Laser Ion acceleration

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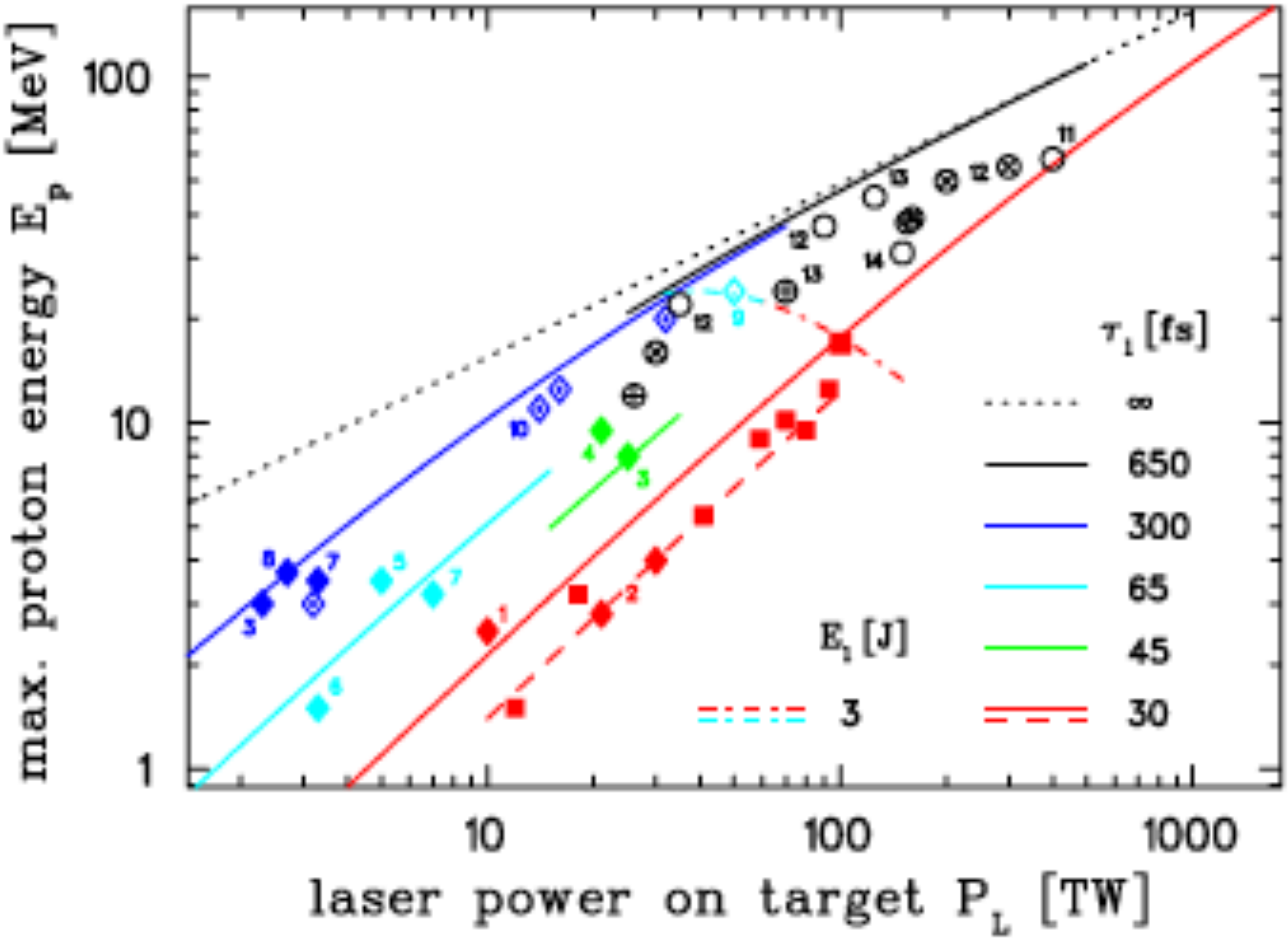
Experimental results



New Journal of Physics 12 **(2010) 045015**

Regimes
of proton acceleration

- Target Normal Sheath Acceleration

  S. C. Wilks *et al.*, Phys. Plasmas **8**, 542 (2001).

- Coulomb Explosion

  S. V. Bulanov, *et al*., Phys. Lett. A **299**, 240 (2002);
  E. Fourkal, I. Velchev, and C.-M. Ma, Phys. Rev. E **71**, 036412 (2005).

- Radiation Pressure Acceleration

  T. Esirkepov, *et al*., Phys. Rev. Lett. **92,** 175003 (2004)

- Magnetic Vortex Acceleration

  T. Zh. Esirkepov, *et al*., JETP Lett. 70, 82 (1999).

  A. V. Kuznetsov, *et al.*,Plasma Phys. Rep. 27, 211 (2001).

Ion Acceleration

Applications

- Proton radiography of dense targets

M. Borghesi, *et. al.*, Fusion Science and Technology 49, 412 (2001)

- Proton/carbon beams for oncological hadrontherapy

S. V. Bulanov and V. S. Khoroshkov,

Plasma. Phys. Rep. 28, 453 (2002)

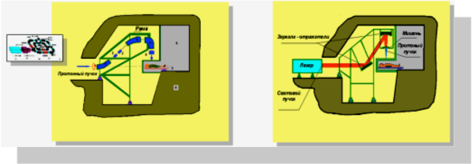
- Fast ignition

M. Roth, *et. al.*, Phys. Rev. Lett. 86, 436 (2001)

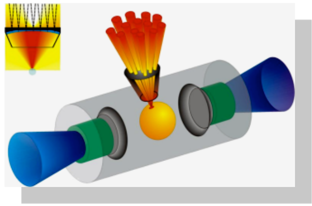
Beam Requirements

- Low emittance
- Short duration
- High energy (for dense matter probing)

- Small energy spread ~1%
- High energy (50-250 MeV)
- Number of particles ~10^{10} sec^{-1}



- Low emittance, focusability
- High flux

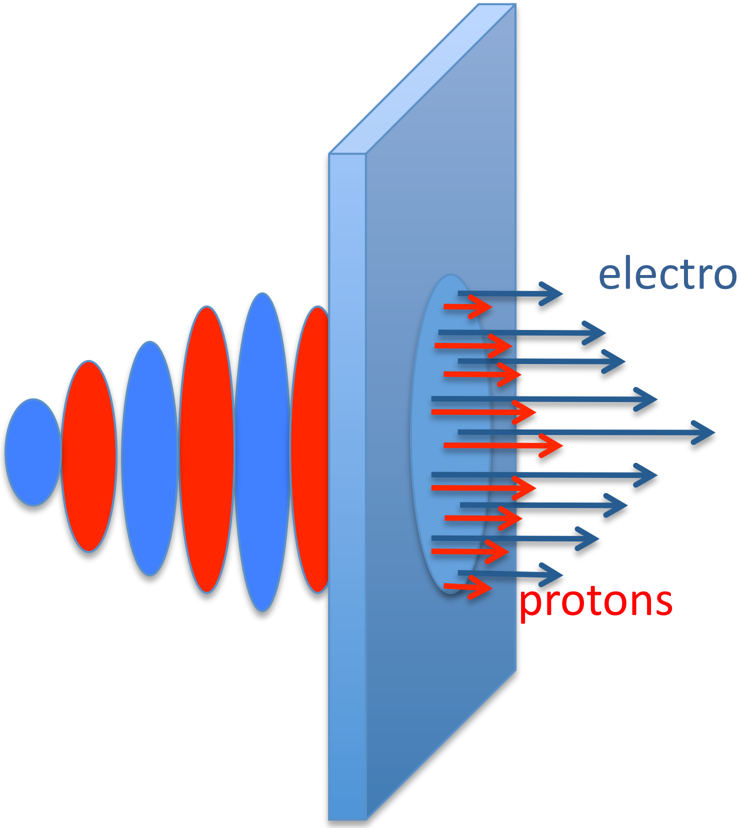


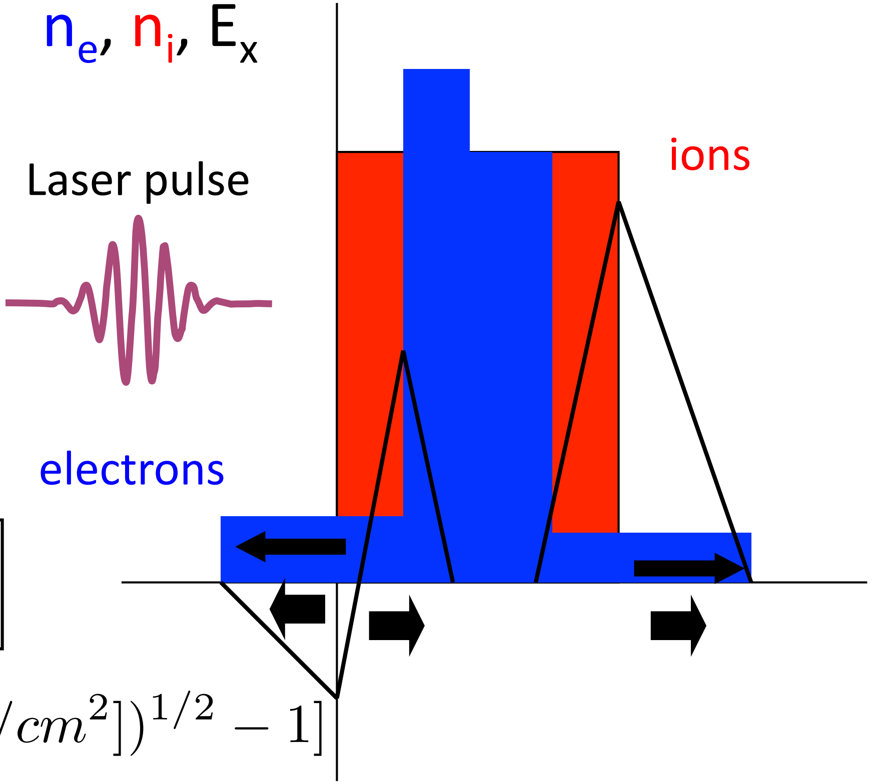
Target Normal Sheath Acceleration

$$\mathcal{E} \sim P^{1/2}$$

Normal Sheath Acceleration

- Poor contrast requires thick target
- Prepulse creates preplasma on surface
- Pulse drives some e$^-$ through target
- Charge separation at rear accelerates protons



