JLAB-TN-07-020

Alignment and Powering Specifications for the 12 GeV Upgrade

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Abstract

The element alignment tolerance and magnet powering specifications for the 12 GeV upgrade are presented. The specifications presented make use of design studies of the 4 GeV CEBAF, operational experience with 6 GeV CEBAF and simulations of the 12 GeV design. The scope of this paper is to verify that the installed equipment meets the specifications for 12 GeV design and to define the specifications and requirements on the new 12 GeV equipment; specifically ArcA and Hall-D.

1 Transverse Alignment

Each element installed on the beam line is not located on the design orbit. In order to determine alignment tolerances, the alignment utilities in DIMAD are used. The study for the 12 GeV design is very similar to that in [1]. One major difference is that in TN0141, transverse shifts were increased until *mathematical* particle loss occurs. In this study the apertures in the Spreader/Arc/Recombiner components are properly defined and **real loss** of particles is used as a basis of determining the transverse misalignment specification. The requirement used to set the tolerance is that no more then 25% of the particles can be lost before corrections. This way beam transport is sufficient for corrections to occur. While it is best if the beam is transported to the end of recombiner, procedurally the insert-able dumps at the nR02 location can be used to terminate the beam at those locations while the `auto-steer` utility corrects the beam in the Arc proper. Thereby reducing the error stack-up for those elements beyond the insert-able dumps. The requirement contained within TN0141 are that the RMS of transverse shifts be less then 200 μm and the angular alignment of quadrupoles must be less then 2/3 mrad.

Aside from the proper definition of aperture, the simulations are carried out in a similar fashion as those in TN0141. The dipole magnets are shifted with the DIMAD `misalignment data definition` command, using option 2. This command/option shifts the entrance and exit of the dipole independently. The quadrupole magnets are shifted with option 1, which shifts the entrance of the quadrupole and then introduces a pitch and yaw onto the quadrupole. All transverse shifts are randomly generated with Gaussian distribution truncated at 2σ. The initial particle distribution, (x, x', y, y', p, dp) is also generated as a Gaussian and truncated at 2σ where σ is the design RMS values and with the centroid of the distributions equal to the design values. The simulations are performed with different seeds and at least ten simulations are performed and averaged.

1.1 Existing Arcs

The studies on the existing Arc lines include Arc6 through Arc9. For existing elements the studies are used to verify that the old 4 GeV specification is sufficient. For new elements the studies serve to provide the 12 GeV alignment tolerance. The 12 GeV beam optics in the Arc proper is identical to the 4 GeV optics, however the beam size is larger due to larger beam emittance. The 12 GeV beam optics in the spreader and recombiner sections are very different then the 4 GeV optics. The beam sizes and optics in Arc1 through Arc5 are sufficiently close the 4 GeV design optics, that these Arcs where not studied and the specification in TN0141 is accepted for these Arcs.

Table 1 contains the summary of the simulations for Arc6 through Arc9. All dipole and quadrupole magnets are misaligned with a Gaussian distribution cut off at 2σ. 5000 particles with design parameters (2σ Gaussian distributions) are launched at the beginning of the spreader and tracked to the insert-able dumplette at the R02 location. The amount of transverse misalignment is increased in 50μm steps until more then 25% particle loss occurs. The full width at base for 75% transmission and pinch points are listed in the last column of Table 1. The tolerance is taken to be half of the full width at base, $|X|, |Y| < 0.5$ mm and $Pitch/Yaw < 1.7$ mrad. For a uniform distribution, this will result in $X_{RMS} < 0.3$ mm and $Pitch/Yaw_{RMS} < 1$ mrad.

Arc	Transverse Full Width at Base	Pitch/Yaw Full Width at Base	Pinch Location
	(mm)	(mrad)	
6	1.2	4.0	6A17
7	1.2	4.0	7A01
8	1.0	3.3	8A25
9	1.2	4.0	9A18

Table 1: Maximum transverse shifts and pitch/yaw angles for at least 75% transmission to the recombiner dumplette for the existing Spreader/Arc/Recombiner sections. The pinch location column lists the first element location where particle loss occurs. The alignment tolerance is half the full width at base value.

