Program Future Information Technology | Institute: PGI-6

Jülich Short-Pulse Particle and Radiation Center

*Ju*SPARC : A Novel Photon Infrastructure at FZJ

Peter Grünberg Institute (PGI-6) / Collaborating Institutes @ FZJ: JSC, IKP

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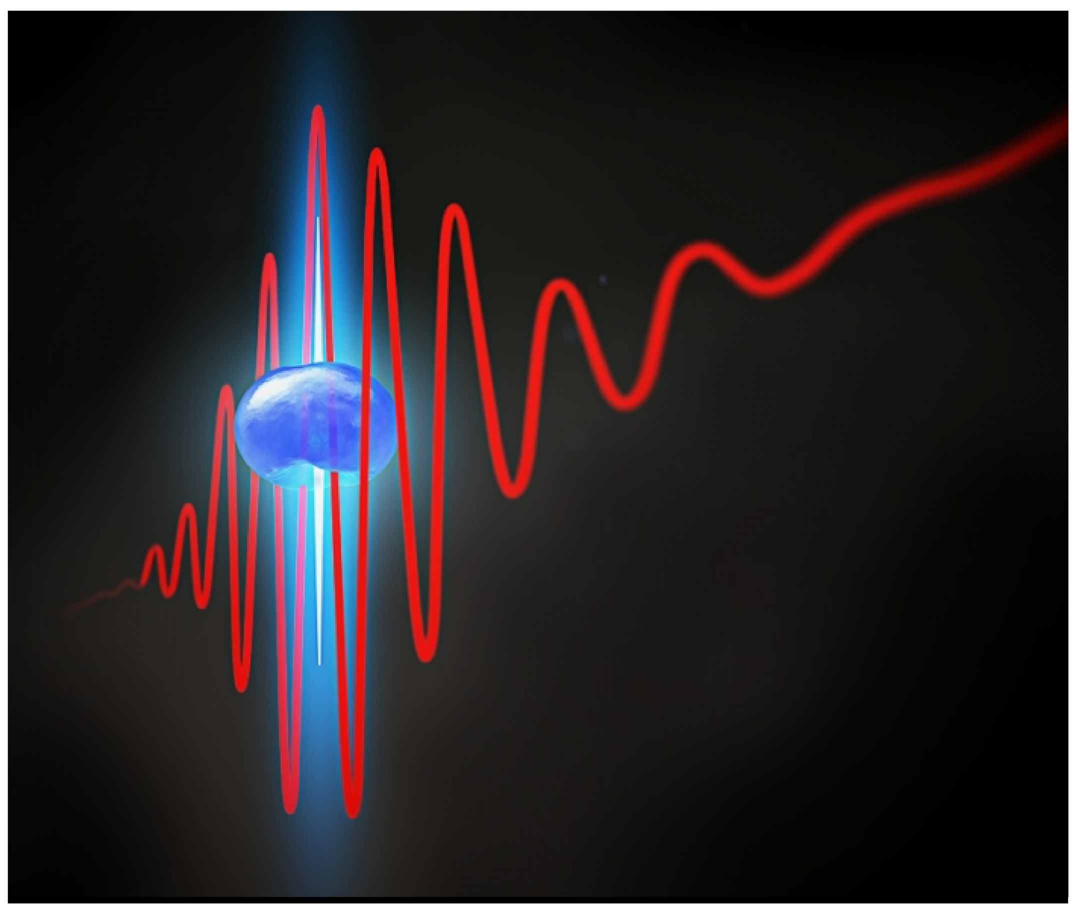
Toward Enhancement of Betatron Radiation Flux



Short and bright X-ray sources are of great importance in different branches of science to study the atomic structures down to sub-nanometer range and ultrashort time scale events. Synchrotrons and free electron lasers are the common sources of X-rays, both of which have limited accessibility because of their huge scale and costs. These limitations could potentially be overcome by laser-driven betatron radiation as a novel femtosecond X-ray source. In this project preparatory simulations are performed to investigate the feasibility of achieving a high X-ray flux and energy using a TW-class laser soon to be installed as part of the *Ju*SPARC facility. Two different injection schemes to enhance the beam current in plasma-based laser-electron acceleration were studied: Injection of ultrashort electron bunches that are emitted from nano-sized clusters and a two-pulse scheme for enchanced self injection.

It was found that ultrashort electron bunches can be trapped inside a wakefield bubble and how the cluster position influences energy and emittance of the accelerated electrons. The double-pulse scheme is applied to optimise self-injection, such that the first pulse creates provides a fully ionized target of electrons available for trapping and acceleration by the second pulse.

