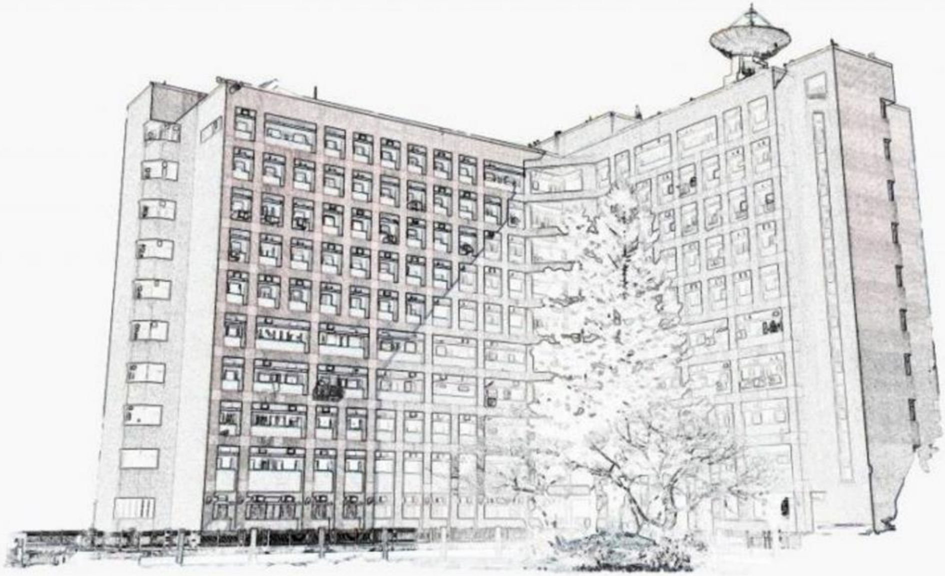
中央大學物理學系

Department of Physics National Central University

Prospects of Laser Plasma Proton Acceleration

Chih-Hao Pai (白植豪)

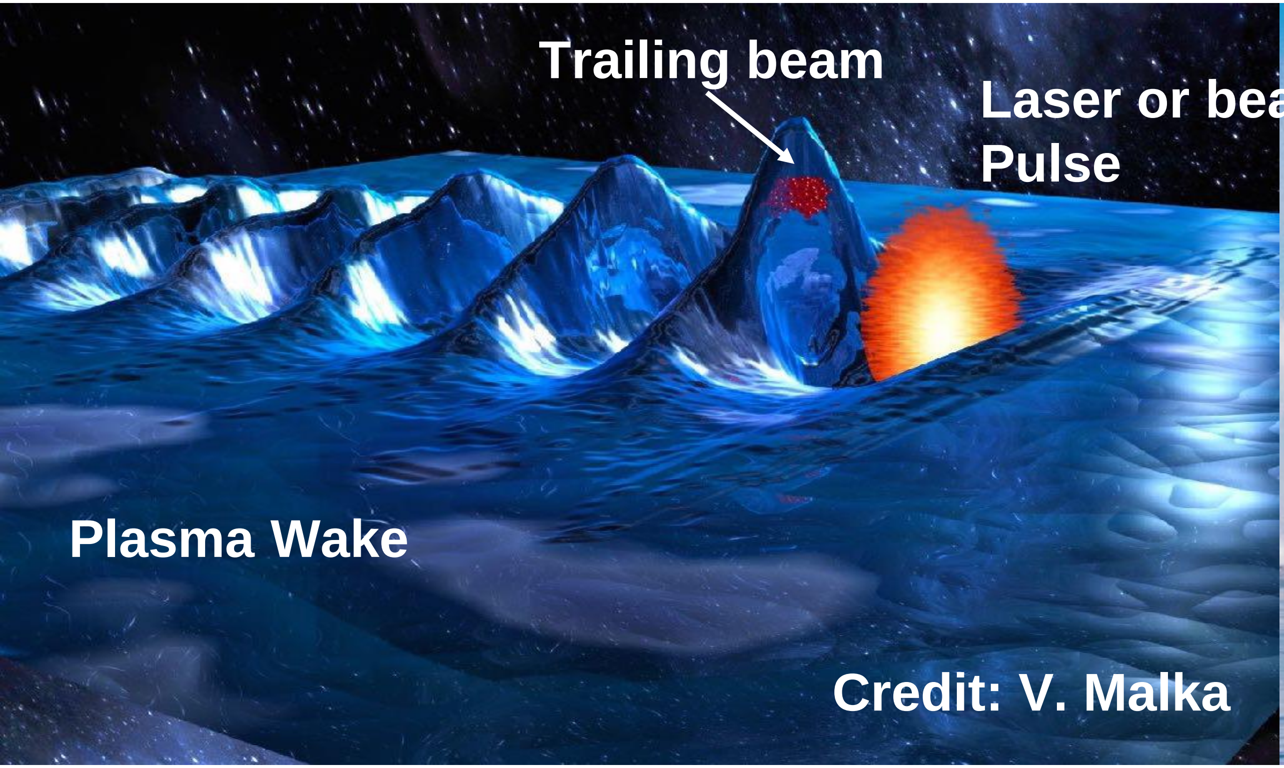
Nov. 23, 2023



Outline

- Laser-plasma proton acceleration
- Properties of laser proton sources
- Potential applications
- Laser-driven neutron sources

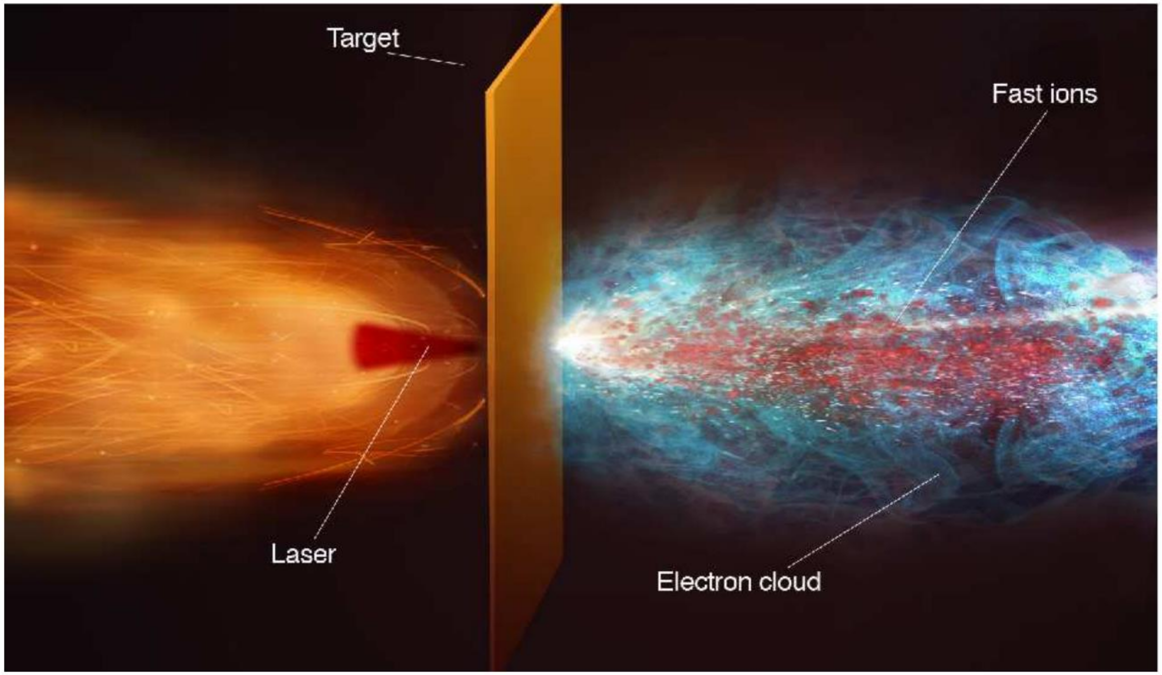
Light speed surfing on plasma wakes

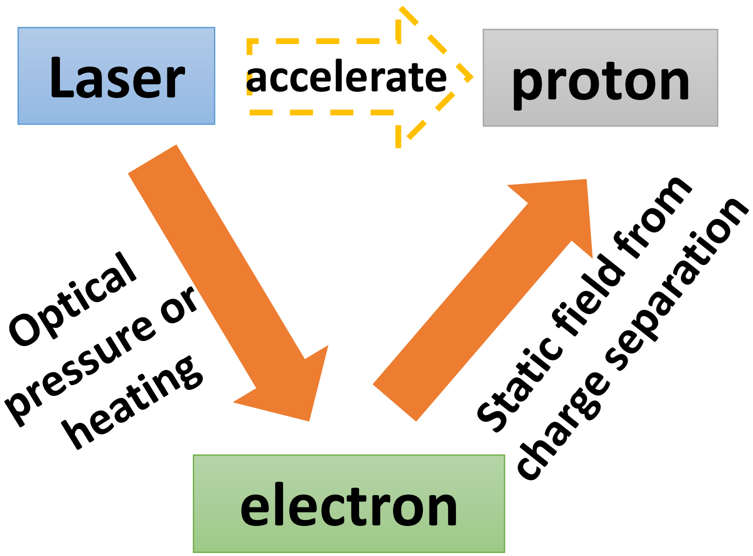


Huge gradient (~100 GV/m) + Tiny structures (~10-100 μm)

T. Tajima and J. M. Dawson PRL (1979) **LWFA**
P. Chen, J. M. Dawson et.al. PRL (1983) **PWFA**

Laser proton acceleration



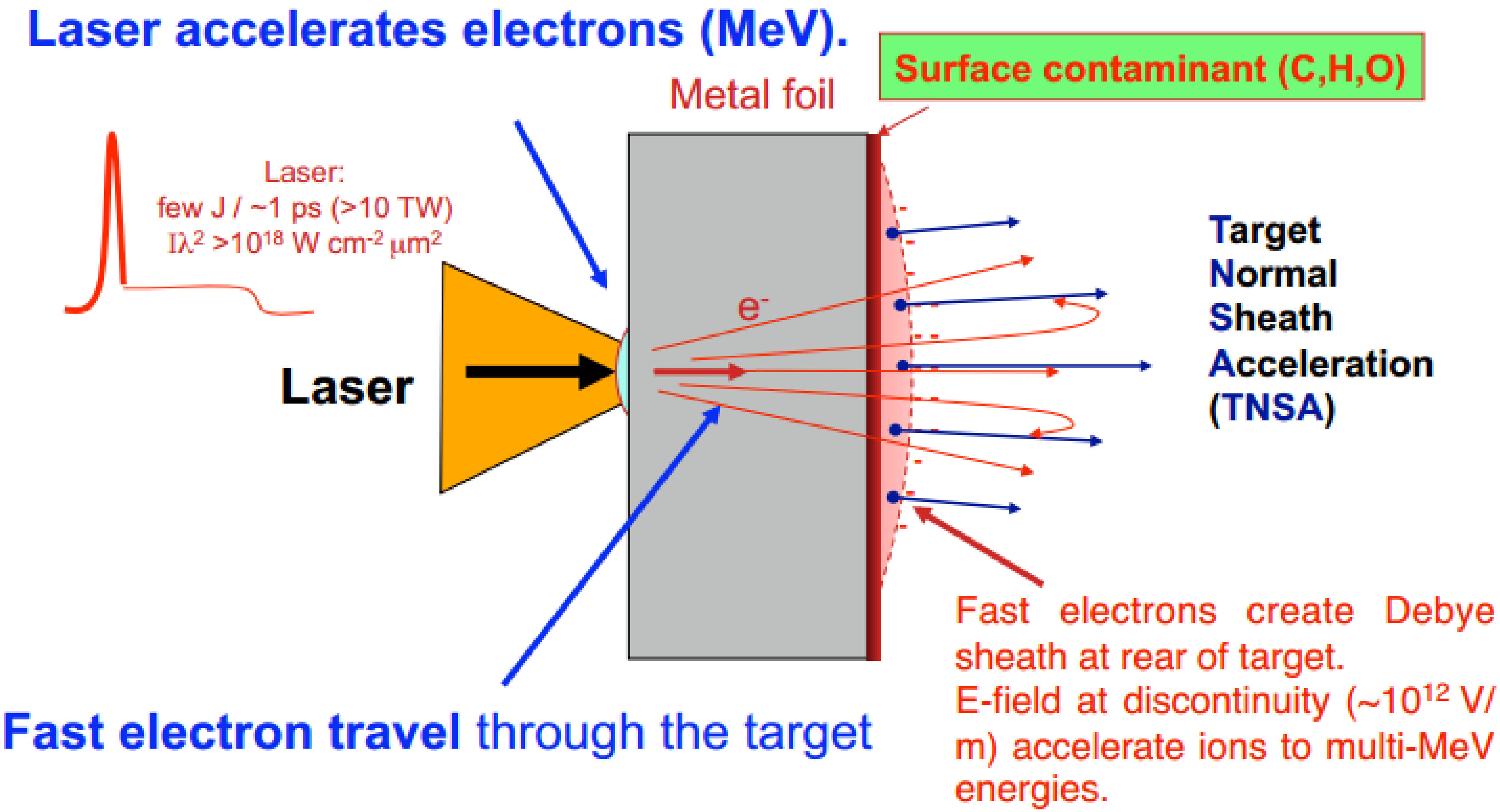


- very high gradient (~TV/m)
- short bunches (~ps) & small size (~10s μm)

Laser proton acceleration has become a very active topic since 2000, and significant progress has been achieved.

