Interaction of a 5 fs laser pulse with nanometer-sized frozen hydrogen droplets

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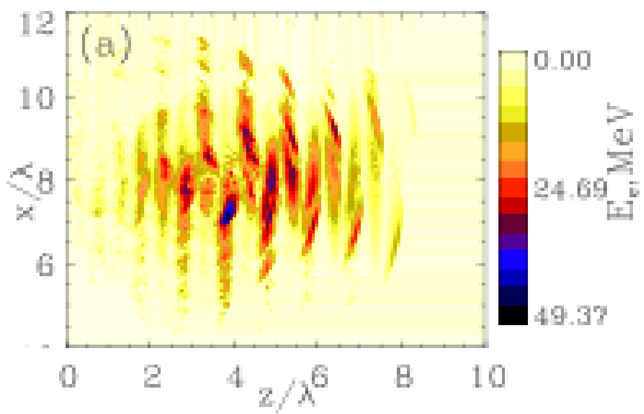
MOTIVATION: generation of short attosecond electron nanobunches in a relevant context for contemporary experiments with ultrashort laser pulses and nm-sized targets.

Main schemes proposed to generate attosecond bunches:

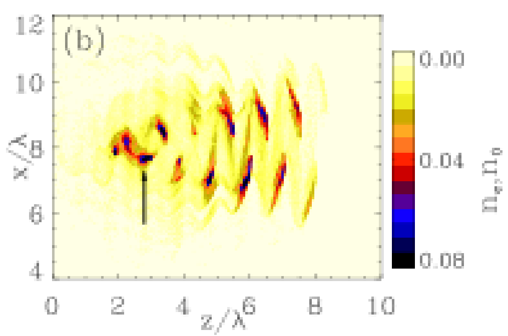
- vacuum acceleration by tailored laser pulses
  (Stupakov, Zolotorev, PRL 93, 2004)
- interaction of p-polarizes laser pulses with overdense plasma boundaries
  (Naumova et al., PRL 93, 2004)
- stochastic slicing of electron pulses.
  (Dodin, Fisch et al., PRL 98, 2007)
- laser-illuminated droplets
  (Lyseikina et al., PRL 104, 2010)
- laser-illuminated ultrathin plasma layers
  (Wu, Meyer-ter-Vehn, PRL 104,2010)
- attosecond electron sheets from laser wakefields
  (Li, Sheng et al., PRL 110, 2013)

Studies on generation of attosecond bunches using laser illumination of droplets make use of Mie theory to explain the alternate angular emission of nanobunches at two symmetric directions depending only on the geometry of the physical system. For the highest intensities differences between density and energy flux are observed. Source : Lyseikina et al., PRL, 2010.

Kinetic energy ⟶



Density ⟶



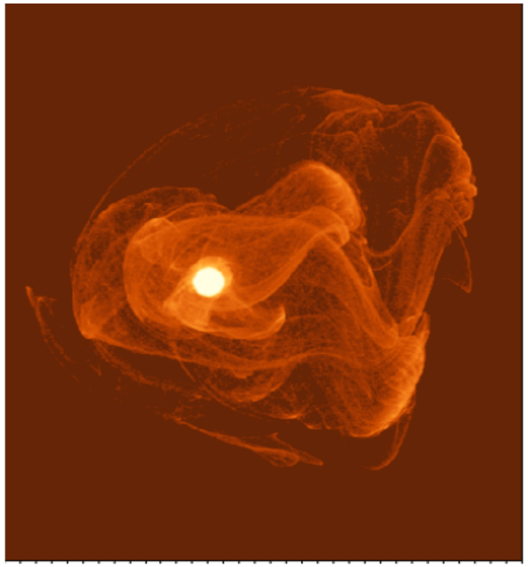
Our investigation:

- Single spherical nanotargets with $n = 100n_c(n_c = 1.8 \times 10^{21} cm^{-3})$
- droplet size $= 100nm \div 1\mu m$
- 5 fs pulse, $I = 1 \times 10^{19} \div 1 \times 10^{21}$
- Focus on small droplet case (with respect to λ)

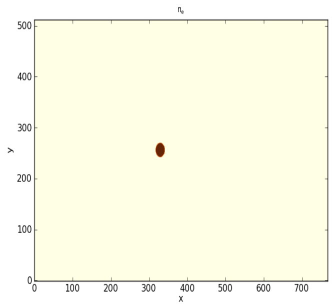
Simulation details:

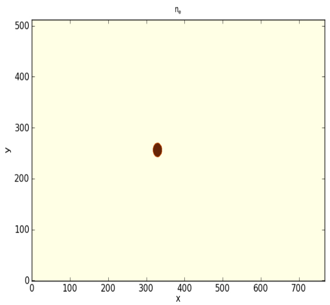
- EPOCH particle-in-cell code
- 34×10^6 particles, $4 \div 20$ micron transverse box side, a few hours simulation time
- $\approx 80 \div 800$ processors on Juropa, $128 \div 1024$ processors on Juqueen

Angular emission of electron bunches (I)

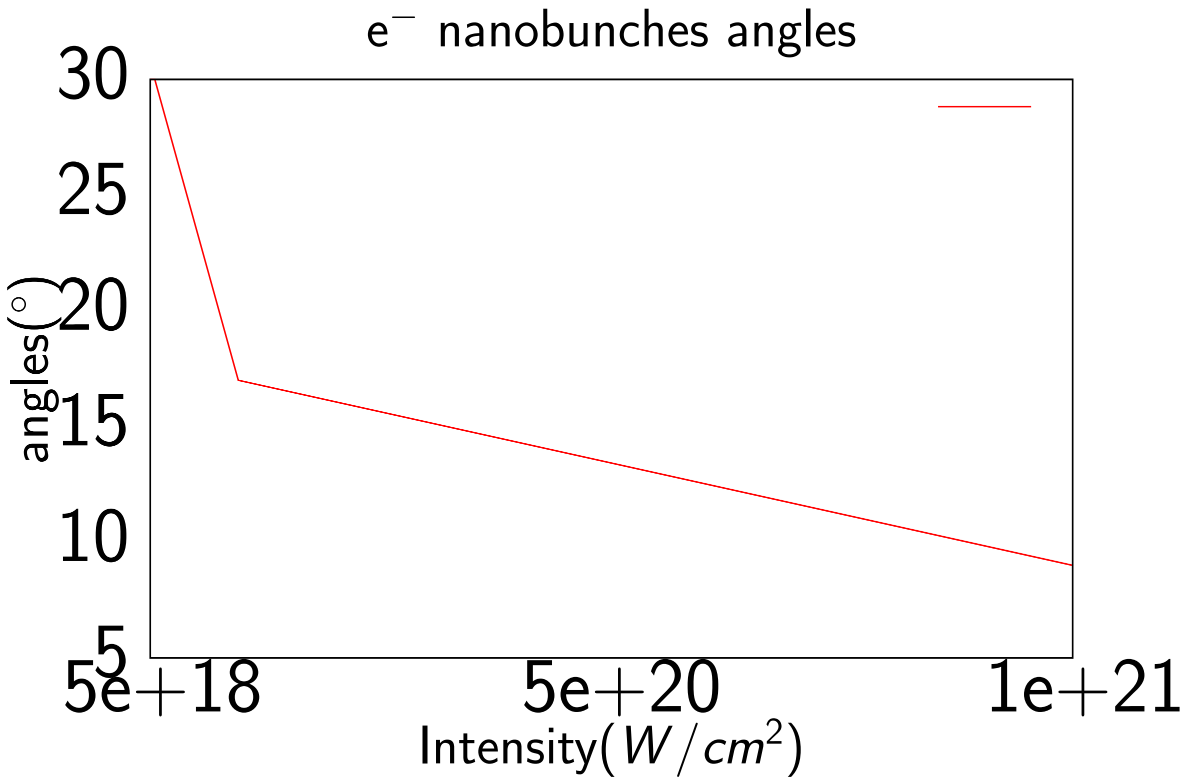


- movie 1: $I = 10^{19} W/cm^2$
- movie 2: $I = 10^{21} W/cm^2$



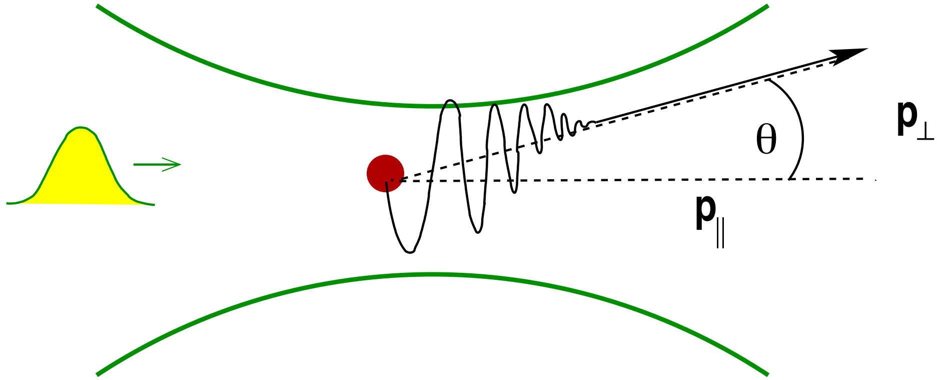


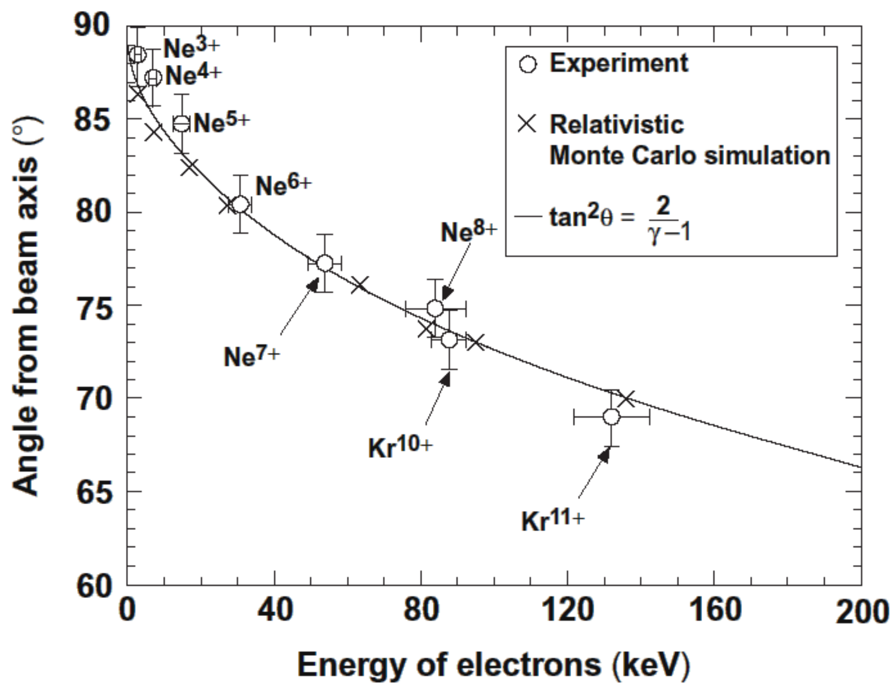
Angular emission of electron bunches (II)



Angle transformation is found by simulations, showing lowering of inclination with increasing intensity.

Usual explanation with vacuum formula for electron emission angles is not working here.





Mie theory foresees no dependance on intensity of the distribution of the scattered electric field. Hypothesis: electron bunches are deviated in vacuum, while escaping from the rear side of the cluster. The component of the velocity that is perpendicular to the surface decreases due to the overcoming of the Coulomb barrier (Andreev,Platonov, Optics and Spectroscopy,2013)

Overcoming condition: $N_{bm}\epsilon_e > e^2 N_{bm}^2 / d_m$.

After the escape $p_y' \approx p_y - e^2 N_{bm}/c d_m$.

