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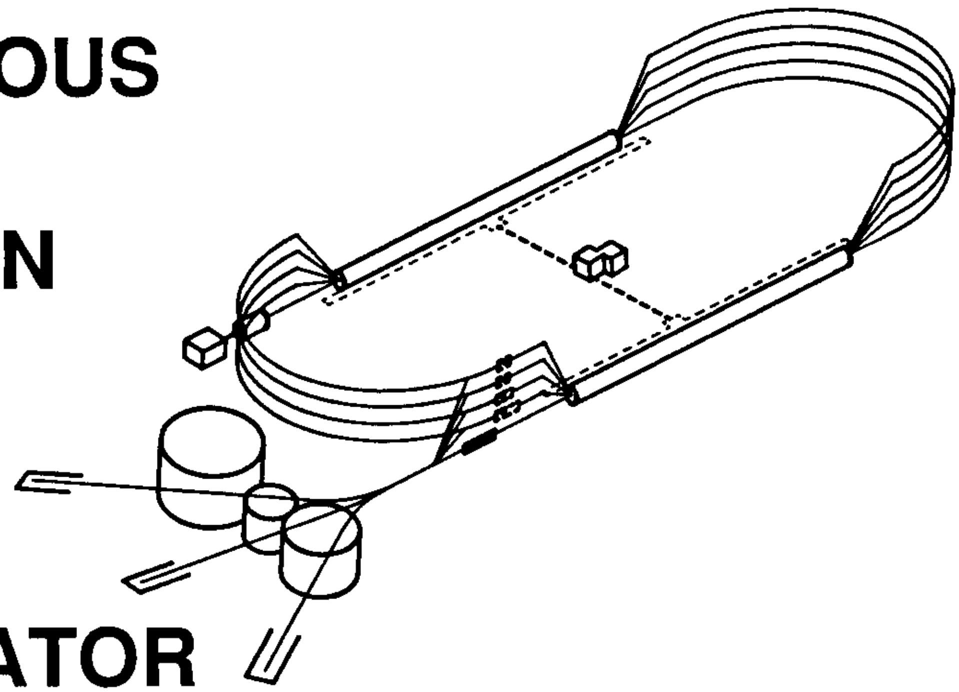

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ABSTRACT

The status of CEBAF accelerator lattice designs is reported. Recent developments are described, including

a. use of split-tune achromatic arcs and retuning of arc phase advances for reduced error sensitivity,
b. a second-order achromatic high-dispersion spectrometer mode for the lowest-energy recirculation arcs,
c. modifications to spreader/recombiners for increased momentum acceptance,
d. initial layouts for transport system diagnostics, and
e. details of beam switchyard design based on a finalized end station configuration.

OVERVIEW OF TRANSPORT SYSTEM LATTICE

The CEBAF superconducting accelerator[1] is a recirculating cw electron linac consisting of a 45 MeV injector linac, two 0.4 GeV main linacs, a recirculator, and a beam switchyard. The main linacs accelerate multiple beams at different energies. Each beam may be recirculated up to five times for a final energy of 4.0 GeV. The recirculator consists of a pair of transport systems that carry beams from each main linac to the other. In each system, a "spreader" separates the beams according to energy. A set of "arc" beam lines (one for each energy) transports the beams to the next linac, where they are made colinear using a "recombiner" and injected. In each, there is a utility "extraction region" lying between the spreader and the semi-circular arc proper. Following the accelerator, the switchyard delivers beam to three end stations. The system concept is shown in Figure 1.

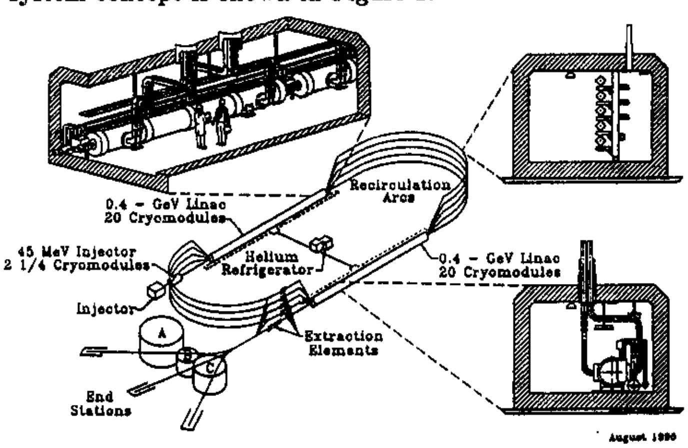

Figure 1. Machine and transport system configuration.

