GENERATION AND DETECTION OF SUPER-STRONG MAGNETIC FIELDS BY ULTRA-INTENSE LASER PULSES

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Outline

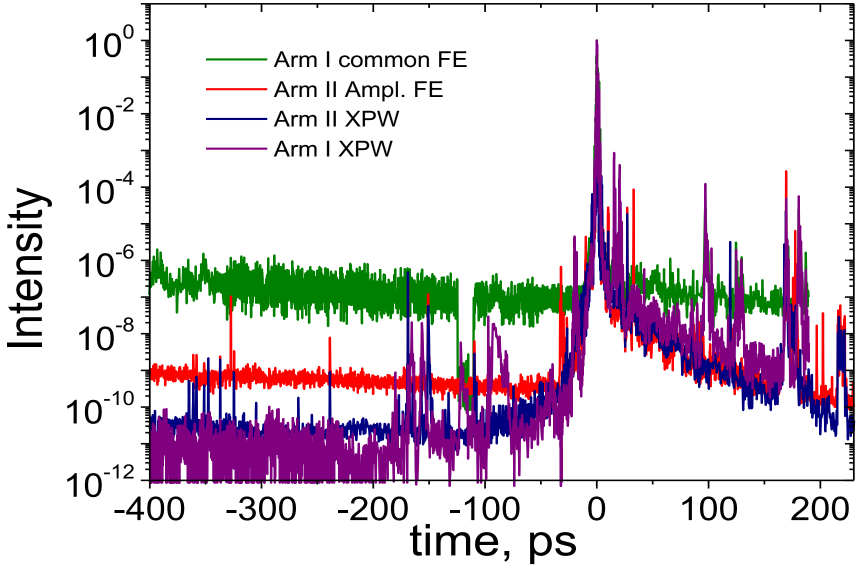
- **Motivation**
- **Generation of B-field by short laser pulse interacting with thin foil and its detection**
- **Fast particle generation in nano-structure targets at ultra-high laser intensity**
- **Electron transport in nano-wires irradiated by relativistic intense laser radiation**
- **Intense B-field generation by short intense laser pulse interaction with nano-wire and gas targets**
- **Conclusion**

Ultra-high temporal contrast with help of plasma mirrors and XPW

MBI TW Ti:Sa Laser

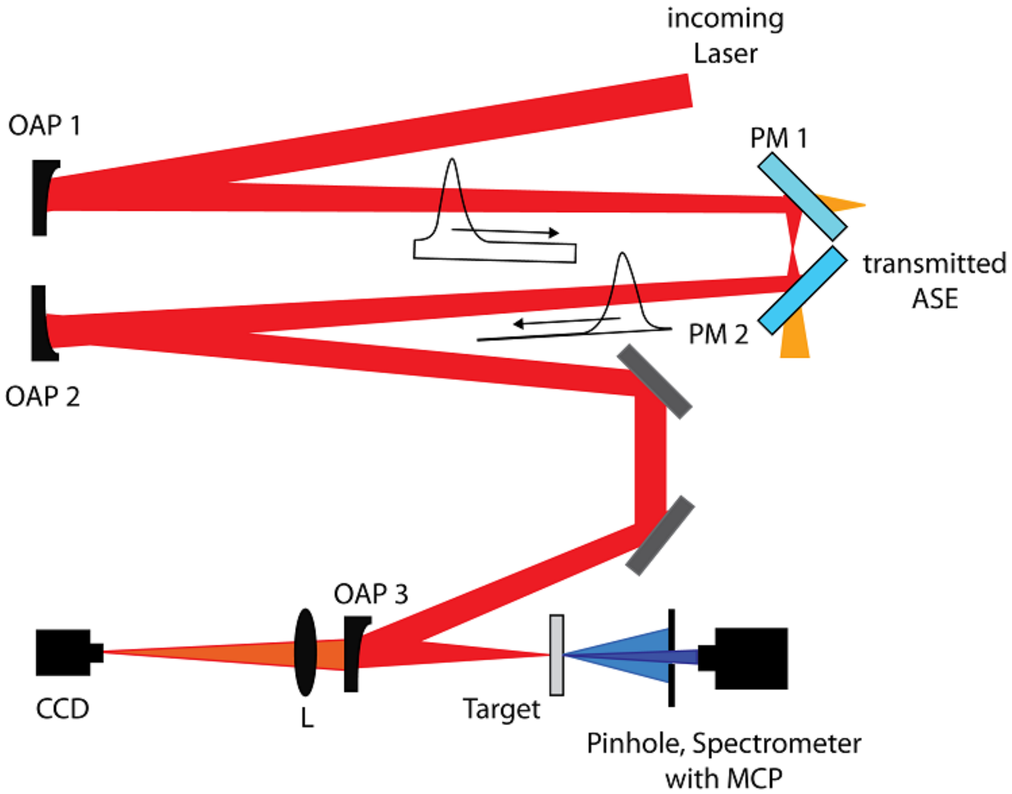
Initial Parameter

- pulse energy > 2 J
- pulse duration < 40 fs
- ns - ASE contrast: 10^{-6} - 10^{-7}



M.Kalashnikov et al., SPIE (2011)

Improvement of 10^4



Double – Plasma Mirror (DPM)

- energy throughput > 70%
- no decrease of focusability

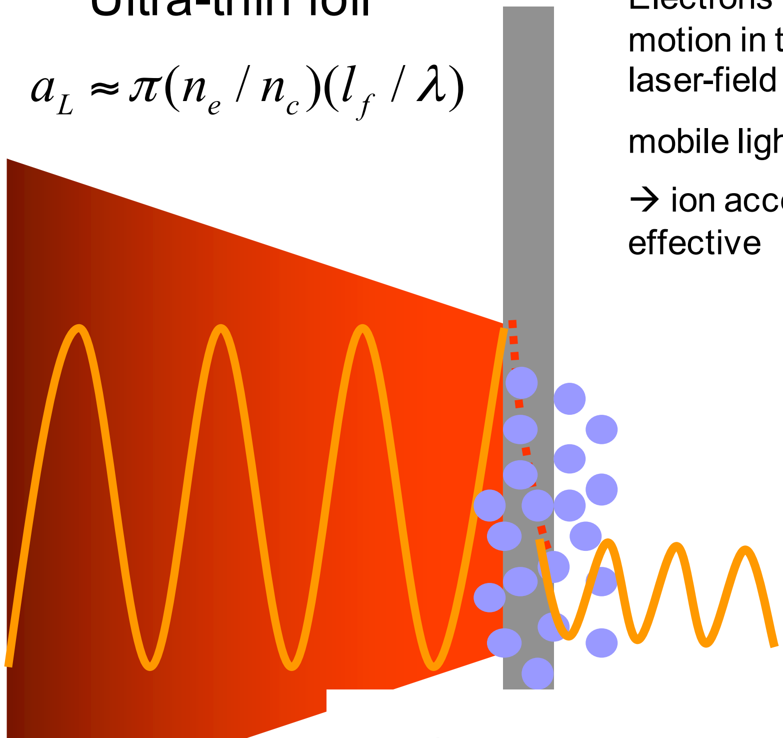
$$K_{PM+XPW} \approx 10^{-14}$$

$$K_{PM} \leq 10^{-10}$$

RPA/TNSA hybrid ion acceleration regime for nano-foil

Ultra-thin foil

$$a_L \approx \pi (n_e / n_c)(l_f / \lambda)$$

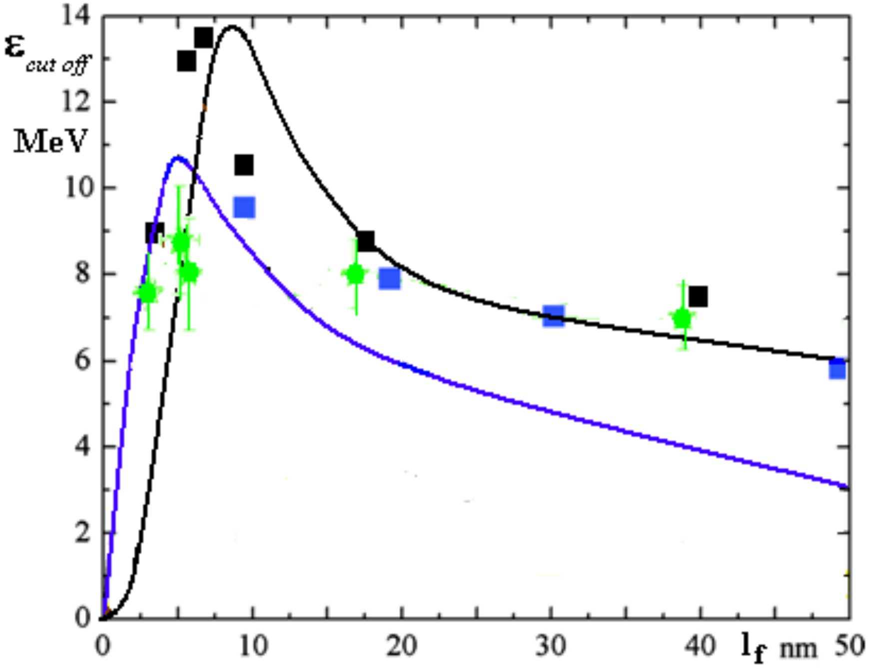


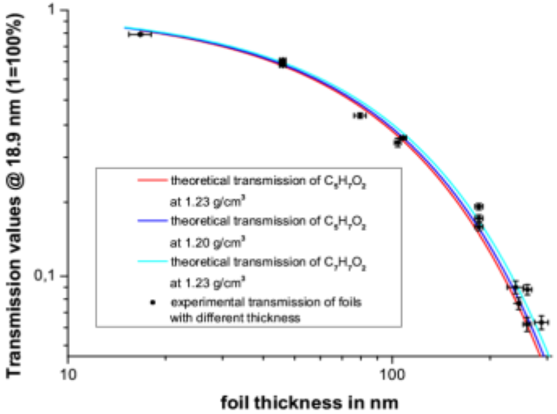
Electrons perform collective motion in the transmitted laser-field for ultrathin foil

mobile light foil

→ ion acceleration is more effective

A.Andreev et al., PoP (2013)

