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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. The aim is to show the feasibility of generating nC charged beams carrying peak currents much higher than those attainable with photoinjectors, together with comparable emittances and energy spread, compatibly with typical FEL requirements. We identified two regimes: the first is based on a LWFA plasma driving scheme on a gas jet modulated in areas of different densities with sharp density gradients. The second regime is the so-called bubble regime, leaving a full electron free zone behind the driving laser pulse: with this technique peak currents in excess of 100 kA are achievable. We have focused on the first regime, because it seems more promising in terms of beam emittance. Simulations carried out using VORPAL show, in fact, that in the first regime, 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 mm·mrad and energy spread around 0.4 %. This beams break the barrier of 10^{18} A/(mm.mrad)^2 in brightness, a value definitely above the ultimate performances of photo-injectors, therefore opening a new range of opportunities for FEL applications. A few examples of FELs driven by such kind of beams injected into laser undulators are finally 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).

Keywords:FEL; High brightness electron beams;LWFA; E.m. Undulator

1. Introduction

Recently a few authors proposed to use plasma injectors as electron beam driver for SASE X-ray FELs : the aim is to design and build compact FELs, taking advantage from the capability of plasma accelerators to produce GeV beams on mm-scale lenghts, to be compared to km based RF linacs. Gruner et al. [1] proposed the use of a plasma injector operated in the bubble regime to generate an electron beam with unprecedented high brightness at an energy of 1 GeV, carrying a beam peak current in excess of 100 kA wih rather good emittance (1 mm.mrad norm.) and low energy spread (0.1 %). This ultra high brightness beam is an ideal candidate to drive FEL's with radiation wavelength down in the Angstrom range: in ref. the transport and matching of this beam into a magnetostatic undulator [1] is analyzed by means of numerical simulations showing the strong blow-up that the beam undergoes along the transport due to its very intense space charge field. The possibility to preserve the beam quality throughout the undulator, as required to maintain the FEL exponential gain regime, is somewhat controversial, mainly because the space charge effects in the longitudinal and in the transverse planes are not negligible on the scale of the FEL gain length.

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 type of regime used in the plasma channel to generate the electron beam and in the energy of the beam itself, which is in the range of a few tens of MeV instead of a few GeV. To this purpose the use of an electromagnetic undulator, ie. a counterpropagating laser pulse of proper wavelength, is foreseen, as recently proposed [2,3]. The technique of controlling the breaking of the plasma wave by tapering the plasma density in the gas-jet is applied, as proposed in [4,5]: we believe this technique is suitable to produce higher quality beams than the bubble regime, though with lower beam currents (tens of kA instead of higher than 100 kA). In addition, the use of a e.m. undultor allows to conceive an ultra-compact device, a few mm of total length, compare to meters of the scheme using GeV beams. If the e.m. laser pulse is of the same wavelength of the laser pulse driving the plasma wave (or close to it) the electron beam does not even need to be extracted from the plasma channel, and the FEL can be driven in absence of space charge effects at all. Indeed the e.m. laser pulse can be injected into the plasma channel, so that the FEL interaction can take place inside the plasma. If the e.m undulator is made out of a CO2 laser pulse, while the plasma density is larger than 10^{19} cm^{-3}, it cannot propagate through the plasma because it is under critical: in this case the typical lay-out is presented in Fig 1.

2. E-beam generation via LWFA

Laser wakefield acceleration (LWFA) of e-beams [6] has been proved to be able to produce high energetic (up to the GeV scale) quasi-monochromatic electron beams [7,8] by using ultra-short (tens of femtosecond long) laser

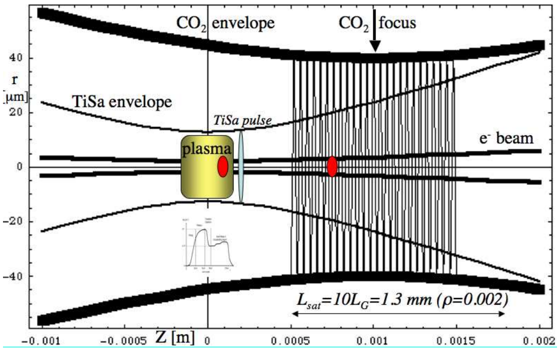

Fig 1: Lay-out of the experiment for the case of the CO2 electromagnetic undulator for which the plasma density is over critical (see text for details)

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. Both experimental and modelling/numerical sides are under active investigation, with emphasis on beam quality, i.e. monochromaticity and low emittance.

