# PERFORMANCE OF A COMBINED SYSTEM USING AN X-RAY FEL OSCILLATOR AND A HIGH-GAIN FEL AMPLIFIER *

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*Abstract*

The LCLS-II at SLAC will feature a 4 GeV CW superconducting (SC) RF linac [1] that can potentially drive a 5th harmonic X-Ray FEL Oscillator to produce fully coherent, 1 MW photon pulses with a 5 meV bandwidth at 14.4 keV [2]. The XFELO output can serve as the input seed signal for a high-gain FEL amplifier employing fs electron beams from the normal conducting SLAC linac, thereby generating coherent, fs x-ray pulses with TW peak powers using a tapered undulator after saturation [3]. Coherent, intense output at several tens of keV will also be feasible if one considers a harmonic generation scheme. Thus, one can potentially reach the 42 keV photon energy required for the MaRIE project [4] by beginning with an XFELO operating at the 3rd harmonic to produce 14.0 keV photons using a 12 GeV SCRF linac, and then subsequently using the high-gain harmonic generation scheme to generate and amplify the 3th harmonic at 42 keV [5]. We report extensive GINGER simulations that determine an optimized parameter set for the combined system.

## INTRODUCTION

Free electron laser (FEL) technology is developing in many labs around the world, for its use in fundamental science research in fields including biological, material, and other physical sciences. An FEL is capable of creating partially coherent, bright x-ray radiation, unlike many other modern machines. Although many FELs are currently operating around the world, there is a continued push for improvement in the field, in order to produce another generation of FEL machines that can provide fully coherent x-rays.

Many current FELs create bright x-rays with limited temporal coherence due to the Self-Amplified Spontaneous Emission (SASE) method of x-ray production. A SASE FEL can achieve significant amplification from shot noise to provide GW x-ray beam with wavelengths on the order of Angstroms for users, but these beams are temporally chaotic. Some machines plan to use self-seeding methods, in which SASE x-ray pulses are sent through a monochromater, in order to purify the spectrum. This light is then amplified in a second portion of the machine, thereby delivering a high-power beam of reduced bandwidth x-rays, as compared to the SASE spectrum. The bandwidth ($\Delta\lambda/\lambda$) from a SASE FEL is order $10^{-3}$, where $\Delta\lambda/\lambda$ for the self-seeded FEL is order $10^{-5}$ [6].

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Another FEL design is the x-ray FEL oscillator (XFELO). The XFELO is a low-gain device, in which a coherent radiation signal is built up in a cavity consisting of diamond Bragg crystals. The crystals reflect the x-rays, that then copropagate with an electron bunch in an undulator within the cavity. The copropagating x-rays act as a seed signal, and stimulate radiation from the electron bunch at the same wavelength. The signal grows, while reducing in bandwidth, due to the narrow bandwidth of the diamond crystals reflectivity. As such, an XFELO can produce light with bandwidth on the order of $10^{-7}$[7].

While the theory of XFELOs is well known, an XFELO machine has yet to be built. The LCLS-II is an ideal project with which an XFELO could be driven, in order to create TW power radiation. The superconducting, 4GeV upgrade of LCLS-II would allow an XFELO to be driven at the 5th harmonic to create 1MW, 14.4keV x-ray pulses, which could then be used to stimulate and amplify radiation from the 14.35GeV LCLS-I beam. A tapered solution, simulated in GINGER [8], is presented here.

Further, due to the coherence and brightness of XFELO x-rays, we propose that a harmonic generation machine with an XFELO seed laser could be used in the Matter-Radiation Interactions in Extremes (MaRIE) experiment at Los Alamos National Laboratory. The MaRIE experiment requires narrow bandwidth, bright x-rays at 42keV or higher photon energies. This paper also outlines a general scheme by which 42keV x-rays could be produced for the MaRIE experiment, in an XFELO driven harmonic generation machine.

## TERAWATT POWER RADIATION AT LCLS-II

In order to produce a bright, terawatt power x-ray laser at LCLS-II, an XFELO could be used be used to create a seed signal to be amplified in a high-gain FEL. Specifically, the 4GeV LCLS-II beam could be used to drive an XFELO at the 4th harmonic, to generate a 1MW, 14.4keV radiation beam, with as low as 5.0meV bandwidth. The laser would then be used to stimulate emission from an LCLS-I amplifier, driven by a 14.35 GeV electron beam. GINGER was used to simulate such an amplifier, and a tapered solution of the LCLS-I type amplifier is presented in Fig. 1. The resulting radiation beam would be extremely stable, because the XFELO is able to produce a fully coherent seed laser for a high-gain amplifer such as the LCLS-I.