A. Macchi, et al., Rev. Mod. Phys. 85, 751 (2013)

Target normal sheath acceleration



TNSA concept proposed by Wilks et al.

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

TNSA beam properties

- **Extreme laminarity: rms emittance < 0.01 π mm-mrad**

  (cf. RF Linacs ~ 1 π mm-mrad)

- **Short duration source: ~ 1 ps *($\Delta E \Delta t < 10^{-6}$ eV-s)*   *(RF beams > ns)***
- **High brightness: 10^{11} –10^{13} protons/ions in a single shot (> 3 MeV)**
- **High current (if stripped of electrons): kA range**

- **Divergent (~ 10s degrees)**
- **Broad spectrum**

Under several respects very different properties than standard accelerator beams (RF synchrotron, cyclotrons, LINAC)

Ultracompact: E~1-10 TV/m =10^5 higher than RF fields
10 MeV acceleration over a μm rather than a m !!

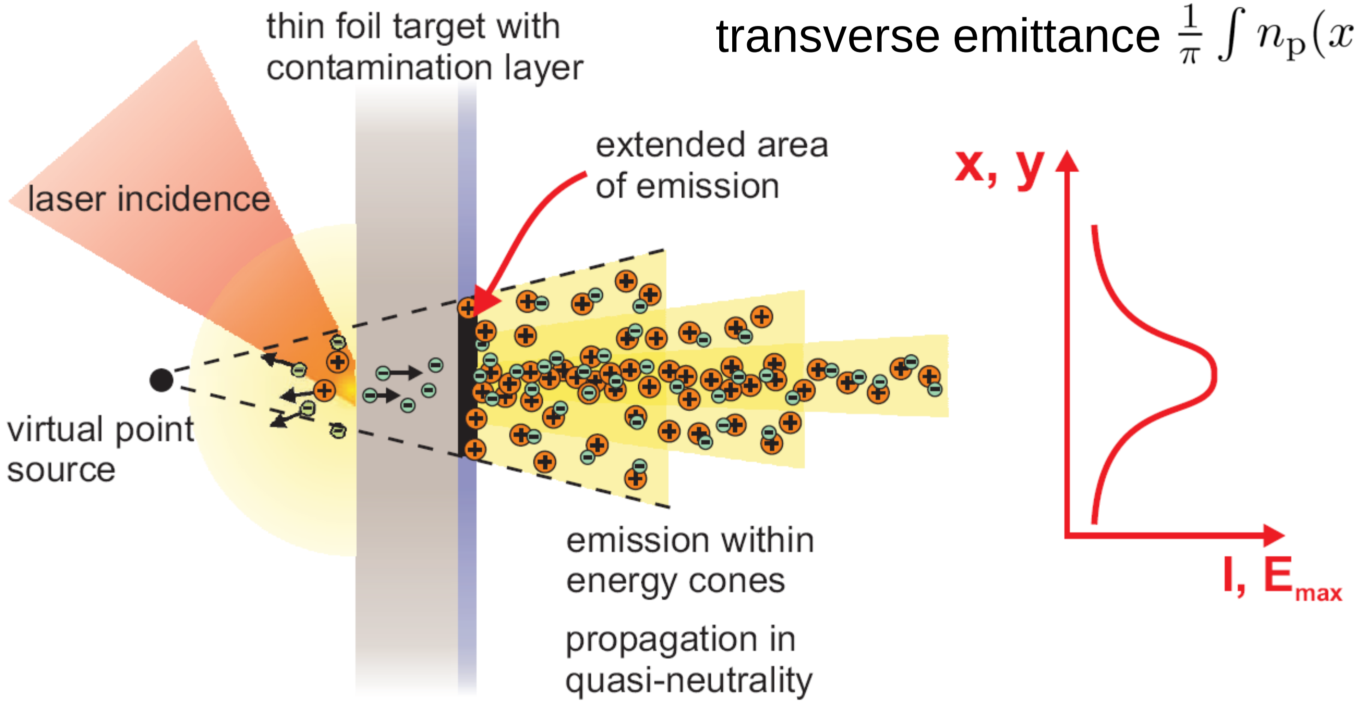
- Synchronized to multi-laser pulses to sub-picosecond.

From M. Borghesi’s slides

TNSA beam properties

Transverse & longitudinal emittance; symmetry & inhomogeneity of the field

transverse emittance $\frac{1}{\pi}\int n_{\mathrm{p}}(x,\,p_{\mathrm{x}})\,dx\,\frac{1}{p_{\mathrm{z}}}dp_{\mathrm{x}}$

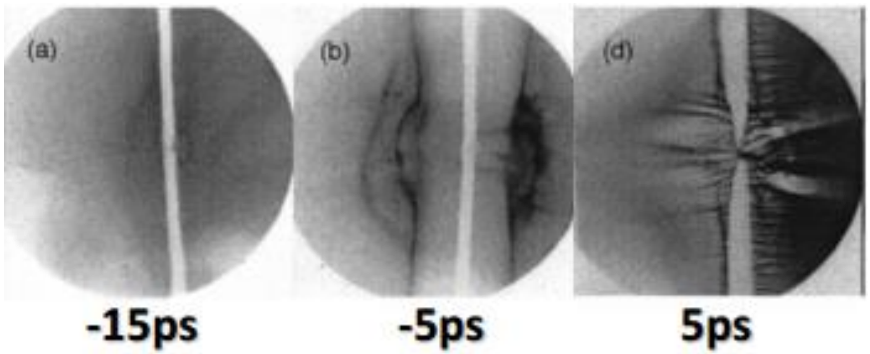


- For laser plasma accelerators, transverse emittance <4 μm mrad are attained, which outmatches conventional accelerators by a factor of 10^3 (e.g. 3.5 mm mrad for the CERN SPS). The excellent beam quality can be ascribed to a very small source size (∼15 μm).

Phys. Rev. Lett. **92**, 542 (2001)

Laser proton acceleration—application

- Probing of strong transient fields in dense plasma on ps timescale



- ~1 μm resolution
- 50 μm Ta wire
- Imaging with 6-7 MeV protons

← **VULCAN Laser, 20J, 10^{19}W/cm^2**

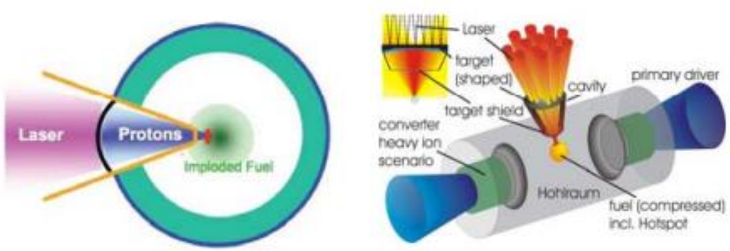
M. Borghesi, Phys. Plasmas (2002)

- Picosecond injectors for conventional accelerators

Cowan, Phys. Rev. Lett. (2004)

- Fast Ignition for ICF

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



- Proton Boron fusion reaction

$$^{11}\mathrm{B} + \mathrm{p} \rightarrow 3\alpha + 8.7\,\mathrm{MeV}$$

- Cancer Therapy

S. V. Bulanov et al., Phys. Lett. A (2002)

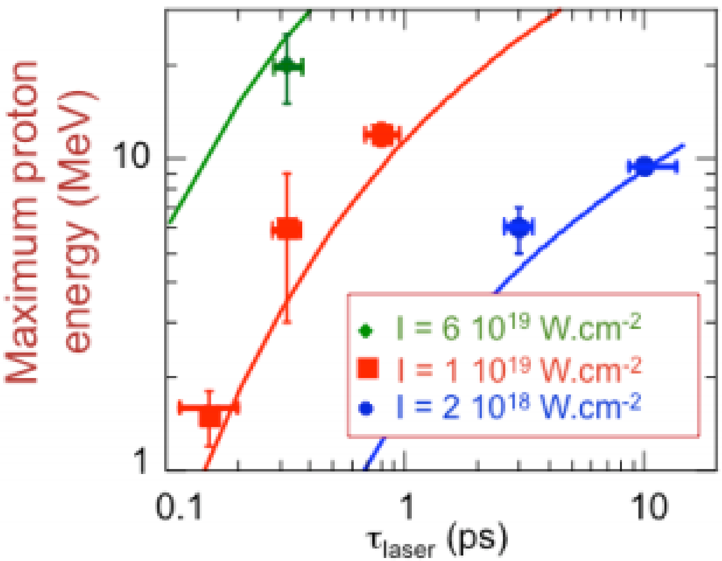
Hadron Cancer Therapy

- **250MeV, 10^9-10^{10} protons/s**
- **ΔE/E ≤ 5%**

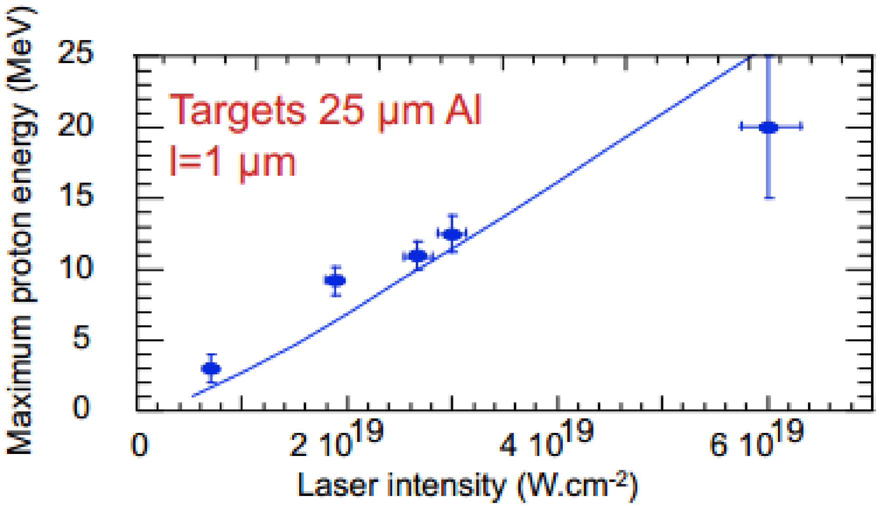
Scaling law with laser parameters

$$v_{\text{front}} \simeq 2c_s \ln(2\tau) = c_s[2\ln(\omega_{pi}t) + \ln 2 - 1].$$

$$\varepsilon \propto c_s^2 \propto KT_{hot} \sim \sqrt{I\lambda^2}$$



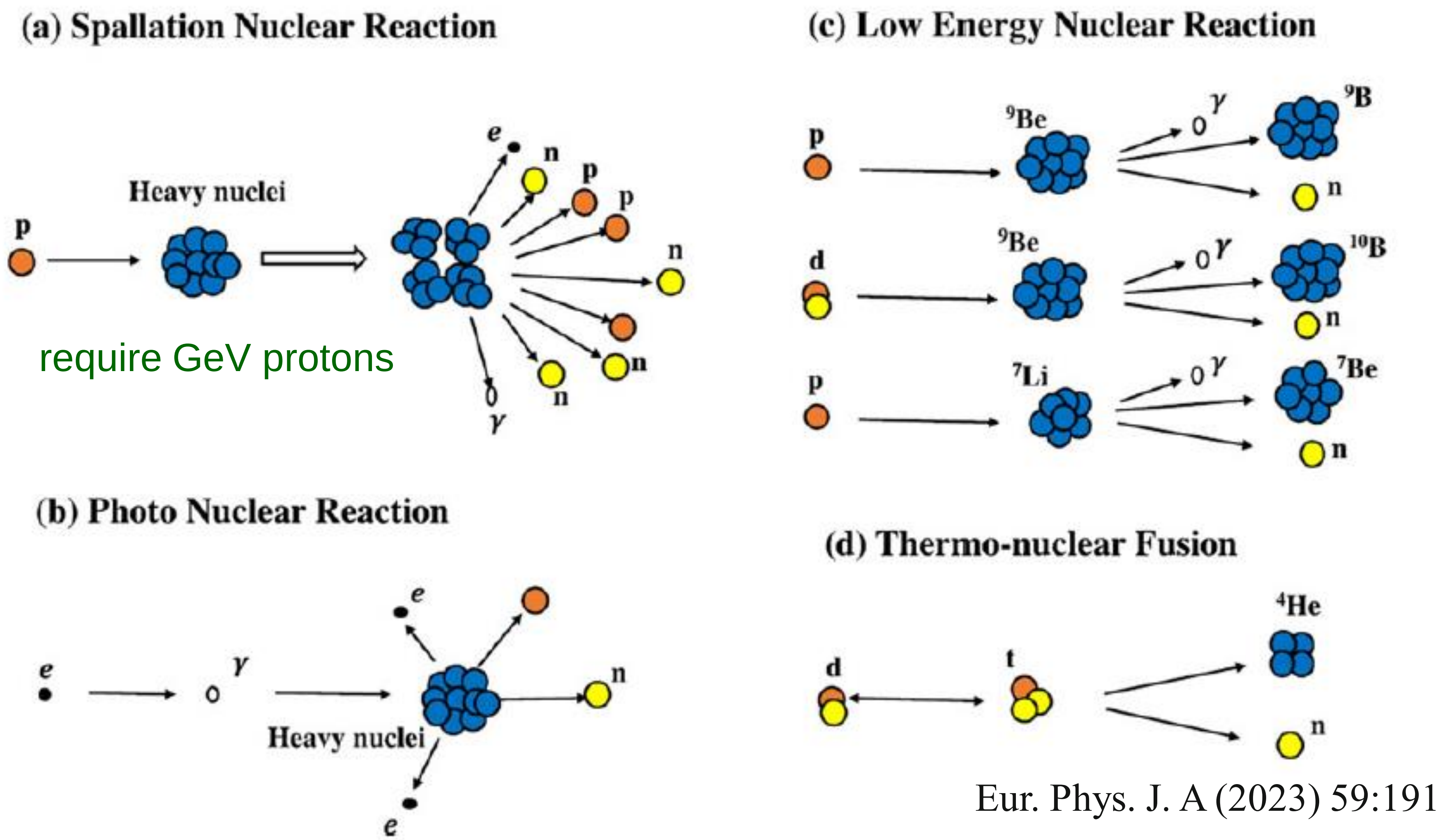
Match with experimental data with t_{acc}~ 1.3 τ_{laser}