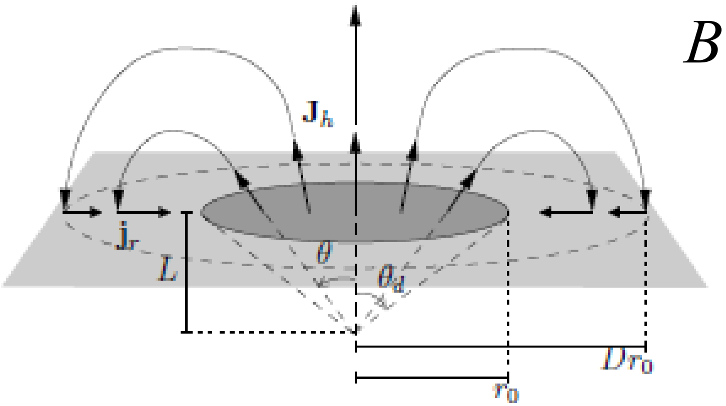




Here black squares are the experimental data, where 45 fs, LP laser pulse with the intensity 5×10^{19}W/cm^2 interacts with DLC foil. Black solid line is the model results. Green stars are the experimental data for CP laser pulse of duration 33 fs and the same intensity. Blue squares are the results of 2D PIC simulations and blue dash line is the result of our analytical model.

Efficiency < 10% at $a_L \approx 10$

B-Model for short laser pulse and thin foil



$$B \approx 4 e r_D n_{eh} \theta_d v_e / c \quad r_D \approx \lambda$$ G.Sarri PRL (2012)]

$$T_{e0} = 0.8 MeV \quad n_{eh} = 1.9 \cdot 10^{20} cm^{-3}$$

$$v_e \theta_d / c \approx 1, \quad B \approx 0.1 E_L$$

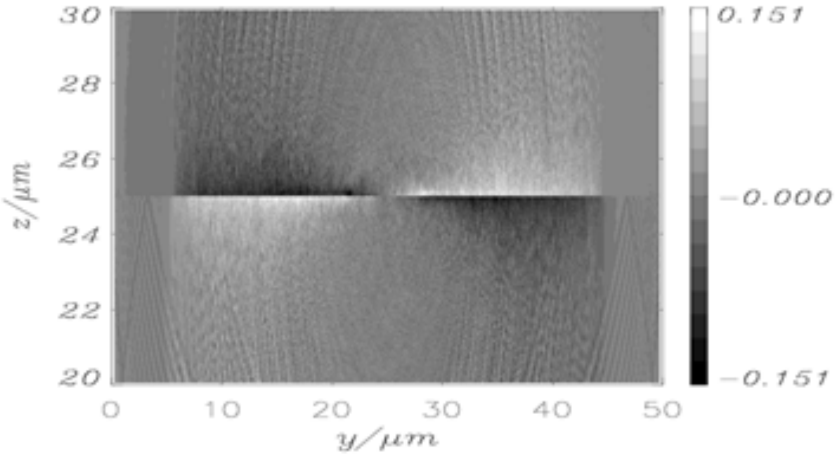
$$B \approx e n_c \lambda_L / 4 \quad n_{eh} \approx n_c / 4$$ W.Schumaker PRL (2013)

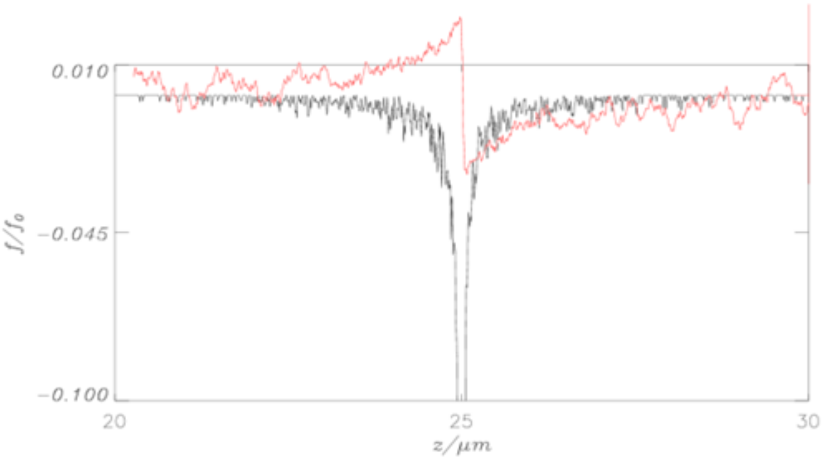
$$n_{eh} / n_{cr} \approx 0.5, \quad \int \eta_e d\varsigma \approx 0.6$$

$$v_t / c = 0.9, r_D \approx 1 \mu m$$

$$B(l) = 4\pi e n_{eh} r_D \frac{v_t}{c} \int \eta_e(\zeta, l) d\zeta \approx 0.15 E_L$$

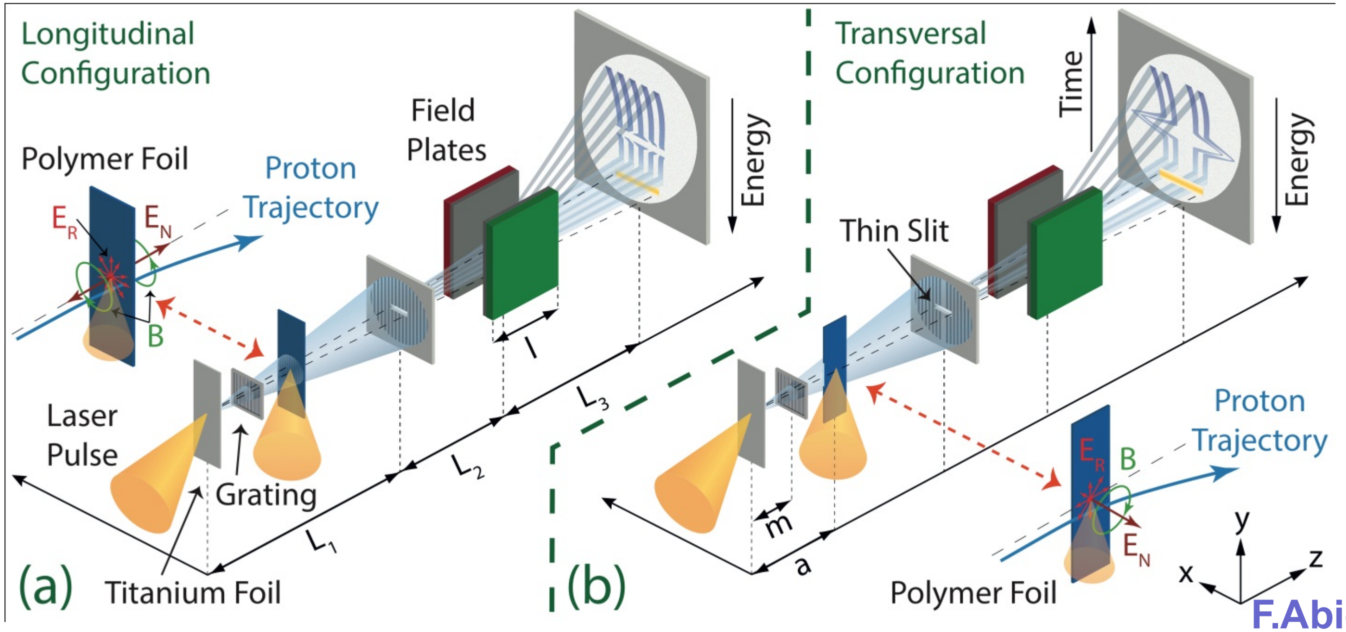
A.Andreev et al. NJP (2011)

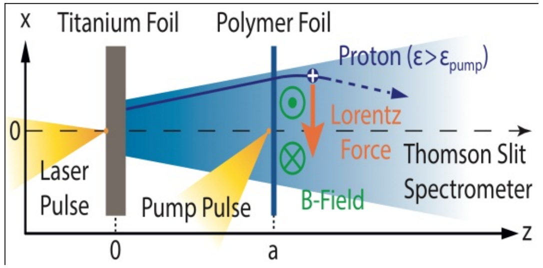




IL=5x10^{19}W/cm^2, tL=33 fs, t=75 fs, DL=6mkm, lin pol, normal incidence, lf=40 nm, C^{+6}, ni=60n$_{cr}$

