LCLS-TN-02-5
January 30, 2002
Revised July 14, 2002

Concerns with Respect to QUAD LI20 901

J. Clendenin

Quad LI20 901 is approximately 3.4 m after Section 20-8C and 5.6 m before Section 21-1B. (There is no Section 21-1A.) The quad has an aperture radius of r=0.01378 m and an effective length of L=0.1068 m. With the present linac 50-GeV lattice it is run at a nominal strength of BDES=GL=(B/r)L=79.738 kG. Thus the field at the pole tip is B=10.288 kG and *the maximum possible dipole strength under any condition (i.e., short or no short) with the quad strength at its nominal value*, which in fact will occur only at the pole tip, is $BL=BL^{max}$=1.0988 kG-m or 0.10988 T-m.

A dipole will bend the beam according to:

$$\theta[rad] = 0.3\frac{\int Bdl[T-m]}{cp[GeV]}.$$

Thus the maximum possible bending angle will occur for a beam just grazing the pole tip, i.e., θ ~1 mrad for a 33 GeV (at Sector 20) beam.

Case 1. Beam is missteered so it just grazes a pole tip, quad strength is normal, beam energy is 33 GeV.

The maximum possible geometric angle of the beam through the 3 accelerator sections of 20-8 is 2 mrad. This would result in a maximum transverse offset of the beam from the center of the quad of ~21 mm, while the pole tip is at 13.8 mm. Thus the quad pole establishes the maximum beam angle. The maximum angle (the beam skims the entrance iris, r=9.5 mm, of 20-8A on the side opposite the subject pole) of a beam just at the pole tip is 1.9 mrad. The pole will bend the beam an additional 1 mrad, but in a direction perpendicular to the plane formed by the incoming beam path and the centerline of the vacuum pipe. Thus the total angle after Quad 901 is ~2.1 mrad. The resulting total offset at the entrance to 21-1B will be ~25 mm. The vacuum pipe between 901 and 21-1B will have a 38-mm radius (3" pipe). Thus the beam will not hit the vacuum pipe.

Case 2. Beam is missteered so it just grazes a pole tip, quad strength is normal, beam energy is low.

As the beam energy decreases, the transverse offset at 21-1B will increase. The beam will not hit the wall of a 3" pipe at the location of 21-1B until the beam energy at Sector 20 is reduced to ≤6 GeV.

Case 3. Beam is centered, quad coil is shorted, beam energy is 33 GeV.

If one or more turns of a quad coil is shorted, B at the pole tip decreases, while at the center of the quad a non-zero dipole term develops. If all the turns of a given pole are shorted, it remains an active pole because of the flux pumped through air and through the connecting back plates by the remaining coils. Let us ignore these mitigating factors and instead assume that for a completely shorted coil the dipole strength in the center of the quad is equal to BL^{max}. (In reality it will be much less, *but it cannot be more*.) This will result in θ~1 mrad, for which the offset at 21-1B is only 5.6 mm, far short of the 38 mm radius of the beam pipe.

How do the calculations for Case 3 compare with experience? We can make the following estimate:

The steering of the beam due to linac quads that have shorted in the Sector 10 region have been successfully compensated using one (or sometimes also part of a second) of the nearby correctors at maximum strength.

The correctors in S-10 are the Linac Type 4; strength is $\int Bd\,l/I = 10^{-2}\,kG - m/A$; the corrector drivers provide a maximum current of ±4 A. Thus BL=4×10^{-2} kG-m. One and a half such correctors is 6×10^{-2} kG-m. The equivalent correction kick at S-20 (where the quad strength is double what it is in S-10) would require 0.12 kG-m. This is significantly less than the dipole strength assumed (for the sake of this presentation) in Case 3 at the center of Quad 901 with a completely shorted coil (but is probably closer to the actual dipole strength at centerline of a shorted quad).

Case 4. Beam is centered, quad coil is shorted, beam energy is low.

As the beam energy decreases, the transverse offset at 21-1B will increase. The beam will not hit the wall of a 3” pipe at the location of 21-1B until the beam energy is reduced to ≤5 GeV.

The beam offsets that result from Cases 1-4 are compared in **Table 1**.

Table 1. Comparison of Beam Offsets Under Various Abnormal Scenarios.

Case	**Offset @ Quad (mm)**	**Energy (GeV)**	**Total Angle after Quad (mrad)**	**Offset @ 21-1B (mm)**
1	13.8	33	2.15	25
2	13.8	6.3	5.2	38
3	0	33	1	5.6
4	0	5	6.8	38

Probabilities for various abnormal scenarios.

