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Error Estimates for CEBAF-ER Phase Delay Chicane Dipoles

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Abstract
Central orbit steering, phase jitter, and focusing error effects due to imperfections and excitation errors in CEBAF-ER phase delay chicane dipoles are analyzed.

Introduction
CEBAF-ER will use a four-dipole phase delay chicane to initiate energy recovery. Various design options for this chicane have been presented elsewhere [1]. At this time, plans call for use of a chicane based on 1 m dipoles (BE equivalents) built from spare coils and surplus material [2]. It will be placed at the end of the South Linac. In this note, we will assess the effect of field strength and excitation errors in these dipoles on beam position and estimate the strength of various focusing errors.

Table 1 presents (approximate) values for parameters relevant to this discussion.

Table 1: Machine and chicane dipole parameters

Parameter	*Value (unit)*
average beam envelope, b_{ave}	20 m
chicane length	8.6 m
dipole length	1 m
bend angle, q	0.2 rad
bend radius, r	5 m
chicane offset	0.6 m
Number of dipoles, N	4
beam energy, E	~ 1 GeV

Centroid Steering – Excitation Errors

Uncorrelated excitation errors of magnitude dq in a set of N beam line dipoles distributed over a reasonable number of betatron oscillations with average beam envelope b_{ave} will lead to an rms orbit error $<x>$ of the following magnitude [3].

$$\langle x \rangle = \sqrt{\frac{N}{2}} b_{\text{ave}} \, dq$$

For dipoles bending by angle q and with a generic error tolerance T, $dq = qT$. The resulting orbit error is then

$$\langle x \rangle = \sqrt{N/2}\, b_{\text{ave}} q\ T\ .$$

In the case of a single chicane, N is small (here, $N=4$), the entire region of interest subtends only a fraction of a betatron wavelength, and there is no focusing interleaved with the dipoles. In this case, the orbit error at the end of the chicane may be construed to be

$$\langle x \rangle = \sqrt{N}\, L_{\text{ave}} q\ T\ ,$$

where L_{ave} is the average distance from a dipole to the end of the chicane, bend parameters are as above, and the root-N is included to account for the uncorrelated nature of the errors.

Chicane geometries suppress correlated errors in position and angle. Thus, a systematic orbit offset does not lead to path length errors (the system is transversely translationally symmetric), and a correlated excitation error is self-suppressing. We assume the dipoles will be powered in series; these effects are therefore ignored here.

Both correlated and uncorrelated orbit and excitation errors in dipoles do lead to path length errors. If an orbit with uncorrelated (e.g., rms) offset $<x>$ traverses N dipoles, a path length error of the following magnitude will result.

$$\langle d\,l \rangle = \sqrt{N} M_{51}^{\text{dipole}} \langle x \rangle \sim \sqrt{N} q\ \langle x \rangle$$

Inserting either of the above results for $<x>$ yields the path length error to be expected from uncorrelated random excitation errors:

$$\langle d\ l \rangle = \frac{N}{\sqrt{2}} b_{\text{ave}} q^{\ 2} T$$

or

$$\langle d\ l \rangle = N L_{\text{ave}} q^{\ 2} T$$

A systematic relative excitation error T will, via the chicane compaction, lead to the following path length differential.

$$dl = M_{56}\ T$$

We now use these expressions to evaluate the effect of various chicane dipole errors.

DC excitation errors – tracking & matching – Finite fabrication tolerances will lead to dipole-to-dipole variation in response to excitation, with resulting variations in core field and field integral. Typical tolerances for such errors are *DB/B* ~ *DBL/BL* ~ 10^{-3}. Given the above expressions, we expect resultant orbit errors to lie between

$$\langle x \rangle = \sqrt{4/2} \times 20 \text{ m} \times 0.2 \text{ rad} \times 10^{-3} \sim 6 \text{ mm}$$

and

$$\langle x \rangle = \sqrt{4} \times 5 \text{ m} \times 0.2 \text{ rad} \times 10^{-3} \sim 2 \text{ mm} \ .$$

These seem within the correction range of typical steering trims. Path length errors resulting from these orbit errors lie within the following range:

$$\langle d\, l \rangle = \frac{2}{\sqrt{2}} \times 20 \text{ m} \times (0.2 \text{ rad})^2 \times 10^{-3} \sim 1 \text{mm}$$

to

$$\langle d\, l \rangle = 2 \times 5 \text{ m} \times (0.2 \text{ rad})^2 \times 10^{-3} \sim 0.4 \text{ mm} \ .$$