Ultrashort electron bunch injection from nano sized clusters

Nano sized cluster have been shown to emit ultrashort, sub-fs high energetic electron bunches, when being hit by high intensity laser pulses, due to Mie like scattering of the laser field [1] as is depicted in figure 1. The scattered wave generates an oscillating dipole moment. Experiments have shown a strong increase in the electron and photon Flux from laser wakefields when gas targets are doped with nano-sized Clusters.[2] Our simulations have shown that such bunches could act as a seed for the laser wakefield. We investigated the influence of the clusters position relative to the centre of the laser focus and found, that in terms of a small phase space volume (low emittance), having the cluster outside of the laser focus is favourable.

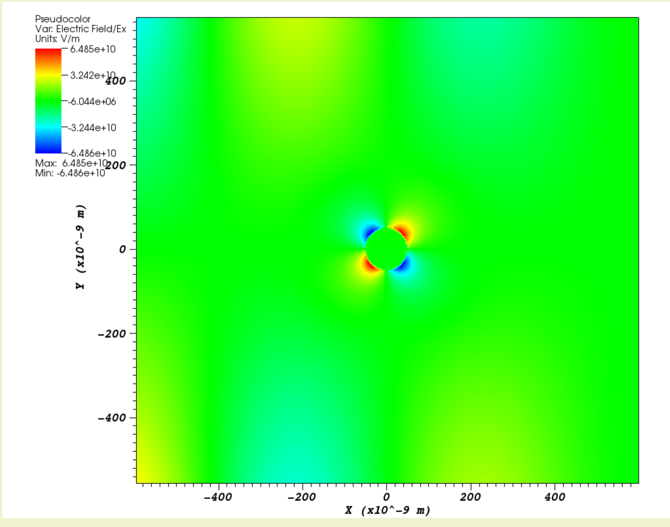


Figure 1: The electric wave of the laser pulse that scattered at the clusters surface, resulting in a oscillating dipole moment which is emitting ultrashort electron bunches from the cluster. Plot is the longitudinal electric field strength.

To investigate the influence of the cluster position relative to the focal spot, PIC simulations using the EPOCH code[3] where preformed on the JURECA cluster. It could be shown that when a cluster has been positioned off-axis, emitted electron bunches will stay compact inside the wakefield. In figure 2 the electron distribution of the injected electron bunches 600 fs after the laser pulse hit a 100 nm SiO^2 cluster. In case of a centered cluster (left), we found that the bunch got ripped apart and fragmented into several sub-bunches. In contrast, a bunch that was emitted from an 10 µm off-axis cluster (right) stayed compact during the acceleration.

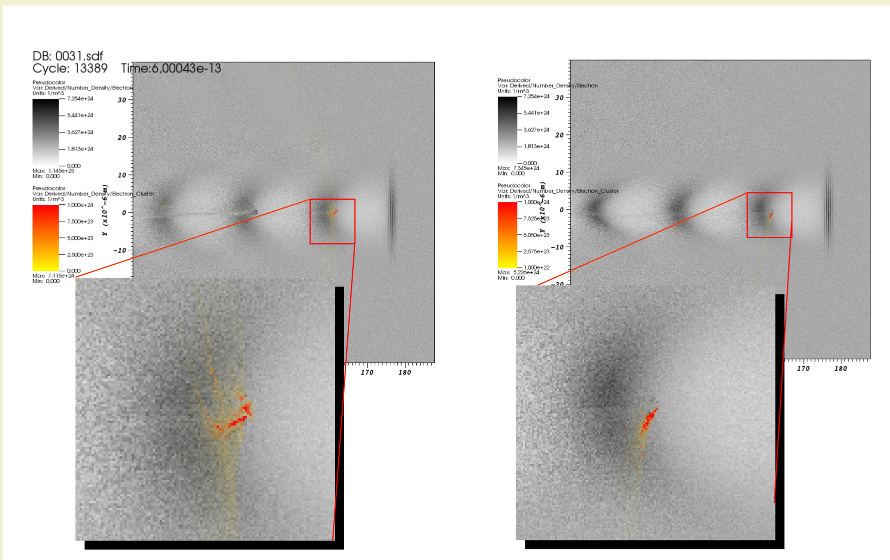


Figure 2: Comparison of spatial distribution of the injected electron bunch from a cluster when it is positioned in the centre(left) and 10µm above the focal spot.

At the same time, more electrons reached higher energies. In figure 2 the angular energy distribution of electrons is plotted. In this plot the forward direction is represented by 0 and 2π.

One can see that, that the emission is pushed towards the laser propagation axis and that the maximal energy doubled from 3 MeV to approximately 6 MeV.

This result motivates to further investigate this injection scheme, especially with respect of the emitted betatron radiation. As the source of this radiation are the accelerated electrons, we hope to find ultra short sub-fs pulses that can be used for time resolved measurement of ultrashort processes on sub-µm scales.