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. Several schemes have been proposed and investigated so far, including injection of externally pre-accelerated e-beams, injection of short burst of newborn electrons produced via tunnelling ionization, transverse-wavebreaking in density downramp [9], transverse injection in the bubble regime [10] and longitudinal wavebreaking in density downramp [4][5].

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 [4]. If the laser pulse waist (w_0) is much larger than the wave wavelength $\lambda_p \cong \sqrt{1.1 \cdot 10^{21} / n_e^2}$ being n_e the plasma electron density in 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 [5].

We searched for parameters giving rise to electron bunches suitable for driving the laser-based FEL source. This means that the e-bunches must have an high current but don't need to be characterized by overall low emittance and energy spread. They should contain slices with very low slice emittance and very low slice energy spread, instead. Simulations were performed with the fully self-

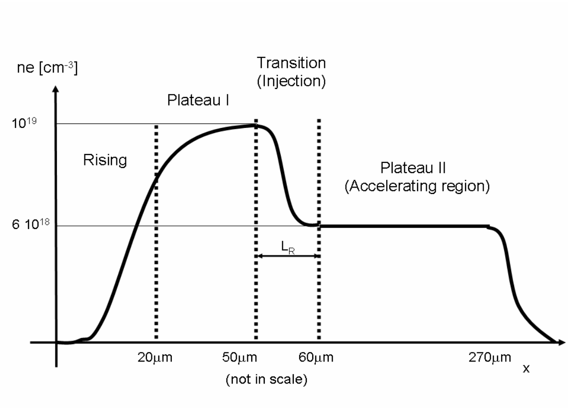

Figure 2. *Background plasma density useful for e-beam injection and acceleration*

consistent Particle-In-Cell (PIC) code VORPAL [11] in the 2.5D (3D in the fields, 2D in the coordinates) configuration.

The initial plasma density profile (see Fig. 2) 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 a 800x120 box with 20 macroparticles/cell, corresponding to a longitudinal and transverse resolution of $\lambda_0/14$ and $\lambda_0/2$, respectively.

In Figure 3 some snapshots of the electronic density are reported. In Fig3a 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 Fig3b the laser pulse is well inside the second plateau (the 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 3c). After an acceleration length of about 200μm the electron beam is still focused (Fig 3d) and gets a maximum energy of about 28MeV.

3. Fel simulations

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

In Fig 4 the beam current along the beam coordinate s is presented, while fig 4 shows the longitudinal phase space. The part shaded, delimited by z=1.1 μm and 1.59 μm, satisfies both conditions of large current and low energy spread. The average values for this part of the bunch are: γ=55.2, I=20 KA, $<\sigma_x>$=0.5μm, and, to be conservative, we have assumed the pessimistic estimates $\delta\gamma/\gamma=1.2\ 10^{-2}$ and $\varepsilon_x=0.3\ \mu m$. We suppose to let the beam defocus up to $<\sigma_x>=5\mu m$ and subject it to the field of a CO_2 laser with wavelength $\lambda_L=10\ \mu m$ and intensity $a_L=0.8$. For these values the radiation wavelength is $\lambda_R=1.35$ nm, the FEL parameter $\rho=310^{-3}$, the cooperation length $L_c=0.14\ \mu m$. The condition $L_b/2\pi L_c=0.566<1$ for a clean single spike production turns out to be satisfied.

The laser beam interaction has been simulated with the code GENESIS 1.3 [12], which tracks the particles in a static wiggler. By exploiting the equivalence between static and electromagnetic undulators we have inserted the mean parameters of the bunch 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=2.5mm. The peak power value is 0.75 GW and the structure of the power on the beam is that typical of superradiance.

