FEL Driver Trim Magnet Field Specifications

D. Douglas

Abstract

Field specifications are given for 1) the field flatness in FEL driver corrector dipoles, 2) field linearity in FEL driver trim quadrupoles, and 3) gradient integral in FEL driver trim skew quadrupoles.

Overview

Three field specifications are required immediately for the FEL driver transport system. These are [1]:

1. specification of required field uniformity in corrector dipoles,
2. specification of required field linearity in trim quadrupoles, and
3. specification of required gradient integral in trim skew quadrupoles.

We derive the first two specifications in this note by using a previously documented method [2] in which the parametric tolerance is set by constraining induced deviations from linear behavior be limited to levels ensuring machine performance. In the third case, the specification is set using a previously documented method [3] in which the trim element is constrained to locally compensate the error, resulting in essentially no impact on machine performance.

Field Uniformity in Corrector Dipoles

Corrector dipole field quality must be good enough to insure adequate system linear aperture. The mechanism for deviations from linearity is illustrated in Figure 1, wherein a positional dependence in the field across a beam (or, a working aperture) leads to a variation in bend angle imposed on various portions of the beam.

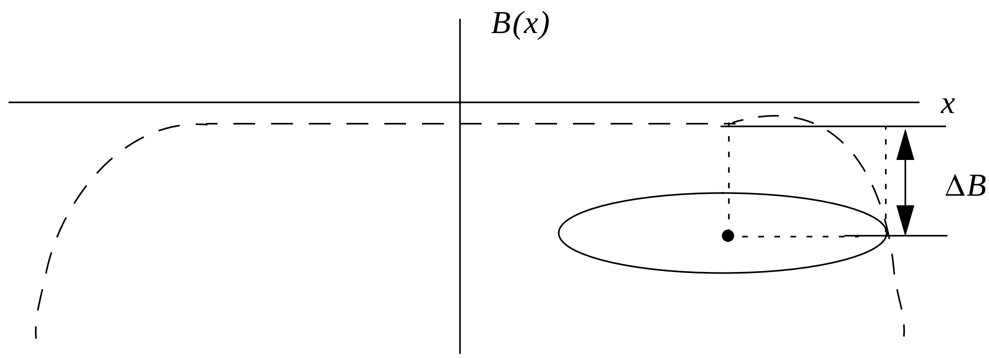

Figure 1: Mechanism for deviations in linearity due to corrector field inhomgeneities.

The center and edge of the beam (or working aperture) will experience a field difference ΔB, leading to the following deviation across the beam (or working aperture) in the bend angle θ imposed by the corrector:

$$\delta\theta = \frac{\Delta B}{B}\theta$$

This angular deviation will drive a betatron oscillation differential between the center and the edge of the phase space volume under consideration, leading to a downstream positional discrepancy $\delta x = M_{12}\delta\theta$; should this occur in N correctors, the resulting "deviation from linearity" will be as follows, where all bracketed quantities indicate "average" or "rms" deviations:

$$\langle\delta x\rangle = \sqrt{N}\langle M_{12}\rangle\langle\frac{\Delta B}{B}\rangle\langle\theta\rangle$$

In the IR FEL Driver transport system, typical values for these quantities are as follows:

$\langle M_{12}\rangle = (5\text{ m})/(\sqrt{2}) \sim 3.5\text{ m}$,
N=45, the number of correctors, and
$\langle\theta\rangle \sim 1.4\text{ mrad}$, the rms expected corrector strength.

As a result, the expected "deviation from linearity" due to corrector field inhomgeneities is related to the field deviation $\langle\Delta B/B\rangle$ by the following scaling relation.

$$\langle\delta x\rangle = 33\times10^{-3}\text{ m }\langle\frac{\Delta B}{B}\rangle$$

