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The Effect of Field Inhomogeneities In or Near the IR Upgrade Driver Compaction Management Elements

D. Douglas

Abstract

We estimate the longitudinal phase space degradation – as manifested by unanticipated energy spread at the dump – driven by magnetic field errors in the vicinity of the compaction-management trim elements of the IR Upgrade Driver.

Overview

Field inhomogeneities will produce differential errors in the field integral applied to beams recirculated in the IR Upgrade Driver energy recovery beam line. This can result in untoward distortion of the transported phase space. Transverse emittance dilution driven by inhomogeneity-induced differential bending can often be operationally managed (though not necessarily corrected!) by adjustment of betatron matching. Longitudinal pathologies may not however be so readily remedied. In particular, if an element in or near the compaction-management trim system differentially bends or focuses the beam, the path length/energy correlation imposed on the beam will be disturbed, with a resulting differential path length deviation from nominal. Such errors will, in turn, lead to incomplete energy compression during energy recovery.

In the following, we estimate the differential energy spread at the dump generated by a field integral error in the compaction-management region of the energy recovery end loop. This estimate will serve to set a scale for the required magnet field quality.

Estimate

A differential field error ΔB over a length l will lead to differential bending of various portions of the beam by an angle $\delta\theta = \Delta Bl/B\rho$. This in turn leads to a path length error δl specified by the angular error and the transfer matrix from the site of the error to the end of the beam line.

$$\delta l = M_{52}\,\delta\theta = M_{52}\,\frac{\Delta Bl}{B\rho}$$

This path length error results in a reinjection phase error, with an attendant degradation of energy compression during energy recovery. Given phasing as shown in Figure 1, the energy error ΔE at the dump due to a path length differential δl will be as follows.

$$\Delta E = E_{linac}\left[\cos\left(\phi_0 + \pi + \frac{2\pi\,\delta l}{\lambda_{RF}}\right) - \cos(\phi_0 + \pi)\right] \approx E_{linac}\sin\phi_0\,\frac{2\pi\,\delta l}{\lambda_{RF}}$$

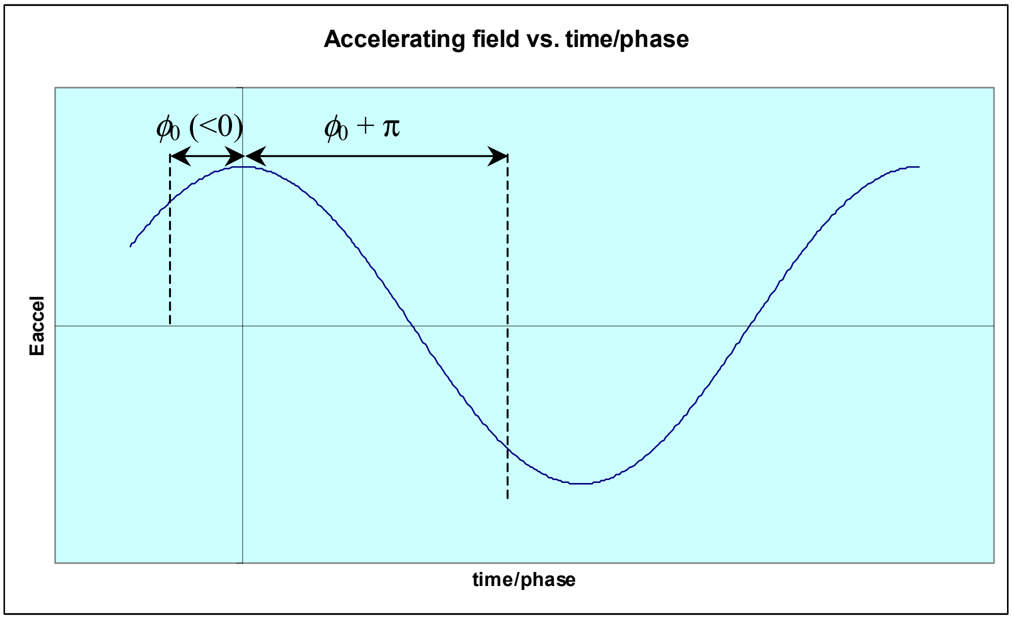

Figure 1: Phase conventions for acceleration and energy recovery in IR Upgrade.

Note that with $\phi_0 < 0$, if $\delta l < 0$ (shorter path length, with associated earlier arrival time), the deccelerating field is smaller – so the beam component recovers with a *higher* energy: $\Delta E > 0$. We remark that this "optics" sign convention is precisely opposite in sign to that used in the machine RF controls.

The energy error at the dump associated with a particular field error in the recirculator is then given by combining the above expressions.

$$\Delta E \approx E_{linac} \sin \phi_0 \frac{2\pi M_{52}}{\lambda_{RF}} \frac{\Delta Bl}{B\rho}$$

A field integral error tolerance can then be specified in terms of the magnitude of the tolerable differential energy error at the dump.

$$\Delta Bl \leq \left| \frac{\Delta E}{E_{linac}} \frac{\lambda_{RF}}{2\pi M_{52}} \frac{B\rho}{\sin \phi_0} \right|$$

For the IR Upgrade at full energy,

$B\rho$ = 33.3564 kg-m/(GeV/c) × 0.210 GeV/c = 7.005 kg-m
E_{linac} = 200 MeV
λ_{RF} = 0.2 m
ϕ_0 =10°

