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IR Upgrade Octupole Trim Requirements

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Abstract

We estimate the field strengths required in IR Upgrade octupole trims.

Use of Octupole Trims

Longitudinal phase space management in the IR Upgrade has been described in some detail elsewhere [1]. Octupoles will be used in the energy recovery transport line of the IR Upgrade to improve the momentum acceptance of the energy compression/energy recovery. The specific actions of the trim are 1) the correction of lattice W_{5666} and 2) the pre-compensation of torsion (ϕ_{RF}^3 dependences) in the RF waveform.

W_{5666} Compensation – Uncompensated variation of path length with $(\delta p/p)^3$ will lead to significant deviations of beam behavior from linearity. Figure 1 illustrates this lattice aberration for the Revision 0.1 IR Upgrade driver design [2]. $M_{56} \sim +0.2$ m and $T_{566} = 0$ in this graph; significant cubic (and higher order) behavior is evident beyond ±5% momentum offset.

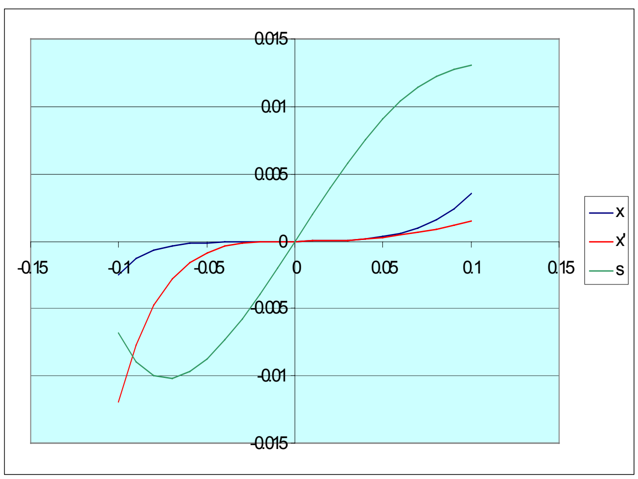
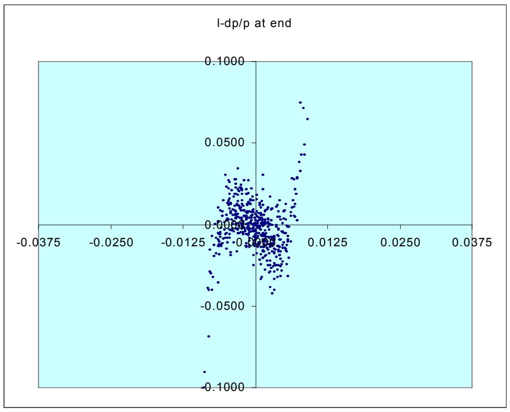


Figure 1: Horizontal position and angle and path length as a function of momentum for transport through a single end-loop of the Revision 0.1 Upgrade Driver design.

An estimate of W_{5666} may be had by noting the cubic rollover begins to force the path length well away from linearity by $\delta p/p = \pm 0.1$; the cubic term and the linear may thus be expected to cancel at a $\delta p/p$ somewhere in the vicinity of ±0.15:

$$M_{56}\delta p/p + W_{5666}(\delta p/p)^3 = 0$$

Inserting the aforementioned values yields W_{5666} = -8.9 m. Correction of this aberration is necessary to effectively compress energy spread during energy recovery. This is illustrated in Figure 2, which shows results of a DIMAD simulation of the energy recovery process in the Revision 0.1 IR Upgrade Driver with and without use of octupoles to compensate W_{5666} [3].



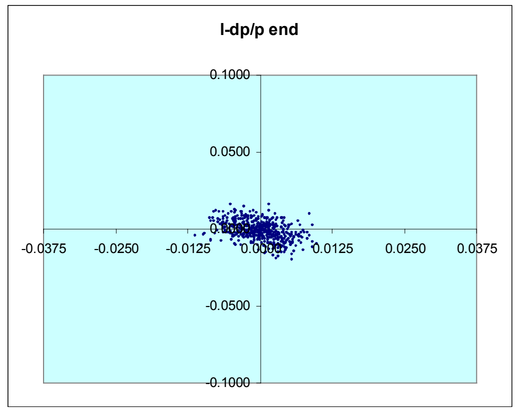


Figure 2: Longitudinal phase space after energy recovery in Revision 0.1 IR Upgrade Driver without (left) and with (right) octupole compensation of W_{5666}.

