RELATIVISTICALLY STRONG LASER PLASMA INTERACTION: ENERGETIC PARTICLES, GAMMA AND THZ RADIATION, MAGNETIC FIELDS

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July 23, 2017

Outline

- Ion (proton) acceleration
  - thin foils with optimal thickness
  - circular vs. linear laser polarization
  - ion acceleration from low-density targets
- Magnetic field generation
- Electron acceleration for X-ray source
- Thz generation

Applications of ion beams

- new high-time resolution diagnostic techniques, since the short ion pulse duration [Borghesi PoP2002];

- ion beam radiography / imaging and lithography;

- applications in energy research (ion “Fast Ignitor” in the inertial fusion energy context) [Roth PRL2001, Bychenkov Sov. Plasma Phys. 2001, Guskov QE2001];

- medical treatment (proton therapy [Bulanov Sov. Plasma Phys. 2002], transmutation of short lived radio-isotopes for positron emission tomography (PET) in hospitals [Fritzler APL2003]);

- short neutron source [Roth PRL2013];

- astrophysical phenomena in the Lab;

- nuclear physics [Bychenkov JETP99].

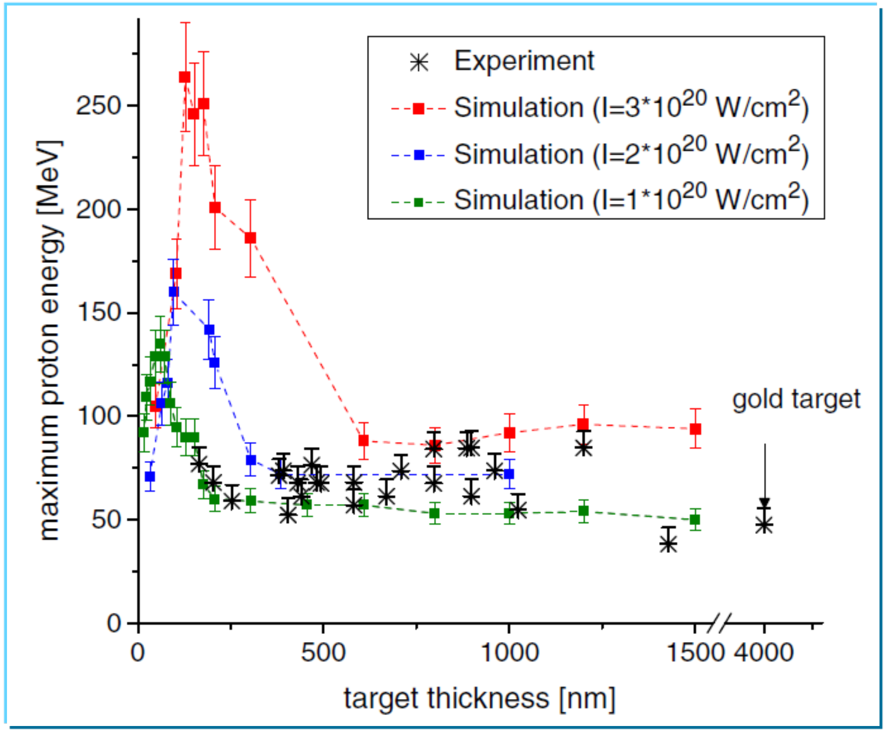
Recent experiments on proton acceleration

F. Wagner et.al PRL 116, 205002 (2016)

Laser: ~160-200J; 500-800 fs;
I ~ (0.7-2.6)×10^{20} W/cm^2

Polymethylpentene foil,
thickness 165-1400 nm,
gold foil, 4 μm

Proton energy 85 МэВ

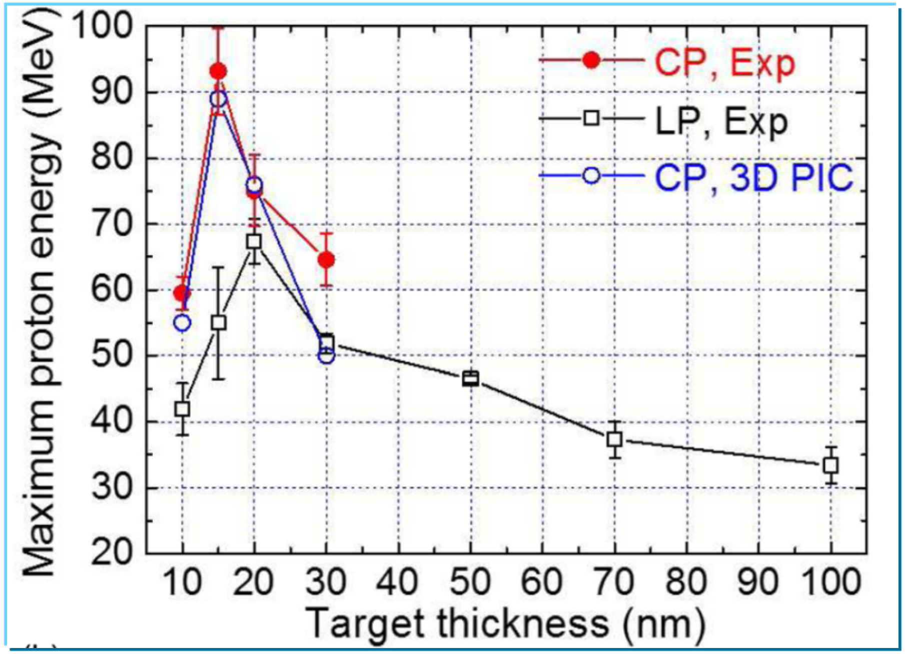


I. J. Kim et.al PoP 23, 070701 (2016)

Laser: ~1 PW; 27J; 30 fs;
8.5 J on target, 6.1×10^{20} W/cm^2

Polymer foil, thickness of 15 nm, (2.5° from normal)

Proton energy 93 МэВ

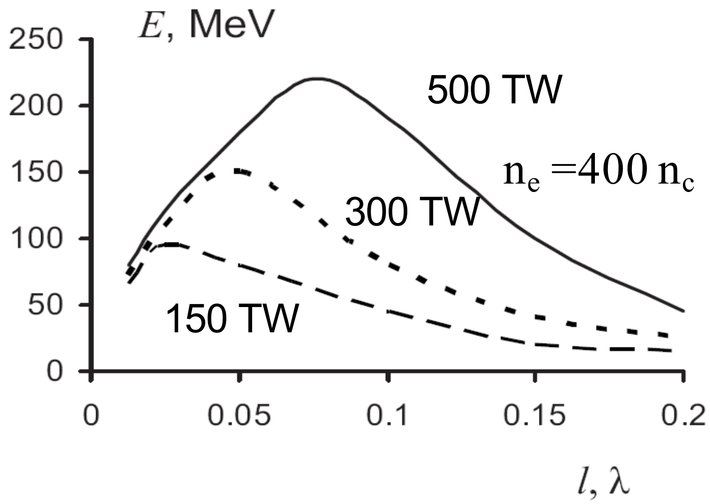


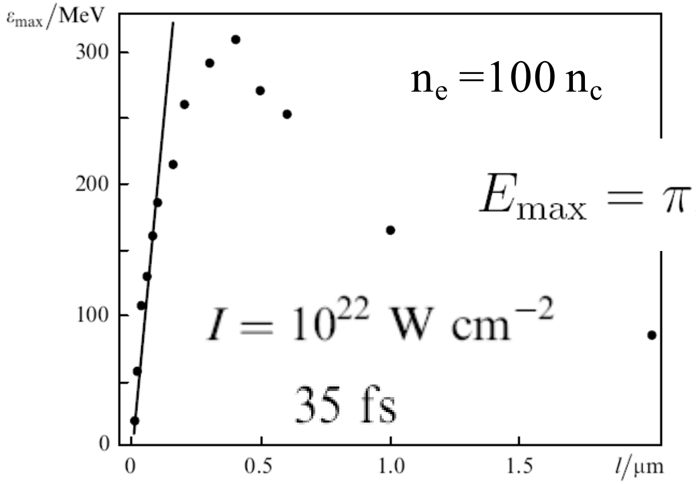
Optimal target thickness

Proton energy from double-layered target

2D PIC simulation

Proton energy from foil target





$$E_{\max} = \pi Z n_{\mathrm{i}} e^2 l d$$

There is optimal thickness for given density and laser intensity !

Coulomb field

$$E_C = 2\pi Z e n_i l$$

Laser field

$$E_L = a\omega m_e c/e$$

$$E_L = E_C \qquad a = 0.85\sqrt{I\lambda^2 10^{-18}}$$

$$a = \pi \frac{n_e}{n_c}\frac{l}{\lambda} \Rightarrow l_{opt} = a\frac{\lambda}{\pi}\frac{n_c}{n_e}$$

Condition of plasma transparency

$$a > \pi \frac{n_{\mathrm{e}}}{n_{\mathrm{c}}}\frac{l}{\lambda}$$

Absorption ?

Ion energy ?

Problem of laser light transmission through plasma layer

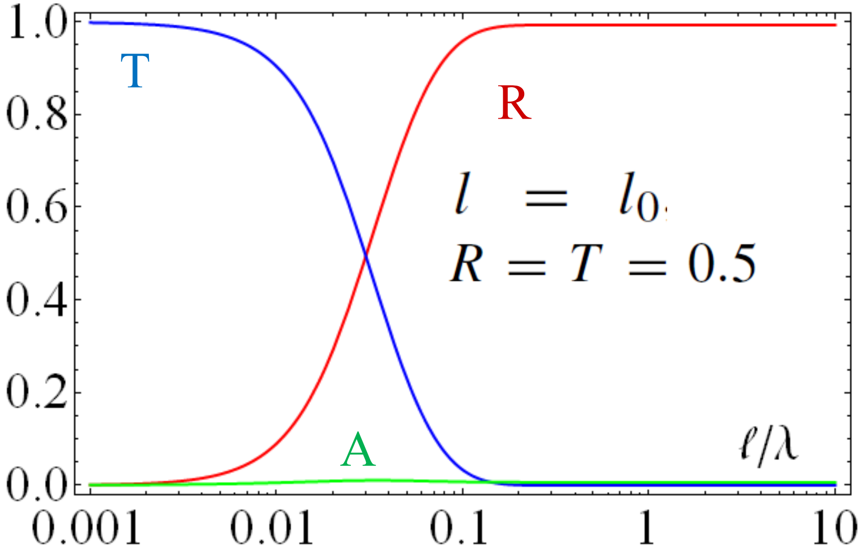
L.D. Landau & E.M. Lifshitz   Electrodynamics of Continuous Media

$$R = \left| \frac{r_{12}(1 - \exp(2i\phi))}{1 - r_{12}^2 \exp(2i\phi)} \right|^2$$ reflection $$r_{12} = \frac{1-\sqrt{\epsilon}}{1+\sqrt{\epsilon}},$$

$$T = \left| \frac{(1 - r_{12}^2)\exp(i\phi)}{1 - r_{12}^2 \exp(2i\phi)} \right|^2$$ transmission $$\phi = \frac{\omega_0}{c} l \sqrt{\epsilon}$$

A=1- R –T absorption

$$\frac{1}{|\epsilon|} \ll \frac{\omega_0}{c} l \ll \frac{1}{\sqrt{|\epsilon|}} \qquad \epsilon \simeq -\frac{n_e}{a_0 n_c}$$



$$R = \left| \frac{1}{1 - i l_0 / l} \right|^2 \qquad T = \left| \frac{1}{1 + i l / l_0} \right|^2$$

$$\frac{l_0}{\lambda} = a_0 \frac{1}{\pi} \frac{n_c}{n_e} \qquad \frac{n_e}{n_c} > 4a_0$$

PIC code for simulation of laser-plasma interaction

$$\frac{\partial f_{i,e}}{\partial t}+\mathbf{v}\frac{\partial f_{i,e}}{\partial \mathbf{r}}+\mathbf{F}_{i,e}\frac{\partial f_{i,e}}{\partial \mathbf{p}}=0,$$

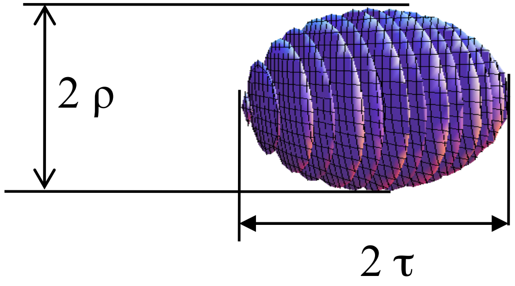
$$\mathbf{F}_{i,e}=q_{i,e}\left(\mathbf{E}+\frac{1}{c}[\mathbf{v},\mathbf{H}]\right),$$

$$\mathrm{rot}\mathbf{H}=\frac{4\pi}{c}\mathbf{j}+\frac{1}{c}\frac{\partial \mathbf{E}}{\partial t},\quad \mathrm{rot}\mathbf{E}=-\frac{1}{c}\frac{\partial \mathbf{H}}{\partial t},$$

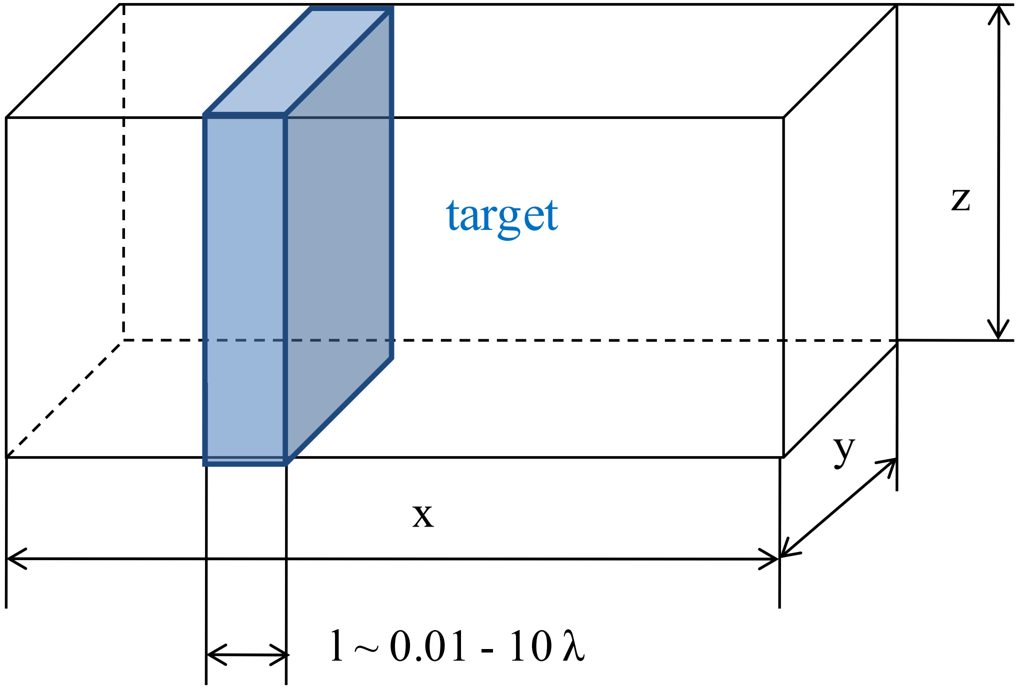
$$\mathrm{div}\mathbf{E}=4\pi\rho,\quad \mathrm{div}\mathbf{H}=0.$$

$$\mathbf{j}=\sum_{i,e}q_{i,e}\int f_{i,e}\mathbf{v}d\mathbf{v},\quad \rho=\sum_{i,e}q_{i,e}\int f_{i,e}d\mathbf{v}$$

Laser pulse



0.3 - 300 J,
5×10^{19} - 5×10^{22} W/cm^2
2 τ = 30 fs
2 ρ = 4 μm
Linear/circular polarization



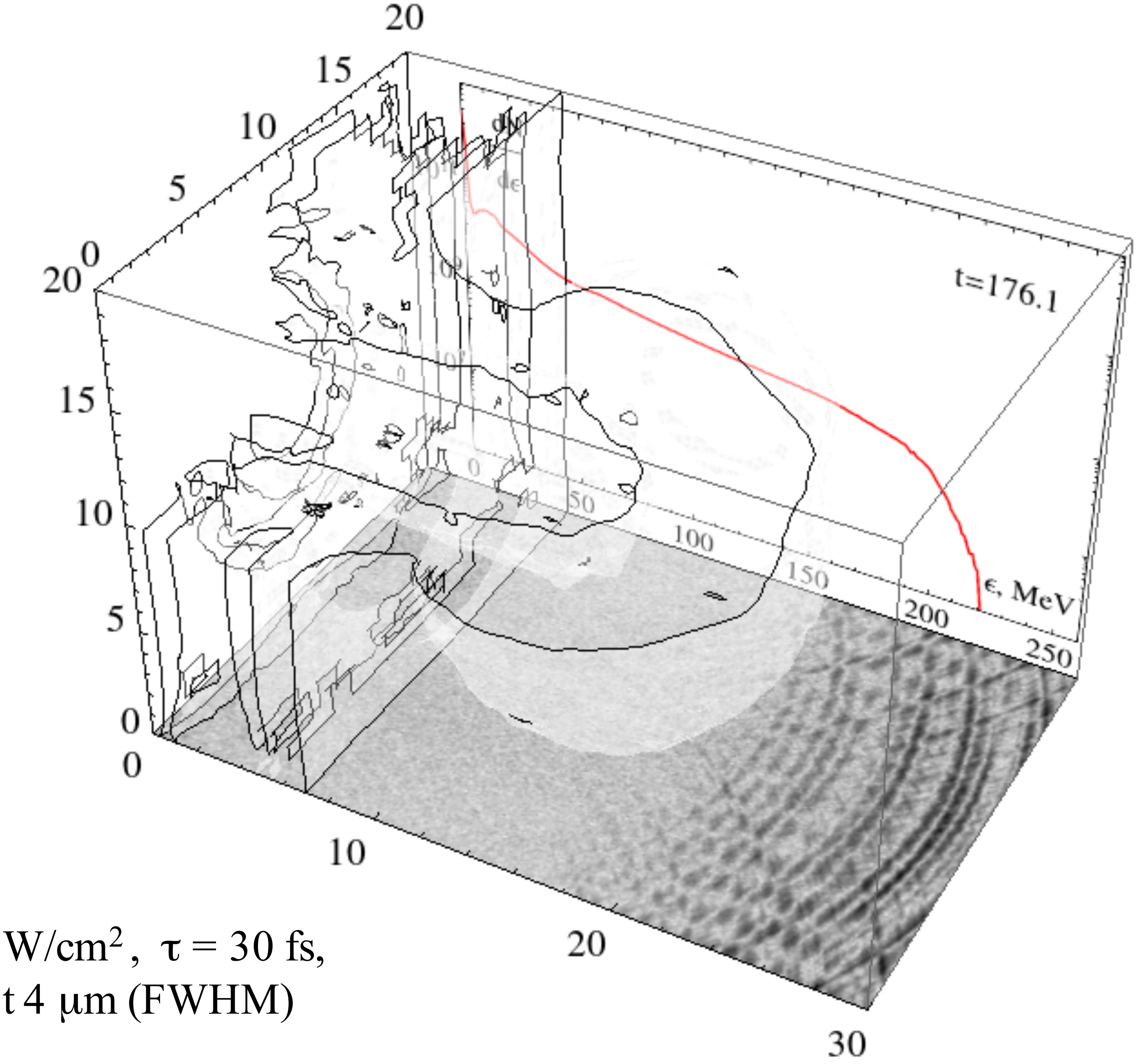
Target
CH_2 foil
(n_e=200 n_c)

electrons
heavy ions
light ions (protons)

x × y × z = 50 λ × 20 λ × 20 λ

Δx × Δ y × Δ z = λ/100 × λ/20 × λ/20

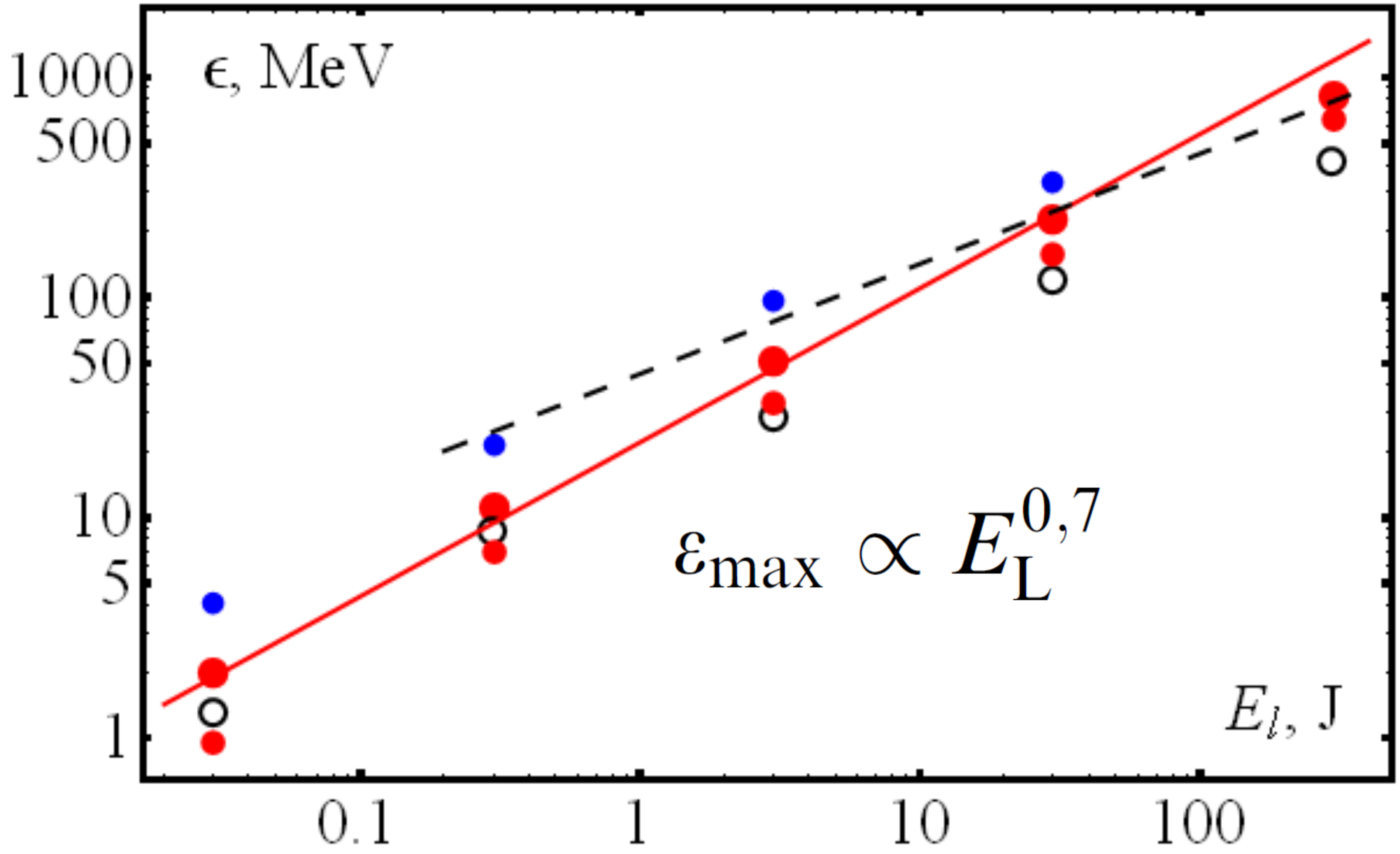
3D proton acceleration by 30 J laser pulse



