low emittance electron source by injection of electron bunches from nano-sized clusters into laser wakefields

Andre Sobotta, Forschungszentrum Jülich, Jülich, Germany, a.sobotta@fz-juelich.de

We present our approach to a single-stage laser wakefield accelerator with low emittance. This is archived by utilizing electron bunches, that are emitted from nano-sized clusters when being irradiated by ultrashort high intensity laser pulses. In this approach electrons are injected into the wakefield by the interaction of the driving laser-pulse with a cluster of the diameter of roughly 100 nm.

As it has been shown before, nano-sized clusters will emit relativistic electron bunches under an intensity and cluster diameter dependent angle, every half-cycle of the driving laser field, due to Mie-like scattering of the electric wave and a subsequent field enhancement on its surface [1] as can be seen in Figure 1.

a) b)

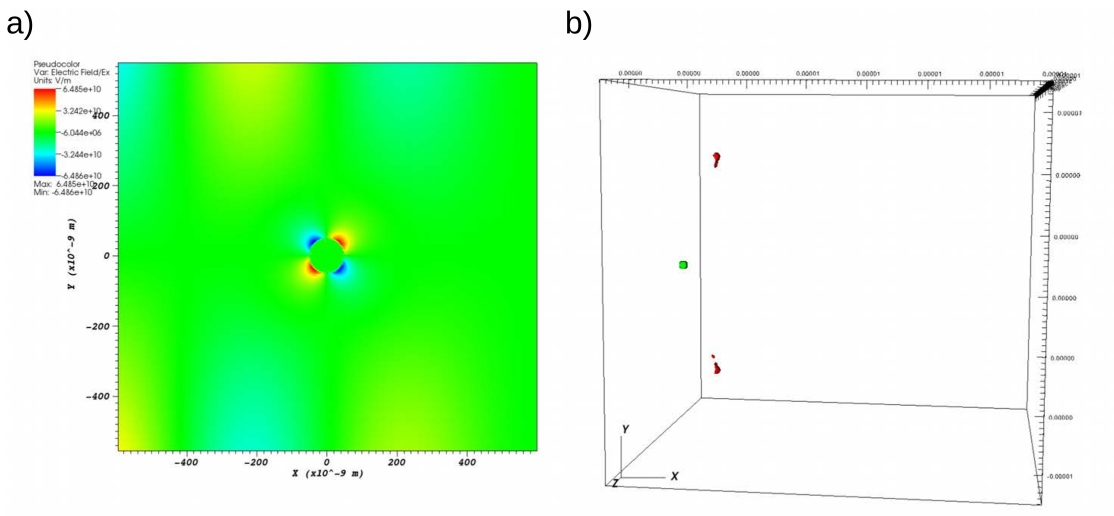

Figure 1: PIC simulation of a 20 fs laser puls interacting with a 100nm sphere. In a) the electric field in x-direction around the cluster is depicted. One can easily see the enchanced field at the clusters surface. On the right one can see two electron bunches (red) are emitted from the ionized sphere (green).

Since all the electrons inside one bunch experience an equal electric field and the time of emission is well defined by the phase of the driving pulse, these bunches exhibit a very narrow energy distribution and a very short longitudinal length of approximately 100 nm. This makes them to perfect candidates for pre-accelerated quasi-monoenergetic seed bunches to be injected into a laser-wakefield.

Particle in cell simulations of the interaction of laser pulse with a gas-jet target, which is enriched with a 100nm cluster have been preformed. With a Gaussian laser pulse of 20 fs duration and a total energy of 40 mJ that is focused to a diameter of 10µm.
These Laser parameters have been chosen to match those of the JuSPARC Laser-system [3], at which experimental confirmation of these results will be preformed in the near future.

Cluster Position

The influence of a clusters initial position on the injection and acceleration process
Was investigated. It was found that it is advantegus to have the cluster not on lasers propagation axis (center of focus) razther than one half gauss width displaced transversaly. As can be seen in Figure 2, this leads to a single bunch of electrons being captured inside the wakefield rather than a blured cloud containing several bunches.

a) b)