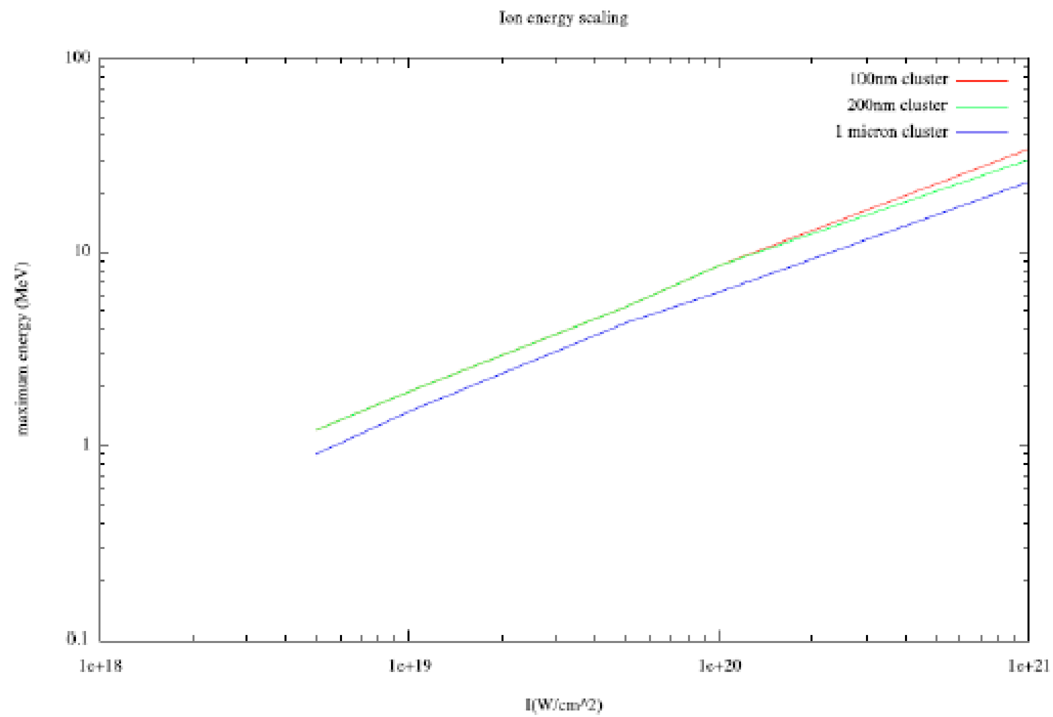
N_{bm} = number of e^- in the bunch

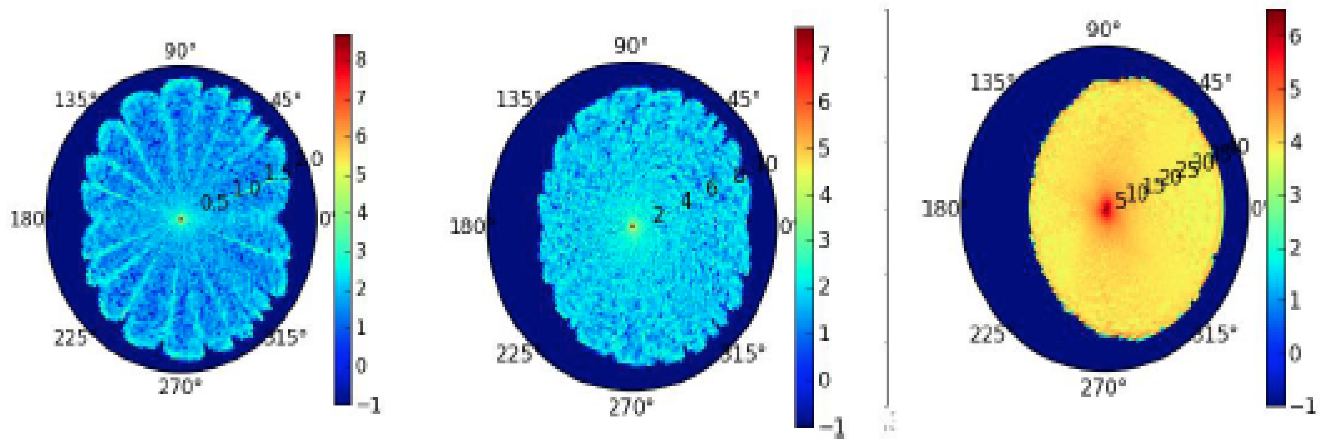
d_m = thickness of the bunch

ϵ_e = threshold energy

Ion energies and polar energy density plots

Ion energies





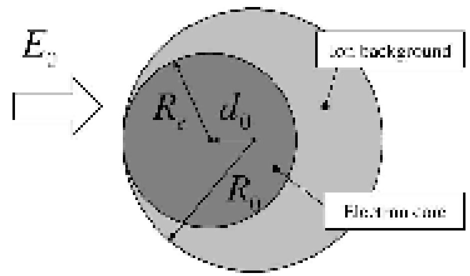
Reference model: equilibrium configuration of a spherical electron cloud confined within a spherical cluster in the presence of a static electric field E_0 , with medium cluster approximation $d_0 < R_0 < \xi$ (Breizman et al., Physics of plasmas,2005).

$$d_0 \equiv 3\frac{|e|E_0}{m_e\omega_{p0}^2} \qquad \text{offset of the electron core,} \tag{1a}$$

$$\xi \equiv \frac{|e|E_0}{m_e\omega^2} \qquad \text{characteristic excursion of e,} \tag{1b}$$

$$\tau_i \approx \sqrt{\frac{m_i R_0}{|e|E_0}} \qquad \text{duration of ion explosion,} \tag{1c}$$

When $\tau << \tau_i$ the short pulse approximation is valid.