<u>Torsion in the RF Waveform</u> – In addition to lattice W_{5666}, cubic variation of RF fields with phase imposes constraints on the energy compression/recovery process. Unless the beam undergoes proper longitudinal matching to the linac (using linear, quadratic, *and* cubic compactions) an excessively large momentum spread will arise at the end of the machine. A simple spreadsheet model [4] suggests a cubic variation of path length with momentum equivalent to a lattice W_{5666} of order 1 to 10 m is required for fully effective energy compression during energy recovery. This is illustrated in Figure 3, which presents recovery/compression simulation results for three Upgrade operational regimes: turn-on (80 MeV), nominal (145 MeV) and full power (210 MeV). High power (extraction efficiencies exceeding 1%) lasing is assumed, with induced momentum spreads exceeding 14% in each case. Overcompensation of the lattice torsional compaction is required to manage the energy spread at the dump, with W_{5666} ~ 2 – 3 m (positive) providing small (few hundred keV) final energy spread.

It is entertaining to note that the turn-on scenario compresses 14% of 80 MeV, or 11.2 MeV, to ~200 keV at 10 MeV, the nominal scenario compresses 14% of 145 MeV, or ~20 MeV, to ~350 keV at 10 MeV, and the full power compresses 14% of 210 MeV (29 MeV) to ~450 keV at the dump. The ratio of initial to final energy spread thus remains roughly 60:1 for all cases, despite the increase in the initial to final energy ratio from 8:1 to 21:1. This must represent some mystical numerological truth, but for the life of me I can't figure it out at the moment. Probably puts the lie to any arguments about injection to final energy ratio, however, at least if you believe it'll work.

