Fast ions generation from nanostructure target irradiated by high intensity short laser pulse

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Outline

- **Motivation**
- **Ion acceleration from Structured Targets**
- **Effective ion acceleration in nano-foils at ultra-high laser intensity**
- **Nano-structure targets and ion acceleration at high laser intensity**
- **Conclusion**

Beam Characteristics and Problems of Laser Based Ion Accelerator

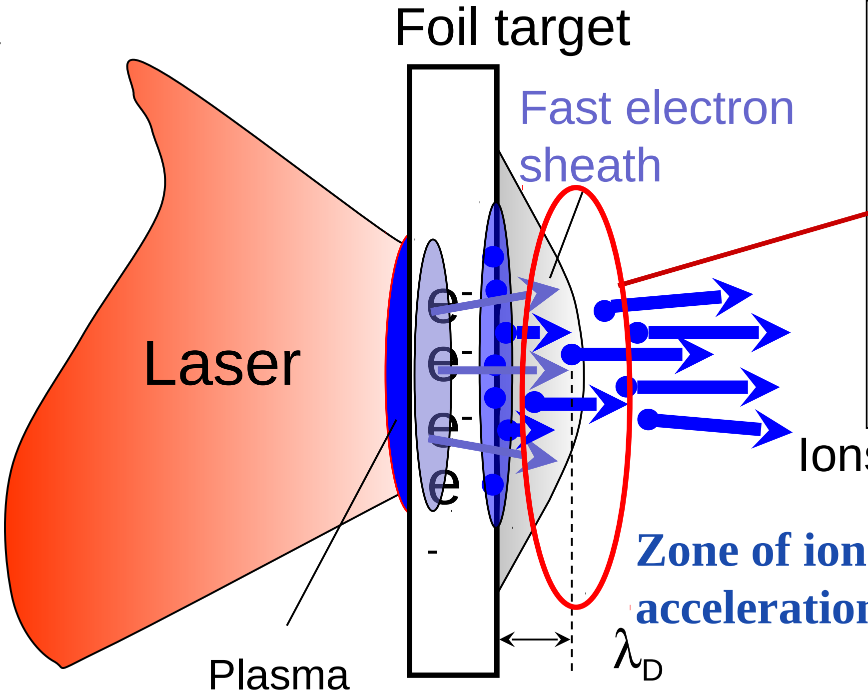
- **Transverse emittance**: $\leq 10^{-3}\pi \times mm \times mrad$
- **Longitudinal emittance**: $\leq 10^{-6} eV \times s$
- **Maximal energy**: $:\ 100 MeV$
- **Energy spread**: $< 100\%$
- **Bunch charge**: $\leq 10^{12}\ ions$
- **Source diameter**: $\leq 10 \mu m$
- **Ion current**: $\leq 10 kA$
- **Rep-rate**: *determined by laser*
- **Laser-ion efficiency**: $< 10\%$
- **Transverse divergence**: $\leq 30°$

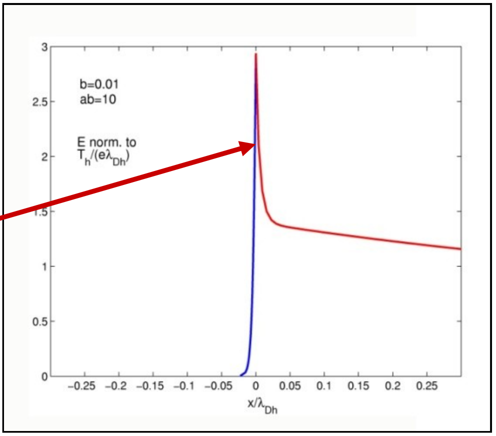
Ion beam quality

--- transverse divergence

--- energy spectrum control

Physics of laser based ion acceleration from standard (foil) target



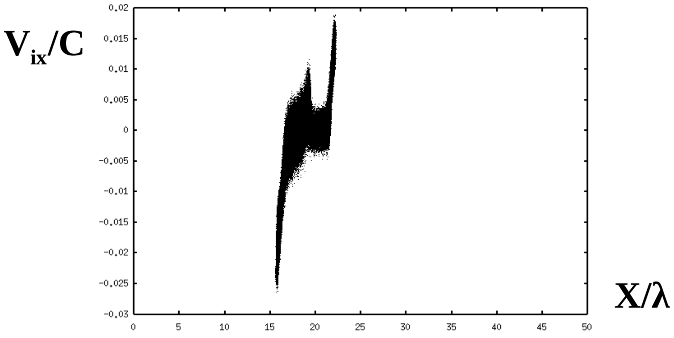


Electric field

$$E_a = T_e / e\,\lambda_D$$

$$\lambda_D = \left(\frac{T_e}{4\pi e^2 n_e}\right)^{1/2}$$

$$\eta_a\,\varepsilon_L = N_e\,T_e$$



$$\varepsilon_i \propto E_a = (4\pi T_e n_e)^{1/2}$$

laser parameter

- fast electron generation on front surface (T_e ~ MeV)
- its propagation through target
- wide sheath formation at rear side (λ_D ~ µm) and electric field (E_a ~ 10^{12} V/m) generation
- ions acceleration (ε_i ~ MeV) due to this electric field

Low energy efficiency from laser to ion beam

Ion beam quality --- energy spectrum control

target parameter
motivates investigation
of target concepts
Mass – and size - limitation

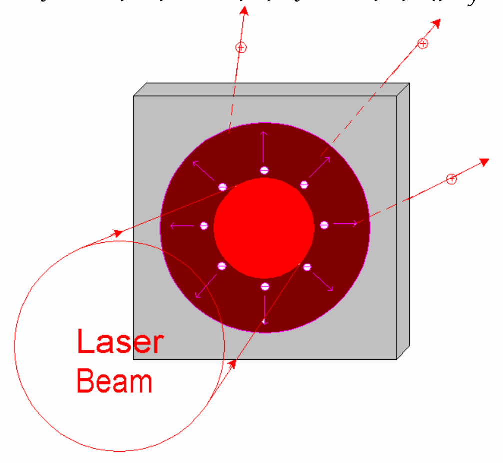
Different target shapes

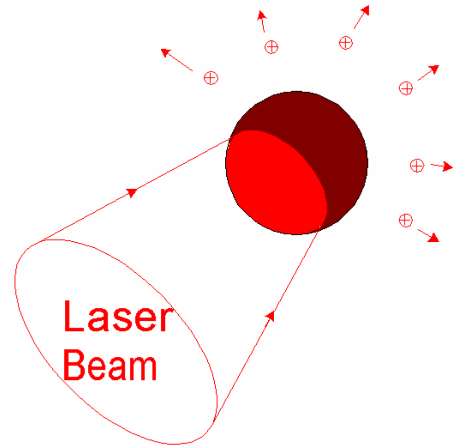
$M_t = m_i N_i = m_i n_i V_t = m_i n_i L_x L_y L_z$

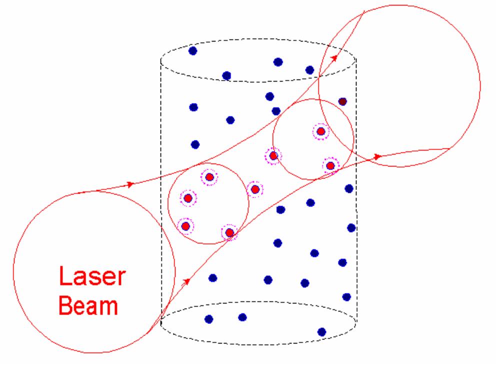
$D_l \approx L_y \approx L_z$

$\varepsilon_i = \eta \varepsilon_l / N_i$

$\eta = \eta_{le} \eta_{ei}$



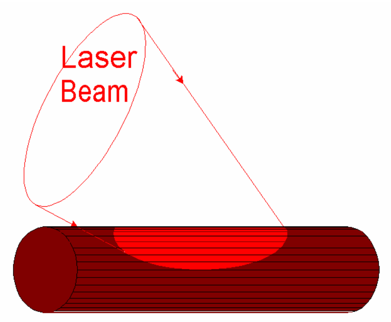


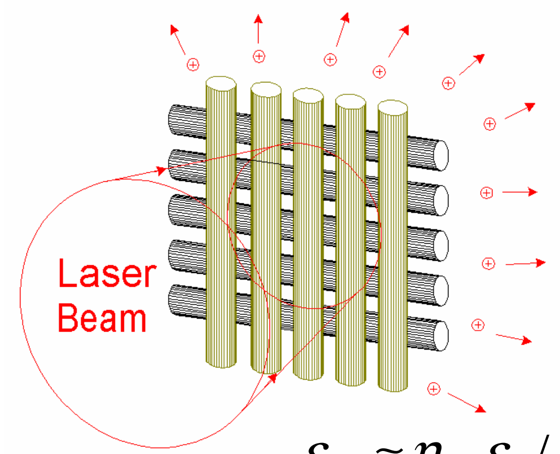


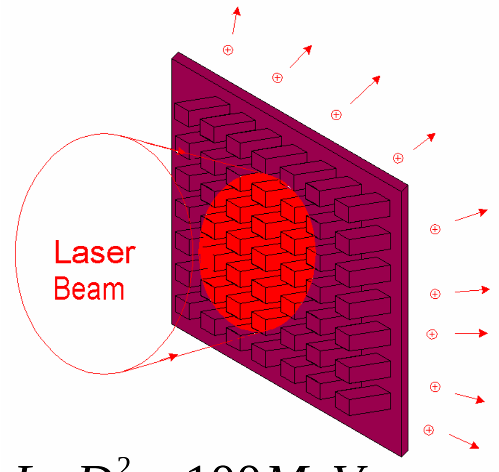
$L_x \approx (\varepsilon_l / \varepsilon_{i\max})(1 / D_l^2 n_i) \approx 5nm$

$\eta_{ei} \approx \varepsilon_i n_i D_l^2 / \eta_{le} \varepsilon_l \approx 0.25$

$n_i L_x = n_{i1} L_{x1} + n_{i2} L_{x2}$



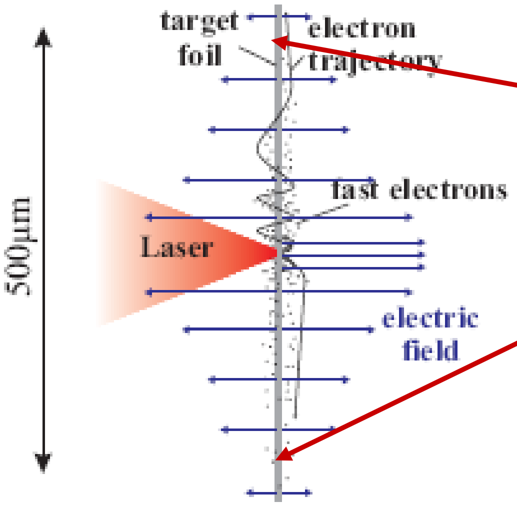




$\varepsilon_{im} \approx \eta_{abs} \varepsilon_l / n_i L_x D_l^2$

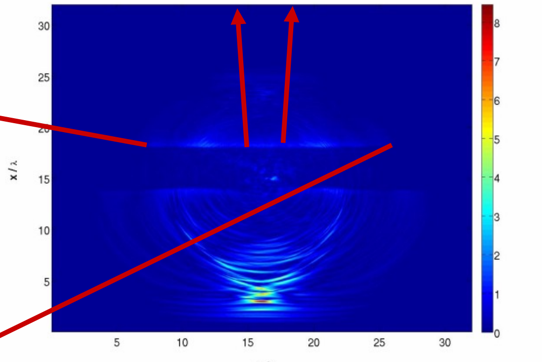
$\varepsilon_{im} \approx \eta_{abs} \varepsilon_l / 2 n_i L_{x2} D_l^2 \approx 100MeV$