J. Fuchs *et al.*, Nature Physics 2, 48 (2006)

This scaling is more suitable for long pulses (100s fs - ps scale)

Laser-driven neutron sources



Eur. Phys. J. A (2023) 59:191

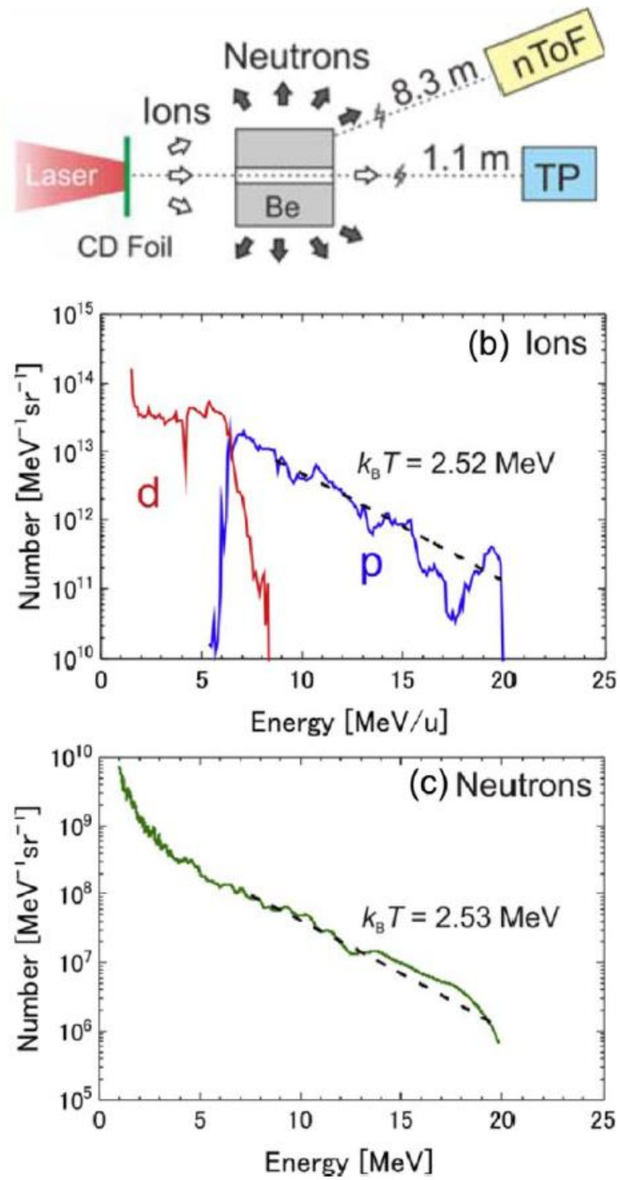
- Compactness of the source
- Neutron pulse shortness
- Transportability of laser beam
- Single-shot measurement
- Multi-beam availability such as x-ray, electron

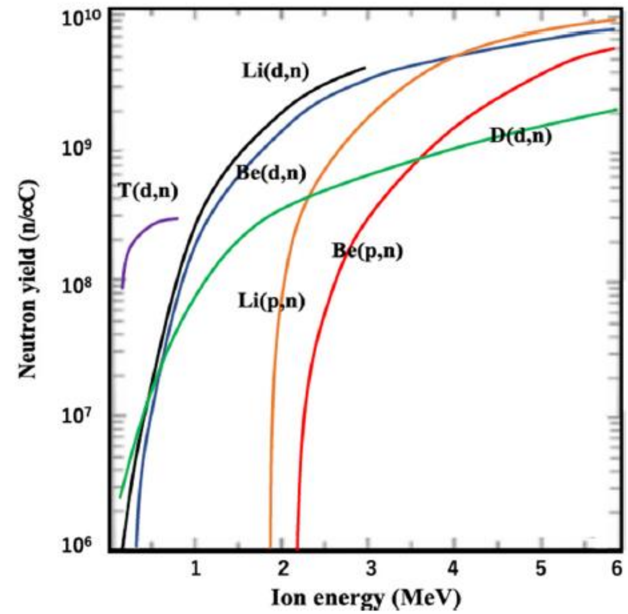
Laser-driven neutron sources-applications

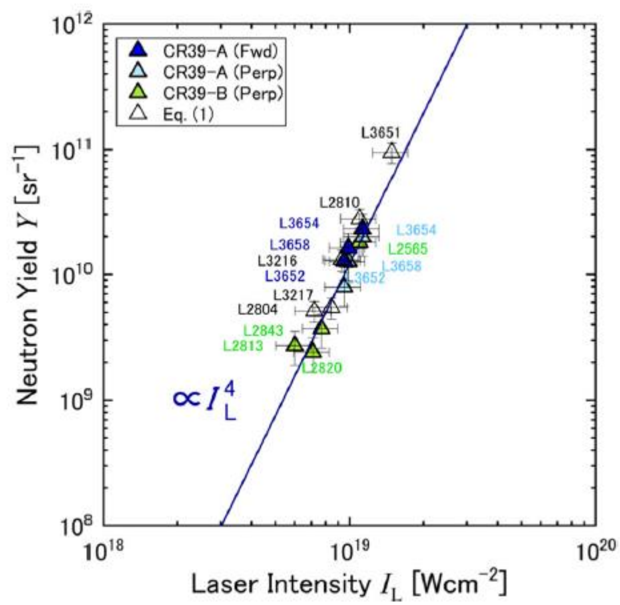
- **Fast neutron (>MeV):** **alternatives probing tool to x-rays**
- **Epi neutron (0.1-100 eV):** **neutron resonance absorption**
- **Thermal neutron (~25 meV, 300 K):** **radiographic analysis**
  $^{7}Li(p,n)^{7}Be$ 1.4×10^{6} n/sr from $H_{2}0$ moderator converted from 1.7×10^{9} n/sr
- **Cold neutron (<5 meV):** **diffraction analysis of crystal structures of metals and proteins**

Eur. Phys. J. A (2023) 59:191

Laser-driven neutron sources







Eur. Phys. J. A (2023) 59:191

Laser-driven neutron sources

Table 1 The configurations of LDNS, the combination of targets, laser parameters and the resulting yield of neutrons generated per a laser shot. CD and CD_2 indicate deuterated polystyrene $(-C_8D_8-)_n$ and deuterated polyethylene $(-C_2D_4-)_n$, respectively

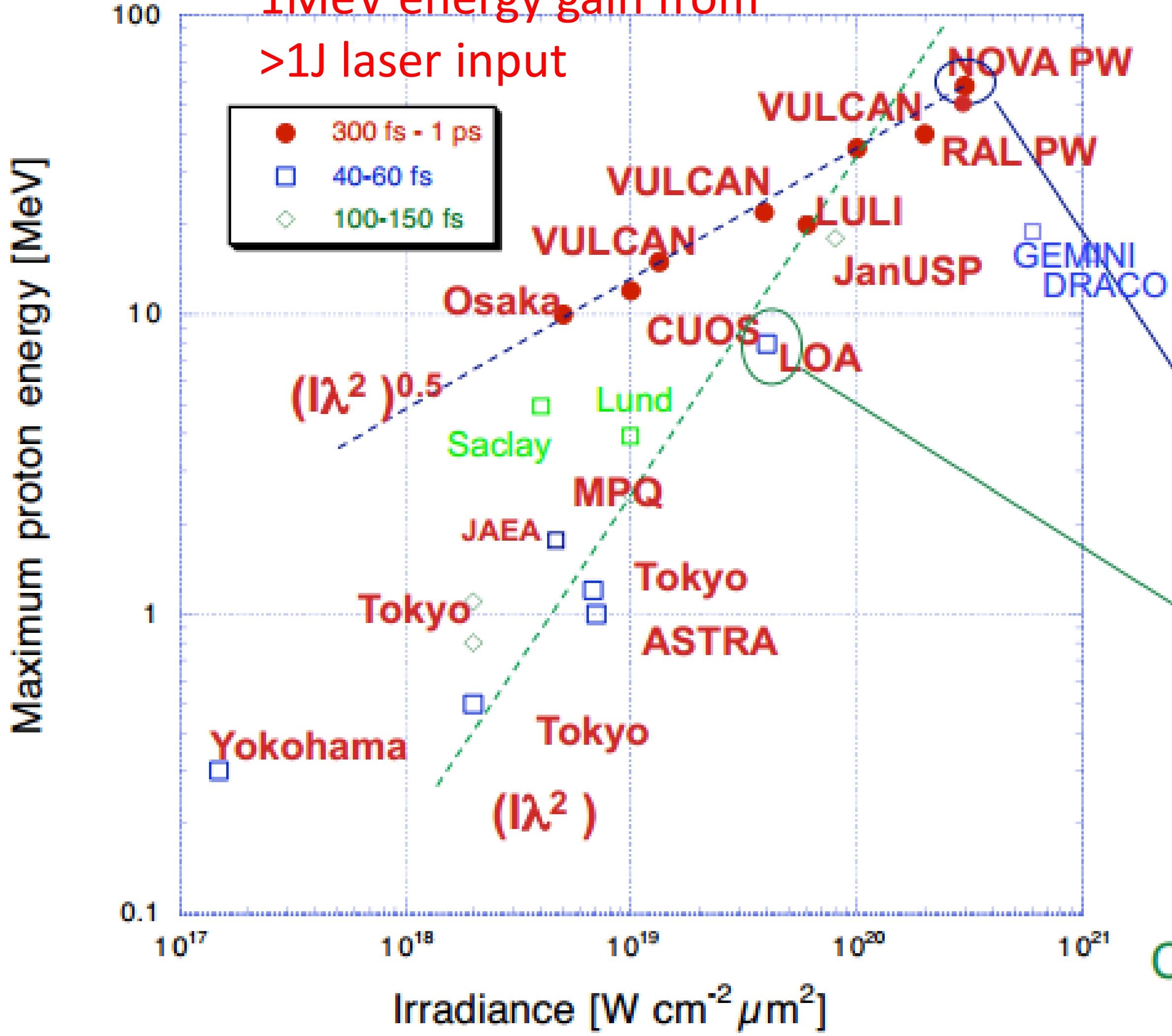
Author	Reaction	Target		Laser configuration			Neutron yield	
		Primary	Secondary	Energy [J]	Intensity [Wcm^{-2}]	Duration [ps]	[n/sr]	[n/sr/J]
Lancaster [7]	Li(p,n)Be	CH	LiF	80	3×10^{19}	1	3.0×10^{8}	3.75×10^{6}
Higginson [8]	Li(p,n)Be	Cu	LiF	140	1×10^{20}	0.7	1.0×10^{8}	7.1×10^{5}
Higginson [9]	Li(d,n)Be	CD_2	LiF	360	2×10^{19}	9	8.0×10^{8}	2.2×10^{6}
Willingale [10]	D(d,n)He	CD	CD	6	2.6×10^{19}	0.4	5.0×10^{4}	8.3×10^{3}
Jung [11]	Be(p,n)B, Be(d,n)	CD_2, CH	Be	80	5×10^{20}	0.6	4.4×10^{9}	5.5×10^{7}
Roth [12]	Be(p,n)B, Be(d,n)	CD_2	Be	80	5×10^{20}	0.6	5.0×10^{9}	6.3×10^{7}
Zulick [13]	Li(p,n)Be	CH_2	LiF	1.1	2×10^{21}	0.04	1.0×10^{7}	9.1×10^{6}
Maksimchuk [14]	D(d,n)He	D_2O ice on Cu	CD	6	2×10^{19}	0.4	4.0×10^{5}	6.7×10^{4}
Storm [15]	Li(p,n)Be	Si_3N_4	Li	60	2×10^{20}	0.18	1.6×10^{7}	2.7×10^{5}
Pomerantz [26]	photo-nuclear	plastic	Cu	90	-	0.15	1.0×10^{7}	1.1×10^{5}
Kar [16]	D(d,n)He	CD	CD	220	3×10^{20}		8.0×10^{8}	3.6×10^{6}
Alejo [17]	D(d,n)He	D_2O ice on Cu	CD	200	2×10^{20}	0.75	2.0×10^{9}	1.0×10^{7}
Kleinschmidt [19]	Be(p,n)B, Be(d,n)	CD	Be	175	2×10^{20}	0.5	1.42×10^{10}	8.1×10^{7}
Zimmer [24]	(p,n), (d,n)	CD	LiF-Be	100	2×10^{20}	0.6	1.43×10^{9}	1.4×10^{7}
Günther [27]	photo-nuclear	foam + high-Z metals	–	20	$\sim 10^{19}$	0.75	1.11×10^{9}	5.5×10^{7}
	(p,n)	foam + Au	–	20	$\sim 10^{19}$	0.75	4.93×10^{9}	2.5×10^{8}
Yogo [25]	Be(p,n)B, Be(d,xn)	CD	Be	900	1×10^{19}	1.5	2.3×10^{10}	2.6×10^{7}
Arikawa [28]	photo-nuclear	SUS with crater	D_2O liq.	4	1×10^{20}	0.03	1.7×10^{7}	4.3×10^{6}

