X-RAY LASER SEEDING FOR SHORT PULSES AND NARROW BANDWIDTH

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Abstract

The performance of an x-ray free electron laser can be substantially enhanced if a coherent seed source is used to provide sufficient initial power that it dominates the spontaneous emission in the early part of the undulator. The FEL output then becomes an amplified reproduction of the input seed having, under certain conditions, the same pulse length and bandwidth. For studies of molecular and atomic time dynamics the pulse length may be very short, reaching below 1 fs with a transform limited bandwidth of a few tenths of a percent. For spectroscopy and diffraction experiments the beam may alternatively be made monochromatic at the level of one part in 10^5 or better, with a pulse length of tens of femtoseconds. Simulation studies of seeded FEL performance at 0.3 nm using the code GINGER are presented.

INTRODUCTION

The first generation of x-ray lasers based on single-pass free electron laser amplifiers have been approved for construction [1,2], and will operate on the principle of self amplification of spontaneous emission (SASE) wherein the electron beam amplifies its own initial spontaneous emission. SASE radiation has the advantage of being self-starting, that is, it does not amplify an initial radiation seed pulse. However, the output (right column of Fig. 1) has a spiky structure in time and frequency. It is not longitudinally transform limited, and suffers from large shot-to-shot fluctuations in power and wavelength.

Longitudinal coherence may be achieved if a coherent seed radiation pulse is introduced. If the seed power dominates the spontaneous emission, then the coherence and timing properties of the seed will be accurately amplified by the FEL. While conventional lasers are attractive as seed sources in the IR, visible, and UV wavelength ranges, strong absorption in materials of shorter wavelength light has until recently prevented emergence of a candidate seed in the x-ray regime.

High harmonic generation of seed power

Two technologies have recently demonstrated experimental results that show promise for future generation of fully coherent x-ray FEL output. The first of these is the generation of high harmonics of a

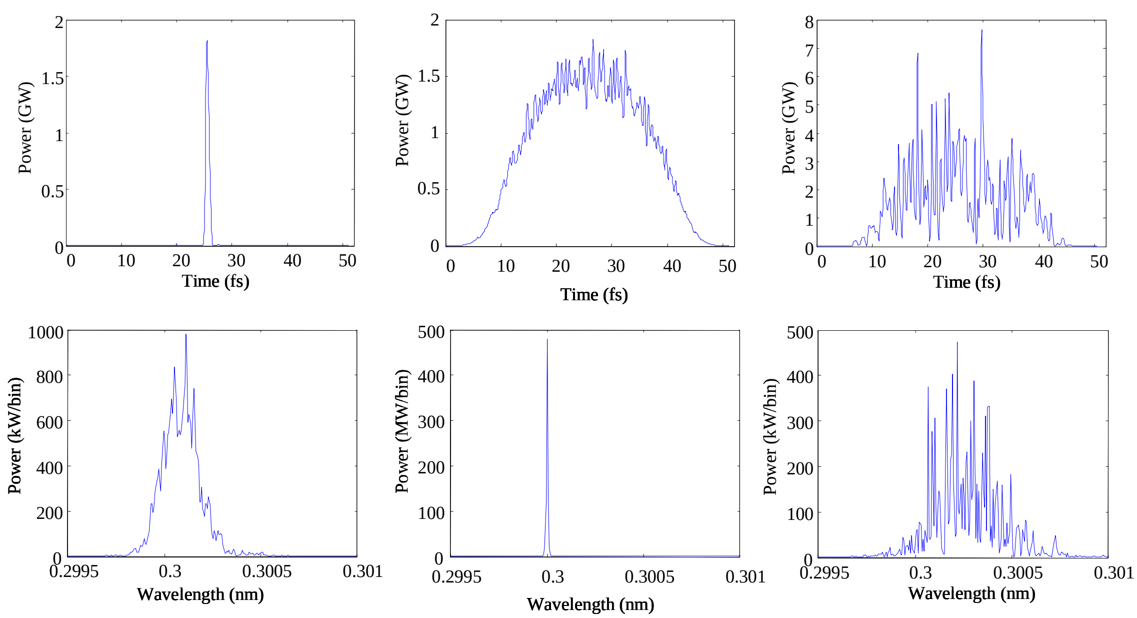

Figure 1: Time dependent GINGER simulations for 3 different initial conditions of 0.3 nm FEL. Top row shows FEL pulse time profile for, from left to right, seeding from a short pulse, seeding from a temporally coherent long pulse, and SASE. The bottom row shows the spectrum associated with each time profile above it. Short pulse FWHM is 0.75 fs from a 50 fs ebeam pulse. Narrow bandwidth seed produced 10^{-5} relative linewidth.