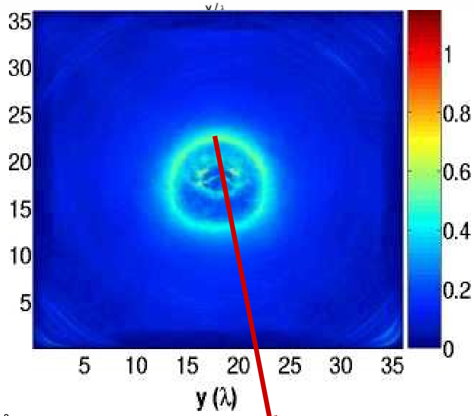
The advantage of MLT

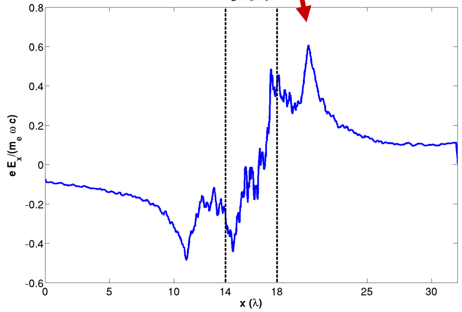


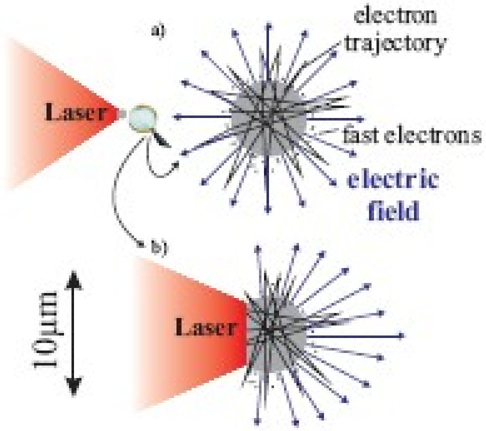
- large spread of electric field
- acceleration restricted to laser pulse duration

Laser beam spot size





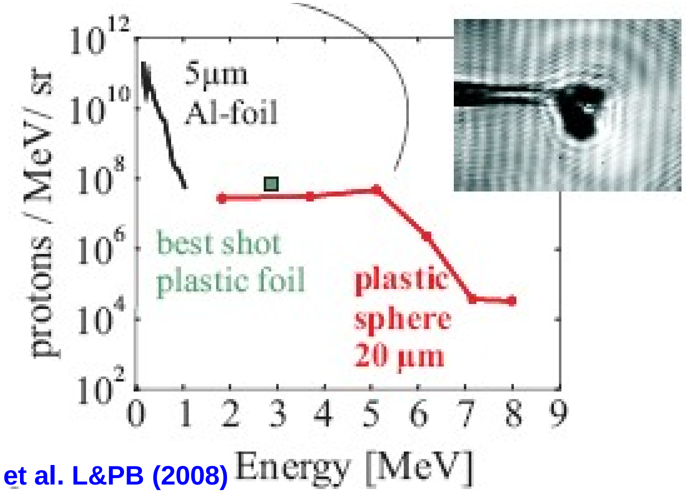


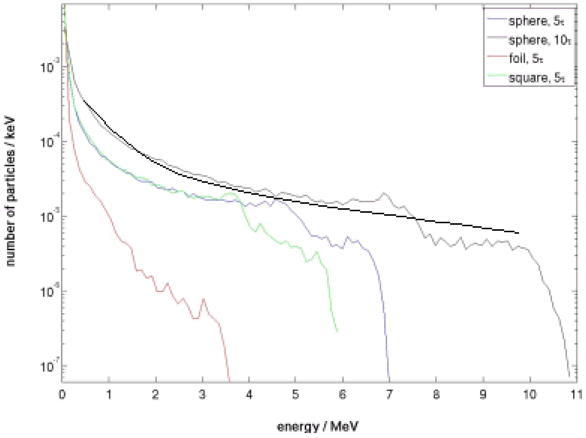


- field is higher and sustained over a longer time due to macroscopically bound hot electrons

Experimental Results

MPQ





a_0 = 10, duration 5T and 10T, beam width 4 λ, plasma size 4 λ

J.Limpouch, A.Andreev et al. L&PB (2008)

Droplet chain target simulation model

PRL 98, 045001 (2007)

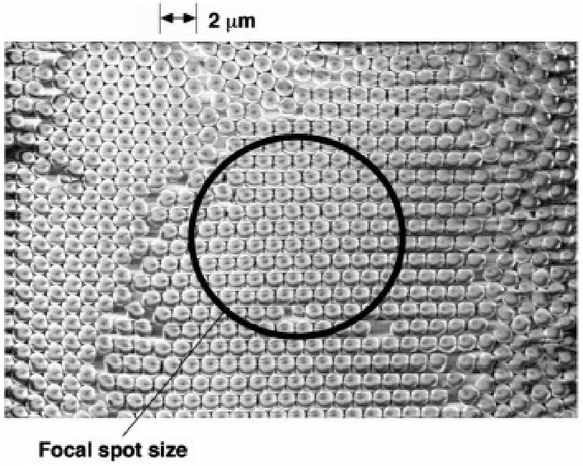
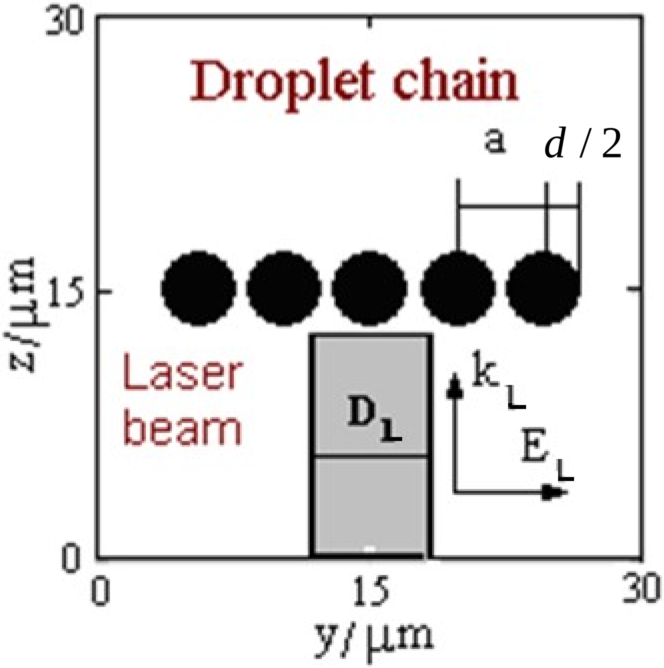
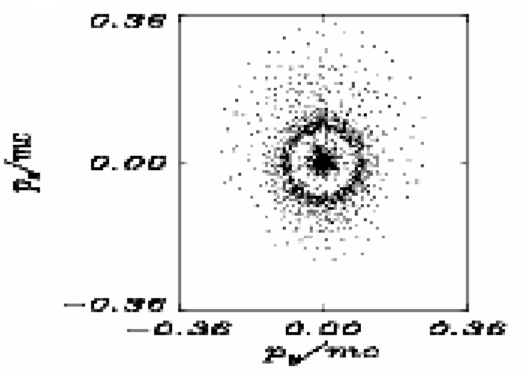


FIG. 1. Scanning electron microscope image of 1 μm diameter polystyrene spheres arrayed on a Cu substrate. The apparent dimples on the spheres are an artifact of the SEM measurement.

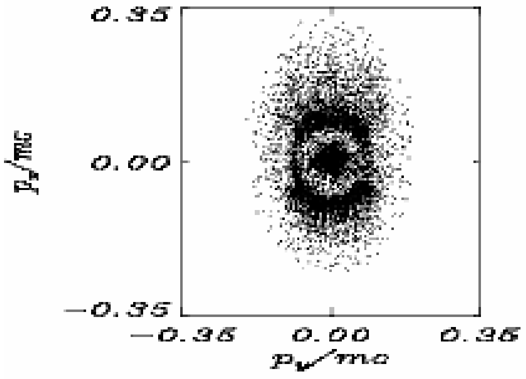
**A.Andreev et al.
L&PB (2009)**

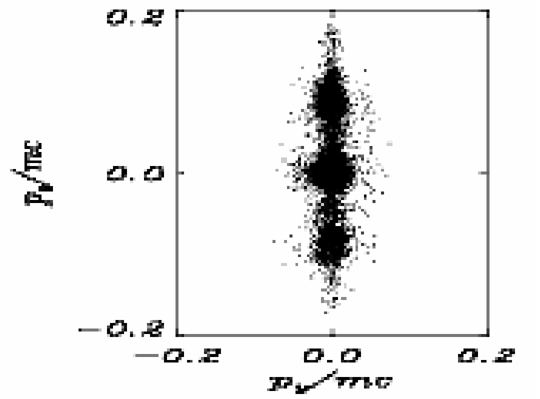


One H droplet



Droplet chain

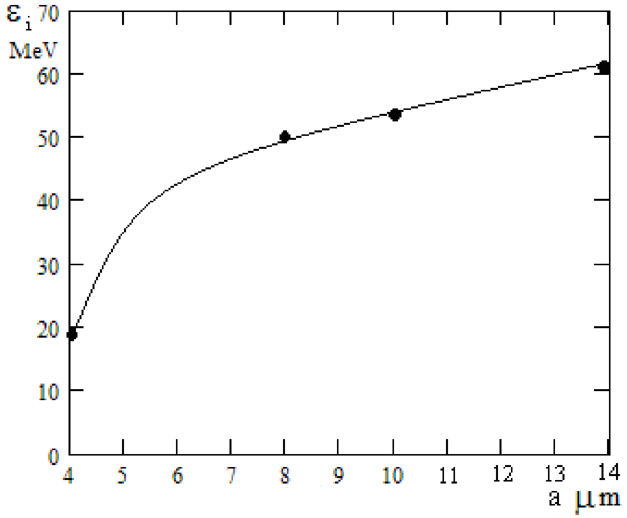




Ion momentum space

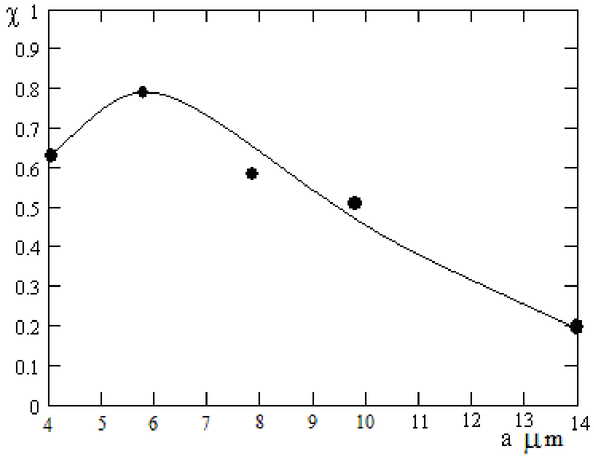
$$d = 4\mu m,\ I_L = 10^{20} W / cm^2,\ t_L = 133\, fs$$

