HARMONIC CASCADE FEL DESIGNS FOR LUX, A FACILTY FOR ULTRAFAST X-RAY SCIENCE*

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Abstract

LUX is a design study to develop concepts for future ultrafast x-ray facilities. Presently, LUX is based on an electron beam accelerated to ~3-GeV energy in a superconducting, recirculating linac. Included in the design are multiple free-electron laser (FEL) beamlines which use the harmonic cascade approach to produce coherent XUV & soft X-ray emission beginning with a strong input seed at ~200-nm wavelength obtained from a "conventional" laser. Each cascade module generally operates in the low-gain regime and is composed of a radiator together with a modulator section, separated by a magnetic chicane. The chicane temporally delays the electron beam pulse in order that a "virgin" pulse region (with undegraded energy spread) be brought into synchronism with the radiation pulse. For a given cascade, the output photon energy can be selected over a wide range by varying the seed laser wavelength and the field strength in the undulators. We present numerical simulation results, as well as those from analytical models, to examine certain aspects of the predicted FEL performance. We also discuss lattice considerations pertinent to harmonic cascade FELs, somesensitivity studies and requirements on the undulator alignment, and temporal pulse evolution initiated by short input radiation seeds.

INTRODUCTION

In the past decade, there has been an increasingly strong interest in developing intense sources of tunable, coherent radiation at extreme ultraviolet and soft x-ray wavelengths. While much of this effort has been concentrated upon SASE-based FEL's, there is an alternative "harmonic cascade" FEL approach [1][2] which begins with a temporally and transversely coherent input signal from a "conventional" laser in the ultraviolet region (*e.g.* $\lambda_{in} \sim 240\,\mathrm{nm}$). This input is then effectively frequency-upshifted via resonant electron-radiation interaction in a series of FEL undulators to produce a short wavelength (*e.g.* $\lambda_f \sim$1 nm) final signal with excellent transverse and temporal coherence.

LUX is a design study underway at LBNL to develop concepts for future ultrafast x-ray facilities with emphasis on parameters complementary to SASE-based projects. Concepts have been developed for an integrated system of ultrafast x-ray techniques and lasers, using laser-seeded harmonic cascade FEL's, rf- and laser-based electron-bunch manipulation, x-ray compression, high-brightness high-repetition rate electron sources, and with timing and synchronization systems as fundamental elements. This paper follows on previous conference contributions [3][4] which have given details of possible cascade layouts together with expected performance and sensitivity to various e-beam and input laser parameters. Here we want to present some additional work that has been performed at LBNL on the LUX concept such as an analytic model for cascade performance, a design for an isochronous bend which would preserve microbunching exiting a modulator at short wavelength scales, some results concerning sensitivity to undulator alignment and tilt, and the temporal evolution of a short input pulse.

ANALYTICAL RESULTS FOR CASCADE PERFORMANCE

An analytic theory for seeded beams (please see [5] for much greater detail) has been developed which allows for the rapid numerical evaluation and optimization power output in low gain harmonic cascades. A key *ansatz* of the theory holds that the "preferred" output mode from the radiator is that which maximizes the output power for a given set of undulator and modulated electron beam parameters. For the first stage, when seeded by a radially-large external laser, the theory predicts that the optimal power output, P, from the radiator scales at wavelength λ as

$$P \approx 4.12\, Z_0\, I^2 N_U\, \zeta\, [J_0(\zeta) - J_1(\zeta)]^2\, J_n^2(j'_{n,1}) \times F_\gamma^2\left(\frac{j'_{n,1}\sigma_\gamma}{\Delta\gamma_M}\right)\left(1 + 4\,\frac{\beta}{L}\frac{\varepsilon_N/\gamma}{\lambda/4\pi}\right)^{-1} . \quad (1)$$

Here, $Z_0 = 377\,\Omega$, I and ε_N are the beam current and normalized emittance, respectively, N_U is the number of radiator undulator periods, n is the harmonic number, $\zeta \equiv a_U^2/2(1 + a_U^2)$, $j'_{n,1}$ is the first zero of the derivative of J_n, $\Delta\gamma_M$ is the energy modulation produced by the upstream modulator, and the function F depends on the energy distribution and decreases with increasing argument. At this optimum, the Rayleigh length will be $Z_R \approx 0.15L + 2\pi\sigma_e^2/\lambda$, where L is the radiator length and σ_e is the electron beam size. Quantitative comparison of the analytic theory predictions (as evaluated via a Mathematica script) with numerical simulations with the GENESIS code show agreement of 20% or better for LUX cascade parameters. Consequently, we believe that the above

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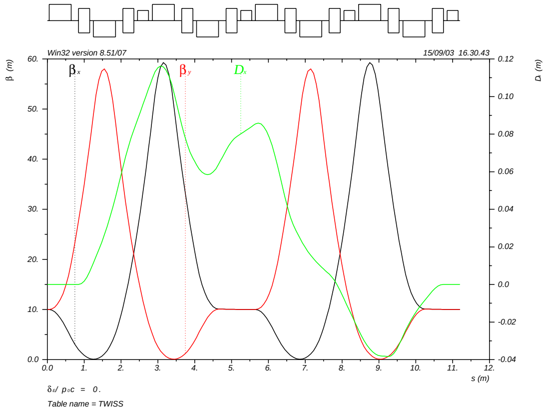

Figure 1: Plots of the bend lattice functions

mentioned ansatz has been confirmed, at least in the LUX operational regime.