conventional laser in a noble gas jet [3]. Very broad bandwidth Ti:Sapphire lasers operating near 800 nm now generate few fs, few cycle output pulses with very high peak fields. The pulse is focused into a gas jet where the high electric field briefly ionizes the atoms before passing and allowing the electron to re-collide with the nucleus creating a short burst of bremsstrahlung at many high harmonics of the 800 nm. Harmonics as short as 3 nm have been achieved, but the best power is in the wavelength range of 10 – 30 nm. This process is known as high harmonic generation (HHG). Power in a particular harmonic may be optimized by pulse shaping of the drive laser. The pulse energy produced by HHG has been limited to a few nJ, which will improve as the technique develops. Even this low energy, in a sufficiently short pulse, is adequate to seed the FEL process.

High gain harmonic generation FEL

Although HHG radiation is much shorter wavelength than other laser-based sources, it is still an order of magnitude or two longer than required for x-ray seeding. This problem has been addressed by the second important technology demonstration, which is an FEL technique that produces coherent short wavelength output from a long wavelength seed.

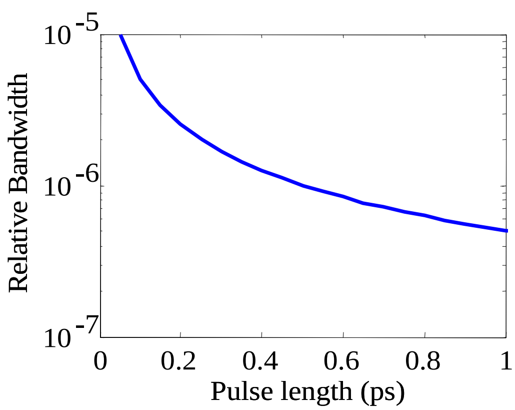

Figure 2: Transform limited bandwidth for different pulse lengths at 0.3 nm wavelength. Energy resolution of meV is possible without the need for monochromaters.

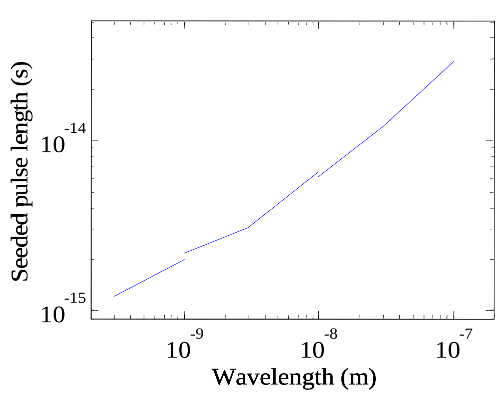

Figure 3: Minimum pulse lengths possible for different wavelengths. The FEL has sufficient gain bandwidth to support pulse lengths less than 1 fs at 0.3 nm wavelength.

When an electron beam is bunched in an undulator, the bunching spectrum contains harmonics of the fundamental frequency. We can take advantage of these harmonics to lase at shorter wavelengths than the input seed using the method of high-gain harmonic-generation (HGHG) [4]. In this method an electron beam is resonant in a first undulator with a long wavelength seed, then the microbunching of the beam is optimized to produce harmonic radiation in a second undulator tuned to that harmonic. The primary role of the first undulator is to produce energy modulation in the electron beam rather than radiation. This energy modulation is converted to temporal bunching optimized for a particular harmonic in a dispersion section consisting of a magnetic chicane. The coherently bunched electron beam radiates at the harmonic frequency in the second undulator, and the pulse energy grows exponentially until saturation is reached.

The description above is of a single-stage HGHG system. This technique has been successfully demonstrated in the IR [5] and UV [6] at BNL. The recent experiments in the UV seeded the electron beam with 800 nm light and lased at the 266 nm 3^{rd} harmonic. The radiation output reached saturation in a substantially shorter distance than possible with SASE, and showed the expected improvements in bandwith, coherence, and stability compared with SASE. A single-stage device can typically lase at the 2^{nd} – 5^{th} harmonic. To achieve shorter wavelengths, multiple stages are required, a technique referred to as cascaded HGHG. Soft x-ray FELs proposed at BESSY [7], Lawrence Berkeley Lab [8], and MIT [9] all plan to use HGHG to produce coherent output.

SEEDING STUDIES

As a guide for numerical studies of seeded FEL output, semi-analytical estimates of the best achievable bandwidth and shortest pulse lengths are shown in figures 2 and 3. The separate curves in fig. 3 use the numerical FEL performance parameterization of Xie [10], and are optimized as a function of wavelength. Figure 2 is a simple analytical estimate of transform limited bandwidth at 0.3 nm.

