SIMULATION STUDIES OF FELS FOR A NEXT GENERATION LIGHT SOURCE

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Abstract

Several possible FEL beamlines for a Next Generation Light Source are studied. These beamlines collectively cover a wide range of photon energies and pulse lengths. Microbunching and transverse offsets within the electron beam, generated through the linac, have the potential to significantly impact the longitudinal and transverse coherence of the x-ray pulses. We evaluate these effects and set tolerances on beam properties required to obtain the desired properties of the x-ray pulses.

INTRODUCTION

The Next Generation Light Source (NGLS) is envisioned to serve as a powerful soft x-ray FEL user facility with multiple beamlines driven by a CW superconducting linear accelerator. The bunch repetition rate could be up to 1 MHz. Here, we study a self-seeded beamline and a two-stage HGHG beamline driven by a UV laser seed. Both beamlines are capable of yielding up to 10^{12} photons/pulse. We study the performance of these beamlines at different photon energies and using different models for the electron bunches. The focus is on start-to-end (S2E) simulations. We shall see that the performance of the FEL beamline is strongly dependent on the quality and especially uniformity of the electron bunch.

BEAMLINE PARAMETERS

The electron bunch charge is taken to be 300 pC, and it is accelerated to 2.4 GeV. The nominal slice parameters are 500 A current, 150 keV rms energy spread, and 0.6 micron emittance. Various full start-to-end simulations starting from the injector [1] and passing through a SC linac [2] are broadly consistent with those values. The peak current is typically not flat but varies from 450 A to 600 A. The energy spread is controlled by the use of a laser heater [3] in order to damp out microbunching instabilities, but can still varies with position within the bunch, typically in the range 150 keV to 200 keV. The slice emittance ranges between 0.5 micron and 0.7 micron. However, the beamlines are designed to be able to handle a worse beam emittance of up to 0.9 μm, as well as an energy spread of 200 keV.

We focus on undulators using superconducting (SC) technology with relatively short undulator period, to provide the full tuning range with reasonably large (not much smaller than unity) dimensionless undulator parameter at the highest photon energy. SC undulators have the advantage of being able to produce higher magnetic fields for a larger gap, especially for undulator periods shorter than 30 mm. This allows for more compact beamlines, lower energy beams, and larger undulator parameters. There is also the possibility that SC undulators will be more robust to the environment resulting from a high average beam power that could approach 1 MW. The magnetic gap is 6 mm, to allow clearance for an inner diameter beampipe of 4 mm. Superconducting technology is especially critical for the x-ray producing undulators. The undulator sections have a length of 3.3 m, typically with breaks of 1.1 m containing a quadrupole, phase shifter, orbit correctors, and several diagnostics. Both beamlines have a final cross-planar undulator [4] for polarization control.

The self-seeding scheme [5, 6], shown in Fig. 1, uses undulators with a 20 mm period. Using Nb_3Sn technology can yield a peak undulator parameter of $K = 5$ [7], and a tuning range of 0.2 – 1.5 keV. The beamline consists of two stages separated by a chicane. Within the chicane, the electron bunch is displaced from the radiation field, and the radiation is passed through a monochromator with resolution $R = 20,000$ (relative FWHM bandwidth of 5×10^{-5}), and 2% efficiency within that bandwidth. The chicane also serves to debunch the beam, allowing the filtered radiation pulse to act as a low-bandwidth seed in the second stage. Because a significant amount of undulator length is required in addition to what is needed to reach saturation using SASE, the practical tuning range for the self-seeding is 0.2 – 1.2 keV. However, the monochromator can be removed to extend the tuning range up to 1.5 keV under SASE operation.

At a resonant photon energy of 1.2 keV, the gain length is 2.0 m, and the effective FEL parameter is 4×10^{-4}. The effective shot noise power is 35 W. To ensure that shot noise is strongly suppressed in the second stage, we intend to keep the seeding power delivered by the monochromator above 100 times this value, or 3.5 kW.

The HGHG beamline, shown in Fig. 2, uses undulators with a 23 mm period, for a peak undulator parameter of $K = 6.8$ and a tuning range of 0.1 – 1 keV. Because the output x-ray pulse must be generated from a UV laser seed through harmonic upshifting, a reasonable practical limit for the highest output photon energy is 0.72 keV, just above the Fe L-edges. This design closely follows that of the FEL-2 beamline of FERMI@Elettra [8], except that the parameters are pushed for a higher overall harmonic jump and longitudinal coherence.

