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# OPTICAL DESIGN OF THE CEBAF BEAM TRANSPORT SYSTEM

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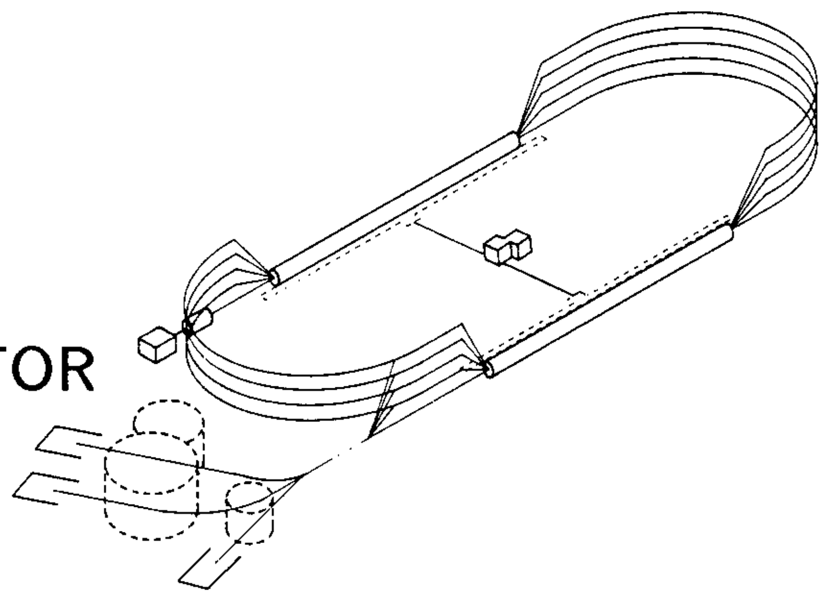

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## Machine Overview

The CEBAF accelerator, a recirculating cw linac, has design values of $0.5 \leq E \leq 4.0$ GeV, $\epsilon = 2 \times 10^{-9}$ m-rad at $E \geq 1$ GeV, with a momentum spread $(\sigma_E/E) = 2.5 \times 10^{-5}$. The conceptual design of this machine has been described elsewhere[1]. As shown in Figure 1, the accelerator consists of a 45 MeV injector, two superconducting cw linac segments, and a recirculator system. Each linac segment provides an energy gain of 0.4 GeV and simultaneously accelerates five beams at different energies. Each beam may be recirculated up to five times through both segments for a final energy of 4.0 GeV. The recirculator system consists of two 180° arcs that individually transport each beam energy from one linac segment to the other for further acceleration. In each arc, a "spreader" separates the beams according to energy. A set of beam lines (one for each energy) transports the beams to the next linac segment, where they are made collinear using a "recombiner" and injected into the linac segment.

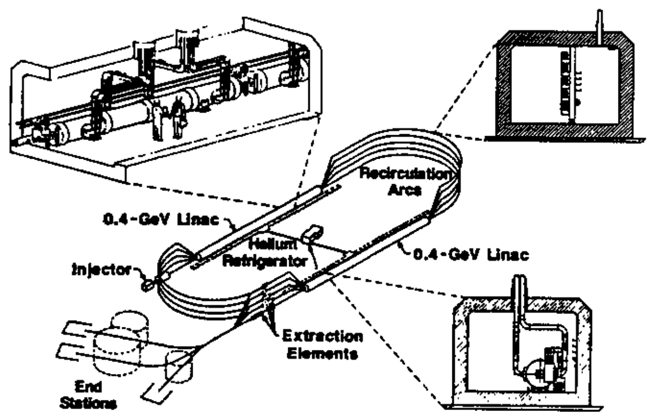


**Figure 1.** Schematic of CEBAF recirculating linac.

The CEBAF beam transport system thus consists of six subsystems: injector optics, linac lattices, spreaders, extraction regions, recirculation arc beam lines, and recombiners. The design goals and modular implementation remain unchanged from previous reports[2]. In this report we describe recent modifications to the beam transport system design. These include: detailing of injector optics and inclusion of an isochronous injection chicane in order to avoid bunch lengthening during injection, use of a "staircase" spreader/recombiner design in order to reduce error sensitivity, use of 1 GHz RF separators for separation and extraction of multiple beams to reduce emittance dilution, and modification of the beam transport system to accomodate a fifth recirculation of the beam.

