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PAX: A PLASMA-DRIVEN ATTOSECOND X-RAY SOURCE*

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Abstract

Plasma accelerators can generate ultra high brightness electron beams which open the door to light sources with smaller physical footprint and properties un-achievable with conventional accelerator technology. In this work [1] we have shown that electron beams from Plasma WakeField Accelerators (PWFAs) can generate coherent tunable soft X-ray pulses with TW peak power and a duration of tens of attoseconds in a m-length undulator. These X-ray pulses are an order of magnitude more powerful, shorter and can be produced with better stability than state-of-the-art X-ray Free Electron Lasers (XFELs). The X-ray emission in this approach is driven by coherent radiation from a pre-bunched, near Mega Ampere (MA) current electron beam of attosecond duration rather than the SASE FEL process starting from noise. This significantly relaxes the restrictive requirements on emittance, energy spread and pointing stability which have thus far hindered the realization of a high-gain FEL driven by a plasma accelerator. Here we discuss the method and progress towards the experimental realization of this concept at the FACET-II accelerator facility.

INTRODUCTION

Plasma accelerator technology has continued to mature in the past decades and has demonstrated the ability to generate well understood electron beams with properties that are attractive for state-of-the-art light source applications. These include fs-duration and kA-level peak current bunches, which combined with the sub-μm emittance predicted from simulation studies leads to ultra-high 5D brightness (10^{17} – 10^{19} Am^{-2}rad^{-2}). All of these properties are typically leveraged in proposed P(L)WFA-FEL schemes which promise to significantly shrink the physical footprint of future FEL facilities.

Another feature of plasma accelerated bunches, which is typically thought of as an obstacle for a plasma-driven FEL, is the presence of a natural energy chirp imparted on the electron beam at the exit of the plasma accelerator stage. In this work we discuss an approach to leverage this existing chirp to further compress the electron beam downstream of the plasma stage to attosecond duration and thereby drive the coherent emission of attosecond soft X-ray pulses in a downstream bending or undulator magnet. This differs from previously considered plasma FEL approaches in that it does not require the microbunching structure that drives the Self-Amplified Sponatenous Emission (SASE) process at X-ray wavelengths to develop from noise during the radiative interaction inside the undulator. This increases by more than an order of magnitude the typical tolerance to trajectory jitter inside the undulator, and the emittance and energy spread at the undulator entrance. This approach was presented for the first time in Ref. [1], and here we discuss progress towards an experimental demonstration of this approach at the FACET-II facility.

PWFA-DRIVEN ATTOSECOND LIGHT SOURCE CONCEPT

We examine the acceleration of electron bunches in a beam-driven PWFA, with the understanding that many of these considerations are similarly applicable to the laser driven case. In the nonlinear blowout regime of PWFA [2,3] the longitudinal electric field has a well-known dependence on the beam co-ordinate inside the bubble ξ and has an approximately linear slope given by $E'_\xi = m_e\omega_p^2/2e$ where $\omega_p^2 = e^2 n_p/m_e\epsilon_0$ is the plasma frequency and n_p is the plasma density. In the case of weak beam loading the energy gain at the exit of a plasma stage of length L_p is given by $\Delta\gamma = \gamma_f - \gamma_i = eE'_\xi L_p\xi/m_ec^2 = 2\pi r_e n_p L_p \xi$ where $r_e = e/m\epsilon_0 c^2$ is the classical electron radius. The relative energy chirp $h \equiv \gamma_f^{-1} d\gamma_f/d\xi$ at the plasma exit can then be written as:

$$h = \frac{2\pi r_e n_p L_p}{\gamma_i + 2\pi r_e n_p L_p \xi_w} \approx \begin{cases} 2\pi r_e n_p L_p \gamma_i^{-1} & \text{for } \Delta\gamma \ll \gamma_i \\ \xi_w^{-1} & \text{for } \Delta\gamma \gg \gamma_i, \end{cases} \tag{1}$$

