Tolerances for magnetic fields in the Gun-To-Linac region of the LCLS Injector*

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January 10, 2006

Abstract
In this technical note, we review the computations which led to the tolerances on residual quadrupole field terms in the magnets of the Gun-To-Linac region of the LCLS Injector. If the dipole terms can be cancelled by appropriately steering the beam, the quadrupole term damages the focusing scheme and generates an asymmetry in the horizontal and vertical emittances. Quadrupole terms deteriorate the emittance compensation process and thus would prevent us from reaching the low emittance requirement of 1mm-mrad projected emittance and 0.9 mm-mrad for the 80%-emittance for a 1nC bunch charge.

Part I – Description of beamline magnets

In figure 1, we show the layout of elements for the LCLS Injector beamline, from the gun to the end of the first linac section.
The four magnets of importance in this study (solenoid S1, quadrupole QG01, bending magnet BXS and solenoid S2) have been represented in blue. Both the QG01 and BXS are switched off for the standard operation of the LCLS. However, remnant magnetic fields in any of those two magnets can damage the emittance. The presence of a quadrupole component in the solenoid has been measured on the Gun-Test-Facility (GTF) solenoid and measurements have been reported in [1] showing values which are of concern for the LCLS solenoid, which is very similar in design to the GTF solenoid.

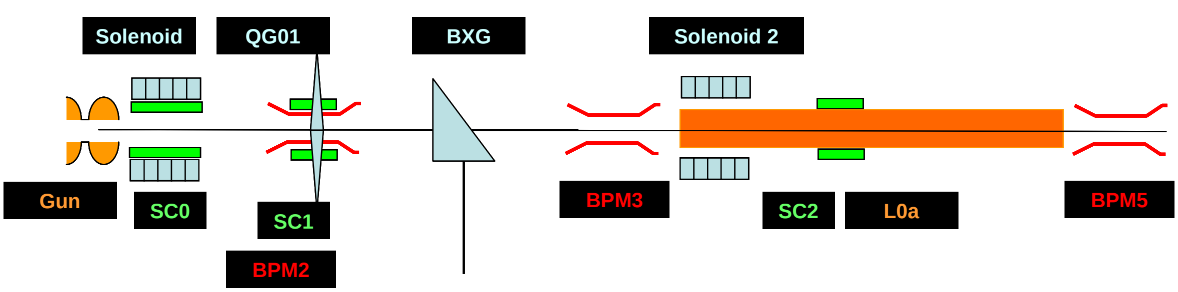

Figure1- Layout of the LCLS injector components from gun to the end of the first accelerating structure.

* Work supported in part by the DOE Contract DE-AC02-76SF00515.
This work was performed in support of the LCLS project at SLAC.

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In this technical note, we describe what level of quadrupole components need to be reached to meet the LCLS injector emittance requirements.

Part II- Quadrupole components in the gun solenoid (SOL1)

The solenoid is the key component for achieving "emittance compensation" in the injector. It provides a linear force which counteracts the linear space charge force which defocuses the beam at low energy.

The magnetic characteristics of the GTF gun solenoid have been measured [1] using rotating coils so that both amplitude and phase of the first 3 multipole components could be mapped along the longitudinal position of the solenoid. A description of the results has been given in figure 9 of [1]. It shows that some quadrupole fields are present at the entrance and at the exit of the ~20 cm long magnet, at the location of the end plates. The phase curve of figure 9 also shows that those two local quadrupole components have a 90 degree phase difference.
This 90 degree phase difference is all the more critical since the beam is rotating by approximately 90 degrees in the transverse (x,y) physical space while travelling through the solenoid. Accordingly, the two quadrupole kicks unfortunately contribute in the same detrimental direction.
As the LCLS solenoid is based on the same mechanical engineering, we suspect that similar quadrupole fields could be present. To model the quadrupole components effect, we assumed an equivalent system of two thin lens quadrupole, one focusing, the other one defocusing , located at +/- 10 cm from the center of the solenoid.

Simulation results

The quadrupole kick experienced by the beam deteriorates the emittance differently in both planes. A priori, one would believe that the error in focusing in one plane could be totally corrected by setting the solenoid field at a different value than the nominal one. For that reason, systematic solenoid field scans were performed. Those scans show that the minimum emittances in the two planes are obtained at two different solenoid settings as expected. But, moreover, both values of minimum emittances are also increased. Using the second solenoid did not helped either in recovering the emittance in a single plane.

The simulations presented here were performed with PARMELA. To avoid the issue of superposition of two maps of fields (quadrupole and solenoid), we applied single kicks out side the PARMELA code. For that purpose, we stopped the simulation at the first kick location, imported the distribution in Matlab, applied the focusing quadrupole kick, exported the distribution back to PARMELA, restarted the simulation and proceeded similarly for the second kick but with a defocusing kick this time. The procedure is totally automated in the Matlab/PARMELA toolbox.

