

# ULTRA-HIGH BRIGHTNESS ELECTRON BEAMS BY ALL-OPTICAL PLASMA-BASED INJECTORS

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## Abstract

We studied the generation of low emittance high current mono-energetic beams from plasma waves driven by ultra-short laser pulses, in view of achieving beam brightness of interest for FEL applications. We have studied a regime based on a LWFA plasma driving scheme on a gas jet modulated in areas of different densities with sharp density gradients. Simulations carried out using VORPAL show that, using a properly density modulated gas jet, it is possible to generate beams at energies of about 30 MeV with peak currents of 20 kA, slice transverse emittances as low as  $0.3 \mu\text{m}$  and energy spread around 0.4 %. This beams break the barrier of  $10^{18} \text{ A}/(\text{mm.mrad})^2$  in brightness, opening a new range of opportunities for FEL applications. An example of FELs driven by such kind of beams injected into laser undulators is shown. The system constituted by the electron beam under the effect of the e.m. undulator has been named AOFEL (for All Optical Free-Electron Laser).

## INTRODUCTION

Recently a few authors proposed to use plasma injectors as electron beam driver for SASE X-ray Free-Electron Lasers: the aim is to design compact FELs. Gruner et al. [1] proposed to operated in the bubble regime to generate an electron beam with very high brightness at 1 GeV, with a beam peak current of 100 kA and rather good emittance (1 mm.mrad norm.) and low energy spread (0.1 %) and to inject the beam in a magnetic undulator.

In this paper we present a different approach, which has in common the goal to use a plasma injector to drive a compact SASE FEL, but differing in the regime used in the plasma channel to generate the beam and in the energy of the electrons, which is in the range of a few tens of MeV. To this purpose the use of an electromagnetic undulator, i.e. a counter propagating laser pulse of proper wavelength, is foreseen, as recently proposed [2]. The technique of controlling the breaking of the plasma wave by tapering the plasma density in the gas-jet is applied, as proposed in [3]: we believe this technique is suitable to produce high quality beams, though with lower beam currents (tens of kA instead of higher than 100 kA). In addition, the use of a e.m. undulator allows to conceive an ultra-compact device, a few mm of total length.

## E-BEAM GENERATION VIA LWFA

Laser wakefield acceleration (LWFA) of e-beams [4] has been proved to be able to produce high energetic (up

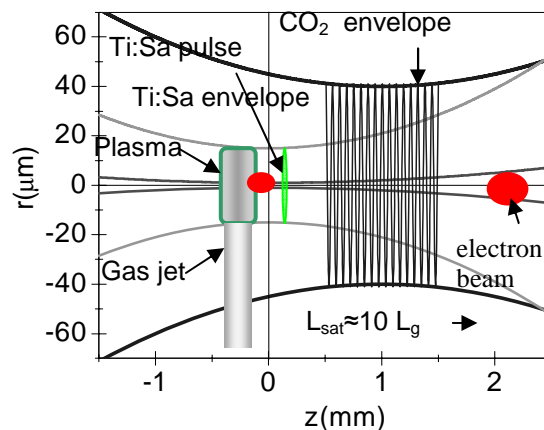


Figure 1: Lay-out of the experiment for the case of the  $\text{CO}_2$  electromagnetic undulator for which the plasma density is over critical (see text for details)

to the GeV scale) quasi-monochromatic electron beams by using ultra-short (tens of femtosecond long) laser pulses and a plasma as accelerating medium. In LWFA the longitudinal ponderomotive force of the laser pulse excites a plasma wave whose longitudinal (i.e. accelerating) electric field can exceeds thousands times that of RF-guns. A critical issue for achieving high-quality e-beams is represented by a good control in particle injection into the plasma wave, whose phase speed equals the group velocity of the laser pulse.