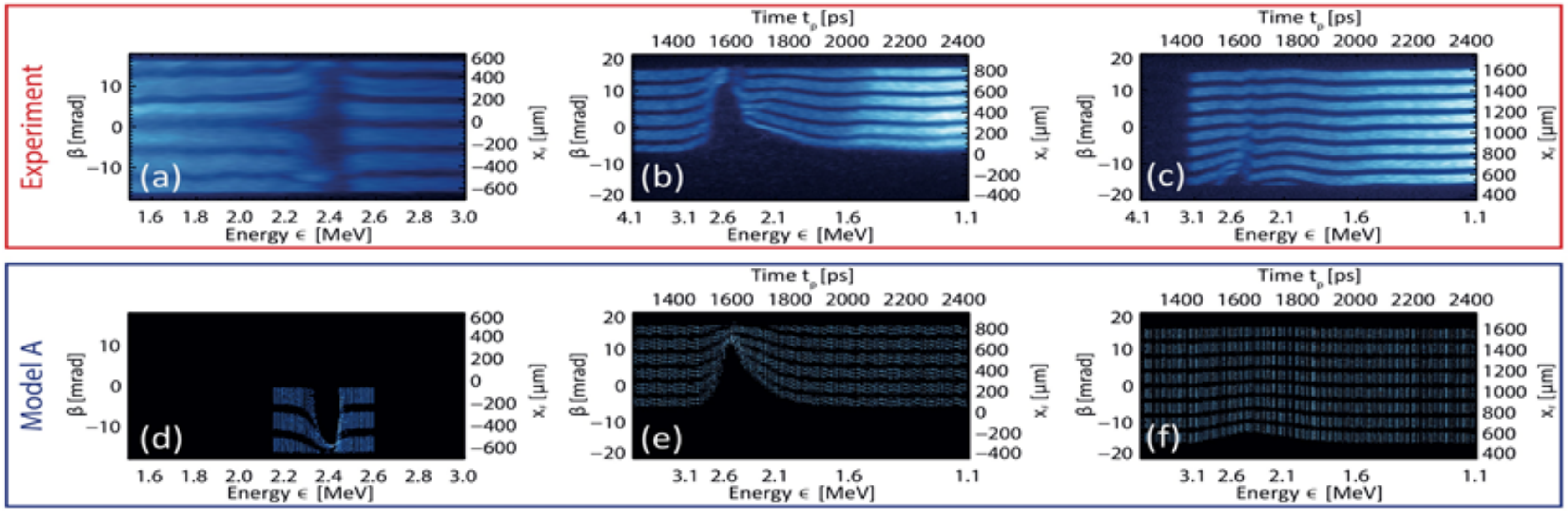
Proton Streak Deflectometry method for E and B field detection at two imaging configurations



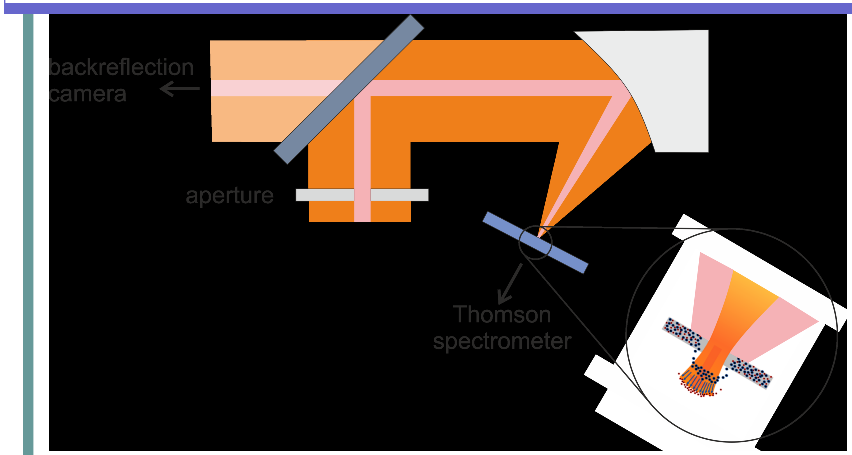


Pump 2x10^{19} W/cm^2, tL=35 fs, oblique incidence, P-pol, polymer foil 30 nm; Probe 10^{19} W/cm^2, tL=25 fs, Ti foil 5 microns; contrast > 10^10

F.Abich, A.Andreev et al. PRAB(2016)



Fs laser induced quasi-periodic nanostructure



5 s exposure, 10 μJ on target. With the reduction of beam diameter, the focal spot size increases to 25microns. Under these conditions we were able to generate LIPSS.

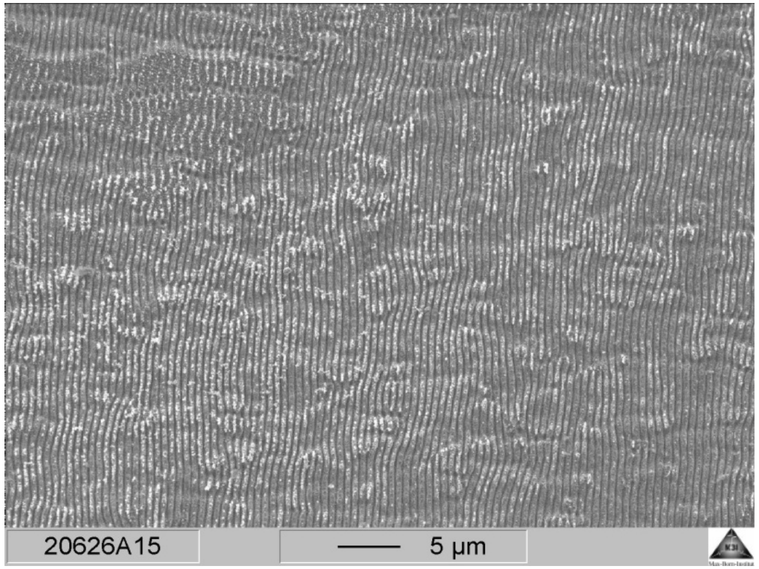
a) LIPSS - laser induced periodic surface structuring. $d_1 \approx d_2 \le 300nm, h \le 500nm$
kHz - fs laser focused on the target

b) The catalyst-free technique to grow nano-rods has been developed using two-stage buffer layers combined with high temperature vapor phase transport nano-rod deposition, which results in
$d_1 \propto d_2 \propto 100nm, h \propto 1000nm$

The results on ripples on Cu created with fs pulses at 800 nm.

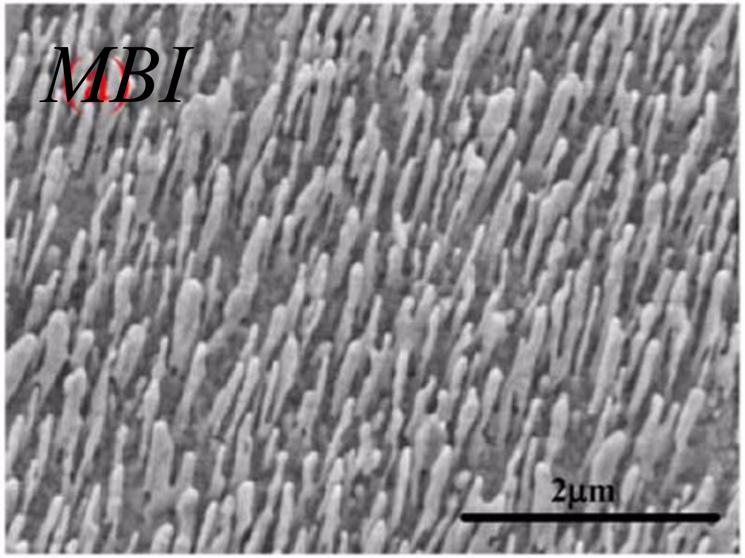
(a)

S.Das et al., APJ (2011)



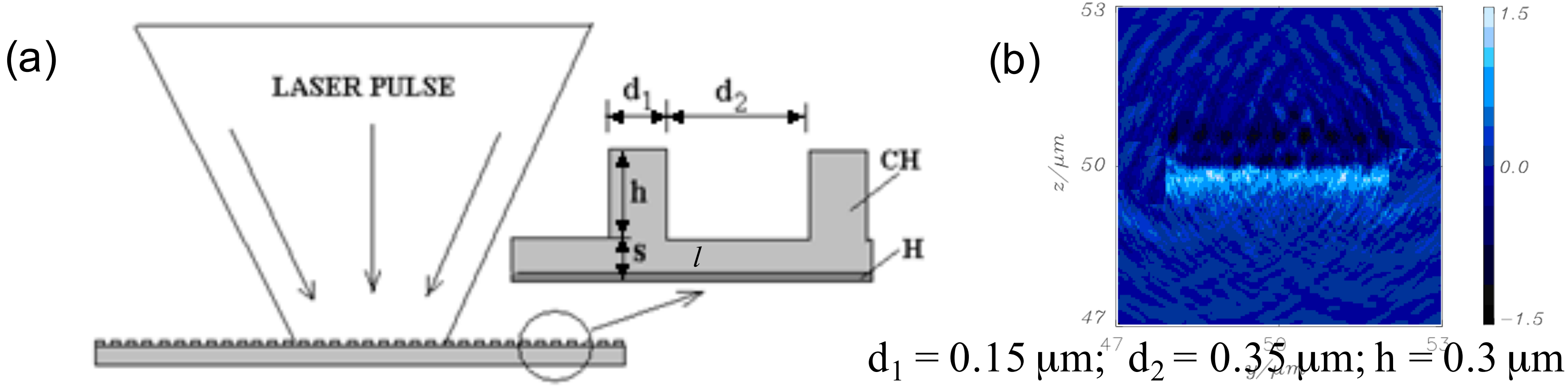
FESEM image of metal nanorods

(b)



