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Ion acceleration by intense few-cycle laser pulses interacting with nanodroplets

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Laser ion acceleration: the MeV regime

- **MeV protons from gold foils with PW-class laser**

(Wilks et al. , Snavely et al., Clarks et al., 2001)

- **Experiments at MBI Berlin with 20 μm droplets and 35 fs laser pulses**

(S.Ter-Avetisyan et al., 2004)

- **mass-limited targets**

(Henig et al. , 2009)

- **radiation pressure acceleration**

(Robinson et al., 2008)

- **light sail, Break-Out Afterburner (BOA)**

(Qiao et al., 2010)

- **proton energies up to 50 MeV and more than 60 MeV**

(Y.Fukuda,I.Pomerantz, 2013)

- **proton energies up to 80 MeV with a 30 fs PW CP laser**

(T.M.Jeong, 2015)

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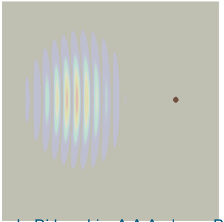
Our investigation (*L. Di Lucchio, A.A. Andreev, P.Gibbon, Phys. Plasmas 22, 053114, 2015*):

- **Single spherical nanotargets,** $n = 100n_c(n_c = 1.8 \times 10^{21} cm^{-3})$
- **droplet size =** $100nm \div 1\mu m$
- **focus size = 1 micron**
- **5 fs pulse,** $I = 1 \times 10^{19} \div 1 \times 10^{21}$ **W/cm^2, compared with 40 fs pulse**
- **Focus on small droplet case (with respect to λ = 800 nm)**

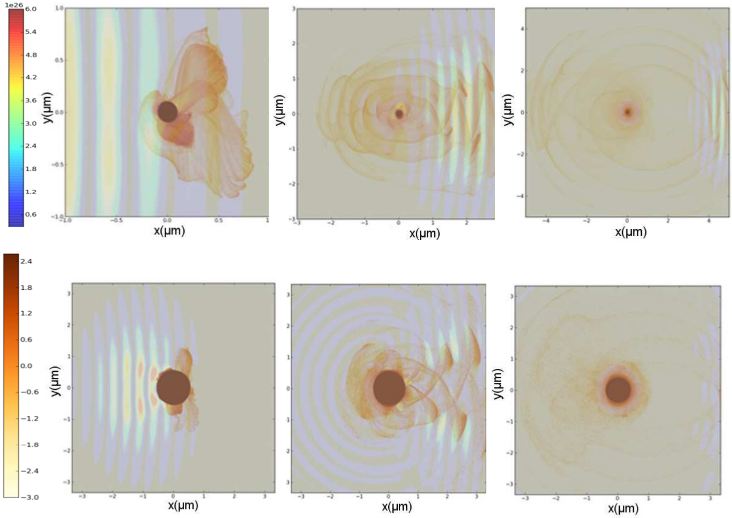


Simulation details:

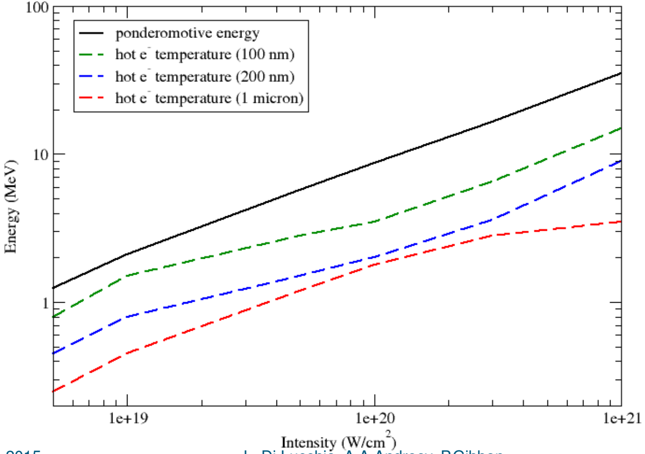
- **EPOCH particle-in-cell code**
- 34×10^6 **particles,** $4 \div 20$ **micron transverse box side, up to** 4600×4600 **cells**
- $\approx 80 \div 800$ **processors on Juropa,** $128 \div 1024$ **processors on Juqueen**
- **final simulation time : 250 fs after the start of the interaction with the laser (up to 24 CPUh)**

typical 3D simulation : maximum 8x12x12 micron size box, up to 600^3 cells, duration=20fs (L. Di Lucchio, P. Gibbon, PRSTAB 18, 023402, 02/ 2015)