A value for M_{52} can be obtained from DIMAD; Figure 2 displays the evolution of M_{52} (from displacement s to the end of beam line) through the energy recovery endloop. Regions with magnetic field are shaded. The average value of M_{52} in the magnetic regions is 0.91 m. The recovered energy spread is, hopefully, to be controlled to ~1%, or 100 keV. A tolerable budget for magnetically induced errors of the type considered here would then be some fraction of this (for each of the 15 magnets involved); we therefore take 30 keV as a working figure. Combining the numbers suggests we need field integral control at the following level.

$$\Delta Bl \leq 21\,\text{G - cm}$$

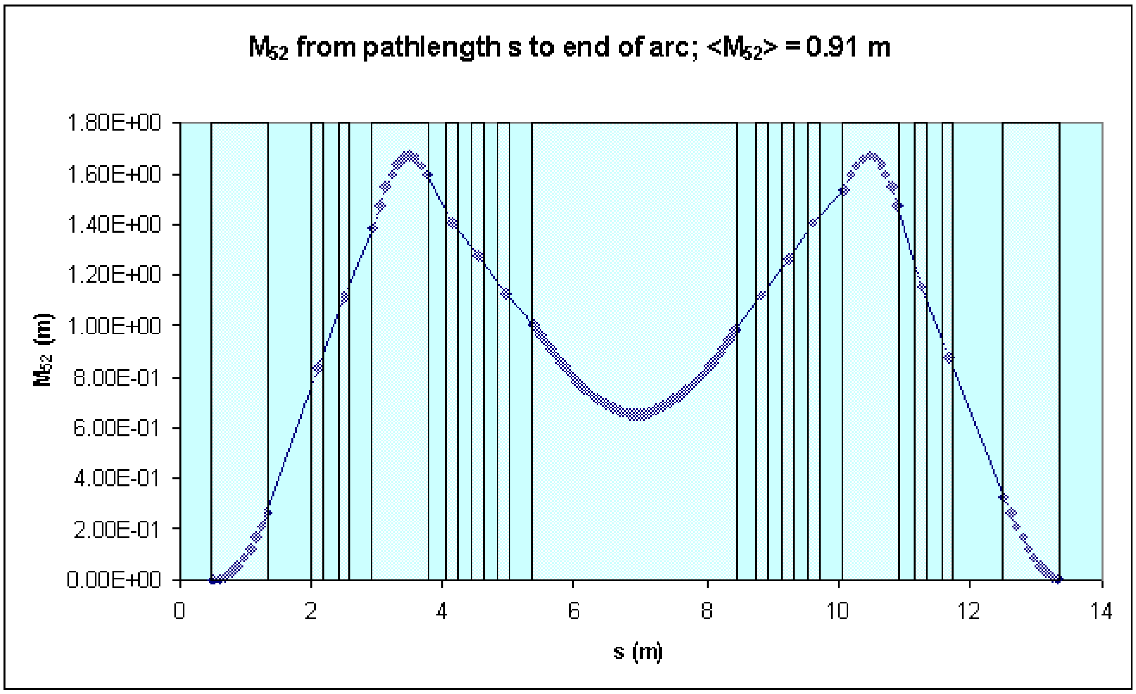

Figure 2: M_{52} from path length s to end of energy recovery recirculation endloop.

Conclusion

Field integral control at the few to several tens of G-cm level will be required in the IR Upgrade to avoid undue energy spread at following energy recovery. This result has entertaining implications for both the IR/UV Upgrade and ERL designs in general. Addressing the more cosmic first, we note that the field integral error specification is inversely proportional to the linac energy gain. This suggests that over a very long linac, one must exercise extreme caution to ensure that the energy spread of the recovered beam is not corrupted to the point of unmanageability, and may have to provide lavish longitudinal phase space diagnostics and control to guarantee reasonable beam quality at the end of the energy recovery cycle.

Implications for the demo are summarized by Table 1, wherein the relative field integral tolerance represented by the above ΔBl specification are presented for each class of magnet in the machine. Brief consideration should cause panic, as these are far tighter than the nominal specifications. Further consideration brings with it a realization that these are really *reproducibility* specifications. Dipole field errors will be compensated by quads and sextupoles, quad errors will be compensated by octupoles, and so forth, during the operational setup of energy recovery. Provided that the lower multipoles (dipole, quad, sextupole) reproduce to the tolerance in Table 1, the system performance should be adequate. The only "absolute" relative tolerance is that for the octupole; inasmuch as it is the "trim of final resort" for large amplitude behavior, it must provide control at the specified level. Fortuitously, the Table 1 requirement matches the 1% specification [1].

Table 1: Implied Relative Field Error Tolerances for IR/UV Upgrade

Magnet	Strength	Bore Radius	Field Integral (at pole, at 210 MeV/c)	*ΔBl/Bl* at 20 g-cm
Dipole (GX, GQ)	θ=43.4^o	N/A	530600 g-cm	3.7×10^{-5}
QX	(1/f)=1/m	3.75 cm	26300 g-cm	7.6×10^{-4}
SF	k_2l = 3/m^2	12.5 cm	32800 g-cm	6.1×10^{-4}
OF	k_3l=1.7/m^3	12.5 cm	2330 g-cm	8.6×10^{-3}

Note: k_n is defined by the TRANSPORT convention $B(x)=B\rho\ k_n\ x^n$.

Reference

[1] D. Douglas and G. Biallas, "IR Upgrade Octupole Trim Requirements", JLAB-TN-01-036, 1 August 2001.