A. Beam missteered at Sector 20. The probability that the beam will be significantly missteered is very low. There is only one case of a significantly missteered high energy beam in the past 14 years. This occurrence during a change in the mix of beams (combinations of ESA beam, FFTB beam, test beams, etc.) could be classified as a human error. If it is assumed that there is one such change per week (so 1 opportunity per week for human error of this type), and if we consider the SLC era to present, 14 years, the probability of a significantly missteered beam anywhere in the linac (operating on average 40 weeks per year) occurring in a given week is $\sim 2\times10^{-3}$.

There are 30 linac sectors, so the probability the missteering occurs at Sector 20 is 3×10^{-2}.

The probability the missteering is large enough to place the beam close to a quadrupole pole tip is conservatively estimated as 5×10^{-1}.

Thus the total probability during a given week for a missteered beam near the Quad 901 pole tip at Sector 20 is $\sim 3\times10^{-5}$.

B. <10-GeV at Sector 20. The probability for a <10 GeV beam at Sector 20 when a 33 GeV beam is expected is very low. The most likely time for this to occur is during start up or when switching the beam back on after an extended period (hours or more) of being off. In these situations, the standard procedure is for the beam to be tuned up or checked at 1 or 10 Hz before switching to 120 Hz. At least since the SLC era (1988 on), upon switching to 120 Hz, the beam at Sector 30 has never been lower than design by more than ~5 GeV. If one assumes there is one such opportunity per week, and that in another 14 years there will actually be a <10-GeV beam at Sector 20 instead of 33 GeV, this is a probability of about 10^{-3}.

Actually it would be very difficult (but not impossible) to transport a <10-GeV beam to Sector 20 without significant beam loss when the lattice is set for much higher energy. This introduces another probability factor. We will here assign the very conservative value of 5×10^{-1}.

The total probability during a given week for a <10-GeV beam at Sector 20 is thus 5×10^{-4}.

C. Quad coil shorted. There are approximately 300 quadrupoles in the linac. If there is 1 shorted coil per year, then the probability in any given week of a quad with a shorted coil is 8×10^{-5}. Most shorts are only partial shorts (some fraction of the total turns in a given coil.) If we assume 10% of the shorts are for the total coil, then the probability during a given week that Quad 901 will experience such a total short is $\sim 10^{-5}$.

D. Quad strength high. The quadrupoles in Sector 20 are in a string, the main current provided by a bulk supply (controlled through LGPS LI20 1). The individual quad currents are adjusted over a narrow range by a booster supply. For the high-energy lattice, the typical bulk current is ~134 A, the booster ~5 A. If either supply is not providing the correct current, it turns the CUD red. Since there are very few bulk supplies, a red LGPS would be unlikely to be missed by the operators. The booster can supply up to 20 A. Thus it alone can change the total field strength of the quad (and thus of any dipole component) by no more than 10%. In a scenario in which the beam sees a dipole component (beam missteered at S-20 or Quad 901 has a shorted coil), the maximum increase in the booster current would produce a steering effect equivalent to a 10% decrease in the beam energy, which for purposes here is insignificant. The bulk supply can go to 200 A, which is an increase of ~33%. In terms of maximum steering, this is equivalent to an energy decrease of 33%, or about 25 GeV at Sector 20 vice 33 GeV. Thus a missteered beam cannot hit the beam pipe before 21-1B even if the Quad 901 power supplies (bulk and booster) are somehow at maximum value. Since a high-energy beam has never been turned on at high repetition rate with the bulk supplies not at their proper value, the probability for this happening is assigned the same value as the probability of <10-GeV above, viz., 10^{-3}.

The probabilities for various scenarios are summarized in Table 2. Relatively conservative estimates have been made. When one considers multiple abnormal scenarios occurring simultaneously, the resulting product of their individual probabilities is multiplied by the number of scenarios to account for a degree of non-independence. Note that for each of Cases 1-4, if it is allowed that the quadrupole strength is increased to its maximum possible value, the resulting probabilities when the beam can hit the vacuum pipe are extremely small compared to that of any of Cases 1-4 where the beam cannot hit the pipe.

Table 2. Summary of Probabilities for Various Abnormal Scenarios

Abnormal Scenario	Maximum neg. result	Probability
A. Beam missteered at Sector 20		3×10^{-5}
B. <10-GeV beam to Sector 20		5×10^{-4}
C. Quad coil shorted		10^{-5}
D. Quad strength high		10^{-3}
Case 1: A	Cannot hit vacuum pipe	3×10^{-5}
Case 2: AxBx2	Beam hits pipe for ≤6 GeV	3×10^{-8}
Case 3: C	Cannot hit vacuum pipe	10^{-5}
Case 4: BxCx2	Beam hits pipe for ≤5 GeV	10^{-8}
AxDx2	Cannot hit vacuum pipe	6×10^{-8}
AxBxDx3		5×10^{-11}
CxDx2	Cannot hit vacuum pipe	2×10^{-8}
BxCxDx3		1.5×10^{-11}

Acknowledgements: F.-J. Decker, J. Seeman and D. Walz have contributed many of the ideas presented in this document.