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†Now at SSCL

The CEBAF beam transport system thus comprises lattices of six major subsystems: injector, linacs, spreader/recombiners (S/R's), extraction regions, semicircular arcs, and switchyard. The goals and modular method of design are unchanged from previous reports[2]. In this report we describe refinements in the system design, including: improved tunings for nominal and spectrometer optics of the arcs, modifications to S/R's to provide additional operational energy bandwidth, initial layouts for diagnostics, and a description of finalized beam switchyard layouts. We remark that system element design and procurement are underway for the lattice under consideration.

OPTIMIZED ARC TUNING

Initial five pass designs exhibited greater error sensitivity than the four pass machine[3]. These lattices employed S/R optics with half- or full- integer phase advances, arc superperiods with equal horizontal and vertical tunes of 5/4, required strong matching quadrupoles, and produced mismatched lattice functions. Simulation indicated an undesirable roll sensitivity[4]. These sensitivities have been reduced through optimization of S/R tunings and splitting of arc tunes to suppress coupling due to roll errors.

The preferred S/R tuning was found to be a phase advance of 3/4 wavelength horizontal, and 5/4 wavelength vertical. This yielded minimal quadrupole strengths and beta function mismatch. Table 1 gives values for two figures of merit specifying error sensitivity for several regions of the machine. They are $\overline{\beta}$, the average beta function value at the quadrupoles, and $\sum|k|\beta$, the sum over all quads of the envelope function at the quad times the absolute value of the quad strength $k \equiv B'/B\rho$. The revised tunings provide lower error sensitivity. We note that the retuning often involves a decrease in tune (and hence, focussing); $\overline{\beta}$ therefore increases ~10 – 20% in some cases, with a corollated increase in sensitivity. The error sensitivity $\sum|k|\beta$ *decreases* however, by up to 100%. The revised tunings have therefore been adopted.

After a suggestion by Heifets[5], arc superperiod tunes were were split to 5/4 horizontal, and 3/4 vertical, to suppress coupling due to roll errors. Because four-fold periodicity and quarter-integer phase advances were retained, all advantages of the second-order pseudo-achromatic solution conveyed[6]. However, the phase advances in each plane no longer accumulate at a near-equal rate, so that error driven coupling is reduced. Figure 2 presents a DIMAD[7] computation of the coupling parameter $|B|$ for test versions of the 3645 MeV recirculation transport line, as a function of rms arc magnetic element roll. All transport elements are randomly transversely misaligned (rms of 300 μm), randomly pitched and yawed (rms of 1 mrad), randomly longitudinally misaligned (rms of 5 mm) and have random imposed excitation errors (rms relative error of 10^{-3}). Cutoffs at 2σ are enforced. The $|B|$ value about the uncorrected orbit, as generated by "rmatrix", is shown for two cases of superperiod tune, as a function of rms roll (imposed on elements in the semi-circular arc *only* – in order to directly test the sensitivity of this portion of the transport line). Five random distributions were tested for each tuning; the split tune case exhibits a smaller spread, and thus a lower roll error sensitivity, than the equal tune case. Table 1 also shows that the split tune superperiod possesses lower general error sensitivities.

