HARMONIC CASCADE FEL DESIGNS FOR LUX*

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Abstract

LUX is a design concept for an ultrafast X-ray science facility, based on an electron beam accelerated to GeV energies in a recirculating linac. Included in the design are short duration (200 fs or shorter FWHM) light sources using multiple stages of higher harmonic generation, seeded by a 200–250 nm laser of similar duration. This laser modulates the energy of a group of electrons within the electron bunch; this section of the electron bunch then produces radiation at a higher harmonic after entering a second, differently tuned undulator. Repeated stages in a cascade yield increasing photon energies up to 1 keV. Most of the undulators in the cascade operate in the low-gain FEL regime. Harmonic cascades have been designed for each pass of the recirculating linac up to a final electron beam energy of 3.1 GeV. For a given cascade, the photon energy can be selected over a wide range by varying the seed laser frequency and the field strength in the undulators. We present simulation results using the codes GENESIS and GINGER, as well as the results of analytical models which predict FEL performance. We discuss lattice considerations pertinent for harmonic cascade FELs, as well as sensitivity studies and requirements on the electron beam.

HARMONIC CASCADE DESIGN

A harmonic cascade involves multiple stages of harmonic generation [1], where each stage uses two undulators and a dispersive section to product outgoing radiation at a harmonic of the incoming radiation. As part of the LUX [2, 3] design concept, harmonic cascades would be used to produce very high harmonics of optical or UV lasers; the radiation would be tunable over a wide range of photon energies by varying the initial laser frequency and the sequence of harmonic numbers, which multiply the photon energy. The design considered here produces photon energies of up to 1 keV.

In the following simulations, the laser seed is assumed to have a peak power of 100 MW and FWHM of 200 fs, and to be tunable over a range of wavelengths including the interval from 200 – 250 nm. Nominal values for the electron beam are 2 μm normalized emittance, a uniform energy spread of +/- 200 keV, and a flat-top current profile having a value of 500 A and with a duration of 2 ps.

Most of the undulators in the cascade operate in the low-gain FEL regime. Because of this, the spontaneous radiation levels remain very low and do not become amplified through the multiple harmonics, and the laser seed synchronizes the entire cascade. The output radiation can still vary due to fluctuations in the seed laser, electron beam, timing, or alignment. The sensitivity to fluctuations and misalignments is studied for each cascade.

We consider a configuration where the beam makes three passes through a recirculating linac, exiting with energies of 1.1, 2.1, and 3.1 GeV. Proper FEL performance requires that the undulator satisfy the resonance condition, $\lambda \simeq \lambda_U(1+a_U^2)/2\gamma^2$, where λ is the radiation wavelength, λ_U is the undulator period, the electron energy is $\gamma m_e c^2$, and $a_U \equiv eB_{\mathrm{RMS}}\lambda_U/2\pi m_e c$ is the normalized undulator field strength; here B_{RMS} is the RMS value of the undulator field on axis. Thus, the undulators must be adjusted each time the output radiation wavelength is changed.

Two different functions are performed by the undulators. In the modulators, the electrons overlap a laser field as they pass through the undulator. This creates a sinusoidal variation in the electron energy with time. Before the electron beam enters the next undulator, it is sent through a dispersive transport section that generates a linear shift in longitudinal position with energy. This can be adjusted to produce substantial bunching of the beam. The beam then enters the radiator, which is tuned to a higher harmonic of the initial laser seed; radiation is produced when the density modulation has Fourier components at the appropriate wavelength.

The energy modulation is at this point transformed into an increase in energy spread σ_γ, which should satisfy $\sigma_\gamma/\gamma < \rho_{\mathrm{FEL}}$, where ρ_{FEL} is the "FEL parameter" [4] which reflects the tolerance of an FEL to deviations from the resonance condition. The electron beam is then delayed relative to the laser field using a chicane, so that in the following modulator the laser field overlaps a "fresh" section of the electron beam.

Most of the undulators are assumed to be of the planar hybrid design, where magnetic poles are sandwiched between alternating high-field permanent magnets. The peak field on axis is related to the gap, g, according to the fit given by K. Halbach [5] (for $SmCo_5$):

$$B_0[T] = 3.33 \exp\left[-\frac{g}{\lambda_U}\left(5.47 - 1.8\frac{g}{\lambda_U}\right)\right]. \quad (1)$$

The magnetic field strength is tuned by adjusting the gap. Tapering of the magnetic field is required for proper matching; here two magnetic periods on each side of the undulators are simply designated as drift space. The final radiators are taken to be helical undulators, which allows for circularly polarized radiation. The undulator parameters for the harmonic cascades are given in Tables 1 and 2; tapering is excluded.