I =5 10^{21} W/cm^2, τ = 30 fs,
focus spot 4 μm (FWHM)

Target – CH_2 foil 0.1 μm (n_e=200 n_c)

Proton acceleration from ultra-thin foils



● τ = 30 fs, ρ = 2 μm

● τ = 30 fs, ρ = 6 μm

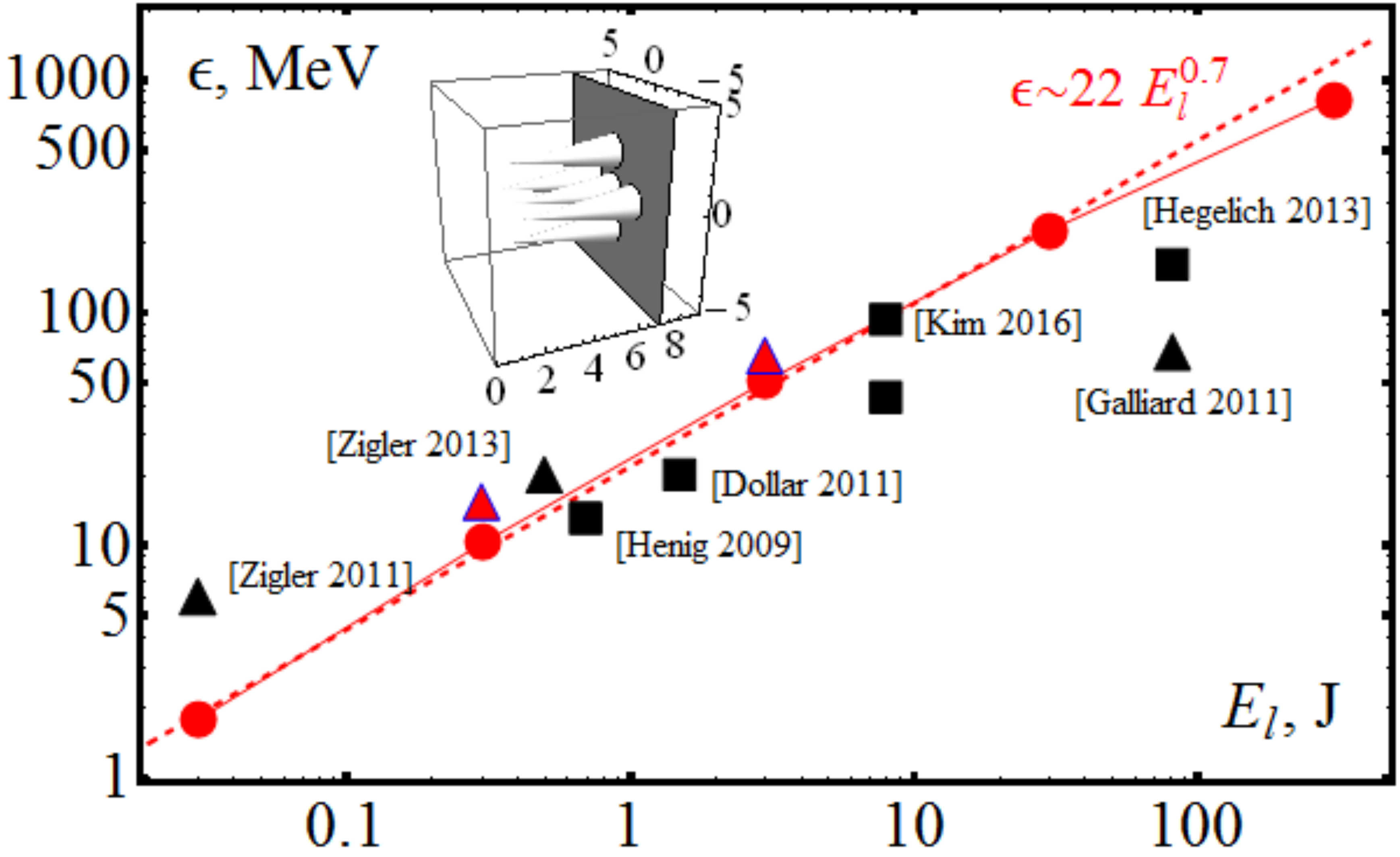
● τ = 30 fs, ρ = 4 μm

○ τ = 150 fs, ρ = 4 μm

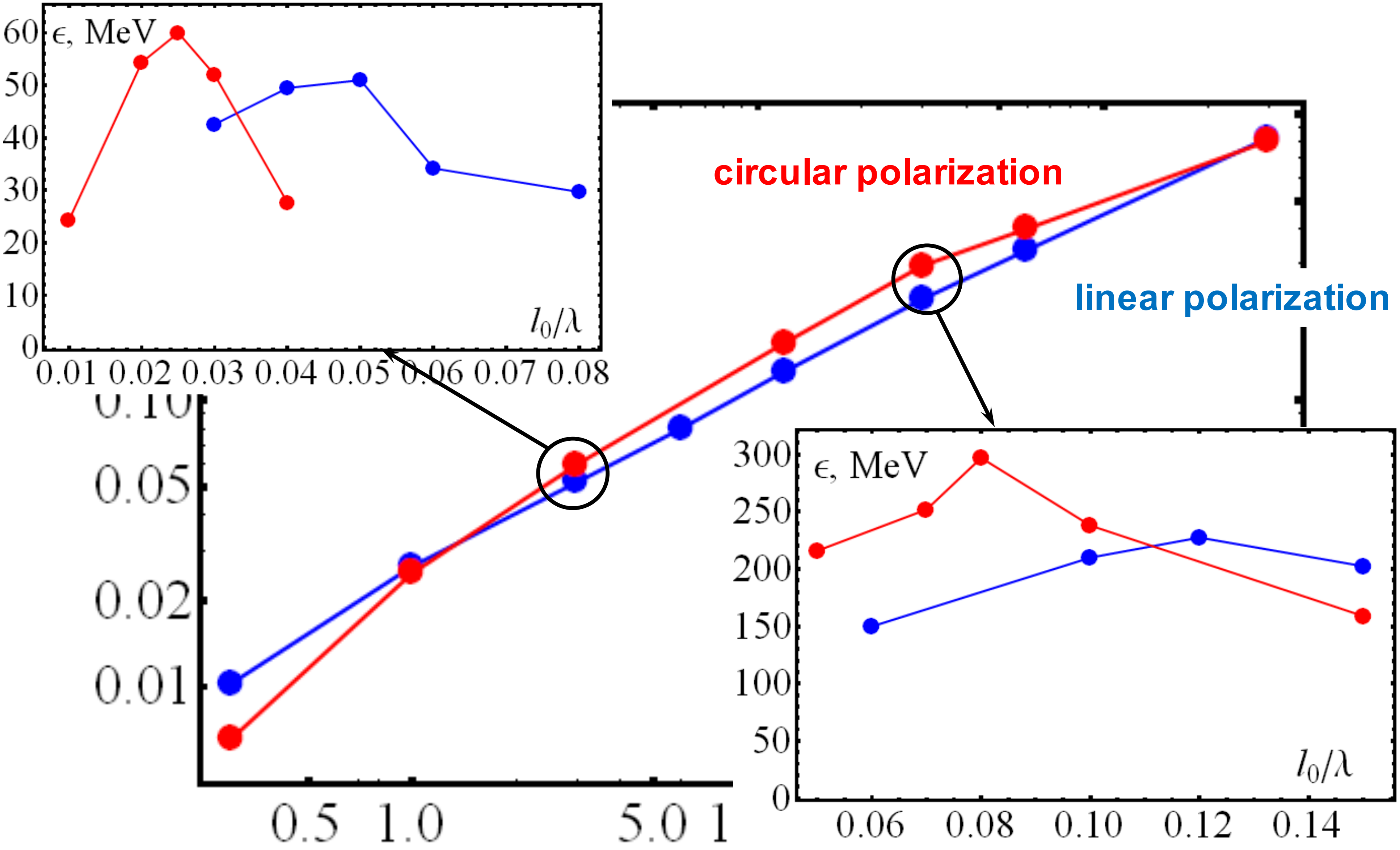
Laser: τ = 30-150 fs, 2-6 μm (FWHM)
$I = 5\times10^{18}$ W/cm^2 --5×10^{22} W/cm^2

Target: CH$_2$ foil (n_e=200 n_c) with optimal thickness l = 0.005λ - λ

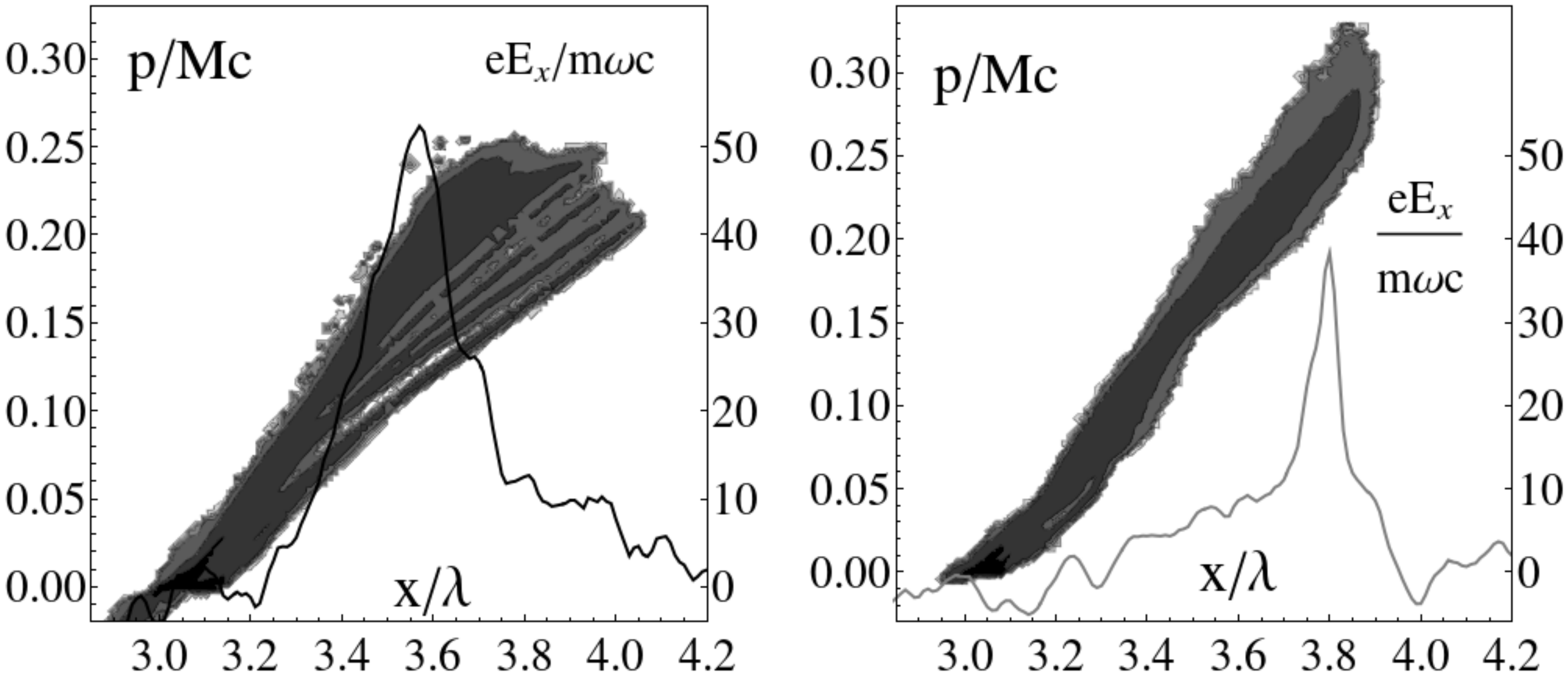
Proton acceleration from ultra-thin foils : simulation vs. experiment



Thin foils: linear vs. circular polarization



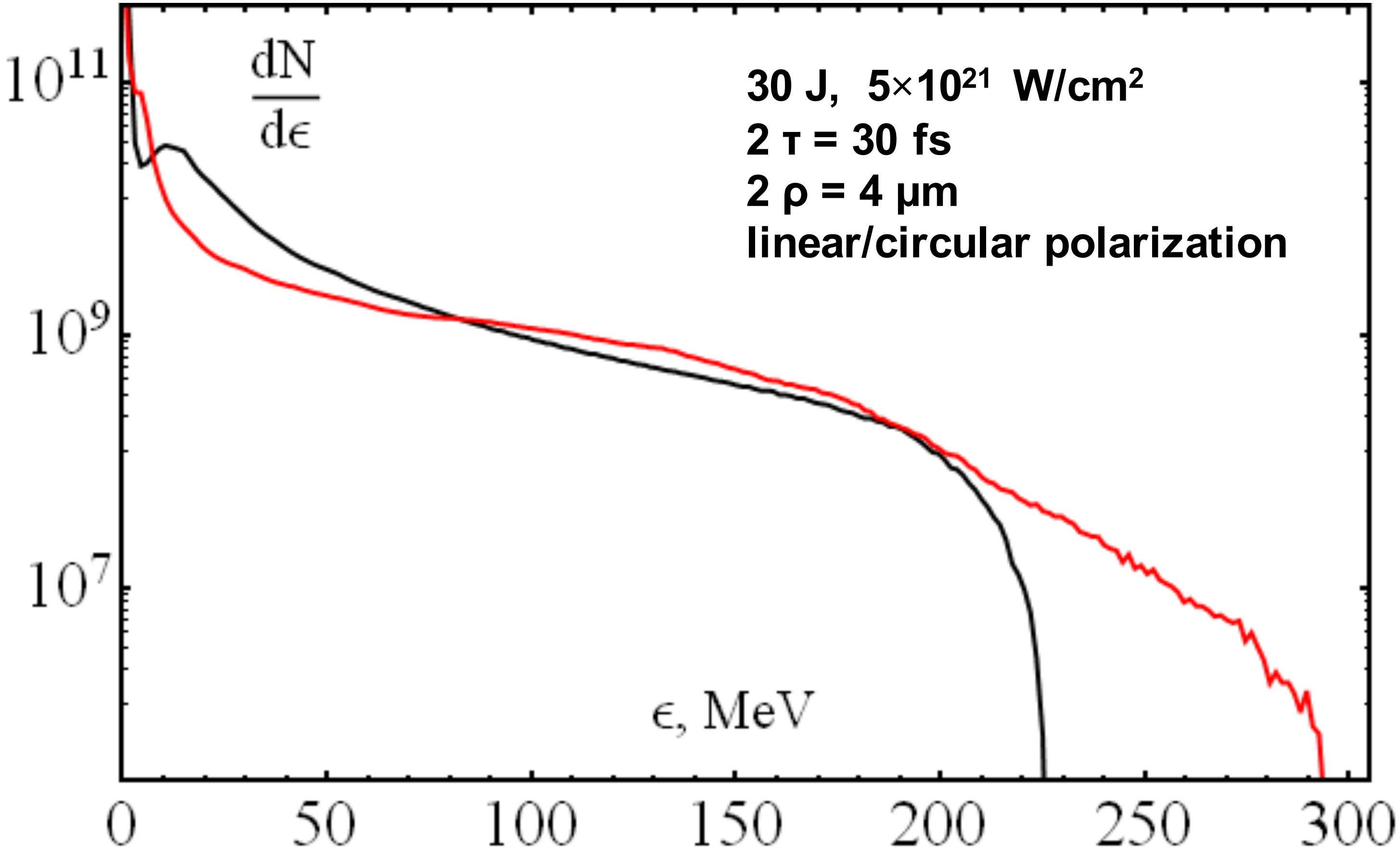
Thin foils: linear vs. circular polarization



30 J, 5×10^{21} W/cm^2
2 τ = 30 fs
2 ρ = 4 μm
linear/circular polarization

Semi-transparent target – possibility to increase interaction time !

Thin foils: linear vs. circular polarization



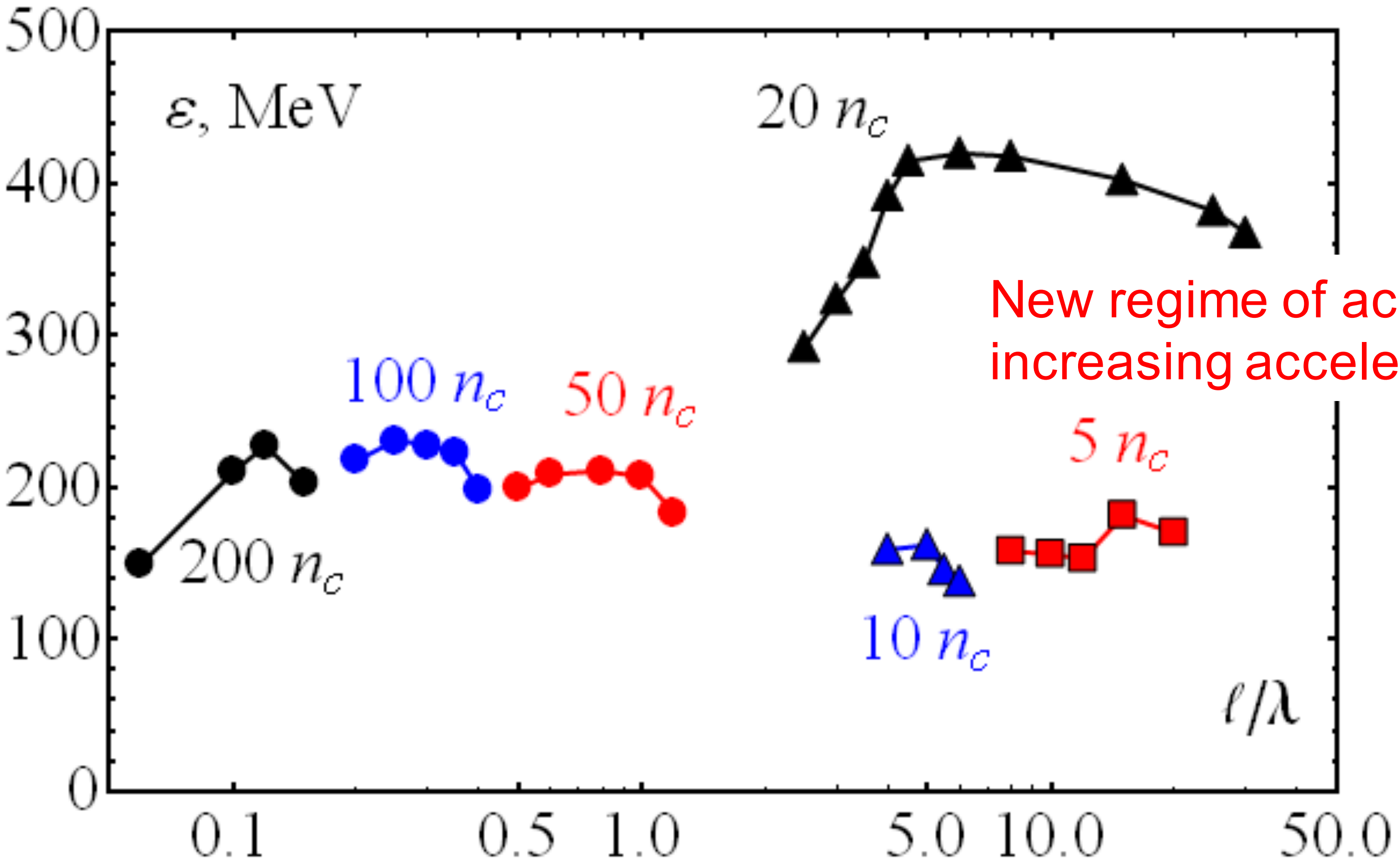
30 J, 5×10^{21} W/cm^2
2 τ = 30 fs
2 ρ = 4 μm
linear/circular polarization

10^9 protons with energy > 200 MeV

2.5×10^9 protons with energy > 200 MeV

1.3 times maximum energy increase

Proton acceleration: maximum energy vs. thickness & density of the target.