Angular efficiency for high intensity laser pulse droplet chain interaction

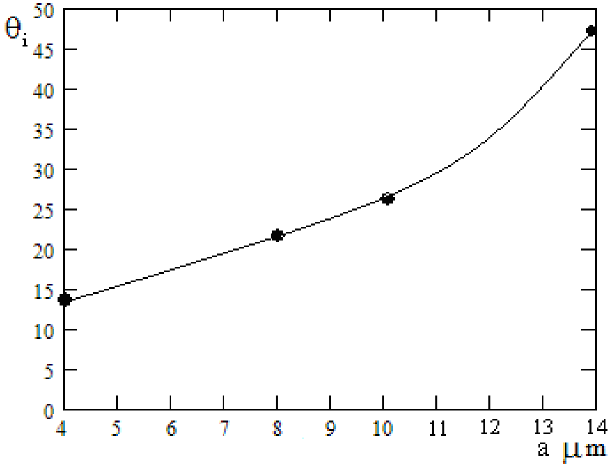


Dependence of maximal proton energy on a - the distance between H droplet centers

$$\chi = \frac{\int_{0}^{10^0} \varepsilon_i (dN_i / d\theta) d\theta}{\int_{0}^{90^0} \varepsilon_i (dN_i / d\theta) d\theta}$$



Efficiency of ion acceleration in the angle 10 degrees as a function of distance between droplet centers



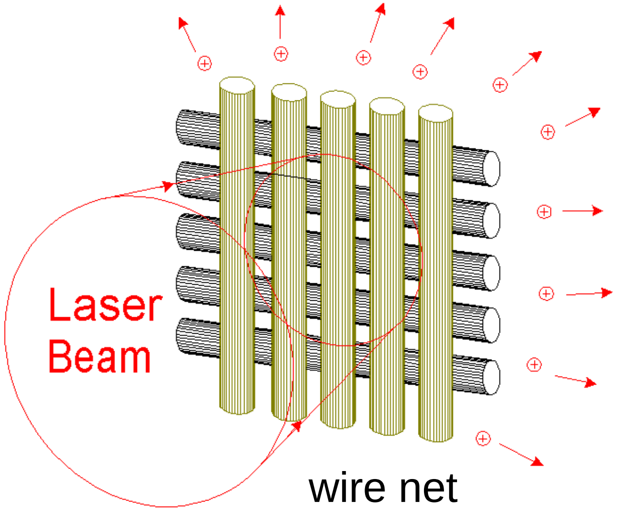
Dependence of average angle of proton trajectory on the distance between droplet centers

$$I_L = 10^{20} W / cm^2$$

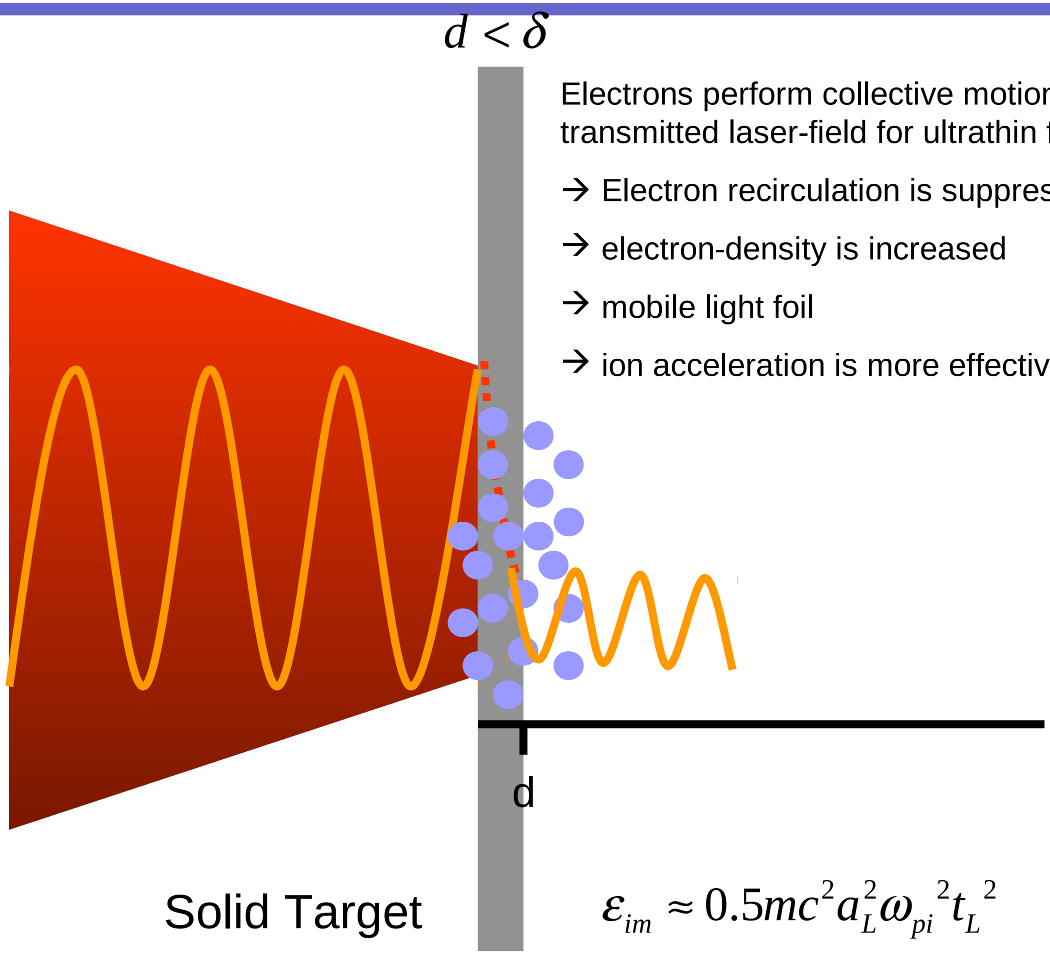
$$t_L = 133\, fs$$

$$d_L = 6 \mu m$$

$$d = 4 \mu m$$



“Radiation Pressure Assisted Ion Acceleration” regime



Electrons perform collective motion in the transmitted laser-field for ultrathin foil

→ Electron recirculation is suppressed

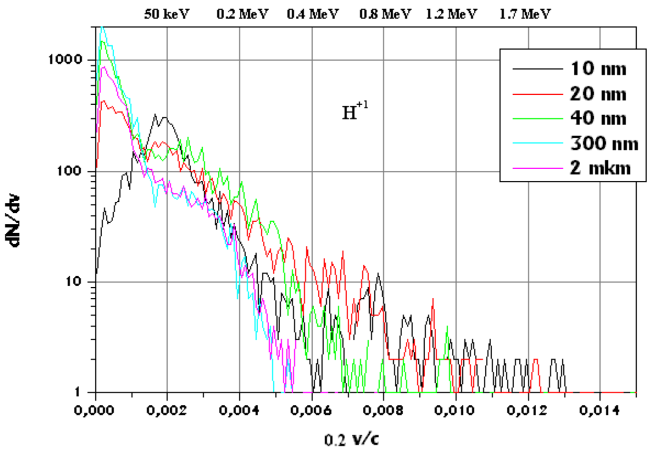
→ electron-density is increased

→ mobile light foil

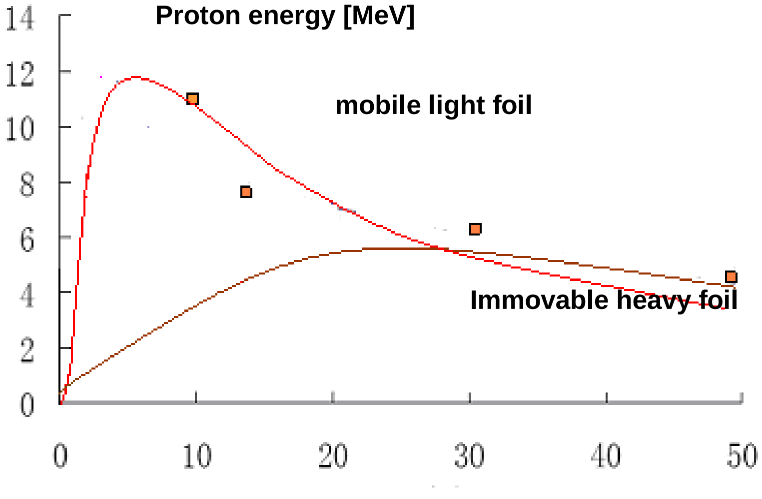
→ ion acceleration is more effective

$$\varepsilon_{im} \approx 0.5mc^2 a_L^2 \omega_{pi}{}^2 t_L{}^2$$

$$d_{opt} \approx 0.3\lambda_L \frac{n_{cr}}{Zn_i} a_L (1+\sqrt{1-\frac{2}{a_L^2}})$$



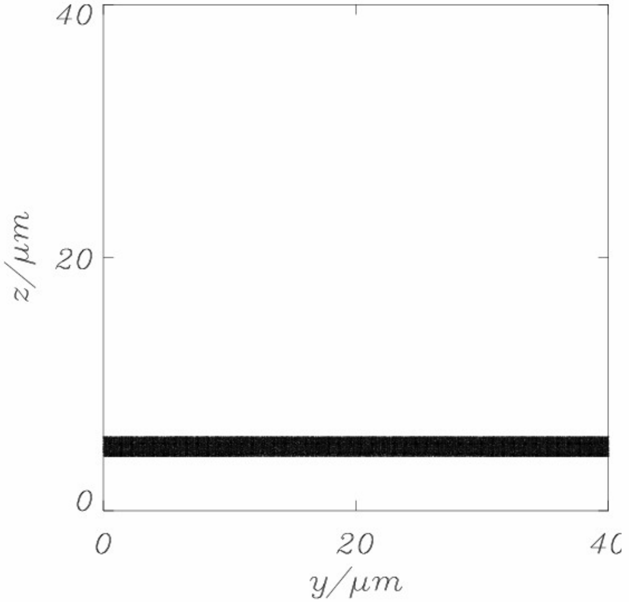
Proton distribution functions at different thickness of Al “rectangle” foil