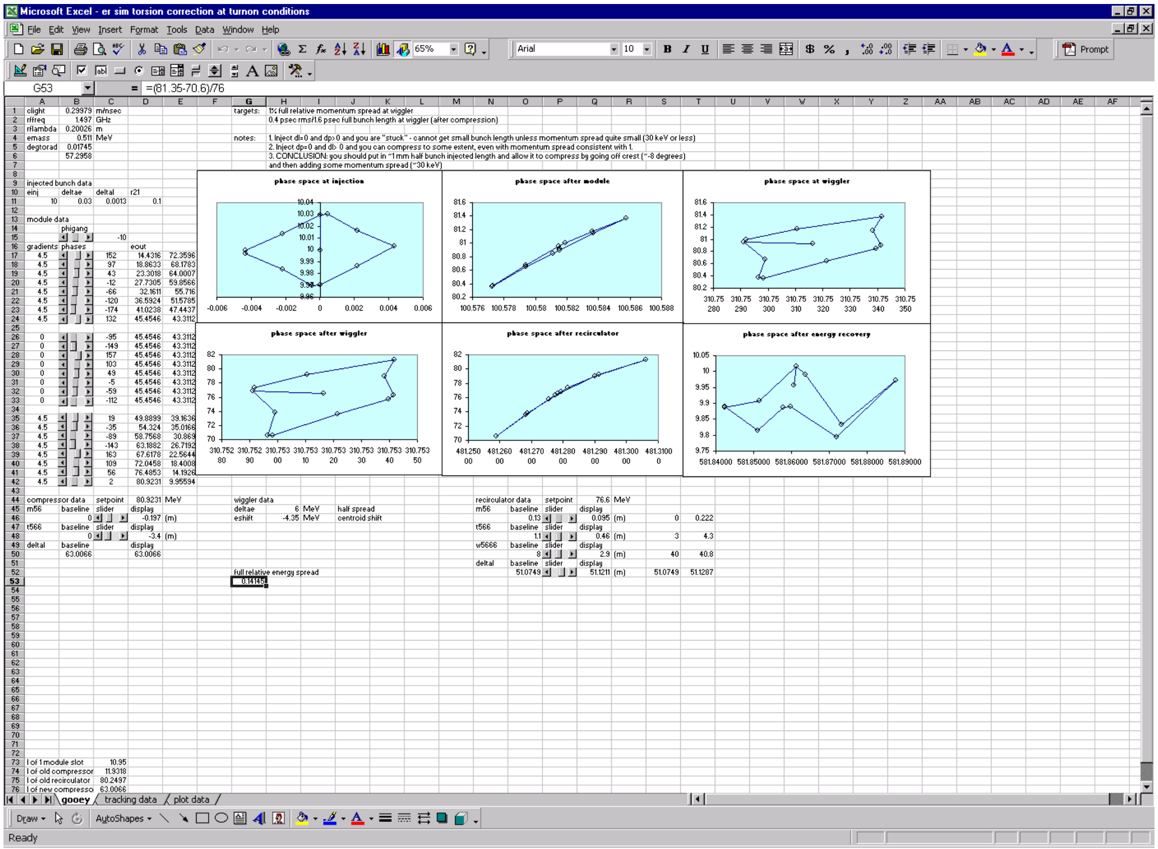


Figure 3a: Simulation for turn-on (80 MeV) operation; lattice W_{5666} = 2.9 m.

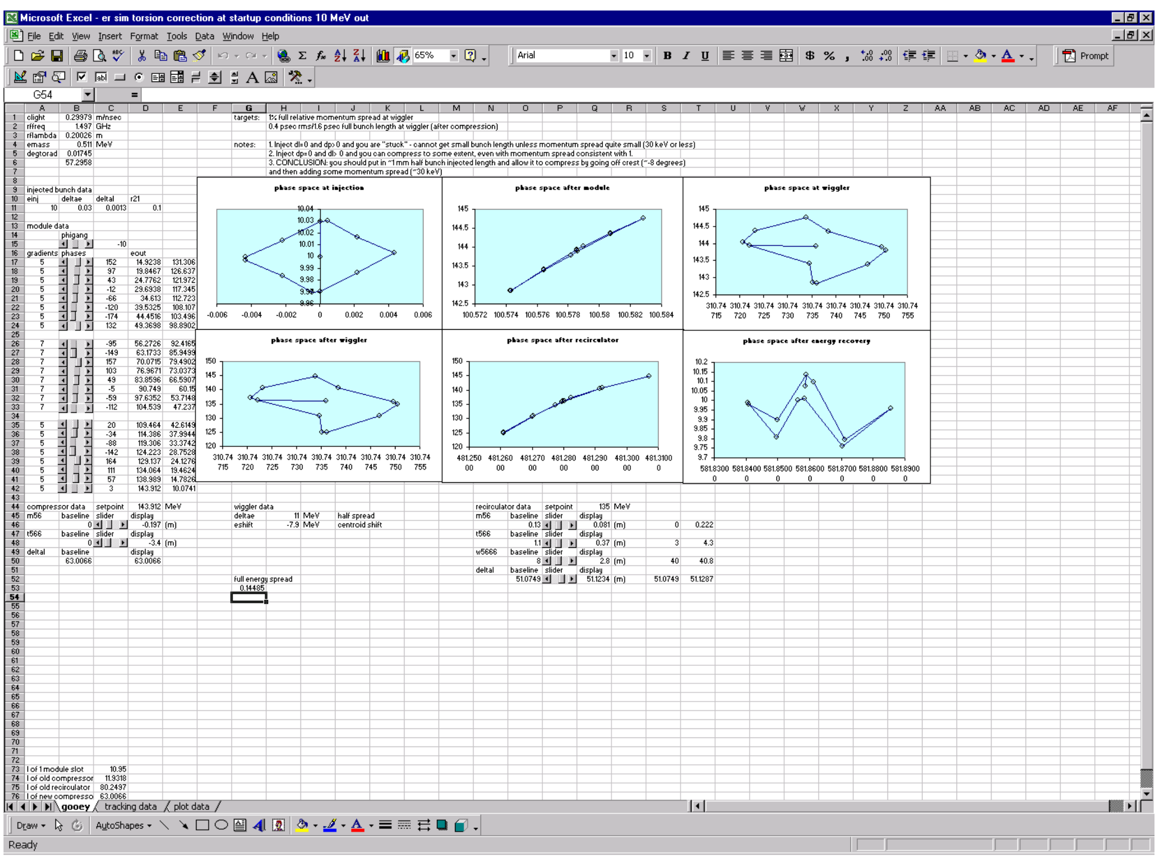


Figure 3b: Simulation for nominal (145 MeV) operation; lattice W_{5666} = 2.8 m.