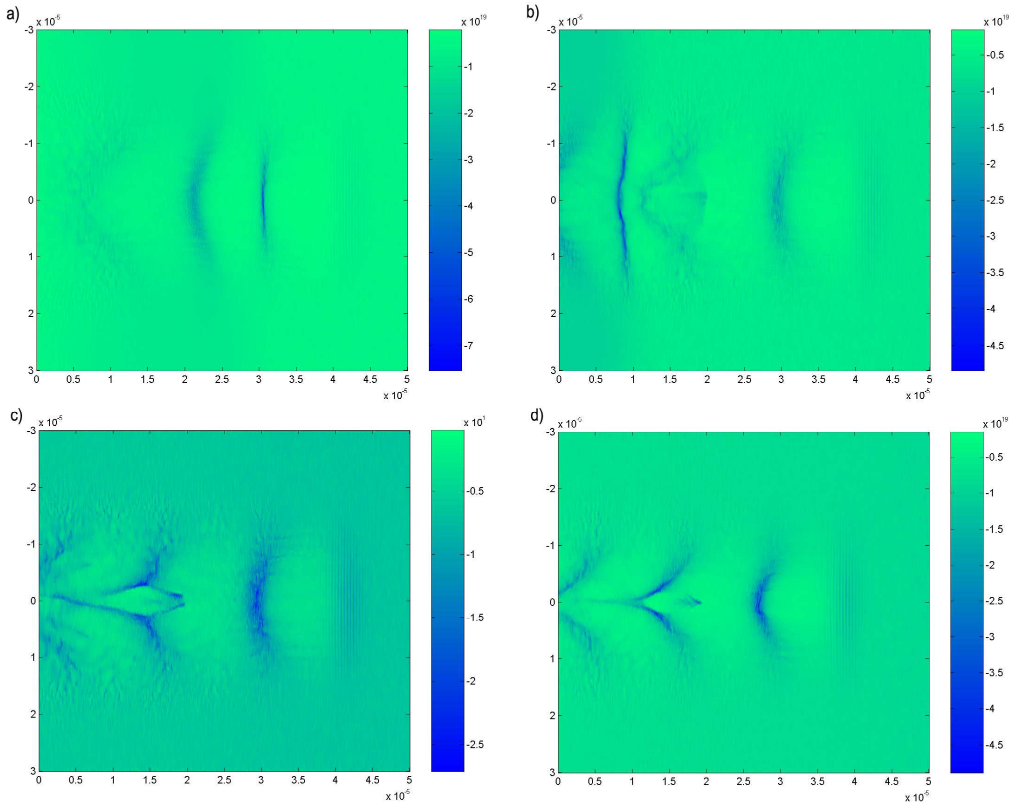

Figure 3. *Snapshot of the electronic density when the laser pulse is in the first plateau (a), the laser pulse is crossing the transition (b), the laser pulse is just in the accelerating region (b) and the laser pulse has propagated for about 200 μm in the accelerating region (d)*

LASER			PLASMA			
Energy (J)	Waist (μm)	Intensity (W/cm^2)	n_{01} (1/cm^3)	L_R (μm)	n_{02} (1/cm^3)	λp (μm)
2.5	25	$7 \cdot 10^{18}$	$1 \cdot 10^{19}$	10	$0,6 \cdot 10^{19}$	13

Table I: *Values of the characteristics of laser and plasma*

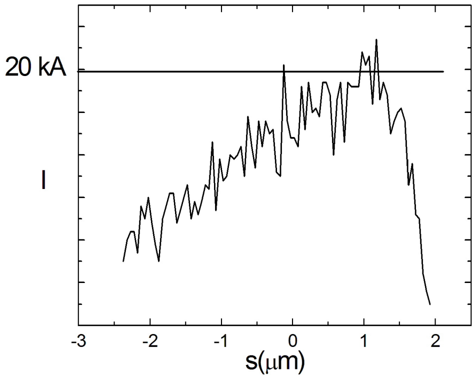

Figure 4: Current I versus the coordinate along the bunch s in μm.