To set a specification on $\langle\Delta B/B\rangle$, we recall that a typical rms spot size in the IR FEL is of order 1/3 to 1/2 mm, and demand that the motion not deviate from linearity by more than this spot size as the beam is moved around the working aperture. This suggests that the following requirement be imposed on field variation across the working aperture of the correctors (specified using the $6\sigma \pm 0.02\text{ m}$ criterion):

$$\boxed{\langle\frac{\Delta B}{B}\rangle < 0.01}$$

Table 1 provides nominal working apertures, over which this criterion is to hold. We note that the resulting deviation from linearity is consistent with values driven by previously specified inhomogeneity constraints in main recirculator dipoles and quadrupoles [2]. It is expected to hold for all "corrector" magnets, both 10 mrad peak angle "steering coils" as well as 30 mrad peak angle "path length correction coils". The specification applies to the latter magnets, despite their greater potential angle, by virtue of the fact that they will not ever be run to 30 mrad (a value used only for energy doubling experiments) when the beam is used for lasing and/or poorly steered. When they are at peak value, the beam will be "small", of order 2 cm in horizontal extent (2 m dispersion times 2% energy spread) and well steered. The nominal excitation of these magnets is expected to be of order a few mrad, so as to produce at most a few mm path length deviation from the nominal 501.5 RF wavelengths.

Table 1: Corrector Working Aperture Requirements [4]

Machine Region	Horizontal Aperture (mm)	Vertical Aperture (mm)
Injection Telescope	43	43
Injection Chicane	67	43
Optical Cavity Chicanes	72	43
End Loops	168	43
Linac Axis/Backlegs	43	43

Field Linearity in Trim Quadrupoles

Similar considerations drive the specification of trim quadrupole field linearity. Figure 2 illustrates the mechanism by which field errors in quadrupoles lead to linear aperture limitations.

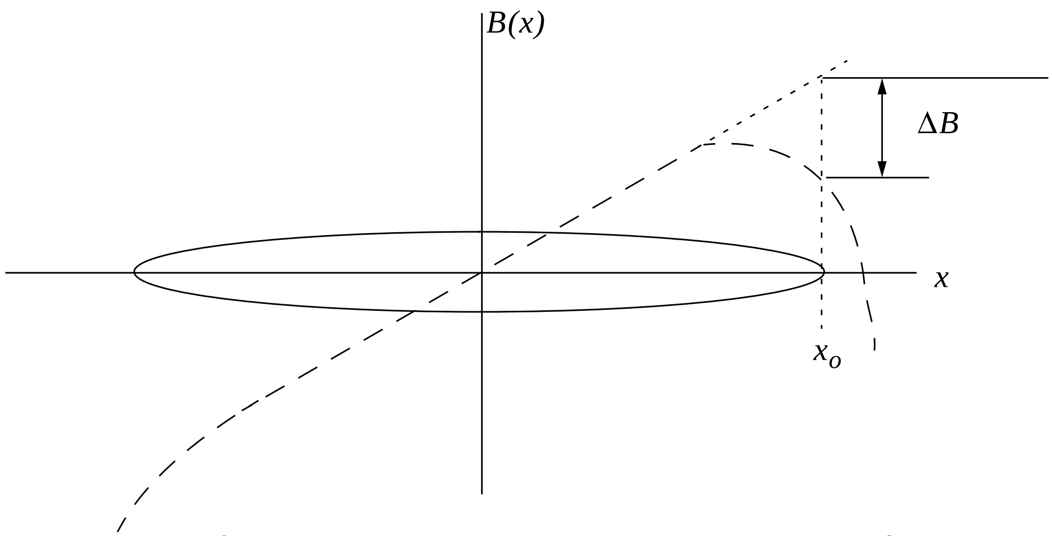

Figure 2: Mechanism for deviations in linearity due to quadrupole field errors.

As with the correctors, the field error ΔB due to nonlinear variations in quad field across the working aperture or phase volume of interest leads to an unanticipated bending error $\delta\theta = (\Delta B / B)\,\theta$, where the angle θ is simply the nominal angular kick supplied by the quadrupole to the phase space point at the edge of the aperture: $\theta = klx_o$. This in turn leads to a discrepancy in the betatron oscillation amplitude associated with edge of the aperture from the values predicted from the linear model. When accumulated over N trim quadrupoles, the resulting deviation from linearity $\langle\delta x\rangle$ is given by the following expression, in which brackets represent rms quantities.

$$\langle \delta x \rangle = \sqrt{N} \langle M_{12} \rangle \langle \frac{\Delta B}{B} \rangle \langle k l x_o \rangle$$

In the IR Driver transport system, the trim quadrupoles typically have parameters as follows:

$\langle M_{12} \rangle = (5 \text{ m})/(\sqrt{2}) \sim 3.5 \text{ m}$,

N=8, the number of trim quads, and

$\langle kl \rangle \sim 0.04/\text{m}$, the rms expected quadrupole strength.