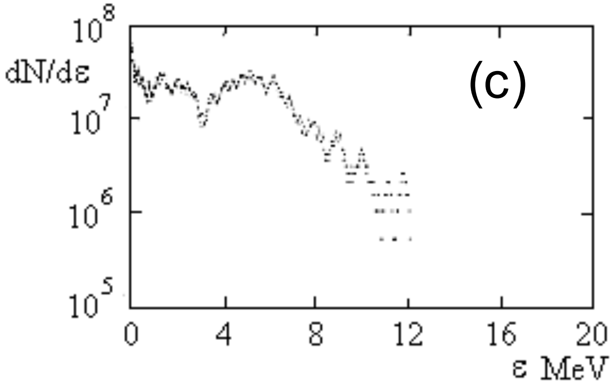
Nano-structure (dynamic) target

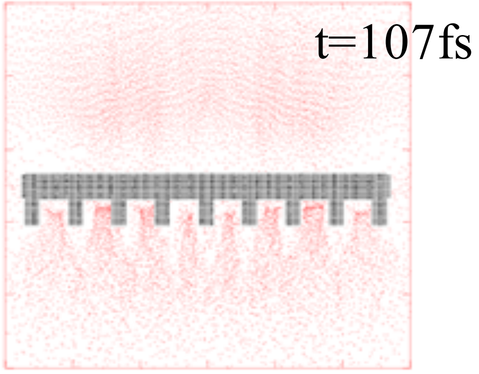
(a) Schematic of the nanostructure target,
(b) Spatial distribution of electric field component normal to the target surface.



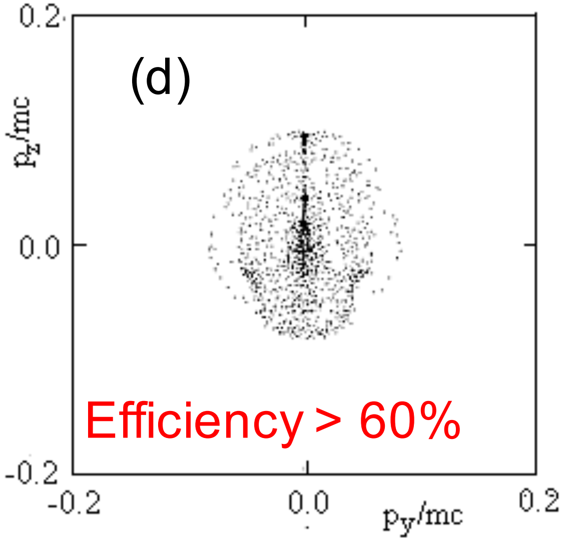
$d_1 = 0.15$ μm; $d_2 = 0.35$ μm; h = 0.3 μm

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





t=107fs



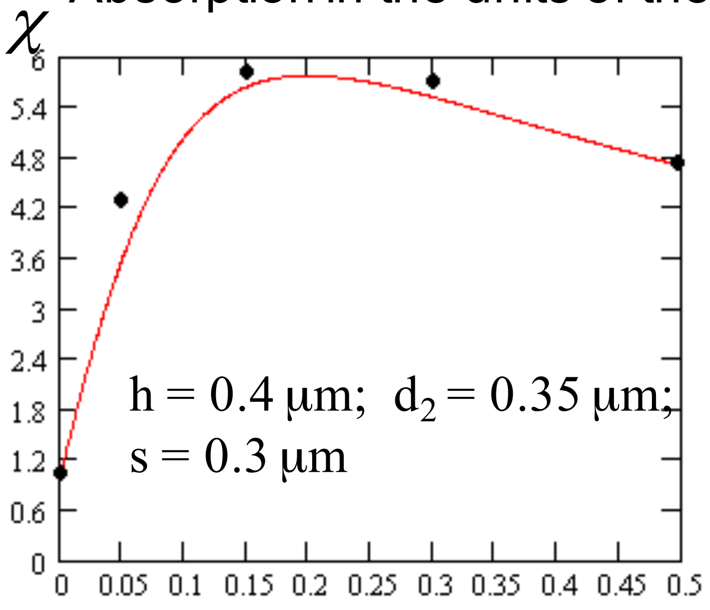
Efficiency > 60%

A.Andreev et al. PoP (2011)

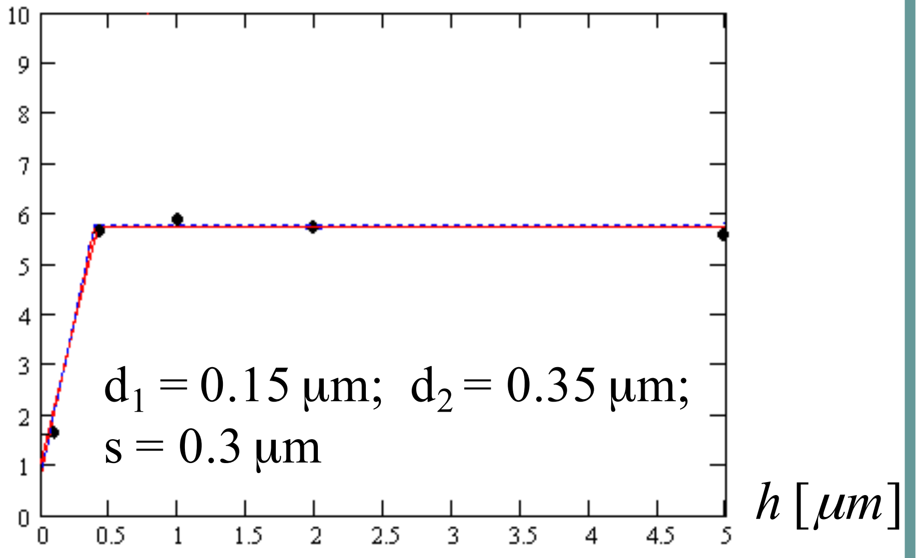
Laser pulse 10^{20}W/cm^2, 15 fs, diameter 3 μm; target C^{+6} H^{+1}, density 0.4g/cm^3, finite 4x4μm

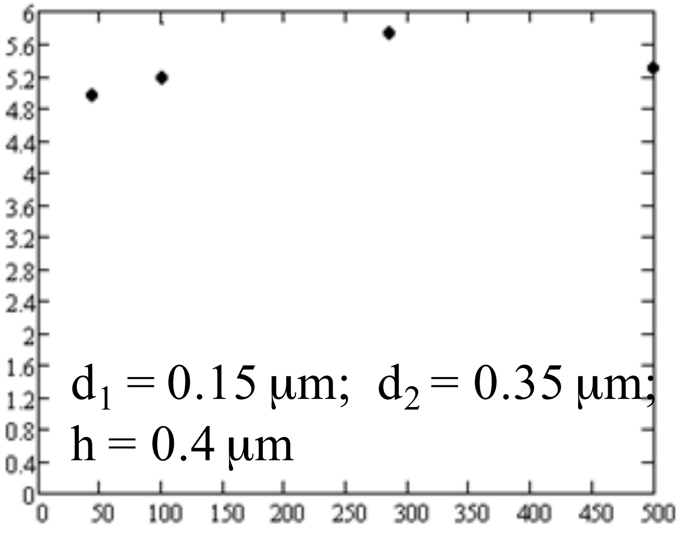
Efficiency of a structure targets

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





$$\chi \approx 1 + \frac{(d_1/2l_{extr})}{\sqrt{1+(d_1/2l_{extr})^2}}\left(\frac{E_0 d_L^2}{e\varepsilon_L}\right)\cdot\frac{1.4h}{(d_1+d_2)}\cdot m_e c^2 I_{18}$$

$\chi < \chi_{\max}$

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

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

Efficiency > 60%

Optimal structure target parameters

Size of electron vacuum orbit

(E_L – laser field)