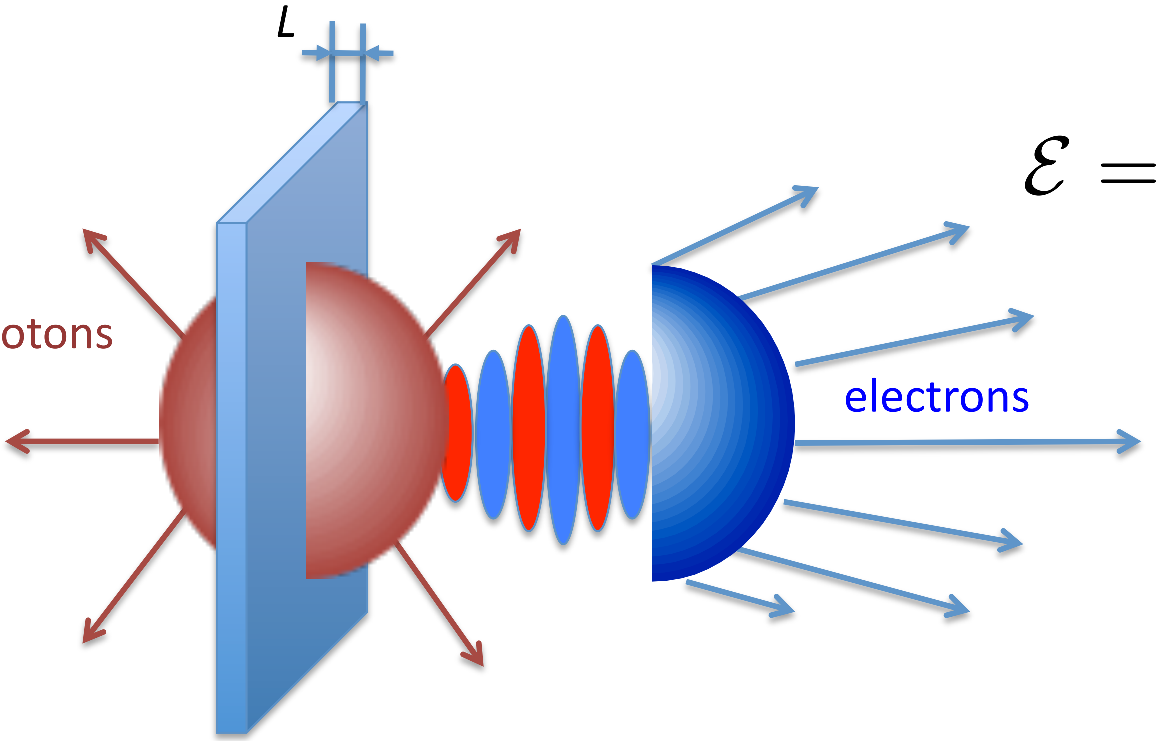


$$\phi_{sweeping} \sim \phi_{pond}$$

$$E_{max/rear} \sim 2Z\phi_{pond}\left[\ln\left(2\frac{\omega_{pi}t}{\sqrt{2e}}\right)\right]$$

$$\phi_{pond} \sim m_e c^2[(1 + I\lambda^2[\mu m]/1.37 \times 10^{18}[W/cm^2])^{1/2} - 1]$$

Coulomb Explosion



$$\mathcal{E} = 2\pi m_e c^2 \frac{n_e}{n_{cr}} \frac{L r_0}{\lambda^2}$$

r_0 is the focal spot radius

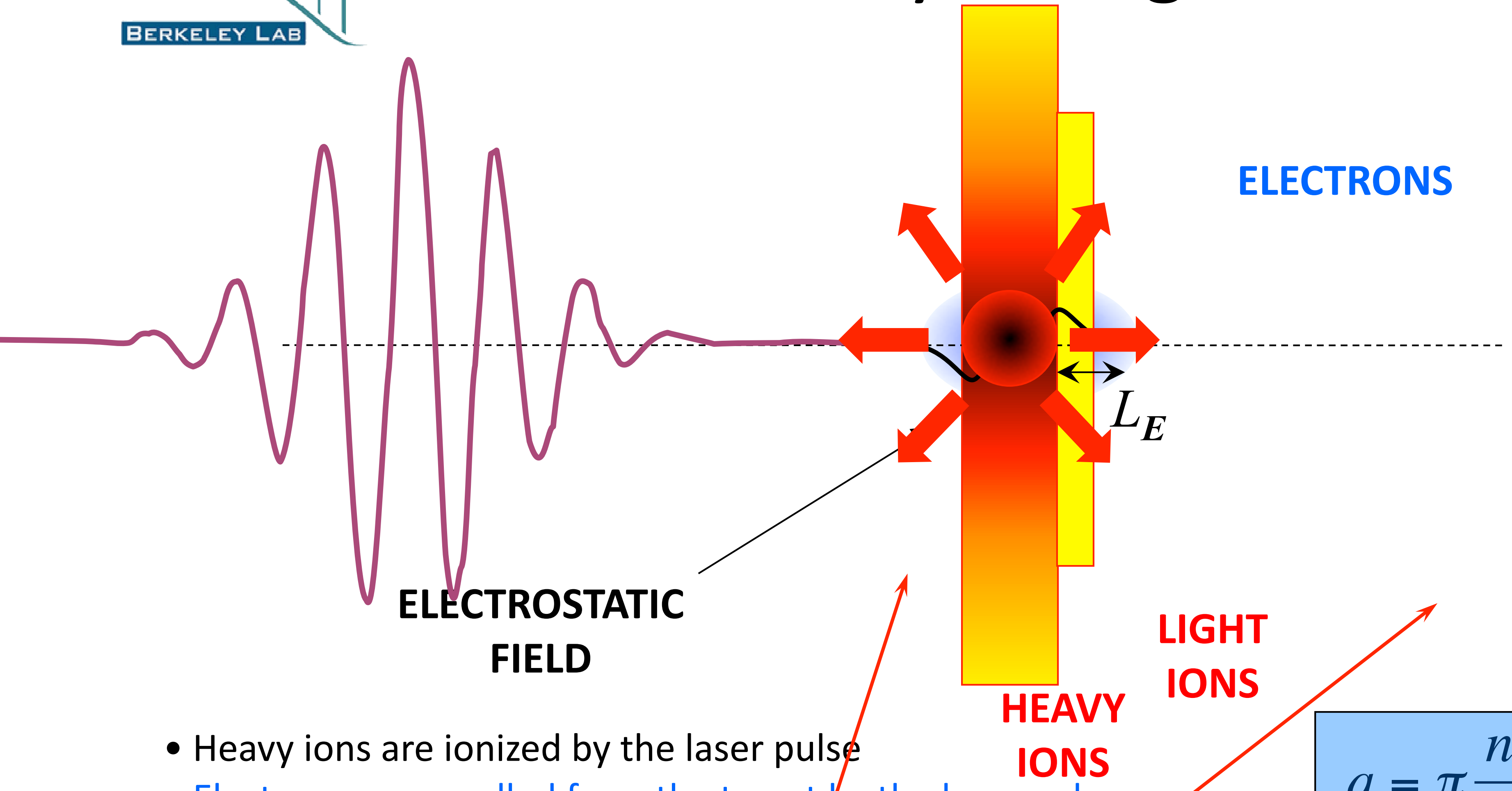
$$\mathcal{E} \sim P^{1/2}$$

$$a = \pi \frac{n_e}{n_{cr}} \frac{l}{\lambda}$$

Coulomb Explosion Regime

- **High contrast allows sub-micron target which become transparent to laser**
- **Pulse propagates through target**
- **Removes most electrons from target**
- **Much larger charge separation at rear**
- **Best designs use high-Z/low-Z layers**