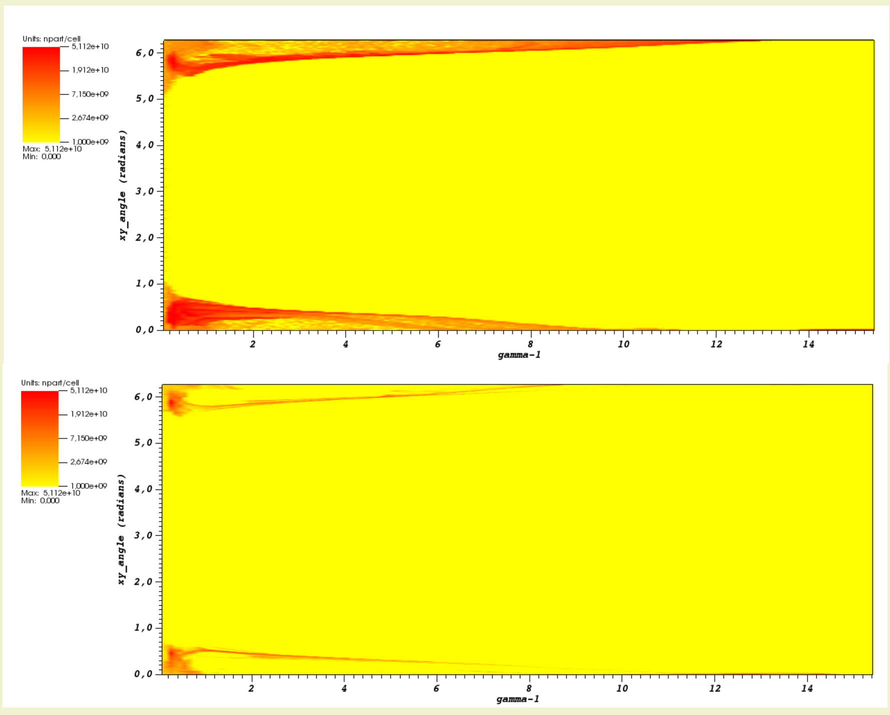


Figure 3: Comparison of the energy distribution of the injected electron bunch from a cluster. (top: off axis, bottom: centre)

[1] Bright betatron X-ray radiation from a laser-driven-clustering gas target, L. M. Chen, W. C. Yan, D. Z. Li, Z. D. Hu, L. Zhang, W. M. Wang, N. Hafz, J. Y. Mao, K. Huang, Y. Ma, J. R. Zhao, J. L. Ma, Y. T. Li, X. Lu, Z. M. Sheng, Z. Y. Wei, J. Gao & J. Zhang, Scientific Reports volume 3, Article number: 1912 (2013)

[2] Relativistic attosecond electron bunch emission from few-cycle laser irradiated nanoscale droplets. Laura Di Lucchio, Paul Gibbon, PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 18,023402 (2015)

[3] T. Arber, K. Bennet, C. Brady, A. Douglas, M. Ramsay, N. Sircombe, P. Gillies, R. Evans, H. Schmitz, A. Bell, et al., Plasma Physics and Controlled Fusion 57, 113001 (2015).

Increased Laser-driven Betatron Radiation Flux and Energy by Self-injection Using Two Collinear Laser Pulses

We propose a scheme for the self-injection of electrons in the bubble acceleration regime using two collinear laser pulses which is promising for achieving higher X-ray flux and energy relative to the standard single pulse scheme. Therefore, the laser pulse is splitted into two pulses of same wavelength, temporal length and focal size. The optimum condition is sought based on maximum achievable electron energy by scanning the pulses delay and energy fraction of each pulse. This scheme is analyzed by a 2D particle-in-cell simulation using the EPOCH code [3] on the JURECA cluster and proves the advantage of using double pulses for self-injection.

