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TRANSPORT OF 12 GeV POSITRON BEAMS AT Ce$^+$BAF *

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Abstract

Jefferson Lab (JLab) is developing a concept to upgrade the Continuous Electron Beam Accelerator Facility (CEBAF) to additionally deliver spin-polarized continuous-wave positron beams for its nuclear physics program users (Ce$^+$BAF 12 GeV). The concept involves repurposing the Low Energy Recirculator Facility (LERF) at JLab as a dual injector, first producing 100-300 MeV spin-polarized electron beams which are subsequently used for the generation and formation of 123 MeV continuous-wave positron beams. The positron beams are transported to CEBAF and injected for acceleration up to 12 GeV, tailored to the requirements of its four experimental halls. Given the higher emittance of the secondary positron beams, the CEBAF optics are optimized for low dispersion and low beta functions to enhance transmission within the Ce$^+$BAF acceptance limits and with an R_{56} to manage the positron beams bunch length and energy spread. Potential bottlenecks are being investigated through both optical modeling and measurements using an electron beam, as well as degraded electron beams, to map the 6d acceptance of CEBAF as it is today. This presentation shares preliminary results from multi-particle tracking simulations of the positron beam up to 11 GeV, including spatial, momentum, and spin characteristics, and explores the feasibility of delivering beams simultaneously to multiple experimental halls via extraction optics.

INTRODUCTION

Polarized positron beams are of growing interest in nuclear physics for studies of nucleon structure and two-photon exchange effects. Jefferson Lab (JLab) has demonstrated, through the PEPPo (Polarized Electrons for Polarized Positrons) concept [1], that such beams can be produced, and is now evaluating their acceleration in CEBAF. The proposed Ce$^+$BAF 12 GeV upgrade aims to deliver either low-current, highly polarized positrons (I > 50 nA, P ≈ 60%) or high-current, unpolarized positrons exceeding 1 µA [2]. This trade-off arises from limitations in positron generation and capture efficiency [3]. While CEBAF currently provides a continuous-wave (cw) electron beam, the upgrade would enable cw positron delivery as well. A comparison of current and proposed CEBAF capabilities is shown in Table 1.

Table 1: CEBAF Operational Electron Machine Parameters and Positron Upgrade Plan Comparison

Parameter	Electrons	Positrons
Hall Multiplicity	4	1 or 2
Energy (ABC/D)	11/12 GeV	11/12 GeV
Beam Rep. [MHz]	249.5/499	249.5/499
Duty Factor	100% cw	100% cw
Unpolarized Int.	170 µA	> 1 µA
Polarized Int.	170 µA	> 50 nA
Beam Polarization	> 85%	> 60%
Fast/Slow Helicity Reversal	1920 Hz / Yes	1920 Hz / Yes

CEBAF supports four nuclear physics experiments across Halls A, B, C, and D, delivering electron beams simultaneously to all halls. In contrast, positron beam delivery may be limited by the current extraction system, specifically the septum blade. To address this, beam dynamics studies are ongoing to accommodate the larger positron beam size, and a septum replacement is under consideration. Accordingly, the hall multiplicity listed in Table 1 may change.

The new injector at LERF and its transport line are designed to support both the CEBAF positron upgrade and the planned CEBAF 22 GeV Fixed Field Alternating Gradient (FFA) upgrade [4].

LERF TO NORTH LINAC OPTICS

The positron upgrade plan is being carried out in accordance with not interfering with the current CEBAF electron beam delivery. To illustrate, the positron transport line makes uses of existing facilities and would have a separate electron injector to impinge on the high Z-material, then it would be accelerated up to 123 MeV [3]. Those positrons then would be injected into the CEBAF north linac for further acceleration up to 12 GeV. The layout, generated from the beam optics survey is given in Fig. 1.

The beam optics design positions the transport beamline suspended from the CEBAF tunnel ceiling along the inner wall, opposite the accelerator on the outer wall. The positron injector merges at north linac, mirroring the last two dipoles of the operational CEBAF electron injector. The transport line maintains a clearance ensuring tunnel access during cart operations. The line descends and joins the junction at the last injector chicane dipole, *MBLR04*. Figure 2 shows a 3D optics plot of this merging section generated with Elegant [5].