Table 1
Error Sensitivities With Revised Tunings

line	ψ_x	ψ_y	$\sum\|k_x\|\beta_x$	$\bar{\beta}_x$	$\sum\|k_y\|\beta_y$	$\bar{\beta}_y$
1245 MeV	1	1.5	183.2	16.9	216.9	16.8
spreader	0.75	1.25	181.6	22.4	104.7	11.4
3245 MeV	0.5	1.5	440.9	45.6	384.8	34.2
recombiner	0.75	1.25	407.0	46.5	201.6	24.7
1245 MeV	1.25	1.25	155.7	20.9	219.3	27.3
arc cell	1.25	0.75	99.2	17.0	156.0	30.5

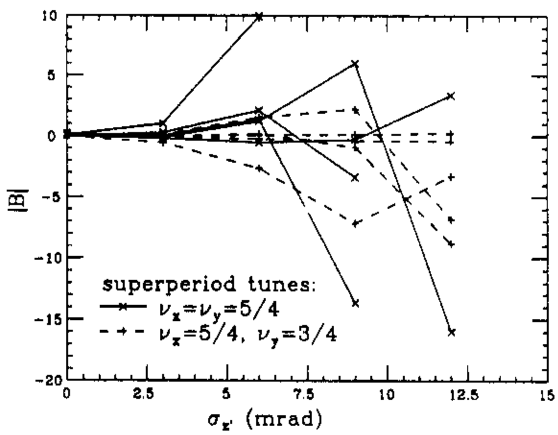

Figure 2. Coupling parameter dependence on rms arc element roll for randomly selected machines for each of two test tunings of the 3645 MeV line.

SECOND-ORDER ACHROMATIC SPECTROMETER MODE

To provide a signal for linac energy gain stabilization, the two lowest energy recirculation lines each support tunings giving a 10 m horizontal dispersion. Originally, these optics employed nonidentical arc superperiods[8]. The first arc superperiod produced the large dispersion; subsequent periods compensated the M_{56} of the first period. Betatron tunes of both types of superperiods differed, but all used the same matched beta functions and were individually dispersion suppressed.

To reduce error sensitivities and suppress chromatic aberrations, new optics have been developed[9]. The solutions are based on designs of Servranckx *et al.*[10] and Guignard[11] for imaginary γ_t hadron synchrotron lattices. Individual superperiods are not dispersion suppressed; four (modulo) quarter-integer tuned superperiods are concatenated to form a globally dispersion suppressed, completely periodic arc, which is then tuned to provide exact isochonicity from linac to linac. The resulting lattice exhibits lower error sensitivity than the previous optics; the peak beta function, average beta function, and figure of merit $\sum|k|\beta$ all decrease by ~20 – 30% in the new tuning. Chromatic behavior improves. Momentum resolution of the system remains constant, as the peak dispersion is fixed at 10 m, and the horizontal spot size at this peak dispersion is the same in either case.

BROADBAND SPREADER-RECOMBINERS

The S/R design is based on specific ratios of incident beam energies. Multiple beams share common dipoles at the front of each S/R; downstream geometry thus depends on the energy ratios of all beams in these elements. These ratios are assumed fixed. Operational flexibility demands this condition be relaxed to allow any of the three linacs (injector, North Linac, and South Linac) to operate at a nondesign energy gain. While holding final energy fixed, the injector should be permitted to operate at up to 85 MeV, and 10% energy-gain differential should be permitted between the North and South linac.

Two schemes to provide increased bandwidth were evaluated. One adds 3 dipoles to each S/R and requires bipolar variation of existing dipoles to give a sufficient number of parameters to maintain beam positions within 2 –3 mm of design values in magnetic elements. This approach suffers in two regards. Operationally, minimizing deviations from design values depends upon balancing variations of *all* magnets from nominal. The setup of each line interacts with that of the others; the lines are not linearly independent. Secondly, this scheme calls for variations in dipole excitation outside of the range available within the construction project; considerable nonscoped engineering effort is required.

The second scheme is a more minimalist one. The leading dipole in the S/R is run at the correct setting for the lowest energy line. This results in an error in the integral field seen by the higher energy beams. Totally uncoupled correction of the remaining beams is not possible; there is no space to install the required elements. The simplest realizable solution is one in which the second common dipole is set to its nominal value for the energy in the second-lowest energy arc. Two dipoles are added, one between common dipoles, acting on all beams except the lowest energy, and the other after the second common dipole, affecting the second line only. The first auxiliary dipole is set to bring the third-lowest energy beam onto center. The second auxiliary dipole is set to put the second-lowest energy beam on center.