The solution presented in Fig. 1 relies on undulator tapering so that the resonance condition is maintained within the undulator as the beam energy decreases. Simulation parameters for these results are listed in Tab. 1. The radiation

Table 1: GINGER Simulations Parameters for Terawatt Radiation from an LCLS-I Amplifier

| Parameter | Simulation Value |
|---|---|
| Beam Energy | 14.35 GeV |
| Energy spread | 4 keV |
| Beam Current | 3 kA |
| $\epsilon_{x,n}/\epsilon_{y,n}$ | 0.5 $\mu$m/ 0.5 $\mu$m |

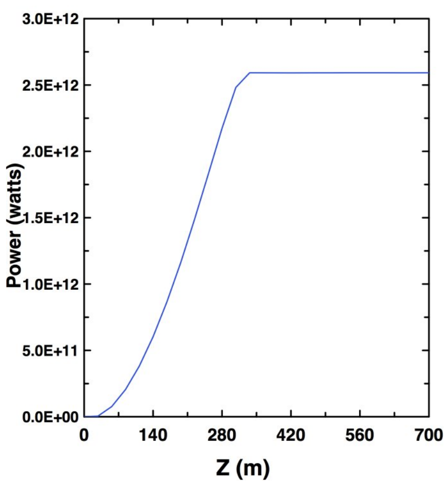


Figure 1: By using a 1MW 14.4keV seed laser generated in an XFELO, a tapered undulator portion could be used to amplify fully coherent TW radiation from an 14.35GeV electron beam, as simulated in GINGER. Tapering begins at 30m, in order to maximize energy transfer to the radiation.

power in this solution surpasses 1TW by 210m, and continues to grow in power. The simulation results suggest that the maximal radiation power at saturation would be greater than 2.5TW. The taper is a polynomial function of $z$, the position along the undulator, that decreases the undulator strength $K$ as a function of the length along the lattice. The polynomial coefficients for the taper were determined by GINGER [8]. A coarse optimization of the tapering start position was done to determine if the saturation point changed significantly. As neither the saturation point nor the maximal radiation power seemed to depend on this parameter, the nominal value was set at 30m, but could easily be changed due to other relevant design constraints.

## MARIE-TYPE HARMONIC GENERATION MACHINE

Harmonic generation machines are often used to produce high energy photons by stimulating radiation at a harmonic of the fundamental radiation mode. Thus, an XFELO could be used to provide the modulating laser in the high gain harmonic generation scheme [9]. Amplifying the 3rd harmonic would result in 42keV photons with ($< 10^{-4}$) bandwidth, suitable for the MaRIE project at Los Alamos National Laboratory. An XFELO drive laser is ideal as a seed laser, again, due to the fully coherent, high power radiation that it provides.

Table 2: GINGER Simulations Parameters for a MaRIE-Type XFELO Driven Harmonic Generation Machine

| Parameter | Simulation Value |
|---|---|
| Beam Energy | 12 GeV |
| Energy spread | 3 keV |
| Beam Current | 3.4 kA |
| $\epsilon_{x,n}/\epsilon_{y,n}$ | 0.2 $\mu$m/ 0.2 $\mu$m |

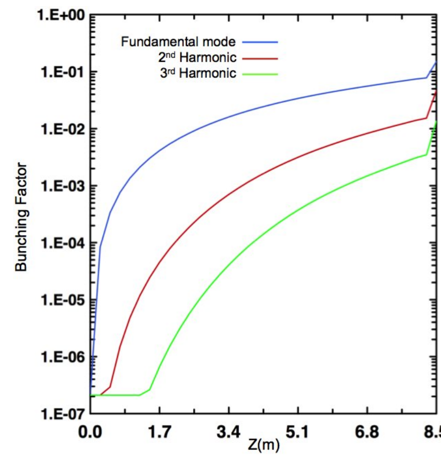


Figure 2: GINGER simulations show the bunching factor for the fundamental, 2nd and 3rd harmonic through the 8.6m modulator. After the 20cm chicane, at 8.2m, the 3rd harmonic bunching increases to a final value of 1.5%.