Simulations results have been plotted in figure2 –a-b-c-d-e.
The case with no kicks was verified to give the nominal projected emittance of 1mm-mrad in both planes for the nominal parameters of 1nC, 10ps flat top laser pulse with 0.7 ps rise/fall time and a 0.6 mm-mrad thermal emittance per mm of laser radius spot size. This case is illustrated in figure2-a.

Figure 2b-c-d-e illustrate the cases of individual quadrupole kicks for which the focal lengths are respectively of 60m, 50m, 40m, and 30m.

A 60 m focal length corresponds to a 3.3 G integrated quadrupole field for our 6MeV beam.

For this particular number, the emittance growth is larger than 5%. It gets distributed in the two planes (horizontal and vertical) either as (0%,10%) or (2%,5%).

Both situations are undesirable for the LCLS so a specification of less than 2G integrated quadrupole field was specified.

Plans to add shimming pieces to cancel those quadrupole components at the location of the end plates are presently contemplated to meet this requirement.

Correction based on the quadrupole QG01, is unlikely to work as the orientation of the quadrupole components in the solenoid magnet have no reason to be the same as that of the QG01 quadrupole.

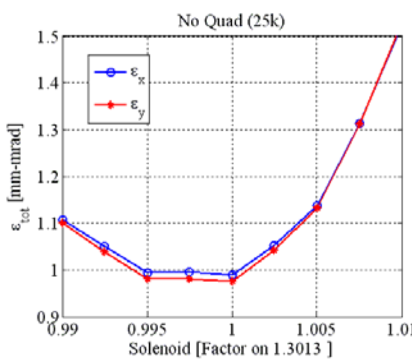


Figure 2 a- No quadrupole component in solenoid

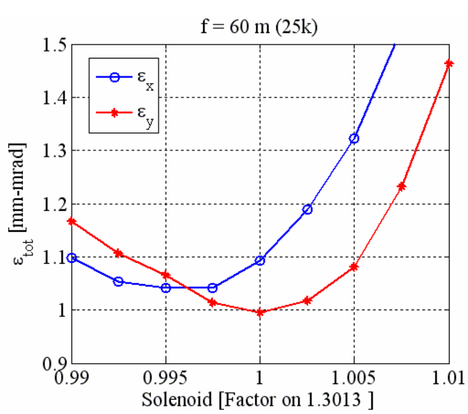


Figure 2b- f = 60 m

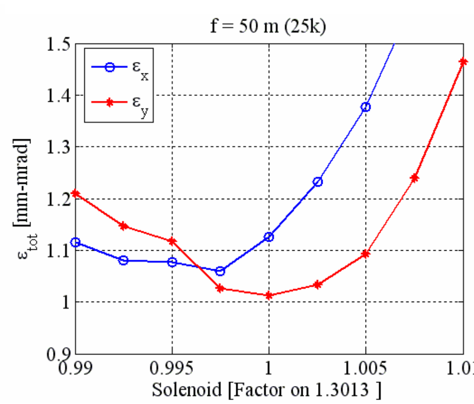
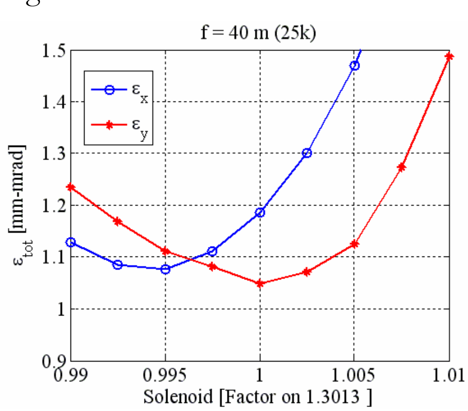


Figure2c- f = 50 m



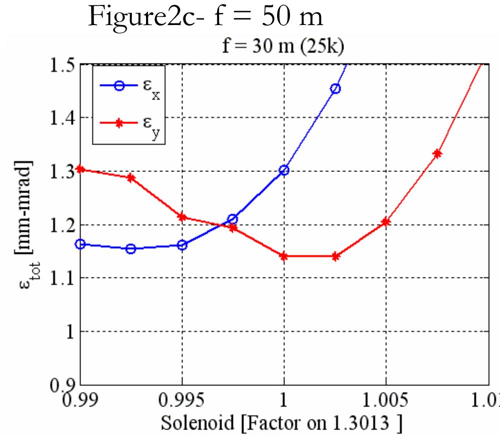


Figure 2d- f = 40 m Figure 2e- f = 30 m

Part III- Remnant field in the QG01 quadrupole

The QG01 quadrupole is located in the straight line of the GTL region as shown in figure 1. However it is not used in the focusing of the straight beam, but only for the beam sent to the gun spectrometer beamline.
For the standard operation, the straight beam should not be perturbed by any remnant quadrupole field.
Degaussing measurements have been performed on a quadrupole of that family. The results have been summarized in [2]. The degaussing procedure proposed meets a maximum 5 G integrated field. We believe , that a maximum integrated field of 3G could be reached.
This tolerance requirement is justified by the simulations results summarized next.