The entire desired operational range is provided if the auxiliary dipoles are bipolar and provide 1 kG-m of field integral. Note that the two highest energy lines have residual position errors; these are small due to the intrinsic small bend angles, and are corrected by steering dipoles further downstream. While correction of each beamline is not totally independent of the others, the number of coupled "knobs" is smaller than in the other scheme and their interaction occurs in a prescribed fashion. This approach has been adopted and is being implemented.

TRANSPORT SYSTEM DIAGNOSTIC ARRAY

The orbit correction methods used at CEBAF will require the use of corrector/monitor pairs. Optimum placement of these devices is critical for acceptable orbit control. Ideally, each quadrupole would have an adjacent beam position monitor (BPM) and horizontal and vertical correction dipoles and for each Unfortunately, this is too costly, and can be redundant (*e.g.*, at some quadrupole doublets and triplets). The number of BPMs can be reduced through proper placement and augmentation of position information using alternative devices, such as beam profile monitors and view-screens.

At present, 549 BPMs will be distributed through the machine. There will be one BPM per single quadrupole or multiplet in the linacs and in all irregular or transitional regions of the machine (S/Rs, extraction regions, first superperiod of arcs). In periodic or regular machine region (downstream periods of recirculation and BSY arcs), BPMs will be placed at roughly every 90 degrees of betatron phase advance. This appears to be the optimum with respect to cost and operational control.

Positional information from BPMs will be augmented by data from 30 profile monitors and 130 view-screens distributed throughout the machine. The total number of positional parameters thus provided will be 709, essentially equal to the number of quadrupoles. Increasing the number of monitors beyond this provides no real benefit; further reductions produce a system that is not fully correctable in certain circumstances.

OVERVIEW OF BEAM SWITCHYARD DESIGN

The beam is extracted at the end of the South Linac, and transported to the three experimental halls: A, B, C. A 1/3-harmonic rf separation of bunches permits simultaneous operation of all three beam lines, and beam energy for each beam line can be taken from any of the five pass energies (nominally, 0.8, 1.6, 2.4, 3.2, and 4.0 GeV).

The transports to each hall are conceptually the same; they consist of a matching section, a bending section composed of 4 (or 8) FODO cells that directs the beam toward the hall, and final matching to the experimental target. The beam lines can be adjusted for optimal experimental conditions. The base-line optical solution is a point-to-point achromatic focus. High dispersion at the target is also possible, and phase-space rotation (*i.e.*, for vertical dispersion) can be accommodated. Current plans are to install a high-resolution spectrometer in Hall A, requiring large dispersion at the target, a high acceptance spectrometer in Hall B requiring an achromatic point-to-point focus and a high-momentum/moderate resolution spectrometer in Hall C requiring a point-to-point focus.

The switchyard configuration is shown in Figure 3.

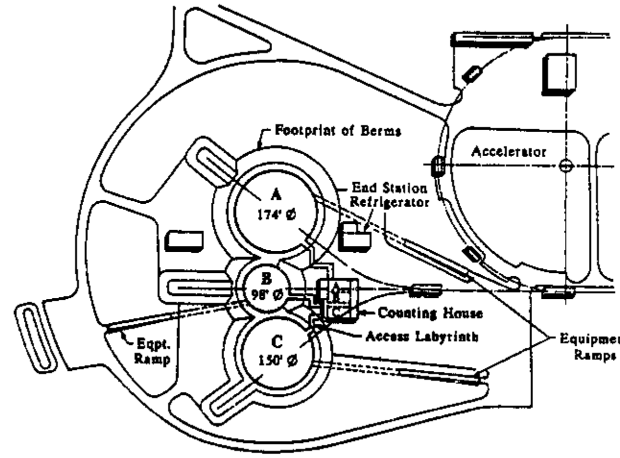

Figure 3. Beam switchyard configuration showing orientation of end stations and BSY transport lines.

ACKNOWLEDGEMENTS

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