- compactness of the source
- neutron pulse shortness
- Transportability of laser beam
- Single-shot measurement
- Multi-beam availability such as x-ray, electron

Eur. Phys. J. A (2023) 59:191

Ion energy results from 2000

1MeV energy gain from
>1J laser input



M.Borghesi *et al*, Fusion Science and Technology, **49**, 412 (2006)
M.Borghesi *et al*, Plasma Phys. Control.Fus., **50**, 124040 (2008)

GEMINI, 3J, 50 fs
7 10^{20} W/cm^2

NOVA/RAL PW,
500J, 0.5 ps,
I ~ 5 10^{20} W/cm^2

LOA,
800 mJ, 40 fs
6 10^{19} W/cm^2

Conversion efficiency <10%

F. Wagner et al. PRL 205002 (2016)

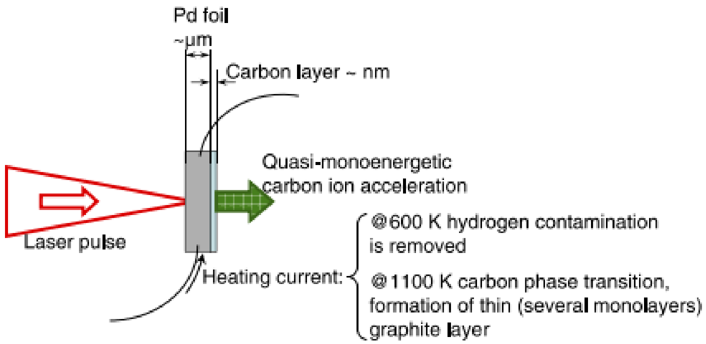
So far, Maximum proton cut-off energy: 85 MeV
@ 200J, 0.5 ps (PHELIX laser system, Germany)

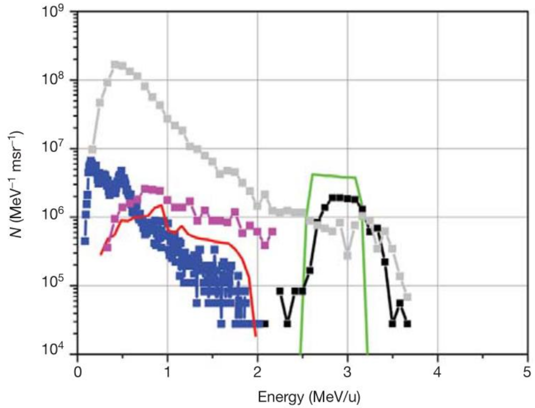
Summary

- Abundant and interesting physics (most are highly nonlinear) happens in the field of laser proton acceleration.
- A novel ion source with new characters
  - Ultrashort, high peak current, small size
  - Relatively big divergence and large energy spread
  - Low repetition rate (1-10 Hz)
- To fully utilize the LPA potential, it still has a long way to go.
- There are still many physical problems unclear, and models are mostly based on 1D geometry.
- Searching for a reliable route to guide this field is still ongoing.

TNSA energy spectra control

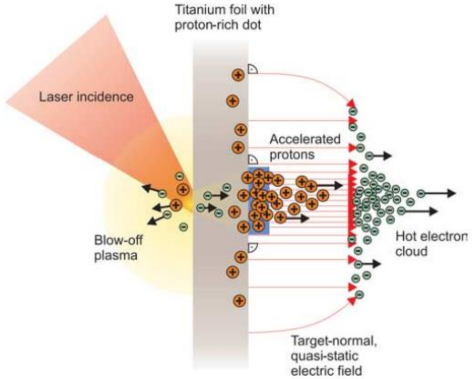
- Multi layer with different species @ experiments

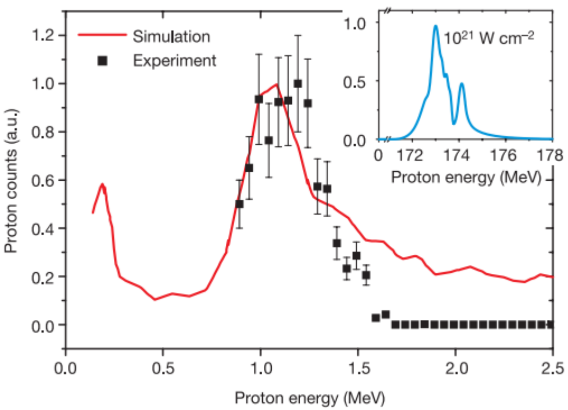




3 MeV/u (17%) C^{6+}

B. M. Hegelich, et al. Nature 439-441 (2006).





1.2 MeV/u (25%) protons

H. Schwoerer et al. Nature 439(7075): 445-448 (2006)

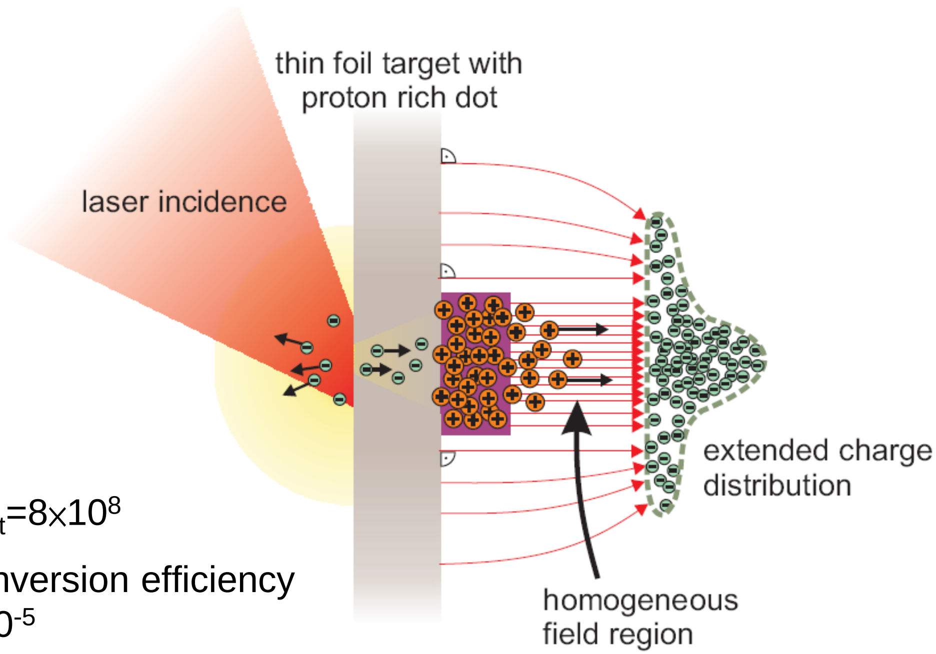
Vol 439|26 January 2006|**doi:10.1038/nature04492**

nature

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

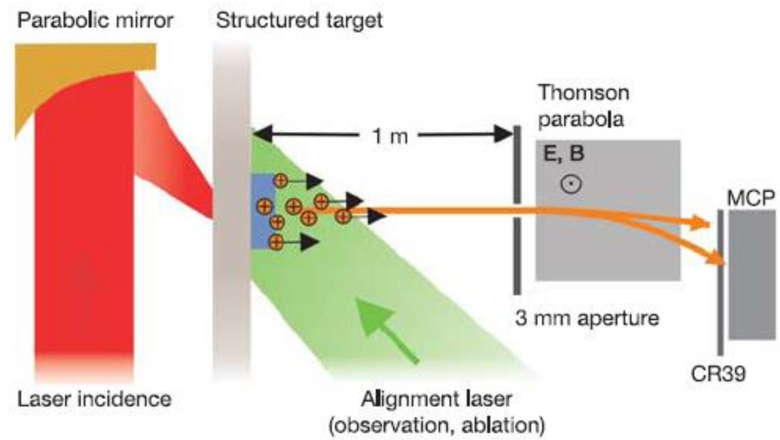
H. Schwoerer[1], S. Pfotenhauer[1], O. Jäckel[1], K.-U. Amthor[1], B. Liesfeld[1], W. Ziegler[1], R. Sauerbrey[1], K. W. D. Ledingham[1,2,3] & T. Esirkepov[4,5]

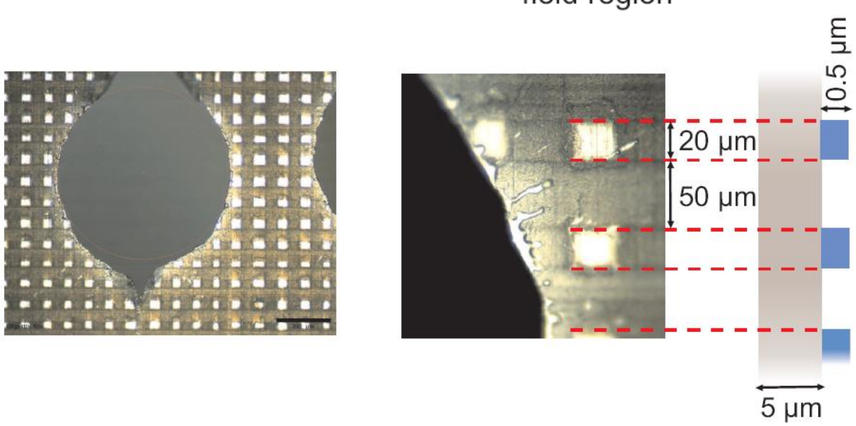
Summary: The spectrum of the accelerated protons has a strong correlation to the initial proton distibution on the target. The accelerating TNSA field features a homogeneous central field region. Thus, if the proton source is confined to this homogeneous region and sufficiently thin, the protons will be detached as a whole and accelerated in a monoenergetic manner.

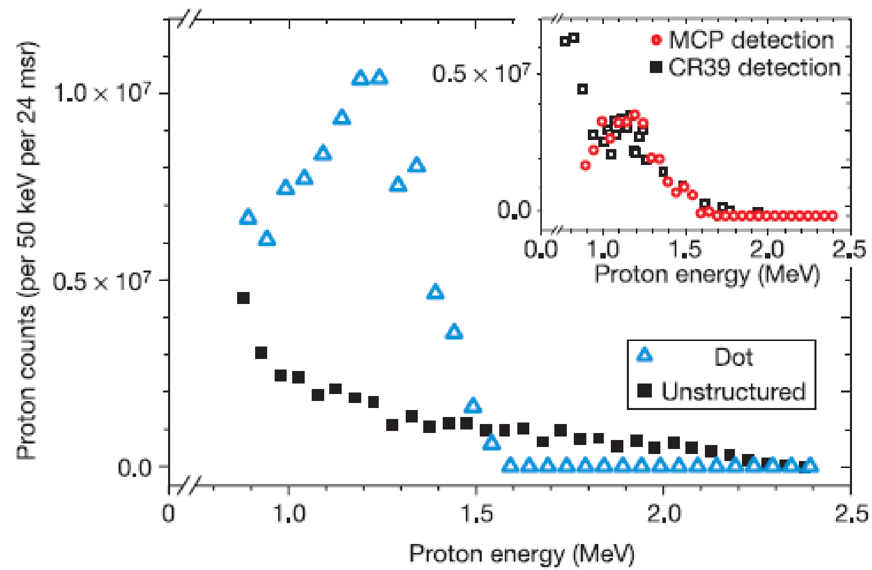


$N_{tot}=8\times10^8$

conversion efficiency $=10^{-5}$

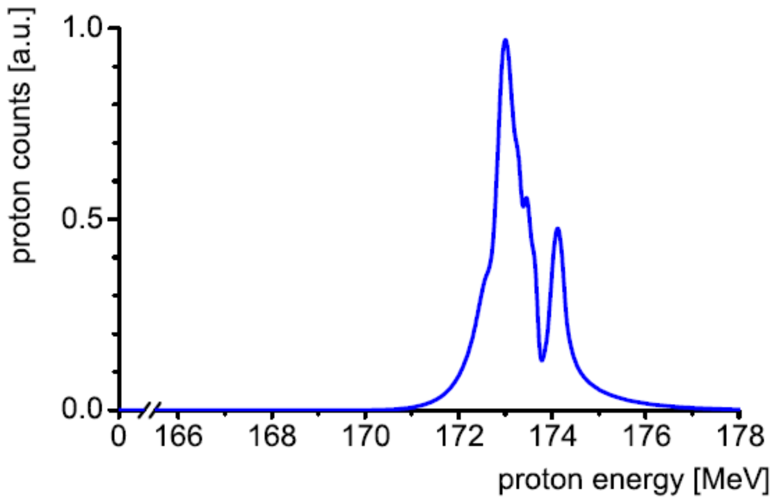






Scaling law of monoenergetic proton beam

Paticle-in-cell simulation results



input parameters:
POLARIS PW laser

$$E_{\mathrm{POL}} = 150\,\mathrm{J} \quad \tau_{\mathrm{POL}} = 150\,\mathrm{fs}$$
$$d_{\mathrm{foc}} = 10\,\mu\mathrm{m}$$
$$I_{\mathrm{POL}} = 1.2 \times 10^{21}\,\mathrm{W/cm^2}$$

scaling law of maximum energy for the optimum critical depth

$$E_{\mathrm{cutoff}} \approx 228\,\mathrm{MeV} \times Z\sqrt{P_{\mathrm{laser}}/1\,\mathrm{PW}} \longrightarrow 228\ \mathrm{MeV}$$

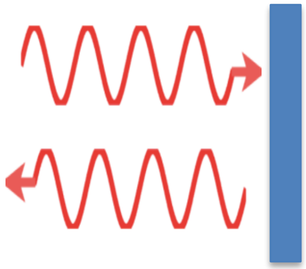
- By implementing this dot acceleration technique in a 100 TW laser system, the proton energy could obtain 72 MeV.