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Table 1: Planar undulator parameters and requirements for harmonic cascades at different energies.

Period (mm)	Energy (GeV)	length (m)	peak B (T)	gap (mm)
140	2.1	2.8	0.74 – 0.83	39 – 43
	3.1	2.8	1.10 – 1.24	27 – 31
80	1.1	2.4	0.89 – 1.00	19 – 22
	2.1	3.2	0.68 – 0.95	19 – 26
	3.1	2.4	1.03 – 1.42	13 – 19
50	1.1	3.0	0.77 – 1.15	10.4 – 14.9
	2.1	6.0	0.73 – 1.10	11.0 – 15.5
	3.1	4.0	1.12 – 1.47	7.8 – 10.7
35	3.1	6.3	0.89 – 1.51	5.3 – 9.3

Table 2: Helical undulator parameters for each cascade.

Period (mm)	Energy (GeV)	length (m)	B on axis (T)
35	1.1	6.3	0.39 – 0.97
	2.1	6.3	0.38 – 0.92
28	3.1	8.4	0.50 – 0.94

SIMULATION RESULTS

Here we present simulation results for select examples of harmonic cascades. These simulations were performed using the GENESIS [6] simulation code, which is fully 3-dimensional, allowing for the inclusion of effects such as beam misalignments. Earlier simulations have been performed by W.M. Fawley [7] using the GINGER code [8].

Each cascade begins with a modulator that has an external laser, tunable from 200 – 250 nm, focussed on it. The laser has peak power of 100 MW and FWHM of 200 fs. Following this are pairs of identical undulators, plus a final radiator. In between the undulators, there are 1.2 m gaps for the dispersive sections and the chicanes.

For the 1.1 GeV electron beam, the cascade has two stages and, including the 1.2 m drifts and the undulator tapering, has a total length of 19.2 m. The output power is shown in Figure 1 for the case of 10 nm wavelength, from an initial laser seed which has a 200 nm wavelength. Harmonic numbers 5 and 20 are used. Even with a Gaussian input laser, the final radiator produces a flat-top laser profile in time, with 213 MW of peak power, FWHM of 180 fs, with 35 fs ramps. The energy per pulse is 39 μJ.

For the 2.1 GeV electron beam, the cascade has three stages and a total length of 34.8 m. For a 2.5 nm wavelength, using harmonics numbers 5, 20, and 80 from a 200 nm laser seed, the final radiator produces a flat-top laser profile in time, with 80 MW of peak power, FWHM of 200 fs, with 35 fs ramps. The energy per pulse is 5.2 μJ.

For the 3.1 GeV electron beam, the cascade has four stages and a total length of 46.0 m. For a 1.0 nm wavelength, using harmonics numbers 4, 16, 64, and 192 from a 200 nm laser seed, the final radiator produces a flat-top laser profile in time, with 41 MW of peak power, FWHM of 150 fs, with 16 fs ramps. The energy per pulse is 6.3 μJ.

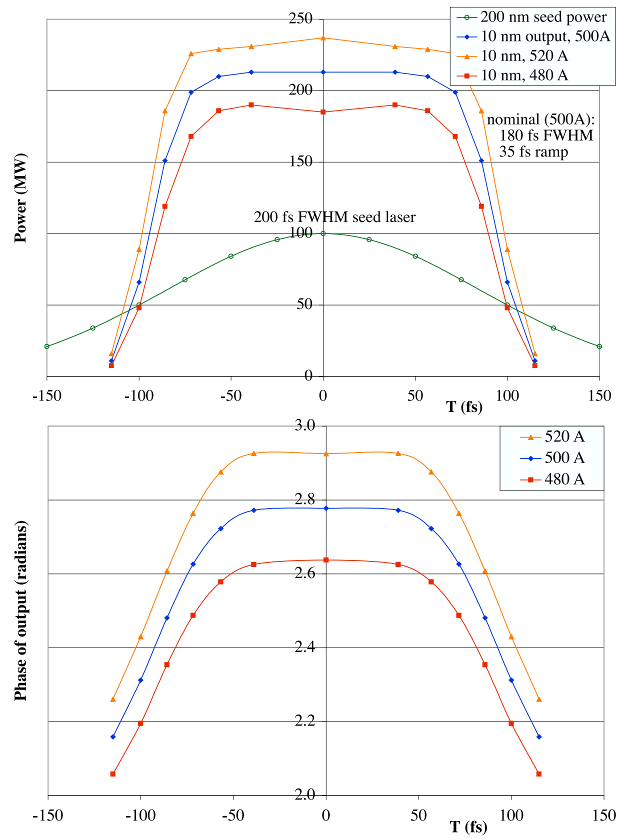

Figure 1: Temporal structure of output power (top) and phase (bottom) at 1.1 GeV, yielding 10 nm radiation from a 200 nm laser seed. Simulations are shown for electron bunch current of 500 A, and 500 $\pm$ 20 A.

