BREAKING THE ATTOSECOND, ANGSTROM AND TV/M FIELD BARRIERS WITH ULTRA-FAST ELECTRON BEAMS*

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Abstract

Recent initiatives at UCLA concerning ultra-short, GeV electron beam generation have been aimed at achieving sub-fs pulses capable of driving X-ray free-electron lasers (FELs) in single-spike mode. This use of very low *Q* beams may allow existing FEL injectors to produce few-100 attosecond pulses, with very high brightness. Towards this end, recent experiments at the LCLS have produced ~2 fs, 20 pC electron pulses. We discuss here extensions of this work, in which we seek to exploit the beam brightness in FELs, in tandem with new developments in cryogenic undulator technology, to create compact accelerator-undulator systems that can lase below 0.15 Å, or be used to permit 1.5 Å operation at 4.5 GeV. In addition, we are now developing experiments which use the present LCLS fs pulses to excite plasma wakefields exceeding 1 TV/m, permitting a table-top TeV accelerator for frontier high energy physics applications.

INTRODUCTION

Use of low charge (*Q*~pC), has been recently proposed as a path to achieving GeV-class beams that may be compressed to the well sub-fs level [1]. Further, these beams should possess very low transverse emittance ε_n, due to scaling at the photocathode as well as during emittance compen and therefore unprecedented brightness, thus enabling new possibilities in future X-ray self-amplified spontaneous emission free-electron lasers (SASE FELs [2]). This scheme gives two advantages in the X-ray FEL: it breaches the fs frontier in X-ray pulse length, and it is should allow single spike SASE FEL operation. Both properties are critical to the exploitation of the revolutionary aspects of coherent X-ray beams derived from the X-ray FEL, as one may resolve properties of atomic and molecular systems at the spatial and temporal scales relevant to electronic motion.

With the advantages of low *Q* operation well appreciated from the FEL and beam physics viewpoints, initial work has been undertaken at the SLAC Linear Coherent Light Source (LCLS) recently. In these tests, 20 pC beams were compressed to σ_t =2 fs, while achieving normalized emittances of $\varepsilon_{n,x(y)} = 0.4(0.14)$ mm-mrad at an energy 14.3 GeV. These beam parameters indicated very high brightness, $B_e = 2I/\varepsilon_{n,x}\varepsilon_{n,y}$, — are predicted to produce single-spike, nm wavelength FEL pulses [3].

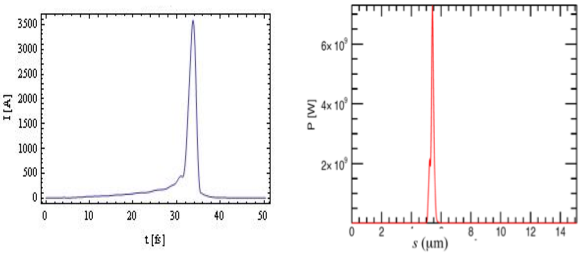

Figure 1. (left) Beam current profile in SPARX 10 pC case; (right) Single spike, fs X-ray pulse.

OPTIMIZED SINGLE SPIKE SASE FEL

In order to scale the performance of an X-ray FEL to single spike level, thus shortening the , even at current brightness levels (few 10^{15} A/(m-rad)^2), one must obtain beam pulses at or below the fs level. The existence of a fully longitudinally coherent pulse with length below a Bohr period permits new classes of measure-ments in femtochemistry and other experiments requiring resolution of atomic electron motion. Unfortunately, with 1 pC of charge, as chosen in our initial study, even though one has sub-fs, single-spike operation, the photon number may be too small to allow single-shot experiments.

Consistent with the experimental progress at SLAC mentioned above, we have thus studied (Fig. 1) SPARX operation with 10 pC. With velocity bunching re-optimized using weaker focusing during emittance compensation, we have achieved an rms pulse length at 2.1 GeV of $\varepsilon_{x,y} = 0.67,0.1$ mm-mrad. With the design SPARX undulator, this produces a single spike of N_γ = 4E11, 2 nm wavelength X-ray photons, above the threshold for many single shot experiments.