Simulations

PARMELA simulations were performed with the 7.6cm long QG01 positioned at its z = 83.82 m location from the cathode.
Solenoid scans were performed again in that case to define if the emittance could be minimized. Also in this case, the second solenoid could not compensate for the increase in the minimum emittance, and the final emittances got deteriorated in both planes.

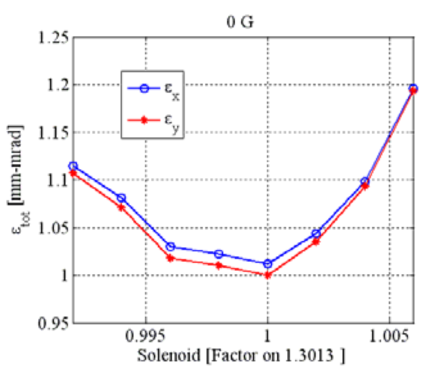


Figure 3a- No Quadrupole field

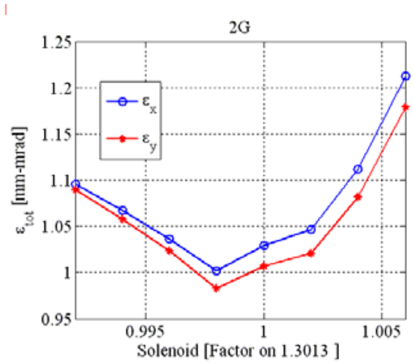


Figure3b- 3 G Integrated field

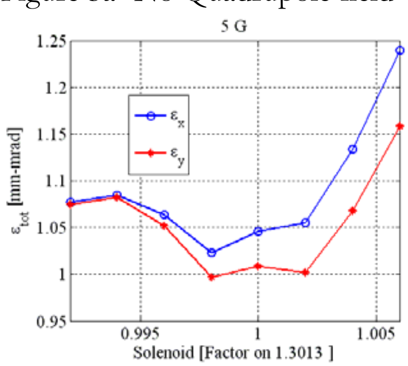


Figure 3c- 5G integrated field

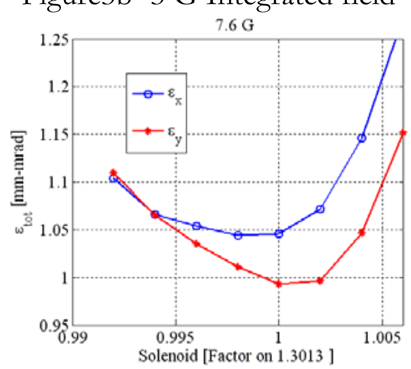
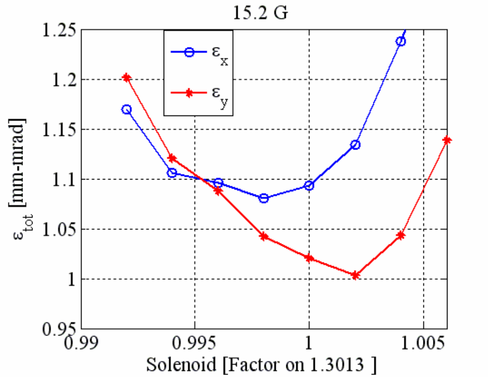


Figure3d- 7.6 G integrated field



Figrue 3e- 15 G of integrated field

Part IV- Remnant quadrupole field in the Spectrometer Bending magnet (BXG)

The BXG magnet is located at z = 111cm from the cathode. For this reason, the computations performed for the QG01 quadrupole magnet located at z = 83.8cm also apply for the quadrupole component of the BXG magnet. Accordingly, we did not repeat the calculation. Even if the tolerance is probably very slightly relaxed compared to that of QG01 remnant field, we set the tolerance to no more than 3 G integrated field.

Part V- Quadrupole components in the second Solenoid (SOL2)

The second solenoid (SOL2) is wrapped around the entrance of L0a. It is used to finalize the emittance compensation process. It provides the focusing which cancels for the defocusing kick seen at the entrance iris of the L0a accelerating structure. The SOL2 magnet allows to decrease by 10-15% the emittance in the case of the LCLS nominal design tuning of 1nC.

Simulations

PARMELA simulations were performed using a procedure similar to that used for the first solenoid studies. In particular, to avoid the problem of overlapping a quadrupole map of field with a solenoidal map of field, single quadrupole kicks were applied outside the procedure.

