X-rays as a diagnostic of laser plasma electron acceleration in cm-long capillary tubes.

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In laser plasma based acceleration schemes [1], intense short-duration laser pulses interacting with under-dense plasmas expel electrons from the regions of high intensity and leave in their wake a plasma wave. This wave is associated to large amplitude space charge electric fields used to accelerate relativistic electrons. In the non linear regimes of laser wakefield, plasma electrons can be completely blown out of the intense laser region, and a fraction of the expelled electrons can be trapped in the accelerating potential of the plasma wave. In addition to the accelerating fields associated to the plasma wave, the accelerated electrons experience transverse fields. Thus these electrons can undergo strong transverse oscillations, or betatron oscillations, giving rise to the emission of synchrotron like radiation, which has been studied theoretically [2] and observed experimentally. [3].

The results of simulations presented in this paper were obtained for parameters close to those of an experiment performed at the Lund Laser Centre [4]. In that experiment, self-injected and accelerated electrons up to 170 MeV, accompanied by X-ray emission, were measured for input intensities as low as $5 \times 10^{17}\,\mathrm{W/cm^2}$, for plasma densities down to $5 \times 10^{18}\,\mathrm{cm^{-3}}$ in 20 mm long capillary tubes, with inner radius between $76\,\mu$m and $127\,\mu$m filled with hydrogen gas. Plasma densities between $3.5 \times 10^{18}\,\mathrm{cm^{-3}}$ and $8 \times 10^{18}\,\mathrm{cm^{-3}}$were explored. The normalized laser amplitude at the entrance is $a_0 = 0.6$. In the regime $a_0 < 1$, self-injection of electrons is not expected to occur in plasmas a few millimeters long at low density. Three dimensional particle-in-cell (PIC) simulations were performed with the CALDER-CIRC code to model electron acceleration and X-ray production in capillary tubes. The capillary tube is modeled by a Heaviside dielectric function.

X-ray emission

The X-ray emission is calculated from Lienard - Wiechert potentials, by post-processing the trajectories of electrons with energy larger than 10 MeV obtained in the PIC simulation.

The emission cone of the radiation calculated for the electrons populations obtained in these simulations extends up to 50 mrad. From geometrical consideration it can be seen that the X-rays will reach the capillary wall. The X-rays are assumed to be absorbed at the glass capillary

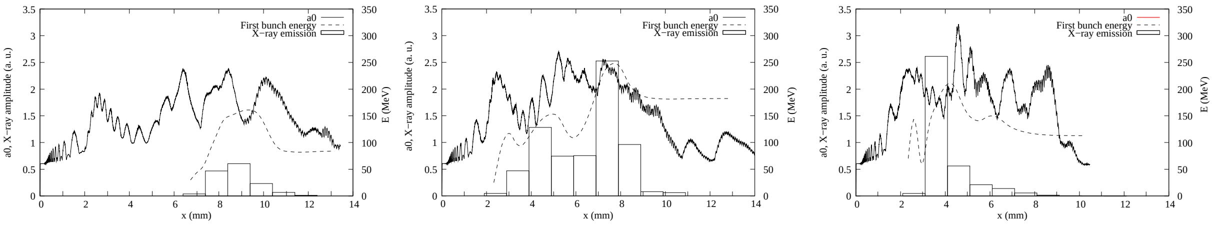

Figure 1: Normalized laser amplitude, a_0, first bunch averaged energy and X-ray emission as a function of laser position x. Left n = 5$\times$ 10^{18} cm^{-3}, middle n = 6.5$\times$ 10^{18} cm^{-3} and rigth n = 8$\times$ 10^{18} cm^{-3}.

wall.

This assumption is valid if the capillary wall surface is not smooth for the considered wavelength range or for large enough incidence angle (measured from the wall surface).

As a consequence only a fraction of the radiation produced along the capillary tube will reach the capillary exit. In order to take this effect into account, we calculate the radiation produced by segments of the trajectories. Due to the finite number of particles, in order to improve the statistics, the emission is calculated over a segment of 1 mm length, and averaged over the ensemble of particles in the volume defined by the product of the segment length with the capillary section.

For example, to calculate the radiation corresponding to x = 5 mm we average the radiation of all the particles with trajectories between the positions 4.5 mm and 5.5 mm.

Figure 1, exhibit the X-ray amplitude emitted on-axis and integrated from 1 keV to 10 keV, the evolution of the normalized laser amplitude, a_0, and the averaged energy of the first electron bunch as a function of the laser position for the 3 values of density.

The bars used to plot the X-ray emission represent the radiation calculated at each position inside a 1 mm interval. The amplitude of the X-ray emission follows the variation of the averaged first bunch energy, reflecting the fact that the emitted power grows [2] as γ^4. The X-ray energy is emitted in the second part of the capillary tube, $x > 6$ mm for $n = 5 \times 10^{18}$ cm^{-3}, at the beginning of the capillary tube, with a peak around 4 mm for n = 8$\times$ 10^{18} cm^{-3} and over a larger distance, between 2 and 10 mm for n = 6.5$\times$ 10^{18} cm^{-3}.

