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Dipole-Ripple-Driven Timing Jitter In the IR Upgrade

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Abstract

We discuss a dipole-ripple-driven effect that may contribute to degraded FEL performance in the IR Upgrade. Estimates are given for both the IR Demo and the IR Upgrade, and anecdotal, possibly misinterpreted and potentially misrepresented information from upgrade commissioning is presented.

Introduction

Initial operation of the IR Upgrade has produced disappointingly low FEL powers. (Okay, so it's a value judgement. But I *am* disappointed…!) A possible power limitation may come from jitter in the arrival time of the electron beam at the wiggler. To ascertain the relevance of this effect, we relate the following (hopefully correct) information. Much of this is word-of-mouth (and thus worth the paper it was printed on…); some of it has been extracted from various FLOG entries. All of it should be taken with a grain of salt.

- Upgrade turn-on has begun with operation at 20^o off-crest. This was done to provide strong longitudinal compression of the injected bunch length (notionally, because the initial operation of the injector might reasonably be expected to provide substandard beam quality) and to allow large deceleration overhead for energy compression during energy recovery (to accommodate the large energy spread expected when lasing at high powers).
- First operation of the Happek device has produced much lower signals (tenths of volts) than those observed in the IR Demo (a few volts), with Golay cell output exhibiting multiple local maxima at different buncher gradient settings (a "low" maximum at 1.75 MV/m and a "high" maximum at 2.5 MV/m). Examination of the beam at each maximum (by reducing the macropulse length to 1 μsec to resolve "ghost" pulse from core beam) indicates the weaker maximum is associated with compression of the ghost pulse train, while the stronger is due to compression of the core beam. Very recent attempts to scan the Happek [1] show the Golay cell output is insensitive to position – indicating that the Happek position is not yet properly set to produce maximum Golay cell response. The maxima occur, moreover, at compaction trim quadrupole settings that agree well (to order 10%) with values predicted by the machine model spread sheet and at trim sextupole settings that are not wildly different (within factors of 2) from those expected from the magnetic design of the "sextupole lites" [2] and the machine modeling calculations.
- Results of PARMELA simulations by Hernandez [3] have been forward propagated by Benson [4] to find that bunch lengths at the wiggler in the IR

Upgrade may be as short at 50 fsec rms at 20^o off crest. This is consistent with observations of momentum spreads of ~2% when running 20^o off-crest and ~1% when running 10^o off-crest [5]. Simulation of FEL performance based on the forward-propagated phase space for the various injector and accelerator operating configurations is consistent with the observed FEL performance [6].

- A THz spectrometer at the end of the optical cavity chicane provides a very rich, but arguably somewhat confusing, THz spectrum [7], suggesting that the bunch may not only be extremely short, but also may be exhibiting evidence of the onset of microbunching [8]. Further, it is thought by some [9] that THz radiation from beam bending in the first GX of the energy recovery arc may be illuminating, heating, and distorting the FEL outcoupling mirror, thereby further affecting FEL performance.
- We have seen that the Happek Golay cell output *halves* when moving from 20^o off crest to 10^o off crest (suggesting that the bunch length doubles). Further, the maximum Happek signal 10^o off crest occurs (as at 20^o, as noted above) for trim quads more or less as predicted by the machine model and at essentially the same sextupole settings as at 20^o. This sextupole behavior is as expected as well – the RF waveform curvature is essentially the same at both operating points. Furthermore, energy compression behaves in a similar manner (*i.e.* close to modeled behavior) for both phase set points.
- Allowing the DLPC to step the beam pulse timing through various portions of the line voltage 60 Hz phase cycle shows beam motion at a noticeable fraction of the spot size at various, but undocumented [10], locations in the machine.

This information suggests that the injector is in fact producing a bright longitudinal phase space which is in fact being overcompressed by the accelerator; the resulting large momentum spread and short bunch contribute to degraded FEL performance. There is, however, an additional system error which may also contribute to degraded FEL output – jitter in beam arrival time at the wiggler

Timing Jitter at the Wiggler

Recirculation of the beam by the transport system disperses the beam both transversely (M_{16}, M_{26}) and longitudinally (M_{56}). For this reason, the dipole strings in the IR Demo and Upgrade were both specified to be run in series with field stability at the 10 ppm level. This specification was imposed on the dipole power supply *current* stability – despite the fact that the solid iron magnets choke AC ripple by roughly an order of magnitude. Thus, in the Demo, the field was likely stable – at full power supply excitation – at the 1 ppm level, and at the nominal half-full operating excitation to ~ 2 ppm or so.

The author was, however, caught in this slight of hand by Bill Merz during Upgrade construction, and thus consented to impose solely the 10 ppm *field* stability specification on the series excitation of the dipole string. Though this sacrifices some of the error budget, simulation and estimates suggest that a series-driven achromatic arc should provide adequate performance if the field is stable to 10 ppm.

Schedule constraints have, however, forced the Upgrade to use a Demo DY dipole, instead of the design GY dipole, in the first arc of the recirculator. Because of the differing excitation curves, the DY is run at high (~200 A) currents on one power supply, while the rest of the arc (GXs, GQs, and GWs) are run on a separate supply at low (~85 A) currents. The DY thus probably provides field stability at the 10 ppm level (if it meets the Upgrade specification schedule) while the remainder of the arc moves *independently* at the 30 ppm level. This has interesting implications with regard to the path length.