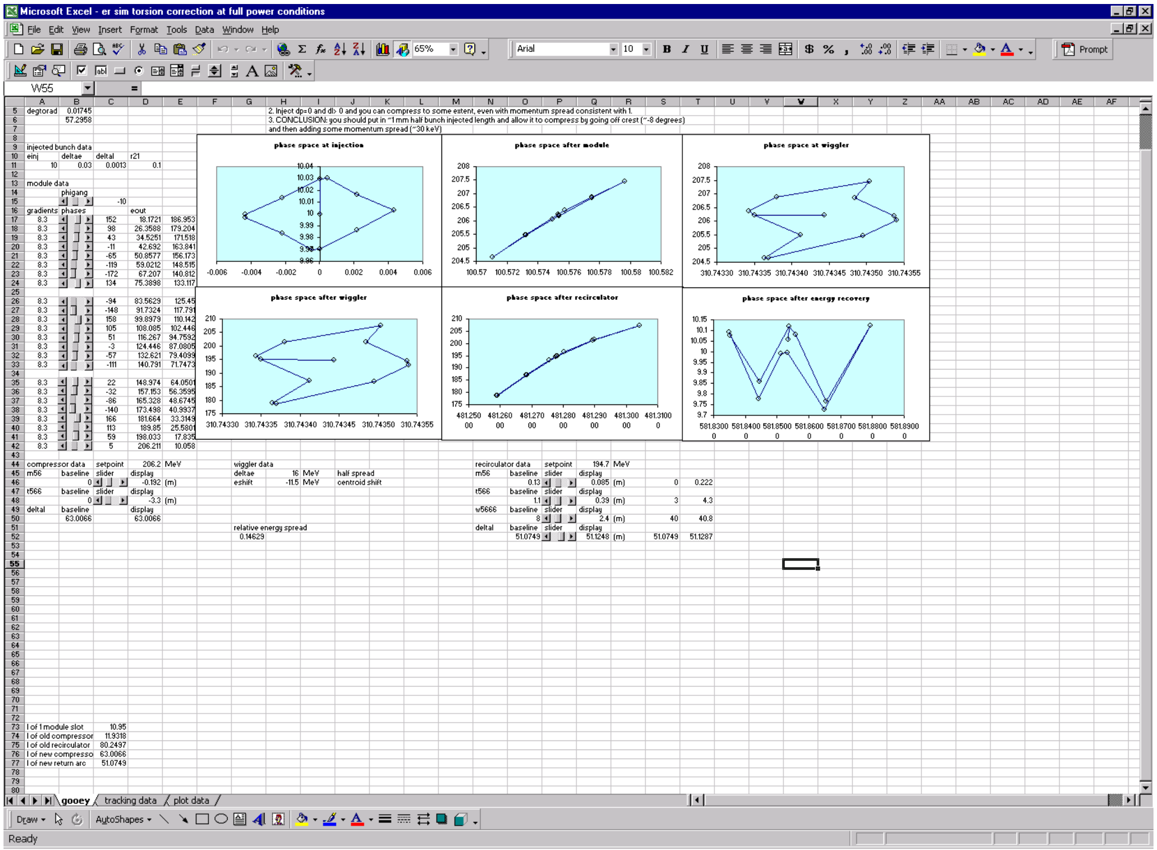


Figure 3c: Simulation for full power (210 MeV) operation; lattice W_{5666} of 2.4 m used.

Compensation Method

Compensation of W_{5666} is possible using the same method as that used for path length, M_{56}, and T_{566} correction [5]. This technique utilizes the symmetry inherent in the π-bend portion of a Bates-style endloop to introduce path length variations without generating correlated orbit errors downstream. Trims are placed at points of non-zero dispersion adjacent to the ends of the π-bend. An angular kick imposed by the first trim can be completely compensated by the second because the transfer matrix for the 180^{o} dipole is –I. This is illustrated in Figure 4.