where $\xi_w = \langle\xi\rangle$ is the average position of the witness beam relative to the center of the bubble. The two limiting cases displayed in Eq. (1) correspond to the situations in which there is large energy gain inside the plasma (which we refer to as a plasma injector) or the case in which there is negligible energy gain inside the plasma (which we refer to as a plasma chirper). Both of these cases have been studied in the numerical simulations and are being targeted for experimental demonstration (see next section). Examining Eq. (1) we can readily see that in the plasma chirper case the exiting chirp can reach large values 0 (%/μm) using existing plasma sources $n_p = 10^{16}$-10^{18} cm^{-3}, $L_p = 0.1 - 1$ m and GeV-energy electron beams. In the plasma injector case where the witness beam is accelerated towards the back of the bubble the exiting chirp can be similarly large as it tends to its asymptotic value $h = \xi_w^{-1} \sim r_m^{-1}$ where $r_m = 2.58\sqrt{\Lambda}c/\omega_p$ is the blowout radius and $\Lambda \equiv \int rn_b dr \sim O(1)$ is the nor-

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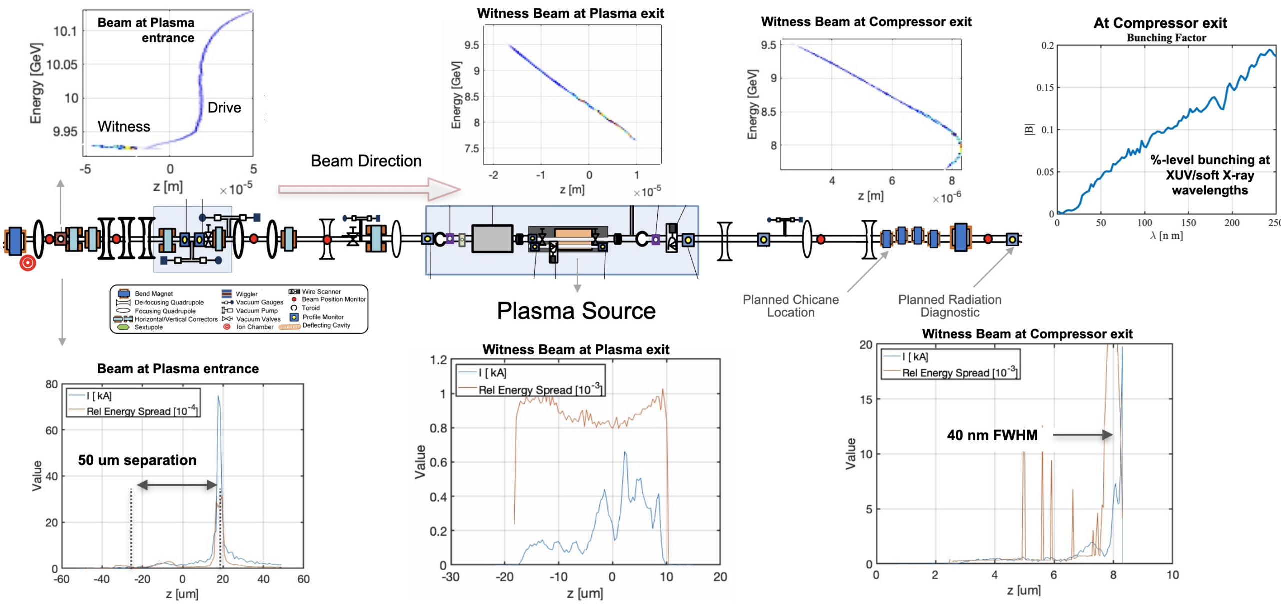

Figure 1: Schematic of the FACET-II Experimental area with the planned location of an additional small chicane and radiation diagnostic to be used for Plasma FEL experiments.

malized charge per unit length of the drive beam [3]. For example, for the parameters considered in Ref. [1] based on Particle In Cell simulations with $\Lambda = 4$ and a density downramp injection mechanism, $\xi_w = 27$ µm the relative chirp at the plasma exit is 3.7% µm.

