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X-RAY PRODUCTION USING LASER-PLASMA ACCELERATORS

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Abstract:

Bubble regime has been investigated using three-dimensional particle-in-cell simulations of ultra-relativistically intense laser pulses with duration a fraction of the plasma wavelength [1]. Electrons trapped inside the bubble experience an electrostatic force and undergo betatron motion. The present work analyzes the spontaneous radiation emitted by electrons undergoing betatron motion in the plasma bubble. Numerical simulations have been used to calculate the expected spectra and spatial distribution of the radiation. We discuss these theoretical results and an experiment at Strathclyde that is being set up to measure the betatron radiation.

Laser-plasma accelerators and betatron oscillations:

A light source capable of delivering pulses of X-rays with femtosecond duration should provide a new probe with a time resolution that would enable investigation of the evolution of molecular and solid state matter. Laser-plasma accelerators represent a new interesting way of generating short pulses of X-rays. The mechanism determining X-ray emission can be sketched through the following steps:

- The propagation of intense laser pulses in underdense plasma generates plasma waves: laser wakefield acceleration (LWFA) occurs when a laser pulse travelling at a velocity close to the speed of light excites a trailing plasma wave or wake through the action of the ponderomotive force which expels electrons from regions of high laser intensity.
- Electrons can be trapped in the wake and surf the electric field of the wake thus gaining energy from the wave .
- If an intense laser pulse is ultra-relativistic and its duration shorter than the plasma wavelength, the ponderomotive force will expel plasma electrons radially and leave a cavitated (bubble) region behind the pulse, surrounded by a high electron density region.
- Electrons are trapped at the rear of the bubble and accelerate along the laser axis, creating a beam with a radial and longitudinal size much smaller than the laser spot diameter [1]. This regime has been observed in 2D particle-in-cell (PIC) (Fig.1).

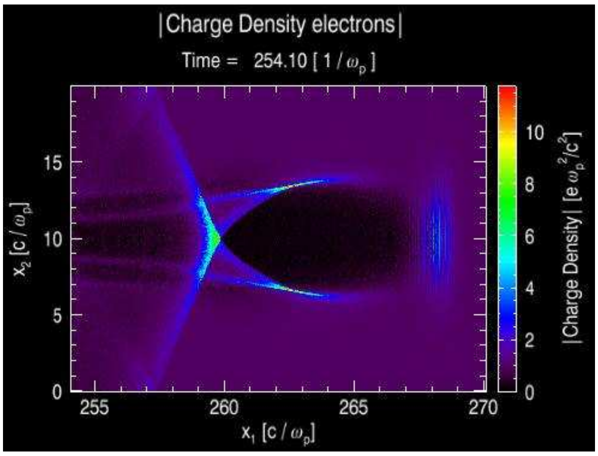

Figure 1: On-axis cut of the electron density in bubble regime conditions. The simulations have been performed using the OSIRIS code [4]

- As relativistic electrons propagate inside the bubble, they experience both a longitudinal accelerating force and a transverse restoring force which causes them to undergo betatron oscillation. The transverse acceleration of the charge results in a collimated beam of synchrotron radiation [5].

Approximating the bubble by a sphere, the Hamiltonian of the system is given by:

$$H = \gamma - \beta_0 P + \rho^2 / 4$$

where γ is the Lorenz factor of the electron $\beta_0 = v/c$, ρ the bubble radius and P the electron momentum.

Knowing the electron trajectories, the radiation emitted per unit frequency and unit solid angle in a given direction of observation **n** can be calculated using the Lienard-Weichert potential and is give by [3]:

$$\frac{d^2 I}{d\omega d\Omega} = \frac{e^2}{4\pi^2 c} \left| \int_{-\infty}^{\infty} \vec{E}\left(\vec{r}, t\right) e^{i\omega(t - \vec{n}\cdot\vec{r}(t)/c)} dt \right|^2$$

where

$$\vec{E}(\vec{r},t) = e\left[\frac{\vec{n}-\vec{\beta}}{\gamma^2(1-\vec{\beta}\cdot\vec{n})^3 R^2}\right]_{ret} + \frac{e}{c}\left[\frac{\vec{n}\times\left[(\vec{n}-\vec{\beta})\times\dot{\vec{\beta}}\right]}{(1-\vec{\beta}\cdot\vec{n})^3 R}\right]_{ret}$$

The energy per unit solid angle per unit time detected at the observation point at time t, emitted by the moving charge at the time $t_0 = t - R(t_0)/c$, is given by the Poynting's vector component along the direction **n**:

$$R^2\left[\vec{S}\cdot\vec{n}\right]_{ret} = R^2 \frac{c}{4\pi}\left|\vec{E}\right|^2 \vec{n}$$

The simulations have been carried out to reproduce the betatron oscillations of electrons during laser-plasma interaction inside a gas-filled capillary. Starting from a random initial particle distribution (Fig.2) we have calculated the expected spectra for different plasma densities and different angles of observation. Some of the results are shown in Fig.3 and Fig.4.