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

Optimal distance between ledges

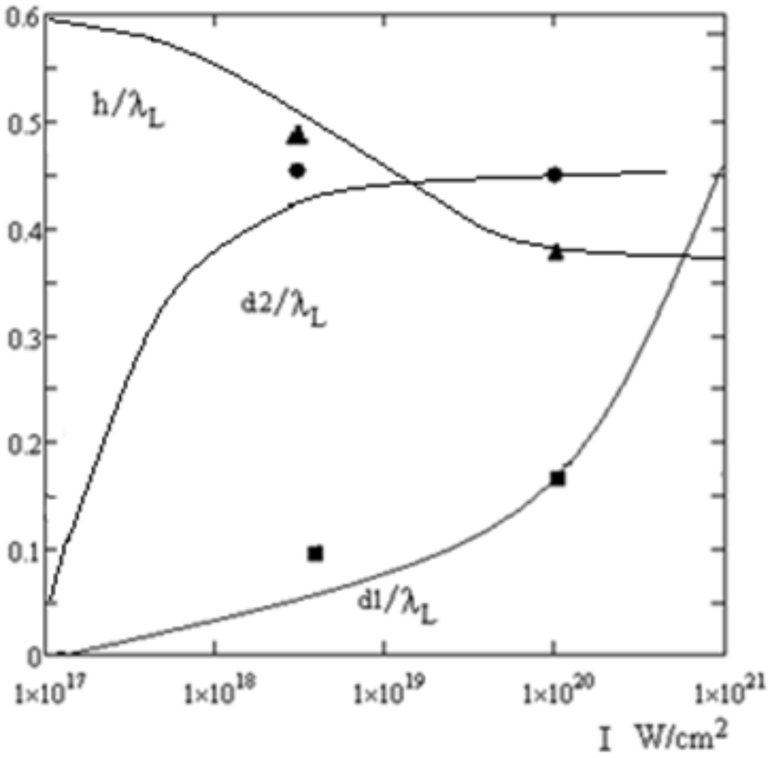
$$d_2 \approx 2 r_{eh}$$

Electron extraction length due to laser field action

$$l_{extr} \approx E_L / e n_e = 4\pi \frac{c}{\omega_{pe}} \frac{\omega}{\omega_{pe}} \sqrt{1.37\, I_{18}}$$

Optimal ledge size

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



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

It’s closed to the calculated optimum

Limitations of a nanostructure targets

Thermal (prepulse) smoothing

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

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

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

Pondermotive (main pulse) smoothing

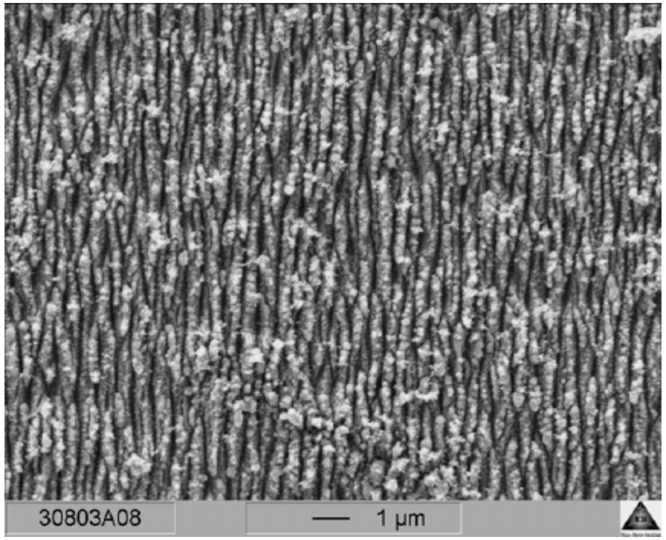
$$E_L^{\ 2} / 4\pi < (en_e h)^2 / 8\pi$$

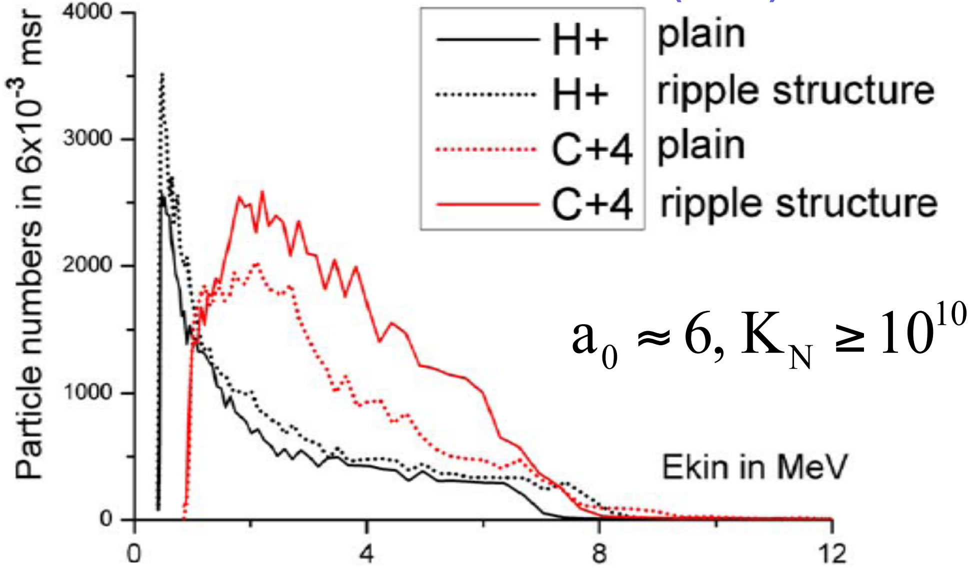
$$(I / 1.37 \cdot 10^{18}\ W/cm^2)^{0.5} < 2\, n_e\ h / n_{cr} \lambda_L$$

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

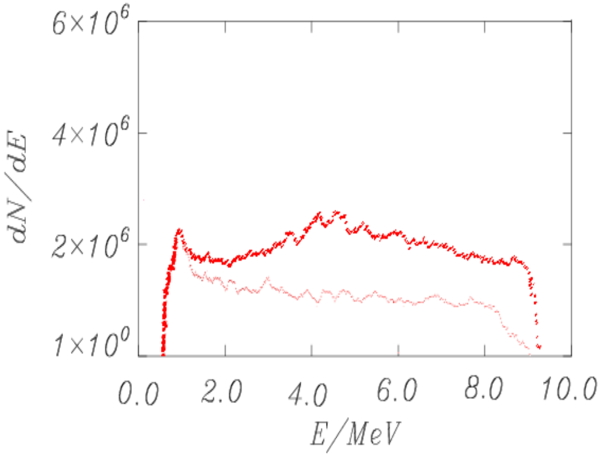
“Ripple” targets

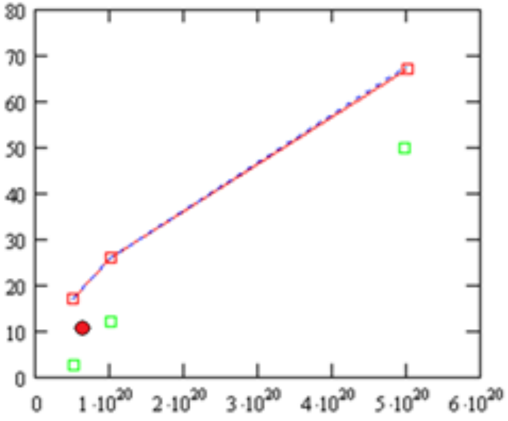
A.Andreev et al. PP&CF (2015)

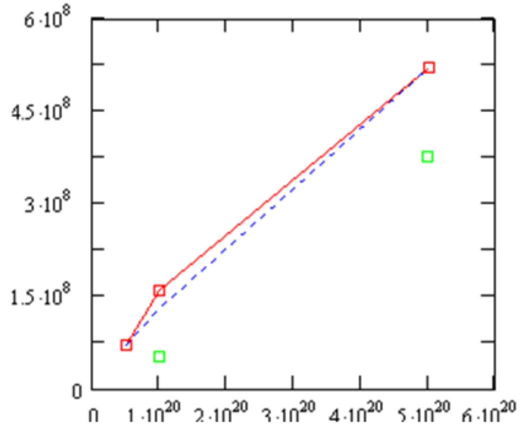




$a_0 \approx 6, K_N \geq 10^{10}$







Red squares – optimal target, Green squares – plane foil

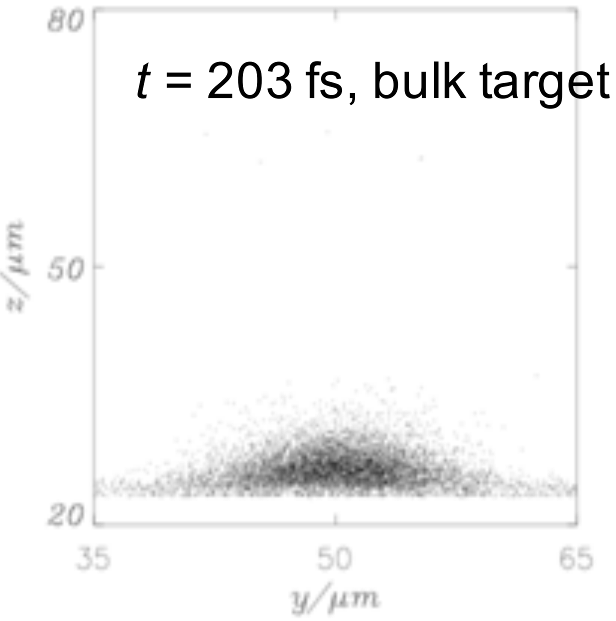
I_L=10^{20} W/cm^2, t_L=30 fs, d_L=3mkm, d_1=200nm, d_2=100nm, h=200nm, Ti^{+15}, C^{+1}

A.Lubcke, A.Andreev et al. Sci. Rep. (2017)