In this paper we will show results of numerical simulation in the nonlinear LWFA regime with longitudinal injection after density downramp. In this scheme the electrons of the crest of the waves are longitudinally injected in the fast running wakefield by a partial break of the wave induced by a sudden change in its phase speed at the transition]. If the laser pulse waist  $w_0$  is much larger than the wave wavelength  $\lambda_p \cong \sqrt{1.1 \cdot 10^{21} / n_e^2}$ ,  $n_e$  being the plasma electron density in  $\text{cm}^{-3}$ , the transverse dynamics is negligible at the transition and an electron bunch with an extremely low transverse emittance is created and injected in the acceleration region of the wave.

We searched for electron bunches suitable for driving the laser-based FEL source, i.e., for bunches that must have a high current but don't need to have overall low emittance and energy spread. They should contain slices with very low slice emittance and very low slice energy spread,

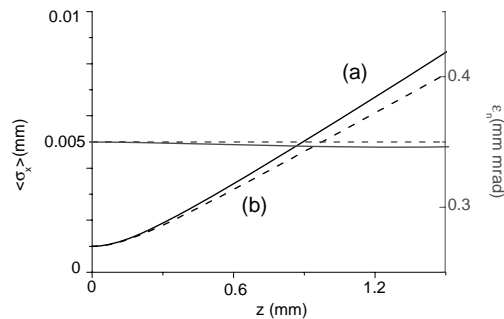


Figure 2: Envelope  $\langle\sigma_x\rangle$  and transverse normalized emittance  $\epsilon_n$  versus  $z$  as given by Astra in vacuum for a typical AOFEL beam with  $I=20$  kA,  $\epsilon_n(z=0)=0.3$  mm mrad,  $\langle\sigma_x\rangle(z=0)=1$  μm and  $\gamma=60$ .

instead. We expect space charge effects to occur over a beam-plasma wavelength scale, which is given by

$$\lambda_{Lbp} = 2\pi\gamma R \sqrt{\frac{2I_0}{I}},$$

$R$  being the beam radius,  $I$  its current,  $\gamma$  the mean Lorentz factor of the electrons and  $I_0 = 17$  kA the Alfvén current. For our typical beam this length is of the order of a cm, much longer than the expected saturation length in the e.m. undulator (which is of the order of 1 mm or a fraction of it). This implies that we should not expect serious emittance degradation due to transverse space charge along the e.m. undulator, as can be seen from fig 2, which presents a simulation made with ASTRA for a typical AOFEL beam initially focussed to 1 μm rms spot size and then freely propagating in a 1.5 mm long drift. The rms beam envelope  $\langle\sigma_x\rangle$  (left scale) and the rms normalized emittance  $\epsilon_n$  (right scale) are shown on the range of interest along the coordinate  $z$ , both with (curves (a)) and without (curves (b)) the effects of the energy spread for  $I=20$  kA,  $\epsilon_n=0.3$  μm and  $\gamma=60$ . The gain length is about 50 μm, so that the beam evolution is followed for about 30 gain lengths. In 1.5 mm of drift the  $\epsilon_n$  does not change significantly, while the envelope evolves as if the space charge is absent.

Simulations were performed with the fully self-consistent Particle-In-Cell (PIC) code VORPAL [5] in the 2.5D (3D in the fields, 2D in the coordinates) configuration.

The initial plasma density profile (see Fig. 3) is composed by a smooth rising edge (laser coming from the left) and a first plateau of density  $n_{01}$ , where appropriate phase of the plasma wave excited in the second plateau (accelerating region). Simulations of the injection-acceleration process were performed in a moving window of longitudinal and transverse size of 50 μm and 60 μm, respectively, sampled in an 800x120 box with 20 macroparticles/cell, corresponding to a longitudinal and transverse resolutions of  $\lambda_0/14$  and  $\lambda_0/2$ , respectively.

