THREE PLUS DECADES OF TAPERED UNDULATOR FEL PHYSICS*

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Abstract

Beginning with the classic 1981 work of Kroll-Morton-Rosenbluth [1], multiple generations of FEL scientists have studied and used experimentally undulator tapering to improve and optimize the radiation output of both amplifier and oscillator FELs. Tapering has undergone a renaissance of interest, in part to make possible TW instantaneous power levels from x-ray FELs. In this talk, I will give a highly personalized (and undoubtedly strongly biased) historical survey of tapering studies beginning with the ELF 35-GHz experiments at Livermore in the mid-1980's and continuing up to quite recent studies at the LCLS at both soft and hard x-ray wavelengths.

SOME GENERAL COMMENTS

Not wanting to put together pages and pages of dusty, historical material covering my tapering experiences since the early 1980's, I will instead limit myself to a few suggestions to my younger, brighter, and far more energetic FEL colleagues concerning subject areas of our current millenium where it is *possible* (but not certain!) that additional work on tapering theory could be useful and productive.

Regarding optimizing "KMR-style" tapers, I think it is quite evident at this FEL 2015 conference that numerous groups (*e.g.,* UCLA/SLAC, Lund, DESY, Diamond/Daresbury) realize that allowing a variable ponderomotive phase $\psi_R(z)$ can lead to much greater power output over a fixed undulator length than would be keeping ψ_R rigidly fixed. (Moreover, as I tried to stress in my talk, KMR themselves knew this and T. Scharlemann and I from the mid-1980's had a ramping option for ψ_R in the FRED&GINGER self-design algorithm). However, it is not clear to me personally that there is a unique (or even semi-unique) strategy that can maximize the trapping fraction in the undulator region just downstream of the nominal saturation point z_{SAT} that will work over a broad range of FEL parameters such as Z_R/L_G, Twiss-β/L_G, $4\pi\varepsilon_N/\lambda_s$, σ_E/ρ , *etc.* (here all the standard abbreviations hold...). My guess is that when emittance and incoherent energy spread are non-trivial relative to the size of the FEL parameter ρ, one may need to be very careful in increasing ψ_R too rapidly in z. Effects such as these mean that if the bucket area does not increase sufficiently quickly with z due to an increasing radiation power, then there will likely be a lot of detrapping in the first couple gain lengths beyond the nominal saturation point from particles near the outer edges of bucket. There is also the issue for high electron beam energy FELs such as LCLS or XFEL that depend upon quadrupole-based strong focusing that the variation of wiggle-period-averaged $p_\parallel$ over a betatron period can be another source of detrapping lightly-bound electrons.

Regarding sidebands, during the olden days of the LLNL high gain amplifier work, I started a paper (never finished after my departure from the shortly-to-collapse LLNL FEL program) on SASE-stimulated sideband limits to stable tapering. This was stimulated by the desire to see if one could get a solid criterion for the necessary seed power (presumably higher due to the detrapping effects of sidebands than would be necessary from just final spectral bandwidth considerations). This subject is now (refreshingly???) current again with the interest in reaching TW power levels from x-ray FELs. My feeling is that there has been no truly definitive work on to what degree will tapering control sideband growth in situations where one wants reasonably stable trapping over as many as 10 gain lengths beyond z_{SAT}. I also suspect that whatever work was done in the 1990's concerning detrapping due to sidebands should likely be redone and extended by considering 2015-style high brightness e-beams in which the particles might be more deeply trapped initially in the saturation region. Moreover, with 3 (or is it 4) orders of additional computational power now available, it is useful for someone to look at the various characteristics of sideband growth (*e.g.*, radiation mode size and shape, sensitivity to different focusing schemes and different ratios of the betatron to the synchrotron wavelength). If in fact SASE-initiated sidebands are a true issue in terms of detrapping, perhaps there are clever schemes in terms of detuning *a' la* I-SASE that can reduce the effective sideband growth rate.

Regarding tapering SASE-mode amplifiers, I do not believe we in the community know at all what the best strategy is in terms of a variable $\psi_R(z)$ that will work over a broad range of parameters. The statistical irregularities of the depths of the ponderomotive wells from one SASE-spike to another suggests there may *not* be one taper that works best for all. Sam Krinsky and Robert Gluckstern) did some very nice work [2] in the early-2000's on the general statistical properties of SASE spikes in the exponential gain region leading up to z_{SAT}. Perhaps some clever soul can do similar analysis that could extend this analysis to a few gain lengths beyond z_{SAT}. Then ideally, this soul could *also* use the resultant properties to find an indication as to how best

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manipulate ψ_R in a way that maximizes both the trapping in the saturation region and then also leads to an optimized power extraction in the next five to ten gain lengths.

Since the effective group velocity of the SASE radiation spikes speeds up to c as one moves beyond z_{SAT}, this change of effective slippage rate might have some consequences in determining the statistically-optimized $\psi_R(z)$ that would not be seen in the time-steady situation. I note that the FEL01 work [3] that was done on SASE-tapering for LCLS-like parameters indicated that a reduced $\psi_R = 0.2$ (relative to the $\approx 0.35 - 0.45$ found for time-steady cases) could retain significant residual trapping out to $z = 200$ m. Thus, it does not seem that the particles fully debunch as a given electron slice passes though the valley of "darkness" between one SASE radiation spike to the next. But here too the great increase in computational power should allow a relatively easy investigation into what might be going on in the case of a very, very long hard x-ray FEL. Looking for various correlations between the relative spike power (including its nearby neighbors in the direction of the beam head) and the trapping/detrapping properties of the electron slices might be quite illuminating. It also might not be too surprising that the taper that optimizes SASE power for a given undulator length is not the exact same one that would maximize the far field brightness nor the one that minimizes shot-to-shot fluctuations in the situation where the electron beam length is comparable to a couple slippage lengths or less. For situations where the electron beam has strong longitudinal variation in properties such as emittance, incoherent energy spread and/or current, the situation is likely even more complex in finding an "optimized" taper for a SASE configuration.

In the end, it is almost certain that the "final" taper optimization will be done in the control room (much as is true for LCLS and FERMI today), perhaps with the benefit of some genetic algorithm. But we are very lucky to be entering a golden age regarding FEL amplifiers in which more than a half-dozen XUV to hard X-ray FELs will be operational by 2018 and the best is almost certainly yet to come for amplifier FELs.

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