CONSTRAINTS ON PULSE DURATION PRODUCED BY ECHO-ENABLED HARMONIC GENERATION[*]

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Abstract

Echo-enabled harmonic generation (EEHG) is well-suited for producing long, coherent pulses at high harmonics of seeding lasers. There have also been schemes proposed to adapt EEHG to output extremely short, sub-fs pulses by beam manipulations or through extremely short seed lasers, but the photon flux is generally lower than that produced by other schemes. For the standard EEHG layout, it is still interesting to consider different parameter regimes and evaluate how short a pulse can be generated. EEHG at high harmonics uses a large dispersive chicane which can change the relative distance of electrons substantially, even longer than a typical FEL coherence length. We evaluate the ability to produce short pulses (in the femtosecond to 10 fs range) using a combination of theory and simulations.

INTRODUCTION

The radiation produced by free electron lasers (FELs) can be enhanced in many ways through seeding techniques. Echo-enabled harmonic generation (EEHG) [1] uses two energy modulations from external lasers to generate a much shorter output wavelength. A schematic of an EEHG beamline is shown in Fig. 1. It has several advantages over seeding schemes with a single seed laser, such as high-gain harmonic generation (HGHG) [2]. EEHG allows for a very large jump in photon energy in a single stage, without requiring the fresh-bunch technique. It is capable of producing narrow bandwidths by having long output pulses and it can also be less sensitive to distortions in the current or energy profile. However, short pulses with a corresponding large bandwidth are also of interest for many scientific applications. Therefore, it is worth exploring how to produce pulses shorter than 10 fs using the EEHG technique. Here, we only examine initial seeding to produce microbunches at the desired wavelength, which then radiate and amplify in a conventional FEL system. Attosecond schemes are not considered.

CONSTRAINTS ON ELECTRON BUNCH DURATION

We first consider using a very short electron bunch to limit the duration of the output radiation. In this case, the main limitation is that the EEHG scheme produces bunching over a multiple of frequency intervals. The frequency components of the electron current profile can interact with these other microbunching components to yield a combination that will either disrupt the FEL gain or introduce a large number of modes. This concern leads to an approximate constraint on the final pulse duration σ_z:

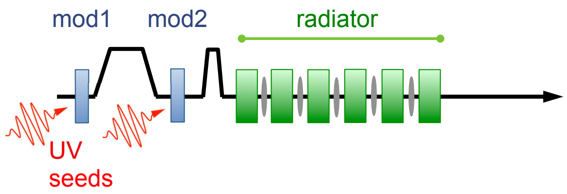

Figure 1: Schematic of an EEHG beamline, showing chicanes, modulating undulators, lasers, and radiating undulators.

$$\sigma_z \geq \frac{\lambda_1 \lambda_2}{\lambda_{\text{echo}}} \frac{E_{M1}}{E_{M2}} \frac{1}{\sqrt{2}\,\pi(|n|^{4/3} + |n|^{2/3})}. \qquad (1)$$

Here $\lambda_{1,2}$ are the wavelengths of the two incident lasers which modulation, λ_{echo} is the desired output wavelength, $E_{M1,2}$ are the amplitudes of the two energy modulations, and n is one of the mode numbers for the wave mixing. Typically, $n = -1$.

This constraint can also be viewed in terms of time. To obtain a given harmonic, the product of E_{M2} and the strength of the dispersive element after the first modulation are tightly constrained. If the second energy modulation is decreased, the dispersion, which can be quite large, has to be increased. Because the dispersion follows the first energy modulation, electrons will be displaced by an amount proportional to the amplitude of the first energy modulation. Thus, even if a very short initial bunch is used, by the time the EEHG manipulations are finished the bunch could be significantly longer, and the output pulse will match this new bunch length. For a short bunch, the induced bunching tends to reach a minimum in the center, and double-peaked pulses are the first sign that the bunch length is becoming too short for a particular EEHG configuration.

CONSTRAINTS ON DURATION OF SEEDING LASERS

Another way to produce short bunches is to use short lasers to only generate bunching over a fraction of the electron bunch. One constraint here is over the duration of the first energy modulation. If it is very short, the chicane will again spread these particles out, leaving a localized low-current hole in the electron bunch. This is the same effect used for laser slicing techniques in storage rings [4]. To

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avoid this, the first laser should be kept long, and the second laser determines the duration of the microbunching. The nonlinear reduction in the duration of the seeded pulse is greatest for the second laser, so it usually determines the bunch length anyway.

