Optical control of betatron oscillation amplitude in a laser wakefield accelerator

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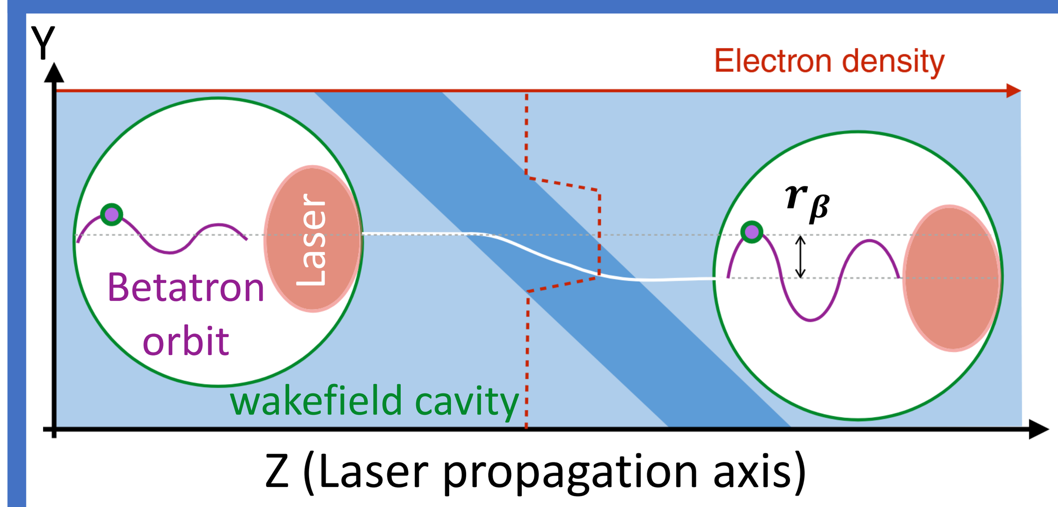
Introduction



A sharp transverse density gradient leads to refraction of the laser pulse and an increase in the amplitude of the betatron oscillations $\boldsymbol{r_\beta}$. The figure is taken from [1].

Scaling for betatron radiation:

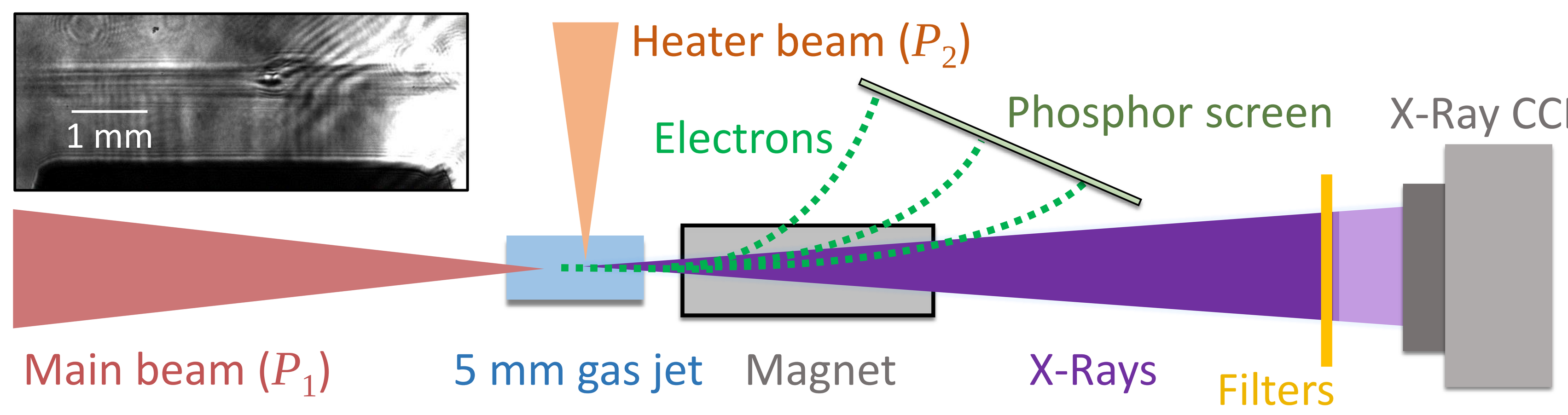
1. Number of emitted photons $N_\gamma \propto N_e N_\beta \boldsymbol{r_\beta}\sqrt{\gamma n_e}$.
2. Critical energy $E_c \propto \gamma^2 n_e \boldsymbol{r_\beta}$.
3. X-rays divergence $\theta_r \propto \boldsymbol{r_\beta}\sqrt{n_e/\gamma}$.

γ – the electron relativistic factor, n_e – electron density, N_e – number of electrons, N_β – number of betatron oscillation periods.

Increasing $\boldsymbol{r_\beta}$ should result in an equal increase in $\boldsymbol{N_\gamma}$, $\boldsymbol{E_c}$, and $\boldsymbol{\theta_r}$.

