Lattice Issues Affecting Longitudinal Phase Space Management During Energy Recovery, Or, "Why the FEL Needs Sextupoles"

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Abstract

Longitudinal phase space management in an energy recovering FEL has been discussed in some detail elsewhere [1]. Guidance from this discussion has been utilized in the design of the Jefferson Lab IR FEL driver [2]. This note provides operation-oriented information about the management of bunch length and momentum spread during energy recovery and details simple schemes for setting linear momentum compaction and correcting nonlinear momentum compaction.

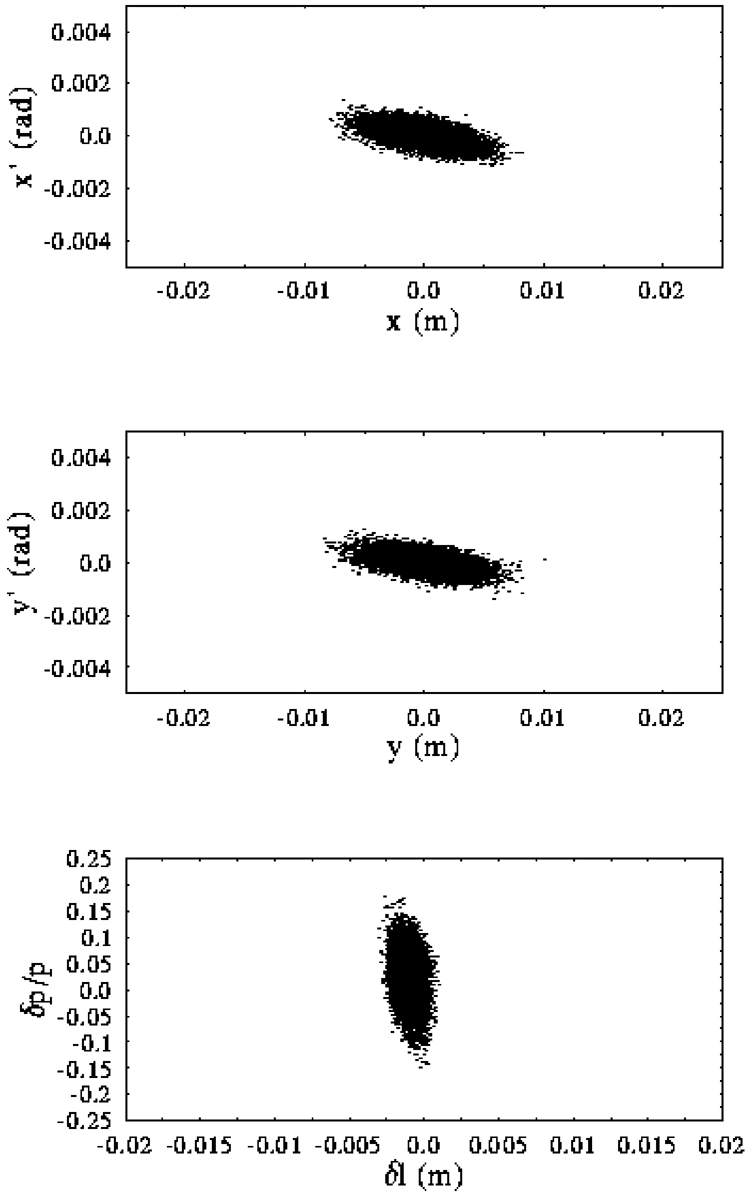
Overview

The baseline FEL driver recirculator design has multiple features that support longitudinal phase space management. There is a magnetic chicane upstream of the wiggler. This chicane serves two functions. It displaces the electron beam from the end of the optical cavity and provides momentum compaction, which, when combined with off-crest acceleration, allows compression of the bunch to very short lengths and very high peak currents.

The recirculator design is, from wiggler to reinjection point, linearly achromatic and nominally isochronous to second order in momentum offset. The choice of magnet hardware parameters sets the transfer matrix elements M_{16}, M_{26}, and M_{56} for this transport to zero; sextupoles are used to zero T_{166}, T_{266}, and T_{566}. To ensure the final beam energy matches that of the injected beam and that the recovered RF power matches that required for acceleration, energy recovery will occur 180^{o} out of phase with acceleration. Trim quadrupoles are provided to allow modification of M_{56} (while retaining achromaticity) to optimize longitudinal performance during energy recovery.

