LCLS COMPRESSOR DIPOLE FIELD QUALITY AND BEAM MEASUREMENTS *

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Abstract

FELs typically use special arrangements of dipole magnets called chicanes to create an energy dependent path length for bunch compression. Ideally, a beam with a linear correlation of energy and longitudinal position forms a shorter bunch with the same energy spread after it passes through the chicane. To a very high degree the chicane should not generate residual dispersion which can convert energy spread into emittance and degrade the FEL. Linear dispersion is correctable, but it is impractical to correct nonlinear dispersion or nonlinear focussing effects which leads to stringent demands on dipole field quality. The first LCLS compressor chicane was initially found to generate substantial emittance growth. Beam-based measurements of the net integrated magnetic field demonstrated that the dipole field quality was not adequate. Subsequently we modified two of the four chicane dipoles to improve their good-field region. When reinstalled we found the chicane generated very little emittance growth, and beam-based measurements confirmed the improved dipole field quality.

INTRODUCTION

FELs and bunch compressors Bunch compressors are an essential part of FELs and are used to create the very high peak beam current required for lasing. At the LCLS there are two bunch compressors of the general form shown in Figure 1. The first of these, called BC1, compresses the bunch longitudinally from a length of 0.83 mm to 0.19 mm. Bunch compression is accomplished by first introducing a linear energy correlation along the longitudinal dimension of the beam (chirp) so that the front of the bunch has a lower energy than the back. As the beam goes through the compressor, the lower energy electrons take a longer path, and the higher energy electrons a shorter path, resulting in an overall shortening of the bunch. For the BC1 compressor, the imposed linear energy correlation results in a relative energy spread $\sigma_\delta = 0.016$.

Field Quality As can be seen in Figure 1, the high, low, and on-energy electrons take nearly the same path through the outer dipoles, but different paths through the inner two dipoles. Ideally the net deflection angle from the compressor is zero for all energy electrons; the deflection from the outer dipoles is supposed to exactly cancel the deflection from the inner dipoles. However, to the extent that the integrated magnetic field of the inner dipoles is different for the different paths, there is a variation in the cancelation for the high, low, and on-energy electrons, and they end up with different angles at the exit of the compressor. If the difference is large enough, the emittance at the exit of the chicane would grow.

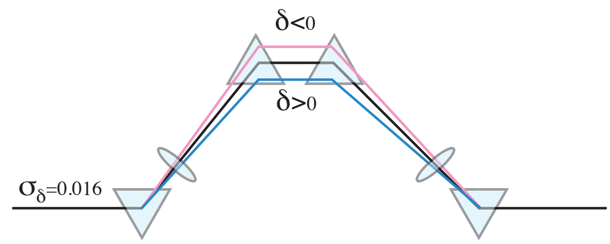

Figure 1: Schematic of a bunch compressor.

Sensitivity to field errors The sensitivity of emittance to the field quality of the inner dipoles is impressive. Assuming an initial normalized emittance, $\gamma\epsilon_x = 1\ \mu m$, the horizontal angular spread σ'_x at the exit of the BC1 compressor is only about 8 μrad. So if the inner two dipoles produced a net deflection angle that differed for the different energy portions of the beam by more than a few microradians, the emittance would be noticeably increased. In BC1 the middle two dipoles, combined, produce a deflection angle of 10 degrees which is about $2 \times 10^5\ \mu rad$, so to avoid horizontal emittance growth the net integrated field should be the same along the paths of high, low and on-energy electrons at a level of a few parts in 10^5.

There is, however, a mitigating factor which reduces the required field uniformity. The BC1 compressor also contains two "corrector quadrupoles" (shown as lenses in Figure 1) which are used to correct linear horizontal dispersion coming out of the compressor. Because they are in a dispersive region, they will contribute a deflection angle linearly proportional to δ and can be set to cancel any linear dependence of horizontal beam position or angle on energy at the exit of BC1. The linear component of the magnetic field variation with horizontal position is corrected for in this manner, as well as any linear dispersion generated by field errors upstream of BC1. The deflections that are nonlinear in horizontal position are uncorrectable and therefore relevant to field quality requirements. In practice, these corrector quadrupoles have proven to be essential. Without them the emittance would be dominated by the effects of residual dispersion from upstream magnets and linear field errors in the inner dipoles.