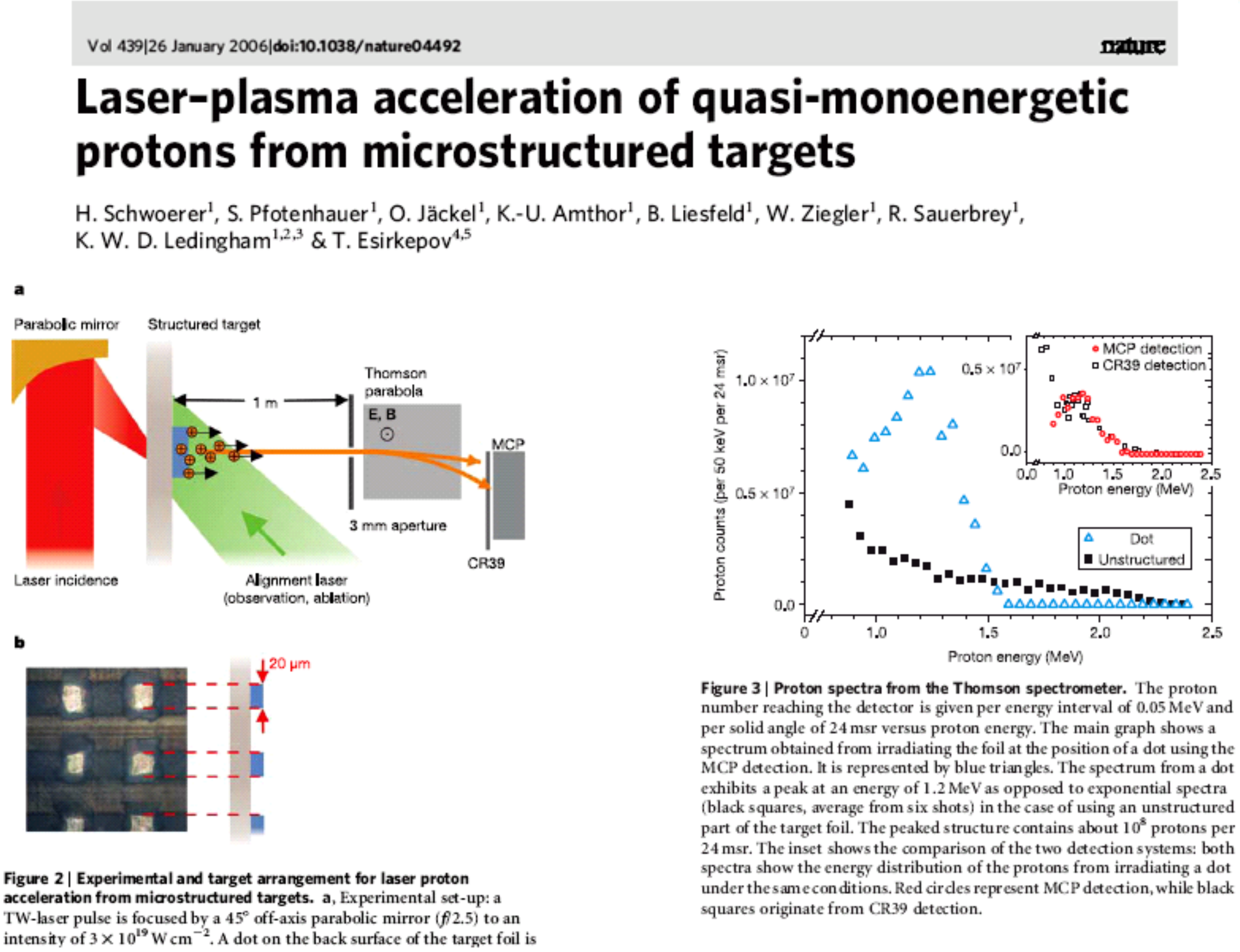
Double layer target



$$a = \pi \frac{n_e}{n_{cr}} \frac{l}{\lambda}$$

- Heavy ions are ionized by the laser pulse
- Electrons are expelled from the target by the laser pulse
- Light ions are accelerated in the charge separation field
- Heavy ion layer explodes due to the Coulomb repulsion of excess positive charge

- **S. V. Bulanov and V. S. Khoroshkov, Plasma. Phys. Rep. 28, 453 (2002)**
- **T. Zh. Esirkepov et al., Phys. Rev. Lett. 89, 175003 (2002).**
- **H. Schwoerer, *et. al.*, Nature 439, 445 (2006)**



Vol 439|26 January 2006|doi:10.1038/nature04492 nature

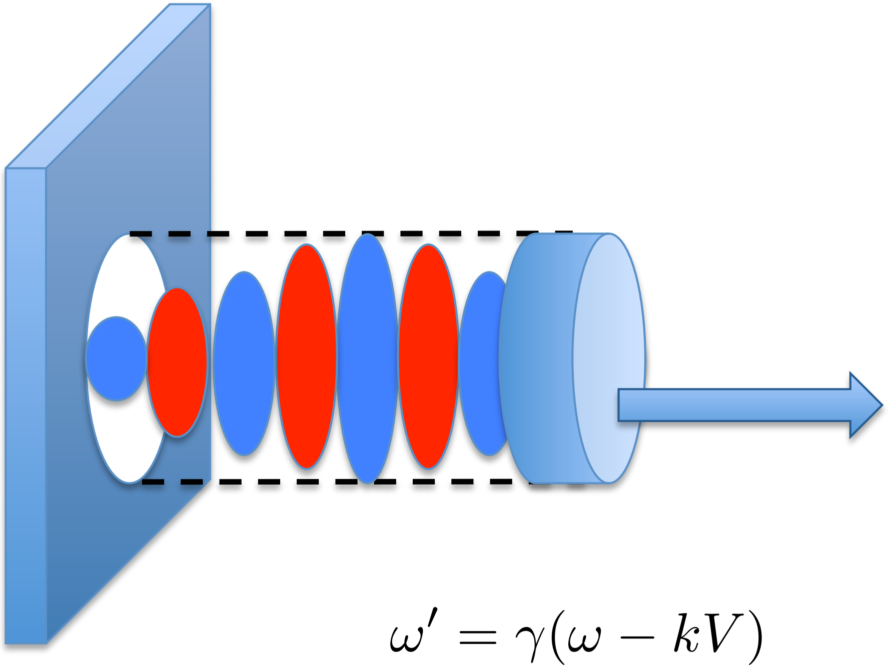
Laser-plasma acceleration of quasi-monoenergetic protons from microstructured targets

H. Schwoerer[1], S. Pfotenhauer[1], O. Jäckel[1], K.-U. Amthor[1], B. Liesfeld[1], W. Ziegler[1], R. Sauerbrey[1],
K. W. D. Ledingham[1,2,3] & T. Esirkepov[4,5]

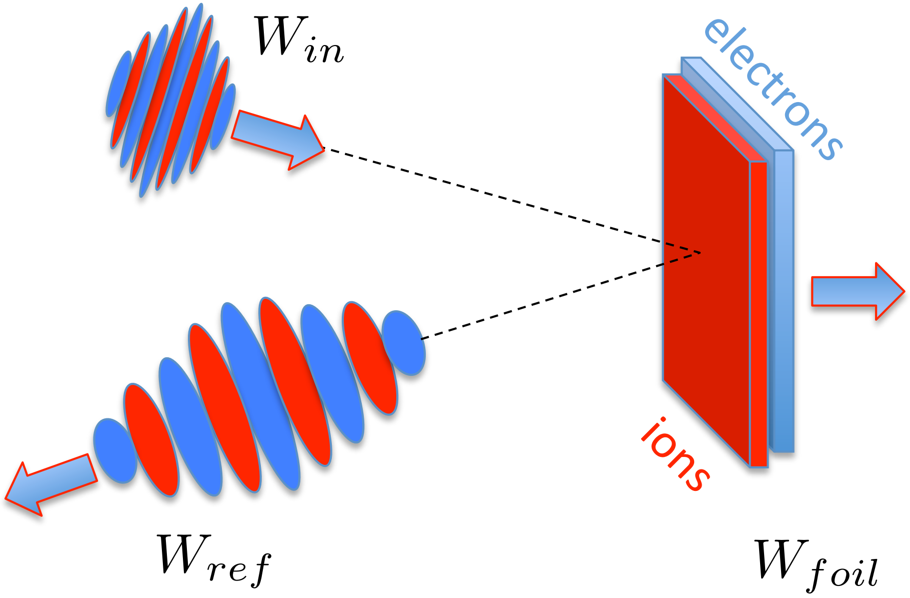
Figure 2 | Experimental and target arrangement for laser proton acceleration from microstructured targets. **a**, Experimental set-up: a TW-laser pulse is focused by a 45° off-axis parabolic mirror (*f*/2.5) to an intensity of 3×10^{19} W cm^{-2}. A dot on the back surface of the target foil is

Figure 3 | Proton spectra from the Thomson spectrometer. The proton number reaching the detector is given per energy interval of 0.05 MeV and per solid angle of 24 msr versus proton energy. The main graph shows a spectrum obtained from irradiating the foil at the position of a dot using the MCP detection. It is represented by blue triangles. The spectrum from a dot exhibits a peak at an energy of 1.2 MeV as opposed to exponential spectra (black squares, average from six shots) in the case of using an unstructured part of the target foil. The peaked structure contains about 10^8 protons per 24 msr. The inset shows the comparison of the two detection systems: both spectra show the energy distribution of the protons from irradiating a dot under the same conditions. Red circles represent MCP detection, while black squares originate from CR39 detection.