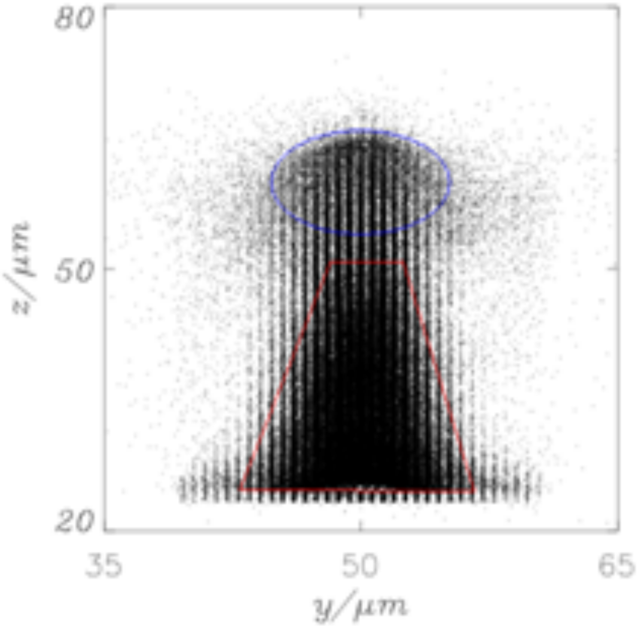
$$\varepsilon_p \approx 17(I_L / 5\cdot10^{19} Wcm^{-2})^{0.6}[MeV]$$

$$N_p \approx 7\cdot10^7 \cdot (I_L / 5\cdot10^{19} Wcm^{-2})^{0.86}$$

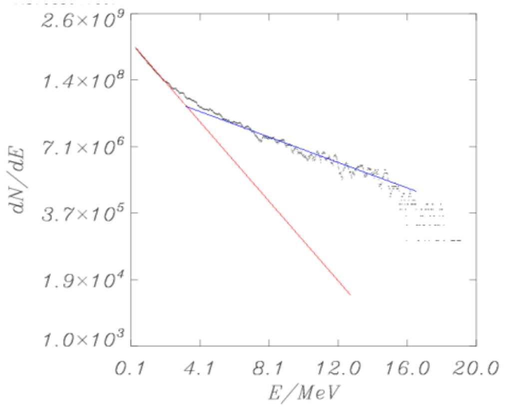
Electron transport efficiency in nano-wires

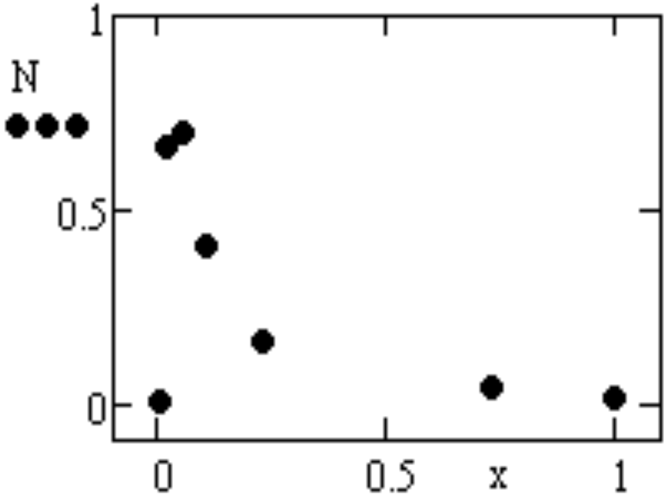


t = 203 fs, bulk target



Wire solid target: C^{+6}
Length 50 microns,
d1=150 nm, d2 = 500 nm
Laser: pulse duration 45 fs,
spot size 4 microns,
intensity 3x10^{19} W/cm^2





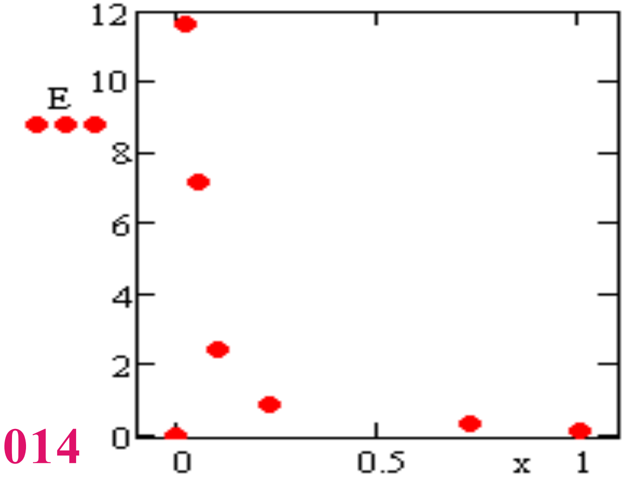
$$l_1(t) \approx \sqrt{l_{10} + \sigma_{zz}\, t\, r_{D1} l_f}$$

$$p_z \geq 0.9mc$$

N=Ne-N0 – relative number of fast electrons,
E=Ee-E0- its relative total energy

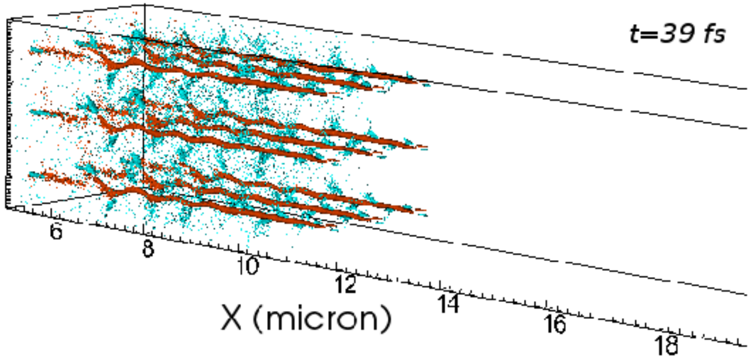
$$x = d_1 / (d_1 + d_2)$$

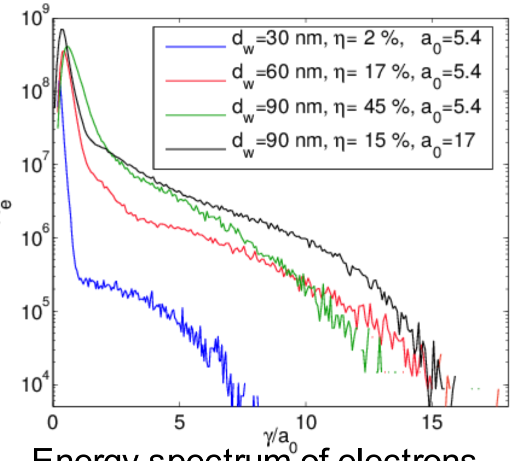
A.Andreev et al. PP&CF 2014



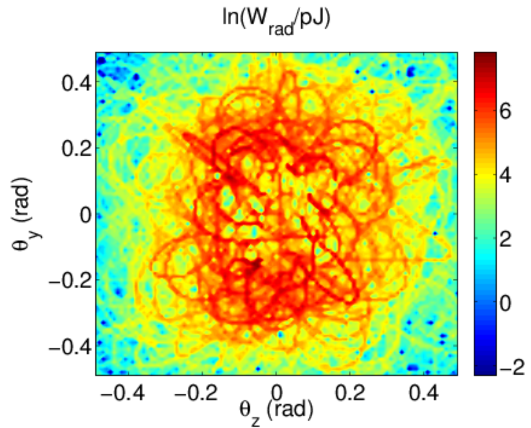
3D simulation results for nano-wire targets

Zs.Lech&A.Andreev PoP(2017)

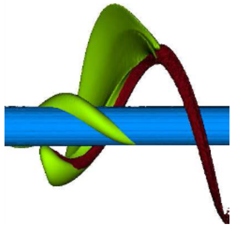




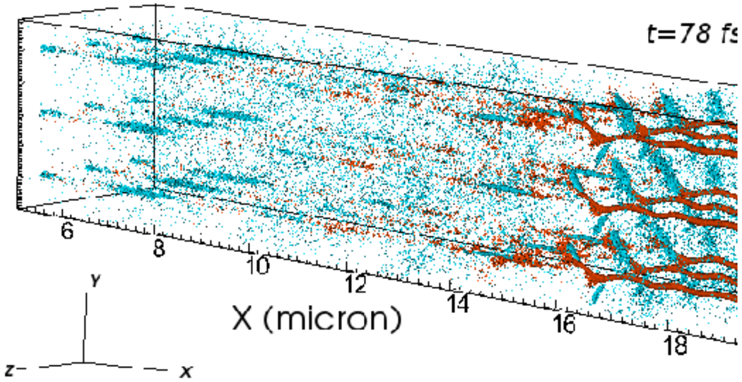
Energy spectrum of electrons
t = 120 fs



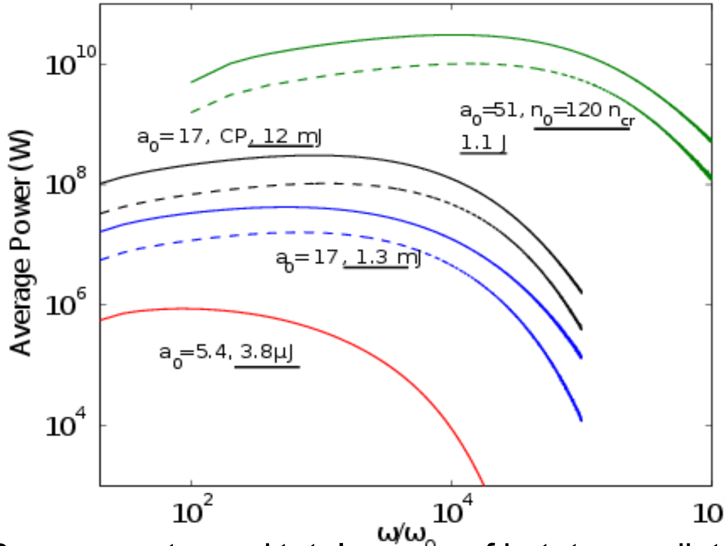
Angular distribution of radiated energy,
θy = arctan(vy/vx), θz = arctan(vz/vx).