The laser seed is taken to be tunable over the range 215 – 260 nm. The duration of the pulse can range from 100 fs down to below 20 fs. The nominal peak power is 200 MW, but for the shortest pulse the peak power will have to

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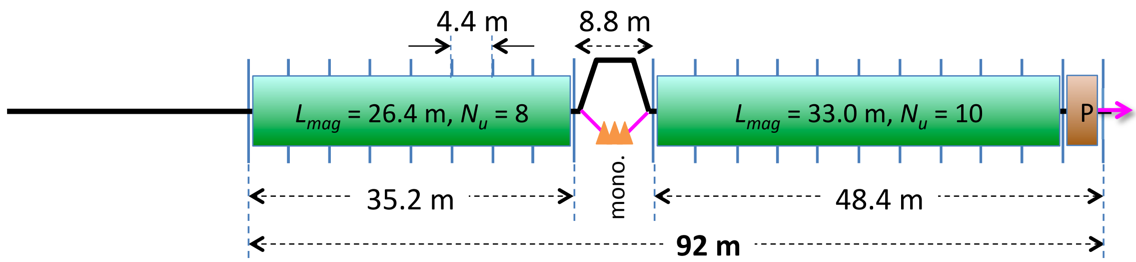

Figure 1: A schematic of the self-seeding configuration.

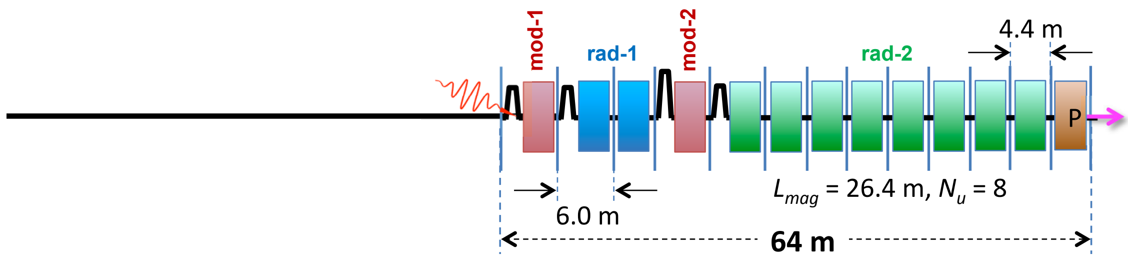

Figure 2: A schematic of the two-stage HGHG configuration.

be increased significantly to make up for slippage. In any case, the energy per pulse will not exceed about 20 μJ. The undulator for interacting with the laser has a 75 mm period.

The HGHG beamline uses two rounds of harmonic generation. The first stage produces radiation at a harmonic of the laser seed. The undulator period for these undulators is taken to be 50 mm. This intermediate photon energy can range up to $\sim$ 105 eV. The lower limit depends on the exact choice of undulator technology. After a radiation pulse of this photon energy is generated, a chicane is used to delay the electron bunch and shift the radiation pulse towards the head of the bunch. This "fresh-bunch" technique [9] allows the second round of harmonic generation to proceed on a portion of the electron bunch with an acceptably small energy spread. Because the two rounds of HGHG must sit on separate portions of the high-quality region in the electron bunch, which has a duration of roughly 300 fs, it is difficult to make use of a seed laser longer than 100 fs. The final x-ray pulse is limited to not much more than 50 fs FWHM.

SIMULATION METHODS

Simulations for a 300 pC electron bunch delivered to the FEL beamlines have been performed in two ways. The same design used used in both cases: a modest amount of compression is performed immediately after the injector, and the rest of the compression occurs in two bunch compressors in the linac. One set of particles was simulated from the injector through the first stage of RF acceleration using the ASTRA code, then tracked through the linac and spreader using Elegant. The longitudinal beam distribution at the entrance of the undulator hall is shown in Fig. 3. The full range of self-forces which lead to longitudinal instabilities have not been included, so the microbunching instability is not accurately modelled. However, the laser heater is modelled at its anticipated setting.

Another set of particles was obtained using the IMPACT code throughout [10]. The longitudinal beam distribution is shown in Fig. 4. More of the self-fields are included, and rather than using macroparticles the full number of electrons in the bunch was simulated. Thus, microbunching should be accurately modeled.