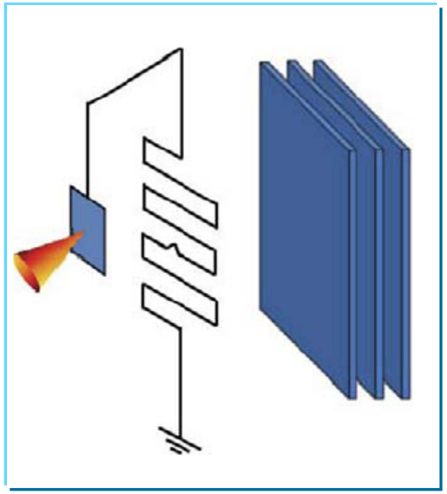


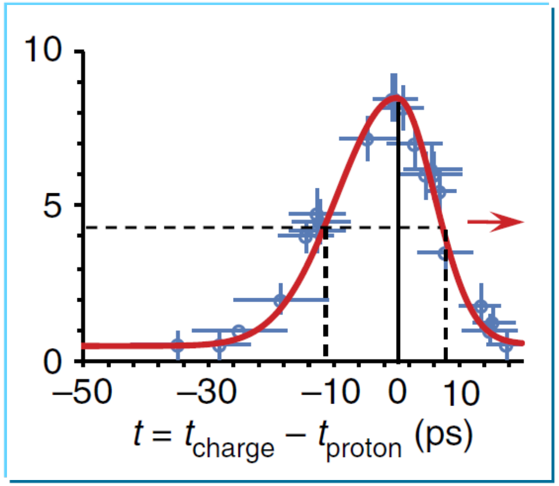
New regime of acceleration – increasing acceleration time !

Laser: τ = 30 fs, 4 μm (FWHM)
I = 5×10^{21} W/cm^2

Target: CH_2 plastic& aerogel

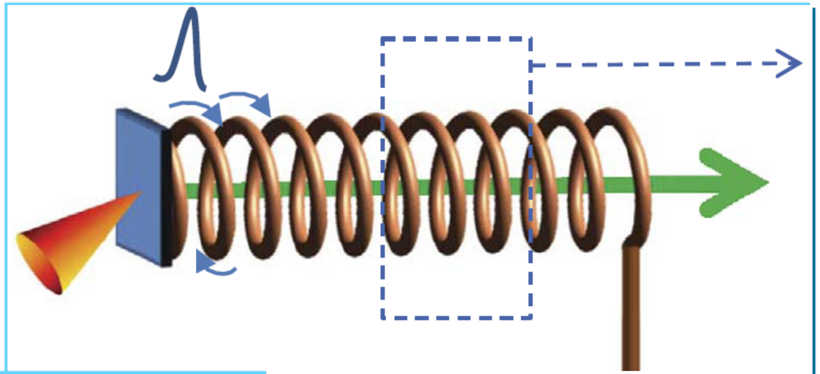
Experiment to increase acceleration time

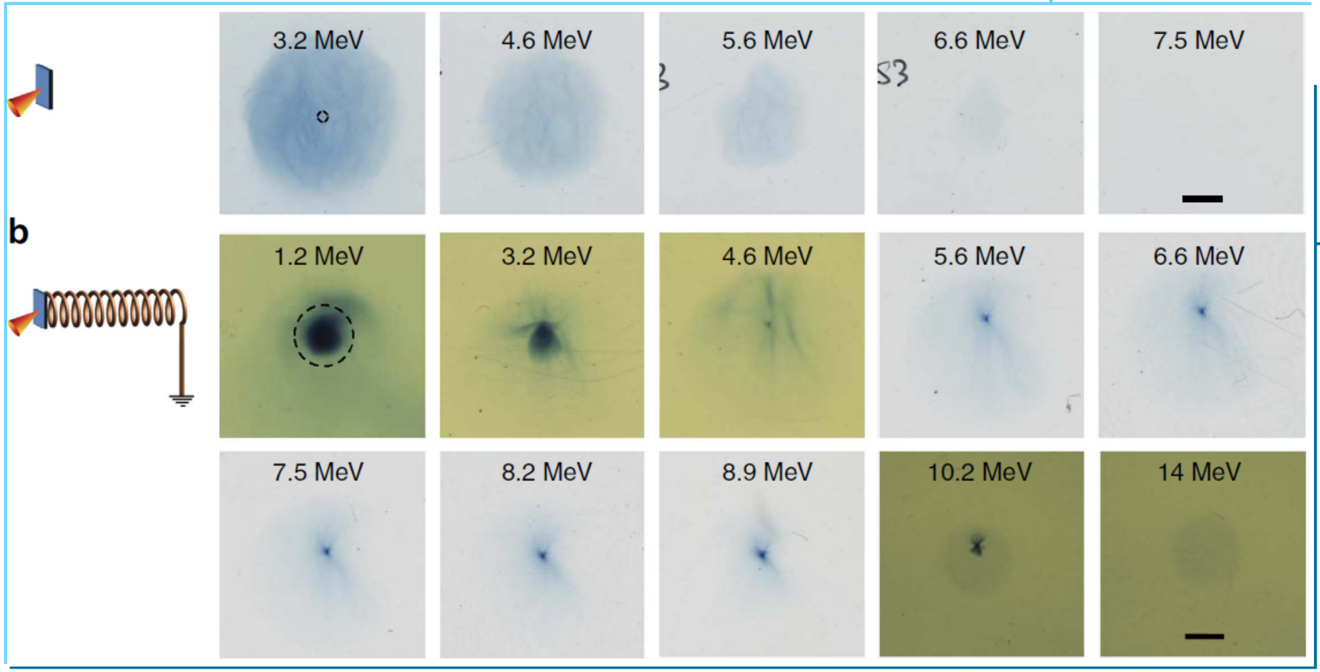




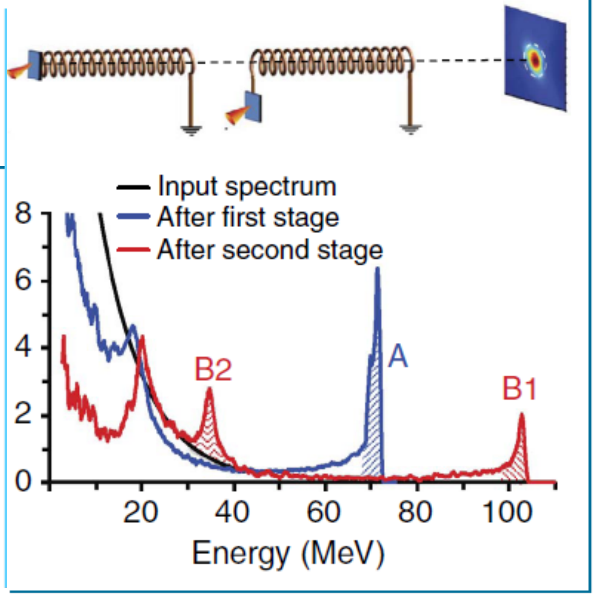
S. Kar et. al Nat. Comm. 7, 10792 (2016)

Laser: ~3 J, 30 fs; I~ 10^{20} W/cm^2

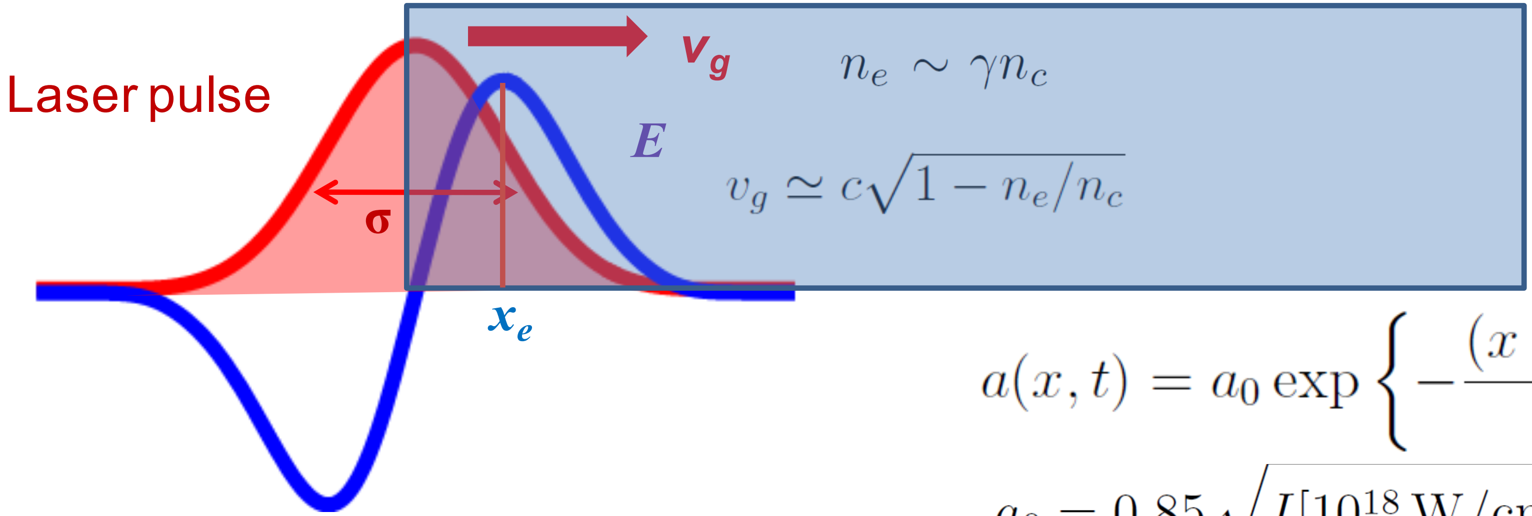




Simulation 30J, 30 fs



Synchronization of ion and field velocities



$$n_e \sim \gamma n_c$$

$$v_g \simeq c\sqrt{1 - n_e/n_c}$$

$$a(x,t) = a_0 \exp\left\{-\frac{(x - x_g(t))^2}{\sigma^2}\right\}$$

$$a_0 = 0.85\sqrt{I[10^{18}\,\mathrm{W/cm^2}]\lambda^2[\mu\,\mathrm{m}^2]}$$

$$F_p(x,t) = -mc^2\,\nabla\sqrt{1 + a^2(x,t)/2}$$

Relativistic ponderomotive force

$$\frac{dp_i}{dt} = eE_0$$

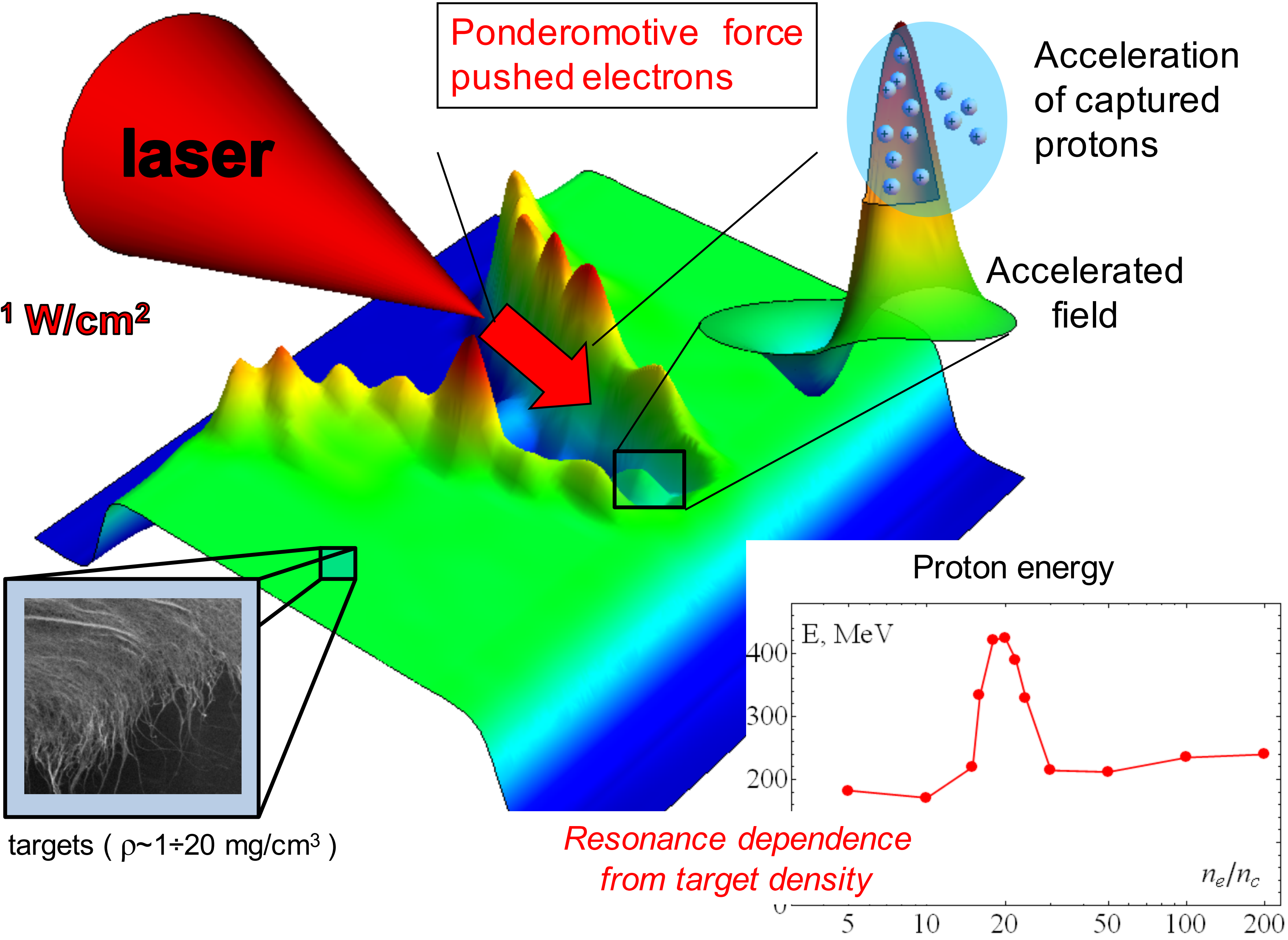
$$\frac{dx_i}{dt} = v_i = \frac{p_i c}{\sqrt{M^2c^2 + p_i^2}}$$

$$v_i = \frac{ctw_0}{\sqrt{w_0^2t^2 + c^2}} \qquad w_0 = \frac{eE_0}{M}$$

$$\boxed{\epsilon = 0.31 a_0 l_0/\sigma \ \text{ MeV}}$$

Proton acceleration by ponderomotive potential

1 PW
30 J
30 fc
5×10^{21} W/cm^2



Ponderomotive force pushed electrons

Acceleration of captured protons

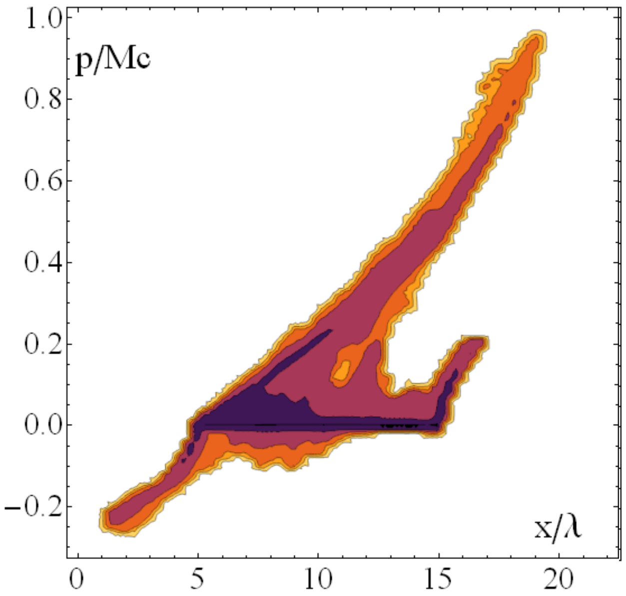
Accelerated field

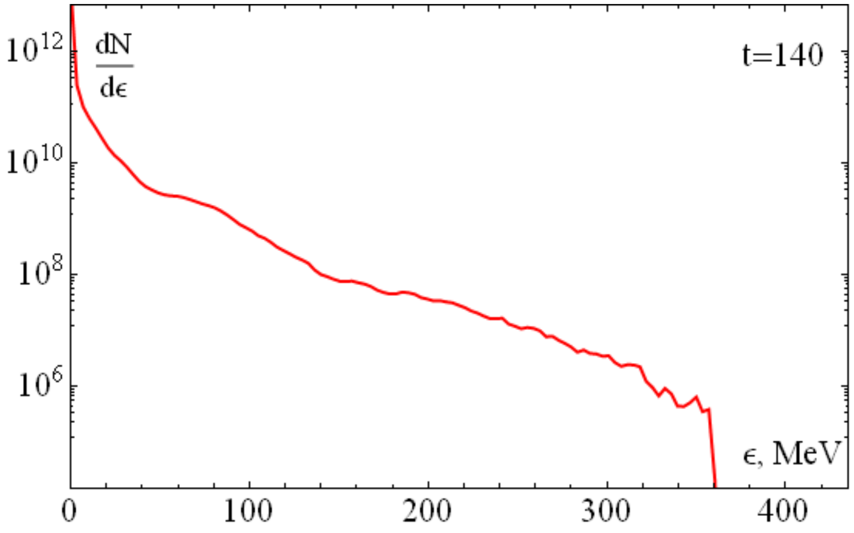
Proton energy

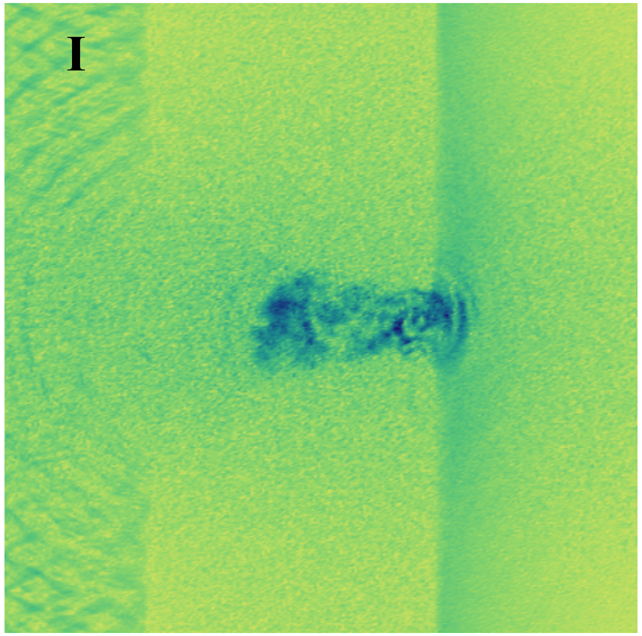
Innovative targets (ρ~1÷20 mg/cm^3)

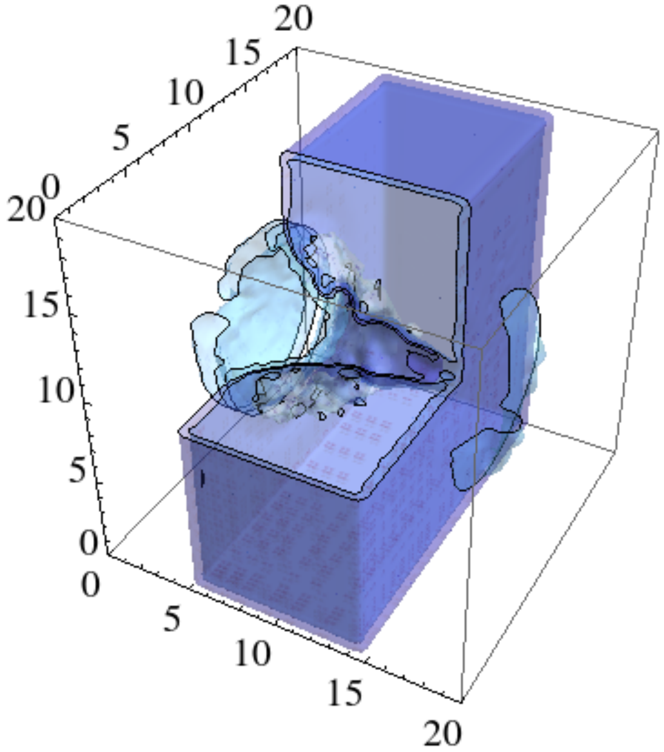
Resonance dependence from target density