In Figure 4 some snapshots of the electron density are reported. In Fig 4a the laser pulse (coming to the left hand side) is crossing the transition and the plasma wave in the first plateau is experiencing nonlinear steepening. In Fig4b the laser pulse is well inside the second plateau (the

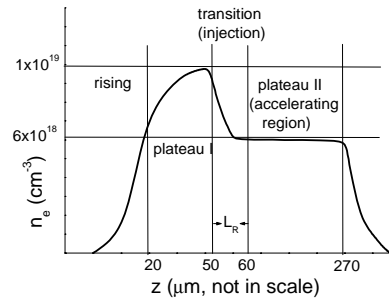


Figure 3: Background plasma density useful for e-beam injection and acceleration

accelerating region) and the second crest of the plasma wave has partially broken. The electrons injected in the wave are suddenly accelerated and focused by the longitudinal and transverse forces of the wakefield (Fig 4c). After an acceleration length of about 200 μm the electron beam is still focused (Fig 4d) and gets a maximum energy of about 28 MeV.

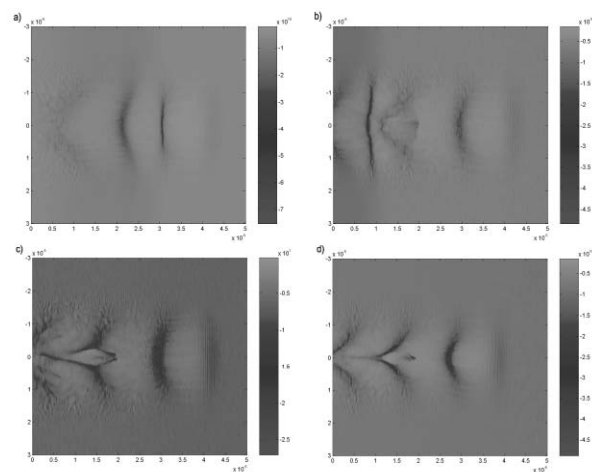


Figure 4: Snapshot of the electronic density when the laser pulse is in the first plateau (a), the laser pulse is crossing the transition (b), the laser pulse is just in the accelerating region (c) and the laser pulse has propagated for about 200 μm in the accelerating region (d)

The final parameters of the initial plasma density have been obtained by an optimization procedure in the parameters double-plateau profile, i.e. the second plateau density, the transition scale-length and the amplitude of the transition. The first parameter controls the plasma wavelength and maximum accelerating gradient in the acceleration region and must be tuned according to the e-beam length and charge. The transition scale-length controls the charge and length of the beam and must be as small as possible in order to ensure the trapping of the largest number of particles, while a tuning in the amplitude of the transition is necessary for selecting the appropriate phase of the particles in the Langmuir wave

## FEL SIMULATIONS

The electron bunch produced by VORPAL has been analysed for finding the slices characterized by the highest brightness for producing FEL radiation [5].

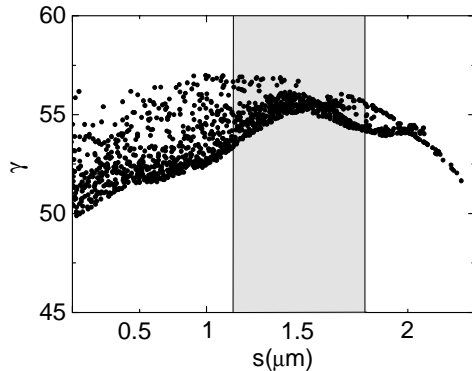


Figure: 5 shows the longitudinal phase space.

Fig 5 shows the longitudinal phase space. The part shaded, delimited by  $z=1.1 \mu\text{m}$  and  $1.59 \mu\text{m}$ , satisfies both conditions of large current and low energy spread. The average values for this part of the bunch are:  $\gamma=55.2$ ,  $I=20 \text{ kA}$ ,  $\langle\sigma_x\rangle=0.5\mu\text{m}$ ,  $\delta\gamma/\gamma=1.2 \cdot 10^{-2}$  and  $\varepsilon_n=0.3 \mu\text{m}$ . We suppose to let the beam defocus up to  $\langle\sigma_x\rangle=5\mu\text{m}$  and subject it to the field of a  $\text{CO}_2$  laser with wavelength  $\lambda_L=10 \mu\text{m}$  and intensity  $a_L=0.8$ . For these values the radiation wavelength is  $\lambda_R=1.35 \text{ nm}$ , the FEL parameter  $\rho=3 \cdot 10^{-3}$ , the cooperation length  $L_c = \frac{\lambda_R}{4\pi\sqrt{3}\rho} = 0.14 \mu\text{m}$ . In

this case,  $L_b/2\pi L_c=0.566$  and the condition  $L_b/2\pi L_c < 1$  for a clean single spike production turns out to be satisfied.

