X-ray betatron source: understanding the effects of laser imperfections

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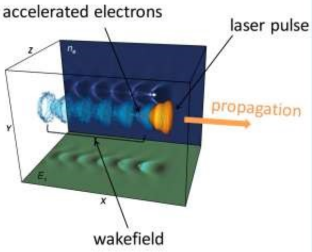
Abstract

Laser Wakefield Acceleration (LWFA) of electrons was first proposed in 1979 by Tajima and Dawson. It consists in sending an ultra-short and intense laser pulse in a low density gas jet. The extremely high intensity of the laser pulse completely ionizes the gas, and creates a high amplitude plasma wave in its wake, which can trap and accelerate an electron beam. Tthis electron beam transversally oscillates during its acceleration and naturally emits radiation, which is often referred as betatron radiation. To understand this phenomenon, a mere Gaussian laser pulse is often used in the simulations. However, laser pulses in current ultra-short TW (TeraWatt) systems are far from being ideal Gaussian beams. The influence of the presence of non-Gaussian features on the laser pulse is investigated here from experiments and 3D Particle-in-Cell simulations. Both the experimental intensity distribution and wavefront are used as input in the simulations. It is shown that a quantitative agreement between experimental data and simulations requires to use realistic pulse features. The performances on the electron acceleration and the betatron X-ray emission are also strongly degraded by these non-Gaussian features. A drop on the X-ray photon number by one order of magnitude was found. This clearly puts forward the limitation of using a Gaussian beam in the simulations, and indicates that experimental X-ray betatron sources should be greatly improved if laser imperfections are reduced.

Laser Wakefield Acceleration (LWFA)

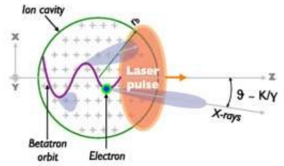
As an alternative to conventional radio-frequency accelerators, LWFA proposes to use the very high electromagnetic fields that can exist in plasma to accelerate particles in very short distances (cm scale):

- An ultra-short, ultra-intense laser pulse is sent on a gas cell.
- Gas is completely ionized into a plasma by the front of the laser pulse.
- Plasma electrons are expelled from the laser path and a positively charged region is created in the laser path.
- Attracted by the bubble, electrons oscillates in the path of the laser, creating the wakefield.
- Electrons can be trapped and accelerated in the wakefield.



Betatron Source

- Accelerating cavity can be represented as a bubble with attracting field for electrons.
- Electrons transversally oscillates during their acceleration [1].
- They emit forward energetic X-rays.



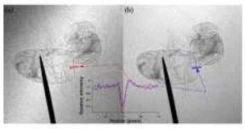
Applications of LWFA

- **Direct use of the electrons:**

High energy electrons radiation therapy [2]

- **Use of the X-rays source:**

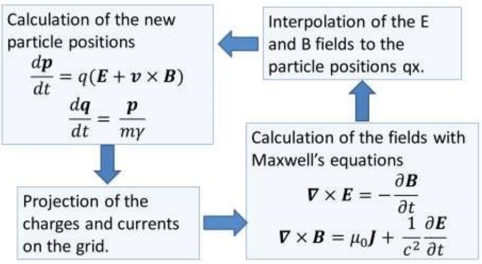
X-ray contrast imaging (high temporal and spatial resolution)



Bee imaged with X-ray betatron beam [3]

Simulation tools

- Simulations are realized with the 3D Particles-In-Cells (PIC) code CALDER [4]
- Electromagnetic fields are calculated on a grid while particles evolve freely in the cells.



Calculation of the new particle positions

$$\frac{d\boldsymbol{p}}{dt} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

$$\frac{d\boldsymbol{q}}{dt} = \frac{\boldsymbol{p}}{m\gamma}$$

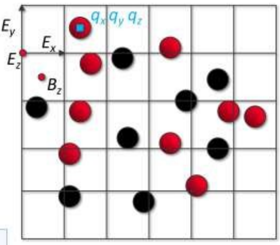
Interpolation of the E and B fields to the particle positions qx.

Calculation of the fields with Maxwell's equations

$$\boldsymbol{\nabla} \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

$$\boldsymbol{\nabla} \times \boldsymbol{B} = \mu_0 \boldsymbol{J} + \frac{1}{c^2}\frac{\partial \boldsymbol{E}}{\partial t}$$

Projection of the charges and currents on the grid.



Up: Grid for field calculation and particles. Left: temporal loop of the PIC code.