3D PIC simulation of SASL

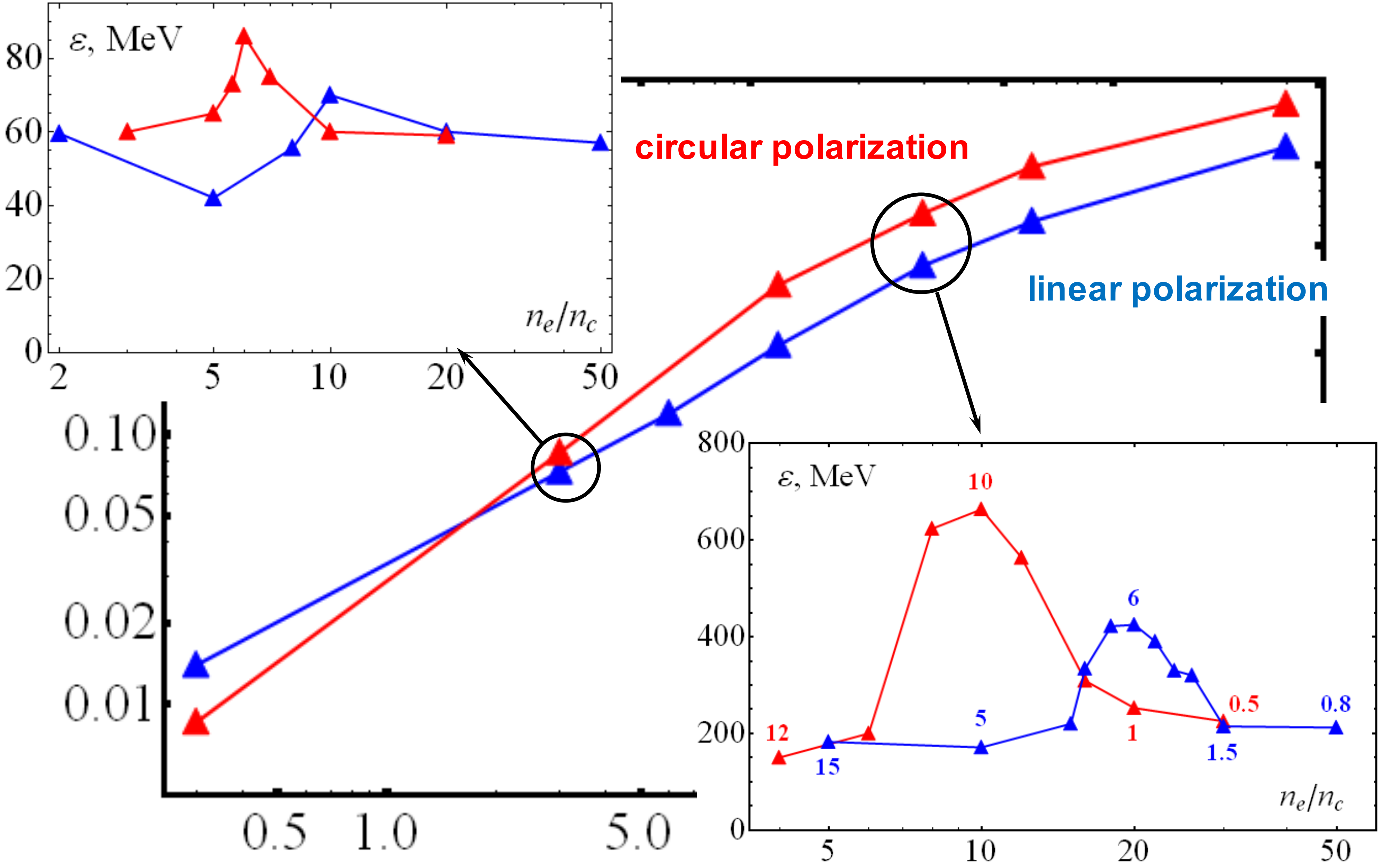




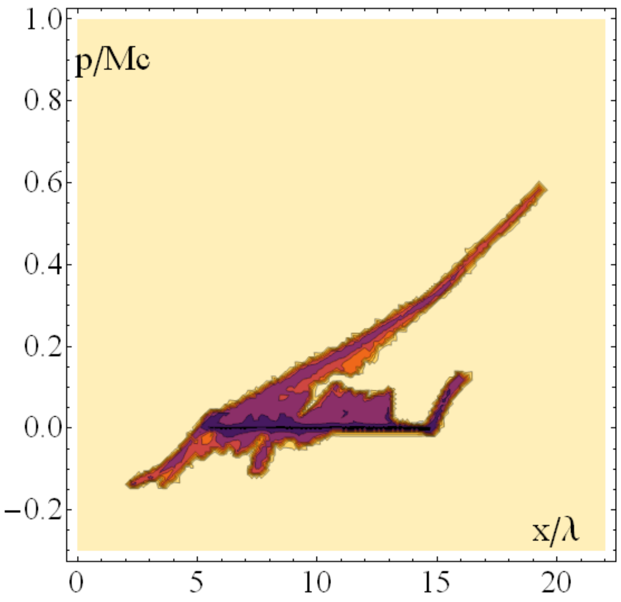


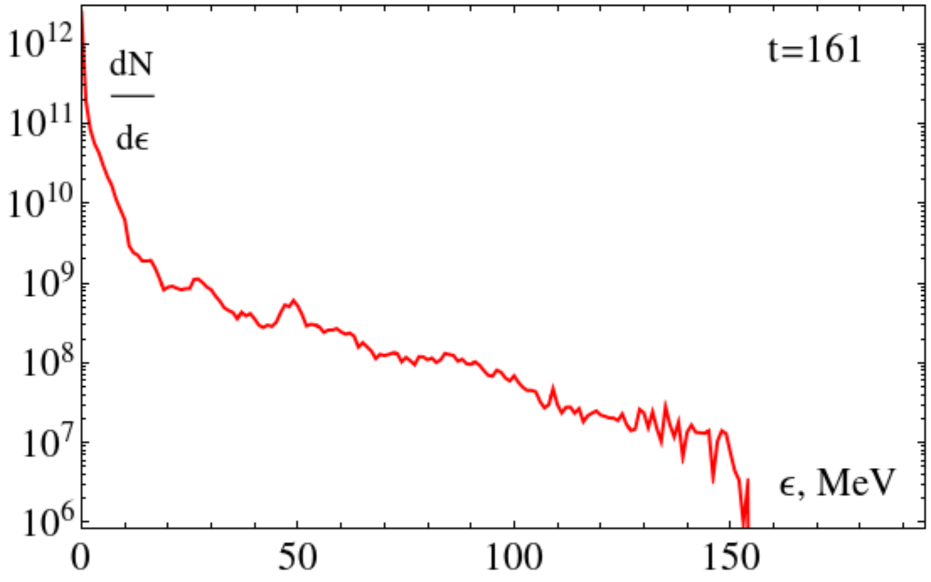


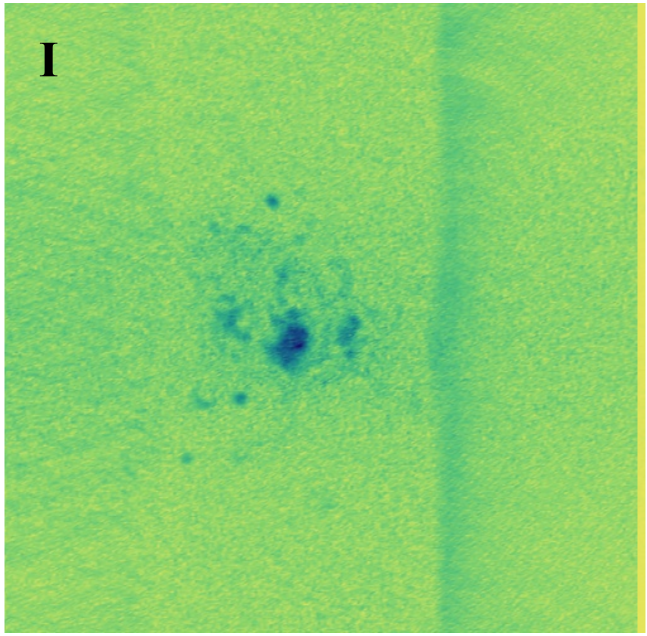
SASL regime: linear vs. circular polarization

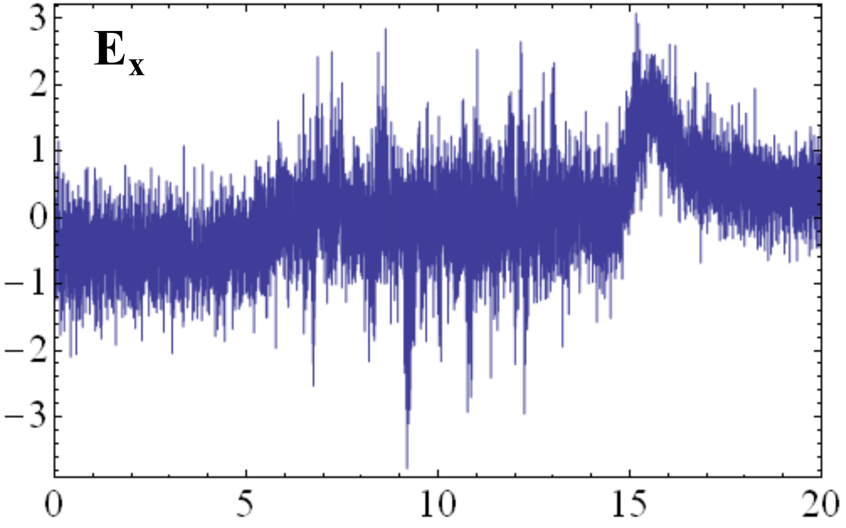


SASL regime for circularly polarized laser pulse

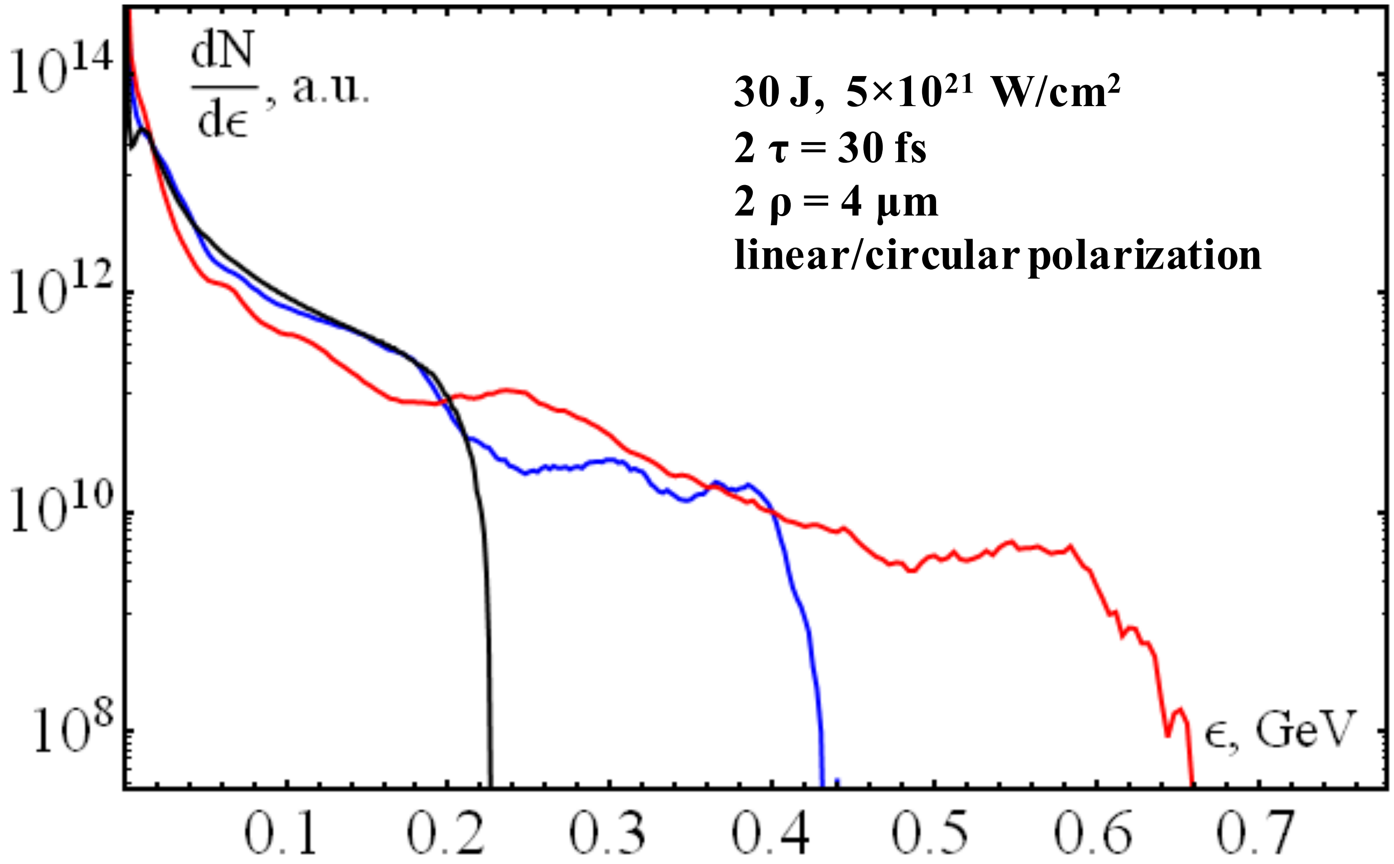








SASL regime: linear vs. circular polarization

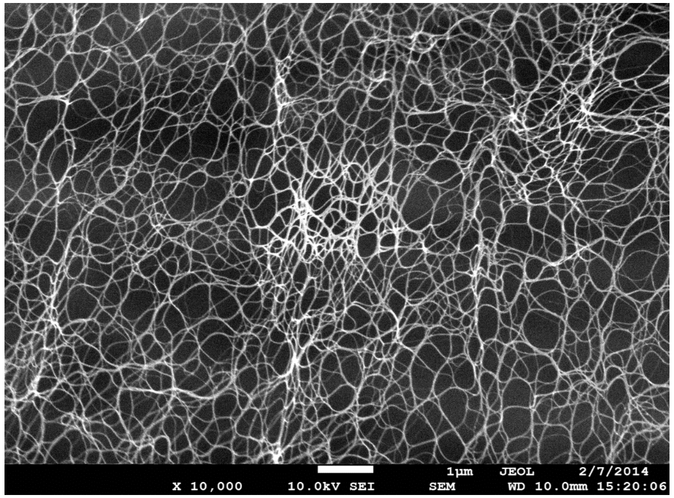


5×10^9 protons with energy > 200 MeV

1.3×10^{10} protons with energy > 200 MeV

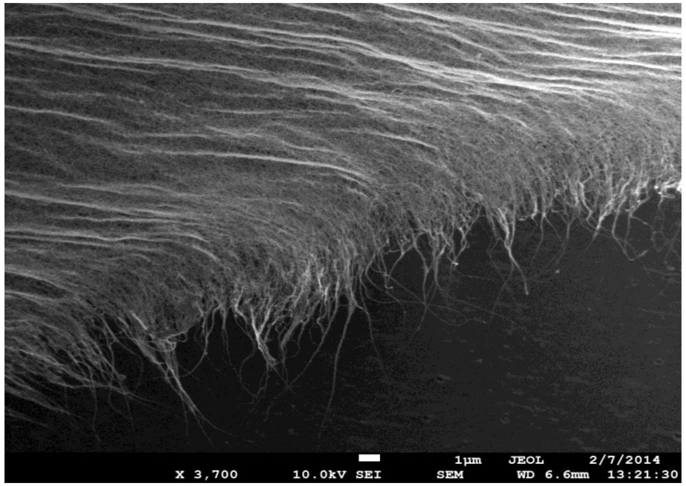
1.6 times maximum energy increase

Innovative low-density targets for particle acceleration

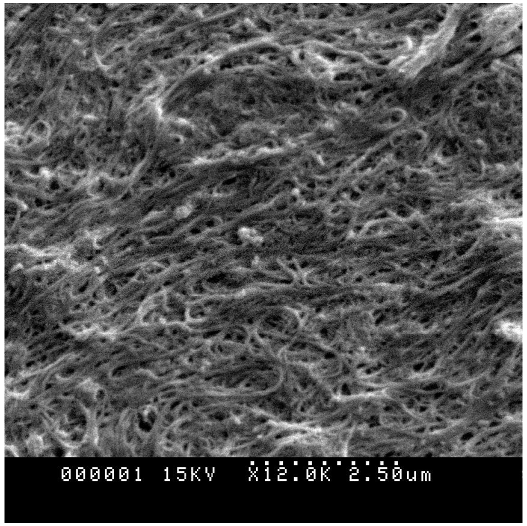


SWNTs with density of 0.1 mg/cm^3

Thickness – 100- 200 nm



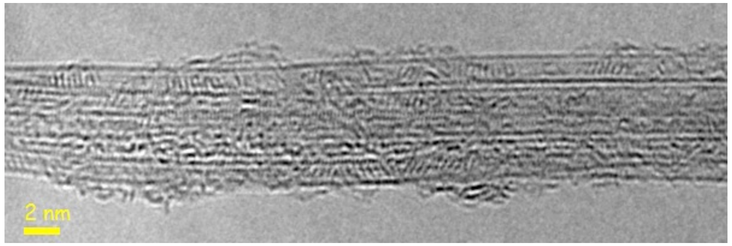
SWNTs with density of 1 mg/cm^3



SWNTs with density of 30-50 mg/cm^3

Thickness – 5- 10 µm

- To enrich the films with hydrogen the nanotubes have been filled with coronene ($C_{24}H_{12}$) molecules.
- 2 mass % of hydrogen can be introduced into films.