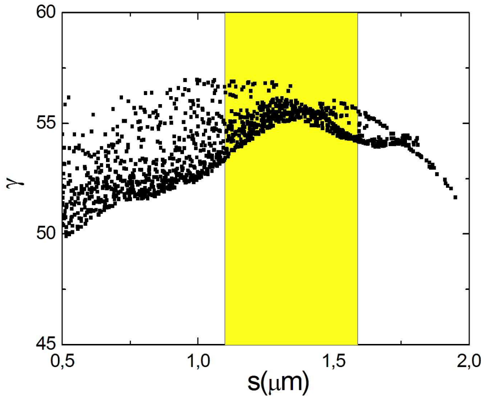

Figure 5: *Longitudinal phase space γ vs s(μm)*

In fact, even if the initial radiation field and bunching present a sequence of several random spikes, during the propagation in the wiggler they clean up assuming a smooth shape on the bunch (see (c)), with a neat, thin spectrum. The saturation occurs at 2.5 mm, the subsequent decrease of average and peak power being due to the slippage of the radiation outside the simulated slices.

The effect of γ, $\delta\gamma/\gamma$ and I profiles has been then analysed. In Fig 7 γ and $\delta\gamma/\gamma$ profiles deduced from the effective particle packet are presented, while Fig. 8 shows the results obtained taking the profiles into account.

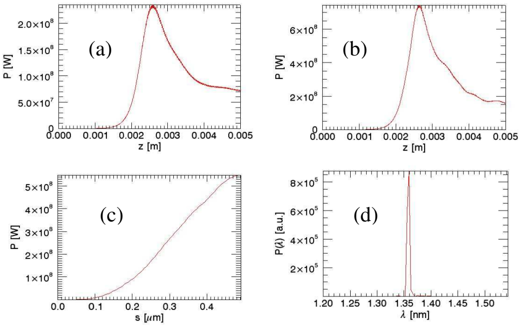

Figure 6: *(a) average power P(W) vs the coordinate along the undulator z (m); (b) peak power along z ; (c) power profile along the bunch coordinate s (μm) at z=2.5 mm; (d) power spectrum at z=2.5 mm.*

A situation substantially similar to the preceding one is shown by the graphs, with a slight reduction of the saturation power and an increase of about 15 % in the saturation length, that turns out to be about 3 mm.

A further step has been the use of the original files by VORPAL, trying a real start-to-end simulation.

The results are presented in Fig 9. The superradiant behaviour maintains, and there is the occurrence of a first large peak of radiation, high in power and temporary very thin, with a FWHM width of about 0.1 μm, corresponding to about 300 attosec, and with a maximum value of 200 MW . The transverse coherence is only partial, with the development of a dozen of peaks, while the temporal coherence is strong as can be seen from the pulse in the frequency domain. The same bunch, but without the defocusing phase, has been simulated in the field of a laser with wavelength λ_L=1 μm. We observe the production of a clean superradiant peak of width less than 0.05 μm (100 attosec), of tens MW and with a clean spectrum.

4. Conclusions

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 KA) electron beam.

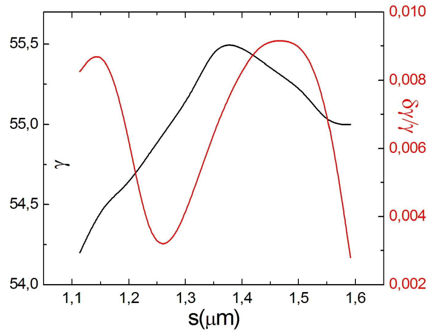

Figure 7: *Profile of γ and $\delta\gamma/\gamma$ vs s deduced by the VORPAL bunch*