Figure 1 shows the electron beam phase space after energy recovery when using the nominal design parameters while lasing. Adiabatic antidamping inflates the ~5% post-FEL momentum spread to ~30%. This is beyond the physical acceptance of the 1G00 dump transport line (nominally, around 10 – 20%, depending on the quadrupole settings and resulting dispersion), and is thus unacceptable.

Figure 1: Phase space following module after energy recovery, with isochronous, design sextupole corrected transport from wiggler to reinjection.



Energy Compression During Energy Recovery

Modifying the recirculator momentum compaction to generate energy compression during energy recovery can alleviate acceptance limitations at the 1G00 dump. We note that as acceleration occurs off crest (to generate bunch length compression), energy recovery will occur off-trough, on a sloped portion of the RF waveform. A nonzero M_{56} value in the recirculator will then create a phase-energy correlation at reinjection, which leads in turn to changes of energy spread after energy recovery. When properly chosen, the recirculator M_{56} can cancel the phase-energy correlation in the linac, leading to an outgoing momentum spread that is independent of the momentum spread at the wiggler. Equivalently, the proper choice of recirculator momentum compaction leads to an M_{66} from wiggler to dump of zero and converts energy spread to bunch length.

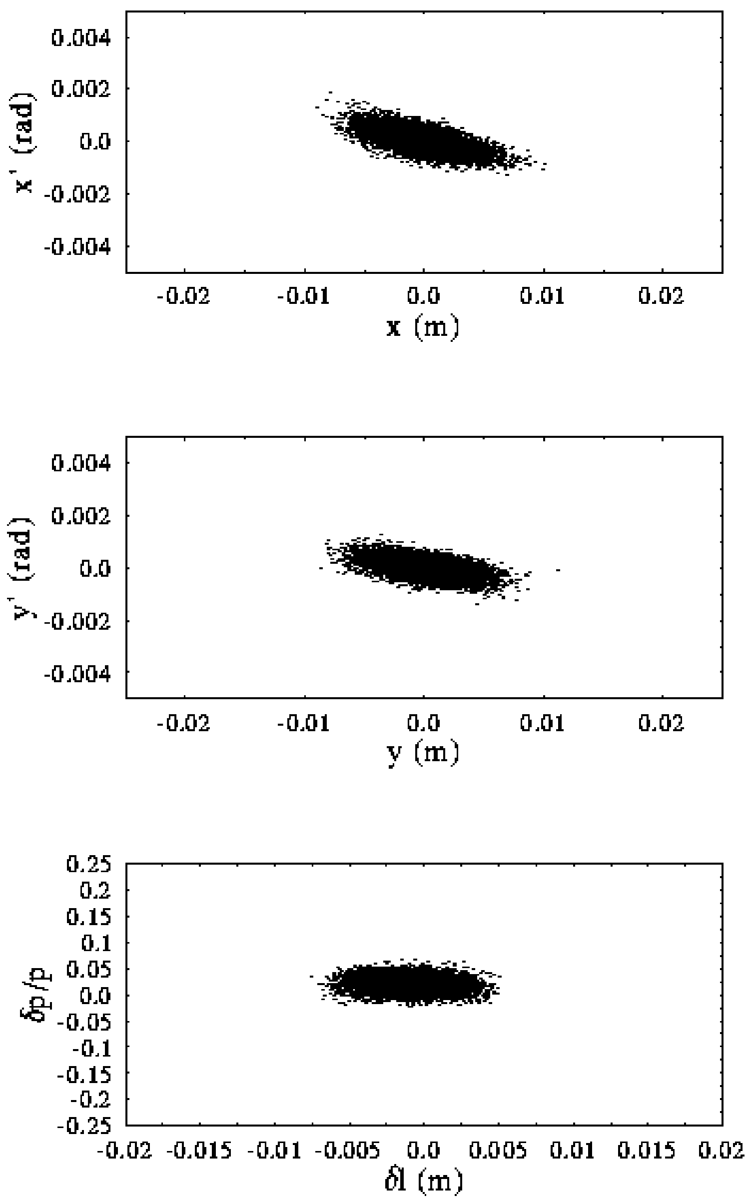
An M_{56} value of ~0.2 m, from wiggler to reinjection point, will provide the desired energy compression during energy recovery [3]. This value is readily generated by proper excitation of a family of trim quads next to the “C-bends”. As these dipoles bend through 180^{o}, a systematic excitation of the adjacent family of quads will not alter dispersion outside of the dipoles, but will change the momentum compaction. An angular kick of *(hd/f)* provided to an off-momentum beam at position *hd* by excitation of the quadrupoles to focal length *f* will then lead to a path length variation of M_{52} *(hd/f)*. The pair of bends therefore generates an M_{56} contribution of 2 M_{52} *(hd/f)*. Noting that M_{52} = 2 m for each bend (the orbit radius is 1 m), we find a focal length of 40 m is required to give the desired compaction.