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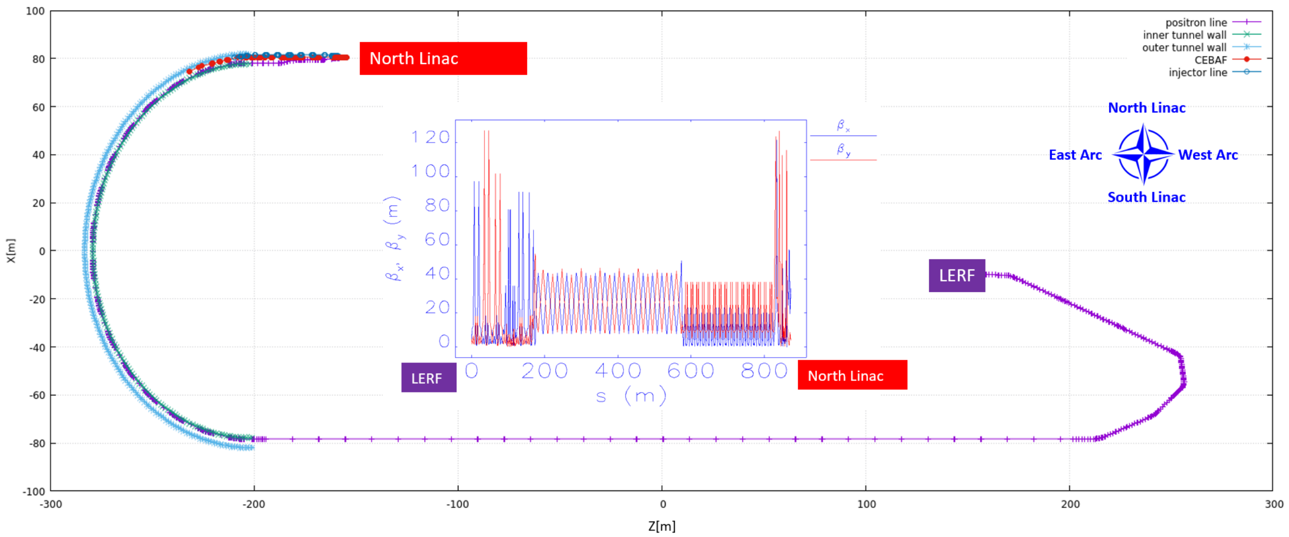

Figure 1: The layout of the positron beamline from LERF to the North Linac is shown in purple, with hyphens indicating the locations of accelerator elements. The actual coordinates of the designed positron transport line and the existing tunnel walls are shown in cyan and light green, respectively. The current CEBAF beamline is indicated in red. The inset displays the beam optics with the transverse β-functions.

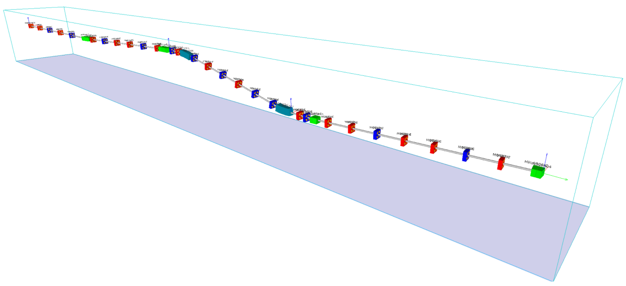

Figure 2: 3D view of the positron transport line descending from the CEBAF tunnel ceiling and bending toward the North Linac. Red and blue rectangles represent focusing and defocusing quadrupoles, cyan rectangles are vertical dipoles, and green rectangles are horizontal dipoles.