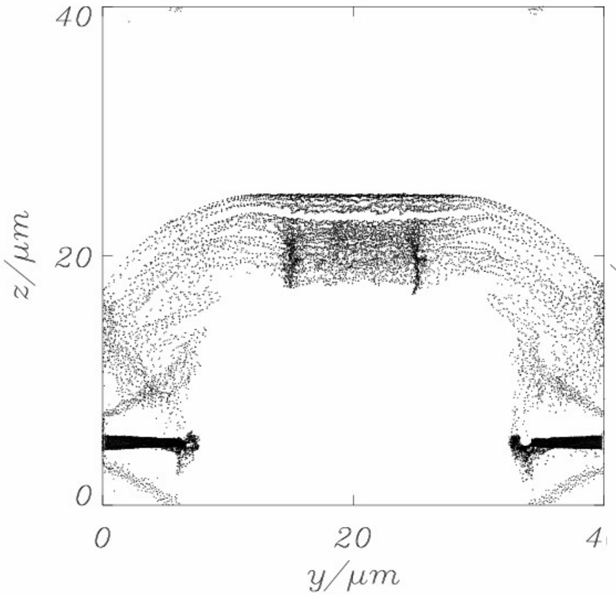
A.Andreev et al., PoP (2010)

Plasma density distributions at different time of laser pulse interaction with over-dense plasma foil target

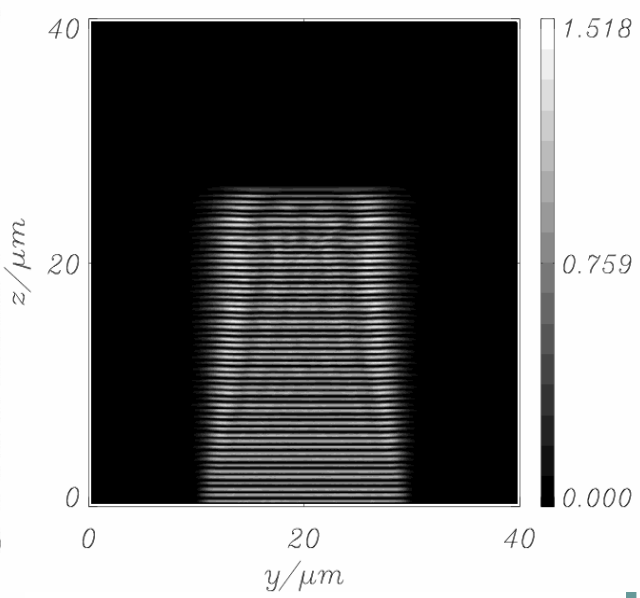
T = 13.3 fs



T = 93.3 fs



T = 93.3 fs



H target of solid density. $I_L = 10^{22} W/cm^2, d_L = 15\mu m, t_L = 40\,fs$

$$E_{0\max} \approx 2\pi e n_e l_f$$

$$I_{th} = cE_{0\max}^{\;2}/4\pi = \pi c e^2 n_e^{\;2} l_f^{\;2}$$

$$l_f > \frac{m_i}{m_e}\frac{\omega}{\omega_{pe}}\frac{c}{\omega_{pe}}$$

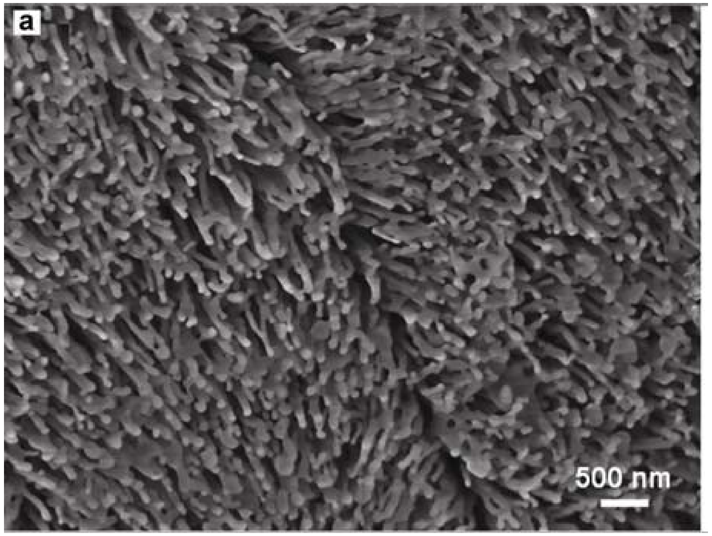
$$I_L < I_{rad} = \left(\frac{3\times10^{25} m^2 c^{3.5}}{2.8\,\pi^{0.5} e^3}\right)^{2/3}$$

$$(1+R)\varepsilon_L / c = N_i p_i = (N_i / c)\sqrt{(\varepsilon_i + m_i c^2)^2 - m_i^{\;2} c^4}$$

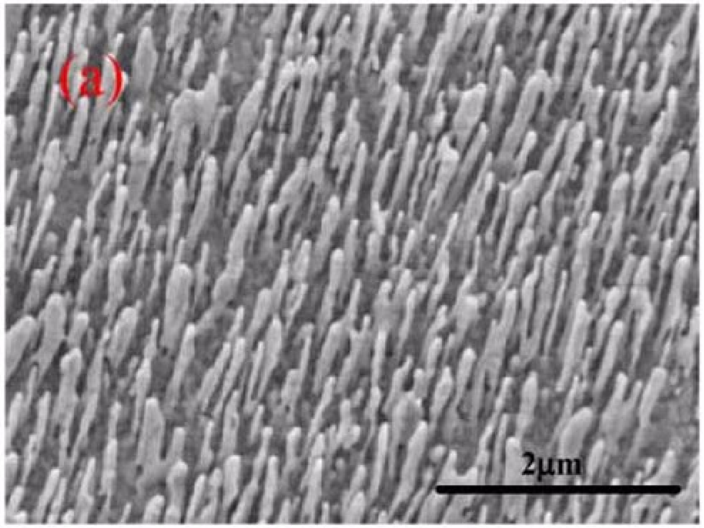
$$(1-R)\varepsilon_L = N_i \varepsilon_i$$

$$\varepsilon_i \approx \frac{\varepsilon_L}{N_i}\,\frac{2\varepsilon_L}{N_i m_i c^2 + 2\varepsilon_L}$$

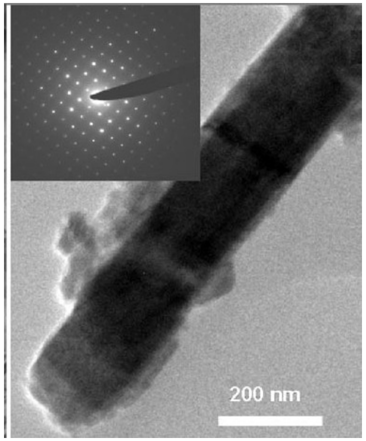
Nanorods and nanotubes



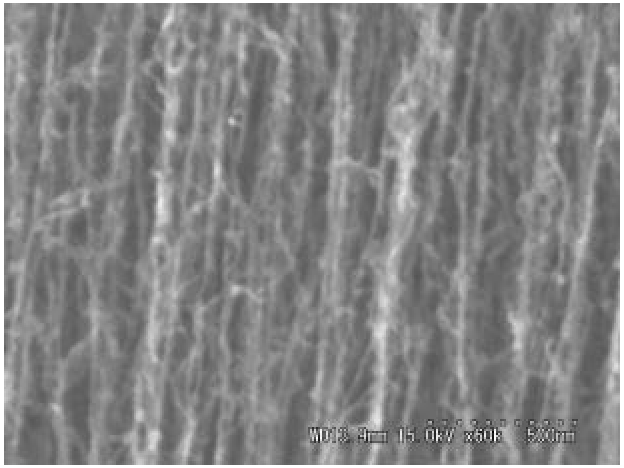
FESEM image of ruby nanorods



FESEM image of gold nanorods



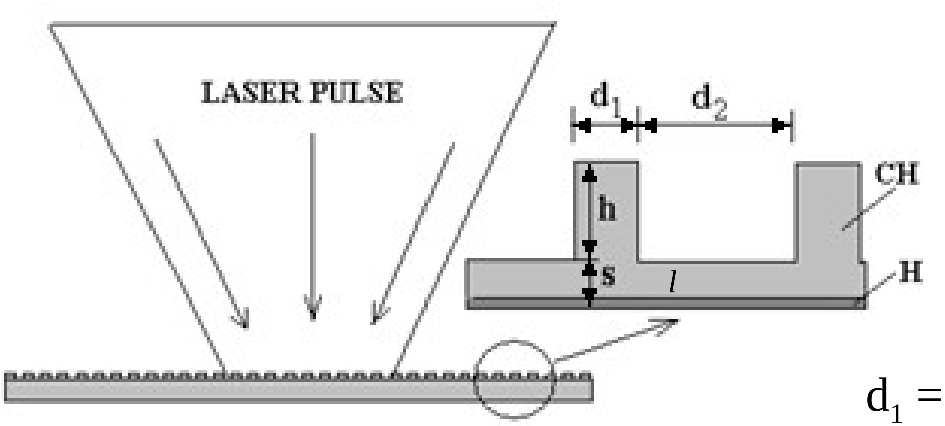
TEM image of a individual MoO3 nanorod

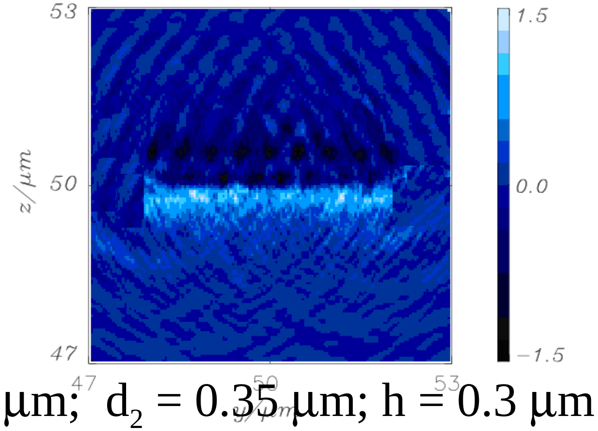


Images of a super long aligned brush-like CNTs

Nano-structure target

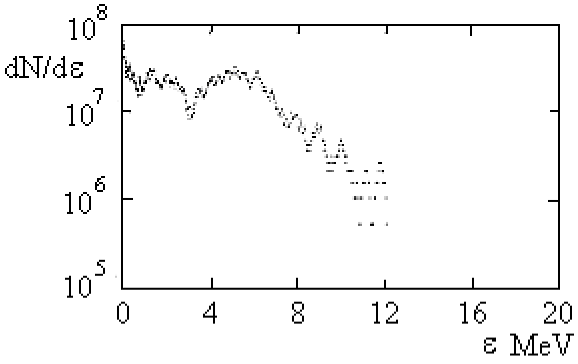
Schematic of the nanostructure target,
Spatial distribution of electric field component normal to the target surface.



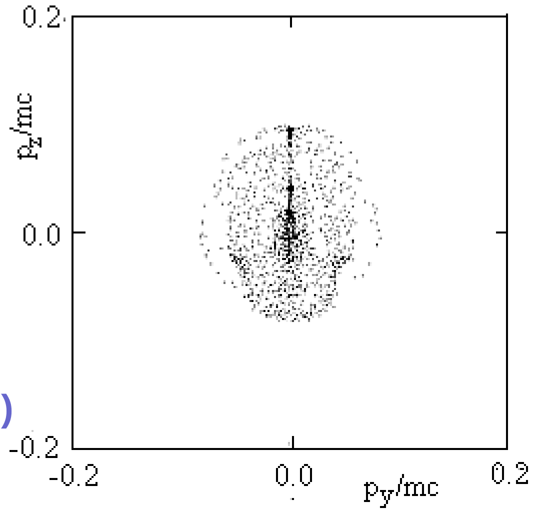


$d_1 = 0.15\ \mu m$; $d_2 = 0.35\ \mu m$; $h = 0.3\ \mu m$

c) Proton distribution function at the end of simulation (600 fs), (d) Phase space of accelerated protons at the same time.