The path length differential δl generated by an angular impulse $\delta x'$ across the 180^{o} dipole with bend radius ρ is as follows.

$$\delta l = M_{52}\delta x' = 2\rho\delta x'$$

The angle can be produced by a dipole trim, in which case δl is a path length (RF phase) correction; if generated by a multipole magnet, δl will serve to modify some order of momentum compaction. Quadrupoles produce M_{56} shifts, sextupoles modify T_{566}, and octupoles compensate W_{5666}. The angular kick imposed on the beam component with momentum offset δp/p by a (2n+2)-pole located at a point of dispersion η is as follows.

$$\delta x' = Bl / B\rho = k_n l\ x^n = k_n l\left[\eta(\delta p / p)\right]^n$$

The resulting path length differential is then proportional to $[\eta(\delta p/p)]^n$.

$$\delta l = 2\rho\delta x' = k_n l\left[\eta(\delta p / p)\right]^n$$

For M_{56}, T_{566}, W_{5666}, … correction, this differential is intended to compensate the (*aberration*)$\times(\delta p/p)^n$ from the lattice and/or the RF waveform. The integrated multipole strength $k_n l$ needed to correct the (2n+2)-pole aberration A_{2n+2} (= M_{56}, T_{566}, W_{5666}, …) is thus:

$$k_n l = A_{2n+2} / \left(2\rho\eta^n\right)$$

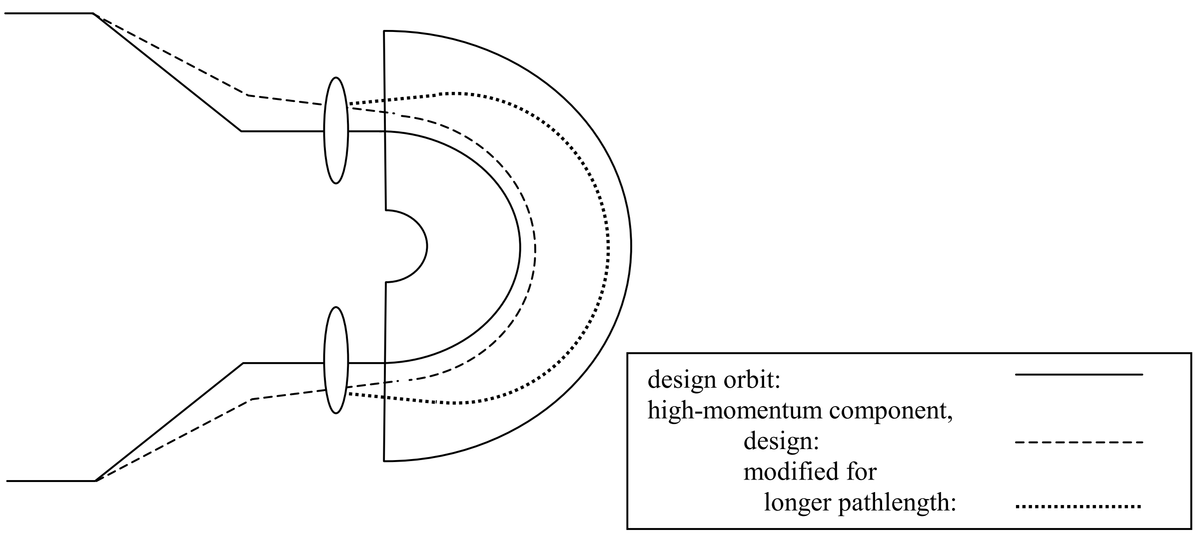


Figure 4: Orbit geometry for generation of path length differential

<u>Strength Estimate</u> – As noted above the Upgrade lattice torsional aberration A_8 = -8.9 m. This is to be corrected by a pair of octupoles, each at a point with 1.4 m dispersion (in the Revision 1.1.1 design). Thus, an integrated multipole strength k_3l = -1.62 / m^3 is needed. This agrees well with the result of DIMAD simulation of energy recovery in the Revision 1.1.1 design, which provides an optimum energy spread at 10 MeV with use of a pair of octupoles each of which is excited to k_3l = -1.7 / m^3. We note that the W_{5666}, or A_8, value cited above was from the Revision 0.1 design; minor changes in beamline layout during the evolution of the Revision 1.1.1 design could easily change the aberration by 10%.

In addition to the lattice torsion, the octupole trims will be used compensate RF waveform variations (drat that high frequency!). The simulations cited above imply a

30% over-correction of W_{5666} is needed; we will allow for 100% over-correction to ensure adequate headroom. The IR Upgrade octupoles must therefore provide an integrated multipole strength $k_3 l$ of order 3.5 / m^3 at momenta of up to 210 MeV/c.