We assume again that the quadrupole components are concentrated at the location of the end plates. For a peak longitudinal field of 1.5kG, which corresponds to the nominal tuning, the rotation angle of the beam is 42 degrees. Accordingly, the worse configuration would correspond to two quadrupole components with a phase of 42 degrees.

To simplify this calculation, we only used a single quadrupole kick located at the entrance plate. To determine the tolerance, we divided the minimum strength obtained with that configuration by 2. For that reason, we give a 6 G integrated quadrupole field as 12G seems to be the onset for a single kick.

Figures 4-a-b-c-d summarize the results from those simulations. In figure4b, the minimum emittance is still that of the case of no quadrupole, but it starts taking off. A clear take-off of emittance can be seen on figure4c for which the single kick corresponds to 20G.

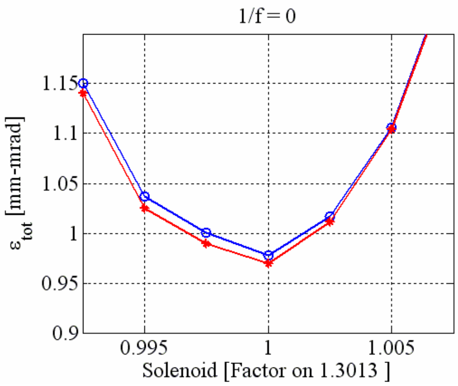


Figure4a- No Quadrupole

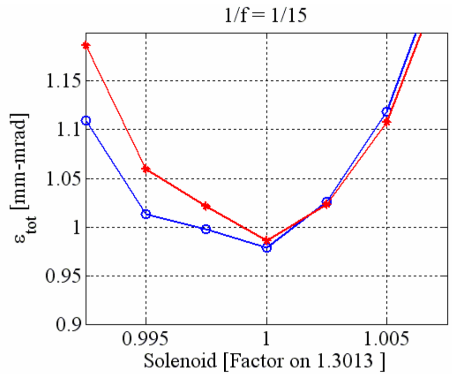


Figure4b- 13.3 G integrated (f = 15m)

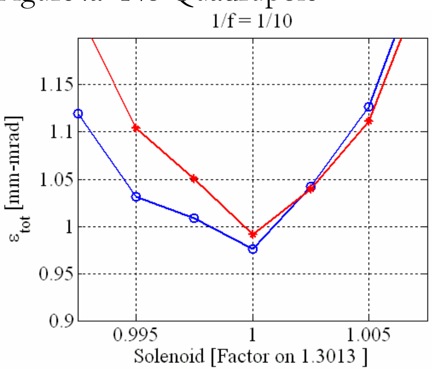


Figure 4c- 20 G integrated (f = 10m)

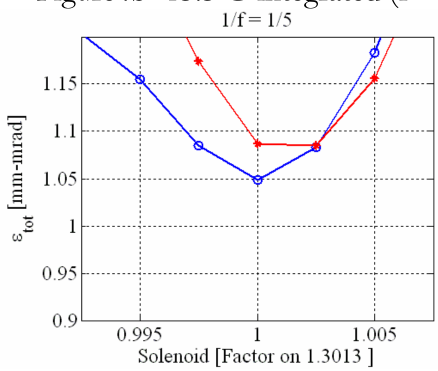


Figure 4d- 100G integrated (f = 5m)

Part VI- Conclusion

The author would like to apologize for not using exactly the same baseline for the nominal deck with no quadrupole field. The projected emittance was 1mm-mrad for the calculations of Part2-3-4, but 0.97 for part V, due to historical evolution of the deck. Anyway, even if the absolute value might be slightly off, as it depends on time step size, spatial meshing and number of particles used, the relative increase on the beamline should be very close to what has been computed here, with 25k distribution particles, and well assessed meshing parameters.
Table1 summarizes the tolerance on those quadrupole components.

Integrated quad. field	S1 (*)	QG01	BXG	S2 (*)
$\partial B/\partial x$ * Leff [G]	2	3	3	6

Table 1- Maximum tolerable quadrupole component expressed as integrated quadrupole field.
(*) for each of the quadrupole component which might be present at the end plates

The level of deterioration of the beam emittance due quadrupole kicks decreases as the beam is traveling along the beamline and the emittance compensation gets finalized.

References:

[1] J. Schmerge "LCLS Gun Solenoid Design Considerations", LCLS-TN-05-14, Jun2005, http://www-ssrl.slac.stanford.edu/lcls/technotes/lcls-tn-05-14.pdf

[2]. A.W. Weidemann "", LCLS-TN-06-3, "A Degaussing Procedure for the QG01 Quadrupole Magnet." (January 2006)