The path length of a beam traversing a set of dipoles is altered if the dipole set has compaction and if the beam is offset in energy and/or the dipole string has a systematic field error. In terms of rms errors, we may write the path length deviation as follows.

$$\langle \delta l \rangle \sim M_{56} \left(\langle \delta E/E \rangle + \langle \Delta B/B \rangle \right)$$

In the IR Demo the longitudinal offset experienced at the wiggler would thus be the compaction of the upstream optical cavity chicane (-0.3 m) times the sum of the rms energy error ($\sim 10^{-4}$) and the rms field error (as noted above, $\sim 10^{-6}$); this gives a value of ~30 μm, or 100 fsec, due nearly entirely to the energy jitter. This is to be compared to the observed bunch length of 400 fsec; this would likely cause only modest degradation of electron bunch/optical mode overlap and would thus not have significant adverse effect on FEL performance.

In contrast, the present IR Upgrade powering scheme has a linac-to-wiggler M_{56} of –0.1 m (when operating 20^{o} off crest), which is produced by cancellation of two large contributions of about 3 m each from the DY and the remainder of the system. Thus, the rms path length error in the Upgrade will be due to energy dither coupling to the –0.1 m global compaction ($-0.1 \text{ m} \times 10^{-4} = 10$ μm, or 33 fsec) compounded with dipole ripple from two independent supplies – one at 10 ppm, the other at 30 ppm – coupling to individual 3 m compactions, for independent jitter of $3 \text{ m} \times 10 \times 10^{-6} \sim 30$ μm = 100 fsec for the DY and $3 \text{ m} \times 30 \times 10^{-6} \sim 90$ μm = 300 fsec for the rest of the arc. Addition in quadrature suggests the jitter will be dominated by the final (GX/GQ/GW) term and will be of order 300 fsec. This is to be contrasted to the 50 fsec bunch length discussed above – so it is apparent that the impact on FEL performance is potentially dramatic!

One should of course take note of the various time scales involved. The RF system stabilizes at 10s or 100s of kHz – so the 33 fsec jitter from RF noise could well be commensurate with FEL turn-on times (10s of μsec), though one might expect high-Q SRF cavities to be well behaved over short time scales. The magnetic field will exhibit two frequency regimes a) 60 Hz line ripple and harmonics thereof, all of which will be damped by the dipole iron and would in any event be tracked by the FEL because its turn-on time is much faster, and b) the 10s of kHz firing rate of the particular circuits (SCRs?) used in the power supplies. The author has no experience to judge the ability of the dipole iron to choke the higher frequencies thus produced, but notes only that they occur at timescales of interest to FEL turn-on and at which the FEL could have difficulty tracking.

If the dipole strings were rippling, we would of course expect to see an associated transverse motion. We noted above that beam motion at the several tenths of a mm to (at most) 1 mm level is, anecdotally, observed when the beam phase is varied relative to line phase (using the "auto phase rotate" feature of the DLPC). The author cannot say whether this is due to low (~60 Hz) noise or is a "beat frequency" resulting from incommensurate frequencies and tracking failure between the dipole power supplies. We note, however, that the machine model suggests that a DY error leading to ~1/2 mm peak orbit motion (such as that observed when not line locked) will give 100 μm path length error at the wiggler. This is consistent with the above estimates of timing error.

Conclusions

- The Upgrade is quite possibly running with very short (well less than 100 fsec rms) bunch lengths
- If individual dipole fields meet the 10 ppm specification set for the Upgrade, the present DY/GX/GQ/GW configuration can lead to significant jitter in bunch arrival time at the wiggler. This may occur at times scales commensurate with FEL turn-on.
- Folklore regarding beam spot sizes and motion when "auto phase rotating" are not inconsistent with this type of error.

Recommendations

- Make more Happek scans to get to the appropriate position for bunch length measurement. A Happek expert should determine the effect of timing jitter on the Happek signal and indicate if the system will see a "smeared out" bunch or just the coherent radiation from the short bunch as it bounces around.
- Make dipole field ripple measurements and characterize the ripple spectrum of the power supplies. Determine if the frequencies so observed are commensurate with FEL turn-on times
- Quantitatively check 60 Hz motion of the beam at documented locations.
- Get the second GY installed – it will suppress the dipole excitation part of this problem, leaving us only with the energy ripple issue.

Remarks

We note that the machine has been migrated to 10^o off crest and, at the time of the hurricane Isabelle shutdown, and awaits tune-up there. This operating point appears to lengthen the bunch and reduce the momentum spread at the wiggler, and thus may alleviate some FEL performance issues. It does, however, require the use of larger momentum compaction for bunch length compression (-0.2 m vs. –0.1 m at 20^o) and therefore will generate more timing jitter when the RF jumps around. It also allows only (1-cos 10^o) ~ 1.5% RF overhead for energy compression during energy recovery, vs. (1-cos 20^o) ~ 6% overhead at 20^o off crest. The dump acceptance (a full acceptance of as much as 12%, [11]), will likely be adequate to accommodate the lower available energy compression.

Notes and References

[1] FLOG, 9/17/2003
[2] R. Wines, private communication
[3] C. Hernandez, private communication
[4] S. Benson, private communication
[5] S. Benson, D. Douglas, unpublished, but FLOGged, at least in part.
[6] S. Benson, private communication.
[7] G. Williams, G. Neil, private communication; the "arguably" is the value judgement of the author, who readily admits to being easily confused.
[8] R. Li, private communication
[9] This was related variously to me by M. Shinn, S. Benson, G. Williams, F. Dylla, and G. Neil, and perhaps others. None of them have ever claimed (at least to me) to have been abducted by extraterrestrials.
[10] This undocumented observation made by the author, M. Shinn, and, if I remember correctly, J. Boyce. We note that A. Grippo urges caution in any attempt to quantitatively ascertain the effect of this particular button on the DLPC, but allows that it probably does *something* to the timing of the beam pulse relative to the timing of the line voltage.
[11] C. Tennant, "IR/UV FEL Upgrade Recovery Dump Transport Design", JLAB-TN-01-038, 10 August 2001.