The octupoles will be positioned immediately adjacent to the GQ reverse bends. The clear aperture should therefore accommodate the 25 cm wide chamber (intended to provide ±7.5% physical acceptance at a point with 1.67 m of dispersion) at this location. A radial bore $r_0 \geq 0.125$ m is therefore assumed. Given this bore and the multipole definition $Bl=B\rho\, k_3 l\, x^3$, the following field integral at 0.125 m is required

$$Bl(r_0) = 33.3564 \text{ kg-m/(GeV/c)} \times 0.21 \text{ GeV/c} \times 3.5/\text{m}^3 \times (0.125 \text{ m})^3 = 0.05 \text{ kg-m} .$$

An octupole with effective length of 20 cm will therefore have to supply 250 g field at the defined radius.

<u>Effectiveness of Correction</u> – Though discussed above, we review the efficacy of this scheme. Figure 2 shows a DIMAD simulation of lattice-only effects during energy compression/recovery without and with octupoles to correct W_{5666} [6]. Correction of path length torsion significantly reduces the momentum spread after energy recovery. Figure 5a shows the longitudinal simulation presented in Figure 3c without octupole correction. It is obvious the bare-lattice W_{5666} of –8.9 m will prevent recovery of beam energy during high power lasing. Figure 5b presents this case with lower FEL extraction efficiency producing only 7% momentum spread at 210 MeV. The large residual momentum spread at the dump is still evident. We therefore conclude that the use of octupoles significantly increases the available aperture, enlarging it from perhaps <7% total to as much as 15%. This gives the "bad news" that octupole correction will probably be necessary to accommodate the design extraction efficiency of 1%, but also brings the "good news" that FEL extraction efficiencies well in excess of the design specification of 1% may be tolerable with octupole correction, allowing generation of output powers greater than the nominal 10 kW [7].

<u>Field Quality Requirements</u> – The desire to energy recover and compress very large momentum spreads places rather stringent constraints on octupole field quality. Given an octupole field integral requirement Bl(@ 0.125 m)=5000 g-cm, we note that 1% field error represents a field integral of 50 g-cm. Were this due, for example, to an error quadrupole field, the associated integrated multipole $k_1 l$ would be as follows.

$$\begin{aligned} k_1 l &= \frac{B' l}{B\rho} = \frac{Bl / r_0}{33.3564 \text{ kg - m/(GeV/c)}\ p} \\ &= \frac{50 \text{ g - cm}/12.5 \text{ cm}}{33.3564 \times 0.21 \text{ kg - m}} \approx \frac{4}{7} \times 10^{-3} / \text{m} \end{aligned}$$

From above, this will lead to a compaction differential $\delta M_{56}=2\rho\eta k_1 l$ of magnitude