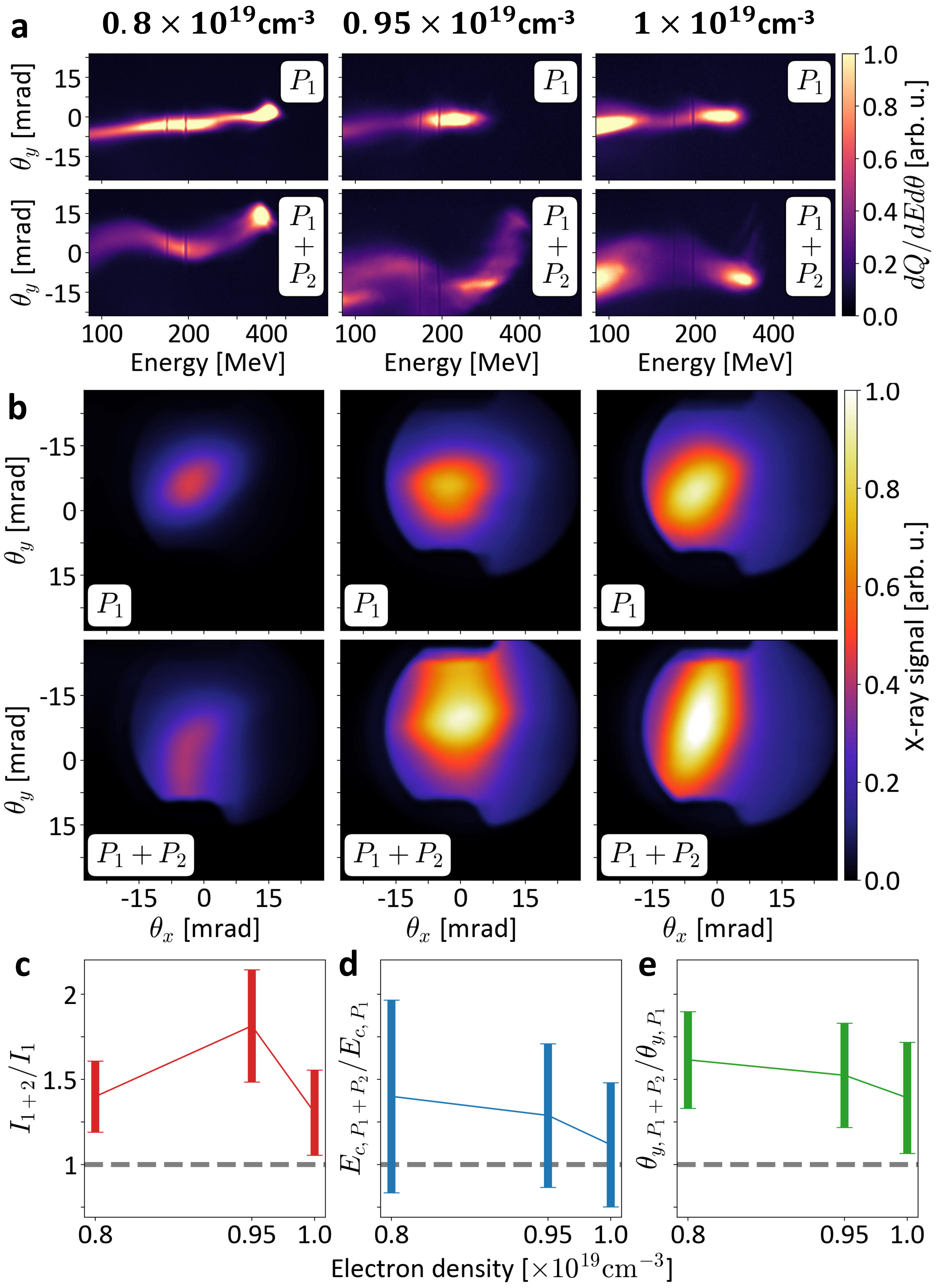
Experimental setup

Top-down schematic view and a typical shadowgraphy image:



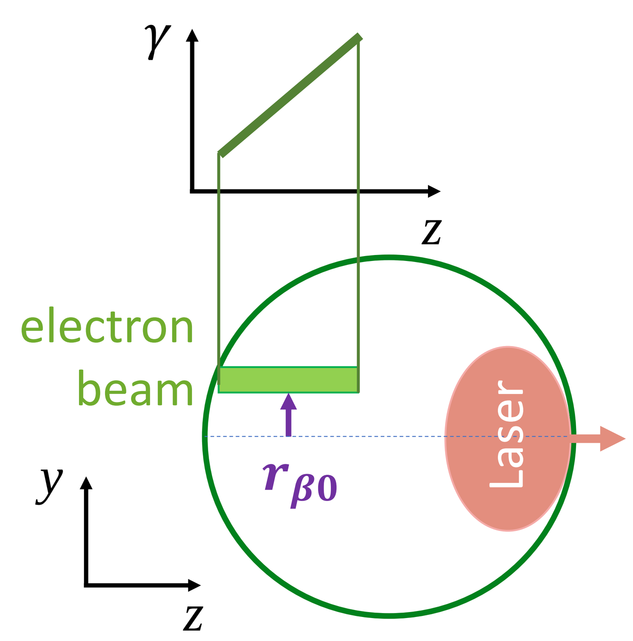
- **Laser system parameters**: repetition rate – 1 Hz, combined energy – 3.2 J, duration – 30 fs, the spectrum centered at 800 nm.
- **80%** of power — to the main beam, **20%** — to the heater beam.
- **Focusing**: the main beam — 1.5 m mirror, the heater beam — 65 cm motorized positive lens.
- **Heater beam:** a line profile created using a deformable mirror.
- **Heater beam:** arrives 3 ns before the main beam.
- **Gas**: mix of He and 1% of N_2.