Summary on ion acceleration

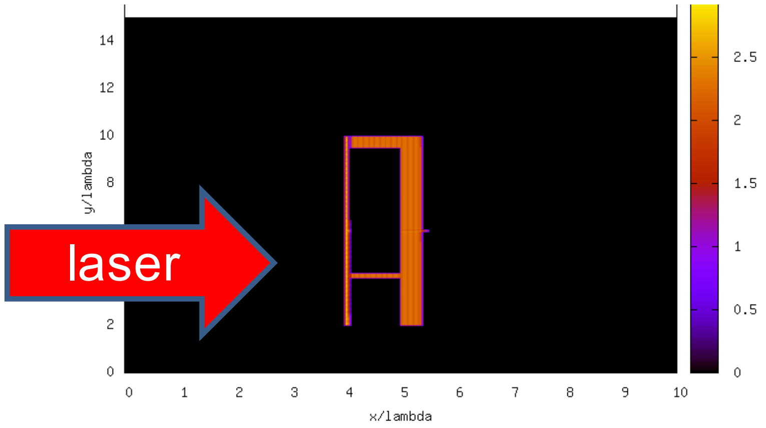
New dependence of maximum proton energy from laser intensity

Circularly polarized laser pulse has advantage in terms of ion acceleration

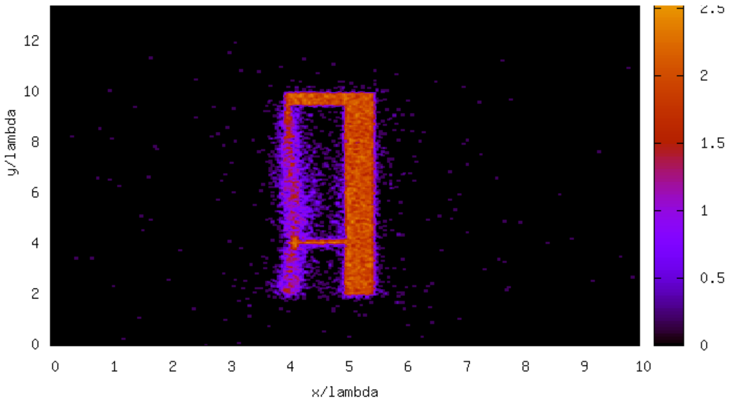
The new mechanism of ion acceleration from low-density targets by slow light is proposed

Magnetic field generation in interaction of short laser pulse with metal target

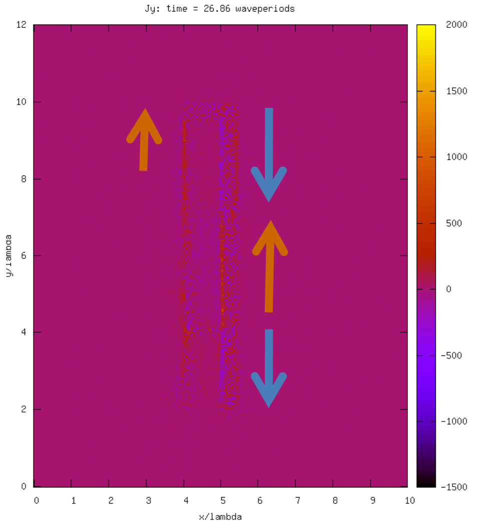
Irradiated metal target



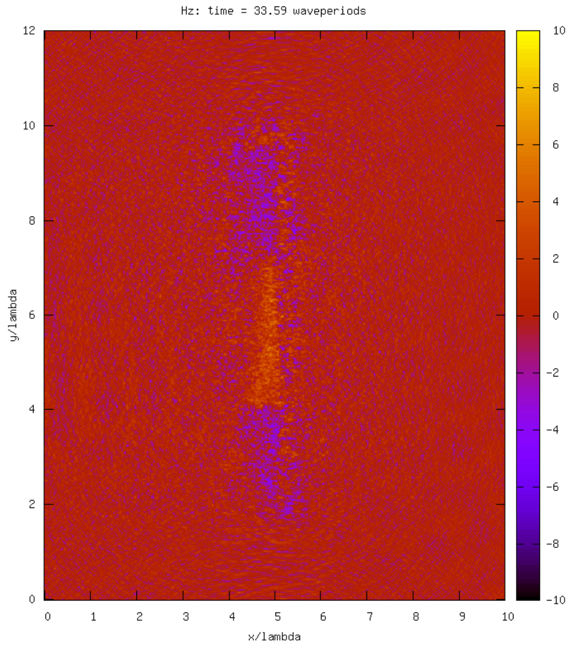
Electron evacuation under action of short laser pulse



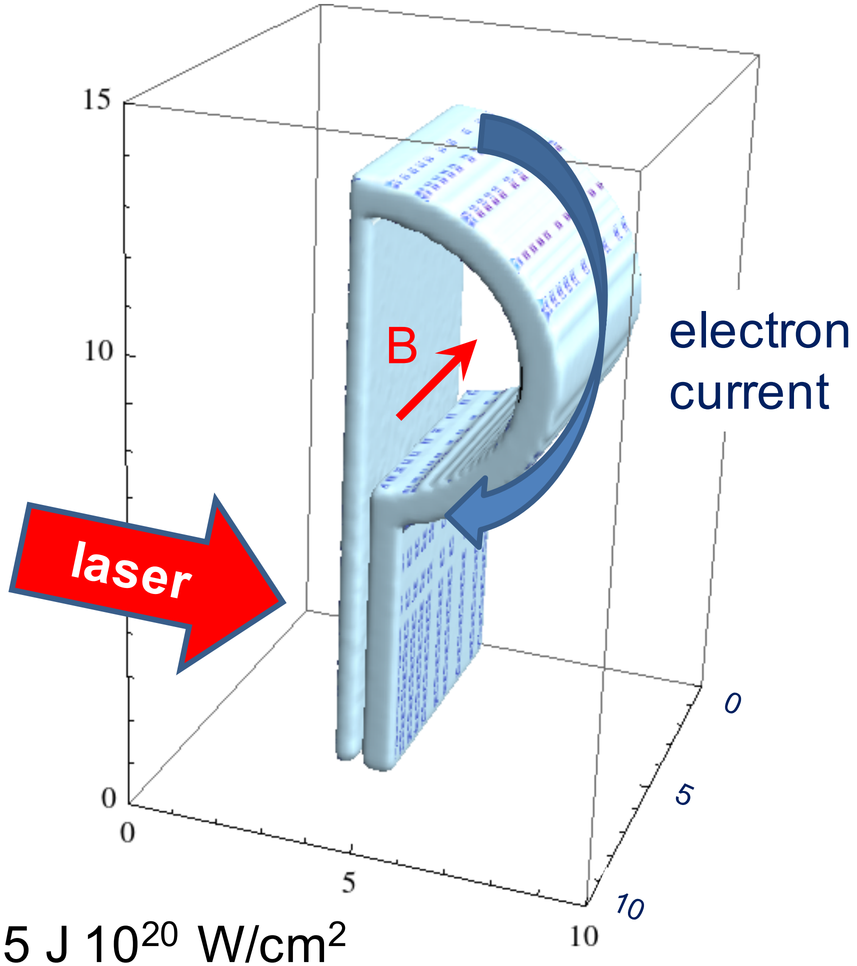
Electron current



Magnetic field

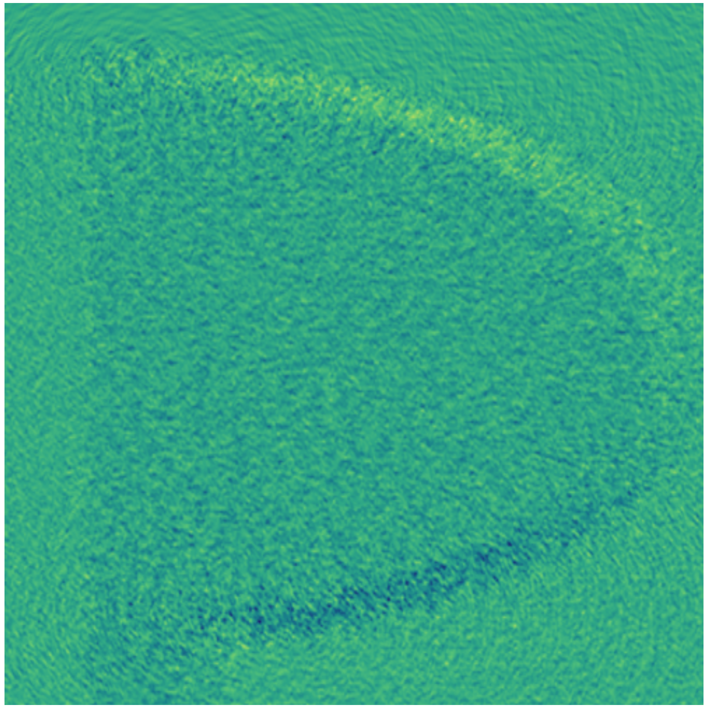


New targets for magnetic field generation



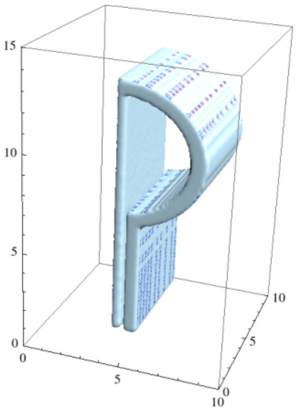
0.5 J 10^{20} W/cm^2
2 τ = 30 fs
2 ρ = 4 μm
linear polarization

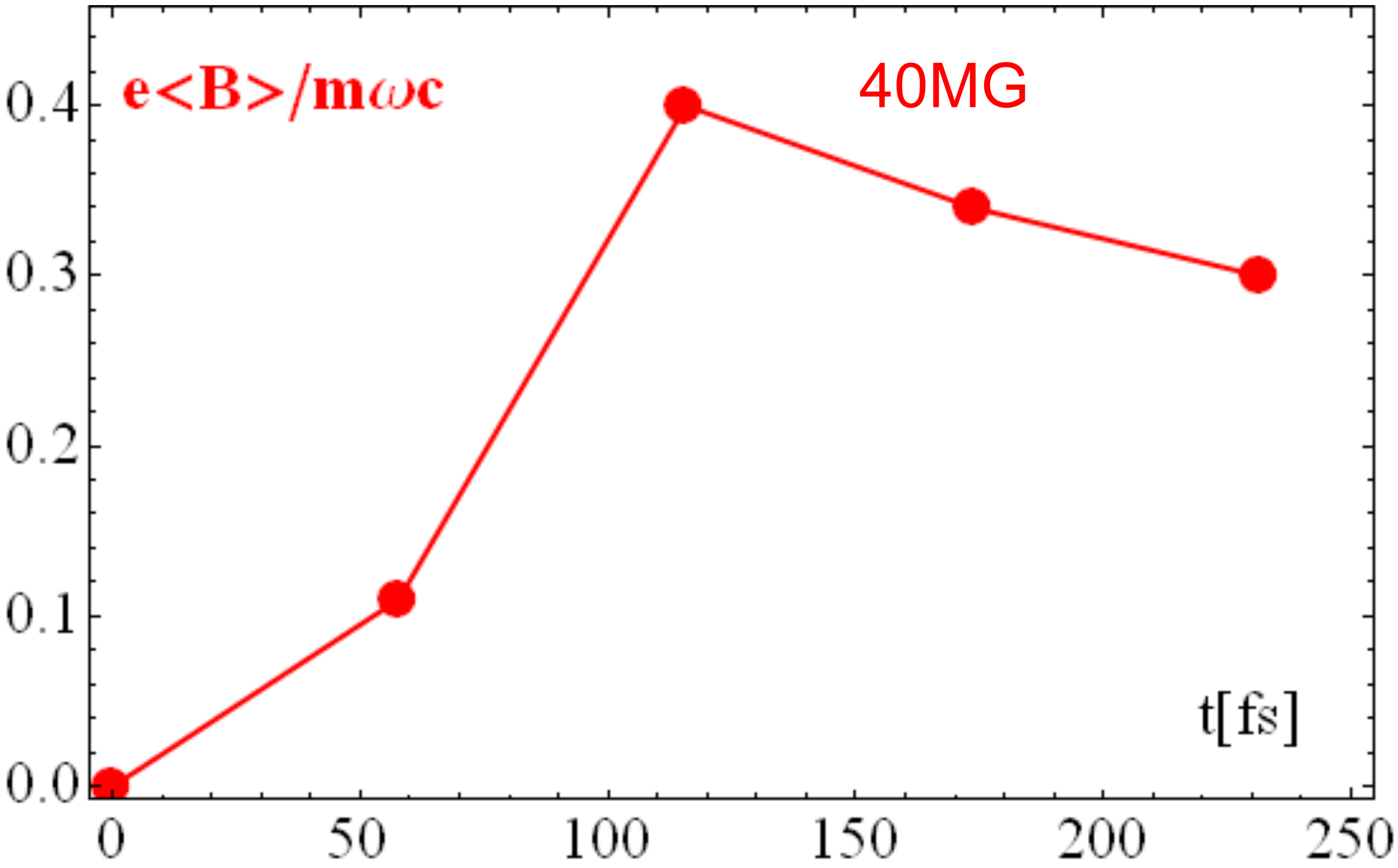
Target – thickness of irradiated foil 0.1 μm



Magnetic field

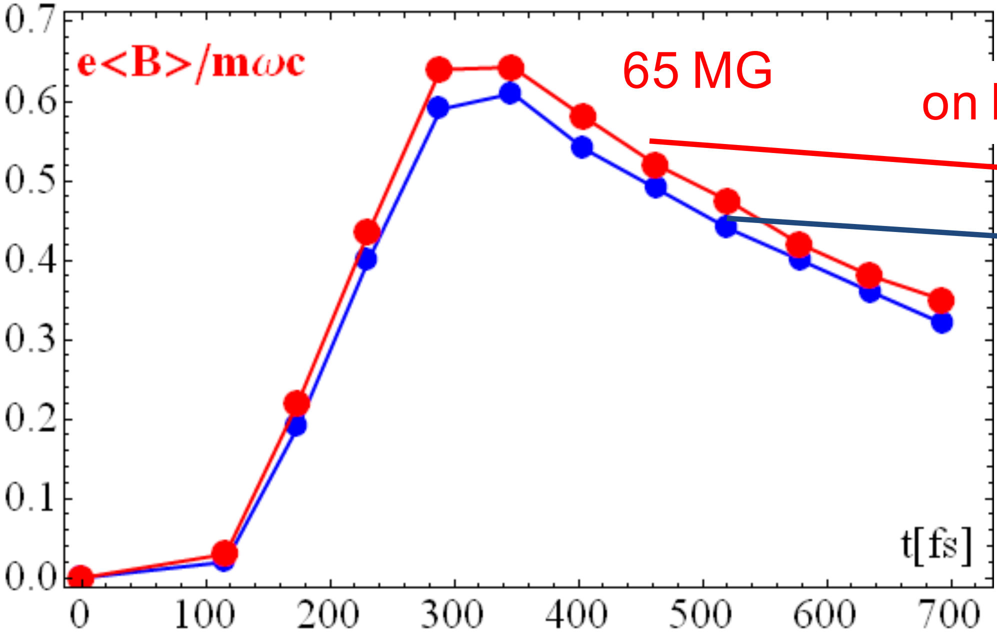
Magnetic field generation by short laser pulse





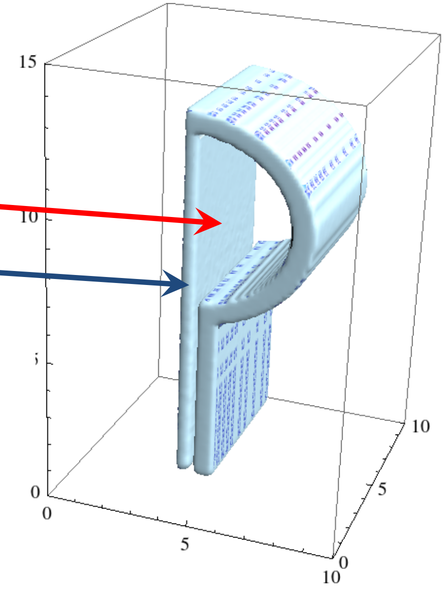
0.5 J 1×10^{20} W/cm^2
2 τ = 30 fs

Dependences from laser pulse duration



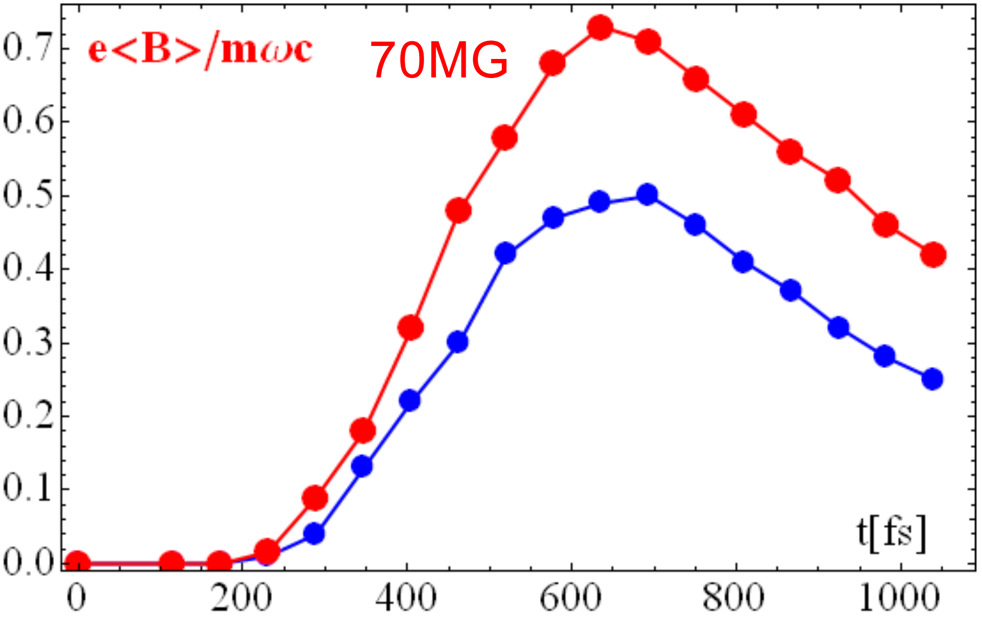
65 MG

on laser axes



near target boundary

0.5 J 2.5×10^{19} W/cm^{2}
2 τ = 120 fs



70MG

0.5 J 10^{19} W/cm^{2}
2 τ = 300 fs

Axial magnetic field generation by intense circularly polarized laser pulses in underdense plasmas

N. Naseri, V. Yu. Bychenkov, and W. Rozmus, PHYS. PLASMAS 17, 083109 2010

Inverse Faraday effect (IFE)

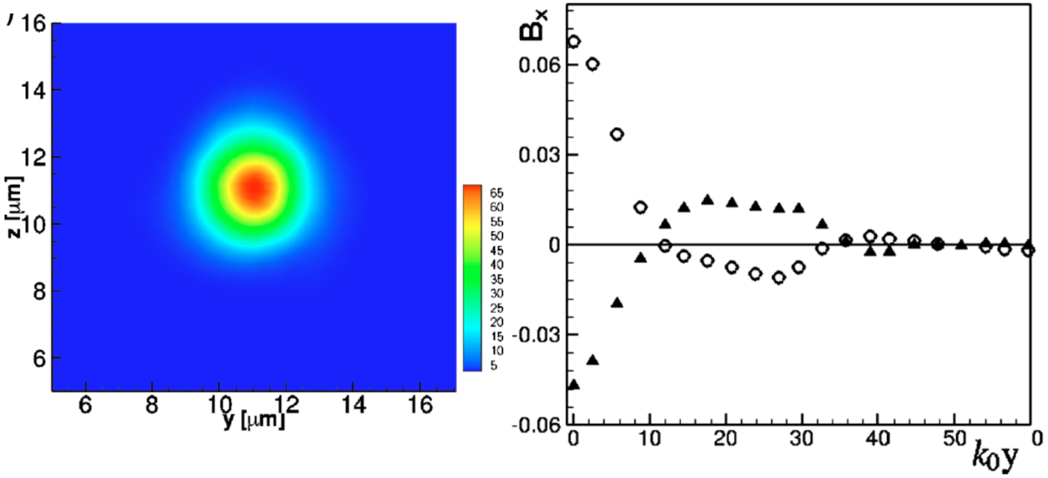
$$\frac{1}{r}\frac{d}{dr}\frac{r\gamma}{n}\frac{d}{dr}B_x - B_x = -\frac{\lambda}{2r}\frac{d}{dr}\frac{ra^2}{n}\frac{d}{dr}\frac{n}{\gamma}$$

$$\gamma = \sqrt{1+a^2}$$

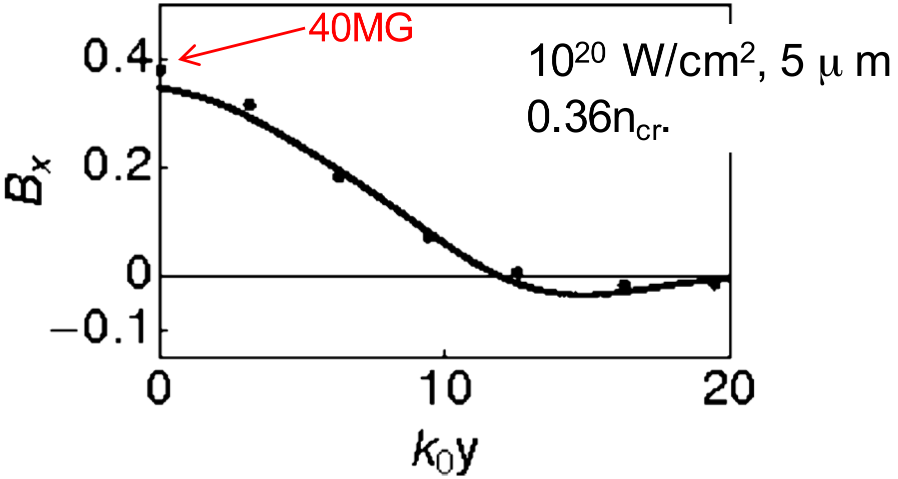
$$k_p r_0 \gg \sqrt{\gamma} \qquad B_x = \frac{\lambda}{2r}\frac{d}{dr}\frac{ra^2}{n}\frac{d}{dr}\frac{n}{\gamma}$$

$$k_p r_0 \ll \sqrt{\gamma} \qquad B_x = \int_r^{\infty} dr \frac{\lambda}{2}\frac{a^2}{\gamma}\frac{d}{dr}\frac{n}{\gamma}$$

Circles and triangles correspond to counterclockwise and clockwise polarization of laser beam



Quasistatic magnetic field calculated from probes located at x=85 μm in simulation box. Initial peak laser intensity is 4.7×10^{19} W/cm^2. The initial FWHM of the laser intensity is 5 μ m and the background plasma density is 0.1n$_{cr}$.



10^{20} W/cm^2, 5 μ m
0.36n$_{cr}$.