ULTRA-COMPACT FELS

Our first generation of studies using very low charge concentrated on exploiting designs optimized for high charge (e.g. LCLS and SPARX). In the course of entering into a related-field, the LWFA-based table-top FEL (TT-FEL), we have confronted the design and realization of a high field, short wavelength undulator based on the used of a cryogenically cooled (to Pr-SmCo-Fe hybrid approach. An undulator for the TT-FEL with 9 mm period

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and >2 T/m (*K*=2.2) has been designed and is now commencing testing at UCLA and at HZ-Berlin.

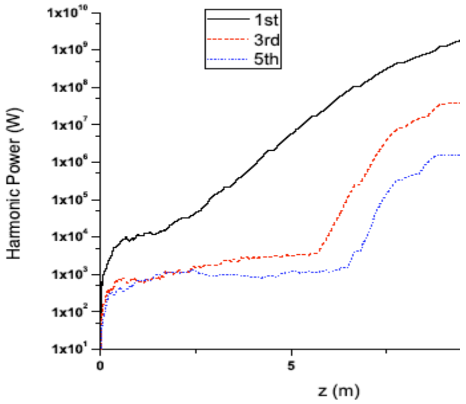

Figure 2. SASE FEL power evolution in cryo-undulator, with SPARX at 2.1 GeV (1 pC, 0.45 fs): <10 saturation length, fundamental at 6.5 Å, 5th harmonic at 1.3 Å.

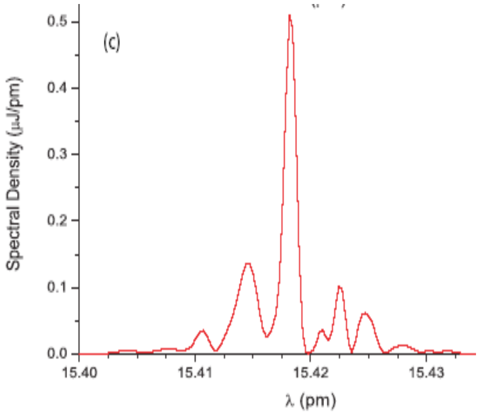

Figure 3. Saturated spectrum at end of >40 m of cryo-undulator using LCLS beam (0.25 pC, 150 as), centered at 0.15 Å.

Beyond this application, however, we are motivated by the possibilities of applying this new technology to IFELs as new light-source injectors, and most compellingly, to FELs with ultra-high brightness beams created at low charge. Such a combination enables extremely compact FELs through very short gain-lengths (i.e. the undulator is short), and diminishing the length of the accelerator through reduced demand on the beam energy. It also allows extension of the FEL operation to very short, sub-Å wavelengths at more common energies (10-20 Gev) as discussed below. A recent simulation study concerning exploitation of the cryogenic undulator, shown in Fig. 2[4], illustrates the power of combining the compact high field undulator with sub-fs, ultra-high brightness beams. The first foresees use of the cryo-undulator with the SPARX injector at 2.1 GeV at 1 ps, with $\sigma_t = 0.45$ fs, and $\varepsilon_{x,y} = 0.06, 0.033$ mm-mrad, a scenario yielding <10 saturation length, with fundamental at 6.5 Å, 5th harmonic at 1.3 Å. Thus one arrives at LCLS-wavelength photons at an injector energy >6 times smaller. Thus the entire system, injector and undulator, may be very compact.

SUB-ANGSTROM FELS

The second compelling application of ultra-high brightness beams with the cryo-undulator relies on the lower emittance associated with low-*Q* operation. Using the LCLS injector in low charge (0.25 pC), one may haved highly compressed beams (150 as rms), that reach unprecedented short FEL wavelengths in the short-wavelength undualtor. In Fig. 3, we show the start-to-end simulation of the saturated spectrum obtained after 40 m of cryo-undulator, with ~0.15 Å achieved. These hard, coherent photons are of interest in probing the dynamics of thicker, high-*Z* systems.

TV/M FIELDS FROM LOW-Q BEAMS

The 20 pC, 2 fs beam observed at the LCLS present new opportunities in coherent emission of electromagnetic radiation, as well as generalized radiation processes such as plasma wake-fields. Beams having short duration may produce coherent EM excitations at frequencies up to a cut-off $\omega_{\max} \approx \sigma_t^{-1}$. As an example, we show in Fig. 4 a calculation of the coherent edge radiation (CER) emitted by the LCLS beam near the entrance of a 1 T magnet. This source is a unique ~30 MW peak source of sub-cycle IR radiation that can be used as with LCLS X-rays in pump-probe experiments, with both sources arising synchronously from the electron beam.