It is of interest, as a diagnostic producing data directly comparable to data accessible experimentally, to calculate the far field emission pattern in a plane perpendicular to the capillary tube, at a position situated after the exit of the tube. In figure 2 the far field emission calculated at the exit of a 2 cm long capillary tube is shown for the 3 different densities.

Figure 2 shows that the beam size and energy distribution are functions of the electron density,

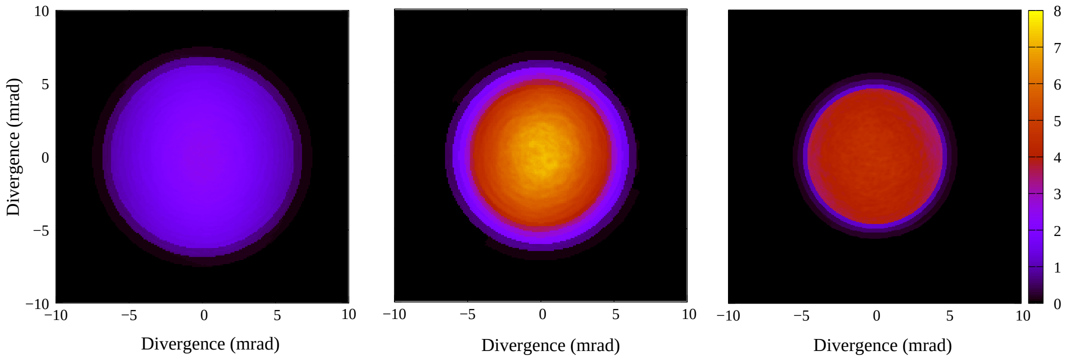

Figure 2: Far field X-ray emission pattern calculated in the transverse plane at the exit of a 2 cm long capillary tube of radius 76 μm for the different densities.

which confirms previous experimental observations[4]. More specifically, together with figure 1, it shows that the beam diameter is larger when the source of X-ray emission is closer to the exit of the tube, and that the change of intensity along the beam radius is related to the existence of an extended source ($n = 6.5 \times 10^{18}\,\mathrm{cm}^{-3}$ case). The resulting X-ray beam diameter is thus a combination of the position and extension of the X-ray source, determined by the electron injection and acceleration process, and of the geometrical aperture determined by the capillary tube diameter and length. It is thus possible to use the characterization of the X-ray beam energy distribution in the far field plane to infer the position of the X-ray source inside the tube.

For example for the case $n = 5 \times 10^{18}\,\mathrm{cm}^{-3}$, the divergence of the X ray far field measured from the X-ray profile obtained from the image of fig. 2 is ± 6.04 mrad and the edge of the beam extends to ± 9.39 mrad. For the capillary radius of 76 μm and 2 cm length, the position of the start of the X-ray emission is calculated as $x_s = 20 - 76/6.04 = 7.4$ mm and it ends at $x_e = 20 - 76/9.39 = 11.9$ mm. It can be checked in figure 1 that this measurement of the X-ray beam radius gives an accurate determination of the X-ray source position and extension along the laser axis.

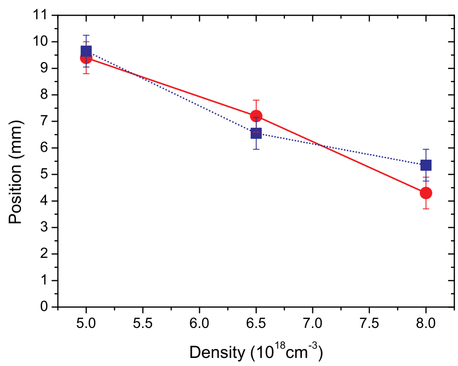

Figure 3: Position of the peak electron energy calculated from X-ray beam radius (blue square) and from electron spectra (red dots) as a function of plasma density.

With the parameters used in this simulation, figures 1 also show that the peak emission of the

X-ray occurs when the first bunch reaches its maximum energy. In figure 3 the position of the peak electron energy is plotted as a function of the electron density, together with the average position of the X-ray emission calculated from the average X-ray beam radius in the far field plane. For the electron peak energy position error bars arise from the window measurement time (0.6 mm). The agreement between these two determinations of the peak energy position shows that the measurement of the X-ray beam energy distribution can be an accurate diagnostic of the acceleration process in this parameter range.

Conclusion

We have presented a numerical analysis of electron self-injection and acceleration and of the associated X-ray emission in capillary tubes, allowing to create long plasmas at moderate densities. The accelerated electrons spectra were calculated and it was shown that the X-ray emission can be used as a diagnostic to determine the region of the plasma where the X-ray are produced and where the maximum electron energy is achieved. The X-ray beam diameter measured after the exit of the capillary tube is found to change with the longitudinal position and extension of the X-ray source, which depends on the plasma density, in agreement with experimental results[4].

References

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