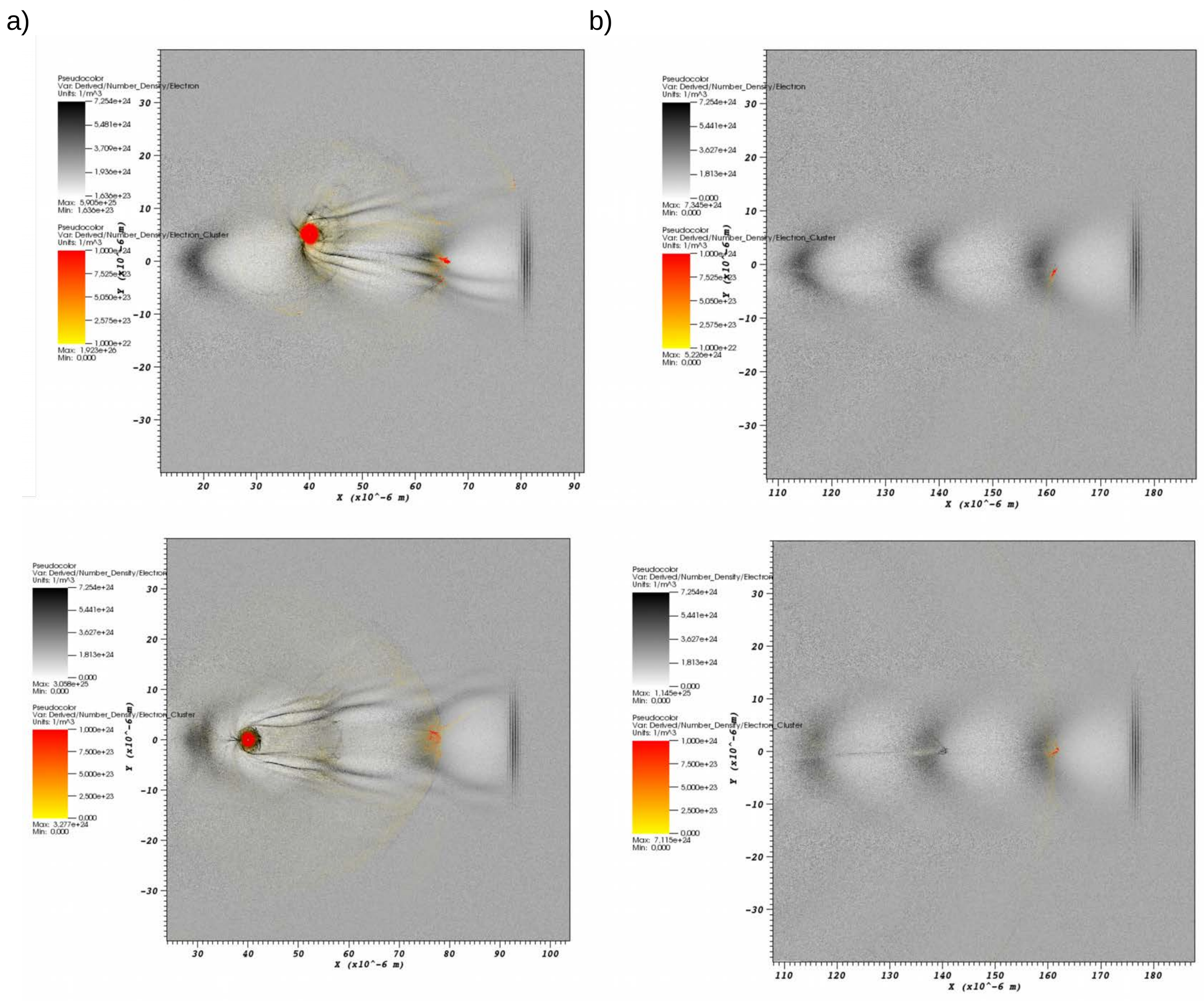

Figure 2: The electron density at t = 320fs (a) and t = 600fs (b). The backgroun plasma is plote in gray While electrons emitted from the cluster is plotted in yellow-red. One can see that the emitted electron bunch gets captured inside the wakefield and stays compact even while beeing accelerated.

Our finding also hold true in terms of the electrons energy distribution. As depicted in Figure 3, electrons will reach an maximal energy of 4 MeV (γ=8) when the cluster was initaly situated on axis while reaching up to 23 MeV (γ=46) when being displaced. Furthermore the bunch gets better coliminated.

a) b)

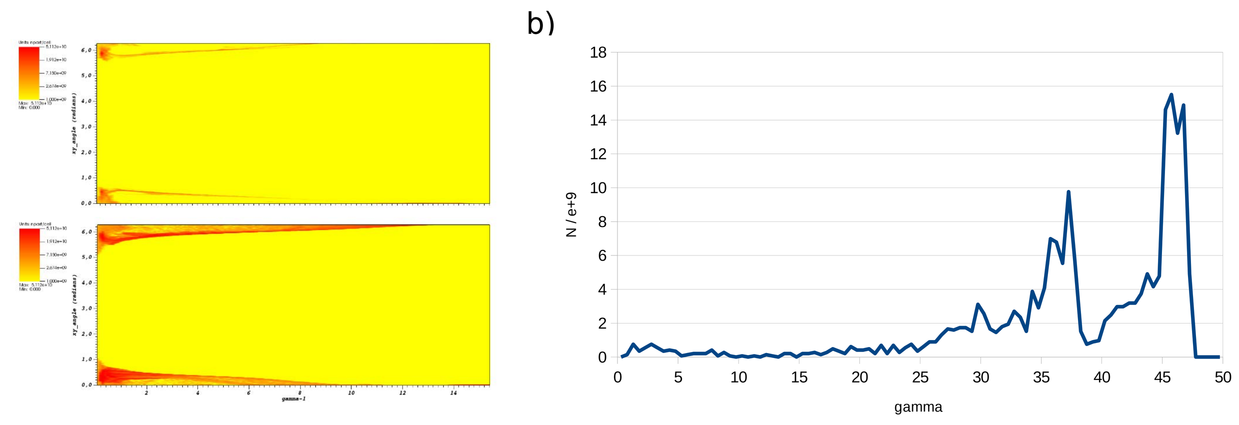

Figure 3:
a) angular energy distribution (cut at γ=16) of the emitted electrons when the cluster was positioned on axis (top) and when being displaced by one gauss width (bottom). It can be seen that if the cluster is displaced, electrons reach higher energies and the bunch gets better Collimated compared to the cluster sitting in the center of the wake-field.
b) full energy spectrum of the electon bunch with a sharp peak at 22 MeV