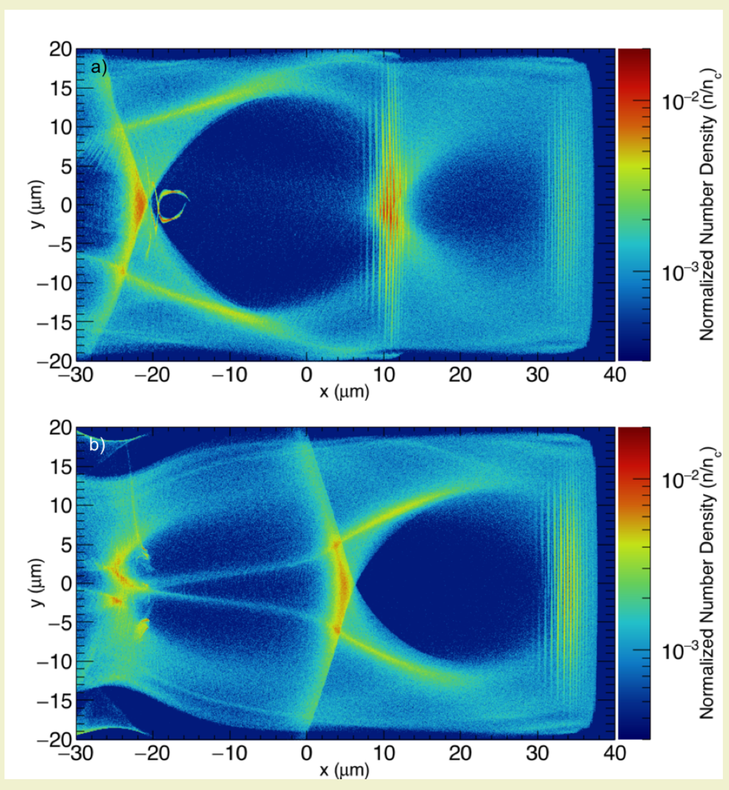


Figure 1: 2D snapshot of the electron number density distribution at t=1500 fs, with the Helium gas target being irradiated by a laser of a_0 = 3.85, for a) the double pulse scheme with the optimum condition, b) single pulse scheme.

- The Bubble regime of electron acceleration [4] is the highly non-linear regime of laser wake field acceleration, evolving a plasma wave following the laser pulse.
- The condition is that laser pulse intensity is high enough to create a cavity, free from background plasma electrons. Moreover, the pulse duration to be in the order of plasma wavelength.
- Some electrons get trapped in the cavity and accelerated.
- Electrons start to wiggle around the laser pulse propagation axis, due to the strong transversal electric field of the ion cavity. This results in betatron radiation, as a femtosecond source of X-ray.

- Figure 1: Electron number density distribution in double and single pulse scheme. Higher number of electrons are trapped in the double-pulse scheme.
- Based on the simulation results, the general optimum condition is that the energy of first pulse to be high enough to meet the bubble condition, and the rest of the energy can be allocated to the first pulse. Furthermore, the delay should correspond to the size of first bubble.
- Figure 2-a: Comparison between the electron distribution in longitudinal momentum phase space (x, p_x) for the optimum conditions. As can be seen, with same laser parameters and same simulation time, electrons reach higher energy in the double pulse case.
- Figure 2-b: Corresponding betatron radiation. Higher radiation energy and flux is achieved using the double-pulse scheme.

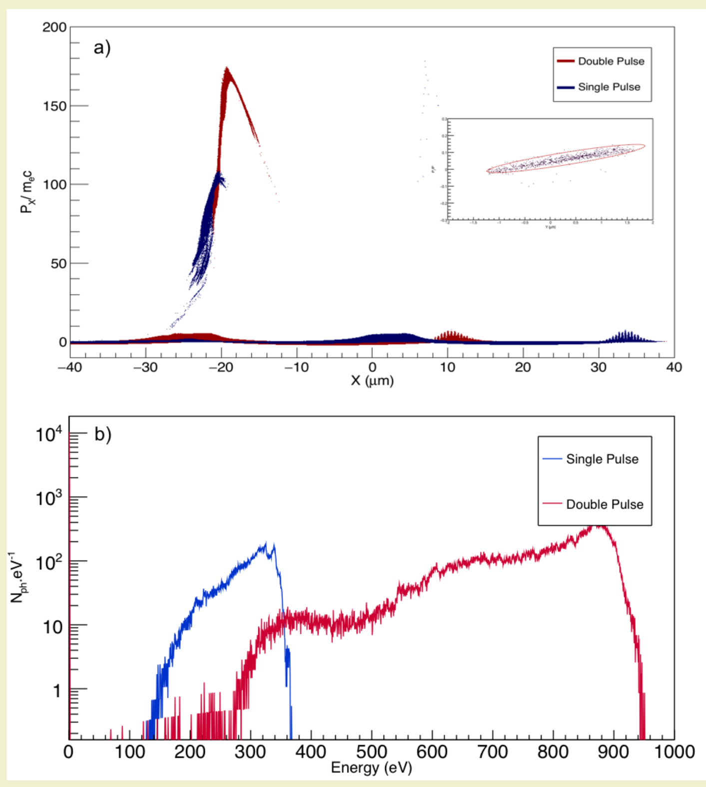


Figure 2: a) Comparison between the electron distribution in momentum phase space (x, p_x) at t=1500 fs. The pulse energy of the laser (2 mJ) is divided between pulses with the second pulse energy being twice as high as the first pulse energy, and a relative delay of 78 fs for the simulation with double pulses. The small inset shows the transverse phase space of the injected electrons in double pulse scheme, with b) Betatron radiation spectra for single pulse and double pulse scheme.

[4] Laser wake field acceleration: the highly non-linear broken-wave regime. A. Pukhov and J. Meyer-ter Vehn Applied Physics B Lasers and Optics, **74** (4-5):355361, 2002.

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