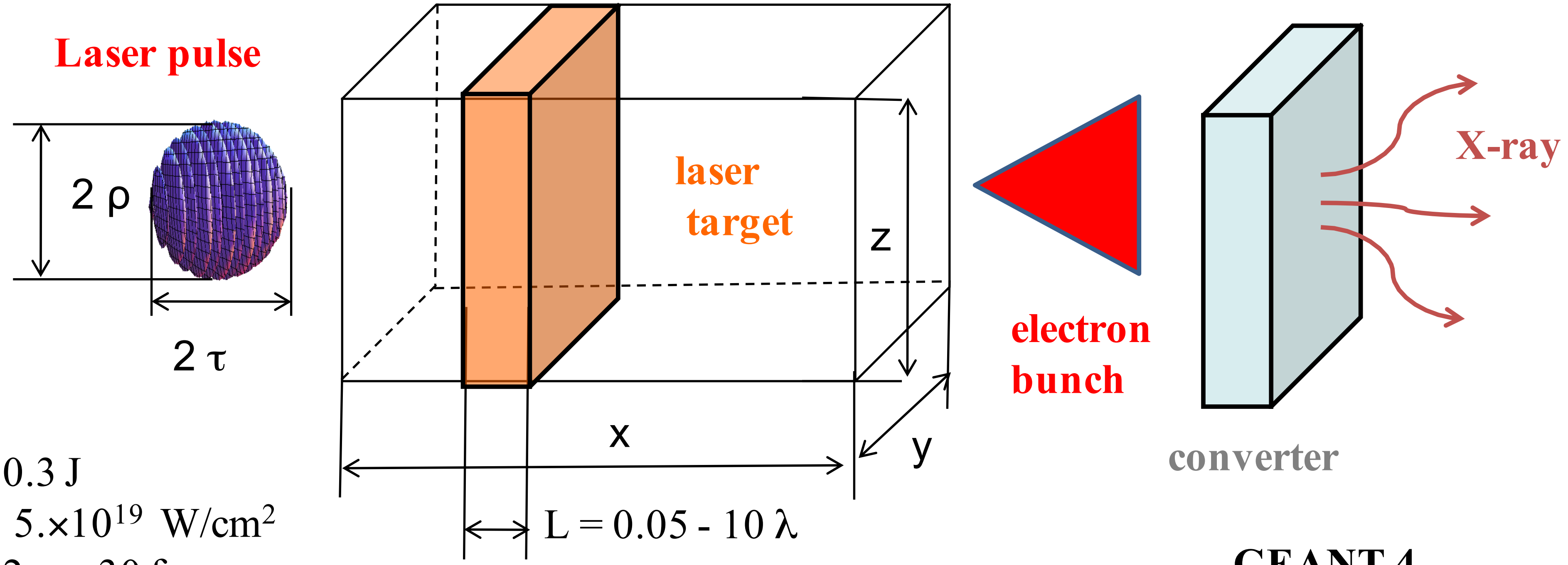
Comparison of the quasistatic magnetic field profiles for a channel obtained from PIC simulation (dots) and by the analytical IFE theory solid curve

Summary on magnetic field generation

The new schema of magnetic field generation in interaction of sub-ps laser pulses with shaped target is proposed.

The generation of quasi-static magnetic field in gas plasmas due to inverse Faraday effect has been studied.

Laser-target interaction and X-ray generation



0.3 J
$5.\times10^{19}$ W/cm^2
$2\ \tau = 30$ fs
$2\ \rho = 4\ \mu$m
linear polarization

Target
- electrons
- ions C^{+6}

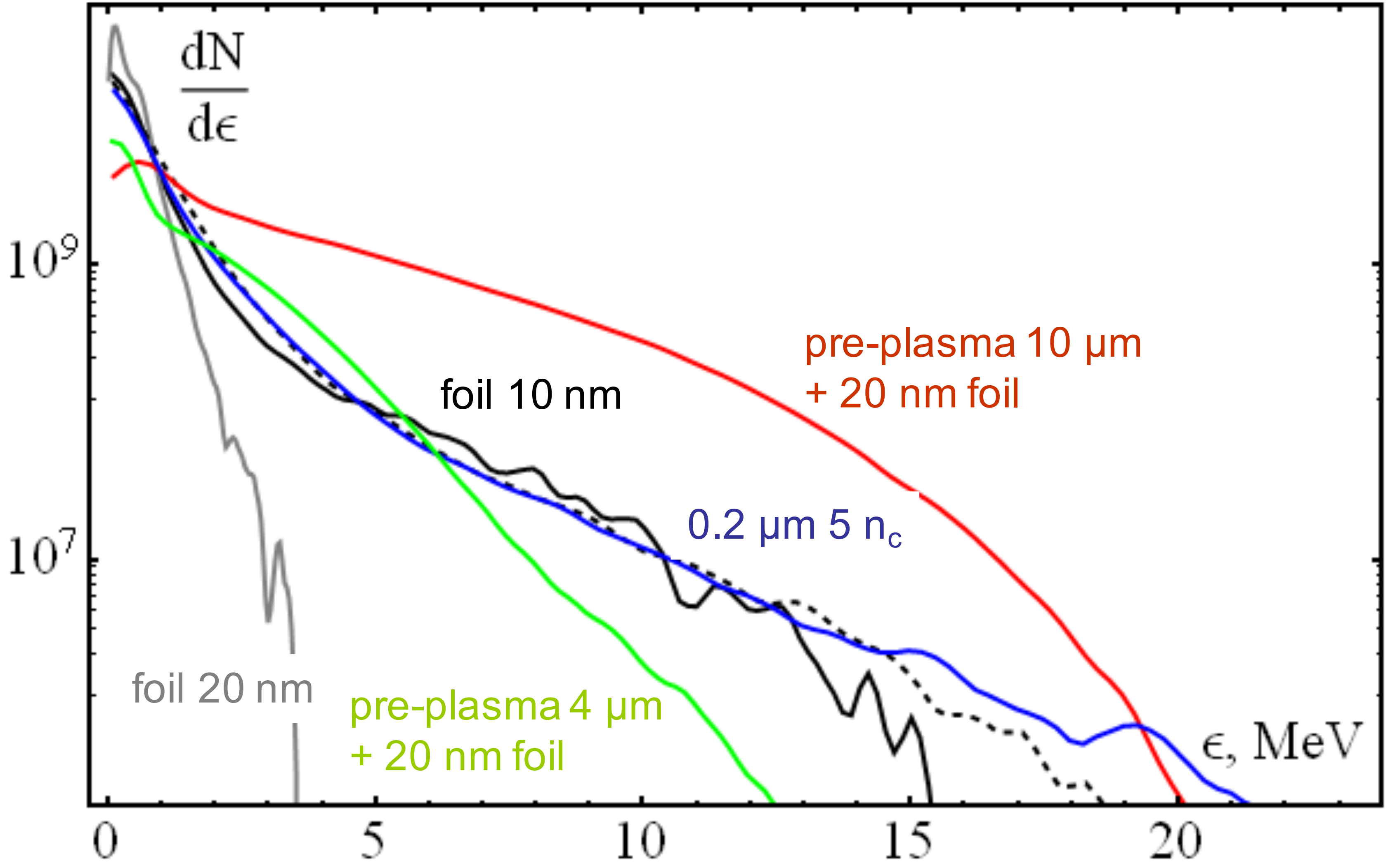
$$x \times y \times z = 18\ \lambda \times 20\ \lambda \times 20\ \lambda$$
$$\Delta x \times \Delta y \times \Delta z = \lambda/100 \times \lambda/20 \times \lambda/20$$

PIC code Mandor ⇨ **Collect all electrons behind target in the angle of 45°**

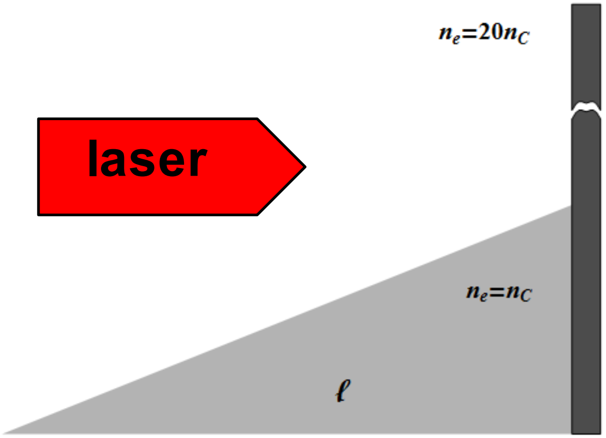
⇧

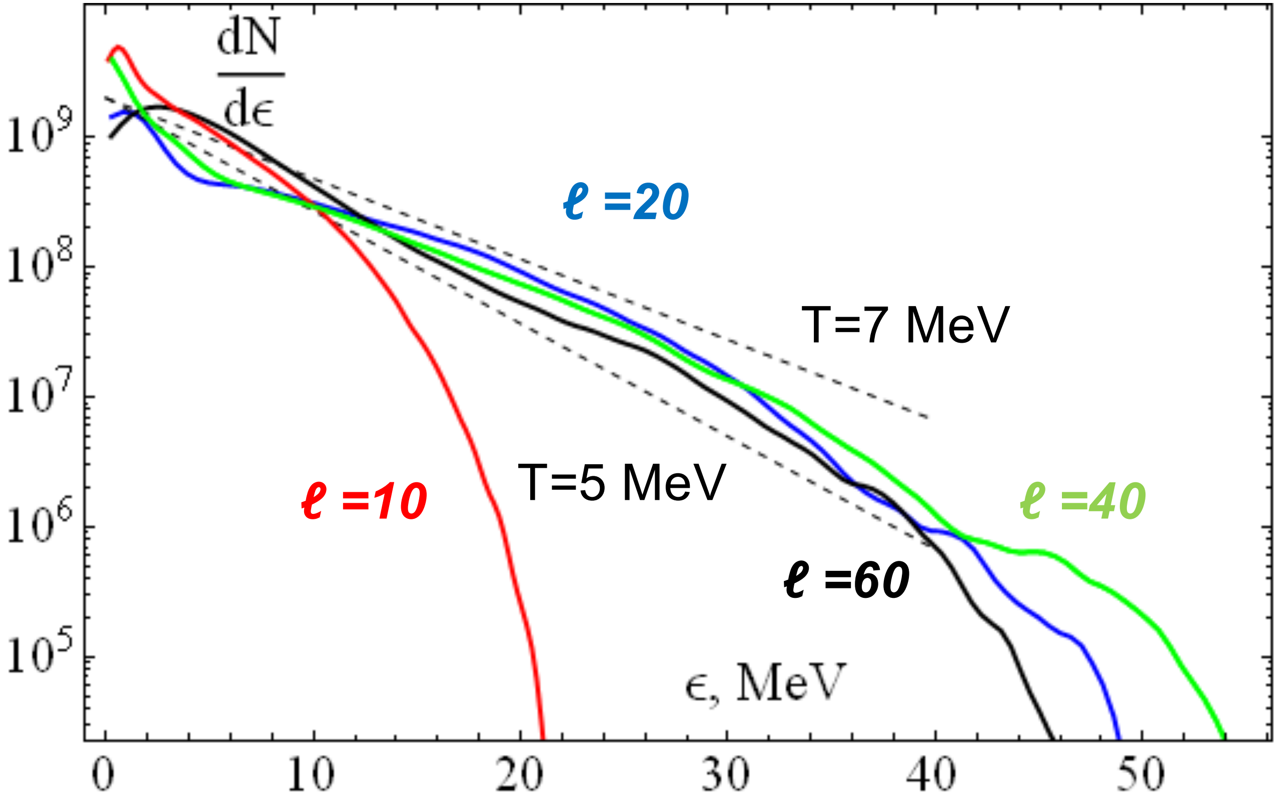
GEANT-4

Optimal target for electron acceleration.



Optimal pre-plasma size for generation of hot electrons





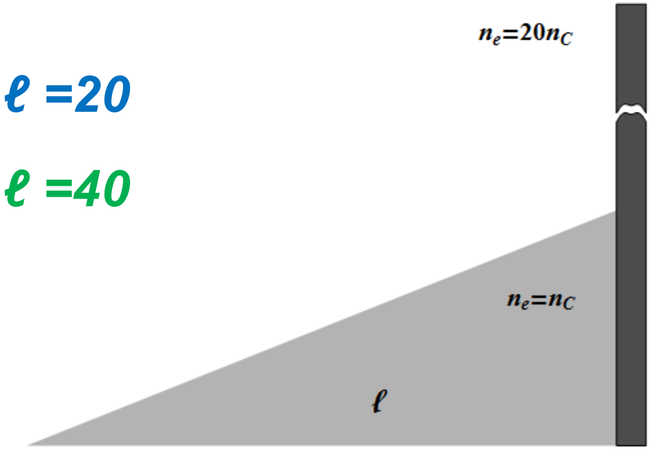
0.3 J,
$5.\times10^{19}$ W/cm^2
$2\,\tau = 30$ fs
$2\,\rho = 4$ μm
linear polarization

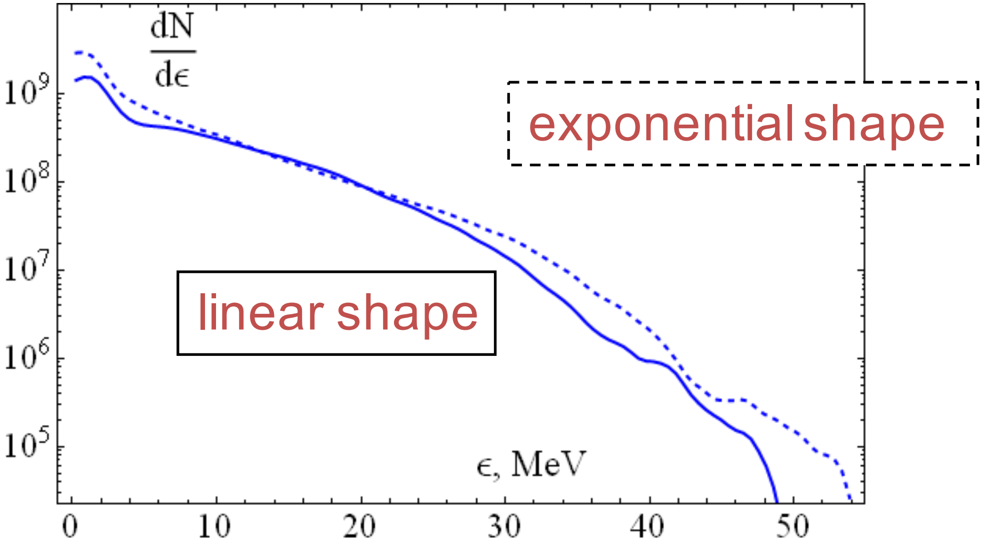
Optimal linear pre-plasma size ~ 20-40 μm

Pre-plasma shape effect on electron acceleration

ℓ =20

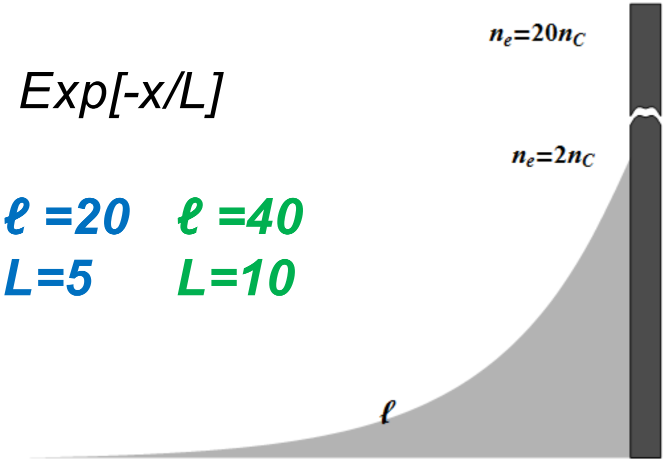
ℓ =40



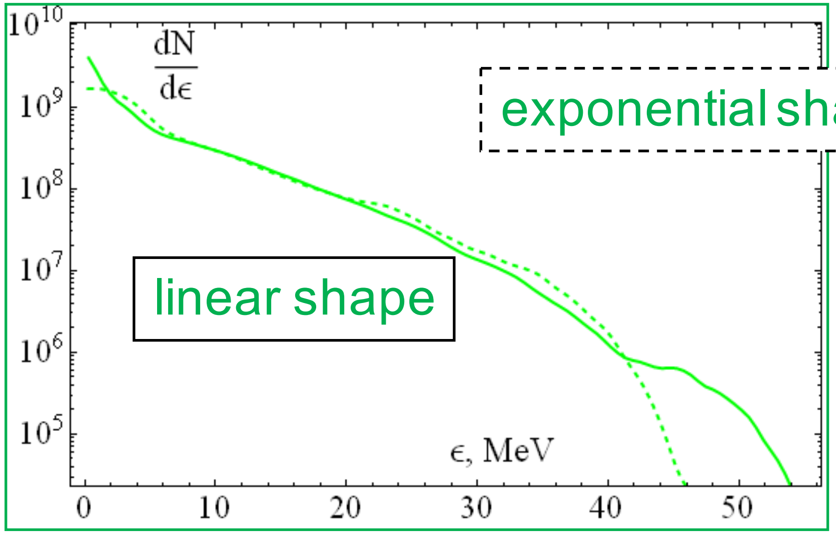

exponential shape

linear shape

Exp[-x/L]