Radiation Pressure Acceleration



$$a = a_0 \sin(\omega t - kx)$$
$$a' = a_0 \sin(\omega' t' - k' x')$$
$$a'_{ref} = a_0 \sin(\omega' t' + k' x')$$
$$a''_{ref} = a_0 \sin(\omega'' t'' + k'' x'')$$



$$\omega' = \gamma(\omega - kV)$$
$$k' = \gamma(k - \omega V)$$
$$\omega'' = \gamma(\omega' + k'V) = \frac{1-\beta}{1+\beta}\omega \approx \frac{\omega}{4\gamma^2}$$
$$W_{ref} = \frac{W_{in}}{4\gamma^2}$$
$$W_{foil} = W_{in}\left(1 - \frac{1}{4\gamma^2}\right)$$

Radiation Pressure Acceleration

$$n_0 l_0 \frac{dp}{dt} = \frac{E_L^2}{2\pi} \frac{(m^2+p^2)-p}{(m^2+p^2)+p}$$

$$P = (E_L'^2/4\pi)(1+|\rho|^2-|\tau|^2) = (E_L'^2/2\pi)(\omega'/\omega)|\rho(\omega')|^2 \qquad \left(\frac{\omega'}{\omega}\right)^2 = \frac{1-\beta}{1+\beta}$$

$$\psi = \int_{-\infty}^{t-x(t)} \frac{E_L^2(\xi)}{4\pi n_e l m_i c} d\xi \qquad max\{\psi\} = \mathcal{E}_L/N_i m_i c^2$$

$$\mathcal{E}_{kin} = m_i c^2 \frac{(2\kappa\psi + h_0 - 1)^2}{2(2\kappa\psi + h_0)}$$

$$max\{\mathcal{E}_{kin}\} = \frac{2\kappa\mathcal{E}_L}{\kappa\mathcal{E}_L + N_i m_i c^2} \frac{\kappa\mathcal{E}_L}{N_i}$$

Radiation Pressure Acceleration

$$\gamma - 1 \ll 1$$

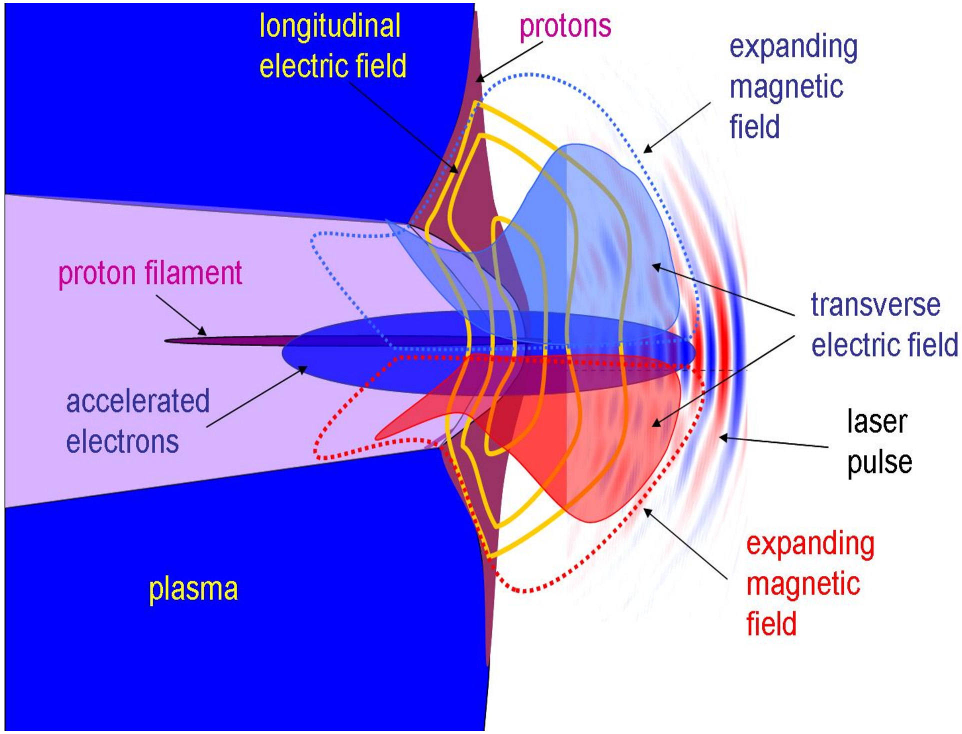
$$\mathcal{E} = 8(10^{11}/N_{tot})^2(M_p/M_i)(\mathcal{E}_L/1J)^2 \text{ MeV}$$

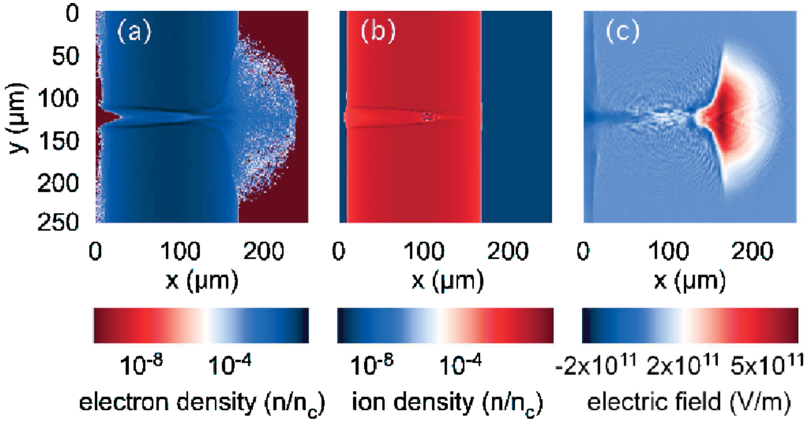
$$\gamma \gg 1$$

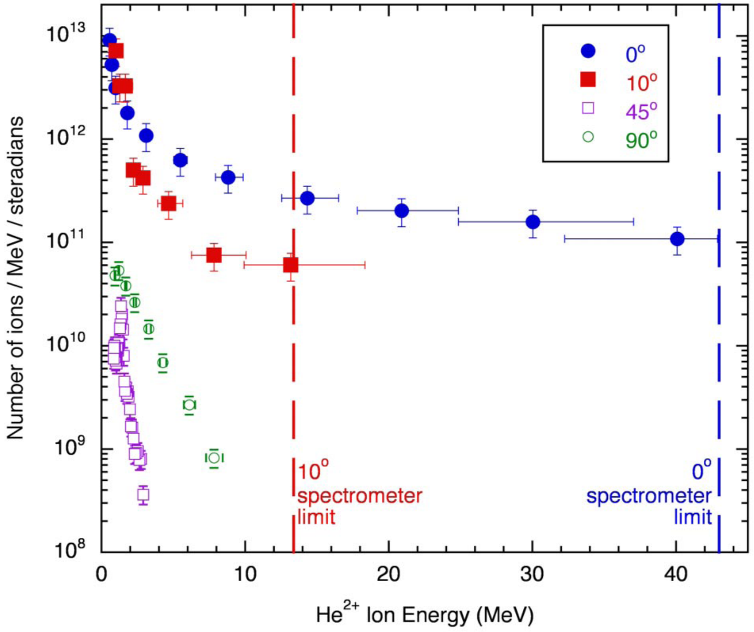
$$\mathcal{E} = 62.5(10^{11}/N_{tot})(M_p/M_i)(\mathcal{E}_L/1\ kJ) \text{ GeV}$$

Magnetic Vortex Acceleration

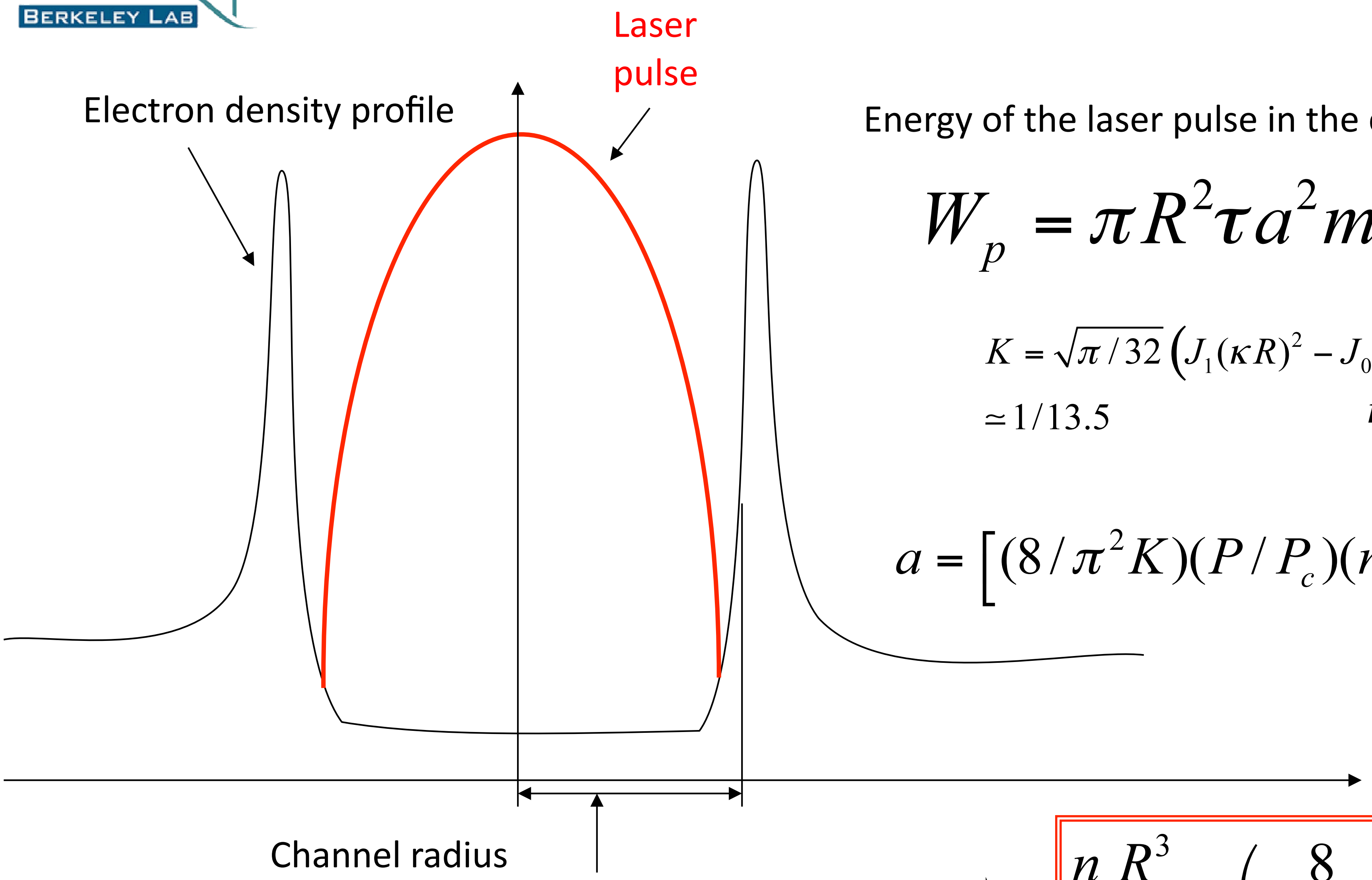
VULCAN: T=1.0 ps, W= 340 J
L. Willingale, *et at.*,
Phys. Rev. Lett. **96**, 245002 (2006)