BEND SECTION DESIGN

The present design of LUX ([3, 6, 7, 8]) has included the option of bending the electron beam immediately following the exit of each modulator. The purpose here was to allow easy access to the radiation beam for experimentalists. However, various colleagues have raised the issue as to whether it is possible to design a bend which would retain the microbunching (and especially that at the higher harmonic wanted for good radiator output) without undue degradation. In the past year we have examined in detail a bending section design to satisfy these concerns.

Type	Length (cm)	Field at 1.5 cm (kG)
Bend (B1)	30	12.7375
Bend (B2)	30	-6.6243
Quad (QF)	60	-2.5513
Quad (QD)	60	2.5423
Sextupole (S1)	60	0.7297
Sextupole (S2)	60	1.5768
Sextupole (S3)	30	-3.6514

Table 1: List of magnets (trims not included), along with their lengths and strengths

First of all, the microbunching length scale of 1 nm is at least an order of magnitude shorter than that examined in any previous study ([9, 10]). There is no doubt that all second order aberrations in time-of-flight will need to be corrected. It remains to be seen whether higher order aberrations are small enough to be effectively ignored. One efficient way of achieving this goal is to take full advantage of the four cell achromat first systematically studied and applied in realistic design by K. Brown ([11]). The basic result of that work was that a beamline is an achromat if it consists of 4 identical FODO cells with 90 degree phase advance in both planes. To the first order, time-of-flight depends on momentum only ($R_{56} \neq 0$). If 2 families of sextupoles are added to correct chromaticity, to the second order, the time-of-flight depends on momentum only ($T_{566} \neq 0$). To maintain bunch structure at the 1 nm level, both R_{56} and T_{566} have to be under control, which means that one extra knob each on the first and second order optics. It is certain that at 2.5 GeV, the knob to adjust T_{566} has to be a sextupole. Yet there are at least two options to cancel and adjust R_{56}. To cancel R_{56}, or to make R_{56} very small, which is the case here, either negative dispersion has to be created or reverse bends must be used. Generally speaking, using reverse bends requires weaker quadrupoles. It was found that third order aberrations are too large if negative dispersion is used to cancel R_{56}. To adjust R_{56}, one option is to use an additional family of quads; this was not adopted due to the concern of the cost and the length of the beamline. Instead, the scheme used here is the redistribution of bending (keeping the total bending angle fixed). As a result, the bending section consists of 4 identical cells. Each cell contains 2 dipole, 2 quadrupole and 3 sextupole magnets. The total bending angle of the beamline is 5 degrees. It turns out that, at sub-micron level, adjusting R_{56} does not affect focusing, making it an independent knob. To shorten the length further, two families of sextupoles are placed inside the quads. The spacing between magnets is 10 cm, except that, after each quad, an extra 10 cm is reserved for BPM and correct/skew quad coils. The key parameters of all main magnets are listed in Table 1 and the lattice functions are shown in Fig. 1.

Preliminary tracking study for the last section (λ=1 nm) has been done to evaluate the performance of the beamline. The initial distribution of electrons was taken directly from a *GINGER* [12] FEL simulation of the LUX harmonic cascade through to the end of the 4-nm modulator. The energy of the electron beam was 2.5 GeV, the normalized transverse emittance (round beam) is 3π mm-mrad and the peak to peak energy modulation is 5 MeV. First, the effect of the remaining aberrations beyond the second order is examined, with fringe field included. The result is that there is no net change in the bunch length.

The effect of errors is simulated through a computer-generated random Gaussian distribution. Up to now, only static errors have been included, which are the setting errors of the dipoles, quadrupoles and sextupoles, the sextupole component in dipoles and quadrupoles, tilt and misalignment of quadrupoles and sextupoles. In order to ensure success in operation, dipole, quadrupole (normal and skew) and sextupole correctors are included in the design. Trim coils are envisioned in each quad and two families of sextupoles that are inside the quads. A 10-cm slot downstream of each quad is reserved for a BPM and a set of dipole corrector/skew quad coils. The currents of the main dipoles are used to restore R_{56} to the optimal value. Specifically, there are 8 horizontal dipole correctors and 8 vertical correctors, all of which are individually powered. The trim quads, skew quads and trim sextupole are grouped into 2 families. In one family, the elements are powered symmetrically about the midpoint of the beamline and, in the other family, they are powered anti-symmetrically. The two currents of the main dipoles are grouped into one family, keeping the difference fixed, hence the total bending angle unchanged. The conclusion is that, with typical errors in accelerators, bunch compression can be restored when trim quads, skew quads, and trim sextupoles are turned on and the dipole correctors are off. Without orbit correction, both trim and skew quads must be energized to maintain the short bunches. On the other hand, practical implementation remains an outstanding issue. A practical scheme is yet to be developed to tune up the beamline and maintain stable operating conditions over time.