The chicane compaction is generated by 0.6 m of dispersion at the central pair of dipoles; thus, M_{56} ~ 2 × 0.2 rad × 0.6 m ~ 0.24 m. A systematic offset of the dipole buss of T~10^{-3} thus leads to a path length shift of

$$dl = M_{56}\, T \sim 0.24 \text{ m} \times 10^{-3} = 0.24 \text{ mm}$$

This can be compensated by a compensatory shift in the buss current. The random-error-generated path length shift evaluated above can similarly be corrected by a shift in the buss current. As we have seen that the random error shift may be ~1 mm, the required relative current offset could be of order 4 × 10^{-3}, corresponding to a dispersive lateral displacement at the center of the chicane of $Dx = h_x\, DB/B$ ~ 0.6 m × 4 × 10^{-3} ~ 2.4 mm.

Relative DC excitation and tracking errors of order 10^{-3} thus seem impose no unmanageable behavior on the system.

<u>*AC excitation errors – ripple*</u> – Current ripple can in principle lead to both transverse and longitudinal beam motion. Transverse motion is readily suppressed by powering the dipole string in series. The achromatic behavior of the chicane then suppresses variations in x and x' due to systematic errors in bend angle. Residual AC motion then derives only from failure of the dipoles to match or track (discussed above) and is of the following magnitude.

$$\langle x \rangle_{AC} \sim \langle x \rangle_{DC}\, T_{AC}$$

Typical CEBAF dipole power supply stability gives T_{AC} ~ 10^{-5}, so that the previous millimeter-order results for $<x>_{DC}$ suggest $<x>_{AC}$ <<1 μm. Orbit-offset-driven longitudinal errors behave similarly.

Systematic longitudinal errors can be more significant. The chicane momentum compaction of 0.24 m will for simple energy recovery be compensated in the downstream arc so as to render the linac-to-linac transport isochronous (but more of this in a moment…). If the chicane and arc dipole strings are independently powered, each will generate an uncorrelated AC path length error of order $dl \sim M_{56}\, T_{AC}$, which, when added in quadrature will give a total AC longitudinal motion of order

$$\langle d\, l \rangle_{AC} \sim \sqrt{2}\, M_{56} T_{AC}$$

This is of magnitude

$$\langle d\, l \rangle_{AC} \sim \sqrt{2} \times 0.24\,\mathrm{m} \times 10^{-5} \sim 3 m\,\mathrm{m}\,.$$

If of concern, this can be completely suppressed by powering the chicane in series with the downstream arc. This may not be a desirable option for three reasons. First, the error effect is small and suppression is probably unnecessary. Secondly, the required electrical switching system may be fussier (and costlier?) to design and install than a separate chicane power supply (particularly if a spare or surplus power supply is available for this application). Finally, the CEBAF-ER Phase 2 current doubling experiment may require operating the downstream arc with a compaction value that will not compensate that of the chicane (nonisochronous operation), in which case the suppression is not available.

In summary, relative AC excitation errors of order 10^{-5} seem to introduce no toward behavior in the system, even with chicane powering independent of that of the associated arc, provided the chicane dipoles are powered in series.

Focusing Errors

Edge Focusing – Entry into a dipole at an angle f relative to the normal will lead to vertical focusing with an effective focal length specified as follows.

$$\frac{1}{f} = \frac{1}{r} \tan f$$

This is well characterized by beam line design and analysis codes; we introduce into our discussion to set the scale of focusing errors expected in the dipoles under consideration. Here, r ~ 5 m and $f = q/2$ ~ 0.1 rad (symmetric entry & exit), so f_{dipole} is of order 50 m. This is about 1/10$^{\text{th}}$ the focusing strength of CEBAF linac quad, for which

$$f_{\text{quad}} = 1/(kl) = 1/(1.2/\mathrm{m}^2 \times 0.15\ \mathrm{m}) \sim 5.6\ \mathrm{m}\,.$$

The entire chicane thus introduces focusing equivalent to a single linac quadrupole (though modulated by the betatron phase advance across the chicane).

Insofar as DC excitation errors will alter dipole bend radii and the orbit orientation relative to the pole faces, tracking & matching errors can cause changes in focusing. For the parameters in use here, $1/f \sim f/r$, so that the variation in focal length is specified as follows.

$$d\left(\frac{1}{f}\right) = -\frac{d\ f}{f^2}$$
$$= \frac{df}{r} - \frac{f\,dr}{r^2}$$

The relative error in focal length is then at most of order

$$\frac{d\ f}{f} \sim \frac{df}{f} + \frac{dr}{r} \sim 2T_{DC}\ .$$

The resulting DC relative focusing error is thus of order 2×10^{-3}, which is constant with the tolerance associated with CEBAF quadrupoles (for which the specification is 10^{-3}). Adverse focusing effects are therefore not anticipated. Similar arguments apply to AC errors, for which the resulting error ($T_{AC} \sim 10^{-5} \Rightarrow (df/f)_{AC} \sim 2 \times 10^{-5}$) is an order of magnitude smaller than the CEBAF quadrupole specification of 10^{-4}.