Sebastian Pfotenhauer, thesis (2006)

Esirkepov, PRL 96, 105001 (2006)

Radiation pressure acceleration

- Light pressure



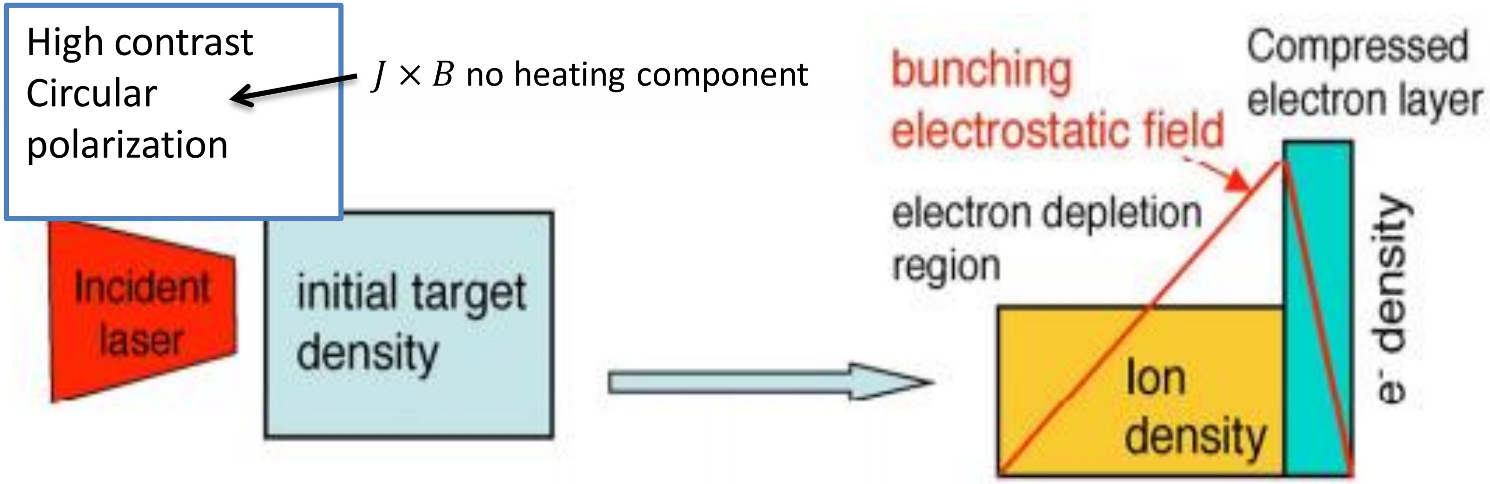
$$P = \frac{2I_L}{c}$$

60 Gbar for 10^{20} Wcm^{-2}

- Radiation pressure acceleration

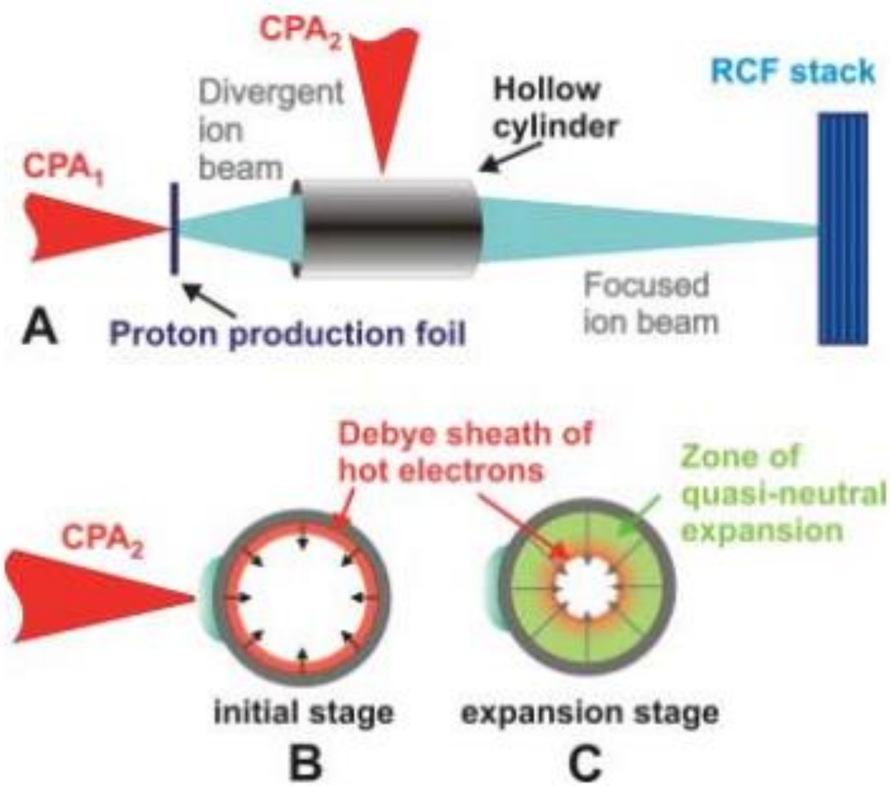
High contrast
Circular
polarization

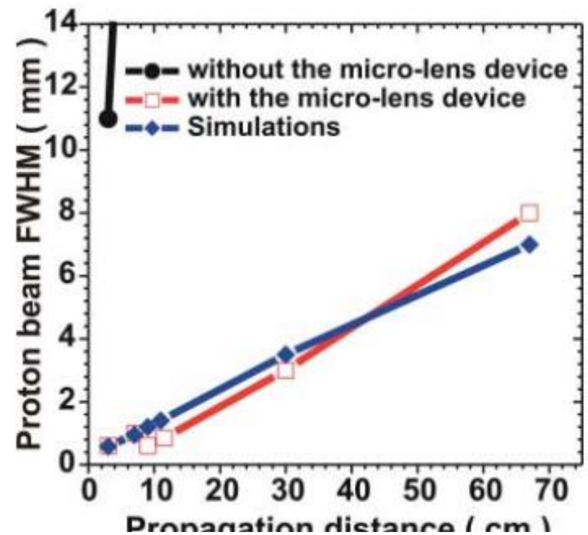
$J \times B$ no heating component

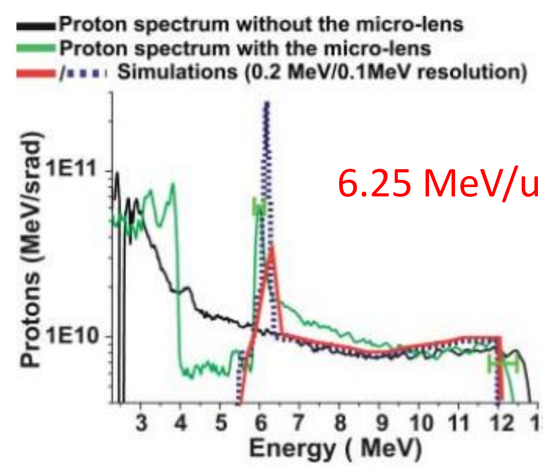


TNSA energy spectra control

- Plasma microlens used to focus and select energy
  - ps-scale transverse E-fields for simultaneously focusing





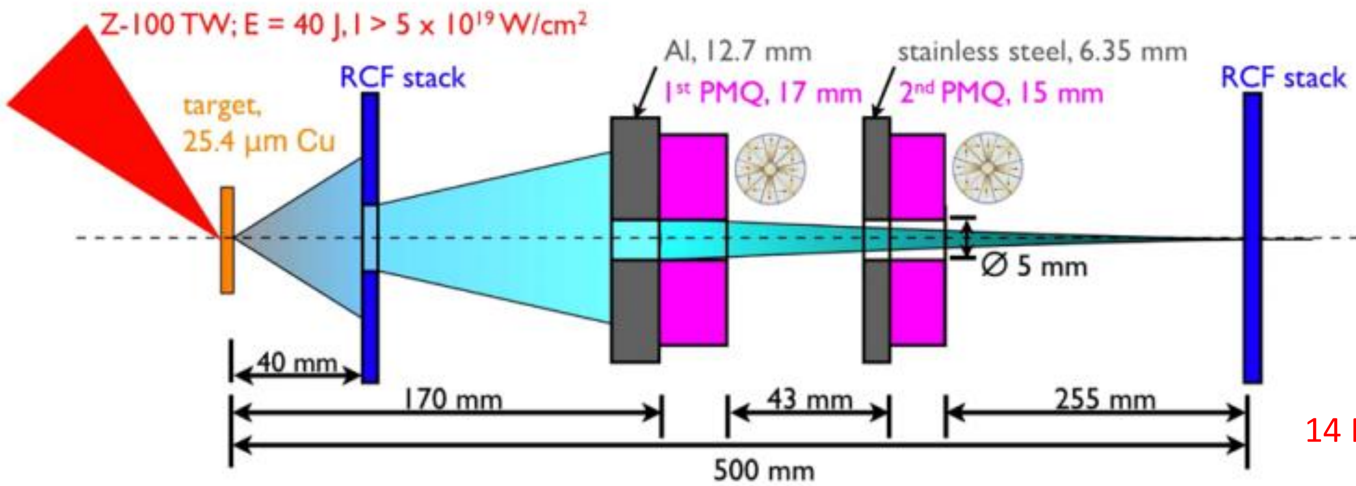


6.25 MeV/u (3%) protons

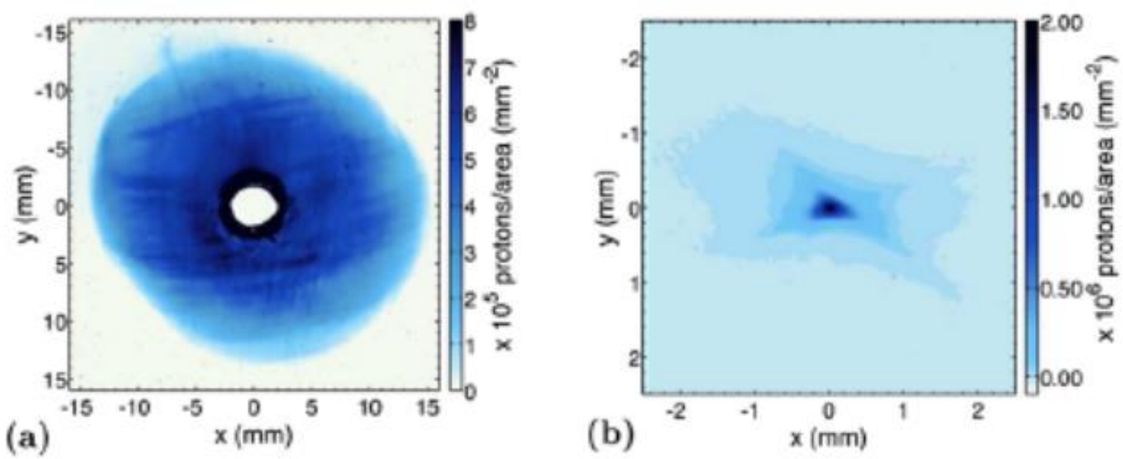
T. Toncian et al. Science. 312(5772): 410-413 (2006)

TNSA energy spectra control

- Conventional permanent quadrupole magnets



14 MeV/u (7%) protons



M.Schollmeyer et al, PRL, **101**, 055004 (2008)

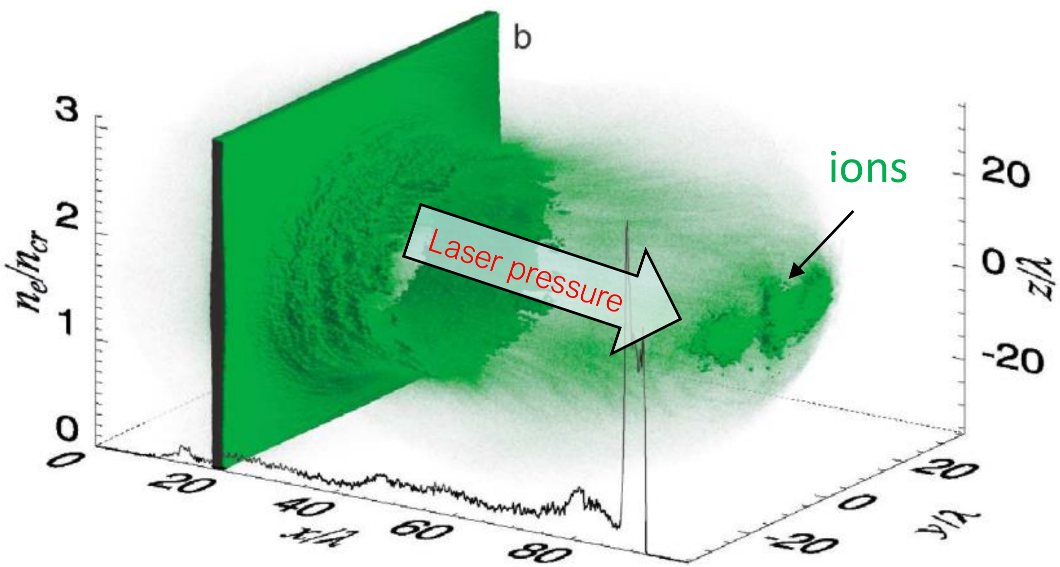
S. Ter-Avetysian et al, Laser& Part.Beam, **26**, 637 (2008)