Energy density for a 100nm and a 1 micron droplet



Hot electron temperature vs. ponderomotive formula



Coulomb explosion

- **Condition for electrons expulsion (Sakabe et al., 2004)**

$$a > \left(\frac{8\pi Ze^2 n}{3mc^2}\right)^{1/2} \equiv 34\left(\frac{Zn}{5\times 10^{22} cm^{-3}}\right)^{1/2} \qquad (1)$$

- **Explosion time (J.Zweiback, 2002)** $\tau_{Coul} \approx 0.8\sqrt{\frac{4\pi\epsilon_0 m_p}{n_p e^2}}$

Thermal expansion

- **ponderomotive energy** $\epsilon_h \approx m_e c^2(\gamma_L - 1), \gamma_L = \sqrt{(1 + a_0^2)}$
- **hydrodynamical equations with cylindrical symmetry**

$$\epsilon_{im} \approx Z\epsilon_{eh} ln^2(c_s t_{ef})/r_{dh}) + \sqrt{(((c_s t_{ef})/r_{dh}))^2 + 1)} \qquad (2)$$

$$r_{dh} \approx \left(\epsilon_{eh}/4\pi e^2 n_{eh}^{1/2}\right), t_{ef} \approx t_L \qquad (3)$$

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A possible fit for the intermediate regime: Murakami and Basko, Phys. of Plasmas 13, 012105 (2006) (I)

- **characteristic dimensionless parameter**

$$\Lambda = \frac{R}{\lambda_D} = R_0 \left(\frac{4\pi e^2 n_{e0}}{T_e 0} \right)^{1/2} \tag{4}$$

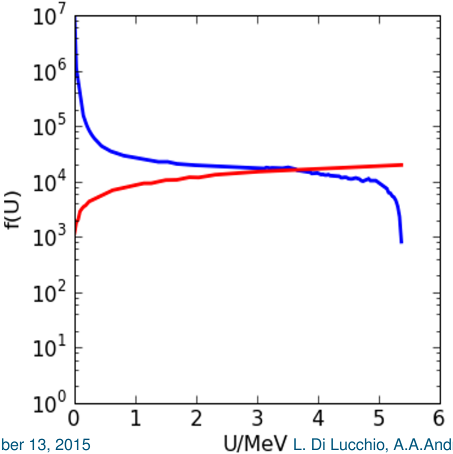
- **maximum ion energy for** $\Lambda >> 1$ **and** $Zm_e/m_i << 1$

$$E_{i,max} = \epsilon_{i0}\xi_f^2, \xi_f^2 = W(0.5\Lambda^2) \tag{5}$$

- **bulk ion energy (spherical case)**

$$\epsilon_{i0} = 2ZT \tag{6}$$

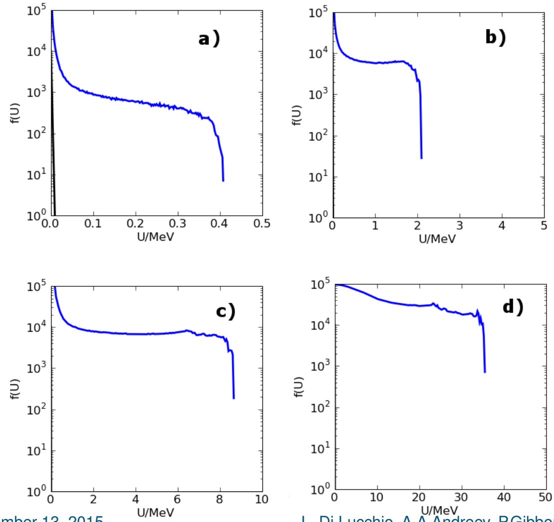
A possible fit for the intermediate regime: Murakami and Basko, Phys. of Plasmas 13, 012105 (2006) (II)