Laser pulse in a waveguide



Energy of the laser pulse in the channel

$$W_p = \pi R^2 \tau a^2 m_e c n_{cr} K$$

$$K = \sqrt{\pi/32}\left(J_1(\kappa R)^2 - J_0(\kappa R)J_2(\kappa R)\right)$$

$$\simeq 1/13.5 \qquad \kappa = 1.84/R$$

$$a = \left[(8/\pi^2 K)(P/P_c)(n_e/n_{cr})\right]^{1/3}$$

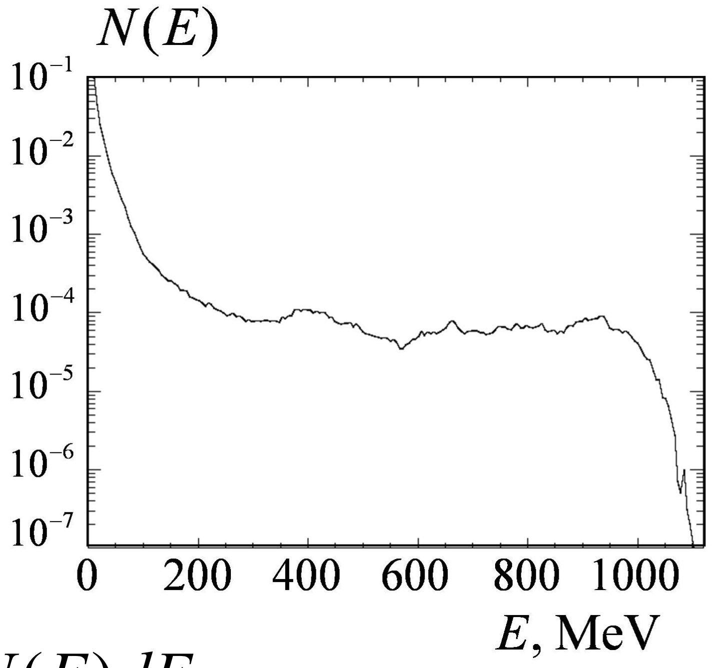
$$\Downarrow$$

$$R = a^{1/2}(\omega/\omega_{pe})\lambda/2 \Rightarrow \boxed{\frac{n_e R^3}{P^{1/2}} = \left(\frac{8}{\pi^2 K}\right)\frac{n_{cr}\lambda^3}{P_c^{1/2}}}$$

Energy of electrons

The energy of electrons accelerated by the laser in the channel

$$W_e = \pi R^2 L_{ch} n_e a m_e c^2$$



If we assume that all the energetic electrons come from the channel, then the number of electrons that were initially in the would-be channel is

$$N_{ch} = \int_{E_{th}}^{E_{\max}} N(E)dE$$

and the average electron energy is $\bar{E} = \frac{1}{N_{ch}} \int_{E_{th}}^{E_{\max}} E N(E)dE$

From the results of 2D PIC simulations $\bar{E} = 93\ \text{MeV}$ and $\bar{E} = a m_e c^2$

The condition of laser pulse energy depletion is

$$W_p = W_e$$

$$\boxed{L_{ch} = a \frac{n_{cr}}{n_e} L_p K}$$

Proton acceleration from near critical density plasma: new scaling

Condition for optimal ion acceleration in the case of thin foils: $a_0 = \sigma$

From relativistic transparency

where $\sigma = \pi \left(\frac{\omega_{pe}}{\omega} \right)^2 \frac{L}{\lambda}$

K. Matsukado, *et al.*, Phys. Rev. Lett. 91, 215001 (2003).
T. Esirkepov et al., Phys. Rev. Lett. 96, 105001 (2006)
A. Yogo, *et al.*, Phys. Rev. E 77, 016401 (2008).

$$\boxed{a = \frac{1}{K}\frac{n_e}{n_{cr}}\frac{L_{ch}}{L_p} \quad or \quad \frac{n_e^{2/3} L_{ch}}{W_p^{1/3}} = C,}$$

$$C = \left(\frac{4K^2 n_{cr} L_p^2}{\pi \lambda^2 m_e c^2} \right)^{1/3}$$

L_p is the laser pulse length

Condition for optimal ion acceleration in the case of a long near critical density plasma slab is based on the requirement of optimal pulse energy depletion (W_p=W_e).

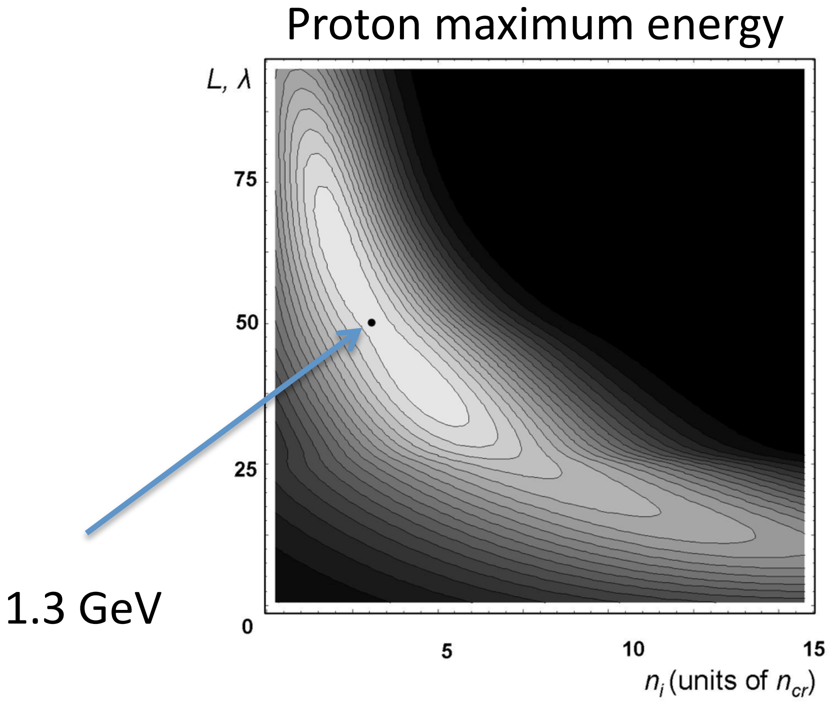
The maximum proton energy scales as $\boxed{E_p \sim P^{2/3}}$

W_e is the energy of electrons, which were initially in the would-be propagation channel

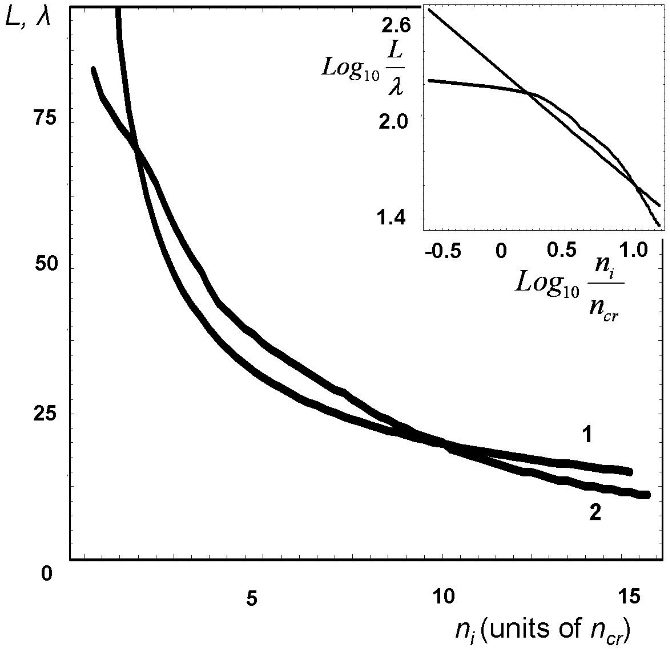
$$\boxed{W_e = \pi R^2 L_{ch} n_e a m_e c^2}$$

Proton acceleration in near-critical density plasmas. Optimal conditions.