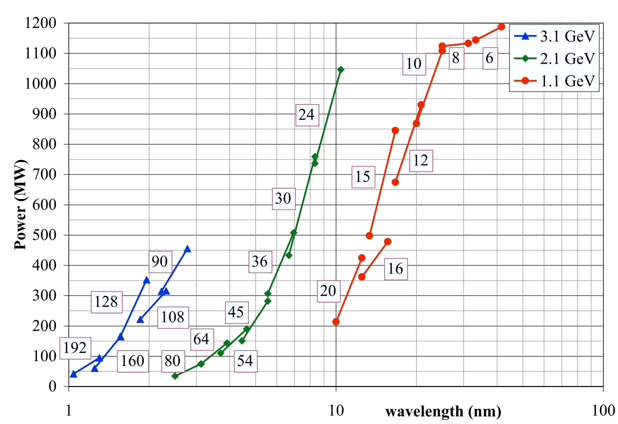

Figure 2: Output power as a function of wavelength for the three energy levels, tuned by varying both the input laser frequency and the harmonic number sequence. Total harmonic number is shown in boxes.

Figure 2 shows the sweep of the cascades at each energy. The output power improves as the wavelength is increased, until the required undulator field strength becomes too high. The three energy levels combine to produce a continuous range of photon energies from 40 eV up to 1.2 keV.

SENSITIVITY STUDIES

The sensitivity studies described here vary the electron beam properties without changing the harmonic cascade parameters, which are tuned for the nominal case. The effect of misalignments are also considered. The results of shifting the beam current by ±4% has already been shown in the Figure 1, including the variation in temporal profile. In Table 3, the results are summarized for the highest photon energy for each cascade.

Table 3: Sensitivity studies: dependence of peak power on electron beam current, emittance, and energy spread, for different harmonic cascades.

Perturbation	Peak power (MW)		
	1.1 GeV 10 nm	2.1 GeV 2.5 nm	3.1 GeV 1.0 nm
Nominal	213	34.6	41.4
I=480 A	185	29.2	38.1
I=520 A	237	38.5	45.8
ϵ_N=2.2 μm	172	25.4	33.0
ϵ_N=1.8 μm	260	39.3	51.3
σ_γ=0.43	189	29.0	34.8
σ_γ=0.35	234	38.8	48.7

Table 4: Output power with misalignments in position and angle.

Misalignments	Peak power (MW)		
	1.1 GeV 10 nm	2.1 GeV 2.5 nm	3.1 GeV 1.0 nm
None	213	34.6	41.4
Position:			
10 μm	207	33.6	38.0
20 μm	195	29.9	30.6
40 μm	158	16.0	15.3
Angle:			
10 μrad	213	34.1	40.6
20 μrad	211	33.0	39.8
40 μrad	201	29.3	38.4

The beam emittance has an especially strong effect because the electron bunch radius and laser beam spot size are comparable in later stages. While phase deviations within the laser seed are a potential problem, fluctuations in laser power should not have a strong effect on the output seed. In particular, the output power is a fairly flat function of the input power. In Table 4, the effect of displacements and misalignments in angle is shown. Each simulation consists of adding misalignments in between each pair of undulators, in both planes. The dominant effect of misalignments is to reduce the overlap between the electron bunch and laser beams. The example with 1 nm output radiation exhibits a reduction of 26% in peak power when the electron bunch is displaced by 20 μm. Misalignments in angle also reduce the peak power; in the 1 nm example, peak power drops by 7% for misalignments of 40 μrad. For comparison, the RMS radius of the electron bunch is 85 μm, and the RMS angle is 40 μrad.

ANALYTIC THEORY

An analytic theory for seeded beams has been developed which allows for rapid predictions and optimization of harmonic cascades. This has been implemented as a Mathematica script. For the first stage, when seeded by a large external laser, the theory predicts that the optimal power output, P, will be

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

Here, $Z_0 = 377\ \Omega$, N_U is the number of undulator periods in the radiator, n is the harmonic number, $\xi = a_U^2/2(1+a_U^2)$, and F_γ depends on the energy distribution and decreases with increasing argument. At this optimum, the Rayleigh length will be $Z_R \simeq 0.15L + 2\pi\sigma_e^2/\lambda$, where L is the length of the undulator and σ_e is the electron beam size. More generally, a numerical and less accurate prediction results, but it is accurate to within 20%.

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