The FEL itself is simulated using GENESIS [11], plus a simple model for the monochromator which matches the overall reduction in bandwidth but not the fine details of the optical elements. In addition to using start-to-end particles in FEL simulations, we also consider resistive wall wakefields in the FEL beamline. The beampipe is taken to be copper at 4K, and to have a diameter of 4 mm. Anomalous skin depth effects are included. The effects of incoherent synchrotron radiation are considered as well. The tail of the electron bunch yields insignificant power and is not included in simulations. In the case of the particle distribution from IMPACT, a randomly selected subpopulation of the electrons was used for simulations.

SELF-SEEDED FEL AT 1.2 KEV

We first show results for the self-seeded beamline tuned to 1.2 keV. At the entrance to the monochromator, the ra-

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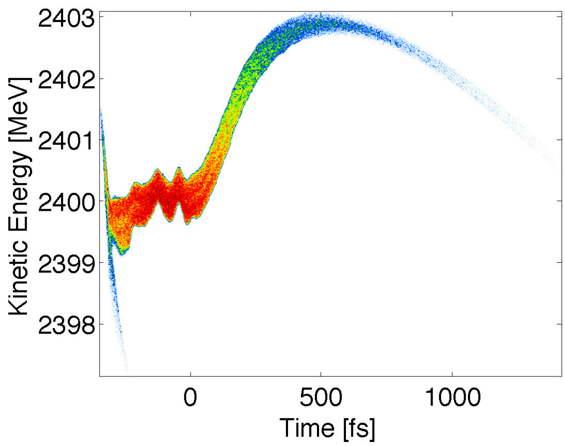

Figure 3: Longitudinal phase space of the beam entering the FEL, obtain from a combination of ASTRA and Elegant simulations.

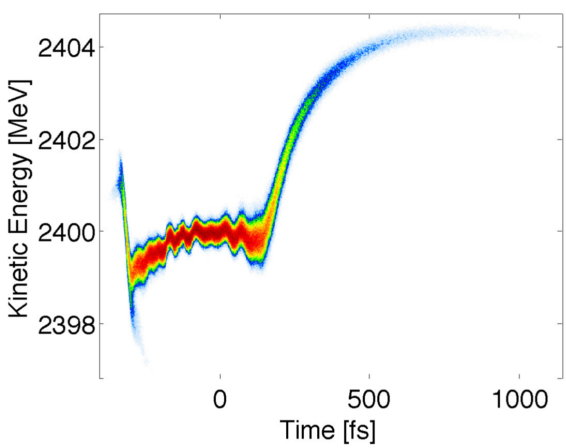

Figure 4: Longitudinal phase space of the beam entering the FEL, obtain from IMPACT simulations.

diation has of order 100 SASE spikes, with peak powers at the level of 10 MW. The total pulse energy is 1.8 μJ. If continued to saturation, the total pulse energy would grow to 140 μJ. The pulse energy is reduced to roughly 2 nJ by the end of the monochromator, due to both reduced bandwidth and low efficiency. In the second stage, the spectrum broadens noticeably from the monochromator bandwidth due to the nonuniform distribution of the electron bunch, in particular because of varying energy chirps. The power profile for the S2E distribution using Elegant is shown in Fig. 5, and the spectrum from each distribution is shown in Fig. 6. The spectrum in each case is compared to the spectrum at the exit of the monochromator (not shown to scale).

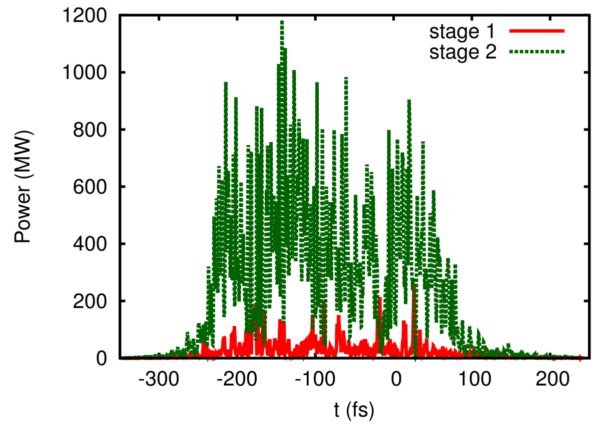

Figure 5: Power profile for the self-seeded beamline tuned to 1.2 keV, for particles from Elegant. The power profile just before the monochromator is also shown.