1.2 ArcA and HallD

The same procedure to is used for the 12 GeV designs of ArcA and Hall-D transport.

For the new tenth Spreader/Arc/Recombiner there is an extreme sensitivity to alignment errors starting at the fourth recombiner quadrupole girder (AR04) to the end of the recombiner. This location is downstream of the proposed insert-able dumplette location for the new ArcA so this region need not see the entire error stack-up. When simulations are terminated at the dumplette location, R02, the beam loss occurs at the sixth quadrupole magnet in the Arc. Simulations show that once corrections have been applied in the beam transports through the Arc to the end of Recombiner.

Transverse alignments for the Hall-D transport line have also been studied and are included in Table 2 along with the ArcA results.

Section	Transverse Full Width at Base	Pitch/Yaw Full Width at Base	Pinch Location
	(mm)	(mrad)	
ArcA	1.0	3.3	AA06
Hall-D	1.2	4.0	5C14A

Table 2: Maximum transverse shifts and pitch/yaw angles for at least 75% transmission to the recombiner dumplette for the new ArcA and Hall-D sections. The pinch location column lists the first element location where particle loss occurs. The alignment tolerance is half the full width at base value.

2 Longitudinal Alignment

Quadrupole longitudinal alignment studies are carried out in a similar fashion to the transverse studies. The results are very similar to those in TN-0141, resulting in a requirement the RMS of the longitudinal displacement be less then 5 mm. Assuming a uniform distribution this results in a tolerance of $|Z| < 8.7$ mm.

Arc dipole magnet longitudinal alignment tolerance is determined from the allowed change in pathlength caused by a systematic shift in the dipole placement. We require that the change in pathlength due to longitudinal alignment be kept to 1° of phase, this is about 20% of the dogleg capacity for Arc8 and Arc9 in the 12 GeV design. If the dipole placement follows a distinct positive, negative, positive, negative $\cdots$ placement, the accumulated change in the pathlength is maximal. A pattern of +3mm,-3mm,+3mm,-3mm,$\cdots$ shifts in the Arc dipole magnets yields a 1° change in phase at the end of the Arc and |Z| < 3 mm is taken as the longitudinal alignment tolerance for Arc dipoles.

3 Field Stability Requirements

The magnetic field quality is a result of the mechanical design of the magnet and the stability of the power supply providing the electrical current. In this section the field stability requirements for the 12 GeV accelerator are defined. The requirements are defined in terms of field stability. The required power supply current stability required to achieve these field stability requirements will depend on the magnet design and other factors. The field stability requirements are divided into two types; correlated (several magnets sharing the same power supply) and uncorrelated (independent power supplies, independent sources).

3.1 Uncorrelated Quadrupole Field Stability

The effect of the quadrupole field ripple is studied by randomly smearing the quadrupole field in a Spreader/Arc/Recombiner section and measuring the growth in the Courant-Snyder invariant at the end of the section. Operationally the Courant-Snyder invariant growth is kept to within a factor of two from start to end during beam delivery. A factor of two over 5 passes, corresponds to $\sim 10\%$ growth per Arc. Additional growth in the Courant Snyder invariant due to quadrupole magnet field ripple is limited to 1% per Arc. Figure 1 shows the results of the simulation for the ArcA.

The simulation consists of 50 or more DIMAD runs at each level of field ripple, each with different seeds. The average and RMS of the Courant-Snyder invariant at the Recombiner section for the runs is calculated. Since the Courant-Snyder invariant is defined to unity for a perfectly matched line, the quantity, the percent growth compared to design in the Courant-Snyder invariant is calculated. Figure 1 is a plot of the simulated amount of quadrupole field ripple and the resulting increase to the Courant-Snyder invariant in the simulations. A linear fit to the data (which is not linear) in the 0.01% to 1% CS region results in a slope of $\frac{\partial CS}{\partial FieldRipple} = 2800$, resulting in a requirement that for less then a 1% growth in Courant-Snyder the uncorrelated field ripple must be less then 3.6×10^{-4} of the nominal field. The 4 GeV specification on uncorrelated quadrupole field ripple was 1×10^{-4}.