## Detailed Injector Optics and Isochronous Injection Chicane

The conceptual design of the CEBAF accelerator allowed for injection into the first linac segment by means of a simple horizontal $\alpha$, $-2\alpha$, $\alpha$ chicane, which guides the 45 MeV injected beam around the beam transport elements used to reinject multiple, higher-energy recirculated beams. Detailed consideration of this geometry revealed that the dependence of the path length through the chicane upon momentum ($M_{56} = 0.4$ m) would, for a beam of the anticipated injected momentum spread ($\Delta E/E \simeq 3.0 \times 10^{-3}$), result in unacceptable bunch lengthening ($\delta l = 1.2$ mm $= 2.2°$). The injector optics were therefore modified in order to suppress this undesirable effect.

The injection chicane was rendered isochronous by the introduction of a quadrupole doublet between the first and final pair of chicane dipoles. The doublet forces the dispersion to be small and positive in the central two dipoles, thereby cancelling the path-lengthening effect of the small negative dispersion in the exterior pair of dipoles. A quadrupole triplet between the central pair of dipoles provides control of the dispersion function and beam transverse envelopes between the central pair of dipoles.

Matching of the beam to the linac acceptance is then accomplished through use of a set of five quadrupoles upstream of the chicane. Beam envelope and dispersion functions for a particular optical solution are displayed in Figure 2. The injector and chicane layout are illustrated in Figure 3.

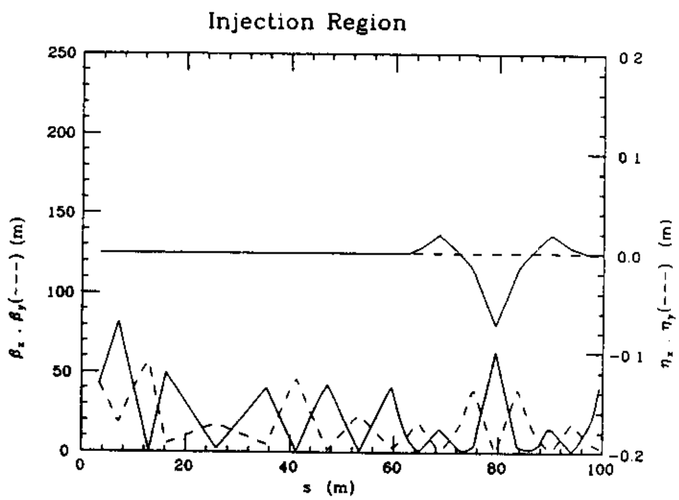


**Figure 2.** Betatron parameters for injector and chicane.

## "Staircase" Spreader/Recombiner

The conceptual design of the CEBAF accelerator employed "spreader" and "recombiner" modules consisting of vertical dispersion suppressors based on a pair of opposing bends separated by a full wavelength in vertical betatron phase[3]. The imposition of an entire betatron wavelength phase advance between two physically adjacent dipoles then required the use of extremely strong focusing elements and generated very large mismatches in beam envelope functions transported through the system. For particular optical solutions required for CEBAF, this dispersion suppressed system exhibited peak betatron envelope functions greater than 500 m and minimum quadrupole focal lengths less than 1.2 m with 0.5 m length quadrupole. Sensitivities to perturbations were therefore extremely high[4].