M.Nishiuschi et al, APL. **94**, 066107 (2009)

K. Harres et al, PoP, 17, 023107 (2010)

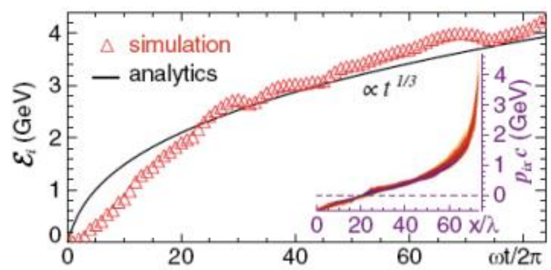
Radiation pressure acceleration

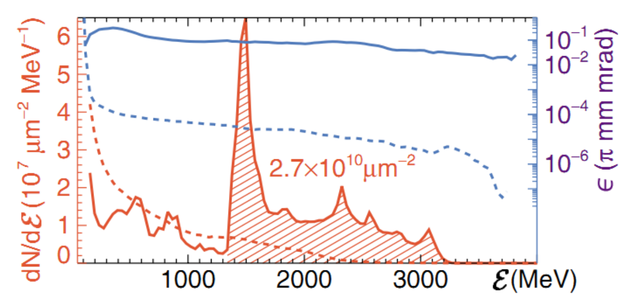
- T. Esirkepov et al proposed the concept of radiation pressure acceleration (RPA) (laser piston model) in 2004.



Ultraintense linearly polarized laser
($a_0 = 316$) with ultrathin foil

$$\frac{d}{dt}(\beta\gamma) = \frac{2I(t_{ret})}{\sigma c^2} R(\omega') \frac{1-\beta}{1+\beta},$$





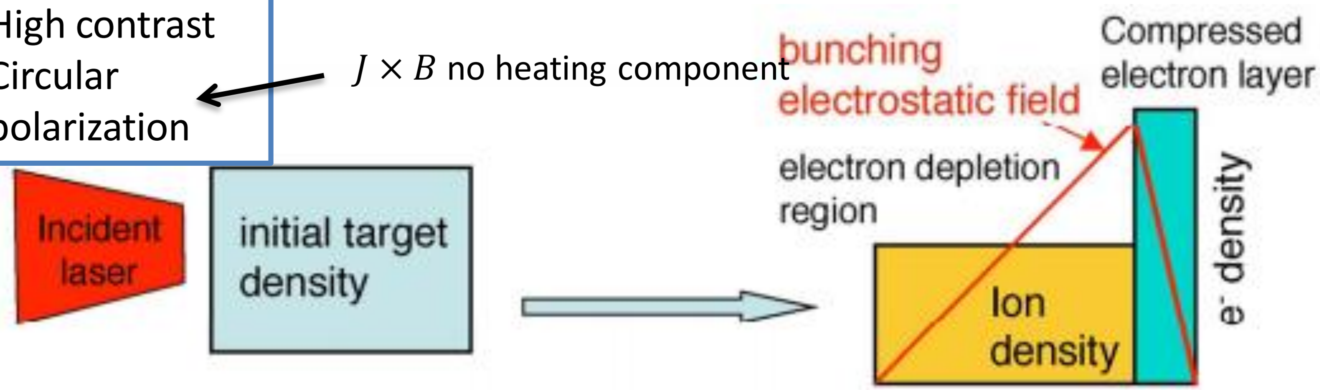
energy conversion efficiency: 40%

Esirkepov, et al.. PRL, 2004. 92(17): 175003

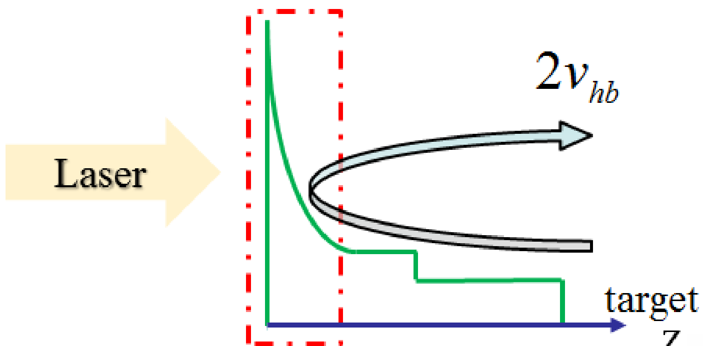
Radiation pressure acceleration

High contrast
Circular
polarization

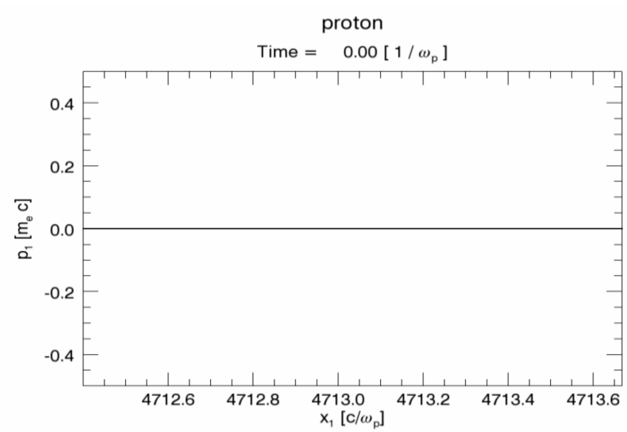
$J \times B$ no heating component



◆Hole boring process (HB) (thick foil)



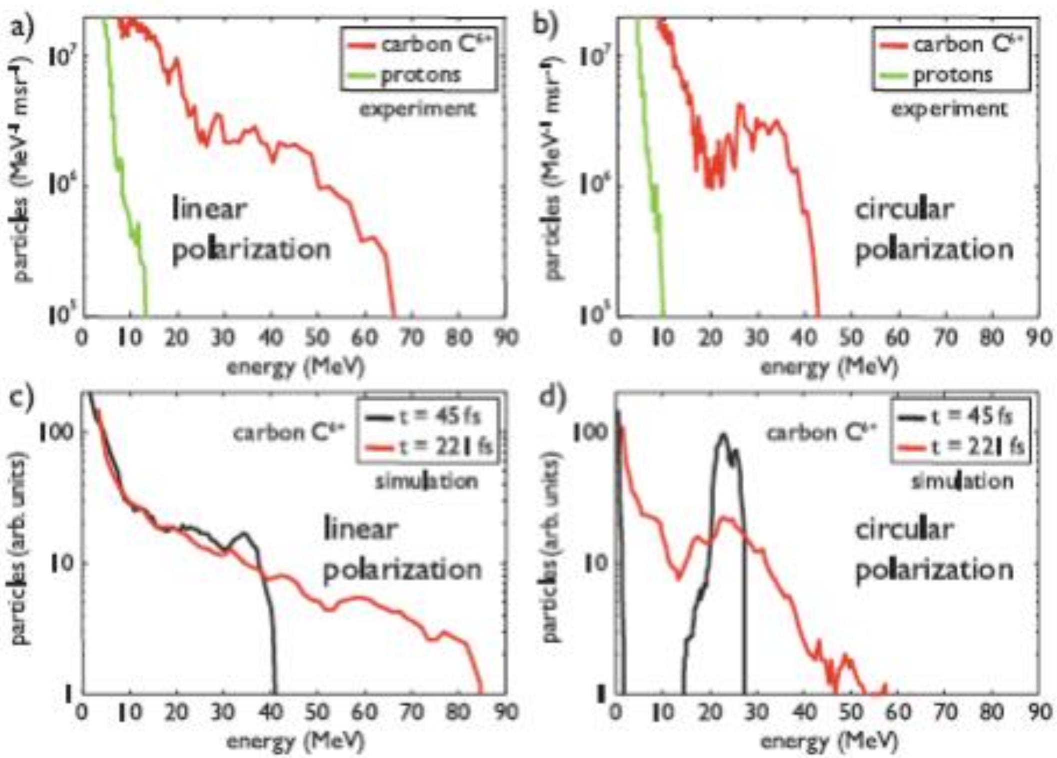
$$v_{hb} = ac\sqrt{\frac{m_e n_c}{M_i n_0}}$$



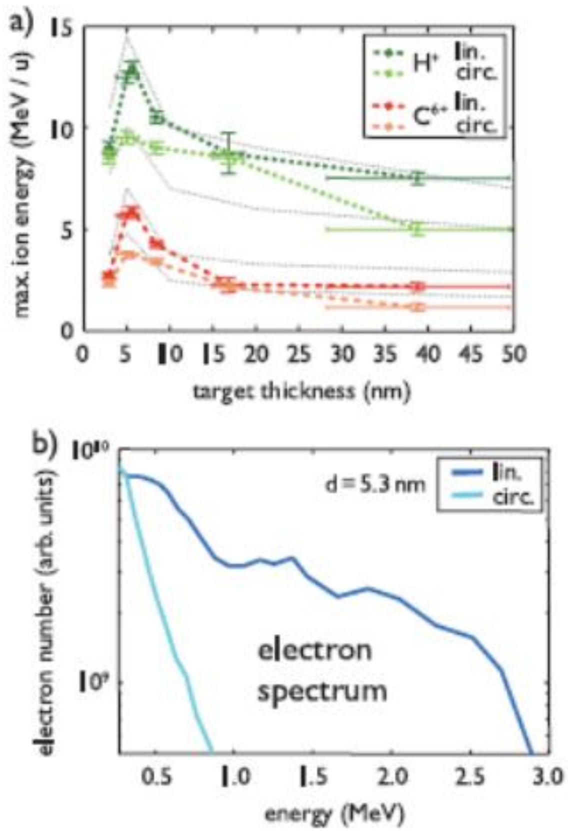
A.Macchi, et al, Phys. Rev. Lett. 94, 165003 (2005).

Radiation pressure acceleration

- Henig et al. first demonstrated the RPA process in experiments at MPQ in 2009.