Good field region The horizontal region over which the high field uniformity needs to be maintained is determined

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in part by the beam size, which is large due to the energy spread, and in part by the distance the curved trajectory of the beam traverses going through each dipole. In the case of BC1 inner dipoles the horizontal beam size, $\sigma_x =$ 6.2 mm, and the curved trajectory traverses $\pm 4.4\ mm$. (The beam size is somewhat larger than the design value of $4.8\ mm$ because we found that it was advantageous to run with a 30% longer electron bunch from the gun which leads to 30% more energy spread and beam size.) Allowance for static orbit changes and reasonable installation and motion tolerances must also be taken into account. These considerations, and simulation results [1], led us to a adopt field uniformity goal of $\pm 5 \times 10^{-4}$ over a region of $\pm 26\ mm$. This regions covers $\pm 3\sigma_x$ for beam size, $\pm 4.4\ mm$ for the trajectory deviation, and about $\pm 3\ mm$ for orbit range and mechanical/motion tolerance.

Emittance growth observed Emittance growth in BC1 was seen during the first commissioning run and was diagnosed to be caused by inadequate dipole field uniformity. The linear and nonlinear field non-uniformities generated large horizontal dispersion errors just beyond BC1. The linear dispersion was corrected using the two corrector quadrupoles, but the remaining nonlinear field caused growth of the normalized horizontal emittance of 40% or more. At best $\gamma\epsilon_x$ went from 1.2 μm before BC1 up to 1.7 μm after BC1. The problem was magnified by the larger-than-design energy spread in BC1 due to a long initial bunch length.

Resolution To improve the field uniformity we decided to modify the poles of the two inner dipoles, BX12 and BX13, during the down-time in the Fall of 2007. After the inner dipoles were modified we routinely were able to get after BC1 $\gamma\epsilon_x$ of 1.0 μm or less, and emittance growth through the compressor was essentially unmeasurable. The estimated emittance growth based on measured second order dispersion was less than 5%, and based on measured first order dispersion was less than 1%, (after correction by the corrector quadrupoles, residual horizontal dispersion was about 0.6 mm). This experience led to the development of beam based measurement techniques which are described in the next section. Some details related to the design, fabrication, shimming and measurements are provided in the last section.

BEAM-BASED MEASUREMENTS

With the compressor dipoles installed and operational, the electron beam itself was be used to measure the integrated field uniformity to a very high precision — comparable or better than was possible with bench measurements. Beam-based methods were not only very sensitive, but also measured small but significant effects that were not included in the bench measurements: magnetic properties of the vacuum chamber, small mechanical changes to the dipoles that occur between bench measurements and assembly on the beamline (in the case of the LCLS the magnets were split and re-assembled), power supply or leakage current effects, effects of nearby iron, and any ambient fields from nearby magnets. Beam measurements necessarily integrate over the path of the beam, and in the case of the BC1 compressor only the combined effect of the two inner dipoles was be measured. Two methods of beam-based measurements were developed: chicane scanning and dispersion measurement.

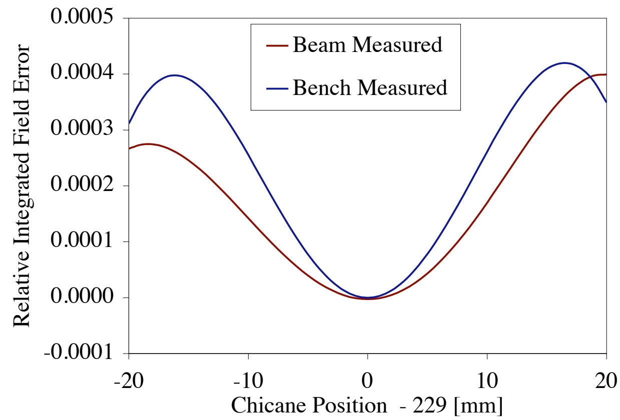

Figure 2: High resolution beam measurements of relative integrated field error compared with the sum of the bench measurements for both inner dipoles with the nonlinear components subtracted off of both.