1 PW laser pulse


Proton maximum energy

1.3 GeV

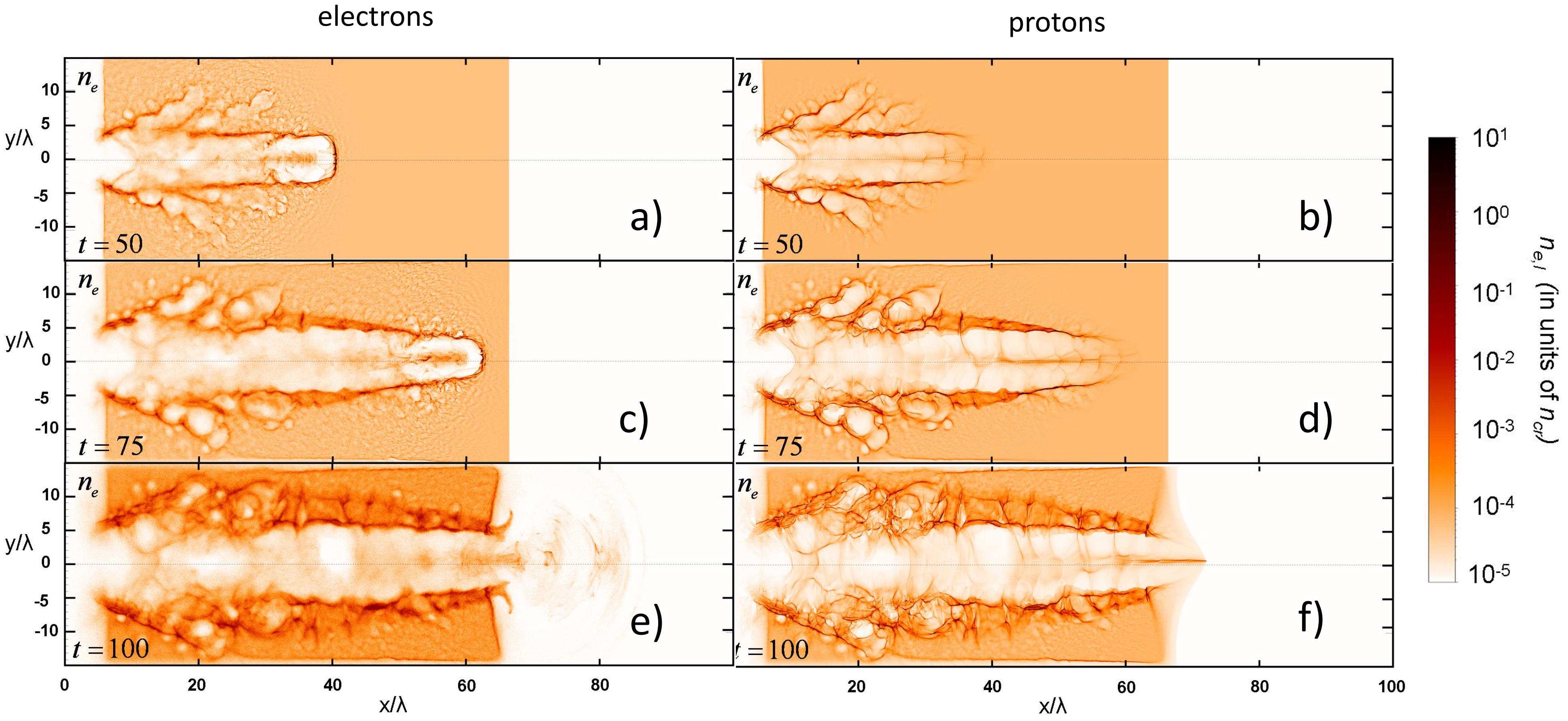


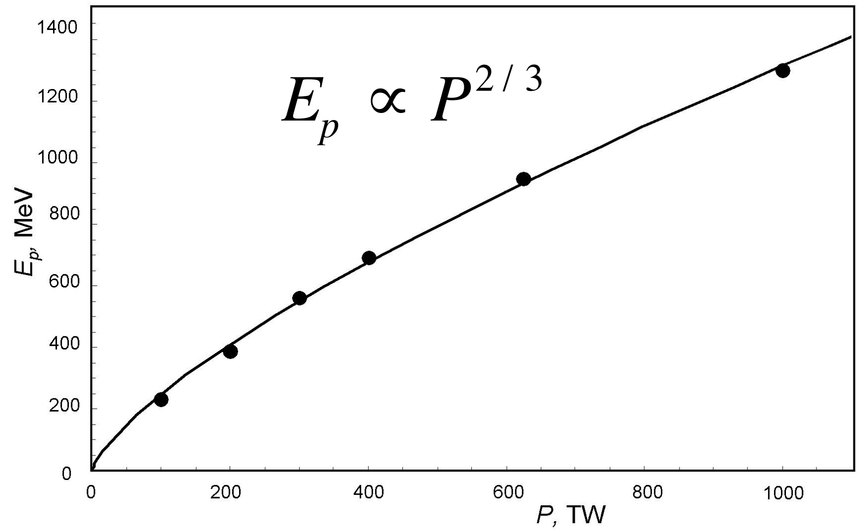
$$\frac{n_e^{2/3} L_{ch}}{W^{1/3}} = \text{constant}$$

The dependence of the target thickness on target density corresponding to maximum accelerated proton energy

S. S. Bulanov, et al., Phys. Plasmas **17**, 043105 (2010)

Ion acceleration from near critical density plasma

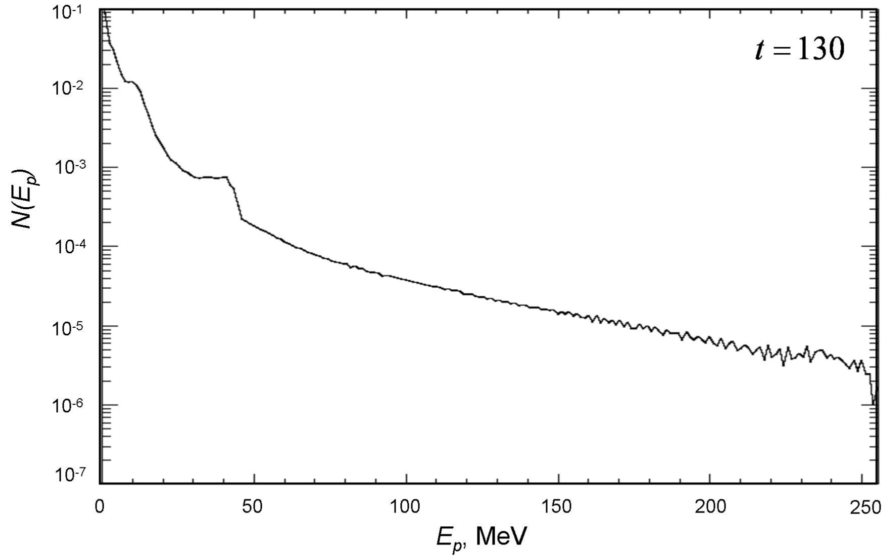




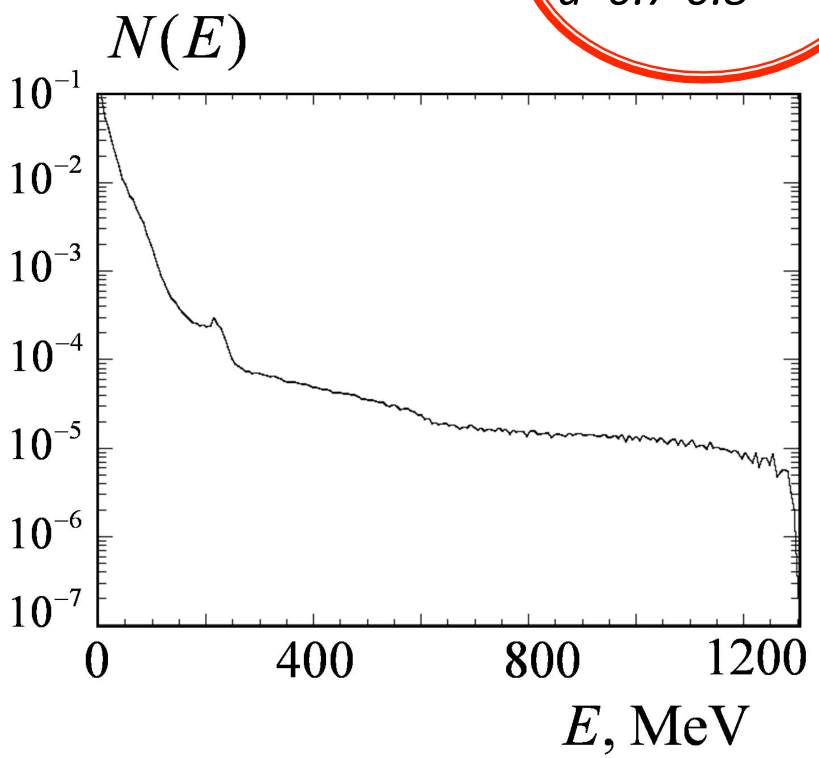
The dependence of the proton maximum energy on the laser pulse power for *n*=$3n_{cr}$ and *f/D=1.5* . The black circles are the results of 2D PIC simulations. The curve is the fit of the data by function bP^a. The thickness of the target was chosen to maximize the proton energy for the given laser pulse parameters and density of the target.