5nm DLC

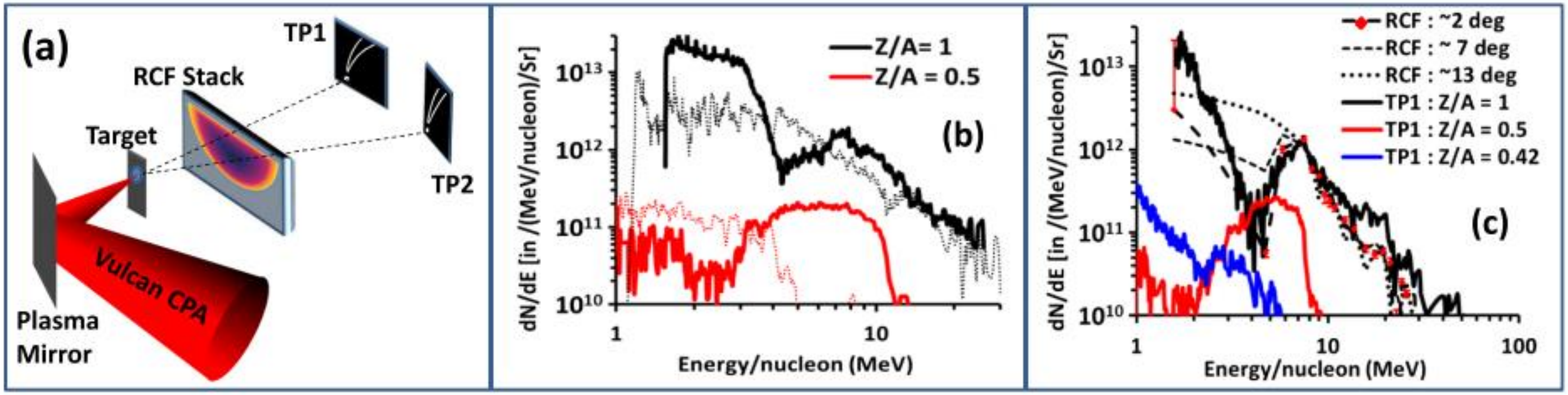


5 MeV/u C^{6+} (30%) @ 15 TW,45 fs, FWHM=3.6um, a0=3.5 (CP) or 5 (LP), MPQ

A. Henig et al. PRL 103,245003 (2009)

Radiation pressure acceleration

- In 2012, S. Kar et al also observed spectra peaks via multi-species @ RAL



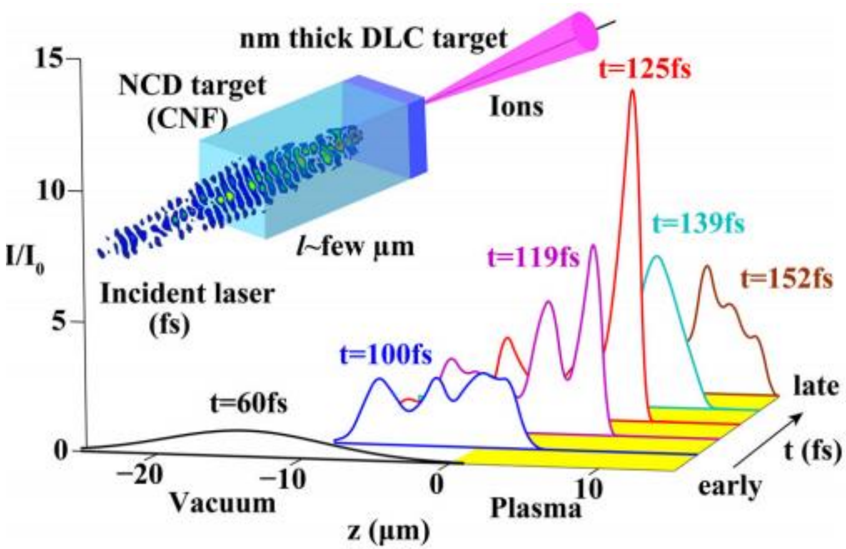
50-100nm Cu
Contaminations: H, C

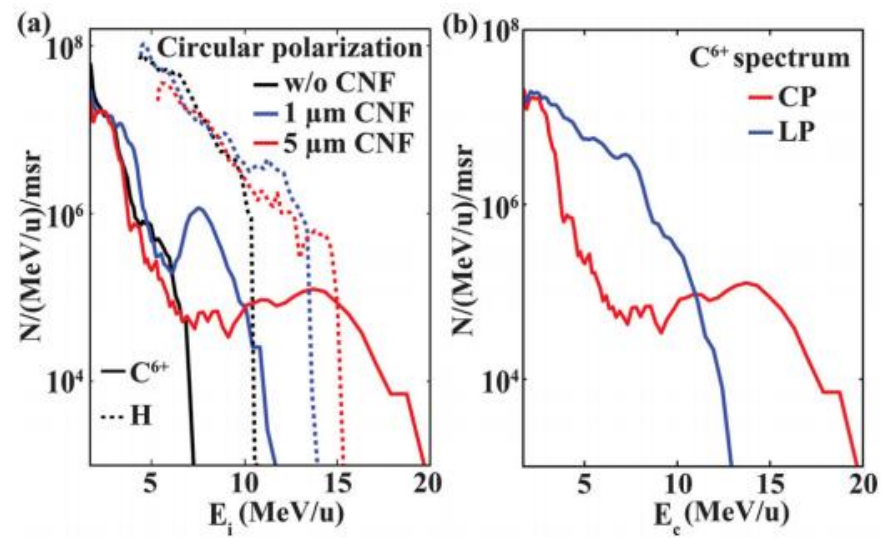
5~10MeV/u protons and carbons @ 250 TW,700~900 fs, FWHM 5um, a0=5-12 (LP), RAL,VULCAN

S. Kar et al. PRL109,185006 (2012)

RPA experiments

- In 2015, Bin et al @MPQ



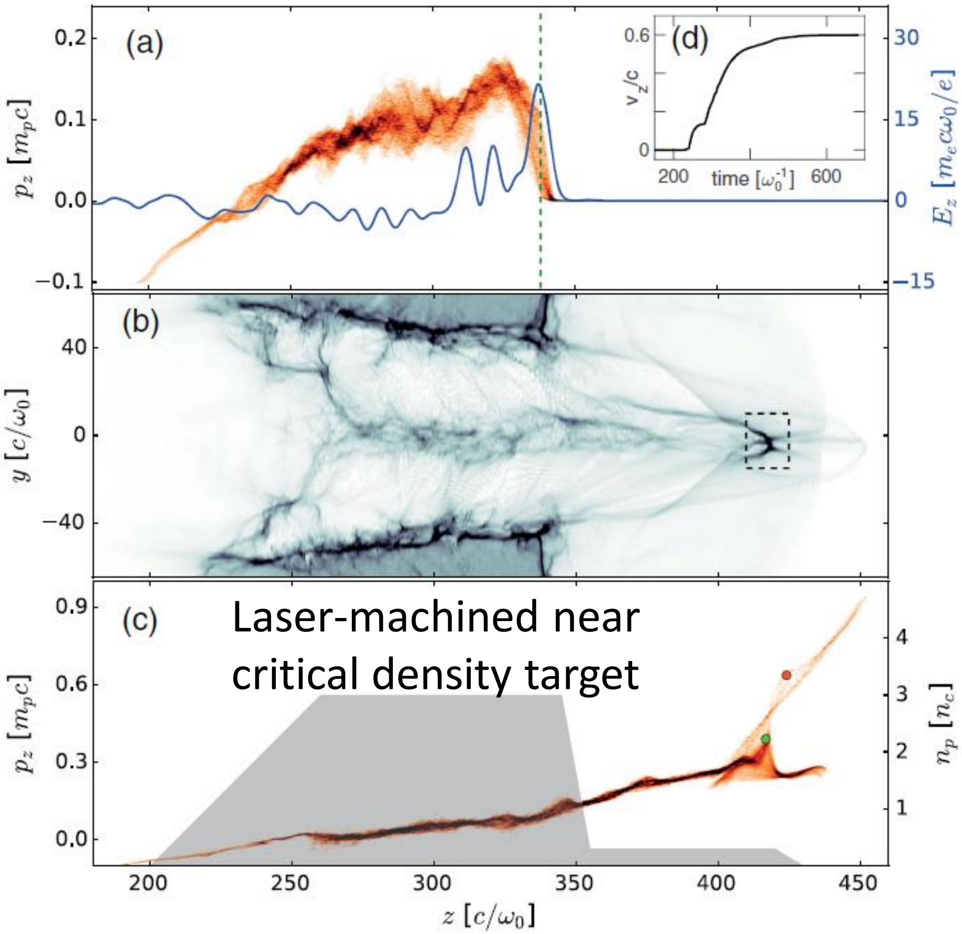


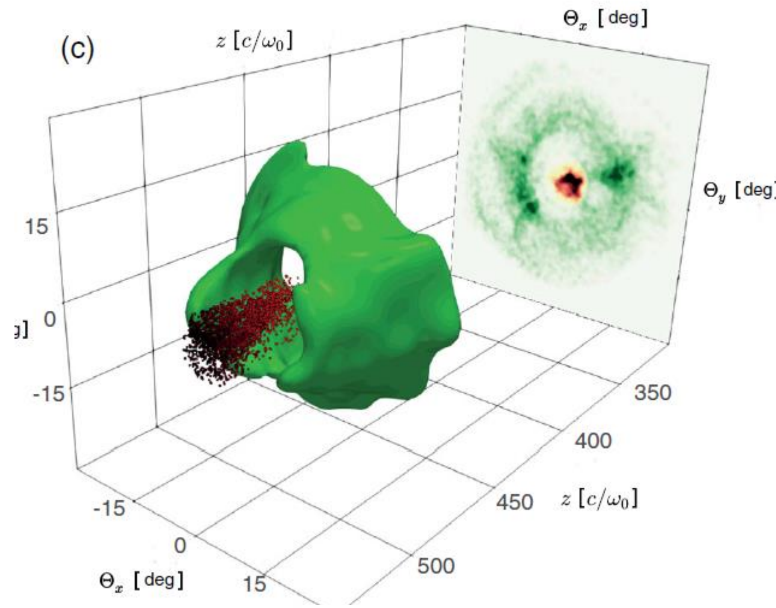
5um CNF (1-3nc) + DLC (nm scale)
80-100 TW, 50fs, FHWM=3.5um, a0=10(LP)

15 MeV/u C^{6+} (70%), 20 MeV maximum

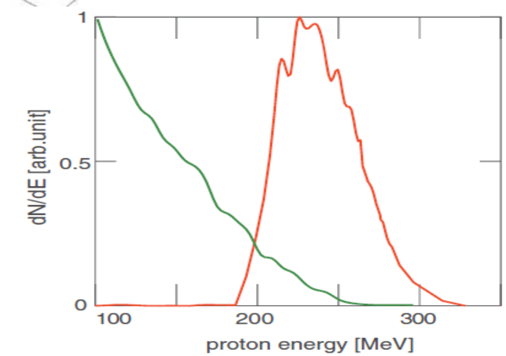
J. H. Bin et al. PRL115,064801 (2015)

Laser proton acceleration in gas targets





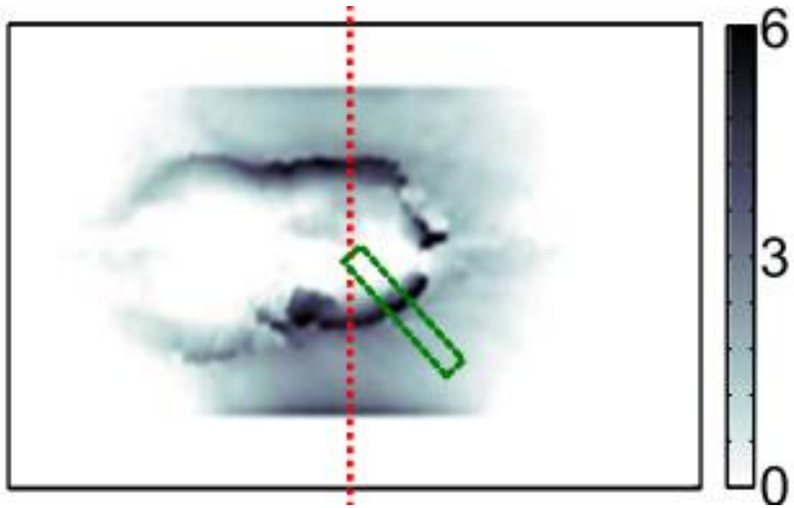
1 PW laser



Wan et al, Phys. Rev. Accelerators and beams 22, 021301 (2019)

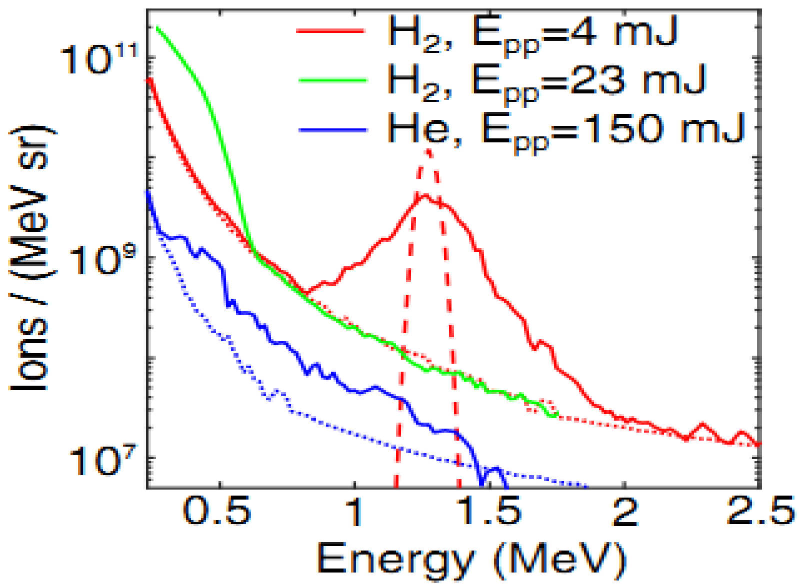
- Protons are first accelerated by the laser acting as a snowplow in plasma, and then by the collisionless shock launched from the sharp density downramp.

ATF experiment-I



CO_2 laser
2.2 TW, 5 ps
w0=65um
a0=1.4

Pre-pulse
25ns earlier
150 mJ for He
4 mJ for H2 (too low, ?)