The positron transport line optics design represents a practical compromise that enables the connection of the LERF building, the existing tunnel, and CEBAF without necessitating tunnel enlargement or significant structural modifications, while still ensuring efficient transport of a large-emittance positron beam. To meet these requirements, the optics are constrained to maintain the transverse beta functions below 130 m and the horizontal dispersion of ± 0.3 m. As shown in Fig. 1, the beamline incorporates a 180-degree turn, running parallel to the CEBAF west arcs. To accommodate this geometry while maintaining compact β and dispersion functions, the arc is implemented using Double-Bend Achromat (DBA) cells. A representative DBA cell is illustrated in Fig. 3.

The dispersion throughout the positron transport line is presented in Fig. 4.

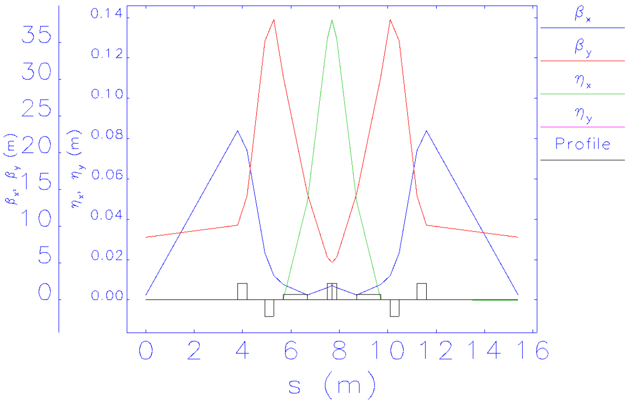

Figure 3: Double Bend Achromat cell designed for the π-turn in the transport line linking the south to the north of CEBAF.

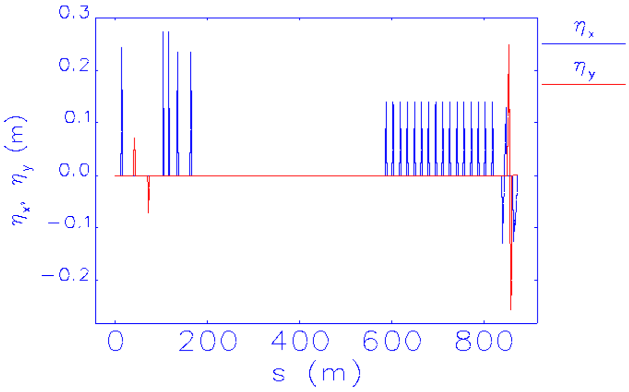

Figure 4: The dispersion function throughout the LERF to the north linac.

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In addition to the large transverse emittance of the positron beam, the longitudinal emittance is also significant. Accordingly, the evolution of the R_{56} element of the transport matrix along the beamline is shown in Fig. 5. At the injection point in the north linac, the matrix element R_{56} is 0.284 m. However, alternative optics solutions have been developed that yield smaller, and even negative, values of R_{56} to enable bunch length compression. Ultimately, the R_{56} profile of the transport line will be adjusted as the project progresses, guided by the longitudinal characteristics of the upstream positron beam [3] and, downstream, by CEBAF acceptance measurements [7].

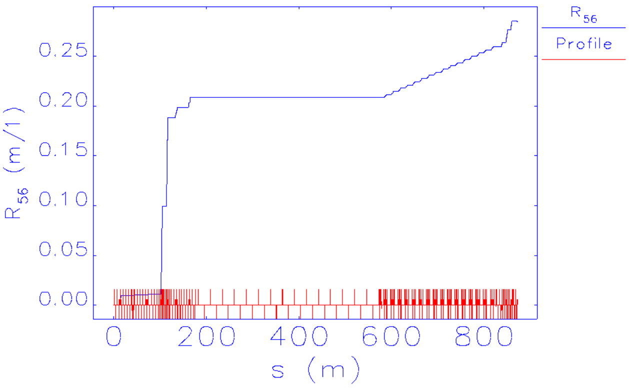

Figure 5: R_{56} evolution through the LERF to NL.