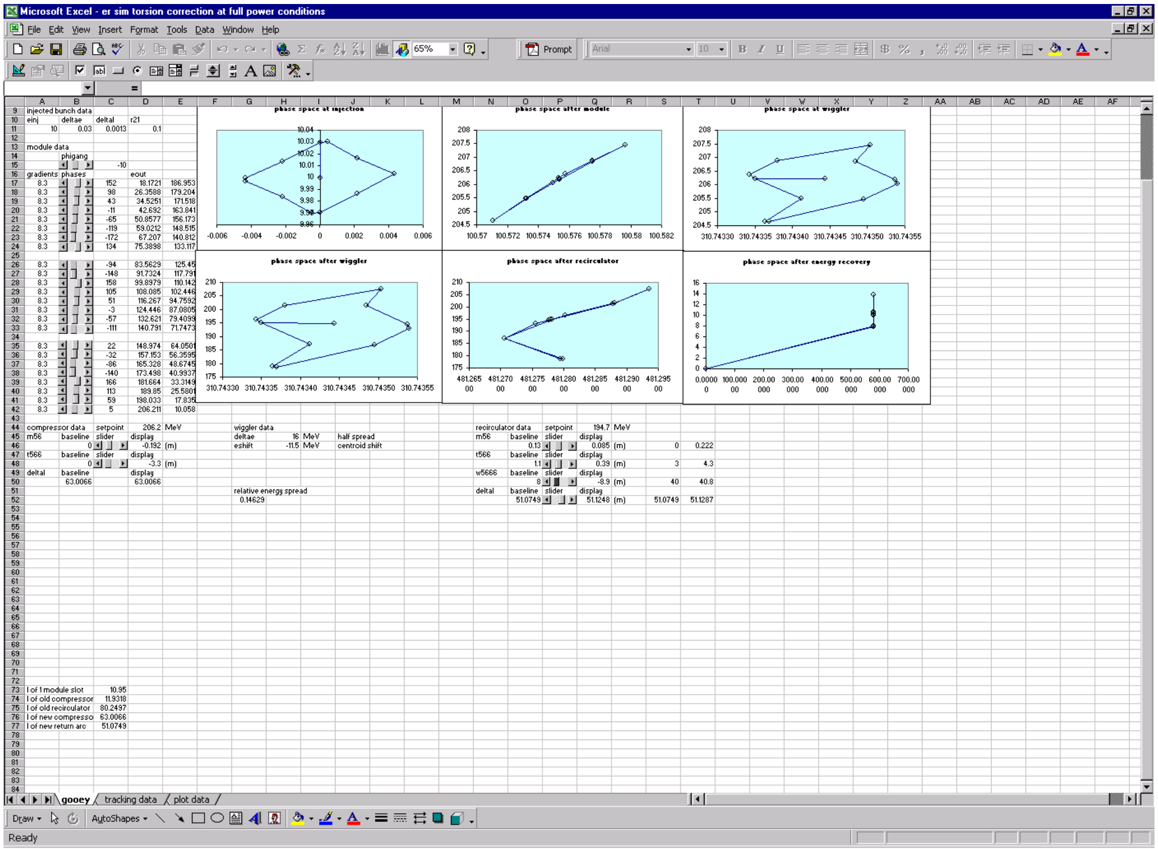


Figure 5a: Simulation of Figure 3c with uncorrected W_{5666}.