$$E_p \sim P^a$$

a=0.7-0.8



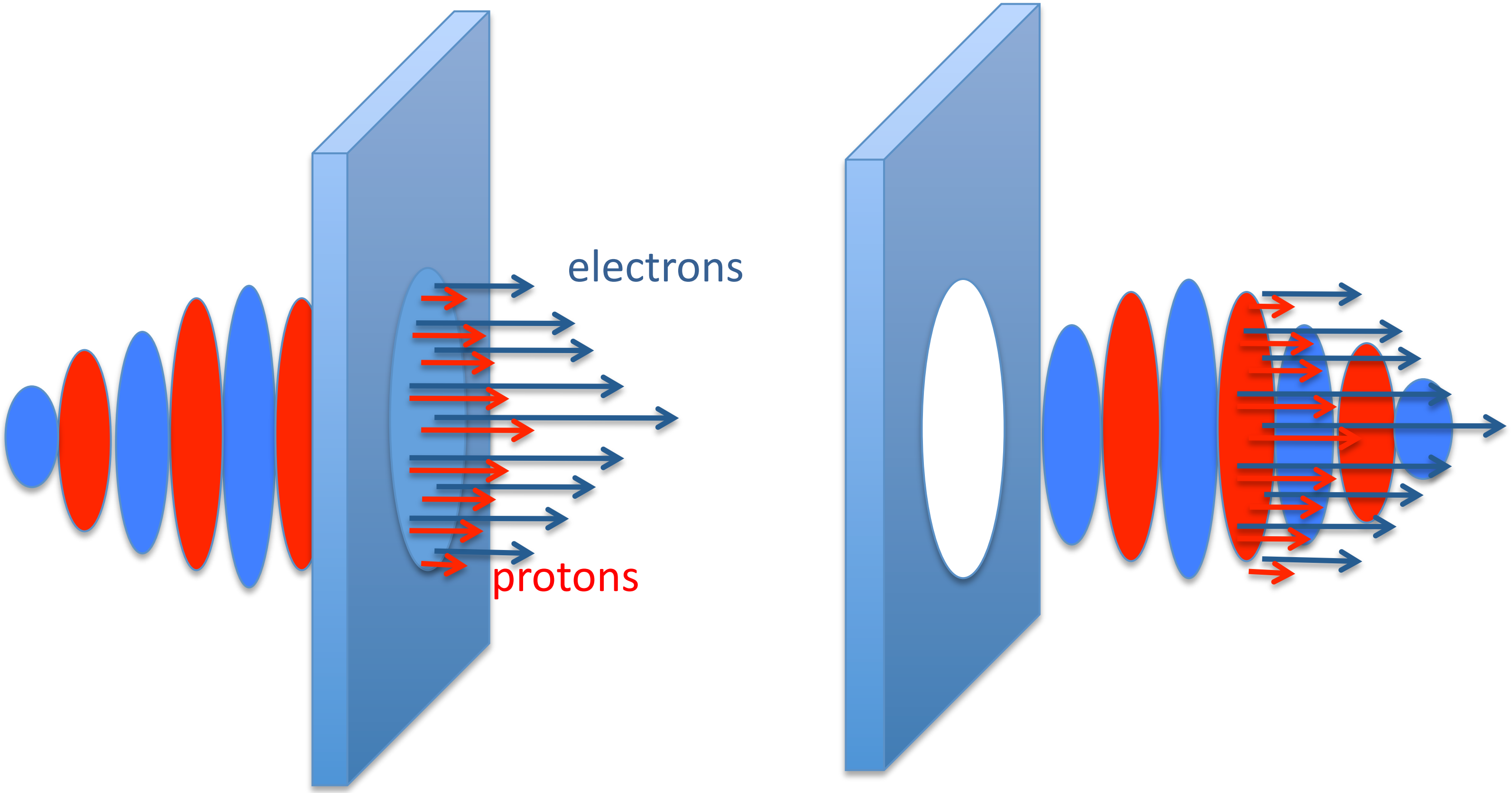
The spectrum of protons accelerated from 1ncr 60 λ thick target by a 100 TW laser pulse.



The spectrum of protons accelerated from 3.0 ncr 50 λ thick target by a 1 PW laser pulse

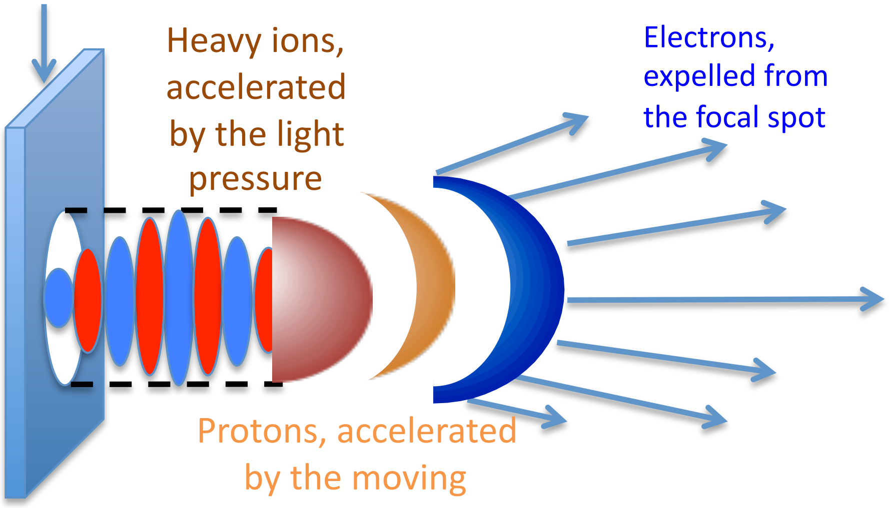
“laser breakout afterburner” BOA

L. Yin, et al., PHYSICS OF PLASMAS 14, 056706 2007



Directed Coulomb Explosion

Ultra-thin solid density foil:
100 nm Al foil

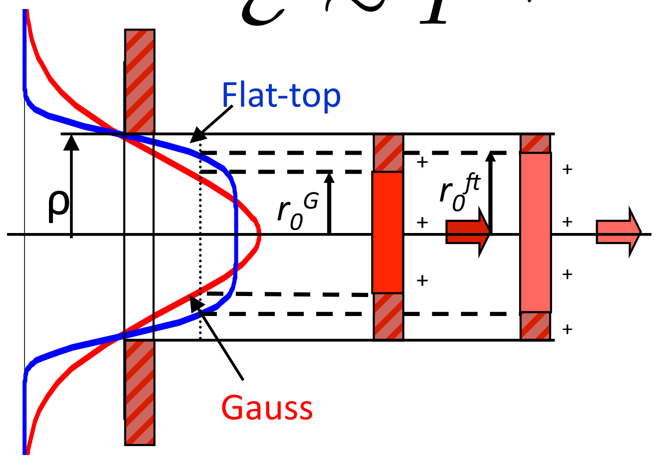


Heavy ions, accelerated by the light pressure

Electrons, expelled from the focal spot

Protons, accelerated by the moving charge separation field

$$\mathcal{E} \sim P^{1/2}$$



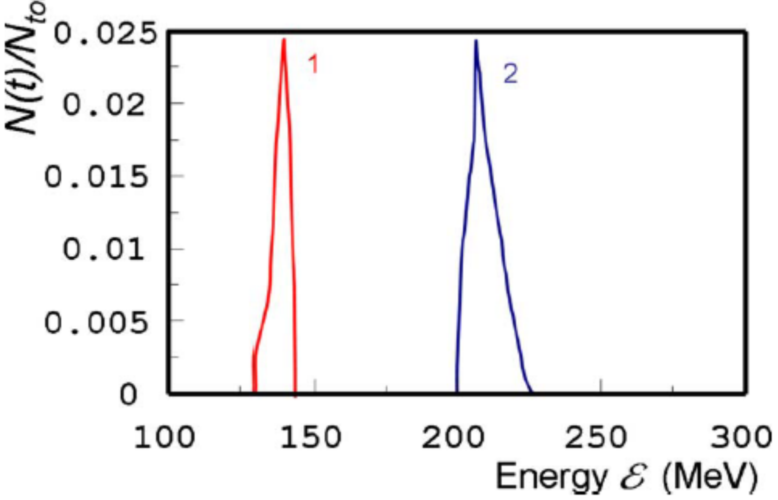
500 TW 30 fs
laser pulse;
1.5 λ focal spot

220 MeV

$$\Delta E/E = 3\%$$

Proton bunch

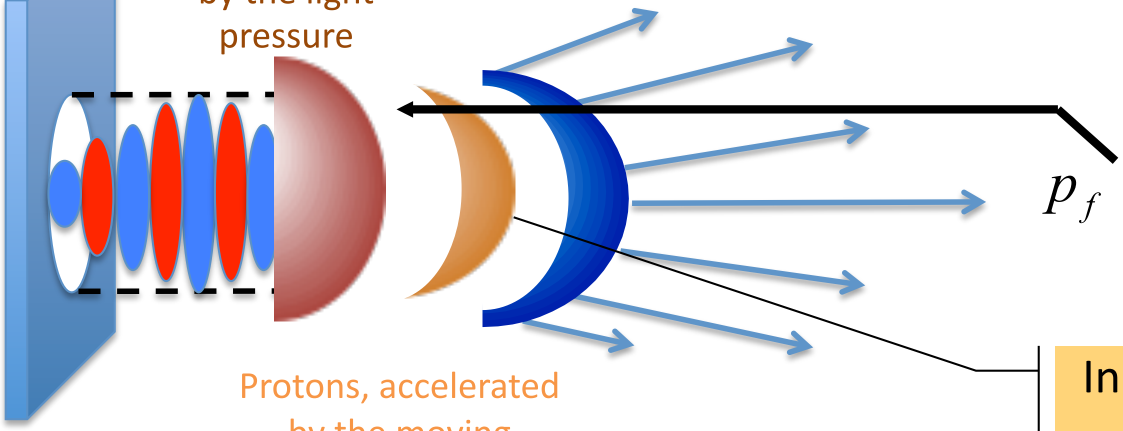
Spectra of protons:
(1) Gaussian pulse
(2) Flat-top pulse



S. S. Bulanov, et al., Med. Phys. 35 (5), 2008.
S. S. Bulanov, et al., Phys. Rev. E 78, 026412 (2008)

Directed Coulomb Explosion regime of proton acceleration

$$\frac{dp}{dt}=\frac{E_L^2[t-x(t)/c]}{2\pi n_e L_{Al}}\,\frac{\sqrt{m_i^2c^2+p^2}-p}{\sqrt{m_i^2c^2+p^2}+p}$$