3.2 Correlated Quadrupole Field Stability

Using the same criteria and similar procedure as in the previous section, the effects of a correlated change in quadrupole field is investigated. The spreader, arc, recombiner system is designed to

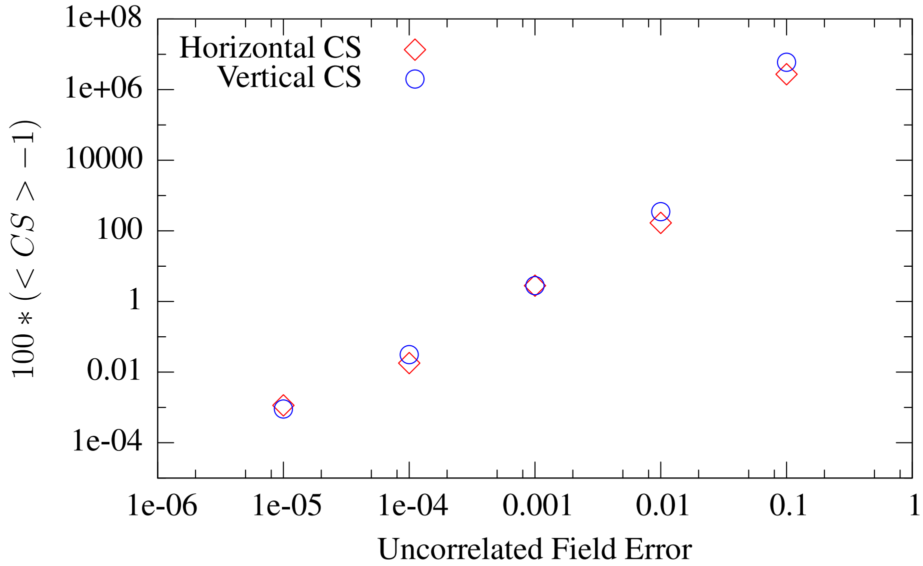

Figure 1: Percent wobble in the Courant-Snyder invariant due to uncorrelated quadrupole field ripple.

be a second order achromat and as such the correlated errors are suppressed when compared to the uncorrelated errors (which change the phasing and reduce error cancellation throughout the system). The results for Arc2 through ArcA are shown in Figure 2 and when compared to the uncorrelated results in Figure 1 the effects of the correlated results are slightly less sensitive then the uncorrelated results for ArcA. The uncorrelated requirement if met, implies that the correlated field stability requirements are satisfied.

3.3 Correlated Dipole Field Stability

Dipole field ripple causes the beam trajectory to change. The new trajectory results in an increase in the orbit RMS and contributes to the RMS error budget. The error budget for the RMS orbit is 600 μm and is required to minimize beam sampling the non-linear fields. We require that the additional RMS orbit due to field instabilities be limited to 100 μm, which when added in quadrature to the 600 μm results in a negligible increase in the RMS orbit. Simulation identical to the previous section are performed. The observable being the the RMS of the beam orbit through the Arc.

The results of DIMAD simulation of the measured RMS orbit for different amounts of dipole field ripple are shown in Figure 3. Linear fits to the data are performed and the resulting slopes are tabulated in Table 3. Also in Table 3 is the requirement on the field ripple.