The laser beam interaction has been simulated with the code GENESIS 1.3 [7], which tracks the particles in a static wiggler. By exploiting the equivalence between static and electromagnetic undulators [3], we have imported the particle of radiating slice into GENESIS 1.3, obtaining the results presented in Fig 6. Window (a) shows the average power  $P$  vs the coordinate along the undulator  $z$ , while window (b) presents the peak power vs  $z$ . In fig 6 (c) there is the shape of the power vs  $s$  and in (d) the spectrum of the X-rays pulse at  $z=2.5\text{mm}$ . The peak power value is  $0.2 \text{ GW}$ , the total energy  $0.12 \mu\text{J}$  and the structure of the power on the beam is that typical of superradiance.

In this paper we propose the possibility of using a LWFA plasma driving scheme on a gas jet modulated in areas of different densities with sharp density gradients to generate a mono-energetic, high current ( $> 20 \text{ KA}$ ) electron beam.

This bunch of electrons, characterized by the presence of low emittance ( $< 0.5 \text{ mm mrad}$ ), low energy spread slices, when interacting with a counter propagating  $\text{CO}_2$  laser pulse, radiates a single spike, highly coherent, ultra-short ( $< 1 \text{ fsec}$ ) X-ray pulse via excitation of a

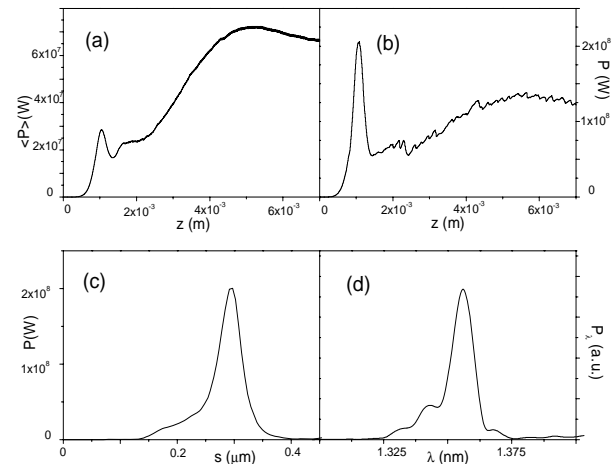


Figure 10: (a) average power  $P(\text{W})$  vs the coordinate along the undulator  $z$  (m); (b) peak power along  $z$ ; (c) power profile along the bunch coordinate  $s$  ( $\mu\text{m}$ ) at  $z=2.5 \text{ mm}$ ; (d) power spectrum at  $z=2.5 \text{ mm}$ .

SASE superradiant FEL instability. The peak power achieved at  $1.2 \text{ nm}$  is of the order of  $200 \text{ MW}$ .

Taking an electromagnetic undulator at  $1 \mu\text{m}$  wavelength the electron beam can drive a  $1 \text{ Ang}$  FEL, with similar performances.

Although the presented analysis is based on three-dimensional simulations, effects due to alignment errors, spatial and temporal jitters, as well as realistic laser pulse profiles for the e.m. undulator and consistent exit from the plasma, that have not been yet considered, must be thoroughly investigated in order to assess the experimental feasibility of such a new FEL scheme. Nevertheless, we believe that our analysis, although very preliminary and missing a full self-consistent start-to-end simulation, shows a potential for the future development of an ultra-compact source of coherent X rays at brilliance levels comparable to those typical of fourth generation light sources. Further work is in progress with more consistent simulations able to describe the exit of the beam from the plasma and the transport through the e.m. undulator, in order to address the problem of performing a real start-to-end simulation from the plasma to the FEL radiation production.

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