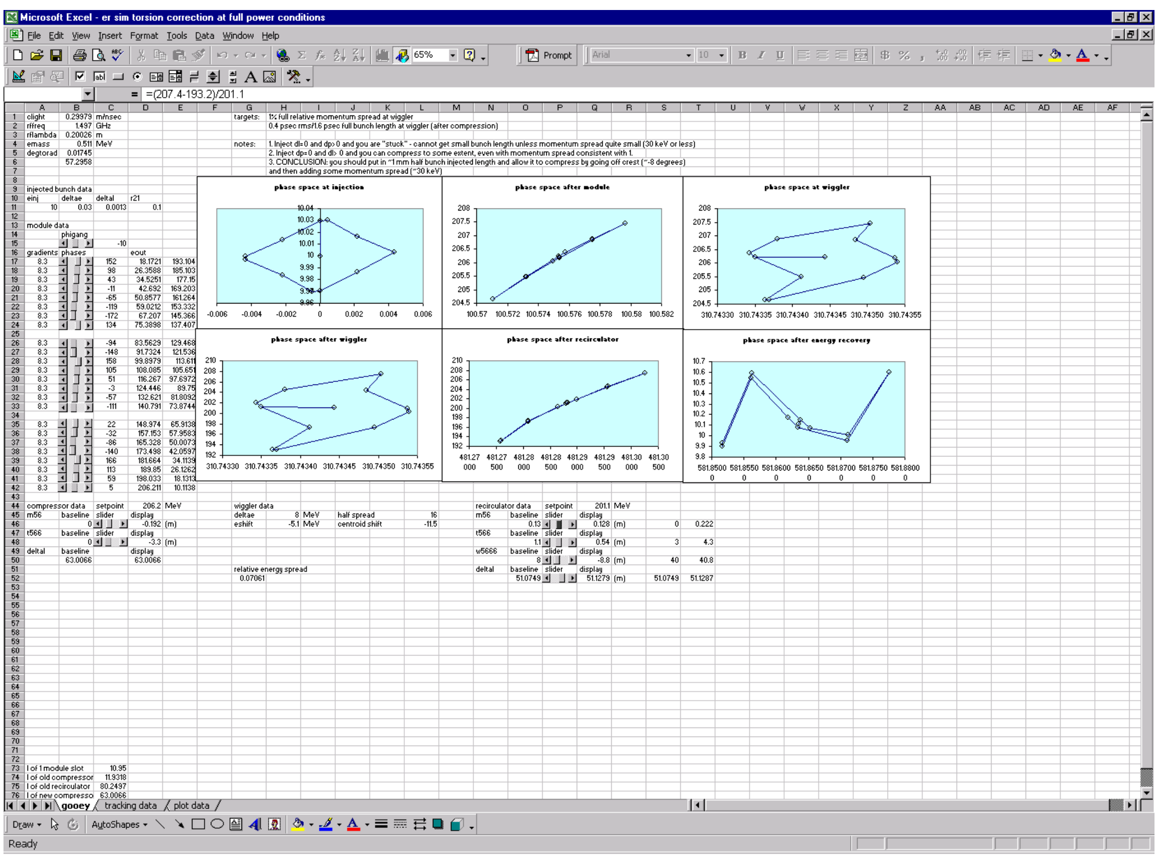


Figure 5b: Figure 3c with uncorrected W_{5666} and reduced initial momentum spread (7%).

$$\delta M_{56}=2 \times 1 \text{ m} \times 1.4 \text{ m} \times (4/7) \times 10^{-3} / \text{m} = 1.6 \times 10^{-3} \text{ m}$$

From the simulation used to generate Figures 3 and 5, we know such a differential can lead to energy shifts in the bunch tails at the dump of order 300 keV. This is a significant effect.

The octupole strength discussed above is intended to compensate a W_{5666} value of order 10 m. A 1% change in this value, 0.1 m, is sufficient in simulation to shift the bunch tail energy by order 200 keV at the dump. This, too, is a significant change. Hence, differential changes in the octupole field integral should be limited to the few 10s of g-cm level – or order 1% of the full field. At the 10 g-cm field integral level, the induced path length shift will be driven by an angular discrepancy

$$\delta x' = Bl/B\rho = 10 \text{ g-cm}/(33.3564 \text{ kg-m/(GeV/c)} \times 0.21 \text{ GeV/c}) = 14\ \mu\text{rad}$$

and thus will be of magnitude

$$\delta l = 2\rho\delta x' = 2 \times 1 \text{ m} \times 14\ \mu\text{rad} = 30\ \mu\text{m}$$

This is 0.054^o of RF phase at 1.497 GHz; given a linac energy gain of 200 MeV and a nominal operating phase 10^o off crest, the resulting energy shift at the dump will be

$$\Delta E = 200 \text{ MeV} \times (\cos(10.054^o) - \cos(10^o)) = 30 \text{ keV}$$

This is significant relative to the desired final energy spread of order a few hundred keV.

These estimates suggest that control of the octupole field integral at the 10 g-cm level be exercised through the working aperture of the magnet. The octupole should thus be a "1% trim", much like the trim quad and sextupoles presently in use in the IR Demo.

Octupole Specification

The following requirements constitute the octupole field and field quality specification:

- Multipole integral: $k_3 l = 3.5/\text{m}^3$ from 80 MeV/c to 210 MeV/c
- Bore: $r_0 > 0.125$ m
- Field integral $Bl(r_0)$=0.05 kg-m at 0.125 m
- Field homogeneity of 1% (field deviations from pure octupole not to exceed 1% over radii < r_0)

References

[1] D. Douglas, “Longitudinal Phase Space Management In the IR FEL Upgrade Driver”, JLAB-TN-00-020, 11 September 2000.

[2] D. Douglas, “IR FEL Upgrade Driver Accelerator Design, Revision 1.0”, JLAB-TN-00-013, 7 June 2000.

[3] *ibid.*

[4] D. Douglas, JLAB-TN-00-020, *op. cit.*

[5] D. Douglas, “IR FEL Driver Accelerator Design”, CEBAF-TN-96-050, 27 September 1996; D. Douglas, “Lattice Issues Affecting Longitudinal Phase Space Management During Energy Recovery, Or, ‘Why the FEL Needs Sextupoles’”, JLAB-TN-98-025, 9 July 1998.

[6] D. Douglas, JLAB-TN-00-013, *op. cit.*

[7] D. Douglas, “Extending the IR Upgrade Driver to Support MegaWatt-Class FEL Performance”, JLAB-TN-01-034, 23 July 2001.