Another constraint is on the duration of the electron bunch. Unseeded portions of the bunch will have a higher growth rate because the energy spread is lowest in these regions. One fix, seemingly counter to the results of Eq. (1), is to increase the first energy modulation to guarantee a large energy spread everywhere. The energy spread could also be spoiled in other ways, including blowing up the emittance or shaping either input laser to selectively increase the energy spread in regions at some distance from the nominal seeded region.

Another method is simply to end the amplification process before the self-amplified spontaneous emission (SASE) radiation has a chance to compete with the strongly seeded but slower growing main pulse. For longer output wavelengths, this can mean as little as a factor of 2 reduction in pulse energy, and a low background of unseeded radiation. At wavelengths near 1 nm, however, it is very challenging to avoid the SASE background. At 1 nm the output pulse duration is constrained to be about half of the duration of the electron bunch (or the un-spoiled portion thereof).

PARAMETERS AND BEAMLINE CONFIGURATION

Beamline parameters are modeled after expected parameters for LCLS-II [5], and are given in Table 1. The first undulator is chosen to have a period of 0.1 m for convenience. For the second modulating undulator, the large magnetic fields would induced too much energy scattering, so the period is lengthened to 0.4 m. The radiating undulators follow the design for the soft x-ray beamline of LCLS-II. To keep magnetic fields below 0.5 T in the chicanes as well, the first chicane is quite long, with a total length of 9.25 m.

Table 1: Nominal Parameters

Electron bunch:	
Energy	4 GeV
Energy spread	0.5 MeV
Peak current	800 A
Emittance	0.4 μm
Beta function	15 m
Lasers:	
Wavelength	260 nm
Undulators:	
Length	3.2 — 3.4 m
Period	0.1 m, 0.4 m, 0.039 m

SIMULATION RESULTS

Simulations were performed using the GENESIS simulation code [3] along with additional processing to incorporate more physical effects. Scattering and resistive wall wake fields are included. The significant alteration of the longitudinal profile of the bunch by the first large chicane is also taken into account. Other effects of the chicane, in particular coherent synchrotron radiation, are not modeled.

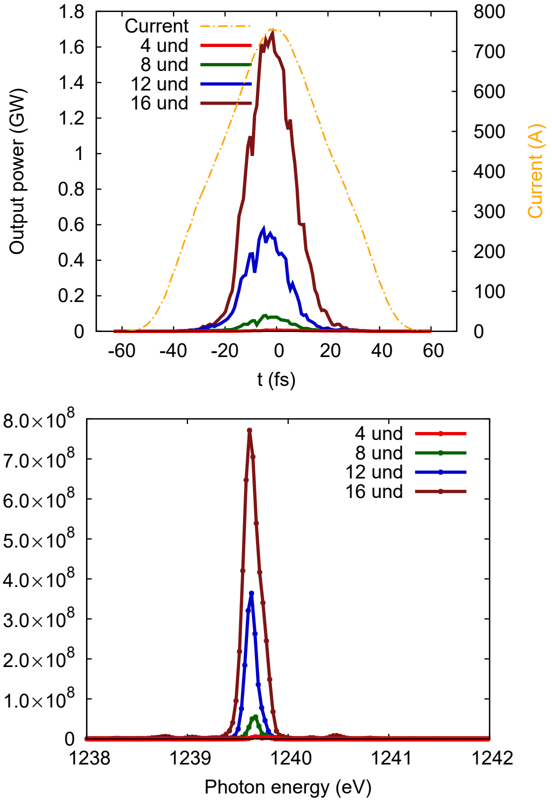

Figure 2: Radiation at 1 nm with a 50 fs bunch and long seed laser pulses. Power (overlaid against the final current profile) and spectrum are shown at various stages along the radiation undulator.

Using a 50 fs long bunch, after 16 undulator sections the pulse energy at 1 nm is 35 μJ with a FWHM of 22 fs and RMS duration 8.7 fs. The spectrum has a FWHM of 200 meV. The output phase typically has a quadratic variation to it. This is typically as short as the output pulse can get using long laser seeds at 1 nm. Shorter bunches experience too much distortion. Using a 25 fs long bunch to radiate at 2 nm does yield an even shorter output pulse, saturating after 12 undulator sections. The pulse energy is 95 μJ with a FWHM of 15 fs, and the FWHM bandwidth is 400 meV.

