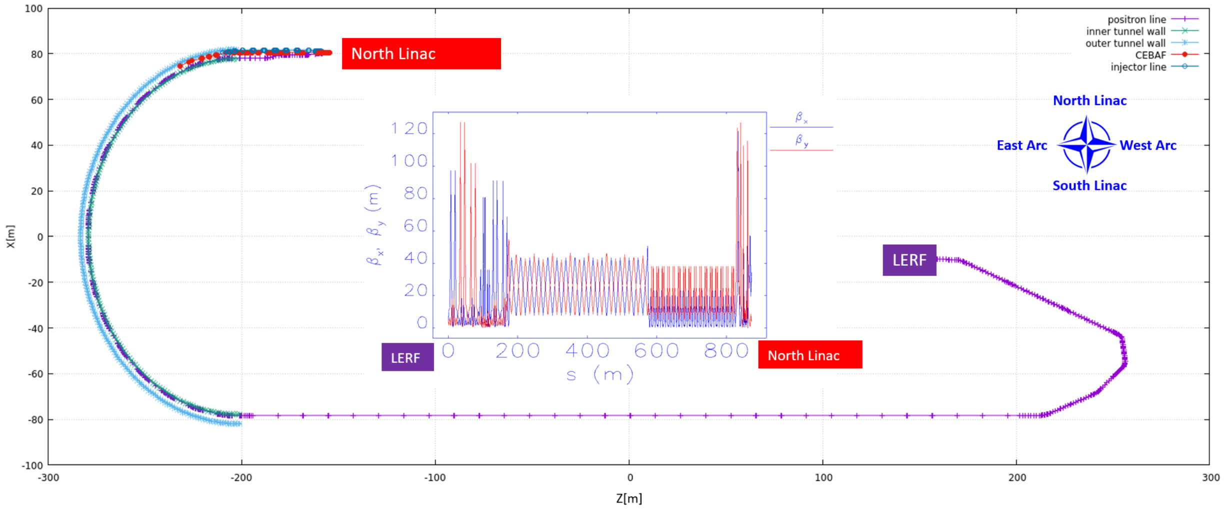

Figure 1: Overall layout of the LERF→NL positron transport line (purple) on top of the CEBAF tunnel footprint, with the existing CEBAF accelerator (red) and the inner/outer tunnel walls (cyan/light green). Inset: horizontal and vertical beta functions over the full 872.5 m.

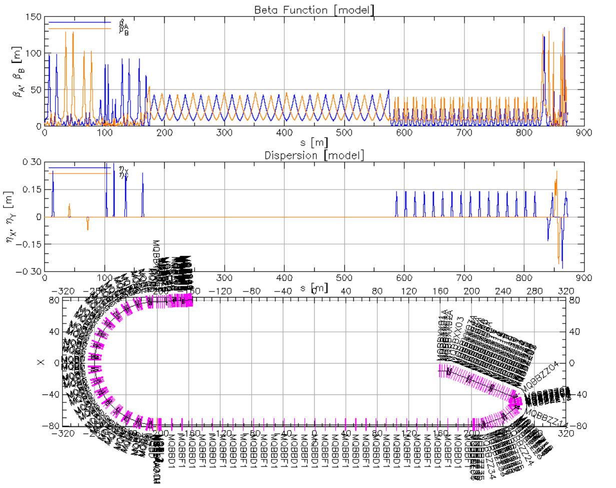

Figure 2: Periodic optics of the transport line from ELEGANT. Top to bottom: $\beta_{x,y}$, $\eta_{x,y}$, and the physical footprint (FODO South, DBA West, NL merger).

developed; the chosen optics provides a smaller transverse dispersion and thus a more transmission margin.

A tracking study simulated the injected positron beam through five recirculation passes of CEBAF to experimental Hall C with an energy of 11 GeV. The transmission to Hall C is 76.5% for the nominal capture parameters. Furthermore, the longitudinal phase space at extraction (Fig. 3) shows a 3 ps rms bunch length on top of an rms momentum spread of 4.5×10^{-4}. This spread is dominated by the energy chirp acquired in the linacs and the path-length spread through the high-energy arcs.