Figure 2 shows the electron beam phase space after energy recovery while lasing when using one family of trim quads adjacent to the C-bends excited to a focal length of 40 m. Sextupole correction is as in Figure 1 (design/ideal values); the reduction of momentum spread is evident. We note that the isochronous transport has M_{66} from wiggler to dump of 4; the nonisochronous transport has M_{66} from wiggler to dump essentially 0. The remnant dispersion produced by this rudimentary trim is small (~4-5 cm in the backleg, 3 cm at reinjection) and operationally tolerable.

Compensation of Nonlinear Momentum Compaction

The design configuration of the recirculator uses two sextupole families and reflective symmetry to cancel T_{166}, T_{266}, and T_{566} from wiggler to reinjection point. Operationally, errors, blunders, and diagnostic limitations may preclude easily implementing this scheme. We therefore have investigated the necessity of sextupole correction and sought simplified methods providing adequate beam performance during energy recovery.

Figure 2: Phase space following module after energy recovery using nonzero momentum compaction in recirculator with design sextupole correction. Significant levels of energy compression are apparent.



The uncorrected design lattice has relatively small T_{166} and T_{266} values of 0.3 m and 0.04 rad, respectively, but the bare T_{566} value is, at 10 m, quite large. A ±2.5% momentum offset would thus lead to a path length deviation and attendant bunch lengthening of 6.25 mm, while the transverse growth is a relatively tolerable 0.2 mm/0.025 mrad. These results indicate that sextupoles are probably not needed to control transverse beam size during energy recovery, but will almost certainly be required to control bunch length and momentum spread.

This conclusion is born out by simulation. Figure 3a shows the electron beam phase space after energy recovery when lasing, using energy compression during energy recovery *without* sextupole correction of the nonlinear momentum compaction (T_{566}). The enormous momentum spread at the dump is frighteningly obvious, and clearly quadratic, so that adjustment of the linear momentum compaction (M_{56}) to different values will be of little help. This is seen to be the case in Figure 3b, wherein the transport has been reset to be isochronous. The change in momentum compaction is completely ineffective at reducing the momentum spread. At least one sextupole family will therefore be required for the correction of T_{566} to achieve successful operation with energy recovery.

The required compensation of nonlinear momentum compaction is at least theoretically possible. The method is similar to that used in the above discussion of correcting linear momentum compaction, in which trim quads adjacent to the C-bends was used to generate M_{56}. The nonlinear momentum compaction is similarly adjusted using a single family of sextupoles adjacent to the C-bends. An imposed T_{566} value of 10 m, from wiggler to reinjection point, will provide the desired result. This value is readily generated by proper excitation of a family of sextupoles immediately adjacent to the C-bends. As these dipoles bend through 180°, a systematic excitation of this family of sextupoles will not significantly alter dispersion or generate geometric aberrations outside of the dipoles, but will change the nonlinear momentum compaction. An angular kick of $((hd)^2 k_2 l)$ provided to an off-momentum beam at position hd by excitation of the sextupoles to field curvature k_2 will then lead to a path length variation of M_{52} $((hd)^2 k_2 l)$. Two such dipoles therefore generate an M_{56} contribution of 2 M_{52} $((hd)^2 k_2 l)$. Noting that M_{52} = 2 m for the C-bends (the bend radius is 1 m), h = 2 m at the sextupoles, and l = 0.15 m for the sextupoles, we find a field curvature of ~4.2 m^{-3} is required to give the desired 10 m correction to T_{566}.

Figure 3a: Phase space after module using energy recovery with energy compression, but without sextupole correction. The impact of the quadratic variation of path length with momentum offset is obvious.