The iso-surface at10^20 W/cm2 (green) and the density of fast electrons at the iso-value 10^22 cm−3 (red), t =10 fs.

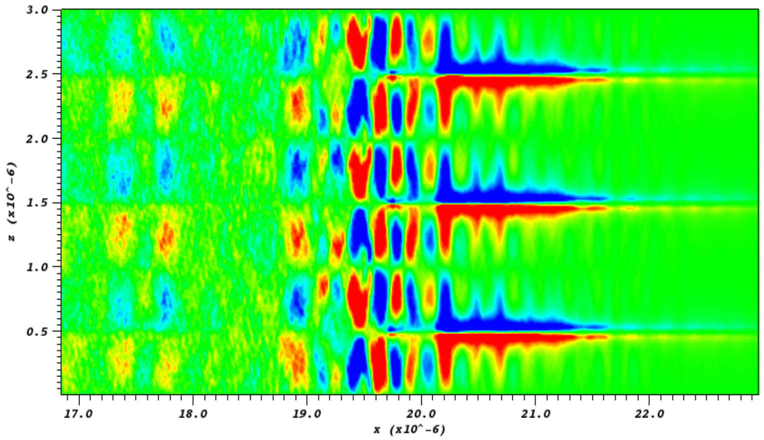


Electrons contributing to the return current (red, jx = 7 · 10^17 A/m2) and forward propagating fast electrons (green, jx = −5 · 10^16 A/m2) at two time instances from a 3D simulation with dw = 90 nm.



Power spectra and total energy of betatron radiation for different intensities. The dashed lines show the spectra measured 0.16< <0.2 radian. Here electron γ > 20.

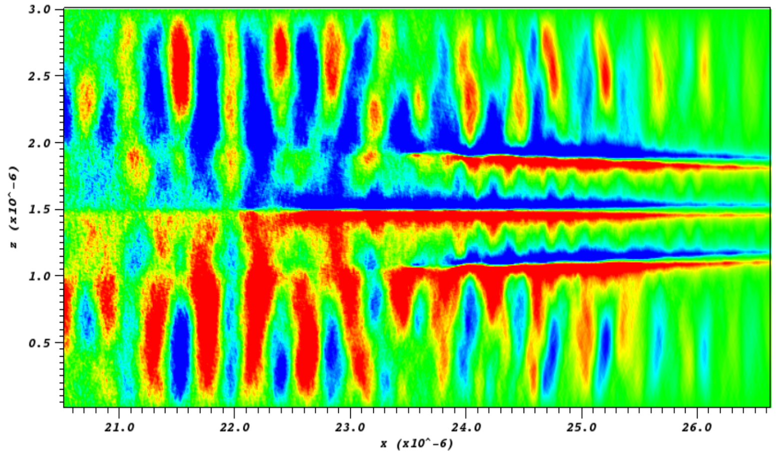
Magnetic field generation by laser short pulse interacting with nano-wires



wire length is 30 microns and the laser pulse duration is 30 fs with$10^{20}\ W/cm^2$

By field at different time moments

$$B_{Lz} = 180kT$$



Analytical modelling

$$B_w \approx \mu_0 e n_0 r_w \upsilon_{ret} \qquad \upsilon_{ret} \approx -n_h \upsilon_{dir} / n_0$$

$$\upsilon_{dir} \approx c \qquad n_h \approx n_0 \cdot (r_w / \Delta r)^2$$

$$B_w \approx \mu_0 e n_0 r_w (r_w / \Delta r)^2 c$$

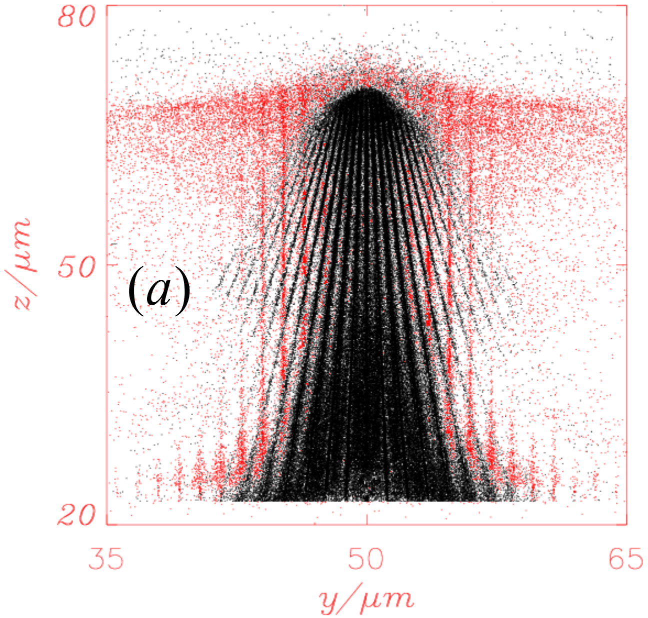
$$I_L = 10^{20} W / cm^2, \quad t_L = 30 fs, \quad r_w = 100 nm, \quad \Delta r = 1 \mu m \qquad B_L = 180 kT$$

$$n_0 = 5 \cdot 10^{23} cm^{-3}, \quad j_{ret} = 2 \cdot 10^{17} A / m^2, \quad \upsilon_{ret} \approx 2.5 \cdot 10^8 cm / s$$

$$B_w \approx 60 kT, \quad B_w^{sim} = 67 kT$$

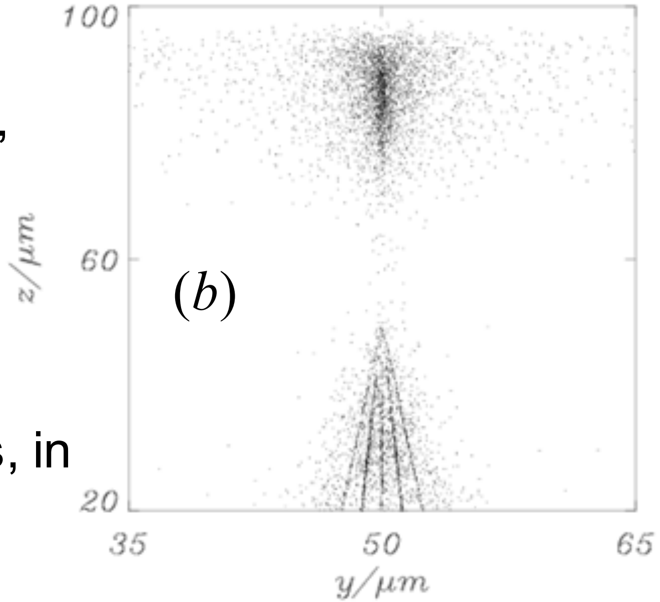
$$E_L \geq e n_0 r_w, \quad \Delta r \approx r_E = e E_L / m \omega_L^2 \qquad B_w^{opt} \approx B_L, \quad Z = 1$$

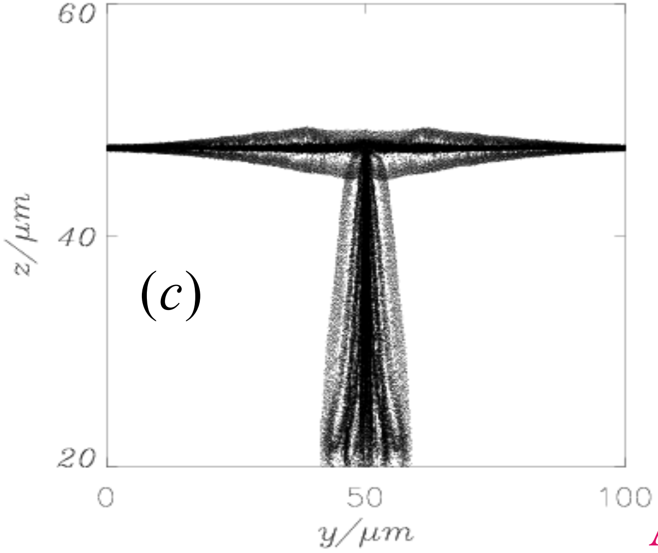
Electron transport in nano-wire cone targets



a) Electron density distribution at *t* = 210 fs, in cone (black) and straight (red) targets