The design M_{56} of the complete Spreader-Arc-Recombiner section is zero. Any correlated dipole field ripple that is sourced throughout this section has no effect on pathlength. For Arc1 and

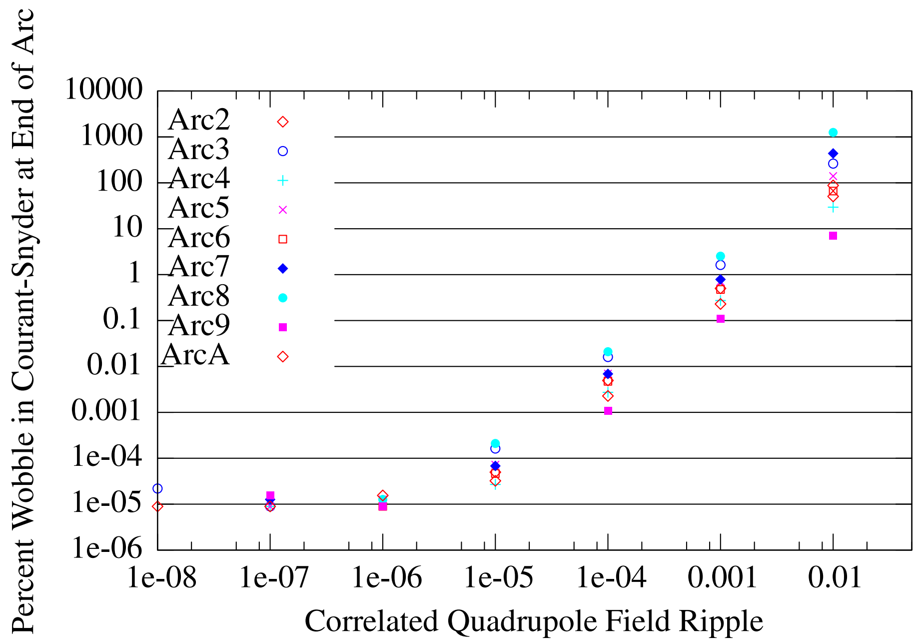

Figure 2: Percent wobble in the Courant-Snyder invariant due to correlated quadrupole field ripple.

Arc2, all the dipoles within the Spreader-Arc-Recombiner are powered from the same source, so a localized source is improbable. For the higher Arcs, the initial "BCOM" magnet is powered independently of the rest of the Spreader-Arc-Recombiner system. A dipole field ripple that is sourced locally will change the traversed pathlength. A changing pathlength will result in an increase in the bunch length and when accelerating through the linac the energy spread will increase. The change in pathlength is proportional the M_{56} of the section between the point sources. The maximum M_{56} between the spreader and recombiner is 0.26 m (Arc3), allowing for a 60 μm changed in pathlength (about 7% of the equivalent bunch length for the design dp/p) this corresponds to $\frac{60\times10^{-6}m}{0.26m} \leq 2.3\times10^{-4}$ requirement on the field ripple. Higher arcs have a more relaxed requirement; M_{56} is smaller for the higher arcs and the energy spread is larger. ArcA, for example, has an energy spread of $dp/p = 2\times10^{-4}$ allowing for a 7% growth in dp/p results in a pathlength equivalent of 160 μm, with $M_{56} = 0.090m$ gives field ripple specification of 1.8×10^{-3} a factor of ten larger then Arc3. Table 4 tabulates the pathlength allowances, M_{56} and allowed field ripple for Arc3 through 10 .

4 Summary

Tables 5 and 6 list the alignment and field ripple specification for dipole and quadrupole magnets in the 12 GeV design. The 12 GeV beam optics are very similar to the 4 GeV design optics. The studies used to determine these specifications are based on the studies used for the 4 GeV design