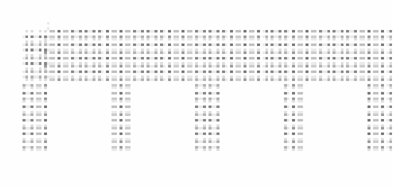


A.Andreev et al. PoP (2011)



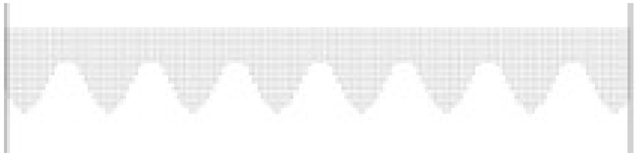
Laser pulse 10^{20}W/cm^2, 15 fs, diameter 3 μm; target C^{+6} H^{+1}, density 0.4g/cm^3, finite 4x4μm

Different shapes of nanostructured target profile



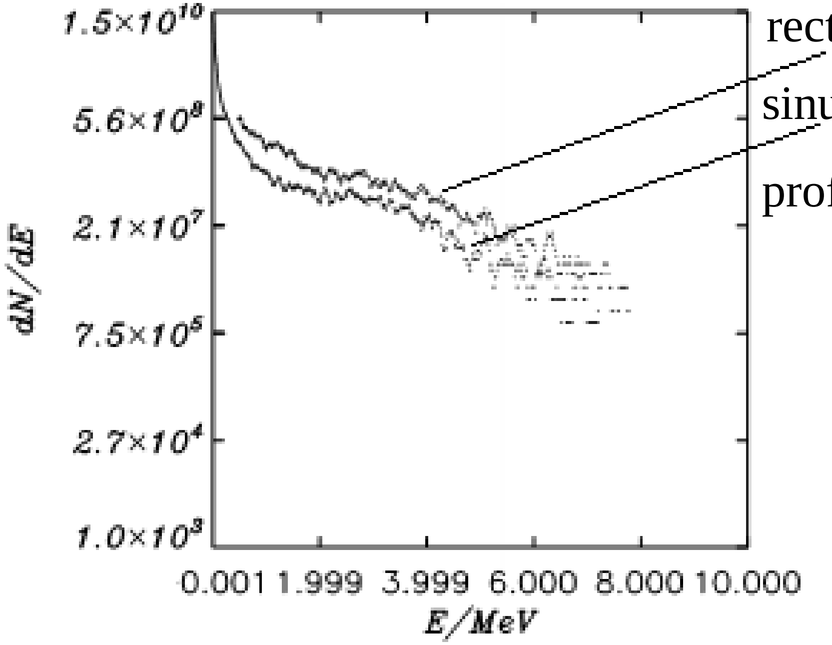
infinite rectangle profile

d_1 = 0.15 μm; d_2 = 0.35 μm; h = 0.4 μm



infinite sinusoidal profile
T=0.8 μm, h=0.5 μm

randomly rough surface

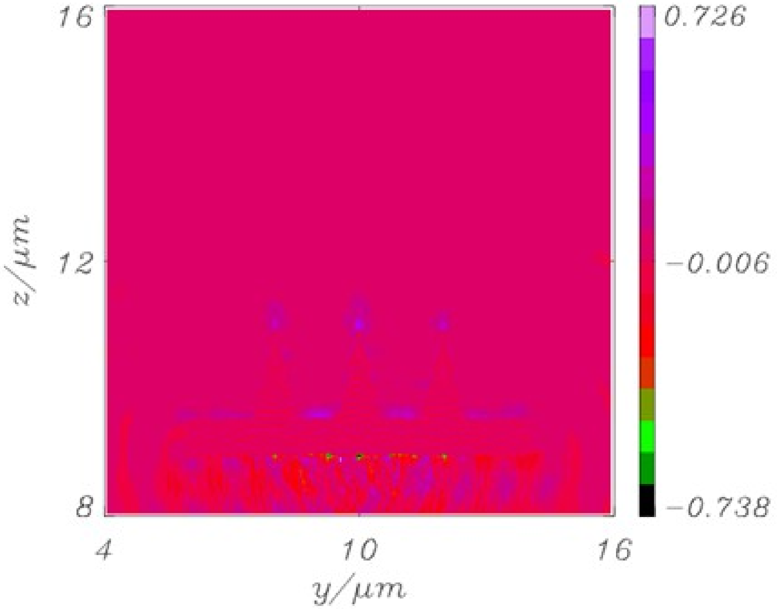


rectangle profile

sinusoidal

profile

protons energy distribution function

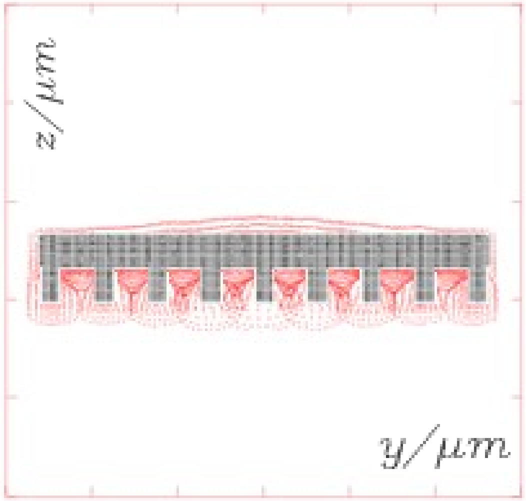


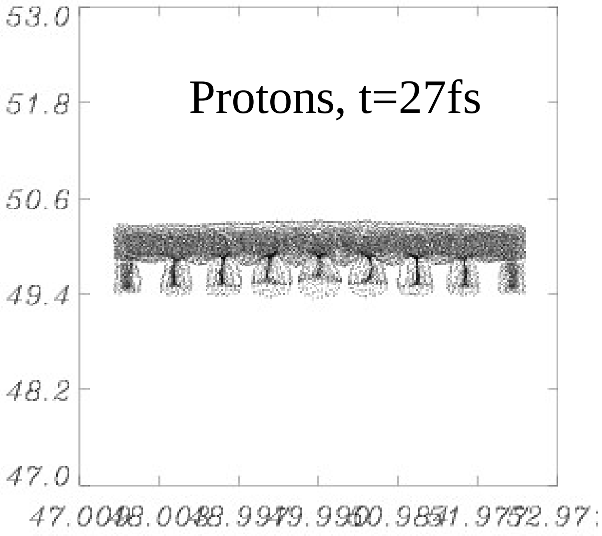
Electric field spatial distribution

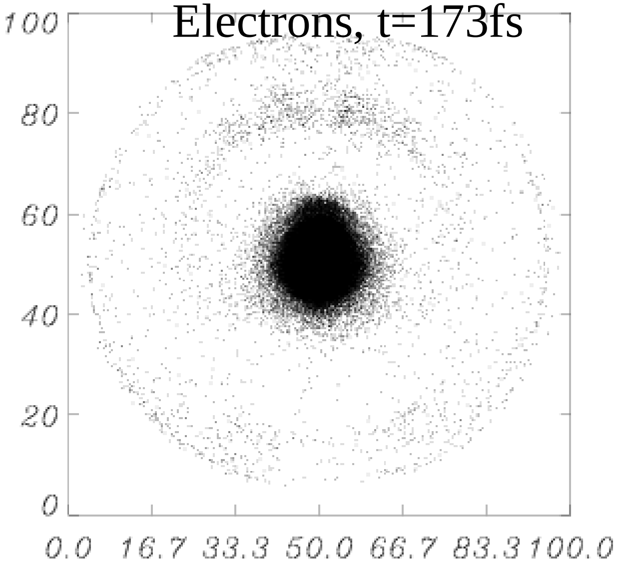
Interaction with MLT C^{+6} H^{+1}

$d_1 = 0.15\ \mu m$; $d_2 = 0.35\ \mu m$; $h = 0.4\ \mu m$ $I_L = 10^{20} W/cm^2, d_L = 4 \mu m, t_L = 66\ fs$