“Yunn Effect” – Feed-down of Nonlinear Field Rolloff – The “Yunn Effect” is an apparent systematic vertical focusing error that has as its source transverse field gradients in CEBAF dipole bodies and ends. It has been discussed in excruciating detail elsewhere [4]; in this context we simply cite the conclusions presented earlier:

1. Dipole body gradients cause the Yunn effect.
2. Dipole end fields, in unshimmed dipoles, reduce the magnitude of the Yunn effect and introduce significant error sextupole fields.
3. Dipole end effects are well compensated by shims. The resulting dipole fields are nearly free of end effects; the dipoles so treated are well modeled by “ideal” dipole ends and a field index in the dipole body to simulate the effect of the body gradient.
4. The so-called “shim models” do not in fact accurately represent CEBAF dipole field behavior. Shim models should be removed from dipoles in the DIMAD decks

In CEBAF-ER, our expectations are:

1. that inclusion in optics models of dipole body gradients at the nominal operating point will improve predictive capability,

2. shimming the dipole ends (as they were shimmed in the CEBAF arcs) will compensate for the nonlinear end effects and may be desirable (more of this below), and
3. insofar as this effect is tolerable in normal CEBAF operation, it will be tolerable here due to the smaller number of dipoles involved.

<u>*Other Field Inhomogeniety Issues*</u> – Field inhomogeneity (nonlinearity) in dipole cores and ends can lead to mismatch (due to the presence of error gradients – as in the Yunn affect discussion above), orbit dependences in optics and beam behavior (nonlinear field variation leading to changing gradient as the beam position is changed) and, in extreme cases, phase space dilution (as different segments of the beam experience different fields). Given the dipole field quality issues discussed in Reference [4], all of these are potential issues. However, the beam size in CEBAF (unlike that in the various JLab FEL drivers, see Reference [3]) is so small that phase space dilution is not likely a problem.

An assessment of the effects due to nonlinear field variations in chicane dipoles is straightforward if we note that rectangular dipoles are transversely translationally invariant in the bending plane and therefore provide no focusing in that plane. Thus, any position-dependent angular deflection can be viewed as arising from an error driven field variation. Thus, for example, two parallel components of the beam at different positions will be differentially bent by an angular error $dq = qT$, where T is the relative field (flatness) error (*DB/B*) across the beam. By arguments analogous to those applied to the orbit errors discussed above, the beam will then evolve with a spot size error of the following magnitude [3].

$$\Delta s_x \sim \sqrt{\frac{N}{2}}\, b_{\mathrm{ave}}\, q\, T$$

For chicane dipole parameters and a field uniformity T of order 10^{-4} (across the beam), this implies a spot size deviation Ds_x ~ 0.6 mm, which does not compare favorably with the nominal beam size (assuming a beam envelope of 20 m and emittance of 1 nm-rad) of 0.14 mm. In practice, this suggests that the field varies by less than 1 part per ten thousand over the beam, and it also suggests that positional dependence of the optics may be an issue.

Of particular concern in this regard is the effect of end fields in these dipoles. As discussed in Reference [4], end effects in the dipoles lead to a significant decapole term in the ends. The orbit is systematically offset by half the sagitta (r(1-cos(q/2) ~ 0.012 m in this case) in the ends, leading to a feed-down of octupole, sextupole, quadrupole, and dipole moments at the site of the beam. Numerically, the dipole steering effects are negligible, the quadrupole effects are small (all eight ends sum to a few percent of a linac quad), but the sextupole effects are significant. The interested reader is directed to the reference for further details; for this discussion, we simply note that end-field correction using the standard CEBAF shims would be prudent and the optics model would be improved by use of dipole body gradients to model the systematic quadrupole moment that is present in this class of bend.

Notes & References

[1] C. Butler, D. Douglas, A. Guerra, and C. Tennant, "Chicane Options for Testing Energy Recovery and Current Doubling in CEBAF", JLAB-TN-02-019, 22 May 2002.

[2] A. Guerra, unpublished.

[3] D. Douglas, "Error Estimates for the IR FEL Transport System", CEBAF-TN-96-035, 15 July 1996.

[4] D. Douglas and B. Yunn, "Dipole Field Inhomogeneities and the 'Yunn Effect'", JLAB-TN-07-019, 30 June 1997.