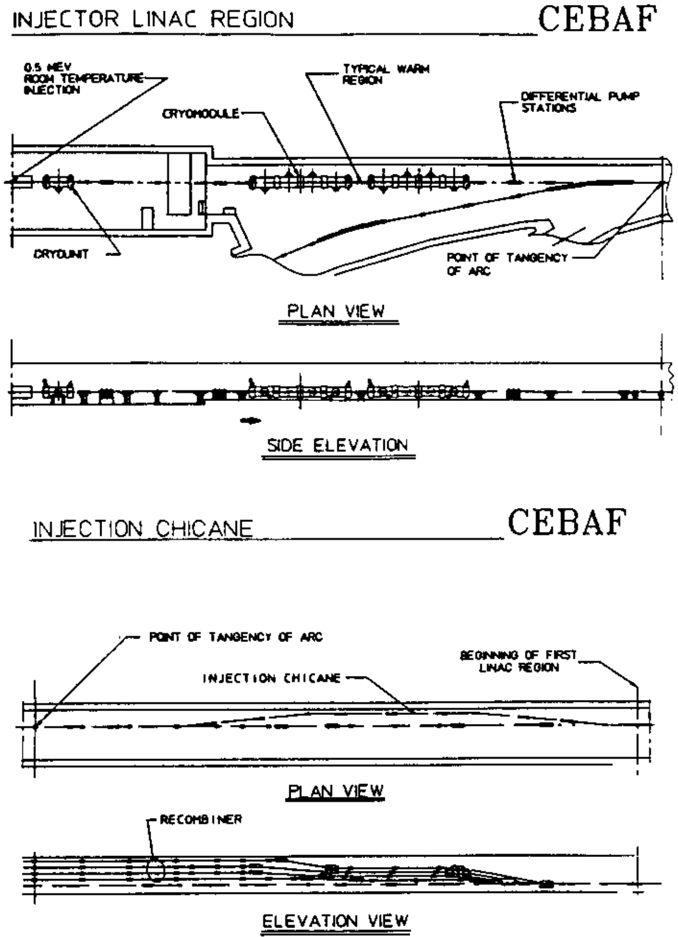


**Figure 3.** Layout of injector and isochronous injection chicane.

In order to reduce this error sensitivity, a variation of systems proposed for a BEVALAC upgrade[5] and the SSC[6] was adopted. A "staircase" consisting of two pairs of opposing bends was constructed. Vertical dispersion was suppressed by introducing, through the use of a quadrupole triplet, a half betatron wavelength in the vertical phase advance between each step of the staircase. As the beam offset is accomplished in approximately the same distance, but with only half the vertical phase advance, the quadrupole strengths, resulting betatron function mismatches, and associated error sensitivities, are significantly reduced. For example, the transport system based on the staircase spreader/recombiner exhibits peak betatron functions of only 250 m, and mininum quadrupole focal lengths greater that 1.9 m with 0.3 m long quadrupoles. Whereas the single-step system typically required eight quadrupoles to achieve a physically realizable match between arc and linac, the staircase system can achieve such a match (usually more robustly, and always with lower quadrupole strengths) with seven quadrupoles.

A staircase spreader layout is shown in Figure 4. Betatron functions for a one-step beam line and a staircase beam line are compared in Figure 5.

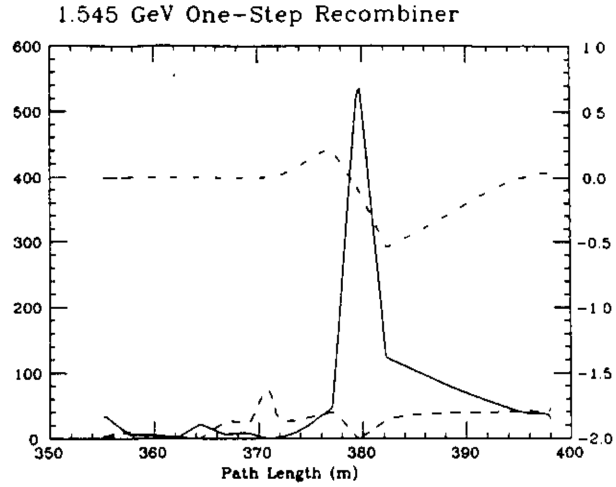


**Figure 5a.** Betatron envelope functions in one-step recombiner.

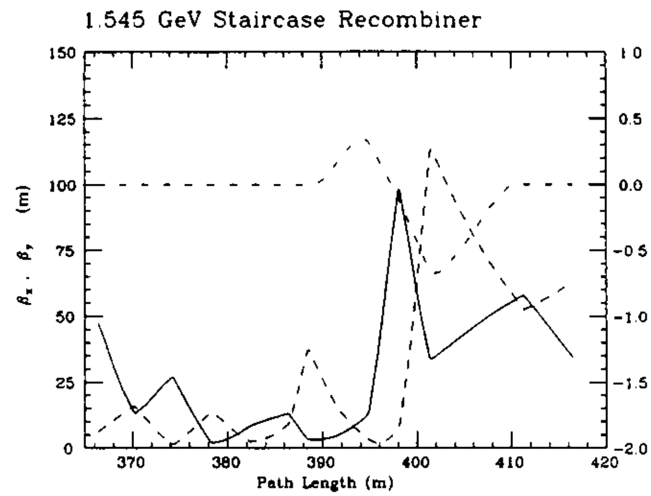


**Figure 5b.** Betatron envelope functions in staircase recombiner.

## 1 GHz RF Separator

Cost and performance considerations have led to a final choice of 1 GHz for the RF separators used to perform separation and extraction of multiple beams. This choice of frequency will provide less transverse emittance dilution from differential head-tail steering and phase and amplitude errors than the original choice of 2.5 GHz[7].

## Five – Pass Optics

A detailed cost analysis of the CEBAF project during FY 1988 indicated that the project cost optimum would occur for a five-, rather a than four-, pass machine. A five-pass beam transport system was therefore designed subject to the following constraints: existing conceptual designs for the individual optical modules were to be employed and all systems were to fit within existing machine slot length allocations.