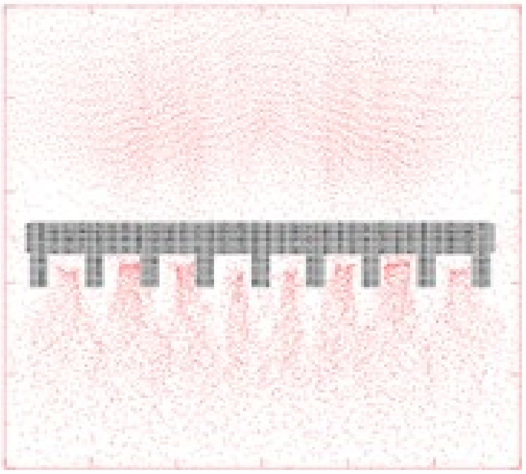
C ions, t=40fs

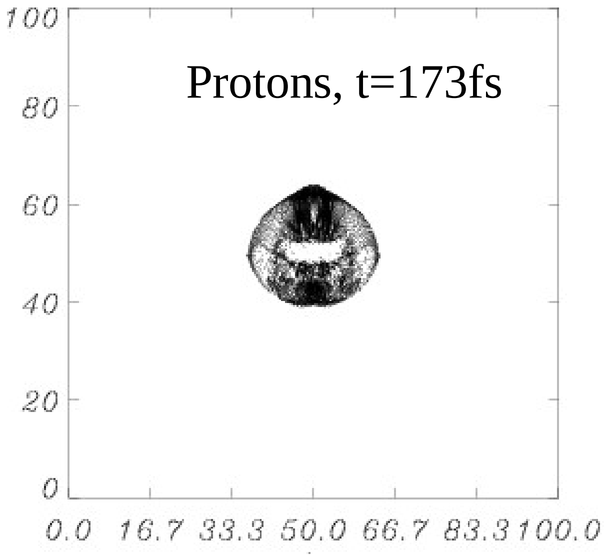


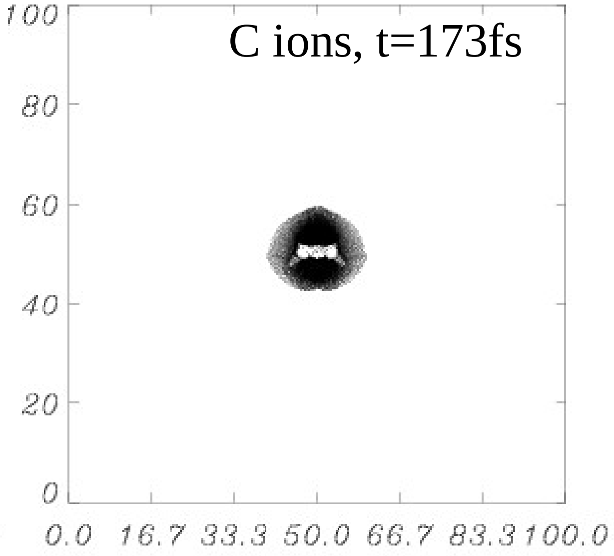

Protons, t=27fs


Electrons, t=173fs

C ions, t=107fs

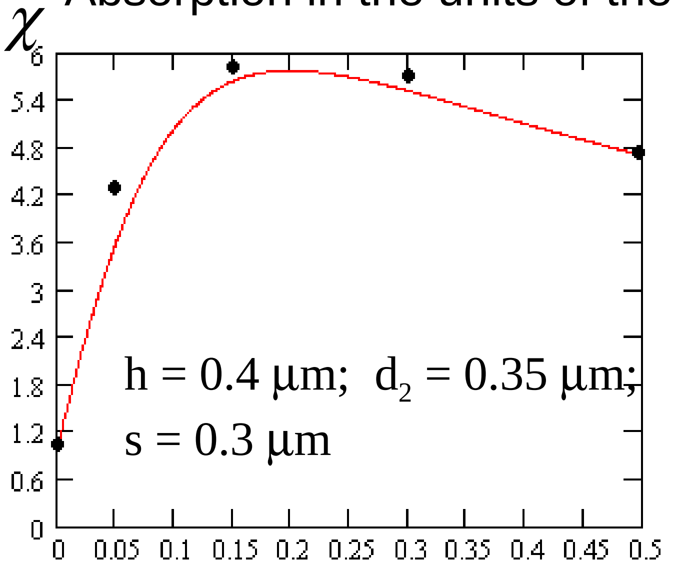



Protons, t=173fs

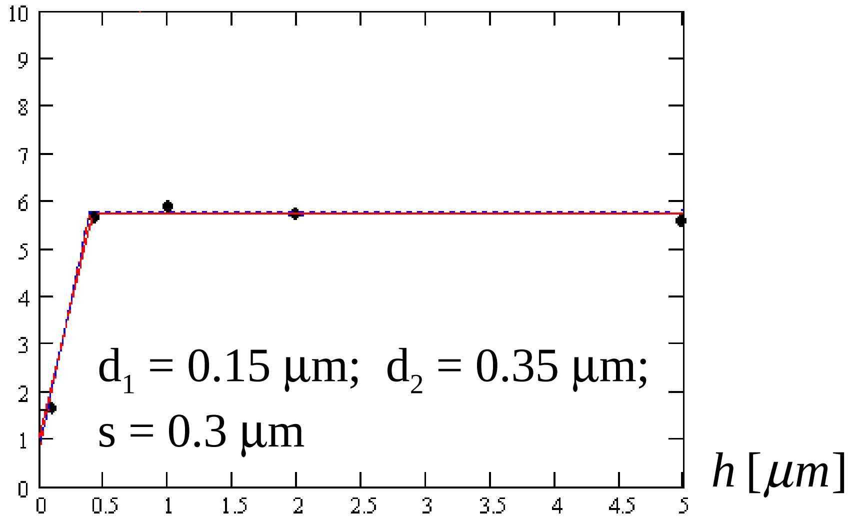

C ions, t=173fs

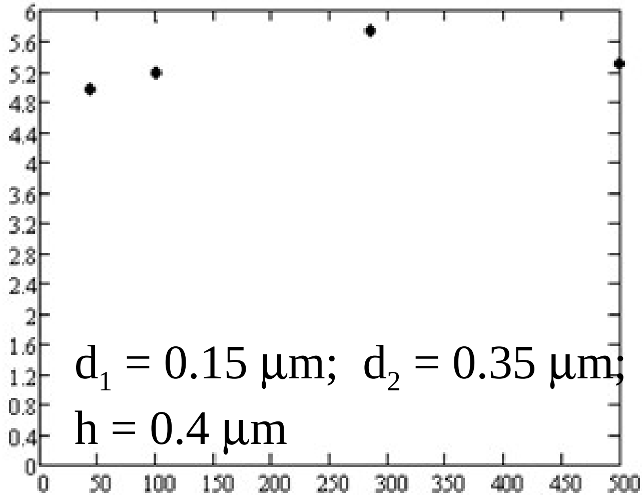
Efficiency of a structure targets

Absorption in the units of the plane 300 nm foil $C^{+6}H^{+1}$ 10^{20} W/cm^2,15 fs, 3 μm



ρ= 0.4 g/cm^3





$$\chi \approx 1 + \frac{(d_1/2l_{extr})}{\sqrt{1+(d_1/2l_{extr})^2}}\left(\frac{hd_L}{e\varepsilon_L}\div\right)\times\frac{1.4d_LE_0}{(d_1+d_2)}\times m_ec^2I_{18}$$

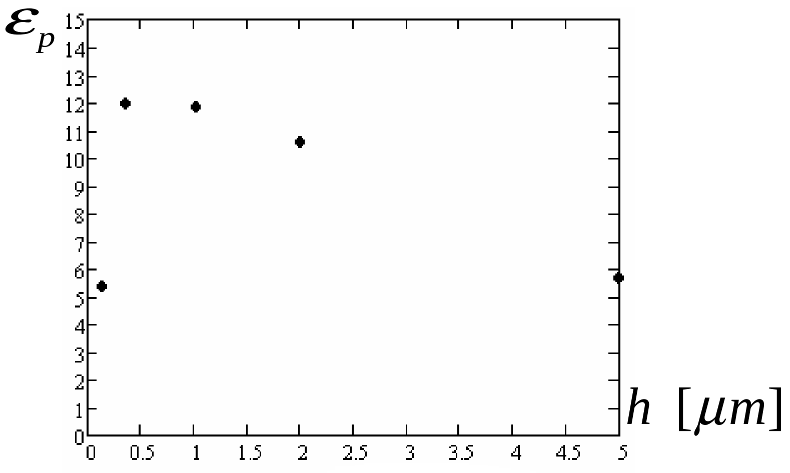
$$\chi < \chi_{\max}$$

$$\chi = \chi_{\max} \qquad \chi > \chi_{\max}$$

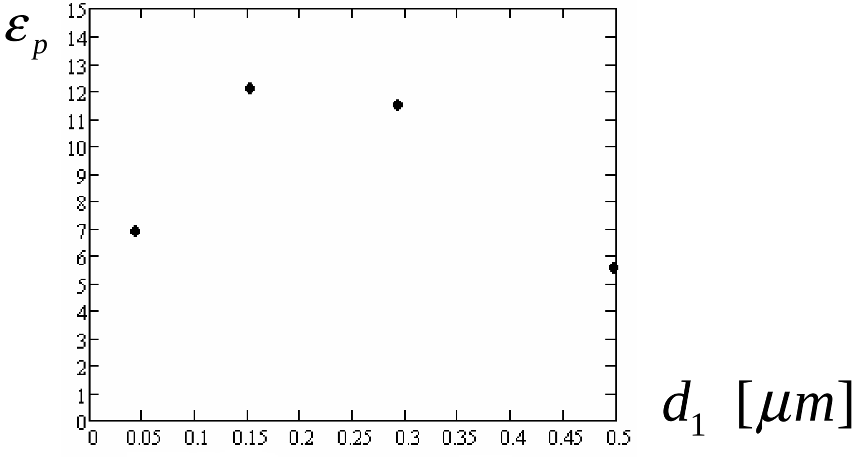
$$\chi\% = \frac{\chi}{1+e^{\frac{\chi-\chi_{\max}}{0.1}}} + \frac{\chi_{\max}}{1+e^{\frac{\chi_{\max}-\chi}{0.1}}}$$

Dependence of maximum proton energy on regular nano-structure target parameters

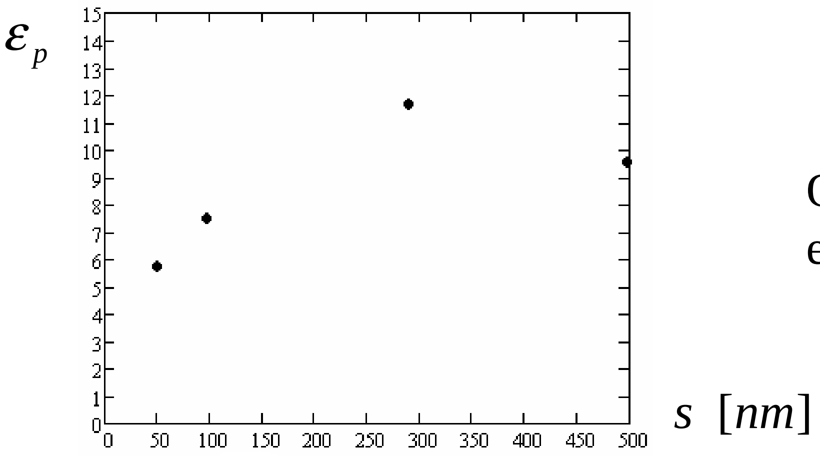
Maximal proton energy in MeV



$d_1 = 0.15$ μm; $d_2 = 0.35$ μm; s = 0.3 μm



h = 0.4 μm; $d_2 = 0.35$ μm; s = 0.3 μm



$d_1 = 0.15$ μm; $d_2 = 0.35$ μm; h = 0.4 μm

Optimal relief height *h* when vacuum electron excursion is about target period

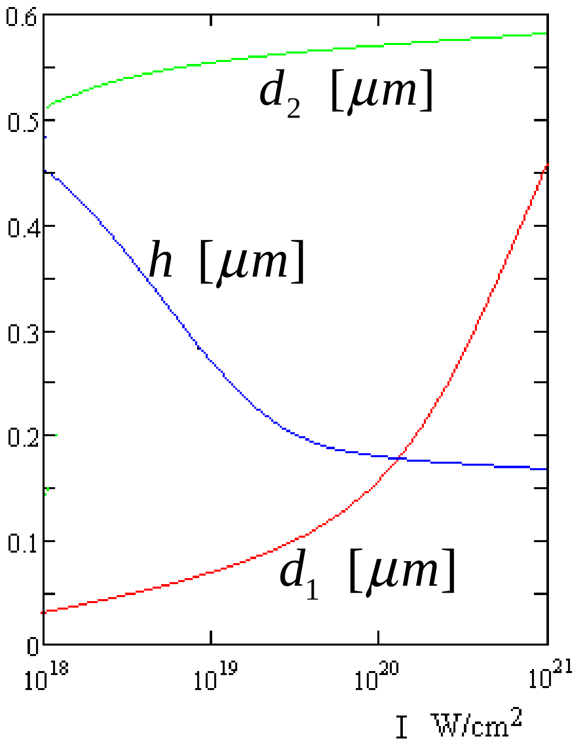
$$h \geq 0.05(d_1 + d_2)\frac{\omega t_L}{\sqrt{I_{18}}}$$

Optimal structure target parameters

Size of electron vacuum orbit

(E_0 – laser field)

$$r_{eh} = \frac{\lambda_L}{2\pi}\sqrt{\frac{1.37 I_{18}}{1+0.7 I_{18}}}$$



Optimal distance between ledges

$$d_2 \approx 2r_{eh}$$

Electron extraction length due to laser field action

$$l_{extr} \approx E_0 / en_e = 4\pi \frac{c}{\omega_{pe}} \frac{\omega}{\omega_{pe}} \sqrt{1.37\ I_{18}}$$