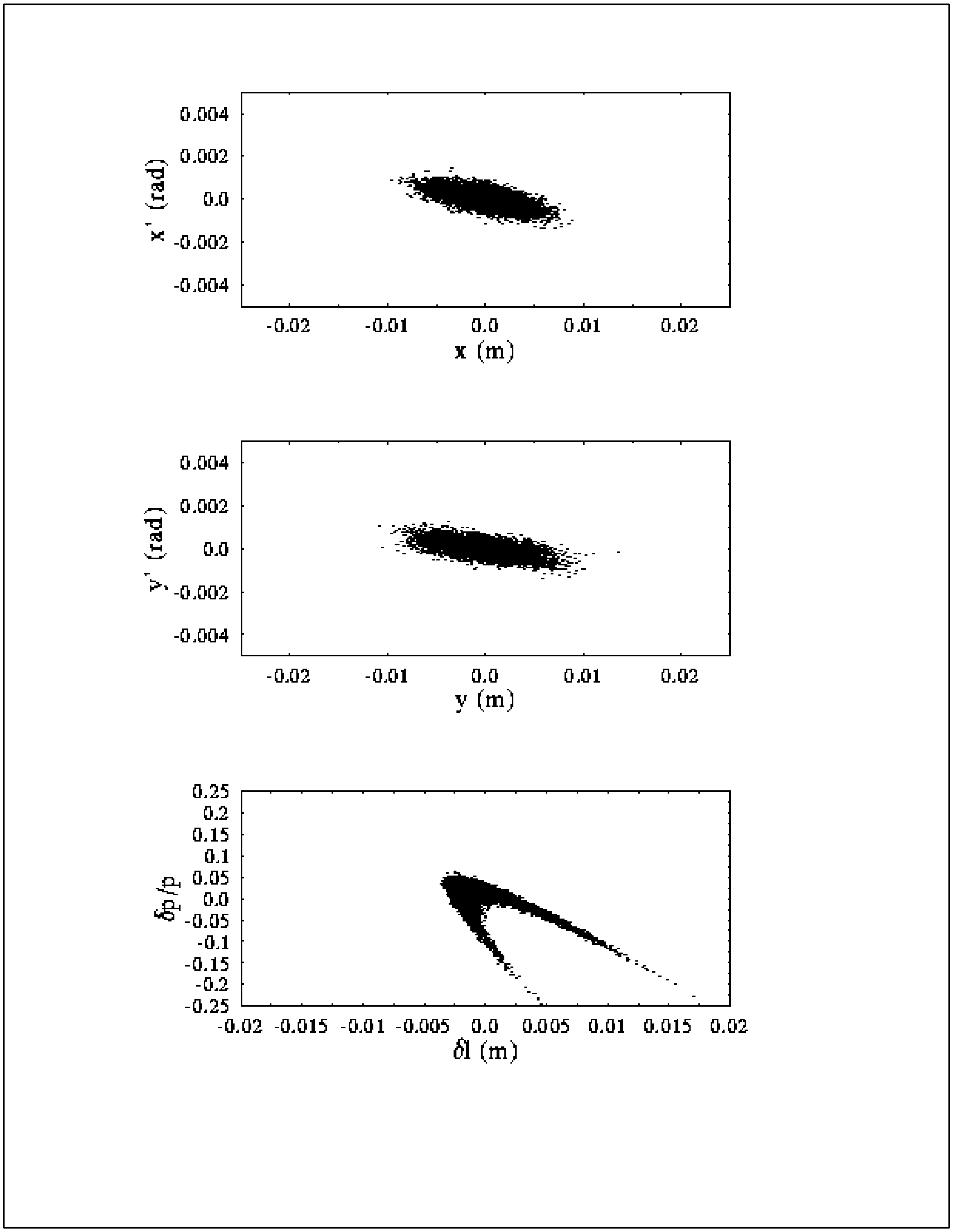


Figure 3b: Phase space after energy recovery with isochronous transport, but without sextupole correction. The impact uncorrected T_{566} persists and is not compensated by the change in linear momentum compaction.