Our simulations predict an electron bunch with an average energy of 12 MeV, an emittance of ε= 0.06 π mm mrad and a fly-by time shorter than 4 fs.

a) b)

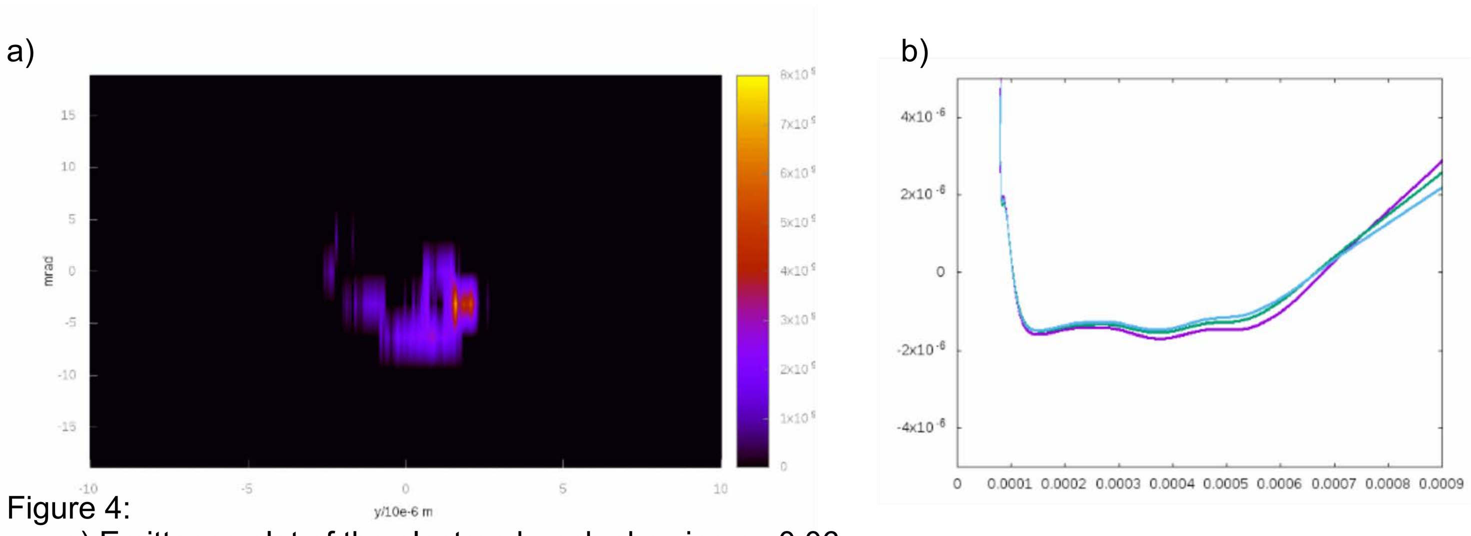

Figure 4:
a) Emittance plot of the electron bunch showing ε= 0.06 π.
b) three typical trajectories of electrons inside the bunch with an energy above 15 MeV. One can see that the trajectories are very well correlated even after leaving the plasma. From their energy and path a critical wavelength of 20nm for emitted X-rays was derived.

As expected, the high energy electrons inside the bunch follow very correlated trajectories, thereby keeping the initaly well defined bunch structure.
The difference in the behavior of displaced and on-axis cluster can be explained by the initial emission of electron bunches. When the cluster is not displaced, the direction of emission of the electron bunches points out of the wakefield and thereby beeing ejected for it.
This is however not the case for a displaced cluster, there bunches are emitted in irection of the wakefield. Furthermore, the emission of the bunches is not symetrical around the propergation axis, but tilted to it. This leads to an additional gain in longitudinal momentum.

Summary

From our simulation we find evidence that electron bunches from nano-sized clusters can be injected into a laser wakefield accelerator. Uring the acceleration process, these bunches keep their spatial volume because of the correlated behavior of the electrons. This might lead to a low emittance electron and X-ray source.

References

[1] L. Di Lucchio, P.Gibbon, "Relativistic attosecond electron bunch emission from few-cycle laser irradiated nanoscale droplets", Physical review / Special topics / Accelerators and beams 18(2), 023402 (2015)
[2] T. D. Arber, K. Bennett, C. S. Brady, A. Lawrence-Douglas, M. G. Ramsay, N. J. Sircombe, P. Gillies, R. G. Evans, H. Schmitz, A. R. Bell, and C. P. Ridgers, "Contemporary particle-in-cell approach to laser-plasma modelling," Plasma Physics and Controlled Fusion, vol. 57, no. 11, pp. 1–26, Nov. 2015
[3] JuSPARC