Chicane scan method The "chicane scan" method involves physically moving the chicane while keeping the beam constant. This has the effect of sweeping the beam horizontally across the inner dipole aperture. Small changes in the integrated field result in measurable orbit differences downstream of the chicane. From the orbit differences the effective deflection angle of the inner dipole pair can be estimated and converted to a net average field error using the average transfer matrix elements. The results of such measurements on the modified dipoles are compared with the bench measurements in Figure 2. The difference between the two measurements is actually extremely small, being less than about 1×10^{-4} over the good field region. The beam measurement shows an asymmetry about the central position of the chicane which is probably due to a real, small, octupole component.

The chicane measurement technique was first used to help diagnose the original field uniformity problem with the inner dipoles. In Figure 3 the chicane scan measurement of the un-modified dipoles are plotted together with that of the modified dipoles. Note the vertical scale is $10\times$ that used in Figure 2.

Dispersion measurements The other beam-based measurement of field quality we employed was a measurement of the residual dispersion. Rather than physically moving the chicane the beam energy is changed, which then causes

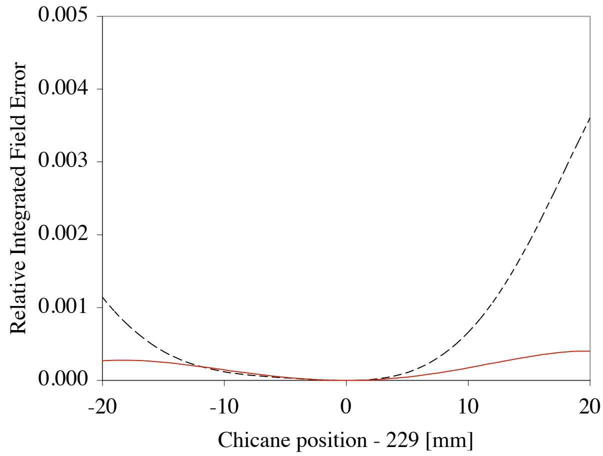

Figure 3: Chicane scan measurements of the net inner dipoles before (solid curve) and after (dashed curve) modificiations to the original dipole.

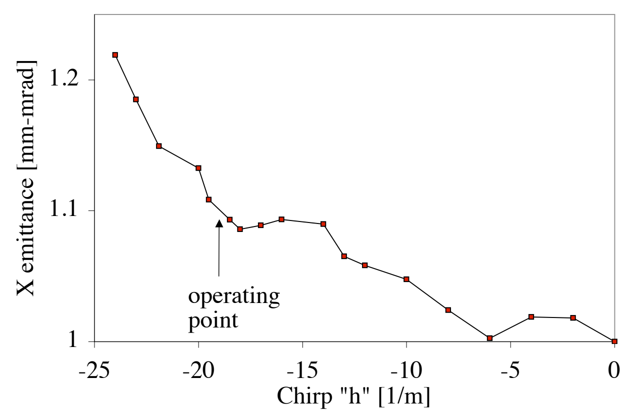

Figure 4: Based on tracking, the calculated normalized emittance after BC1 is plotted as a function of the chirp parameter for an initial emittance of 1.0 μm.

the beam to move horizontally in the inner dipoles. The resulting orbit motion downstream of the chicane was then used to determine the deviation of the net bend angle as a function of beam position in the inner dipoles. Energy restrictions effectively limited the beam motion to about $\pm 7\ mm$ in the inner dipoles, but this technique had the advantage of not mechanically or magnetically changing the dipoles.