At 1 nm it is difficult to obtain significantly shorter pulses by using a short seed laser. At 2 nm this method is more effective, although it still helps to have a bunch that is not more than 10× longer than the desired output pulse. After 8 undulators, the pulse energy at 2 nm is 14 μJ, about a factor of 2 less energy than at saturation, but the output pulse is much cleaner with a FWHM of 5 fs and RMS duration of only 3.3 fs, without any thresholds or curve fitting. The FWHM bandwidth is 700 meV, but there is a significant sideband as well.

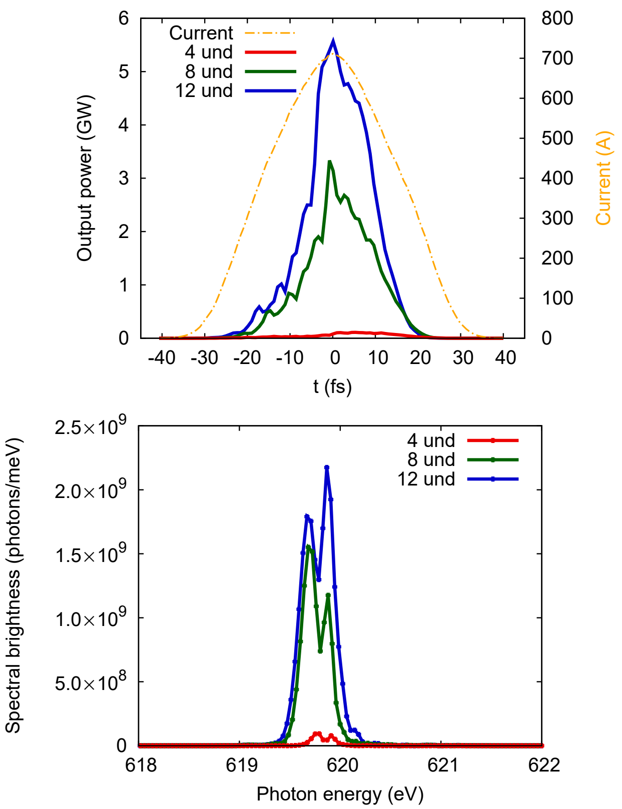

Figure 3: Radiation at 2 nm with a 25 fs bunch and long seed laser pulses. Power (overlaid against the final current profile) and spectrum are shown at various stages along the radiation undulator.

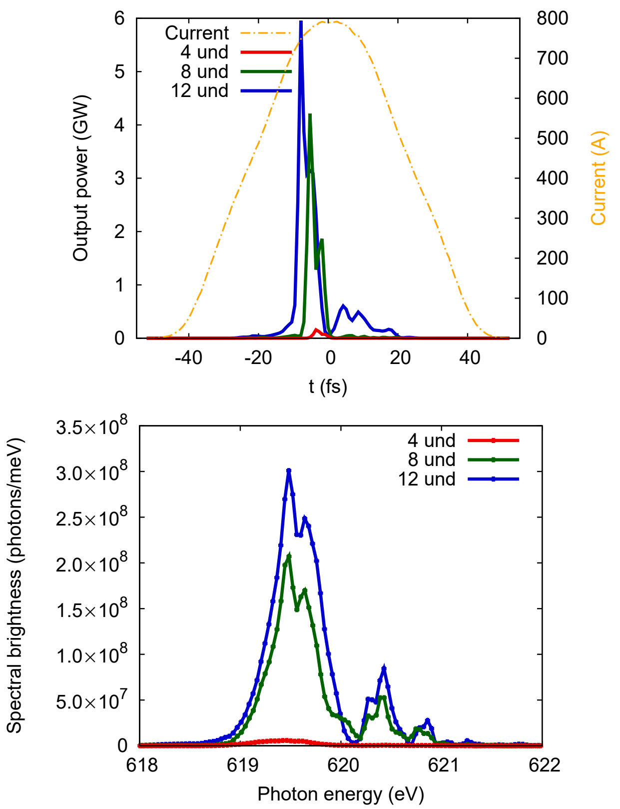

Figure 4: Radiation at 2 nm with a 50 fs bunch and a 10 fs FWHM duration for the second seed laser. Power (overlaid against the final current profile) and spectrum are shown at various stages along the radiation undulator.

CONCLUSION

It is possible to generate high-quality, soft x-rays with pulse durations below 10 fs using echo-enabled harmonic generation. The pulse duration can be selected either by the electron bunch length or the second modulating laser. However, if electron bunch is too long, then the SASE background can only be suppressed by ending the beamline before reaching saturation. This provides another option to produce short, coherent radiation in the soft x-ray regime. This method should provide stable, high-power radiation pulses, but it remains to be seen how much of an impact microbunching will have on the pulse profile.

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