Optimal ledge size

$$d_1 \geq 2l_{extr}$$

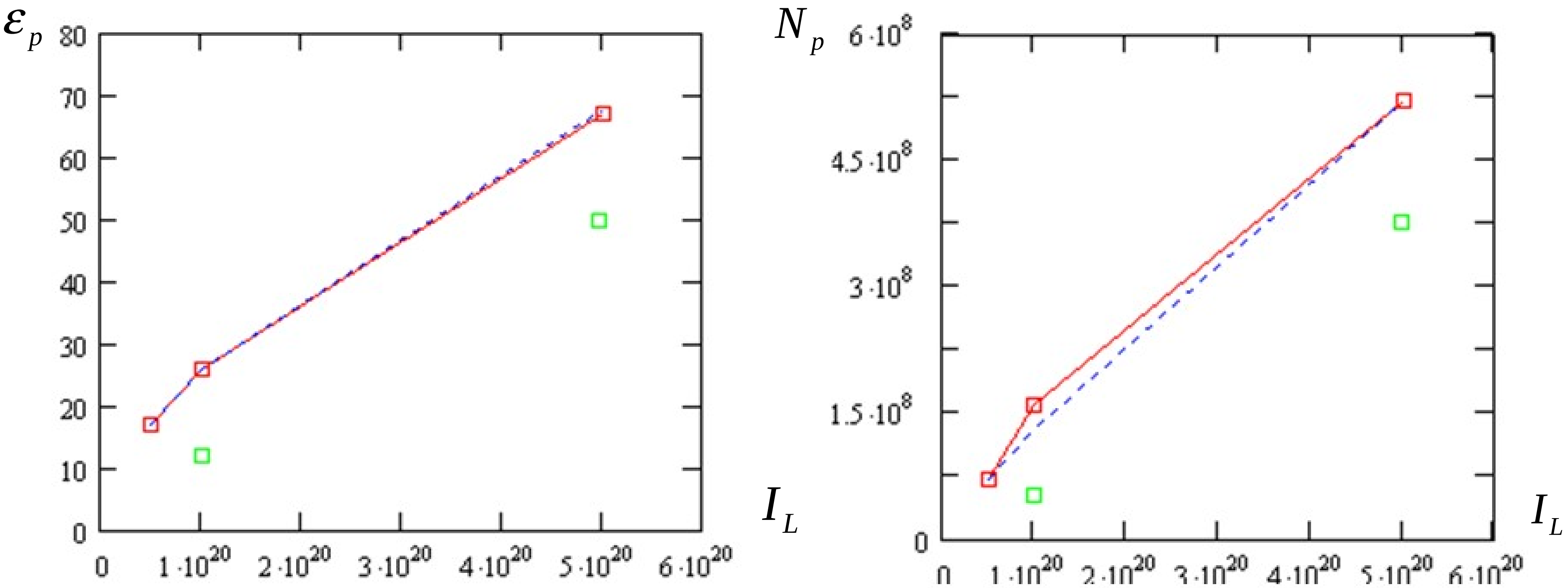
Optimal relief height *h* when vacuum electron excursion is about target period

$$h \approx 0.05(d_1 + d_2)\frac{\omega t_L}{\sqrt{I_{18}}}$$

For $I_{18} = 100,\ \tau_L = 15\ fs,\ \lambda_L = 0.8\ \mu m$ $d_1 = 0.15\ \mu m,\ d_2 = 0.4\ \mu m,\ h = 0.2\ \mu m$

It’s closed to the calculated optimum

Dependence of maximal ion energy and its number on laser intensity at optimal structure targets



$$\varepsilon_p \approx 17(I_L / 5\times 10^{19} Wcm^{-2})^{0.6}[MeV]$$

$$N_p \approx 7\times 10^7 \times (I_L / 5\times 10^{19} Wcm^{-2})^{0.86}$$

$$\varepsilon_C \approx 69(I_L / 5\times 10^{19} Wcm^{-2})^{0.62}[MeV]$$

$$N_C \approx 7.4\times 10^7 \times (I_L / 5\times 10^{19} Wcm^{-2})^{0.75}$$

Green squares – plane foil

Transition to the piston regime

$$(1+R)\varepsilon_L / c = N_C(I_L)\sqrt{\varepsilon_C{}^2(I_L)/c^2 - m_i{}^2c^2}$$

$$(1-R)\varepsilon_L = N_C(I_L)(\varepsilon_C(I_L) - m_ic^2) + F(I_L)$$

$$\eta + R = 1$$

$$N_C(I) = N_i(I_L / I_{cr})^{0.8} \quad I_L < I_{cr}$$

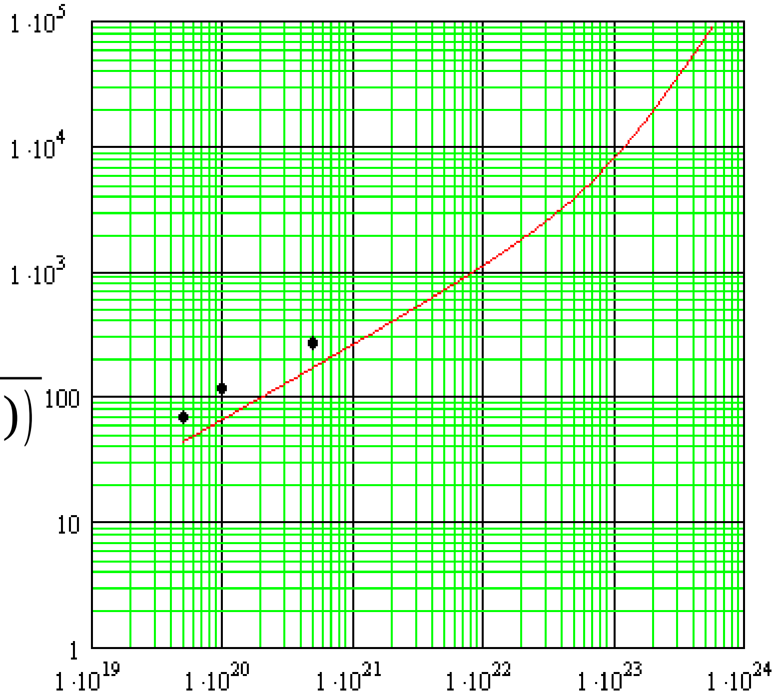
$$N_C(I) = N_i \quad I_L > I_{cr}$$

$$F(I_L) = N_{0C}\Delta(\varepsilon_{0C})\left(\frac{I_{cr} - I_L}{I_{cr} - I_{0L}}\right)$$

$$I_{0L} = 5\times10^{20} W / cm^2$$

$$I_{cr} = \pi ce^2n_e{}^2l_f{}^2 \qquad \Delta = 0.35\,10^{16} \; eV$$

$$\varepsilon_C - m_ic^2 = \frac{2\varepsilon_L - F(I_L)}{N_C(I_L)}\,\frac{\left(2\varepsilon_L - F(I_L)\right)}{2m_ic^2N_C(I_L) + 2\left(2\varepsilon_L - F(I_L)\right)}$$



Limitations of a nanostructure targets

Thermal (prepulse) smoothing

$$l_T \approx \sqrt{T_p \times \tau_p / m_e \nu_{ei}} > s \qquad T_p : \eta_p I_p \tau_p / Z_p n_i s$$

$$\tau_p \sqrt{Z_p T_p / m_i} = \tau_p \sqrt{\eta_p I_p \tau_p / m_i n_i s} < 0.5\, d_2$$

$$I_p \le 10^9 W / cm^2, \qquad \tau_p \le 1ns \qquad K_m \ge 10^{10}, \quad I_L \ge 10^{19} W / cm^2$$

Pondermotive (main pulse) smoothing

$$E_L{}^2 / 4\pi < (en_e h)^2 / 8\pi$$

$$(I / 1.37 \times 10^{18}\ W / cm^2)^{0.5} < 2\, n_e\, h / n_{cr} \lambda_L$$

$$I_L \le 10^{21} W / cm^2$$

Stability of the relief structures during the laser-foil interaction

Stability of the relief structures for a stationary target

$$(I / 1.37 \times 10^{18}\ W / cm^2)^{0.5} << 2\, n_e\, h / n_{cr} \lambda_L$$

$$I\tau_L < 1.37\ \ 10^{18}\ \ W / cm^2 \sqrt{\frac{5\, d_2\, m_i}{Z \omega_L c m_e}}$$

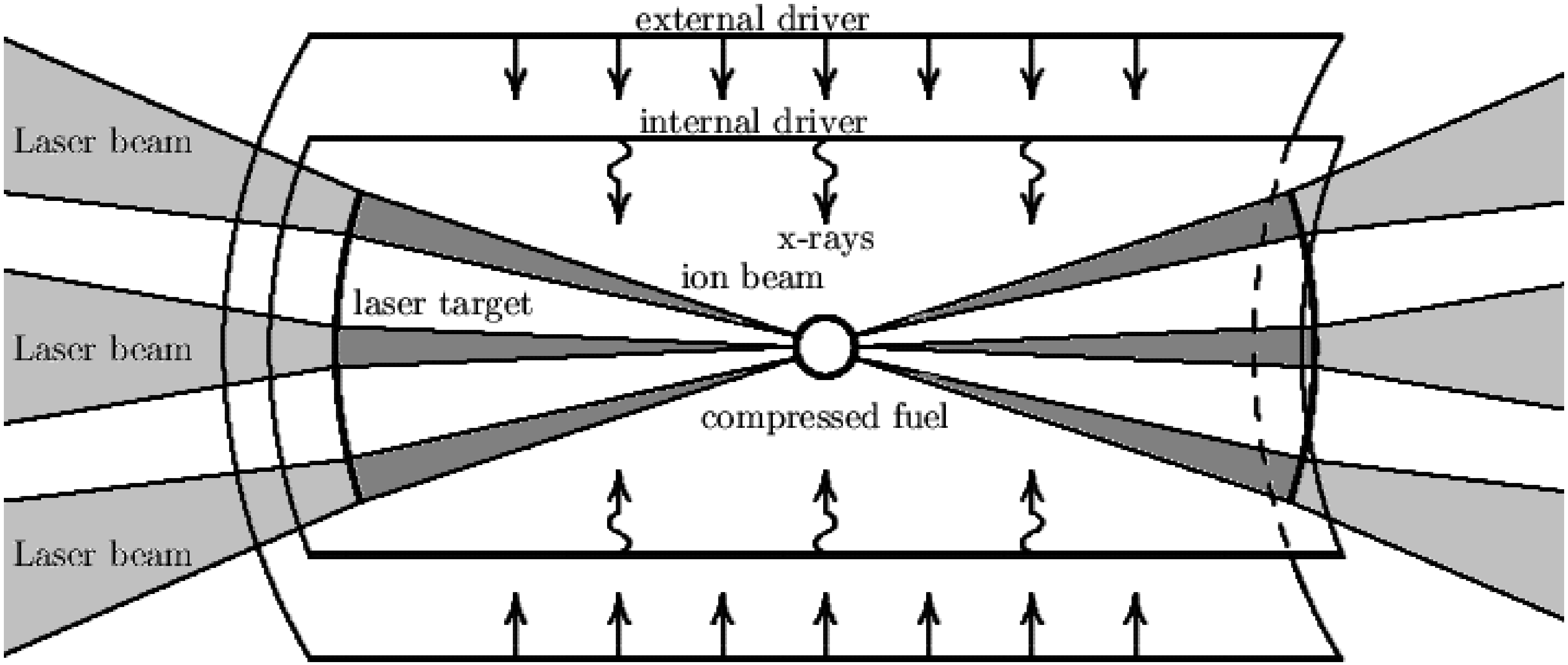
Stability of the relief and the substrate for an accelerated target