Such strongly-chirped electron bunches can be fully compressed in a downstream chicane with small bend angles, limiting the impact of deleterious collective effects like CSR on the electron bunch distribution. At full compression where $R_{56} = -h^{-1}$ the bunch length for a Gaussian beam with initial RMS bunch length σ_{zi} is $\sigma_{zf}^2 = \frac{\gamma_i^2\sigma_{\delta i}^2}{\gamma_f^2 h^2} + 2r^2h^2\sigma_{zi}^4$ where $r \equiv T_{566}/R_{56} \approx$ -3/2 for a chicane. Second order compression effects can be neglected for sufficiently short bunches ($2r^2\sigma_{zi}^2 \ll \gamma_i\sigma_{\delta i}/\gamma_f$), however in general they will contribute to increasing the final bunch length. The final bunch length at the exit of the compressor in the plasma injector and plasma chirper case is given by substituting the limiting expressions in Eq. (1) for the chirp:

$$\sigma_{zf}^2 \approx \begin{cases} \left(\frac{\gamma_i}{2\pi r_e n_p L_p}\right)^2 \sigma_{\delta i}^2 + \frac{9}{2}\left(\frac{\gamma_i}{2\pi r_e n_p L_p}\right)^{-2} \sigma_{zi}^4; \Delta\gamma \ll \gamma_i \\ \xi_w^2\sigma_{\delta i}^2 + \frac{9}{2}\xi_w^{-2}\sigma_{zi}^4 \qquad ; \Delta\gamma \gg \gamma_i, \end{cases} \tag{2}$$

which is a useful for evaluating the bunching factor $b = \langle e^{ikz}\rangle = \exp(-k^2\sigma_{zf}^2/2)$ of a Gaussian beam at the compressor exit. In the case where second order compression effects are non-negligible the longitudinal phase space becomes distorted and the current profile exhibits strongly non-Gaussian features which can lead to current spikes with significant bunching content at short wavelengths on the order of the bunch length. We present a numerical example of such a configuration in the following section where nm-level compression of electron beams leads to percent-level bunching at XUV/soft X-ray wavelengths. Such a pre-bunched beam can be used to drive coherent emission generating attosecond XUV/X-ray pulses in a bend magnet or short downstream undulator.

PROGRESS TOWARDS EXPERIMENTAL DEMONSTRATION AT FACET-II

In this section we describe the parameters and experimental setup of the planned Plasma-driven Attosecond X-ray (PAX) experiment at FACET-II. Figure 1 shows a schematic of the experimental area with a series of electron beam longitudinal phase spaces at different locations along the beamline (before the plasma, after the plasma and after the final compression stage). The electron distribution is tracked from the start of the FACET-II RF photoinjector to the exit of the final chicane downstream of the plasma source where it is fully compressed and generates coherent radiation in the final bend of the bunch compressor. The start-to-end simulation uses General Particle Tracer [4] to simulate the photoinjector, Lucretia [5] to simulate the linac upstream and downstream of the plasma source and PLEBS [6] to simulate the PWFA process.

Our simulations use similar parameters to the baseline two-bunch configuration of the FACET-II facility (see Table III in Ref [7]) with a smaller drive-witness bunch separation and a lower witness beam charge. The plasma source is based on a Lithium vapor oven with a plasma density $n_p = 3.5 \times 10^{16}$ cm^{-3} and a flattop region of length $L_p = 0.5$ m. This is the same plasma source that will be used for many of the PWFA experiments at FACET-II [8]. We use a <50 pC witness beam charge (20 pC in the example in Fig. 1) in order to minimize the slice energy spread at the plasma entrance, reduce the beam loading and maxi-

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mize the chirp induced on the witness beam in the PWFA stage. The drive-witness separation of 50 µm is chosen to place the witness beam in the decelerating phase of the wake such that the witness beam is chirped while its energy is simultaneously reduced by ~ 20%. This choice is made so that we can generate the required R_{56} using a weak chicane with few-mrad bend angles and < 2.5 m total length such that it fits in the beamline between the existing quadrupole focusing triplet and the electron spectrometer dipole (see Fig. 1).