The transverse normalized emittances and the longitudinal beam sizes (σ_5: rms bunch length, σ_6: rms momentum spread) from the LERF to Hall C are shown in Fig. 4. The spikes in the bend sections originate partly from the ELEGANT sigma-matrix coordinate transformations through dispersion-

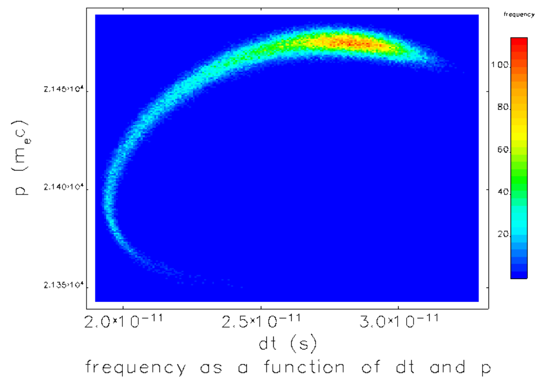

Figure 3: Longitudinal phase space at the Hall C extraction point after five passes through CEBAF.

coupled elements; the residual growth at the start of each acceleration pass reflects genuine chromatic and energy-position correlations. Synchrotron radiation is included with bend slicing; collective effects are not included at this stage.

Spin Tracking

The ELEGANT optics has been converted into a BMAD [8] deck, where dispersions and their derivatives are matched to better than 1 µm. Spin tracking is then performed using BMAD's integrated T-BMT solver, the same workflow used for the FFA@CEBAF spin- and tune-evolution studies [9]. The expected spin precession through the line is $\theta_s = a\gamma\,\phi_{\text{dipole}}$ with $\phi_{\text{dipole}} = 360°$ and $a\gamma \simeq 0.279$ at 123 MeV, giving $\theta_s \simeq 100°$. For a fully longitudinally polarized injected beam ($s_z = 1$), the BMAD simulation returns $\langle s_x\rangle \approx -0.99$, $\langle s_y\rangle \approx 0$, $\langle s_z\rangle \approx -0.17$, i.e. $\theta_s \simeq 99.7°$. This is an excellent agreement with the analytical estimate.

Ce$^+$BAF ACCEPTANCE

The dominant transmission limitation is not within LERF→NL transport line but expected due to the exist-

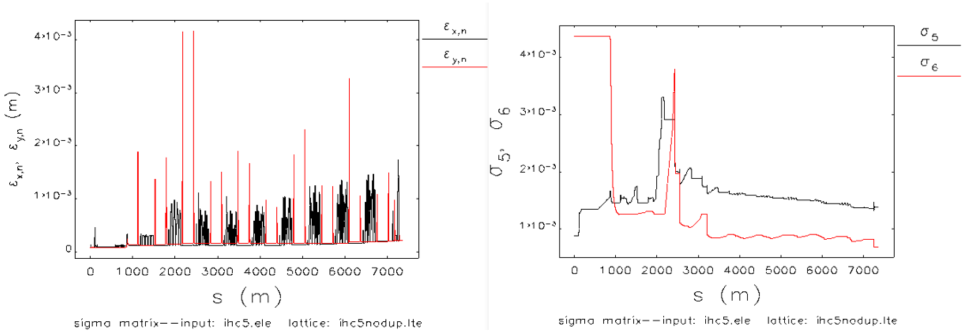

Figure 4: LERF→Hall C tracking with 10^4 macroparticles. Left: $\varepsilon_{x,n}$ (blue), $\varepsilon_{y,n}$ (red). Right: rms bunch length σ_5 (blue) and rms momentum spread σ_6 (red).

ing acceptance of CEBAF. We therefore scan the injected beam over a $(\epsilon_n, \sigma_z, \Delta p/p)$ grid and propagate the resulting beams through the full LERF→Hall C trajectory. The resulting transmission is shown as a 3-D scatter in Fig. 5; a smooth $(\epsilon_n, \Delta p/p)$ slice at nominal σ_z is shown in Fig. 6 and clearly shows the strong sensitivity to the momentum spread.