Time dependent runs of the GINGER FEL code [11] have been performed to numerically verify the estimated performance. These runs do not model the entire HGHG process from long wavelength seed to final FEL output, but rather assume a particular input seed power and pulse length at the entrance of the final radiator section and study the FEL gain and pulse properties. A simulation model of the entire cascaded FEL process is under development and will be reported in the future.

The electron beam properties for these runs were 0.8 μm RMS normalized emittance, 10^{-4} relative energy spread, and 2 kA peak current, consistent with the

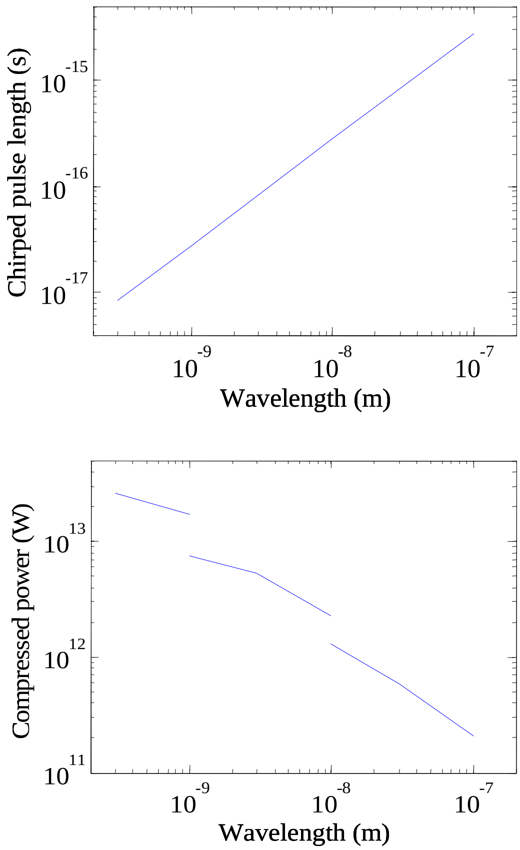

Figure 4: Top plot shows theoretical pulse length achievable for chirped pulse amplification using FEL. Bottom plot shows peak power.

proposed MIT source [12]. The FWHM of the electron beam was approximately 50 fs for a total charge of just 100 pC. Figure 1 shows the spectrum and pulse length for both seeded and SASE FEL output at 0.3 nm. The left column of the figure shows a simulation output of the FEL when seeded with a short input pulse. The seed parameters for this case are FWHM of 0.5 fs and 10 MW peak power for total pulse energy of 5 nJ. The output pulse length was 0.75 fs FWHM with a nearly transform limited bandwidth indicating good coherence and limited pulse stretching due to slippage of the electron beam relative to the radiation. Saturation length is 20 m to produce peak power of 2 GW and total pulse energy of 1.5 μJ, much shorter than the 59 m required for SASE saturation at the same power. Note that although the peak power is the same as SASE, the total pulse energy is lower because of the short pulse length.

The middle column of figure 1 shows a GINGER simulation of a bandwidth seeded FEL at 0.3 nm. In this case the seed pulse energy was still 5 nJ but the pulse length was 50 fs to overlap the full electron beam. The FWHM of the output spectrum is 10^{-5} in good agreement with the analytical estimate. The bandwidth seeded FEL produces the same peak power and pulse energy as the SASE output, but the bandwidth is nearly two orders of magnitude narrower, producing a much brighter beam with all photons in the same mode.

CHIRPED PULSE AMPLIFICATION

In the absence of a time/frequency correlation (chirp), the minimum pulse length achievable is determined by the gain bandwidth of the FEL. By imposing a chirp on the input seed laser pulse, and a matching time/energy correlation on the overlapping electron beam it is possible to produce a high power output pulse with the same chirp as the input. This output x-ray pulse may then be compressed with a grating or asymmetrically cut crystal to compress in the same manner as chirped pulse amplifiers are used for conventional lasers in the visible and IR. Figure 4 shows the minimum pulse length and maximum peak power versus wavelength for a pulse having a 6% chirp (3% electron beam chirp), and assuming that it can be fully compressed. The maximum amount of compression possible is determined by the ratio of chirp amplitude to FEL bandwidth. In practice, effects such as slippage, phase distortions in the FEL gain process, and nonlinearities in the x-ray compressors will limit the maximum compression to a smaller value. However it may be possible to generate sub-fs pulses with peak powers approaching 1 TW.

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