TRACKING IN Ce$^+$BAF

The positron transmission line from LERF to the North Linac (NL) has been optimized using both accelerator codes ELEGANT [5] and BMAD [6]. BMAD was selected for its dedicated spin dynamics tracking capabilities. The analytical expression for the spin rotation angle, θ_{spin}, can be calculated using the relativistic Lorentz factor γ, the anomalous magnetic moment a, and the total bend angle of the particle trajectory, ϕ_{dipole}:

$$\theta_{\text{spin}} = a\gamma\phi_{\text{dipole}}. \tag{1}$$

For the LERF-to-NL line, the total dipole bending angle is $\phi_{\text{dipole}} = 360°$, which yields a spin rotation angle of $\theta_{\text{spin}} \approx 100°$. Assuming an initial longitudinal polarization of $sz = 1$ in BMAD spin tracking simulation using 10000 macro-particles, the spin components are $sx \approx -0.99$, $sy \approx 0$ and $sz \approx -0.17$ which agrees with the analytical calculations, the BMAD result is shown in Fig. 6.

Finally, the positron beam is tracked from LERF through Ce$^+$BAF to Hall C over five passes. The resulting longitudinal phase space is shown in Fig. 7, with initial and final beam parameters summarized in Table 2.

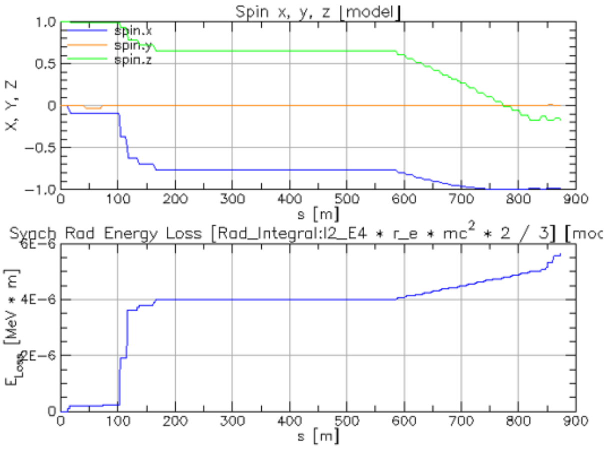

Figure 6: Polarization tracking in LERF to NL transport line using BMAD.

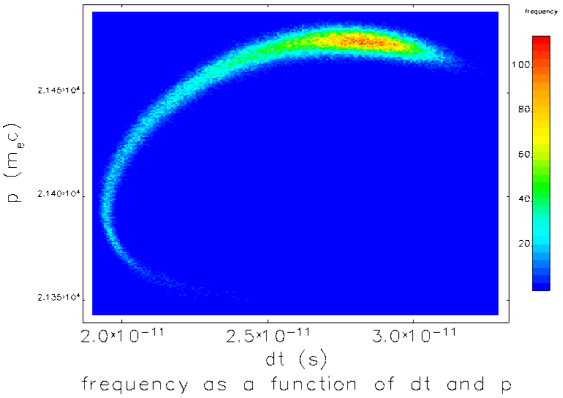

Figure 7: Multi-particle tracking from LERF to Hall C.

Table 2: Initial and Final Tracking Parameters

Parameter	Injected	Extracted
Energy [MeV]	123	10966
Current [nA]	170	114
RMS Momentum Spread [%]	0.6	0.045
RMS Bunch Length [ps]	2	3
Norm. Trans. Emit. [mm.mrad]	40/40†	211/98

†Under optimization.

CONCLUSION

The 123 MeV positron transport line from LERF to the North Linac is developed as part of the 12 GeV positron CEBAF upgrade (Ce$^+$BAF). Designed with bipolar power supplies, this line can transport either 123 MeV positrons for Ce$^+$BAF or 650 MeV electrons for CEBAF 22 GeV FFA upgrade. Minimal new tunnel excavation was required, and the transport line does not obstruct existing CEBAF operations. Stretching 872.5 m, the beamline optics features low beta and dispersion functions, enabling nearly perfect transmission to the North Linac. Additionally, alternative R_{56} optics have been developed to allow longitudinal phase space manipulation as needed.

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