The simulations show the witness bunch exiting the plasma with a slice energy spread of 9×10^{-4} before entering the final compressor, which is configured with an R_{56} = 120 µm to achieve a final bunch length of 40 nm FWHM. As is shown in Fig. 1, the current profile at the exit of the compressor is distinctly non-Gaussian with a large current spike at the head followed by a rapidly decaying tail. The bunching factor resulting from such a distribution has few-percent level magnitude at wavelengths as short as 20 nm and in the experiment we plan on measuring these frequency components by analyzing the Coherent Synchrotron Radiation (CSR) spectrum in the XUV/soft X-ray range from the radiation emitted in the last dipole of the bunch compressor. Analytical calculations of the CSR spectrum emitted in the last dipole are shown in Fig. 2. The example shows 21 µJ of energy radiated in the 5-25 eV range at an observation distance of 5 m over a 38 mm horizontal stripe. The CSR will be out-coupled through an in-vacuum mirror located in

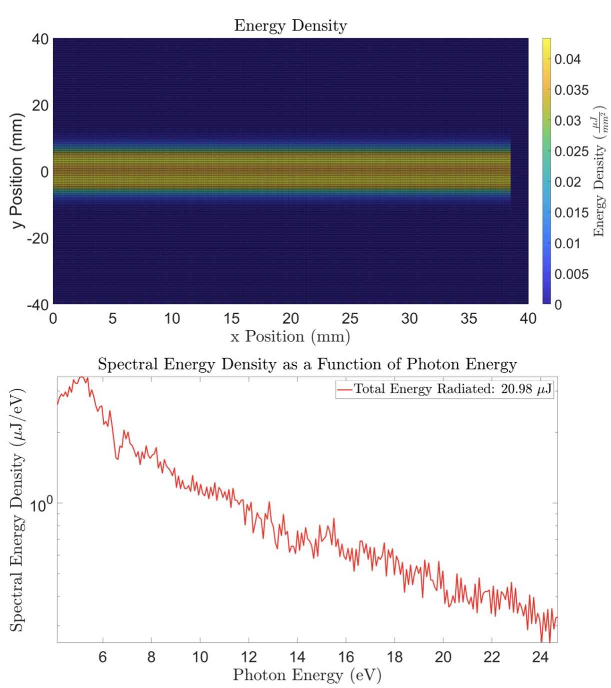

Figure 2: Analytic calculation of CSR spectrum emitted by the fully compressed witness beam in the final dipole of the chicane located downstream of the plasma source (see Fig. 1 for schematic).

a downstream vacuum chamber and directed into an XUV spectrometer for spectral analysis.

The second phase of the experiment will utilize a single drive bunch from the FACET-II linac and a witness electron beam generated by a plasma injector in a configuration similar to that described in Ref. [1]. This will make use of a different gas-jet plasma source of cm-length and plasma density $n_p \sim 10^{17}$-10^{18} cm^{-3} that are being developed for studying ultra-low emittance beam generation in plasmas and different plasma injection schemes [8]. The goal of this second phase of experiments would be to generate and measure attosecond XUV/X-ray pulses with a short (m-length) undulator which would be installed between at the exit of the compressor chicane and the electron beam dump.

CONCLUSION

We have discussed the concept and plans for a plasma driven attosecond XUV/soft X-ray generation experiment at the FACET-II facility. Our approach relies on compressing the witness beam downstream of the PWFA stage to attosecond bunch length and we have discussed its applicability in both a plasma-injector configuration and a plasma chirper setup where the witness beam is generated by an RF photocathode. Progress towards the experimental realization of this concept will enable higher power photon pulses of near single-cycle duration in the soft X-ray range, expanding the capability of existing attosecond high harmonic generation or attosecond XFEL sources.

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