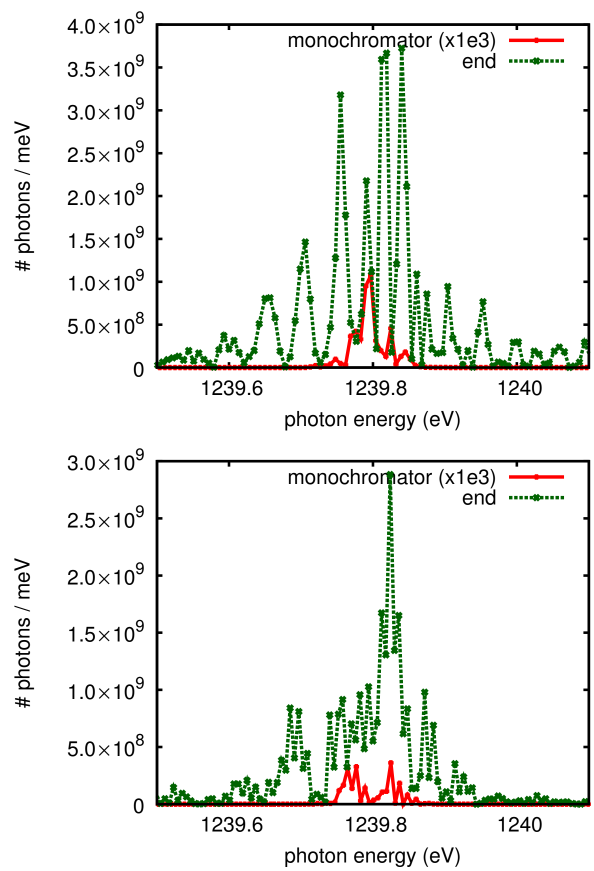

Figure 6: Spectra from full S2E runs for the self-seeded beamline tuned to 1.2 keV, for particles from Elegant (top) and IMPACT (bottom). The spectrum exiting the monochromator is also shown, though not to scale.

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HGHG AT 0.72 KEV

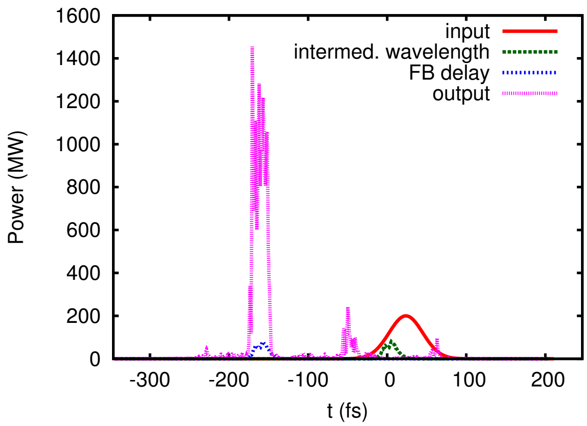

Figure 7: Power profile at various stages of the HGHG beamline tuned to 0.72 keV, for particles from Elegant.

We now consider the two-stage HGHG beamline tuned to a photon energy of 720 eV. The intermediate photon energy is 103 eV. The radiation at four different points in the FEL beamline is shown in Fig. 7: the input laser in red, the first harmonic jump to 103 eV in green, the same pulse after the fresh bunch delay in blue, and the x-ray pulse in purple. This example uses particles from the combination of the ASTRA and Elegant simulation codes. The power produced near the edges of the input laser pulse are numerical artifacts and are not realistic; they arise from the fact that there is just enough energy modulation to randomize the initial quiet-loading, while at the same time the energy spread is not large enough to suppress the FEL instability. The input laser with 50 fs FWHM duration produces an output pulse with a FWHM of $\sim$ 20 fs.

The spectrum from each distribution is shown in Fig. 6. The spectrum obtained using particles from ASTRA and Elegant has a FWHM bandwidth of 150 meV, or 1.6 times the transform limit. The spectrum obtained using particles from IMPACT simulations is significantly broader and shows two separated peaks, yielding a FWHM bandwidth of 230 meV. This increase in bandwidth is due to short-wavelength microbunching in the core of the beam.