Experimental results



(**a**) – electron beam spectra, averaged over ~70 shots each. (**b**) – betatron X-ray beam profiles, averaged over ~20 consecutive shots each. (**c**) – ratios of the total X-ray signal. (**d**) – ratios of the X-ray critical energy. (**e**) – ratios of the vertical divergence of the X-ray profiles.

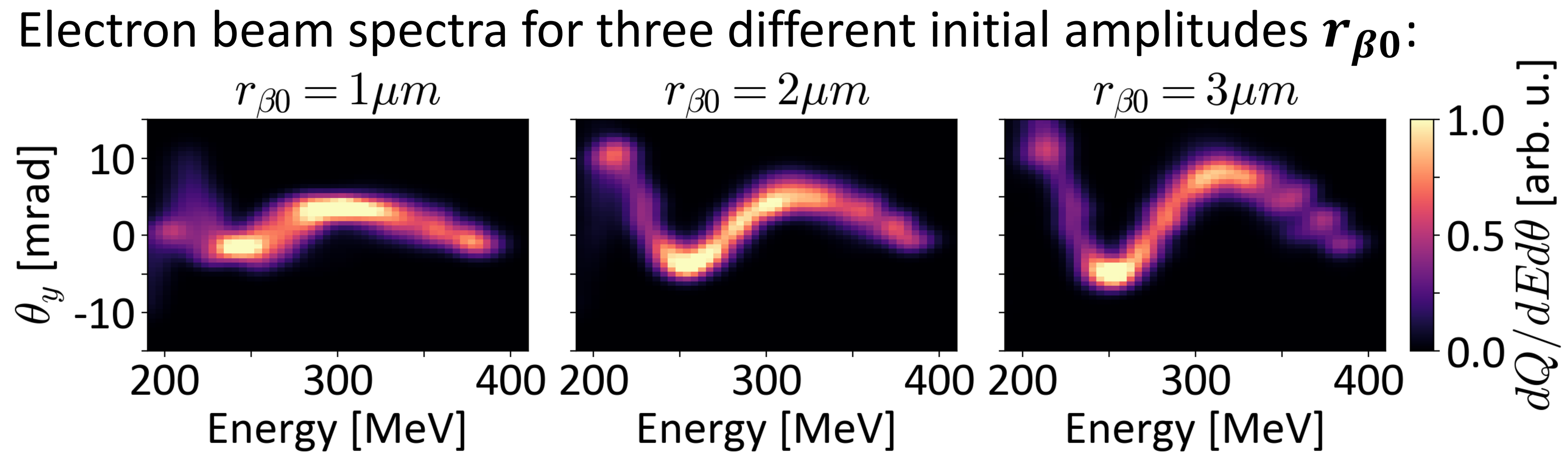
Numerical results and discussion



Toy model simulated with WarpX [2]:

- **Laser parameters**: $a_0 = 2, w_0 = 18\ \mu m$, $\tau_{FWHM} = 30$ fs, linear polarized along y.
- **Plasma**: He, 0.3×10^{19} cm^{-3}, 2 mm.
- **Electron beam**: tracer electrons, initially linear dependence of energy on longitudinal position.

Electron beam spectra for three different initial amplitudes $\boldsymbol{r_{\beta 0}}$:



We demonstrate that:

- a shock wave created by a heater beam can increase the amplitude of betatron oscillations;
- the increase of the amplitude is inferred from the increase of total X-ray flux, X-ray critical energy, X-ray divergence, and oscillations on the electron beam spectrum;
- the increase of the amplitude is stable over 70 shots;
- numerical simulations show correlation between the betatron and electron spectrum oscillation amplitude.

The proposed method can be used to enhance and control betatron x-rays produced by laser wakefield accelerators.

References and acknowledgments

[1] Kozlova, Michaela, et al. "Hard X rays from laser-wakefield accelerators in density tailored plasmas." *Physical Review X* 10.1 (2020): 011061.

[2] Fedeli, Luca, et al. "Pushing the frontier in the design of laser-based electron accelerators with groundbreaking mesh-refined particle-in-cell simulations on exascale-class supercomputers." *SC22: international conference for high performance computing, networking, storage and analysis*. IEEE, 2022.

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