- Requirements for one simulation on parallel PIC code:

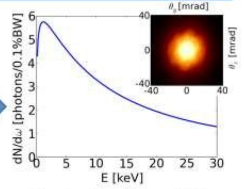
$100 \times 100 \times 100$ µm³, 10^{-12} s ⇨ 10^9 cells $+10^9$ particles, 10^5 iterations ⇨ ~ 10 hours, 2000 cores

× ~50 simulations → 10^6 hours

- X-rays emission are then post-processed from the trajectories of the electrons using:

Classical calculation of the radiation

$$\frac{d^2I}{d\omega d\Omega} = \frac{e^2}{4\pi^2 c}\frac{1}{4\pi\varepsilon_0}\left|\int_{-\infty}^{\infty} \frac{n \times [(n-\beta)\times\dot{\beta}]}{(1-\beta.n)^2} e^{i\omega(t-n.r/c)}\right|^2$$

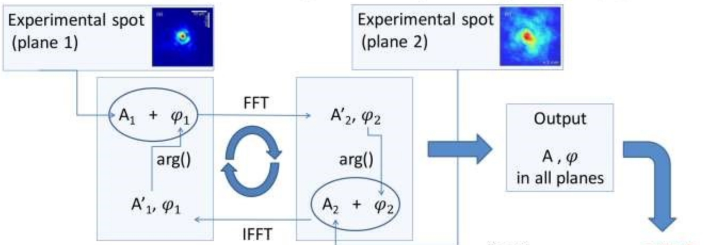


Shorter simulations (~10^3 particles, 10^4 time steps) :
-> a few hours on 100 cores

- Synchrotron like radiation
- Broadband energy spectra
- Short source (few fs)

Numerical modeling : phase reconstruction

- LWFA simulations generally use Gaussian pulses instead of the complex experimental laser pulse. Here, the wavefront and transverse intensity distribution are reconstructed using the Gerchberg-Saxton algorithm (GSA) [5].



Experimental spot (plane 1)

Experimental spot (plane 2)

$A_1 + \varphi_1$ $\xrightarrow{\text{FFT}}$ A'_2, φ_2

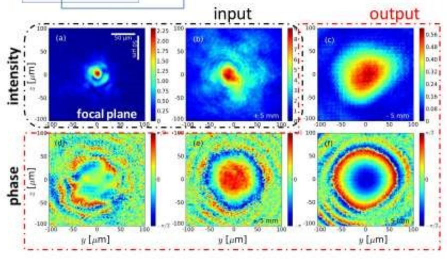
arg()

arg()

A'_1, φ_1 $\xleftarrow{\text{IFFT}}$ $A_2 + \varphi_2$

Output

A , φ
in all planes



Phase is reconstructed from the intensity distribution in two planes.
→ Reconstructed phase exhibits a laser asymmetry before and after the focal plane.
→ This underlines that experimental laser is far from a perfect Gaussian beam.

Three different cases are compared (all with E = 1, 35 J and λ_0 = 0.8 µm):

1. Gaussian laser pulse with E = 1, 35 J, τ_0 = 30 fs, w_0= 18 µm *(blue)*
2. Experimental transverse profile + null wavefront *(green)*
3. Experimental transverse profile + reconstructed wavefront *(red)*

Plasma density : $n_e = 6 \times 10^{18}$ cm^{-3}

- Different nozzle length are used (from 3 mm to 7 mm)
- Position of the laser focal plane is moved so to maximize the X-ray output

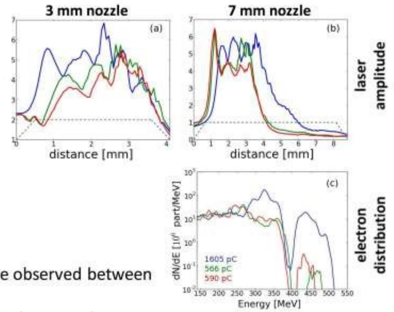
Results : Laser focusing and electron acceleration

- Experimentally, the focal plane position is moved further in the plasma for longer nozzles.
- Focal plane position is important because of the laser asymmetry : the laser spot must first homogenize in the plasma, which delays focalization and electron injection (a) for the 3 mm nozzle.

→ Most of the laser energy is lost and doesn't transmit to the wakefield and emitted particles.

- High differences in electron charge and energy are observed between experimental-like laser and Gaussian beam (c).

→ Using a Gaussian beam overestimates the electron charge and energy



5 mm nozzle

Results : Effects on the betatron source

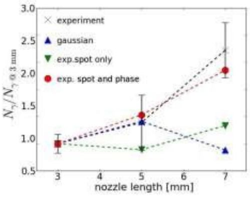
- As a consequence of the lower electron charge and energy, X-ray emission is strongly reduced.
- Number of photons can be reduced by one order of magnitude compared with the Gaussian beam.
- Because of the more homogeneous laser spot for the 7 mm nozzle, there is less difference with the Gaussian beam.

→ Only the laser with experimental spot and phase can reproduce the experimental trend for photon emission.

Number of photons (simulation)

Nozzle	3 mm	5 mm	7 mm
Gaussian	5.1×10^9	7.2×10^9	4.5×10^9
Exp. spot	1.8×10^9	1.6×10^9	2.4×10^9
Exp. spot and phase	8.5×10^8	1.3×10^9	2.0×10^9

Normalized number of photons



Other effects : Phase effects are responsible of a directional shift of the Xray emission (~5 mrad). This experimentally observed effect can not be explained by a gaussian beam.

References

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