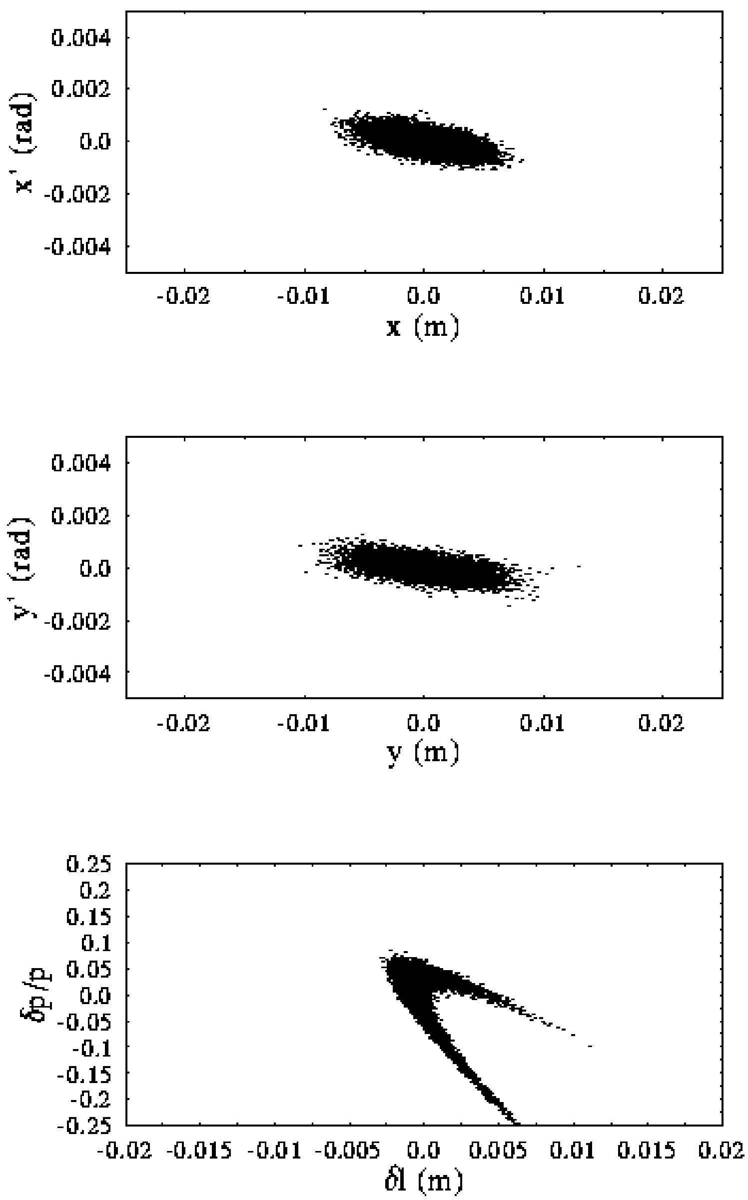


Figure 4 illustrates the result of such a simple correction. It shows the electron beam phase space after energy recovery when lasing, using energy compression during energy recovery and sextupole correction of the nonlinear momentum compaction (T_{566}). The phase space is nearly the same as in the design case, with horizontal tails probably associated with uncorrected residual T_{166} and T_{266} values of -2 m and -0.5 rad, respectively. The simple one family correction of nonlinear momentum compaction thus appears to be operationally adequate.

Conclusions

Both linear and quadratic variations of path length with momentum must be properly adjusted in the recirculator to avoid large momentum spread (in excess of beamline acceptance) at the energy recovery dump. This adjustment can be done as an optimization of energy compression during energy recovery by using two knobs – a family of trim quads to set M_{56}, and a single family of sextupoles to compensate T_{566}.

The energy recovery dump transport quadrupoles must be set to provide some suppression of dispersion in the beam line. The maximum dispersion must be limited to ~0.5 m to avoid momentum acceptance problems with the energy recovered beam, which will have a momentum spread of order 10% after optimization of the recirculation transport and deceleration.

Acknowledgements

I would like to thank Jay Benesch and Joe Bisognano for a useful discussion on spot size management in the energy recovery dump line.

References

[1] D. Douglas, A. Hutton, Ch. Leemann, and D. Neuffer, "Analytic Modeling and Lattice Scaling Relations for FEL Driver Accelerators", CEBAF-TN-95-015, 21 March 1995.

[2] D. Douglas, "Lattice Design for a High-Power Infrared FEL", to appear in the Proceedings of the 1997 IEEE Particle Accelerator Conference (Vancouver, B. C., May 1997); see also links from http://www.jlab.org/~douglas .

[3] G. Neil and L. Merminga have both quoted the 0.2 m number to me; this value has been verified with DIMAD simulation.

Figure 4: Phase space after energy recovery with energy compression and simple one-family sextupole correction of T_{566}. Improvement in final momentum spread is dramatic.