R=100 nm, I =10^{20} W/cm^2

$\Lambda = 0.95, E_{i,max} = 2.24$ MeV

Ion energy spectrum for a 100 nm droplet, t=200 fs



$\tau_L = 5fs$

a) I=10^{18} W/cm^2

b) I=10^{19} W/cm^2

c) I=10^{20} W/cm^2

d) I=10^{21} W/cm^2

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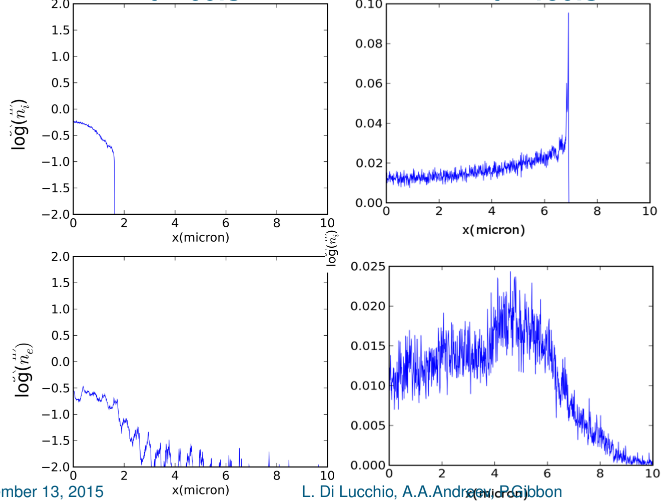
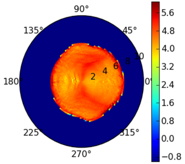
Shock formation (100 nm droplet, 40 fs pulse)

t = 60fs **t = 150fs** **I =10^{20} W/cm^2**

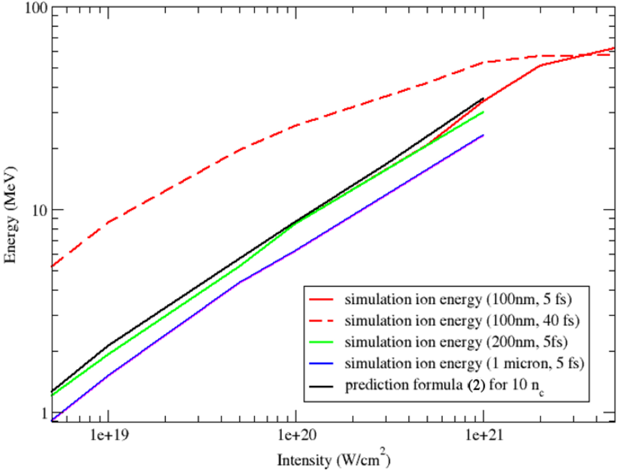


Polar energy



5 fs vs 40 fs laser pulse (t=200 fs)

τ_L = 5fs, $E_{max} \sim I^{2/3}$ τ_L = 40fs, $E_{max} \sim I^{1/2}$



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Conclusions

- Angular emission of electron bunches at relativistic intensities deviates from Mie prediction following an intensity dependant behaviour as described in *L. Di Lucchio , P. Gibbon, PRSTAB 18, 023402, 02/ 2015*
- As soon as the bunches leave the droplet, an electron cloud is formed around the ion core
- Ion expansion follows an intermediate regime between hydrodynamical expansion and Coulomb explosion
- maximum ion energies achievable with a 2-cycle laser pulse behave $\sim I^{2/3}$
- Maximum attainable ion energies are of the order of a few MeV (*L. Di Lucchio, A.A. Andreev, P.Gibbon, Phys. Plasmas 22, 053114, 2015*)