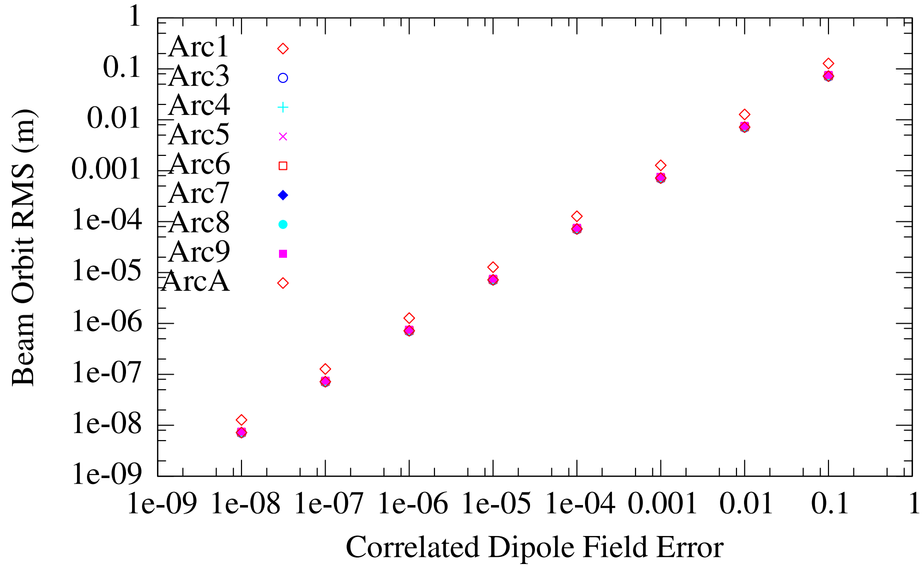

Figure 3: Growth in the measured beam size due to correlated dipole field ripple.

and in most cases reproduce the results found in [1].

References

[1] D. Douglas, J. Tang, R. York "Preliminary Alignment and Powering Tolerances for Arc Beam Transport System", `JLAB-TN-0141`.

[2] A. Bogacz and Y. Roblin "Magnetic Field Specification for the Multipole Content of Dipole and Quadrupole Magnets in the 12 GeV Upgrade", `JLAB-TN-07-018`.

Arc	Slope	Allowed Growth	Field Ripple Specification
	(m/Field Error)	(m)	
1	1.28	0.000100	7.8×10^{-5}
2			
3	0.712	0.000100	1.4×10^{-4}
4	0.717	0.000100	1.4×10^{-4}
5	0.722	0.000100	1.4×10^{-4}
6	0.728	0.000100	1.4×10^{-4}
7	0.741	0.000100	1.4×10^{-4}
8	0.709	0.000100	1.4×10^{-4}
9	0.760	0.000100	1.3×10^{-4}
10	0.719	0.000100	1.4×10^{-4}

Table 3: The 12 GeV requirements correlated dipole field stability.

Arc	Allowed Pathlength Growth	M_{56}	Field Ripple Specification
	(μm)	(m)	
3	60	0.264	2.3×10^{-4}
4	66	0.189	3.5×10^{-4}
5	82	0.107	7.7×10^{-4}
6	103	0.136	7.6×10^{-4}
7	112	0.064	1.8×10^{-3}
8	128	0.068	1.9×10^{-3}
9	147	0.084	1.8×10^{-3}
10	158	0.090	1.8×10^{-3}

Table 4: The 12 GeV requirements for correlated dipole field stability based on maintaining the dp/p to an 7% based on pathlength variation at the end of the recombiner.

Parameter	Units	Specification
|X|,|Y| transverse	mm	<0.5
|Z|	mm	< 3
Roll	mrad	<1
AC field Ripple(correlated)	% field	<1.3×10^{-4}

Table 5: The 12 GeV requirements for dipole magnets. Tolerances are for magnet placement relative to the design location and for field strength relative to design strength.

Parameter	Units	Specification
|X|,|Y| transverse	mm	< 0.5
|Z|	mm	< 9
Pitch/Yaw	mrad	<5/3
AC field Ripple(uncorrelated)	% field	$<3 \times 10^{-4}$
AC field Ripple(correlated)	% field	$<3 \times 10^{-4}$

Table 6: The 12 GeV requirements for quadrupole magnets. Tolerances are for magnet placement relative to the design location and for field strength relative to design strength.