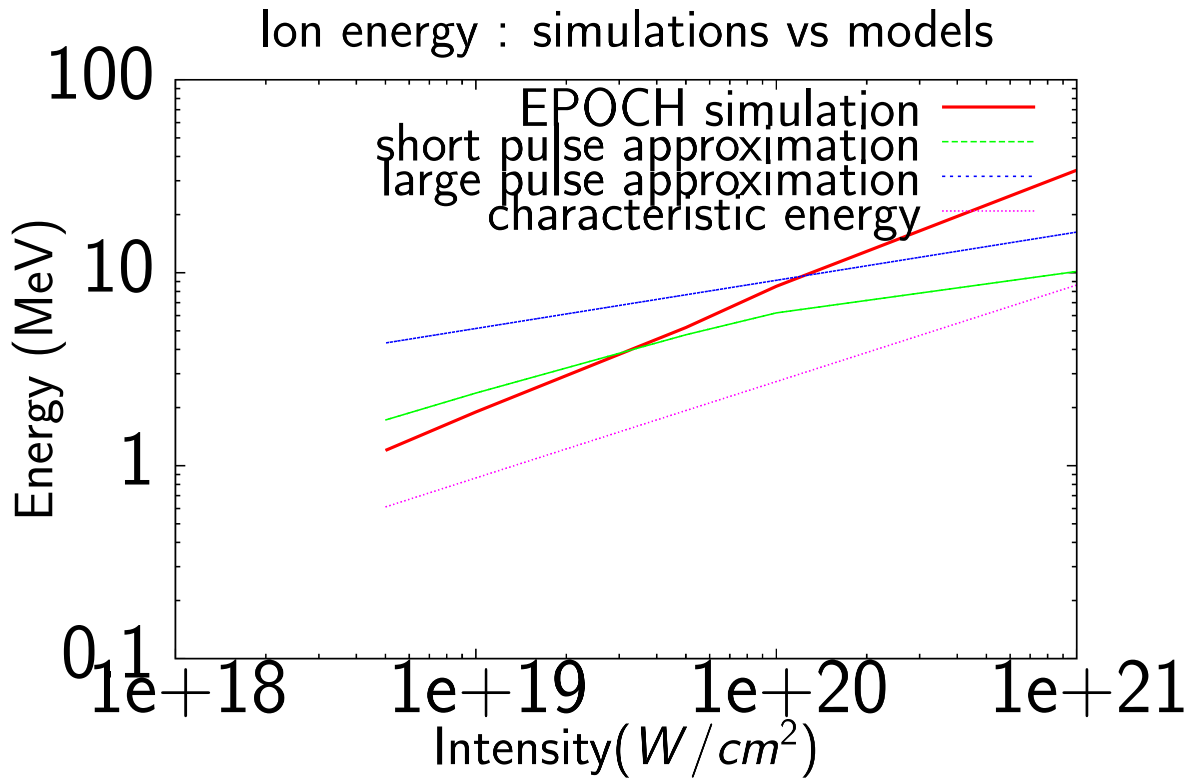


GOAL : establishing possible effects due to laser pulse ultrashort duration

Available models:

- $\epsilon_i = \frac{m_i \omega_{pi}^2 [r_0^3 - (R_0 - d0)^3]}{3 r_0}$,
  short laser pulse approximation;
- $\epsilon_{char} \approx |e| E_0 R_0$,
  characteristic energy;
- $\epsilon_i \approx |e| E_0 R_0 \sqrt{\frac{R_0 m_e \omega_{p0}^2}{|e| E_0}}$,
  long laser pulse approximation;
- $E_{max} = 4\pi Z^2 e^2 n R^2 / 3 \approx 300 Z^2 \left(\frac{n}{5 \times 10^{22}} \right) \times \left(\frac{R}{1 \mu m} \right) \mathrm{MeV} \approx 10 MeV$,
  Coulomb explosion energy.

All models underestimate the ion energy scaling . The short and laser pulse approximation are only valid for some points of the curve.



Conclusions

- Angular emission of electron bunches at relativistic intensities deviates from Mie prediction towards the laser axis.
- outcoming electron bunches are directed at certain angles according to Mie theory, divergences are observed for the highest intensities in the angular energy distribution
- ion energies exceed the expected ponderomotive energy both in the nonlinear and in the Coulomb explosion regime

Further work:

- reconstruct the mechanism which is responsible for the deviation for Mie angle in angular kinetic energy distribution
- investigate quantitative dependance on laser intensity of ion energies