Simulations We simulated emittance growth in BC1 based on tracking through the measured fields. The correlated energy spread is $\sigma_\delta \sim h\sigma_z$, where h is the 'chirp' or relative energy deviation slope along the electron bunch. As more chirp is applied, the horizontal size of the beam gets larger through the relation $\sigma_x \sim \eta_x\sigma_\delta$, where η_x is the horizontal dispersion function. In Figure 4 we show the predicted emittance growth as a function of h. For our nominal compression, (bunch length $\sigma_z = 830$ μm) we need $h \sim 19$ m^{-1}, and we should expect about $\Delta\epsilon_n/\epsilon_n \sim 10\%$ emittance growth with the modified dipole magnets. Slight bumps in the emittance growth curve arise because of corresponding features in the integrated field profile.

INNER DIPOLE DETAILS

Below we discuss some of the most relevant details related to the modification of the inner dipoles. Further details are given in reference [2].

Design The inner dipoles of BC1 compressor were required to move horizontally up to 250 mm. This capability, in part, favored relatively short and small dipoles. After it was determine that the field uniformity of the installed dipoles was not sufficient, the pole design was modified. We had to keep the same overall package size so the vacuum chamber and support hardware would not need to be re-designed as well. The original dipoles had a 100 mm

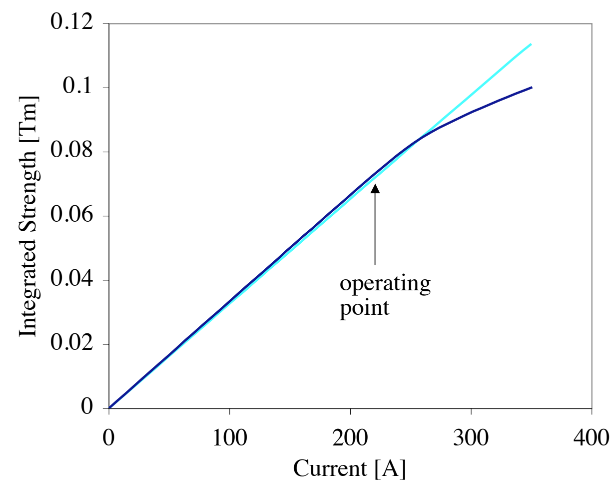

Figure 5: Integrated strength as a function of main coil current for the unmodified (light blue) and modified (dark blue) BX12 magnet.

wide pole, a total gap height of 43.5 mm and a length of 160 mm. The modified design increased the pole width to 180 mm and slightly reduced the gap to 43.0 mm. The modified design compromised maximum field strength in order to obtain a larger good-field region as is shown in Figure 5.

Modeling Because of the large gap/length ratio (43/160), approximately 25% of the integrated vertical field strength came from regions beyond the pole ends. We used a 3D model electromagnetic ANSYS model to determine the overall strength and saturation effects, so we could optimized the basic pole width. This model was sufficient to estimate the strength to about 1% accuracy. However, it was not sufficient to calculate the field uniformity at the 10^{-4} level that was needed. Instead we used 2D models for guidance and relied on iterative shimming and measurement to get the final field uniformity.

Table 1: These measurements, (in inches), are taken from the mechanical inspection of the modified magnet gaps.

	BX12	BX13
Parallelism	.0004	.0003
Flatness (top)	.00087	.00092
Flatness (bot)	.00076	.00057

Fabrication A somewhat unusual fabrication method for pole modifications was chosen to minimize field errors. After rough machining, the modified poles were assembled onto the yoke halves, and the halves were bolted together. This assembly was put into a high precision EDM machine, and the entire gap profile was cut in one set-up. The tolerance stack-up, which would have ordinarily included size and form tolerances independently for the various pieces, was reduced to tolerances for a single gap only. Selected mechanical measurements of the gap in the assembled dipoles are reported in Table 1.