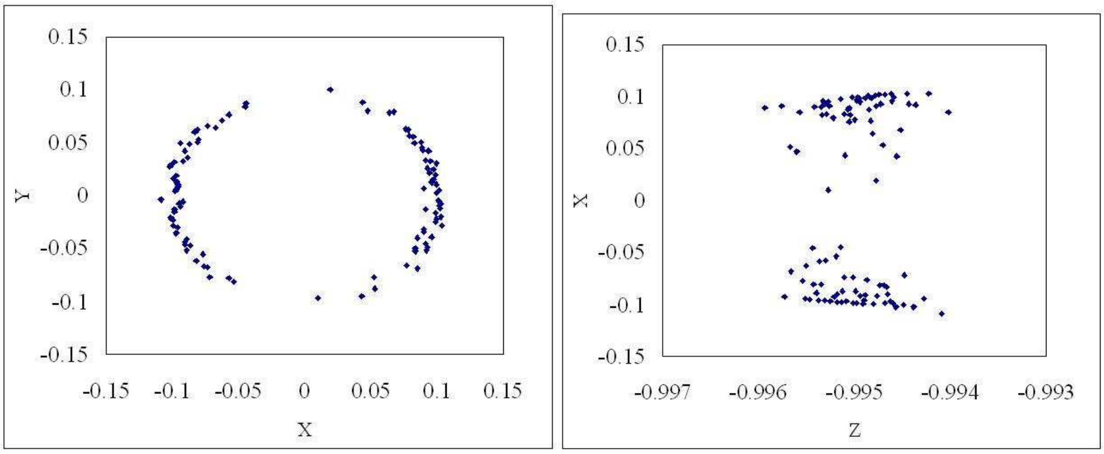

Figure 2: Initial particles distribution in the x and y direction: the distances are normalized to the bubble radius.

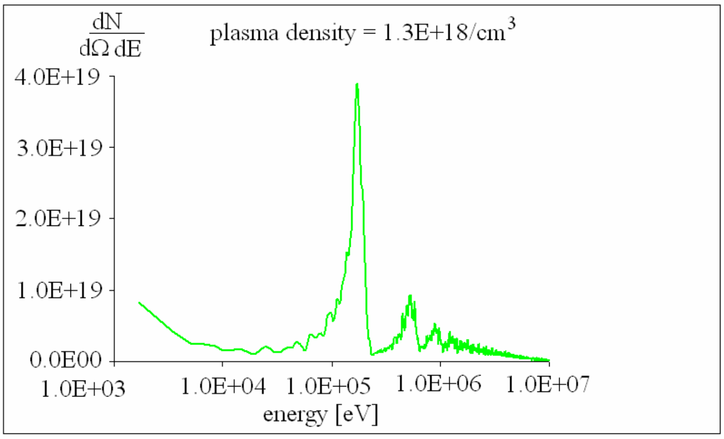

Figure 3: Betatron radiation energy spectrum on-axis. The differential number of photons emitted is plotted as a function of the energy.

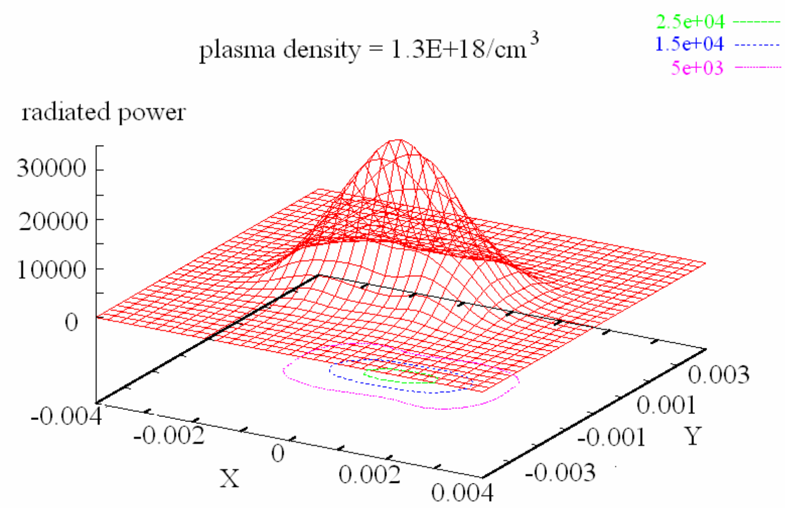

Figure 3: Spatial distribution of betatron radiation calculated for plasma density=1.3 10^{18} cm^3.

Discussion

The simulations results show that electrons will be accelerated up to a gamma factor varying from 1000 to 2000, depending on the plasma density. The energy peak of the betatron radiation emitted is expected to vary from 50 to 250 keV and the divergence angle from 2 to 10 mrad, which defines the conditions necessary for detecting the X-rays. The X-ray detector must detect over spectral range and be positioned such that all the radiation can be collected.
An X-ray camera and a solid state detector are being considered for imaging and spectroscopic measurement, which is a compromise between detection efficiency, geometrical requirements and price.

Conclusions

We have discussed the expected X-ray emitted by electrons undergoing betatron oscillations in bubble regime laser plasma interaction. The simulation results represent the starting point for an experimental set up to measure betatron radiation. The arbitrary initial conditions will be verified using the experimental results, which will be compared with simulations. Moreover, it should be possible to investigate the electron trapping process and its influence on the X-ray production. A study will be carried out both theoretically and experimentally with the objective of optimising the X-ray beam parameters.

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References

[1] Malka V. et al., Plasma Phys.Control.Fusion, 47:481–490, (2005)

[2] Phuoc K., Burgy F., Rousseau J. P., Malka V., Rousse A., Phys.of Plasmas, 12:023101-1–023101-8, 2005.

[3] Jackson J. D., Classical Electrodynamics (Second Edition), Wiley, 1975.

[4] R. A. Fonseca, L. O. Silva et al Computational Science — ICCS 2331/2008: 342-351 (2002)

[5] Phuoc K., Burgy F., Rousseau J. P., Malka V., Rousse A., Phys.of Plasmas, 12:023101-1–023101-8, 2005