ANALYSIS

To understand the reason for degraded spectral bandwidth, it is necessary to look at the variation of the slice average energy with longitudinal position. In addition to the initial longitudinal distribution at the first undulator, resistive wall wakefields induce additional energy chirps in the electron beam as it propagates through the undulators. These energy variations lead to position-dependent shifts in radiation phase because of dispersion in the undulator and, for the HGHG beamline, the chicanes.

For self-seeding, the main phase variations are due to microbunching and to the curvature in the longitudinal distribution at $t \simeq 100$ fs. The peak wake field near the head of the pulse mostly misses the target region of the beam where the current is high. In this case, a good approximation for the shift in phase after the monochromator due to energy deviations in the electron bunch is given by:

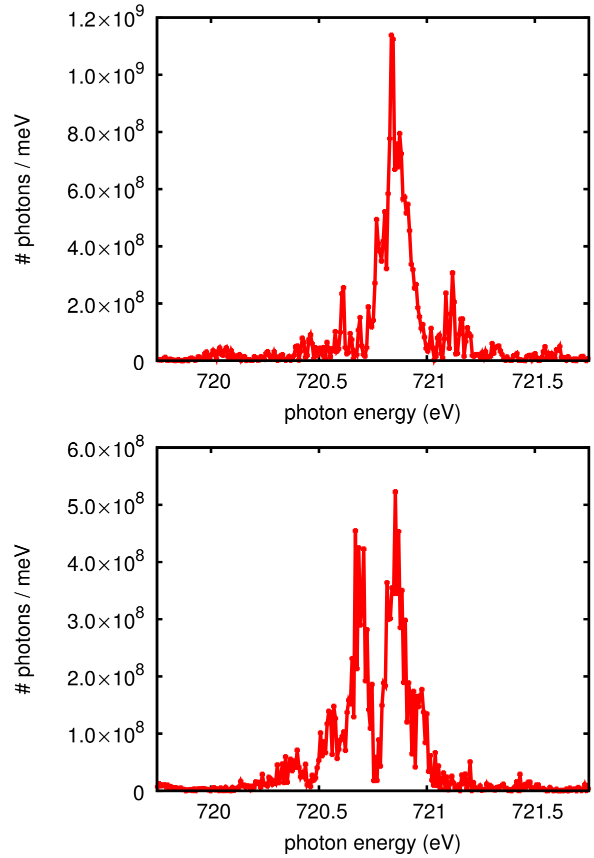

Figure 8: Spectra from full S2E runs for the self-seeded beamline tuned to 1.2 keV, for particles from Elegant (top) and IMPACT (bottom). The spectrum exiting the monochromator is also shown, though not to scale.

$$\Delta\theta \simeq 0.6 \times 4\pi \, \frac{L_u - 1.5 L_g}{\lambda_u} \, \eta \, , \qquad (1)$$

where η is the relative energy offset from the optimal value. This expression holds in the exponential regime before saturation. Variations in the value of η are largely responsible for the generation of radiation outside of the bandwidth of the monochromator.

For the HGHG beamline, the dominant source of dispersion is the first chicane, so the phase shift is roughly given by

$$\Delta\theta \simeq \frac{2\pi}{\lambda} R_{56}^{(1)} \eta \, . \qquad (2)$$

In the current design, the first chicane is chosen to have $R_{56}^{(1)} \simeq 20\ \mu$m. Combined with short-wavelength energy modulations from the microbunching stability cause the spectrum to have two distinct peaks. Their separation by about 200 meV corresponds to a large phase modulation

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with a period of roughly 10 fs. This period short enough for two microbunching oscillations to fit inside the span of the output pulse. We can see from the expressions for phase errors that the sensitivity to energy chirps scales in proportion to the output photon energy.

CONCLUSIONS

Start-to-end examples of soft x-ray FELs have been studied based on electron beams simulated from the injector. Both a self-seeded FEL at 1.2 keV and an HGHG FEL at 0.72 keV have been considered. Despite the structure within the electron distribution, the spectrum is increased by at most a factor of two from that of more idealized calculations. One choice made to achieve good coherence of the x-ray pulse was to set a relatively low nominal peak current of 500 A, allowing for a modest amount of bunch compression and reducing the effect fo wakes and CSR. Other techniques for improving the coherence of the output pulse should be evaluated, in order to allow for higher peak current in the core of the electron bunch if so desired.

ACKNOWLEDGMENTS

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