A tolerance on $\langle \Delta B/B \rangle$ can then be set for a selected working aperture x_o using the following scaling relation.

$$\langle \delta x \rangle = 0.4 \langle \frac{\Delta B}{B} \rangle x_o$$

The trim quadrupoles will be used in highly dispersed locations; beam sizes will approach 10 cm (2 m dispersion times 5% momentum spread) when the FEL is lasing. We therefore require a “linear aperture” of at least $\pm 5 \text{ cm}$ in these elements. Using this value for x_o, we find

$$\langle \delta x \rangle = 0.02 \langle \frac{\Delta B}{B} \rangle$$

so that the constraint that the system be linear to order of the beam size requires the following specification on field errors hold in the trim quads:

$$\boxed{\langle \frac{\Delta B}{B} \rangle < 0.01}$$

The relative field error at $\pm 5 \text{ cm}$ in the trim quads should not exceed 1% of the nominal field value.

This specification can be reviewed from an operational viewpoint. The trim quadrupoles will be used to adjust the lattice dispersion. Discrepancies in field will therefore lead to undesirable dispersion errors. The anticipated dispersion error from the type of field inhomogeneity described above is as follows:

$$\langle \delta \eta \rangle = \sqrt{N} \langle M_{12} \rangle \langle \frac{\Delta B}{B} \rangle \langle k l \eta \rangle$$

Typical values for most parameters are given above; at the trim quads, $\eta \sim 1 - 2 \text{ m}$. Thus, the anticipated dispersion error in the dispersion will be as follows.

$$\langle \delta \eta \rangle = 0.4 \text{ m} \langle \frac{\Delta B}{B} \rangle$$

A 10% field tolerance gives 4 cm dispersion error and 2 mm spot size error (for 5% momentum spread), which is not acceptable (this is close to doubling the nominal full spot size!), while 1% field tolerance gives 4 mm dispersion error and a 200 μm spot growth, a more reasonable degradation. This confirms the suitability of the 1% tolerance.

Gradient Integral in Trim Skew Quadrupoles

Four trim skew quadrupoles will be placed in the system – at both ends of the cryounit and cryomodule, immediately adjacent to the end cans – and will be used to locally cancel the HOM-generated skew quadrupole fields in the SRF cavities. The required magnitude can be estimated using information provided by Z. Li [5]. Figure 3 is a reproduction of Figure 3-20 in Reference [5]; it, and the associated text, tell us that for all but the lowest injection energies, the HOM coupler of an on-crest cavity run at 2.5 MeV energy gain will impose a skew quadrupole gradient integral of about 4.3 g on the beam.