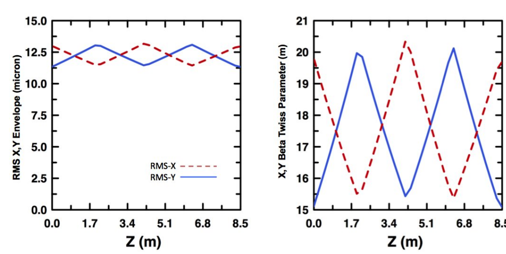


Figure 3: The modulator optics were kept similar to current LCLS FODO optics, such that the radiator could follow the modulator without the need of matching optics.

Simulations, with parameters listed in Tab. 2, suggest that an XFELO could generate radiation up to 19MW at 14keV, which is assumed for this study. Such a laser could be used to generate an appropriately bunched electron beam in a modulator such that a radiator operating at the 3rd harmonic could lase at 42keV. Specifically in our simulations, a 19MW seed laser was used to create a energy modulation in a 12GeV electron beam, then sent through a chicane in order to create density modulation. The modulator was designed to maximize bunching at the 3rd harmonic. Figure 2 shows the 3rd harmonic bunching through the modulator; the bunching builds gradually along the undulator length, and is

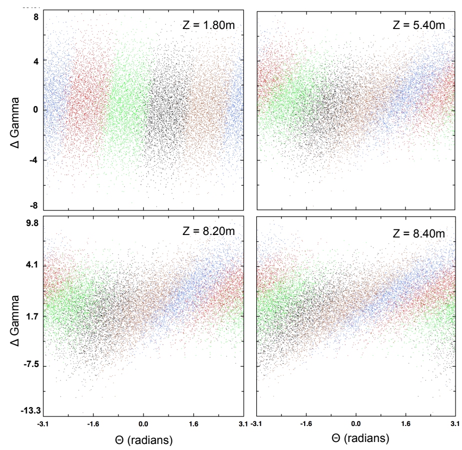


Figure 4: Shown are the GINGER simulations of the electron beam phase space through the modulator at a) 1.80m, b) 5.40m, c) 8.20m, d) 8.40m. The energy modulation that builds gradually until 8.20m, turns into a density modulation after the chicane and remains at 1.5% until the end of the modulator.

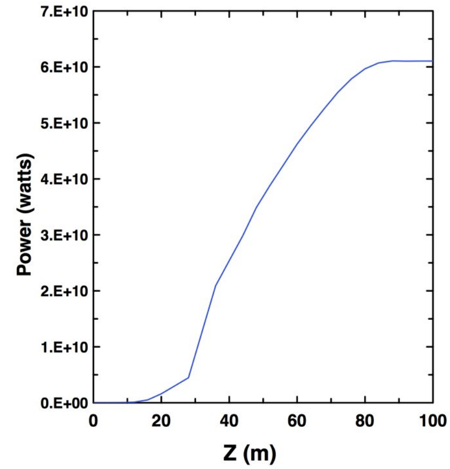


Figure 5: Shown is the fully tapered radiation power profile for the MaRIE radiator, which saturates at > 60GW. As can be seen, the FEL process saturates near 100m, thus the radiator could be short enough to fit in a small experimental area if necessary.

increased to a final value around 1.5% after the chicane. The length of the modulator includes the chicane, which is 0.2m long. GINGER scans were used to determine the optimal $r_{56}$, which was determined to be $r_{56} = 4.20 \times 10^{-8}$m. In designing the modulator, the optics were kept similar to the current LCLS FODO lattice, shown in Fig. 3, but could be adjusted in order to accomodate machine design goals. Further, by maintaining the optics through the modulator, the radiator can follow directly after the modulator without the need for matching optics in between. The beam phase space is shown in Fig. 4, at various locations through the modulator. The energy modulation is visible until $z = 8.20m$, after which the chicane converts the energy modulation into density modulation. After the density modulation is maximized such that there is significant bunching at the 3rd harmonic, the beam is sent into the radiator portion of the FEL, where is coherently radiates at 42keV. In order to maximize the power of the radiation beam, the tapered solution, shown in Fig. 5, was optimized for shortest saturation length. This was done due to the potential space constraints at the MaRIE site. The taper was, again, a polynomial taper, done in GINGER [8].

## CONCLUSIONS AND FUTURE WORK

Further research will include updating the TW study to 8GeV; the operating power of the LCLS-II was updated after our study was completed. In addition, further optimization of such a lattice would determine whether such a machine is feasible at LCLS-II. For the MaRIE project, although our simulations suggest that narrow bandwidth, stable MW radiation at 42keV could be possible, time-dependent simulations will be necessary to determine the bandwidth of this design. Thus, future studies could include time-dependent simulations, and optimization of the accelerator optics for this design.

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