Shimming Simply making the poles wider helps increase the size of the good-field region but is not enough to reach the target specification for field quality. For further optimization we used an iterative process of shimming and measuring. The field profile of the modified dipoles was first measured without any shims in place and was found to be in reasonable agreement with the ANSYS prediction. The sextupole and decapole multipoles were both negative and larger than desired. We then made up four shims out of steel strips 2 inches wide and a length to match the poles. They were arranged symmetrically in the dipole gap: top/bottom and right/left. The horizontal separation of the shims was optimized so that the measured integrated field strength was the same at the dipole center and at a point about 34 mm from center. Based on a rough theoretical model of the effect of the shims, if the field at 34 mm was about the same as at the center, the shims were near their best positions. At first .010 inch thick shims were used, but they were found to be a bit too weak and were replaced by .015 inch thick shims. After a few iterations the optimal position was found, and a full field scan was performed.

Bench Measurements Using a scanning wire the integrated magnetic field was measured as a function of horizontal position. The results are plotted in Figure 6. These measurements were verified with Hall probe and rotating coil measurements. The data were fit to a sixth order polynomial to yield the set of multipole coefficients given in Table 2. The effect of shimming was to make the sextupole term (b_2) roughly equal and opposite of the decapole term (b_4) in the region of interest. The odd numbered coefficients tend to be small because of the symmetry and reflect the overall geometrical accuracy of the top and bottom pole pieces. After modification the net nonlinear part of integrated field deviation satisfies the target goal of

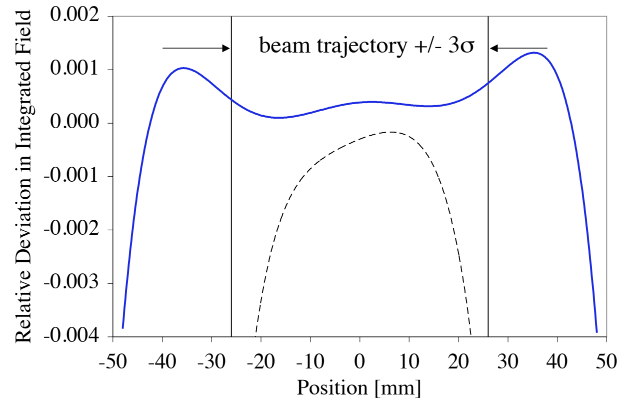

Figure 6: The solid(dashed) curve shows bench measurements of BX12 after(before) final modification and shimming.

Table 2: Measured normalized multipole coefficients, evaluated at a reference radius of 20 mm, for the modified BX12 and BX13 dipoles.

Coefficient	BX12	BX13
$\lvert b_1/b_0\rvert$	1.51E-04	-4.35E-05
$\lvert b_2/b_0\rvert$	-6.35E-04	-6.86E-04
$\lvert b_3/b_0\rvert$	-1.40E-05	-1.01E-05
$\lvert b_4/b_0\rvert$	6.42E-04	5.62E-04
$\lvert b_5/b_0\rvert$	-2.60E-06	7.76E-06
$\lvert b_6/b_0\rvert$	-1.15E-04	-9.85E-05

$\pm 5 \times 10^{-4}$ relative integrated field variation over ± 26 mm, even though some individual nonlinear terms do not.

CONCLUSION

The sensitivity of emittance to field quality of the inner dipoles of an FEL bunch compressor was amply demonstrated during the early commissioning of the LCLS. *In-situ* correction of linear gradient errors and linear dispersion was essential. Modifications to the dipoles to enlarge and improve the good-field-region were also found to be necessary and were successfully carried out. Chicane scanning and dispersion measurement methods were used, with excellent sensitivity, to measure overall field error both before and after the modification.

REFERENCES

[1] P. Emma, *Design, Parameters, and Tolerances for the LCLS First Bunch Compressor Chicane, BC1*, (2004).

[2] J. Welch, et. al., *Report on Modications to the BX12 and BX13 BC1 Dipoles*, LCLS-TN-07-12, (2007)