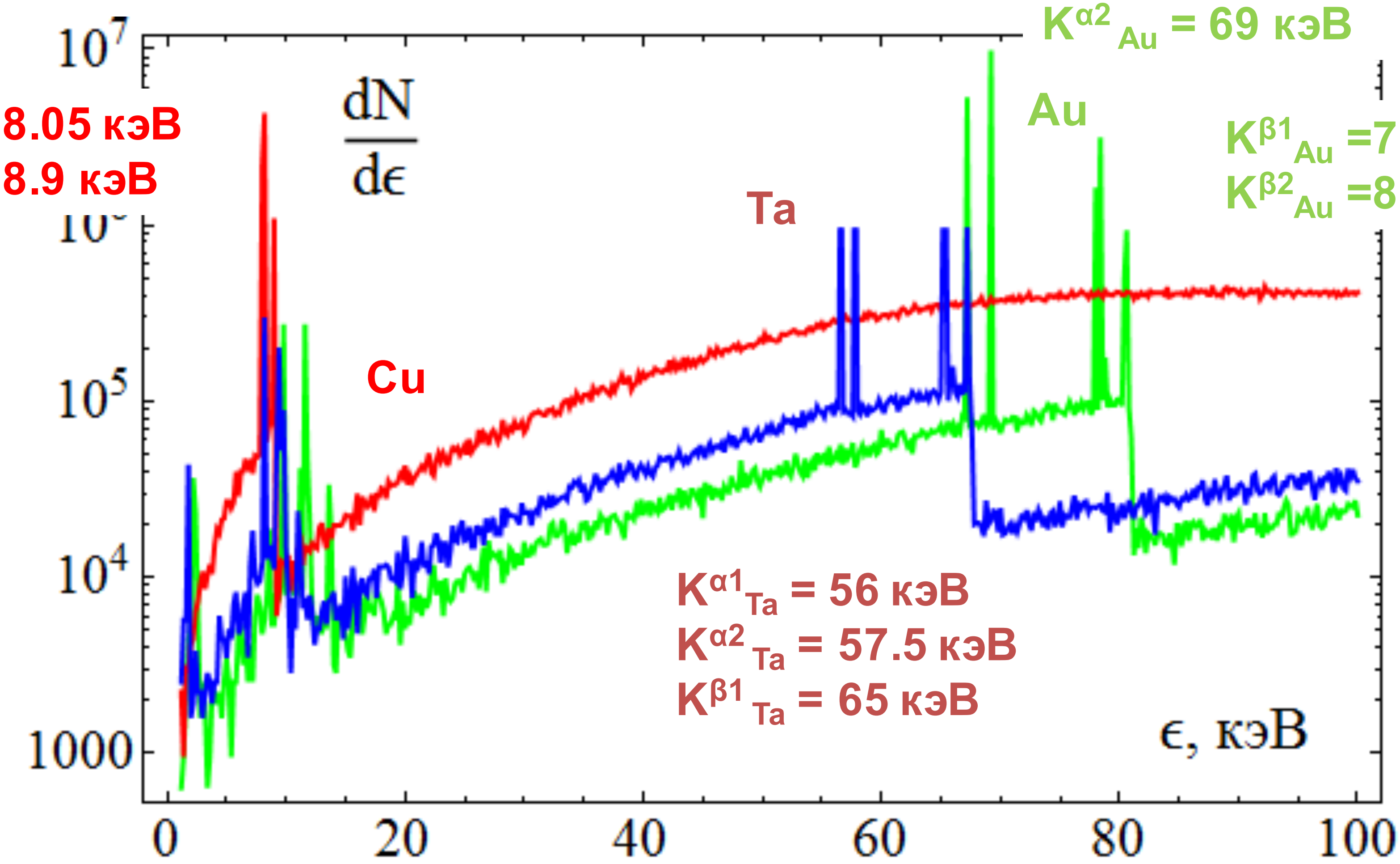


ℓ =20 ***ℓ =40***
L=5 ***L=10***


exponential shape

linear shape

X-ray generation: characteristic spectra



K^{α}_{Cu} = 8.05 кэВ
K^{β}_{Cu} = 8.9 кэВ

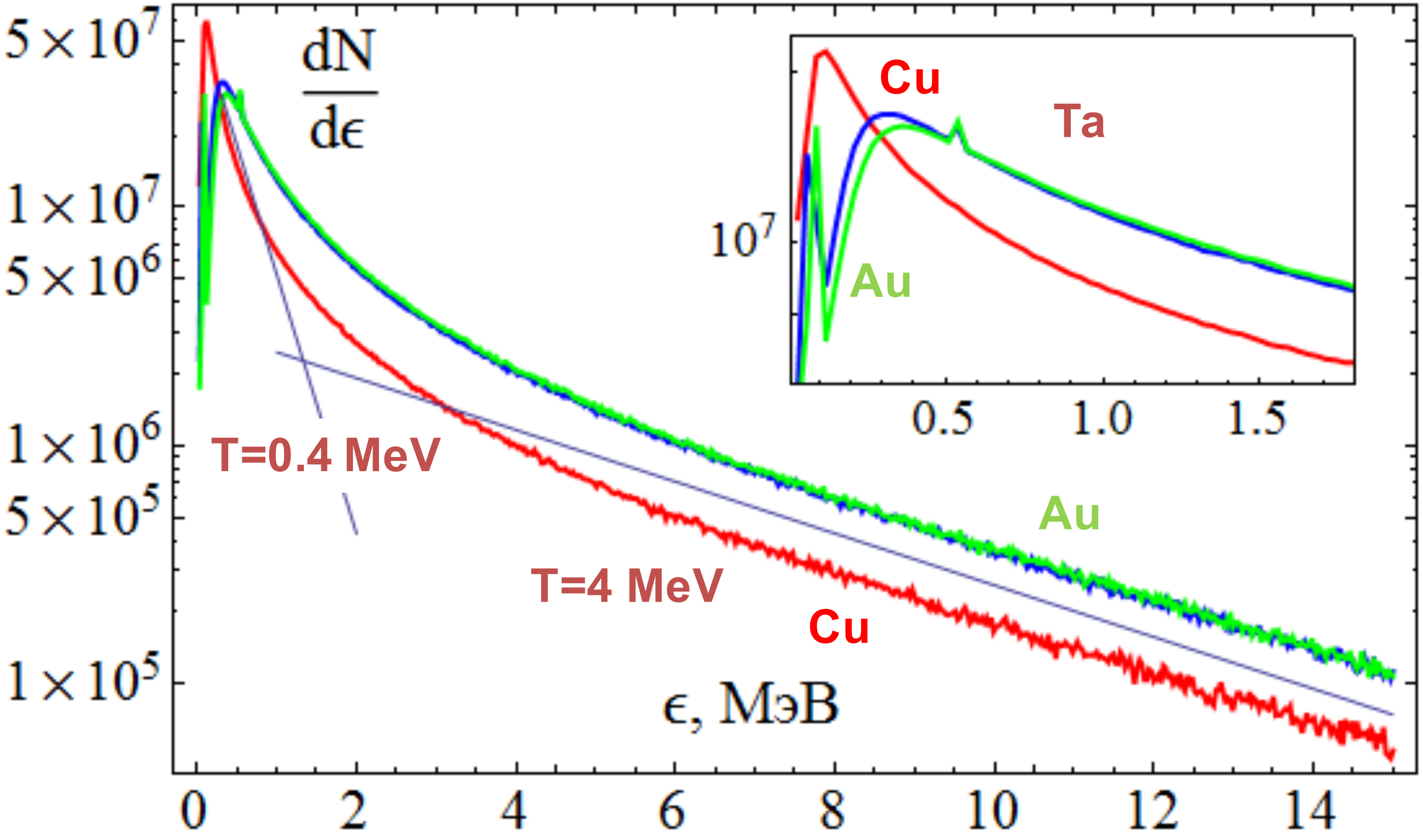
$K^{\alpha 1}_{Au}$ = 67кэВ
$K^{\alpha 2}_{Au}$ = 69 кэВ

$K^{\beta 1}_{Au}$ =78 кэВ
$K^{\beta 2}_{Au}$ =80 кэВ

$K^{\alpha 1}_{Ta}$ = 56 кэВ
$K^{\alpha 2}_{Ta}$ = 57.5 кэВ
$K^{\beta 1}_{Ta}$ = 65 кэВ

Target with thickness of 2 mm

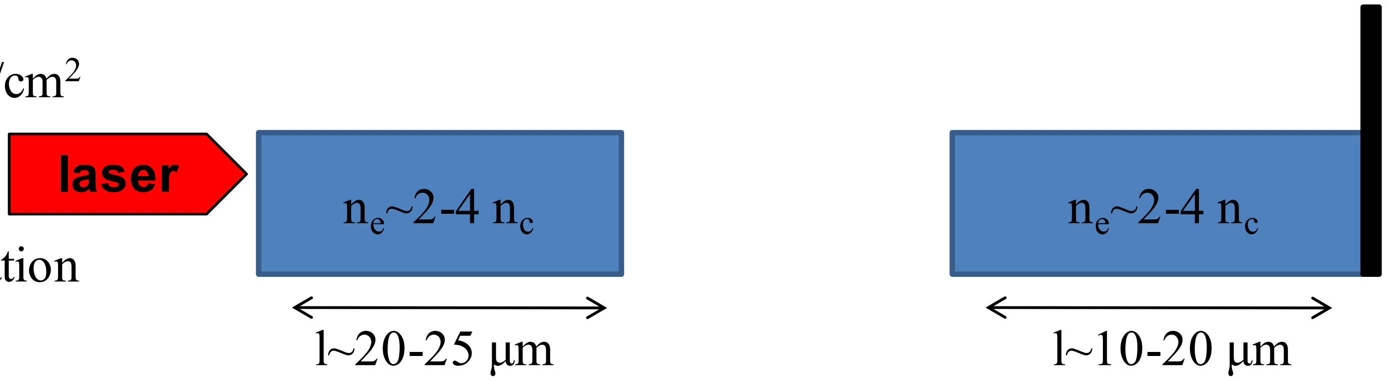
X-ray generation: bremsstrahlung spectra



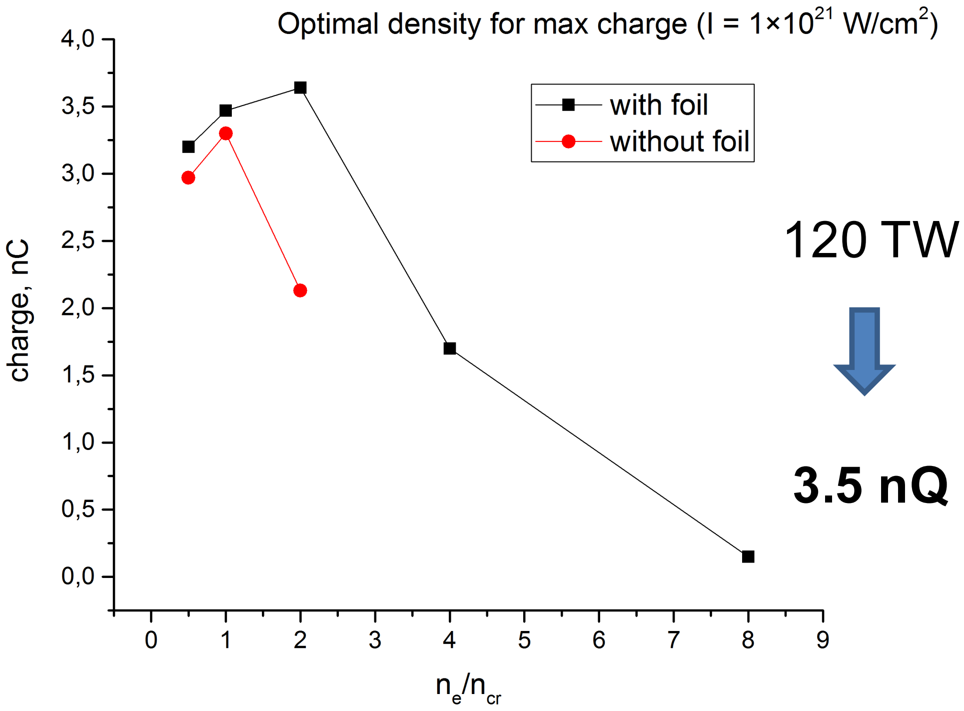
Conversion efficiency laser – X-ray ~ $5×10^{-5}$

Low-density targets for electron acceleration

5.4 J, 10^{21} W/cm^2
2 τ = 30 fs
2 ρ = 4 μm
linear polarization



Charge of electron bunch with energy more than 30 MeV



120 TW

↓

3.5 nQ

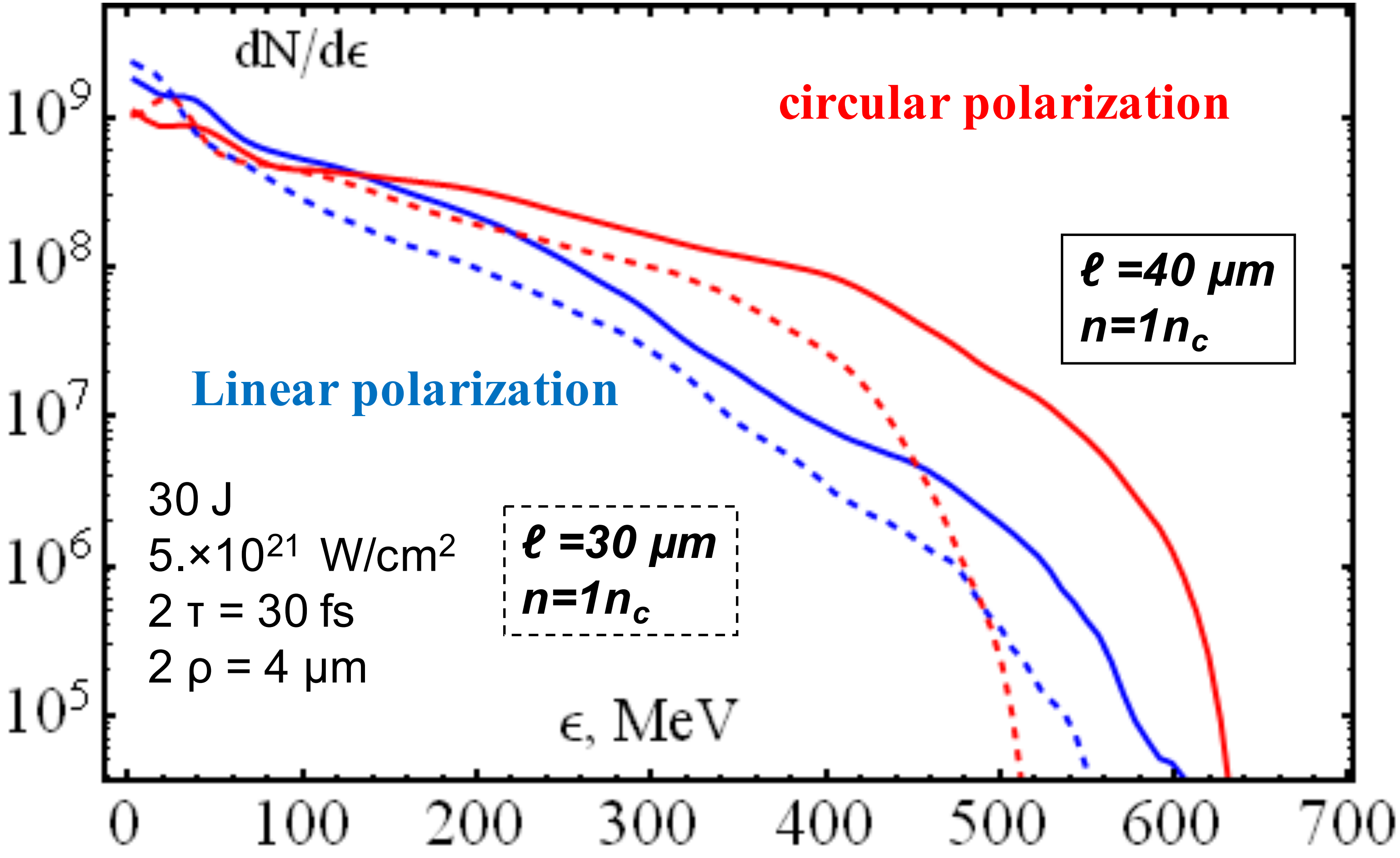
Deep γ-radiography
(10-20 cm dense matter)

Single shot radiography:
150 nQ

↓

Several-PW lasers

Electron acceleration from low-density targets. Linear/circular polarization.



Circular polarization has advantage for electron acceleration !

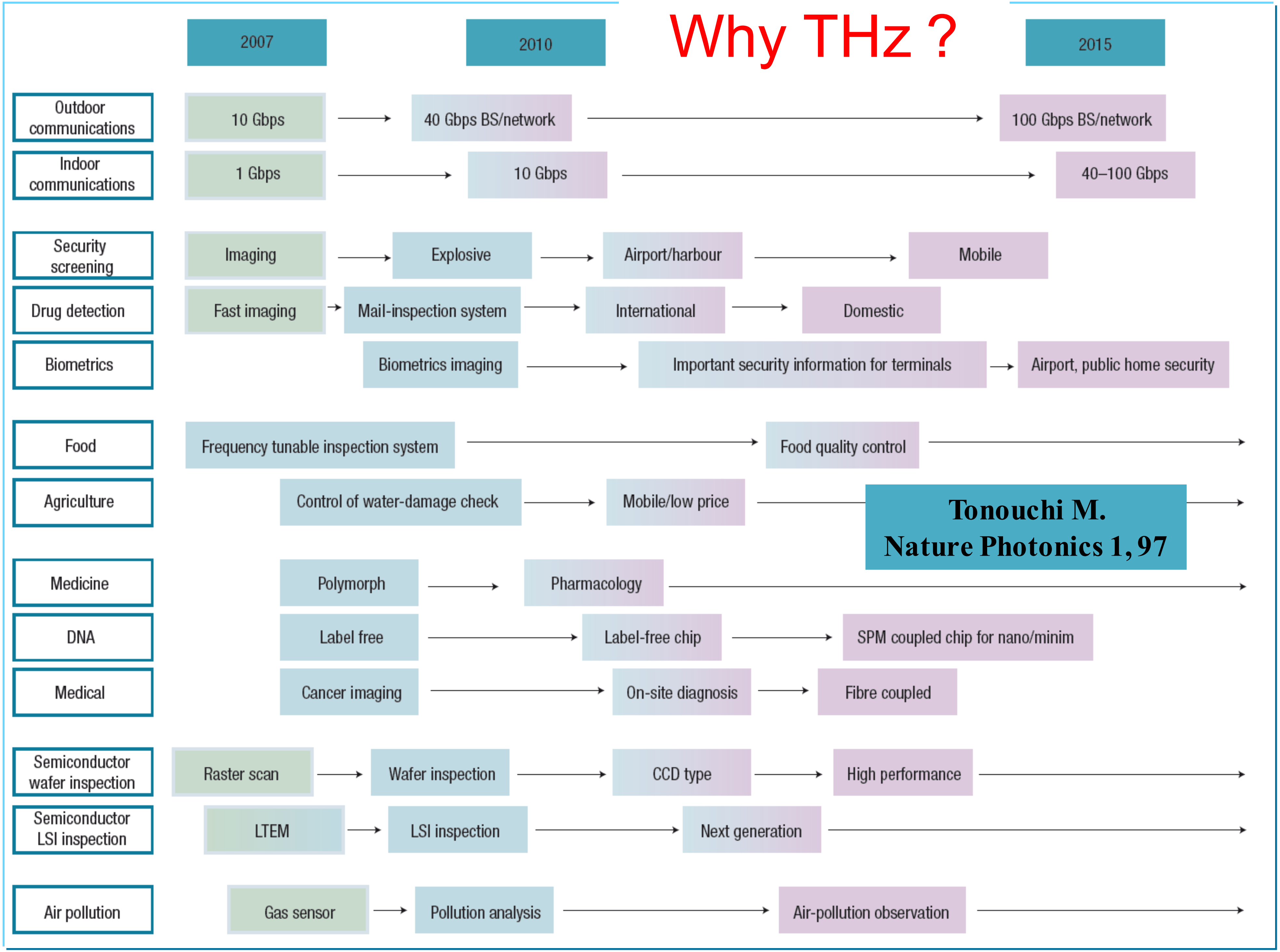
Summary on electron source for X-ray

- Optimal pre-plasma size (~ 40 μm) results in increase of number and maximum energy of electrons accelerated by short laser pulses

- Hard X-ray with temperature of 4 MeV generated by short laser pulse with energy of 300 mJ with efficiency of ~ 5×10^{-5}

- Low-density targets as well as circularly polarized laser pulses have advantage in terms of generation maximum number of hot electrons

Why THz ?



2007 2010 2015

Outdoor communications: 10 Gbps → 40 Gbps BS/network → 100 Gbps BS/network

Indoor communications: 1 Gbps → 10 Gbps → 40–100 Gbps

Security screening: Imaging → Explosive → Airport/harbour → Mobile

Drug detection: Fast imaging → Mail-inspection system → International → Domestic

Biometrics: Biometrics imaging → Important security information for terminals → Airport, public home security

Food: Frequency tunable inspection system → Food quality control →

Agriculture: Control of water-damage check → Mobile/low price →

Medicine: Polymorph → Pharmacology →

DNA: Label free → Label-free chip → SPM coupled chip for nano/minim

Medical: Cancer imaging → On-site diagnosis → Fibre coupled

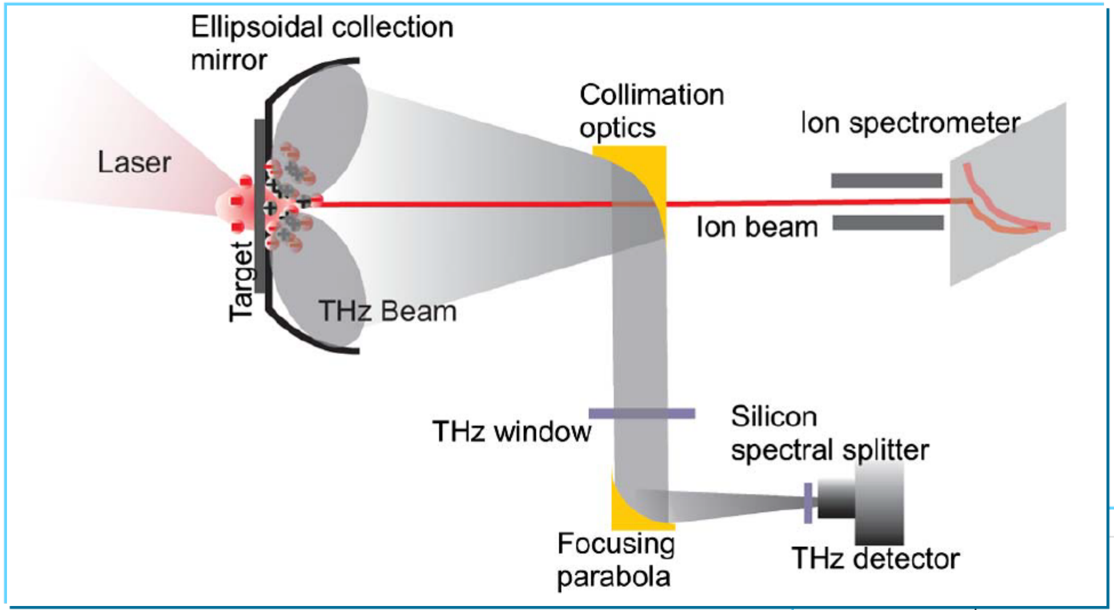
Semiconductor wafer inspection: Raster scan → Wafer inspection → CCD type → High performance →