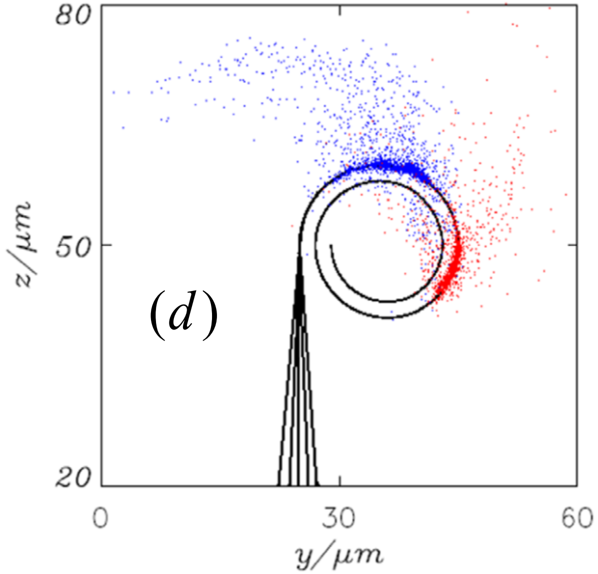
b) Electron density distribution at *t* = 277 fs, in cone&wire target





c) Ion density distribution at t=288 fs

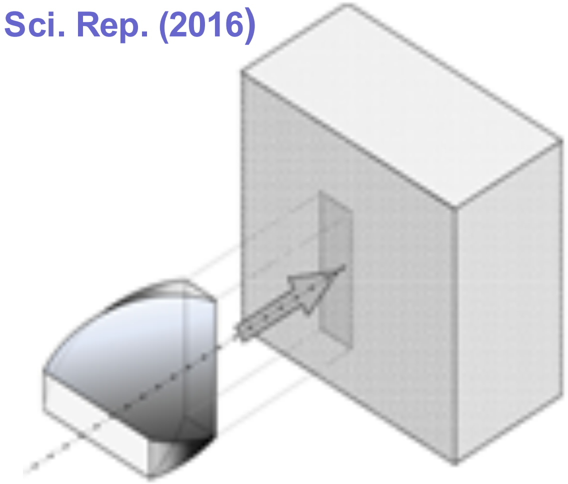
d) Electron density distribution at *t* = 277 fs, in cone and dented wire target

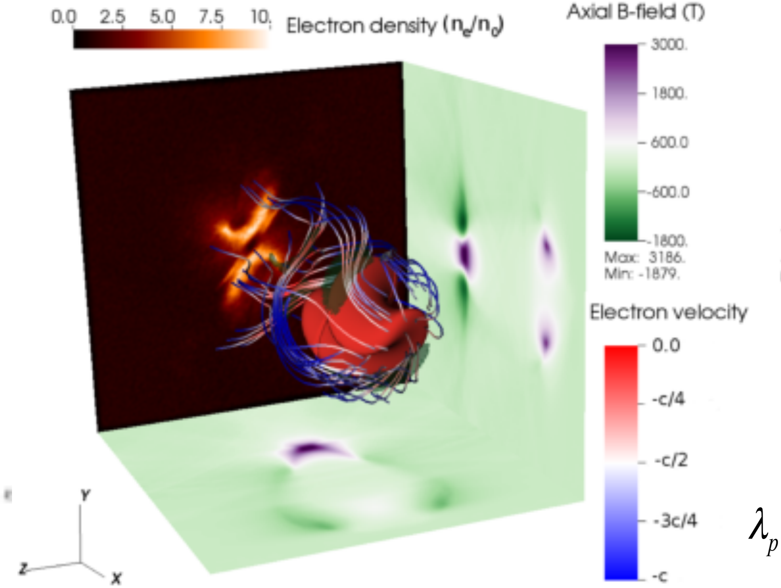


A.Andreev et al. JETPL 2013

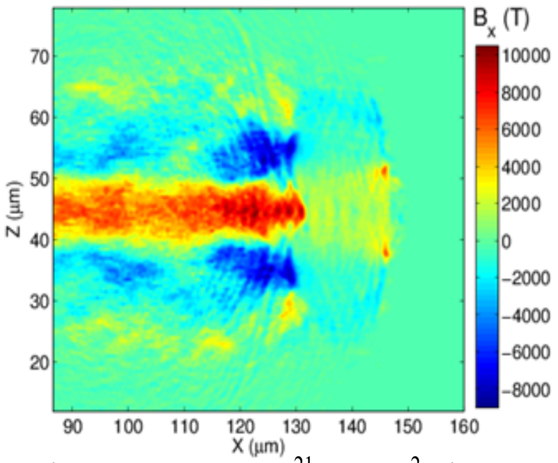
GigaGauss magnetic field generation by screw shape laser pulse in under-dense plasma

Z.Lech&A.Andreev et al., Sci. Rep. (2016)



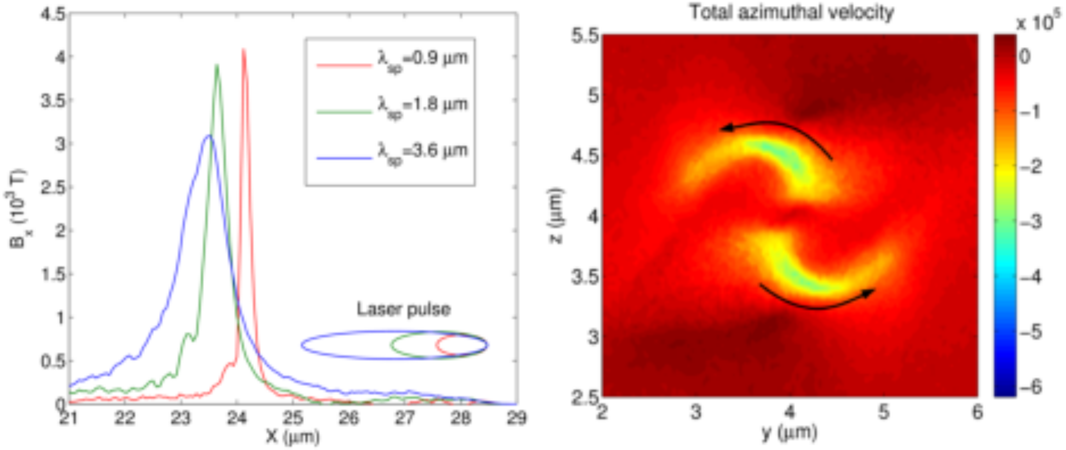


Laser intensity 1.6 × 10^21 W/cm2, pulse width 1.8 μm, pulse length is equal to spiral step 1.8 μm; electron density is 0.6 × 10−3ncr.



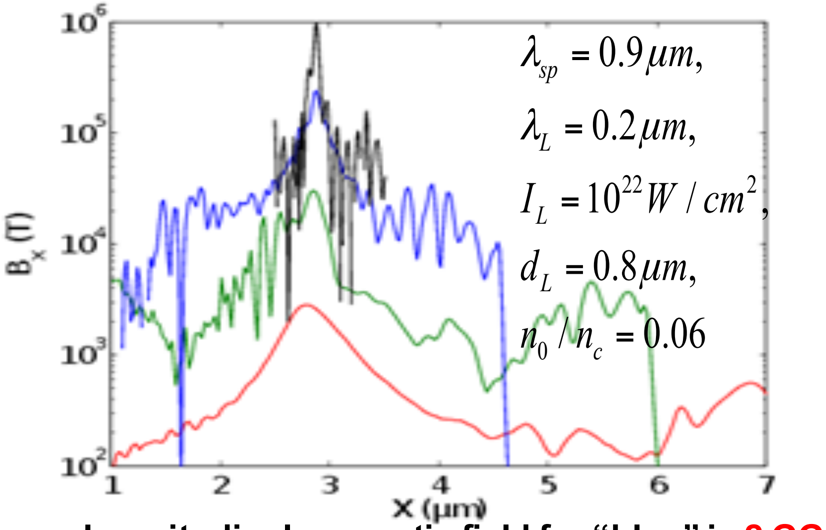
$$\lambda_p \le \lambda_{sp} = 7\,\mu m, I_L = 10^{21} W/cm^2, \lambda_L = 0.8\,\mu m,$$

$$n_0 = 0.04 n_c, d_L = 14\,\mu m$$



(a) Longitudinal magnetic field along the axis of propagation

(b) total azimuthal velocity distribution at bubble back for λsp=0.9 μm.



$$\lambda_{sp} = 0.9\,\mu m,$$

$$\lambda_L = 0.2\,\mu m,$$

$$I_L = 10^{22} W/cm^2,$$

$$d_L = 0.8\,\mu m,$$

$$n_0/n_c = 0.06$$

Longitudinal magnetic field for “blue” is 2 GG

Conclusion

- **Optimal nano-structure of the considered targets permits to get almost total absorption of laser pulse. Profile shape has a weak influence on the absorption. 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 a structure by a laser prepulse 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-wires exhibit a large coefficient of laser energy conversion to kinetic energy of a fast electrons. Its bunch can propagate as far as several hundred micrometers in such targets.**
- **The scheme of generation of short, energetic, dense electron nano-bunches is offered for the interaction at big angle of incidence of laser pulse with thin semilimited target. Such target creates three streams of electron bunches propagating in specular, incident and refracted directions in relation to the laser axis. Conversion efficiency into fast electrons is a few percents.**
- **The obtained atto-pulse generation and focusing with energy conversion efficiency of a few percent by cone-shaped target enables the peak intensity of the filtered fields in the focus to reach the value of the incident radiation.**

Thank you to all of you for listening!