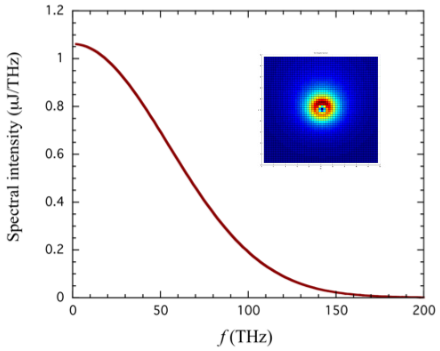

Figure 4. Simulated CER spectrum from LCLS 2 fs beam; (inset) far-field CER angular profile.

Further, in the context of plasma wakefields, the amplitude E of the radiated field scales as $E \propto eN_b(\omega_{\max}/c)^2 \propto eN_b\sigma_z^{-2}$, implying the coherence condition $k_p\sigma_z \approx 1$. This scaling has been investigated experimentally [5,6], theoretically and computationally [7], and its validity even in the nonlinear "blowout" regime [8] has been understood. The blowout regime operation is desired, as the plasma electrons are evacuated from the beam channel, producing E_z dependent only on $\zeta = z - ct$. Further, the nominally uniform ion density n_i gives focusing linear in radius r. Both of these qualities are needed to produce beams with the phase space density demanded by applications in HEP and light sources.

To match the plasma density to optimze the wake-fields, one chooses $n_0 \cong 7 \times 10^{19}$ cm^{-3}. Further, if one focuses the beam to ~110 nm rms using permanent magnet quadrupoles, the beam surface fields are ~1 TV/m, thus enabling ionization of various gas species deep into the barrier suppression regime, achieved for the first time in a sub-cycle format. This allows straightforward creation of the appropriate plasma from 3 atm hydrogen gas, as well as creating a new laboratory tool for high-field atomic physics. In this case, the beam is much denser than the plasma $n_b / n_0 > 20$. The resulting blowout regime wakes would exceed 1 TV/m (Fig. 5), ~20 times larger than that obtained in high-*Q* experiments.

Subsequently, the initially mismatched (β_{eq} = 140 μm) beam focuses yet more tightly, so that $n_b / n_0 > 100$. In this case, the beam is so dense that the ions may collapse (Fig. 6), destroying the uniformity n_i, and giving rise to nonlinear fields [9]. This scenario may allow the first measurement of this effect, which is potentially disastrous for linear colliders.

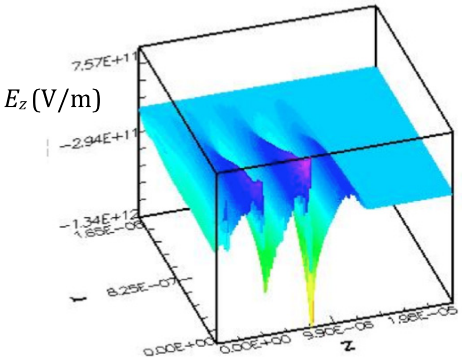

Figure 5. PWFA longitudinal wakes from LCLS 2 fs beam in matched plasma density.

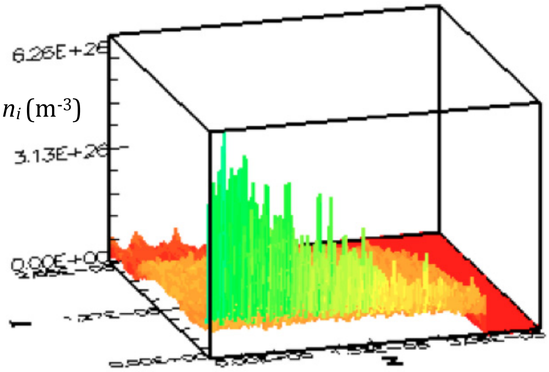

Figure 6. Ion density evolution in TV/m PWFA experiment with LCLS beam.

With such a rich program, a proposal to perform the TV/m PWFA experiment at SLAC is now being pursued by this collaboration. With beam time at the LCLS per se at a premium, the collaboration is presently examining alternative beamlines near the LCLS that may have larger availability.

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