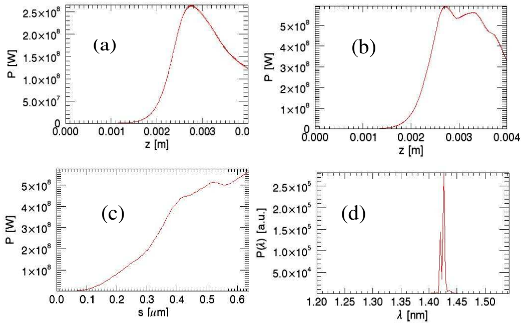

Figure 8*: (a) average power P(W) vs the coordinate along the undulator z (m); (b) peak power along z ; (c) power profile along the bunch coordinate s (μm) at z=2.5 mm; (d) power spectrum at z=2.5 mm.*

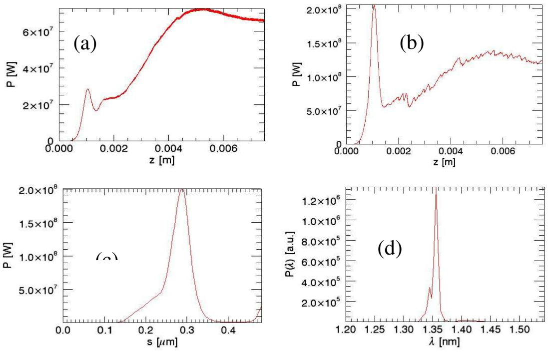

Figure 9: *(a) average power P(W) vs the coordinate along the undulator z (m); (b) peak power along z ; (c) power profile along the bunch coordinate s (μm) at z=2.5 mm; (d) power spectrum at z=2.5 mm.*

This bunch of electrons, characterized by the presence of low emittance (<0.5 mmmrad), low energy spread slices, when interacting with a counter propagating CO_2 laser pulse, radiates a single spike, highly coherent, ultra-short (< 1 fsec) X-ray pulse via excitation of a SASE superradiant FEL instability. The peak power achieved at 1.2 nm is of the order of 200 MW.

Taking an electromagnetic undulator at 1 μm wavelength the electron beam can drive a 1 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 will have to be thoroughly investigated in order to asses the experimental feasibility of such a new FEL scheme. Nevertheless, we believe that our analysis 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.

References

[1] F. Grüner, S. Becker, U. Schramm, T. Eichner, M. Fuchs, R. Weingartner, D. Habs, J. Meyer-ter-Vehn, M. Geissler, M. Ferrario, L. Serafini, B. Van der Geer, H. Backe, W. Lauth, S. Reiche *Design considerations for table-top, laser-based VUV and X-ray free electron lasers*, Appl. Phys. B **86**, 431-435 (2007)

[2] A. Bacci, C. Maroli, V. Petrillo, L. Serafini: Europ. Phys. Journ.-Appl.Phys. (2006) 2006080

[3] A. Bacci, M. Ferrario, C. Maroli, V. Petrillo, L. Serafini:
Phys. Rev. ST Accel. Beams 9, 060704 (2006)

[4] S. Bulanov, N. Naumova, F. Pegoraro and J. Sakai, Phys. Rev. E 58 R5257 (1998)

[5] P. Tomassini, M. Galimberti, A. Giulietti, D. Giulietti, L.A. Gizzi, L. Labate and F. Pegoraro, Phys. Rev. ST-AB 6, 121301 (2003)

[6] T. Tajima and J.M. Dawson, Phys. Rev. Lett. 43, 267 (1979);

[7] S.P.D.Mangles et al, Nature (London) 445,741 (2004); C.G.R. Geddes et al. Nature (London) 431, 538 (2004); J.Faure et al. Nature (London) 431, 541 (2004);

8] W.P. Leemans et al. , Nature Phys. 2, 696 (2006)

[9] R.G. Hemker, N.M. Hafz and M. Uesaka, Phys. Rev. ST-AB 5, 041301 (2002)

[10] A. Pukhov, J. Meyer-ter-Vehn, Appl. Phys. B **74**, 355 (2002)

[11] VORPAL: a versatile plasma simulation code, Chet Nieter and John R. Cary, Journal of Computational Physics, Volume 196, Issue 2, p. 448-472 (20 May 2004).

[12] S. Reiche, Nucl. Instrum. Methods Phys. Res. A 429, 243 (1999); S. Reiche: Genesis 1.3; http:// pbpl.physics.ucla.edu/ ~reiche