$$\frac{\Delta x}{s} = \frac{E_L{}^2 \tau_L{}^2 (1+R)}{8\pi m_i n_i s^2} = \frac{(1+R)}{2} \left(\frac{I}{1.37\times10^{18}\ \ W\, \mu m^2 / cm^2} \right) \left(\frac{Z m_e n_{cr}}{m_i n_e} \right) \left(\frac{c\tau_L}{s} \right)^2$$

$$c\tau_L \le s \frac{n_e}{n_{cr}} \sqrt{\frac{m_i}{Z m_e}} \sqrt{\frac{s^2}{d_2 \lambda_L}} \qquad \Gamma(k_y, I_{18}) = \omega_L \sqrt{\frac{2 Z m_e I_{18} k_y c^2 \sqrt{1+4\pi^2 h^2 / (d_1+d_2)^2}}{m_i \omega_{pe}{}^2 s}}$$

$$\omega_L t_L \sqrt{\frac{4\pi Z m_e I_{18} c^2 \sqrt{1+4\pi^2 h^2 / (d_1+d_2)^2}}{m_i \omega_{pe}{}^2 s (d_1+d_2)}} = \sqrt{\frac{\Delta x}{s} \frac{8\pi s \sqrt{1+4\pi^2 h^2 / (d_1+d_2)^2}}{(1+R)(d_1+d_2)}} < \ln(2)$$

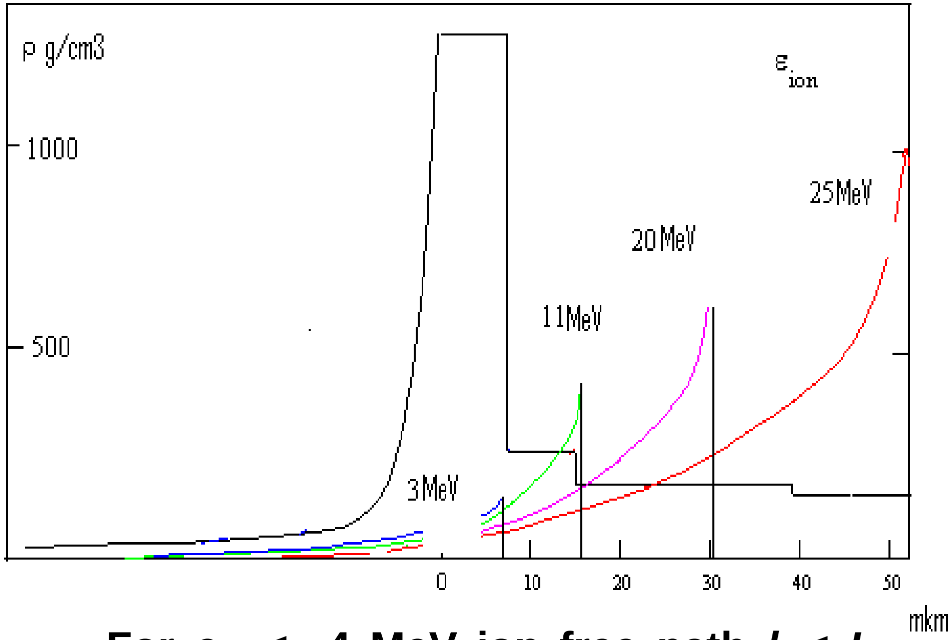
“Dynamic Hohlraum & Fast Proton Ignition” scheme for ICF



http://zhurnal.ape.relarn.ru/articles/2003/033.pdf

Ignition of compressed DT-fuel by laser triggered fast ion beam

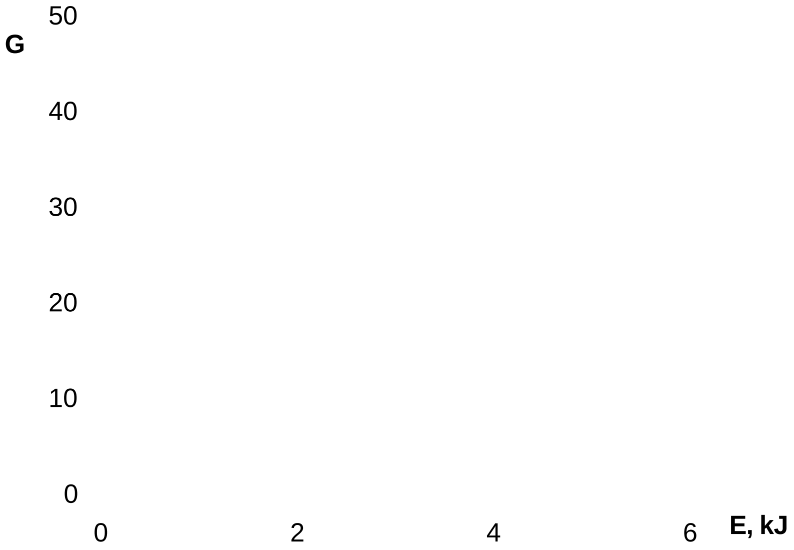
Code TRITON [S.Zaharov et al.] simulations: Triangle pulse shape with duration $t_x = 4ns$, intensity $I_x = 4\text{x}10^{14}\ W/cm^2$, E_x = 213 kJ; Fe – shell target: R_0 = 1 mm, ΔR = 25 μm; DT fuel: ΔR_f = 67 μm, ρ_{fs} = 0.213 g/cm³, $\rho_{fg} = 5.5\text{x}10^{-4}$ g/cm³



For e_i < 4 MeV ion free path $l_i < L_p$ – plasma corona scale of inhomogenity

$l_i > R_k$ at e_i > 25 MeV. $l_i \leq L_p + 0.2\ R_k$ at $e_i \approx$ 11 MeV

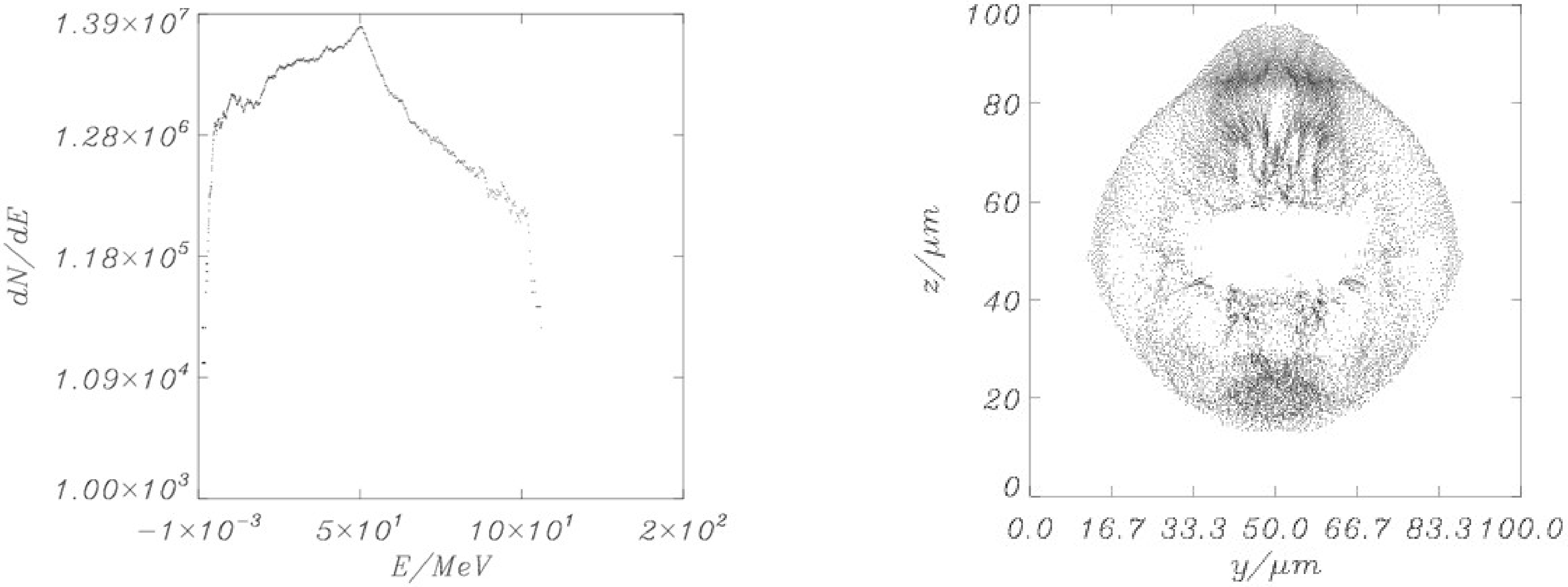
$E_i = e_i N_p \approx$ 1 kJ, $E_{loss} \approx$ 200 J, $N_i \approx 10^{15}$



TERA code [A.Levkovskiy et al.] simulations

Dependence of the target gain G from the energy of ignition E

Calculation of laser parameters to produce $\propto 10^{15}$ protons with energy $\propto 20$ MeV



Proton distribution functions of CH nano limited target at t= 426 fs

$d_1 = 0.15\ \mu m$; $d_2 = 0.35\ \mu m$; $h = 0.4\ \mu m$ $\quad I_L = 10^{20} W/cm^2, d_L = 4\mu m, t_L = 66\, fs$

$N_p \approx 2\times 10^{11} \quad \bar{\varepsilon}_p \approx 50 MeV \qquad N_p \approx 10^{15}, \quad d_L \approx 300\mu m$

$I_L = 0.6\times 10^{20} W/cm^2, d_L = 330\mu m, t_L = 50\, fs \qquad \eta_{abs} \approx 1 \qquad \eta_{Lp} \approx 0.2$

$\bar{\varepsilon}_p \approx 20 MeV \qquad N_p \varepsilon_p \approx 1kJ \qquad \varepsilon_L = 5kJ$

Conclusion

- **Optimal structure of a foil target permits to get almost total absorption of laser pulse.**
- **The absorbed laser energy is mainly transformed into an energy of heavy ions for homogeneous target and redistribution of this energy into light ions is possible for heterogeneous target**
- **For effective acceleration of ions the volume of the relief should be less than the volume of the substrate foil.**
- **In our case, degradation of the structures by the ambipolar electric field generated at the target surface is the most important factor.**
- **For this scheme to work, one needs a very high-contrast laser-pulse and a nanosecond laser pre-pulse duration**
- **Nano-structure target can be used for FI scheme**