Semiconductor LSI inspection: LTEM → LSI inspection → Next generation →

Air pollution: Gas sensor → Pollution analysis → Air-pollution observation →

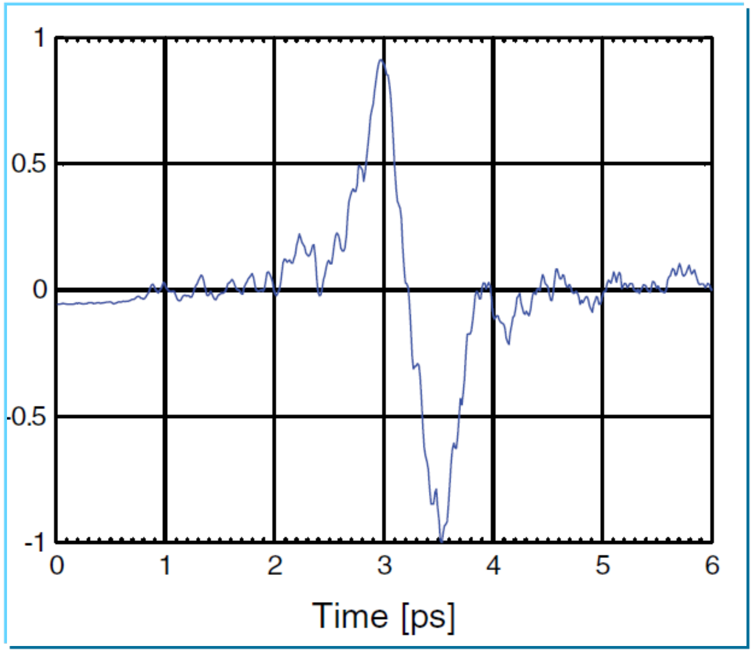
Tonouchi M.
Nature Photonics 1, 97

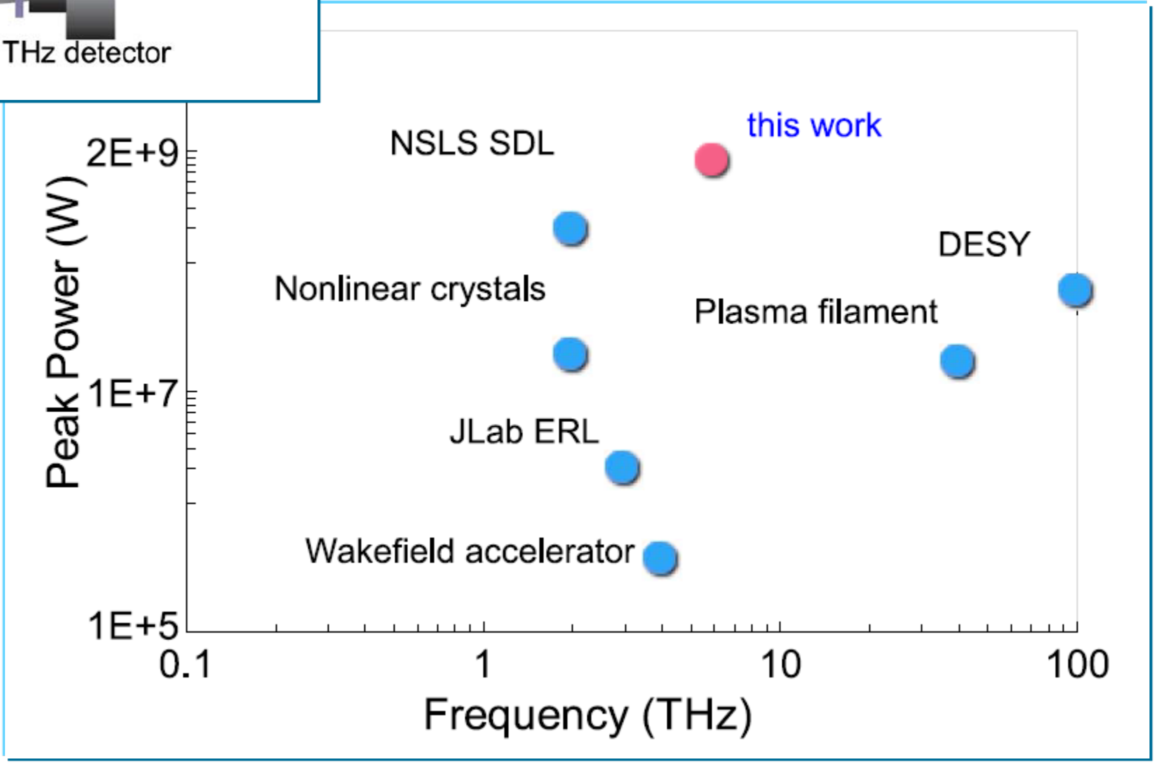
THz due to laser-plasma interaction



Gopal A et al. Phys. Rev. Lett. 111 074802 (2013)

Laser pulse ~ 1J, 30 fs
THz pulse ~ 460 μJ

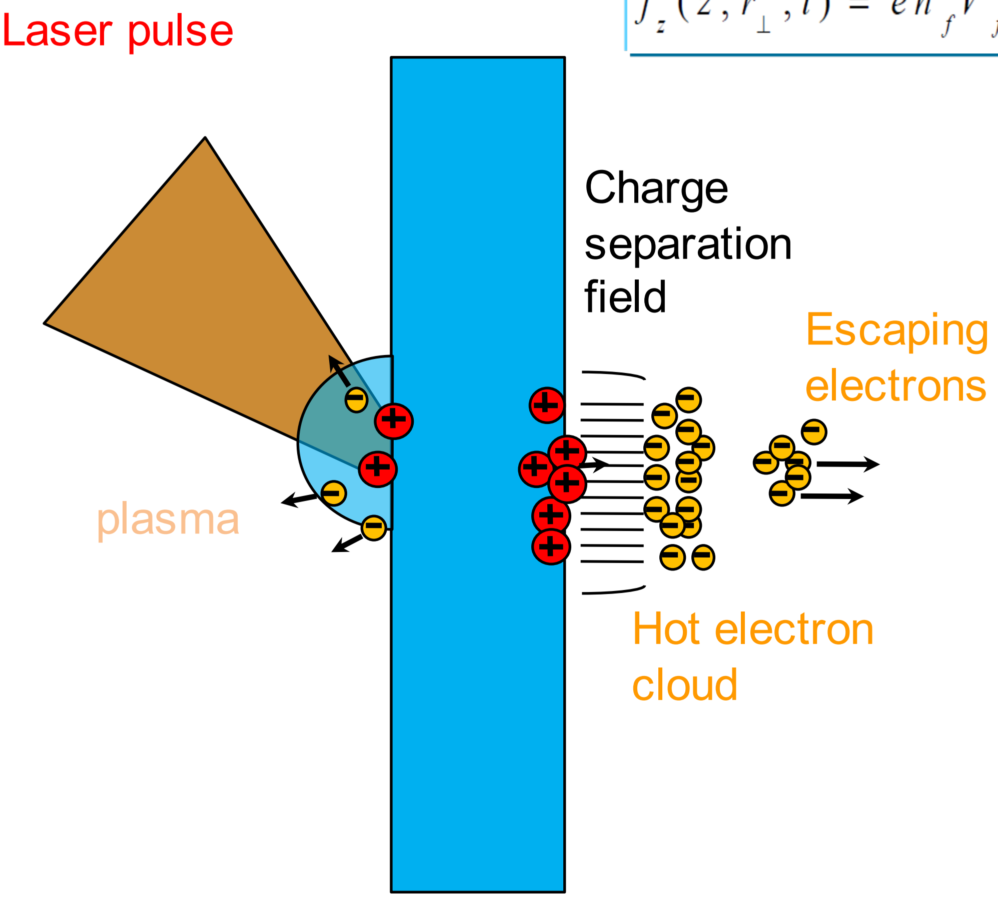




The possible mechanisms of THz generation

$$j_z(z,r_\perp,t) = e n_f V_f \theta(t)\theta(z - V_f t + L)\theta(V_f t - z)\exp(-r_\perp^2/R^2)$$

A.S. Kuratov, A.V. Brantov, et al
Quantum Electronics 46, 1023 (2016)



Laser pulse

Charge separation field

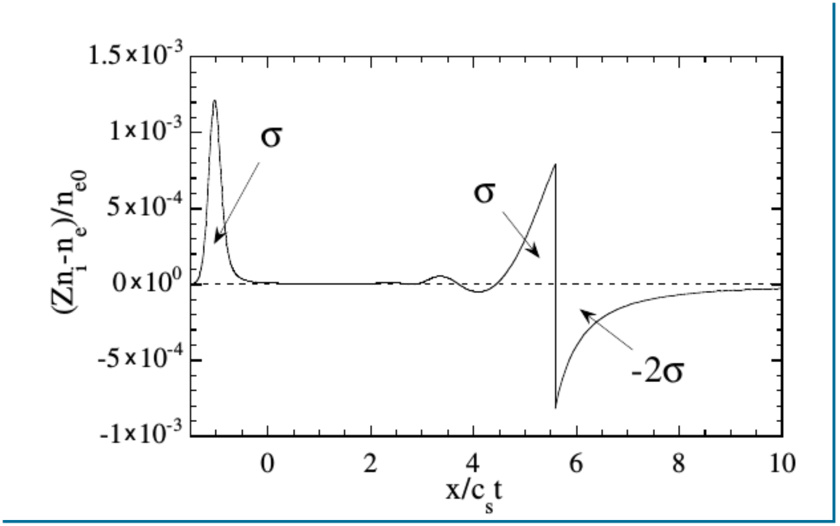
Escaping electrons

plasma

Hot electron cloud

$$j_z(z,r_\perp,t) = enc_s r_D \Theta(t)\exp(-\alpha t/\tau_0)[\delta(z - c_s t\tau)\tau\Theta(\tau_0 - t) + \delta(z - 2c_s t + c_s\tau_0)\Theta(t - \tau_0)]\exp(-r_\perp^2/R^2)$$

Theory of plasma expansion



Mora P. Phys. Rev. Lett. 90, 185002 (2003)

Estimates of THz generation

2J laser pulse , 30 fs, $a_0=10$

$$W^{\mathrm{w}} \approx 2\times 10^{-7}\left(\frac{\omega_{\mathrm{m}}}{10^{12}\,\mathrm{s}^{-1}}\right)\left(\frac{\tau_{\mathrm{L}}}{30\ \mathrm{fs}}\right)^{2} a_0^2(1+\ln a_0)$$

Radiation energy due to escaping electrons

THz pulse of 600 μJ

$$W^{\mathrm{w}}(\omega) = 9.6\times 10^{-3}\,\frac{\eta a_0^2 \omega_{\mathrm{m}}^3 R^4 m^2 c}{e^2}$$

Radiation energy due to plasma expansion

THz pulse of 0.1 μJ

$$W^{\mathrm{s}} \approx 1.6\times 10^{-8}\left(\frac{\omega_{\mathrm{m}}}{10^{13}\,\mathrm{s}^{-1}}\right)^{3/2}\left(\frac{\tau_{\mathrm{L}}}{30\ \mathrm{fs}}\right)^{2} a_0^2$$

Surface wave energy due to escaping electrons

THz pulse of 2 μJ

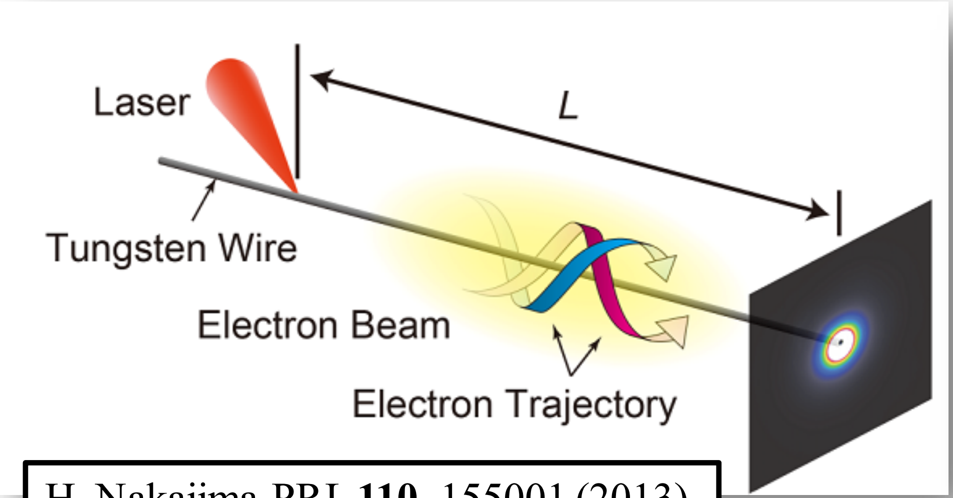
The main source of surface waves – formation of charge-separation field

$$4\pi\mathbf{j}_0 = -\partial\mathbf{E}_0/\partial t \qquad j_z(x,r,t) = \frac{m_e c^2 a_0}{2\pi^{3/2} e\tau(z+\sqrt{2\mathrm{e}\lambda_{De}})}\exp(-t^2/\tau^2 - r^2/R^2)$$

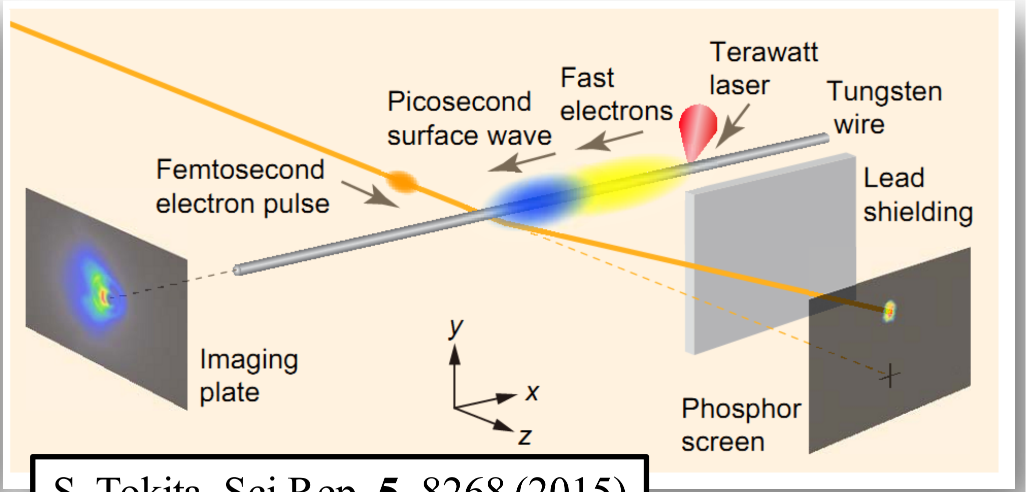
$$\partial T_e/\partial t = m_e c^2 a_0 \exp(-t^2/\tau^2 - r^2/L^2)/\sqrt{\pi}\tau$$

Surface wave THz pulse with energy of 500 μJ

Generation of surface wave along wire



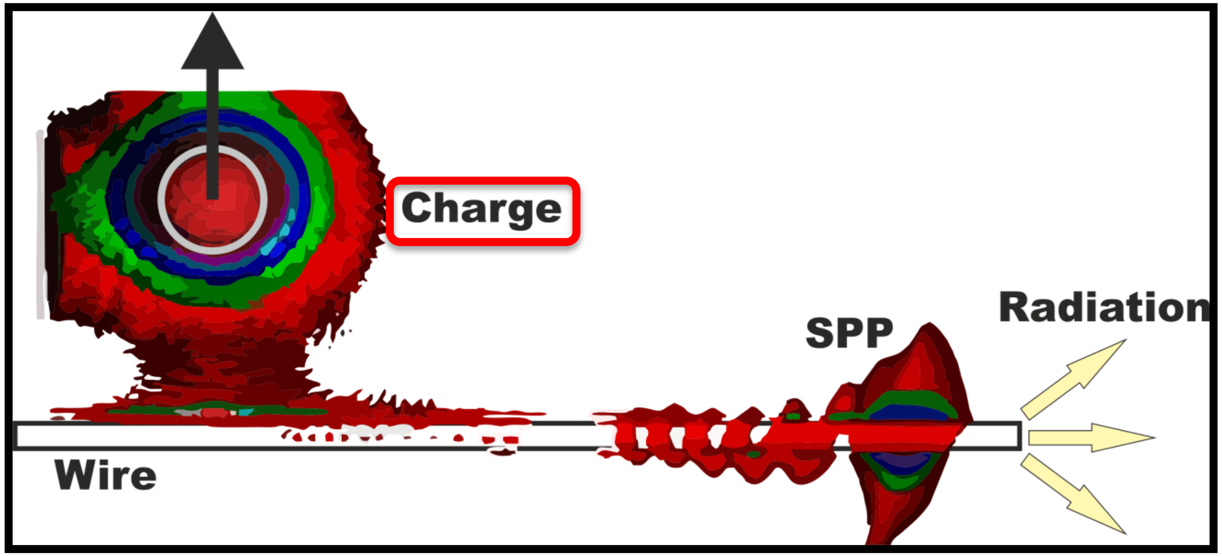
H. Nakajima PRL **110**, 155001 (2013)



S. Tokita Sci.Rep. **5**, 8268 (2015)

- Generation of MeV electrons
- THz antenna
- High coefficient of energy conversion from laser pulse to EM wave

Surface wave generation due to electrons evacuation by laser pulse



Estimation electrons charge

$$T_h = m_e c^2 \left(\sqrt{1 + a^2} - 1 \right)$$

$$a^2 = 2 I_0 / n_c m_e c^3$$

$$P_h = n_h T_h \qquad P_h c = \eta I_0$$

$$Q \sim \pi R_0^2 \sqrt{\frac{I_0}{c}}$$

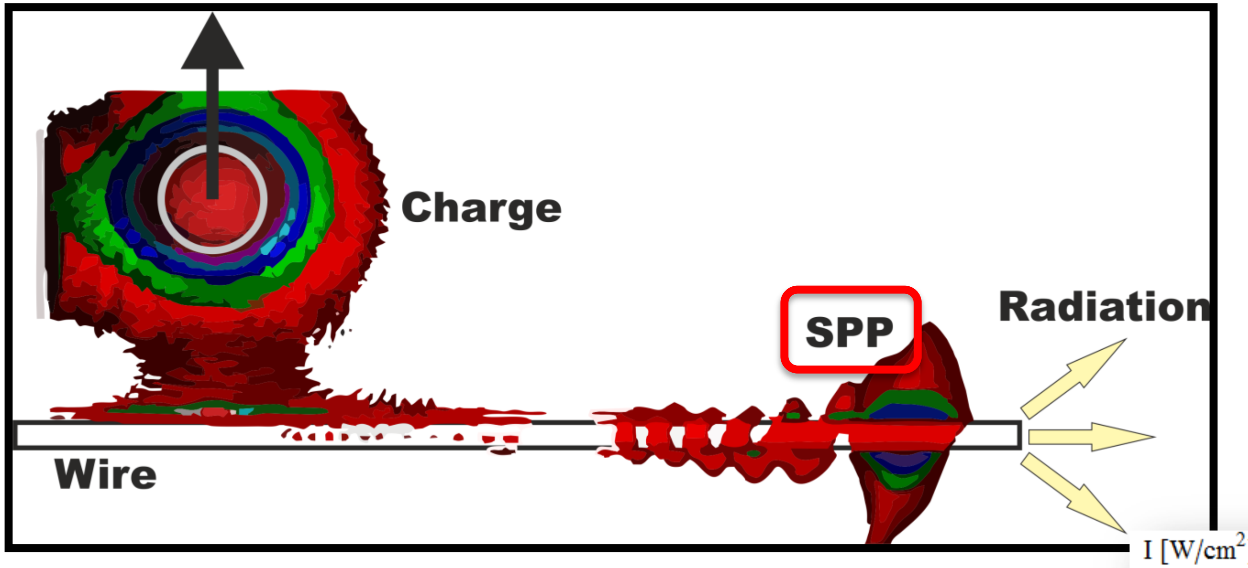
Laser radiation:

$I_0 = 10^{18..19}$ W/cm^2
$R_0 = 5\text{-}10$ mkm

Hot electrons charge:

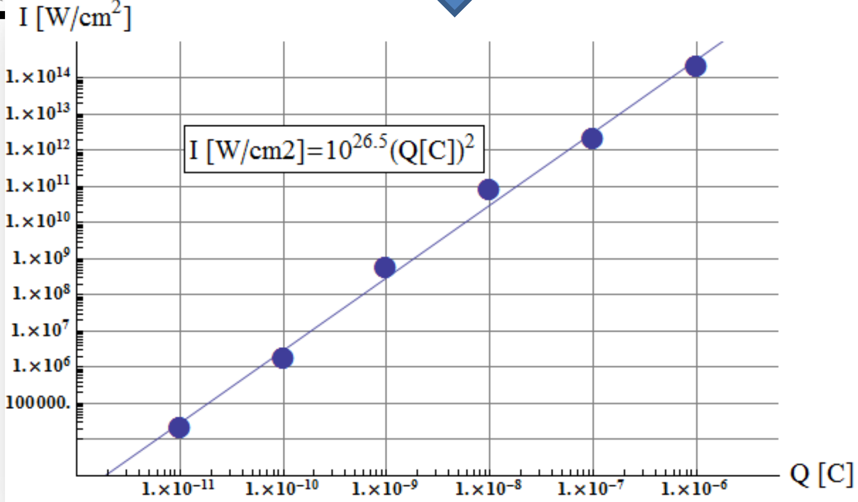
$Q = 10^{-9..-8}$ C

Surface plasma wave excitation



Numerical simulation

- FDTD method for solving Maxwell’s equations
- ADE method for metal modeling



Hot electron charge:

Q ~ 10$^{-9..-8}$ C

Peak intensity of SPP:

I ~ 10$^{10..9}$ W/cm^2

I [W/cm^2] = 10$^{26.5}$(Q[C])^2

Summary on THz radiation

- Laser pulse with $I_0 \sim 10^{18}$ W/cм^2 generate surface waves with peak intensity $I_{SW} \sim 10^{9..10}$ W/cм^2, which may propagate along wire up to several cm and radiate EM wave with intensity of $I_1 \sim 10^{7..8}$ W/cм^2
- Surface plasma waves spectral intensity maximum is the order of ~ c/R
- Laser pulse energy conversion coefficient from laser energy to EMW may reach 10^{-4}

Conclusion

- Utilization of laser pulse with circular polarization results in noticeable increase of maximum proton energy both from thin foils in directed Coulomb explosion regime and from low-density targets in synchronized laser-triggered ion acceleration (SASL) regime.
- Low density carbon nanotube films of wide varieties of thicknesses and hydrogenation are now available for high field science experiments. They are well fitted for ion and electrons acceleration by short laser pulse.
- Optimal pre-plasma size results in increase of number and maximum energy of electrons used for generation of X-ray and gamma –radiation.

Thank you for attention