UNDULATOR MISALIGNMENT SENSITIVITY

We have conducted a survey study of the sensitivity of radiator output to undulator misalignments and tilts using the *GENESIS* [13] simulation code. For wavelengths as short at 1 nm, offsets of up to 10 microns do not lower the output power by more than 15%. For 20-micron offsets, at 2- and 1-nm wavelengths the power drops by 25% and 40%, respectively. Offsets of 40 mcirons essentially eliminate the power at the shortest wavelengths and reduce it by 40% at 10-nm. Simple angular tilts of up to 2 μrad do not appreciably reduce the output whereas there is a $\approx$40% loss for a 4-μrad tilt; increasing the tilt to 8 μrad essentially turns off the device at wavelengths 2.0-nm and shorter. These results suggest reasonably careful (but not absurdly intricate) alignment will be necessary for operation below 10-nm wavelength.

SHORT PULSE EVOLUTION

Some user applications may require output radiation pulse durations much shorter than the nominal $\approx$ 200 fs adopted in our sample design for LUX. For a *high gain* FEL cascade initiated with a Gaussian temporal profile, Saldin *et al.*[14] have predicted that the rms radiation pulse duration will tend to shrink by a factor $\sqrt{M}$ from one stage to the next where M is the harmonic ratio between the modulator resonant wavelength and that of the radiator immediately downstream. A high power, low gain design cascade is less sensitive to input power variations and one therefore expects less shrinkage. Moreover, in the extreme limit where the radiation pulse duration is quite short, one expects that slippage effects will place a lower limit on the output pulse duration from each stage.

To study these phenomena, we initiated a LUX cascade with a Gaussian temporal profile seed pulse with σ_t =5 fs (11.2-fs FWHM) and examined the downstream $P(t)$. *GINGER* simulations were done in full time-dependent mode and included shot noise effects. In order to obtain sufficient energy modulation in the first stage, the peak input power was increased to 2.5 GW from the nominal time-steady value of 1.0 GW. Figure 2 shows the temporal output power profiles from each radiator stage. The FWHM temporal duration first increases to $\approx$15 fs at λ=48 nm, presumably because τ_{slip}=24 fs, but then shrinks back to a nearly constant $\approx$11 fs in the next 3 stages, in strong contrast to the scaling observed in [14]. Since the slippage is less than 3 fs in the 4- and 1-nm stages, the lack of additional pulse shrinkage must be due the design features of a low gain, high power configuration. Some noise modulation appears on the 1-nm output $P(t)$ but the pulse remains nearly completely temporally coherent.

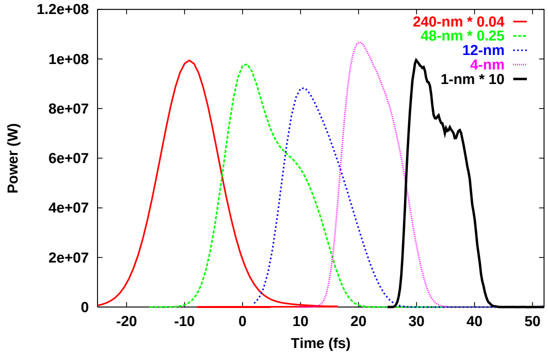

Figure 2: Predicted $P(t)$ profiles at different stages for a LUX cascade initiated with a Gaussian profile pulse with a 5-fs RMS duration. Each curve has been scaled by the indicated factor to fit on the plot.

REFERENCES

[1] L.H. Yu, *Phys. Rev. A*, **44**, 5178 (1991).

[2] R. Bonifacio *et al.*, *Nucl. Inst. Meth. A*, **296**, 787 (1990).

[3] W.M. Fawley *et al.*, *Proc. 2003 Particle Accel. Conf.*, **IEEE 03CH37423**, 923 (2003).

[4] G. Penn *et al.*, *EPAC2004*, Paper MOPKF074 (2004).

[5] G. Penn, J. Wurtele and M. Reinsch, "Analytic Model of harmonic Generation in the Low-Gain FEL Regime", Paper MOPOS57, these proceedings.

[6] J. Corlett *et al.*, LBNL report LBNL-51766 (2002).

[7] J. Corlett *et al.*, *Proc. 2003 Particle Accel. Conf.*, **IEEE 03CH37423**, 186 (2003).

[8] A. A. Zholents *et al.*, *Beam Transport Lattice in a Cascaded Harmonic FEL* LBNL CBP Tech Note-281 (2003).

[9] S. Chattopadyay *et al.*, LBNL report LBNL-39788 (1997).

[10] A. Zholents, M. Zolotorev and W. Wan, *Proc. 2001 Particle Accel. Conf.*, **IEEE 01CH37268**, 723 (2001).

[11] K. L. Brown, *IEEE Trans. Nucl. Sci.*, **NS-26**, 3490 (1979).

[12] W.M. Fawley, LBNL report LBNL-49625 (2002).

[13] S. Reiche, *Nucl. Inst. Meth. A*, **429**, 243 (1999).

[14] E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, *Opt. Comm.*, **202**, 169 (2002).