Heavy ions, accelerated by the light pressure

Protons, accelerated by the moving charge separation field

$$p_f=\frac{2W_L}{N_i m_i c^2}$$

To the frame moving with the heavy ions

In the moving frame

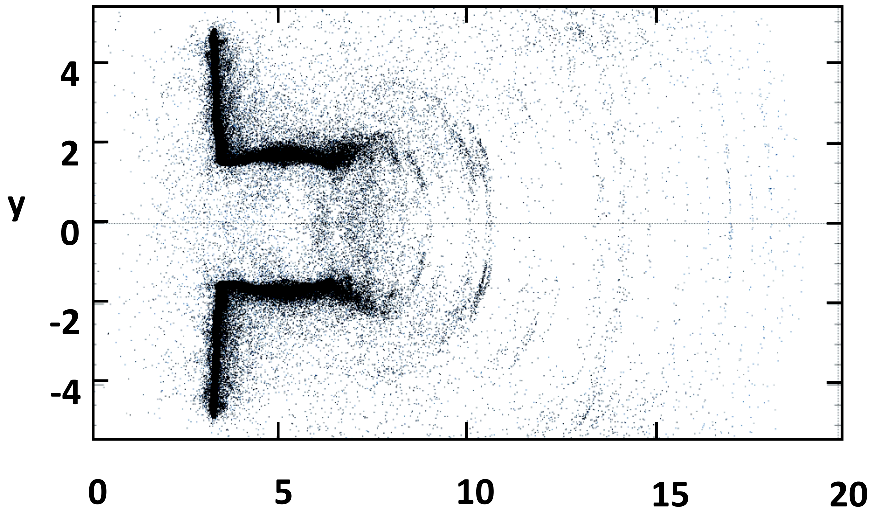
$$W'_p=2\pi\kappa m_e c^2\,\frac{n_e}{n_{cr}}\,\frac{L_{Al}R}{\lambda^2}$$

To laboratory frame

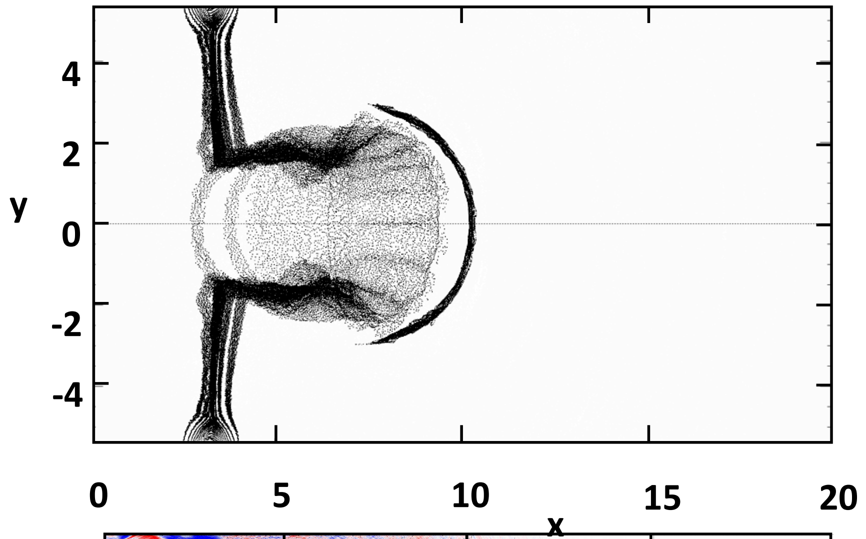
$$W_p=\frac{W'_p+Vp'}{\sqrt{1-V^2/c^2}}=W'_p\sqrt{1+p_f^2}+p_f\sqrt{2m_pW'_p}$$

Directed Coulomb Explosion

Electron density

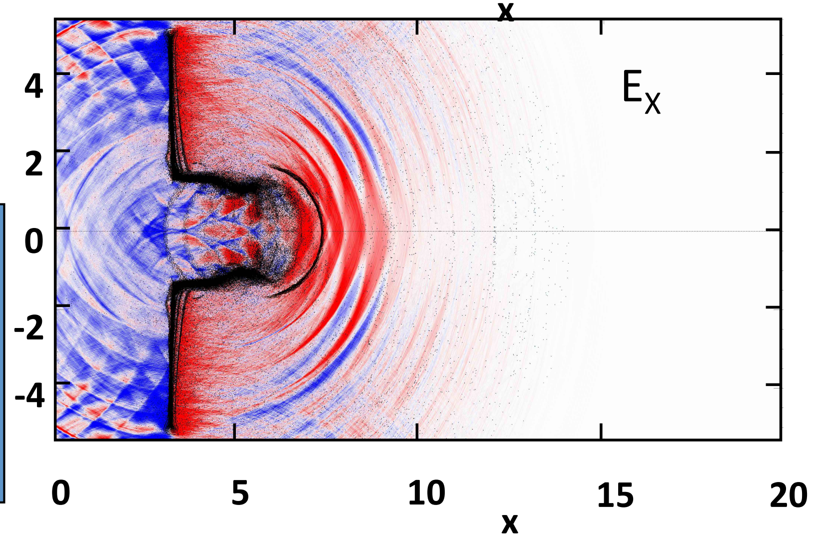


Ion density



Parameters of simulation
Simulation box: 20 λ x 10 λ
Grid mesh size: λ/200
Laser pulse: 500 TW
Linearly polarized (z)
Focused: f/D=1.5
Foil: first layer Al^{+13},
electron density 400n$_{cr}$
second layer H^{+},
electron density 30 n$_{cr}$

the anticipated experimental conditions for the Hercules laser at U of M
V. Yanovsky, et al., Optics Express, 16, 2109 (2008).



Flying mirrors (FM).

Double Doppler Effect

A. Einstein, Ann. Phys. (Leipzig) 17, 891 (1905)

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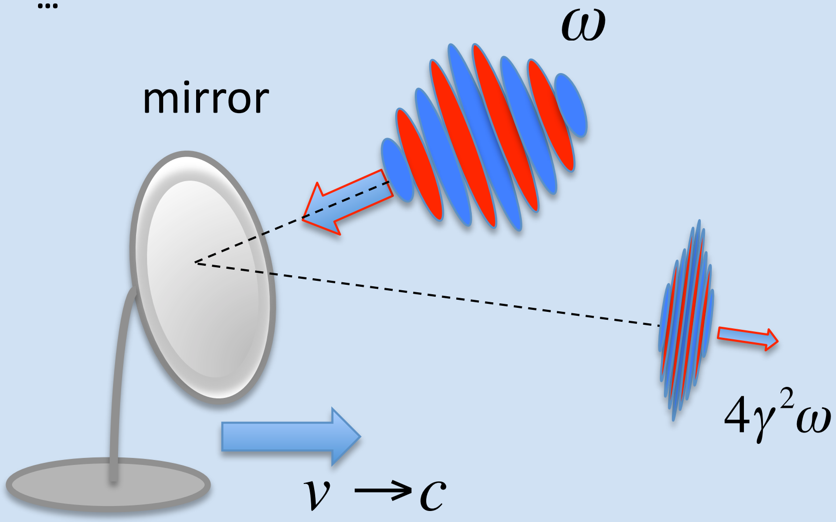
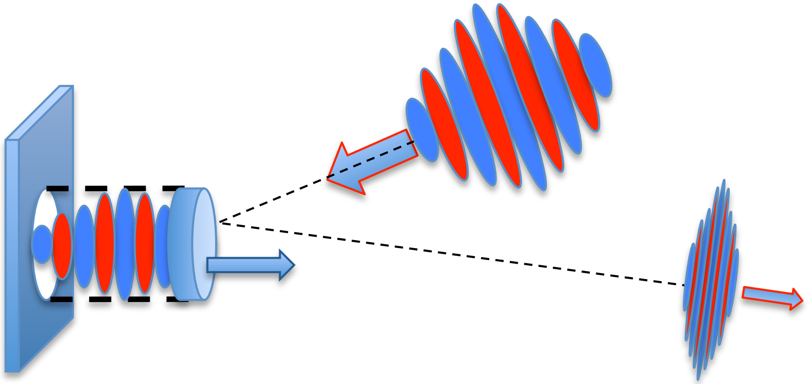


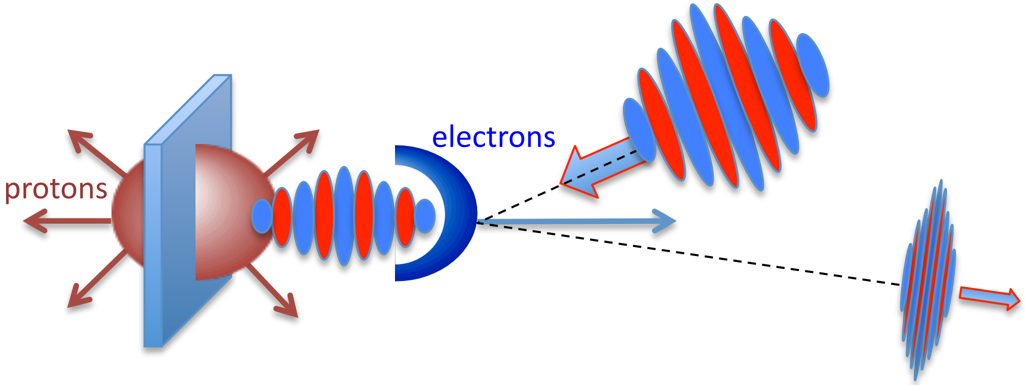
FM from Radiation Pressure Acceleration

T.Zh. Esirkepov, et al., Phys. Rev. Lett. 103 (2009) 025002.



FM from Coulomb Explosion

V.V. Kulagin, et al., Phys. Rev. Lett. **99,** 124801 (2007);
D. Habs, et al., Appl. Phys. B **93**, 349 (2008);
J. Meyer-ter-Vehn, H.-C. Wu, Eur. Phys. J. D **55,** 433 (2009);
H.-C. Wu, et al., Phys. Rev. Lett. 104, 234801 (2010).



FM from multiple electron layers (DCE)

S. S. Bulanov, et al., Phys. Lett. A **374**, 476 (2010).