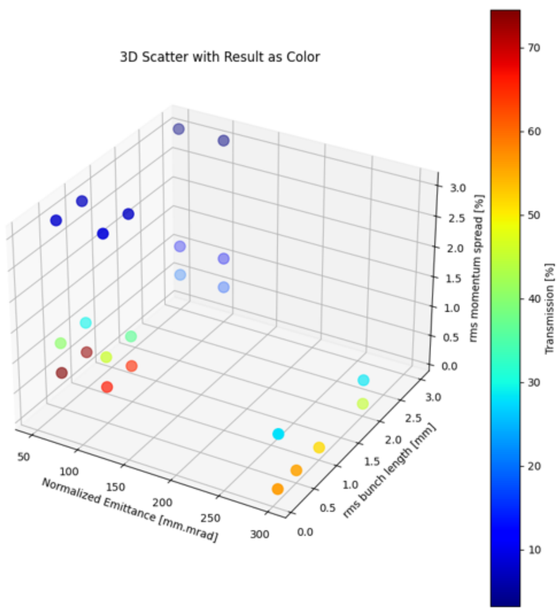

Figure 5: LERF→Hall C transmission as a 3-D scatter over $(\epsilon_n, \sigma_z, \Delta p/p)$; color encodes the transmission [%].

The scan shows that the momentum spread has a much steeper impact on the transmission than either the transverse emittance or the bunch length. For $\sigma_z < 1$ mm and $\epsilon_n < 100$ mm·mrad, transmission $\geq 70\%$ is achieved only for $\Delta p/p < 0.5\%$. The largest single loss source is the first NL cryomodule, where more than 8% of the injected particles are lost due to the transverse beam size and chromatic mismatch. These three inequalities therefore define the design target for the upstream positron capture section [2, 3] and provide the quantitative input for ongoing RF-phase and matching studies in CEBAF [10].

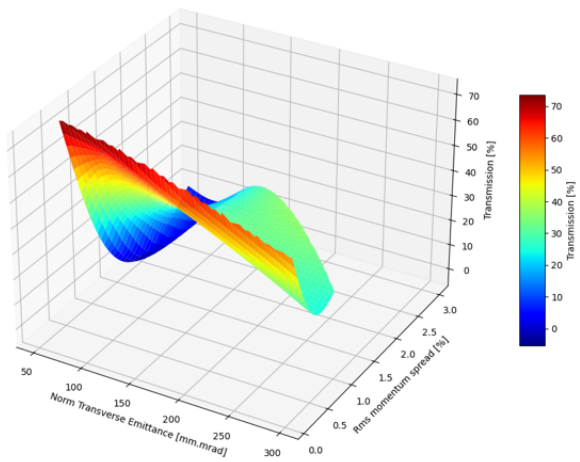

Figure 6: LERF→Hall C transmission vs. normalized transverse emittances and rms momentum spread (nominal σ_z). The momentum spread dominates the loss.

CONCLUSIONS

A 123 MeV positron transport line from LERF to the CEBAF North Linac has been designed within the existing tunnel without obstructing electron operation, and with bipolar power supplies that also enable 650 MeV electron transport for the FFA@CEBAF upgrade. The optics combines a FODO South straight, a DBA West arc and a dispersion-suppressing NL merger, giving $\beta_{x,y} < 130$ m and $|\eta_x| < 0.3$ m over the full 872.5 m. ELEGANT tracking yields >99% transmission to the NL for nominal capture parameters, and BMAD spin tracking confirms a ∼100° spin rotation in agreement with the analytical $a\gamma\,\phi_{\mathrm{dipole}}$ prediction. A 6D acceptance scan identifies the momentum spread as the dominant transmission limitation. The target injector parameters in rms are set to $\epsilon_n < 100$ mm·mrad, $\sigma_z < 1$ mm, $\Delta p/p < 0.5\%$ for $\geq 70\%$ end-to-end transmission to Hall C.

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