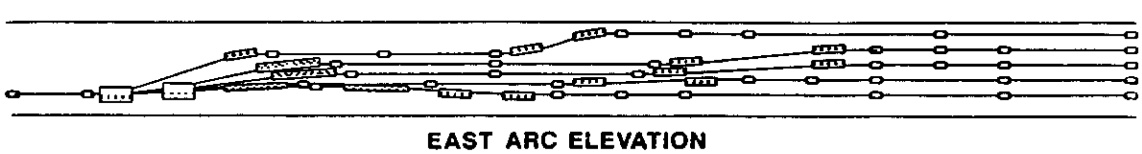


**Figure 4.** Layout of staircase spreader (for five-pass machine)

The use of five passes has the following implications on the beam transport system. Firstly, more beams, in closer energy ratios must be separated or recombined in the spreader/recombiner modules (within a fixed distance, subject to our slot-length constraint). Secondly, greater vertical separation between the lowest and highest energy beams is required (by virtue of fixed beam-to-beam separation and the greater number of beams). Finally, linac focusing (set to transport the first pass in a periodic, matched, structure) will by virtue of the lower first pass energy be reduced in the higher energy passes. As a consequence, the following changes have been made or observed in moving from four to five passes. First, stronger bending was employed in the spreaders and recombiners in order to separate the various beams at different energy. Secondly, increased vertical dispersion was generated during beam separation (due to increased vertical offset of the lowest energy beam). Thirdly, increased quadrupole strength was required to suppress the increased vertical dispersion in the fixed slot length. This increased quadrupole strength, together with the decreased linac focusing in higher passes, leads to greater betatron mismatch during beam separation and recombination for reinjection. Finally, the machine's total beam path length increases by approximately 20%.

The five pass transport system geometry therefore exhibits a $\sim$ 20% increase in vertical dispersion, as well a $\sim$ 20% decrease in linac focusing. These lead to approximately a 20% increase in quadrupole strength in the beam transport system. The beam envelope mismatch is thereby aggravated and betatron functions thus increase by $\sim$ 20% overall. The parameter $k\beta\eta L$ (where $k = B'/B\rho$ is the quadrupole gradient, $\beta$ the mean betatron function value, $\eta$ the dispersion and $L$ the machine length) provides a figure of merit describing relative machine sensitivity to misalignment, and mispowering errors, as well as to magnetic inhomogenieties. The five-pass transport system is approximately $(1.2)^4$, or 2, times as error sensitive as the four-pass machine.

Although the five-pass transport system was designed with the assumption of fixed slot length imposed, we find that relaxing this assumption does not readily lead to less error-sensitive solutions. Increased drift lengths in the lattice will indeed reduce the quadrupole strengths required (roughly as the reciprocal of the drift length). However, the beam envelope functions (specified, ultimately, by the linac focusing) will diverge as the square of the drift lengths employed. Thus, the error sensitivity is increased, rather than reduced, by increasing the slot length. The minimum slot length that can be used (while still successfully separating various beams at different energy for recirculation) is thus most favorable. The existing slot length, which is specified by minimum clearences for beam transport elements used to separate the beams, is therefore optimum.

It is observed that the impact of five recirculations is not limited to the spreader and recombiner modules alone. The use of stronger bending in the spreaders and recombiners leads to an increase in the path length dependence on momentum in these regions. To insure isochronous transport from linac to linac, the resulting change in $M_{56}$ must be compensated in the periodic arc beam transport channels. We require that the geometry of all such beam lines be similar so that they will align verticaly within the tunnel. This fixed geometry must compensate $M_{56}$ values from the spreaders and recombiners ranging from near 0 cm/% (for the highest energy line) to $-1.2$ cm/% (for the lowest energy line of the five-pass transport system). The range of $M_{56}$ values for the previous four-pass design was roughly half as great, which leads to some increase of the arc quadrupole strengths and betatron envelope functions in the arcs of the five-pass machine relative to the four-pass machine. The relative increase in error sensitivity is approximately a factor of two.

## Summary

The isochronicity of the injector chicane design and the choice of a lower frequency for the rf separator extraction system have made the machine phase space design values inherently more achievable.

The new "stair case" spreader/recombiner design has reduced sensitivity to lattice errors by a factor of two. This gain in reduced sensitivity is offset by the increased lattice error sensitivity of the five-pass design over that for the previous four-pass design.

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3. *ibid.*
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5. J. Staples, private communication.
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