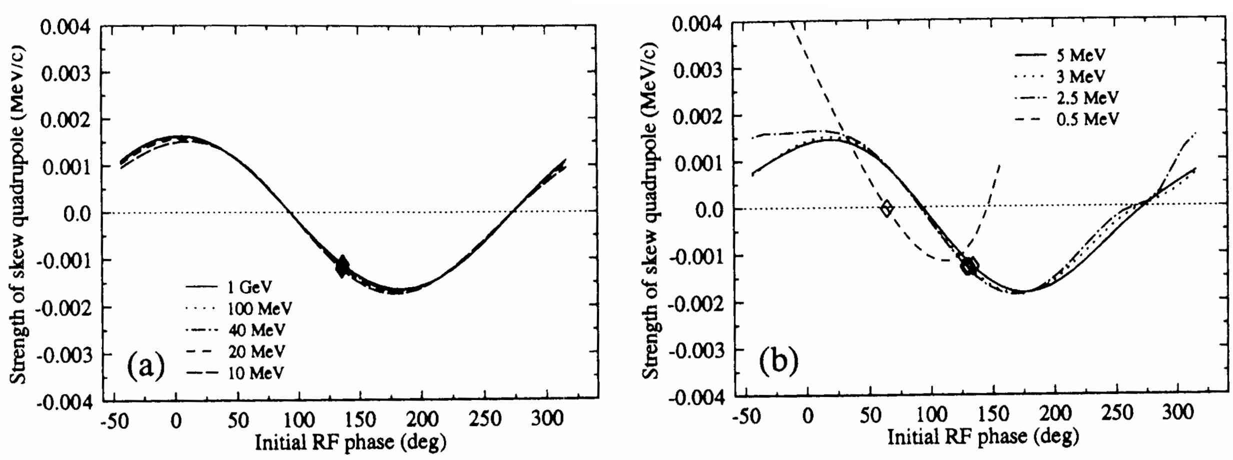

Figure 3: Skew quadrupole momentum impulse from HOM coupler of CEBAF cavity run at 2.5 MeV energy gain, for various injection energies.

The trim skew quads will be excited to locally compensate this gradient integral. Two features of the above behavior must be accommodated. First, the cavity energy gain will be higher in the FEL than in the thesis study. Secondly, the cavities of the FEL will not necessarily be phased in the same fashion as those in the thesis study. In particular, the cavities at higher energy may be off crest, and the phase slip in the first cavity (which contributes to the asymmetry of the curve) will differ from that in the thesis study (because of the different energy gain). An initial estimate suggests this may lead to ~10^{o} difference in the location of the crest phase (these are indicated by diamonds on the curves).

As a consequence, the trim skew quads will differ in gradient integral from the values required in the CEBAF linac. The first skew quad (in front of the cryounit) will not be compensating a zero skew quad gradient integral, nor will the integral to be compensated in higher energy cavities be 4.3 g. Rather, the first cavity will lie order 10^{o} in phase off zero, and the magnitude of all skew quads will be inflated by the increase in cavity gradient. We therefore specify the required gradient integrals as follows:

Injector Skew Quads. These will both be specified to compensate the anticipated maximum skew quad gradient integral of a cavity at the average energy of the unit (5 MeV) with the energy gain used in the unit (5 MeV per cavity). This implies that the required skew quad gradient integral is as follows:

$$\begin{aligned} B'l &= 4.3\text{ g} \times 1.5\text{ (scale factor for max.)} \times \left(\frac{5\text{ MeV}}{2.5\text{ MeV}}\right)\text{ (scale factor for energy gain)} \\ &= 12.9\text{ g} \end{aligned}$$

Cryomodule Skew Quads. These will both be specified to compensate the anticipate maximum skew quad gradient integral of four cavities operated at the nominal energy gain used in the module (4 MeV). This implies that the required skew quad gradient integral is as follows:

$$\begin{aligned} B'l &= 4\text{ (cavities)} \times 4.3\text{ g} \times 1.5\text{ (scale factor for max.)} \\ &\quad \times \left(\frac{4\text{ MeV}}{2.5\text{ MeV}}\right)\text{ (scale factor for energy gain)} \\ &= 41.3\text{ g} \end{aligned}$$

This is somewhat higher than the nominal 32 g used in the CEBAF system to compensate 8 cavities distributed over 2 cryomodules, but should be well within the range available with the CEBAF-standard air core skew quads.

References

[1] G. Biallas, private communication.

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

[3] D. Douglas, “Effect and Compensation of HOM-Generated Skew Quadrupole Fields in the CEBAF Linacs”, CEBAF-TN-95-037, 13 June 1995.

[4] Horizontal values in the chicanes and end loops are based on the working aperture of adjacent dipoles (as estimated by Karn and Douglas on 20 December 1996). Vertical values everywhere and horizontal values on the linac/backleg axes and in the injection line are based on the $6\sigma \pm 0.02$ m rule thumb using an rms betatron size of 1/2 mm.

[5] Z. Li, “Beam Dynamics in the CEBAF Superconducting Cavities,” Ph. D thesis, College of William and Mary, March 1995.