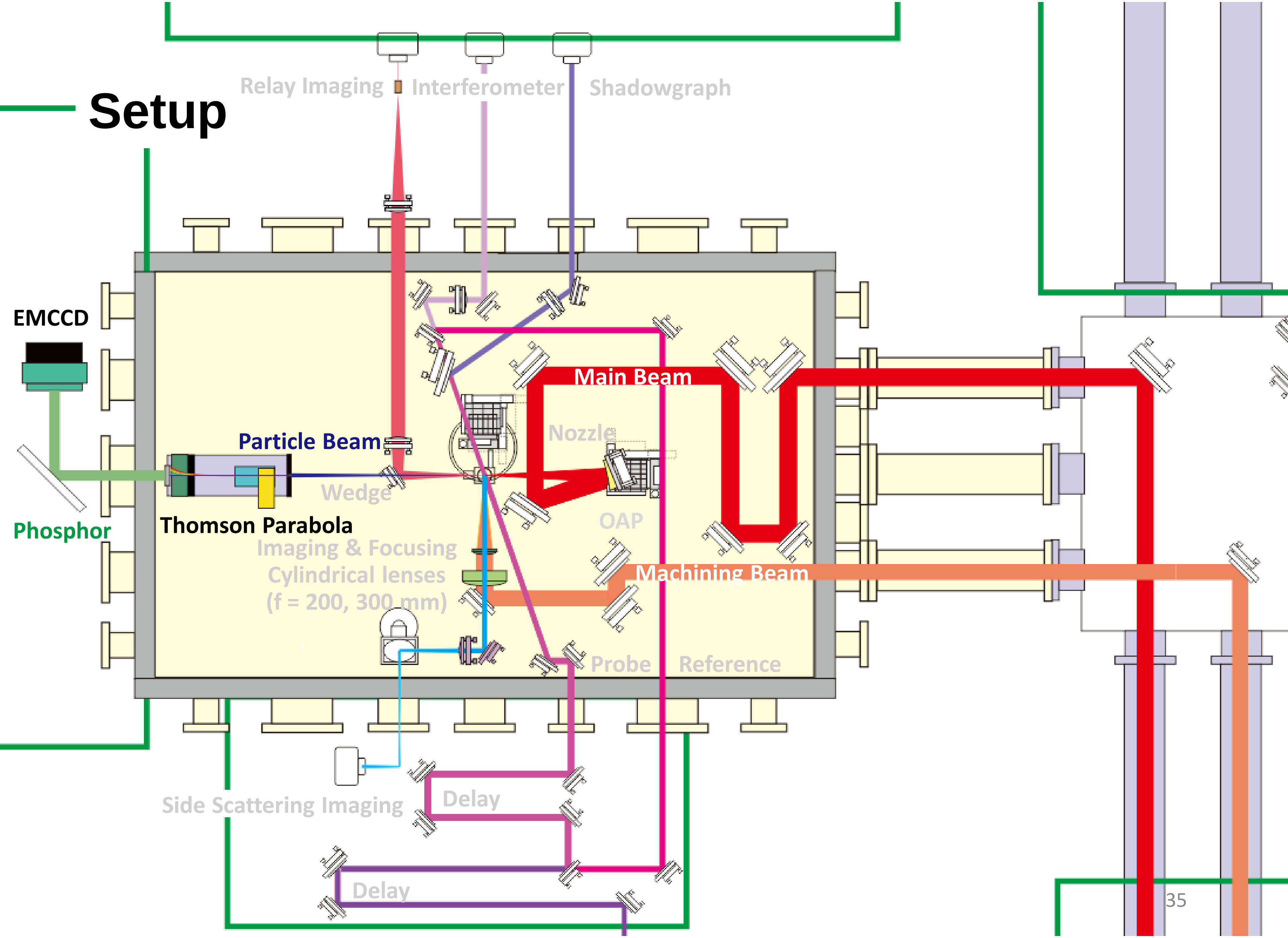
Controlled prepulse could generate a steepened, variable front density gradient.

It is very beneficial for shock formation.

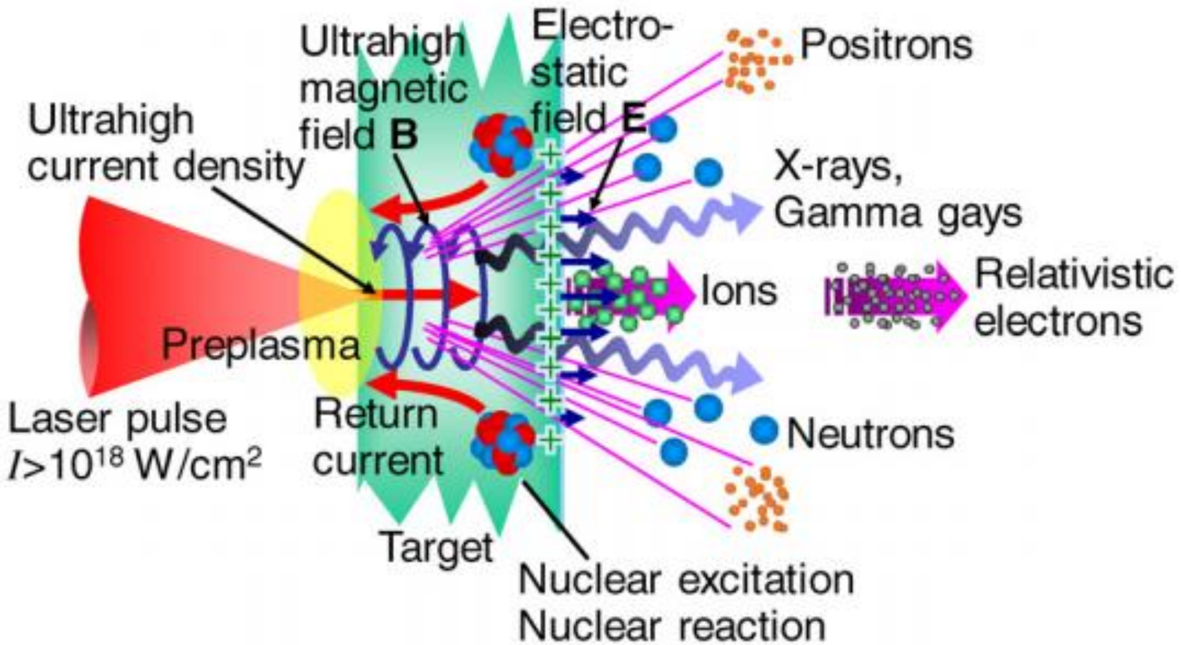
~ 1.2 MeV proton (~ 5%)@ BNL-IC

O. Tresca et al. PRL 115, 094802 (2015)

Setup


Relay Imaging
Interferometer
Shadowgraph
EMCCD
Main Beam
Nozzle
Particle Beam
Wedge
OAP
Phosphor
Thomson Parabola
Imaging & Focusing
Cylindrical lenses
(f = 200, 300 mm)
Machining Beam
Probe
Reference
Side Scattering Imaging
Delay
Delay

Laser interaction with near- or over-critical density plasma



$$\omega_0^2 = \omega_p^2 + k^2c^2$$
$$\omega_0 < \omega_p$$

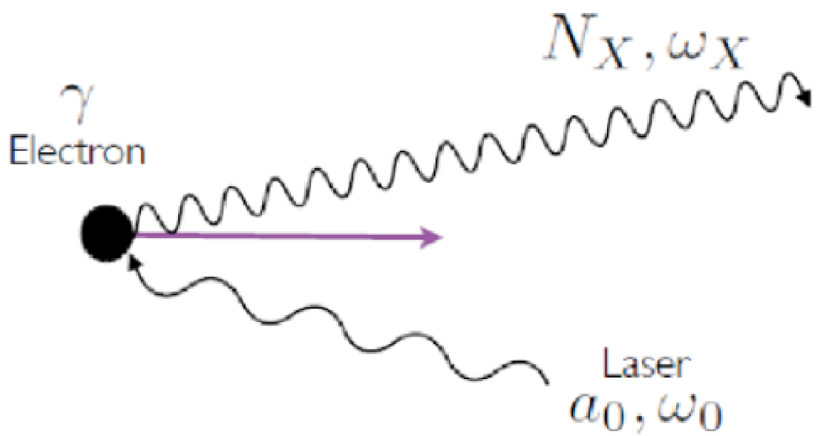
$$\omega_p = \sqrt{\frac{n_e e^2}{m\varepsilon_0}}$$

1. H Daido, et al. Proc. 10th Int. Conf. on X-Ray Lasers (Berlin: Springer) pp 595–605 (2007)
2. H Daido, et al. Rep. Prog. Phys.75 056401 (2012)

Various phenomena

- high-energy electrons with broad spectra
- Ions accelerated by charge-separation electric field
- X-rays or high-order harmonics
- THz induced by surface current
- secondary particles and radiation (e.g. neutrons, positrons hard x-ray and gamma radiation,

Inverse Compton Scattering (ICS)



Doppler upshift : high energy photons with modest electrons energy :

$\omega_x = 4\gamma^2\omega_0$

For example :

20 MeV electrons can produce 10 keV photons

200 MeV electrons can produce 1 MeV photons

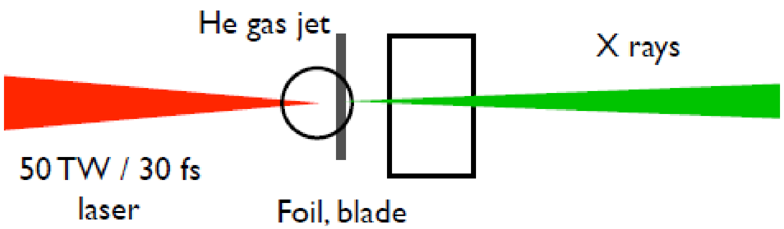
The number of photons depends on the electron charge N_e and a_0^2 : $N_x \propto a_0^2 \times N_e$

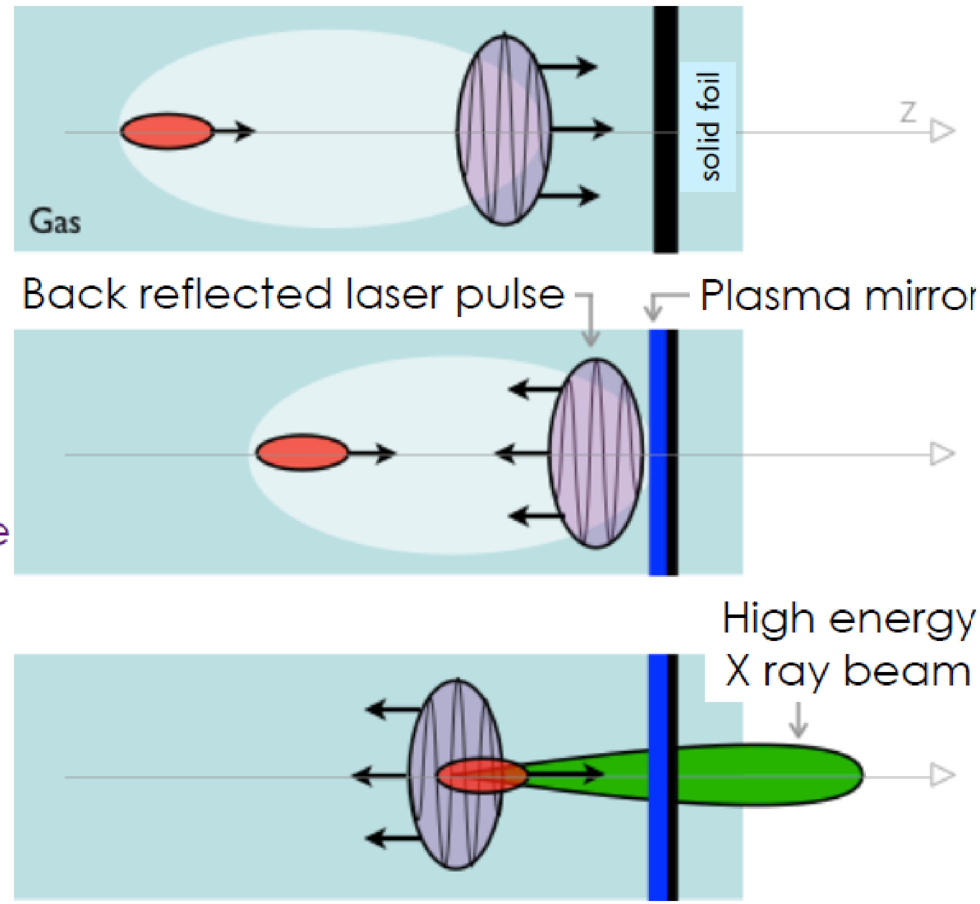
Duration (fs), source size (μm) = electron bunch length and electron beam size

Spectral bandwidth : $\Delta E/E \propto 2\Delta\gamma/\gamma,\ \gamma^2\Delta\theta^2$

Ta Phuoc, et al. Nature Photon 6 (2012)

ICS with 1 laser beam





A single laser pulse

A plasma mirror reflects the laser beam

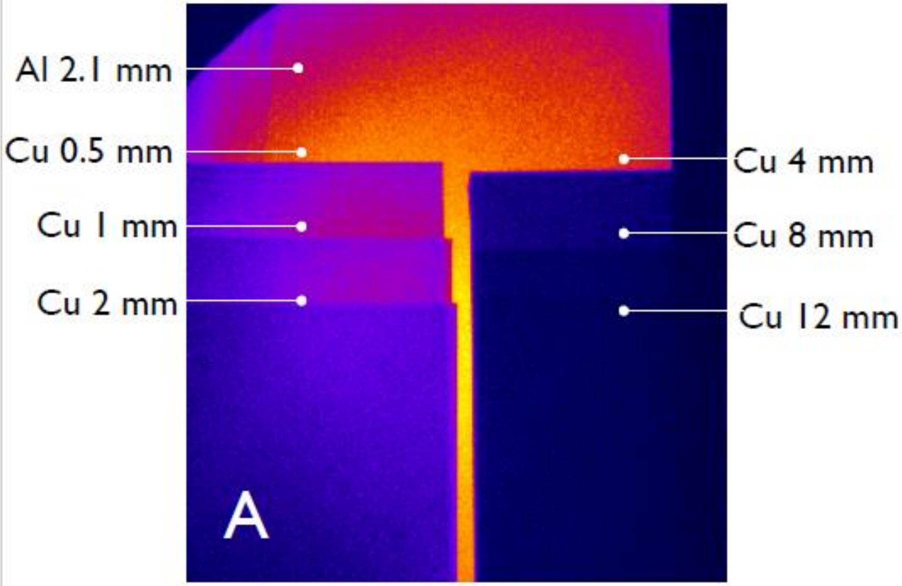
The back reflected laser collides with the accelerated electrons

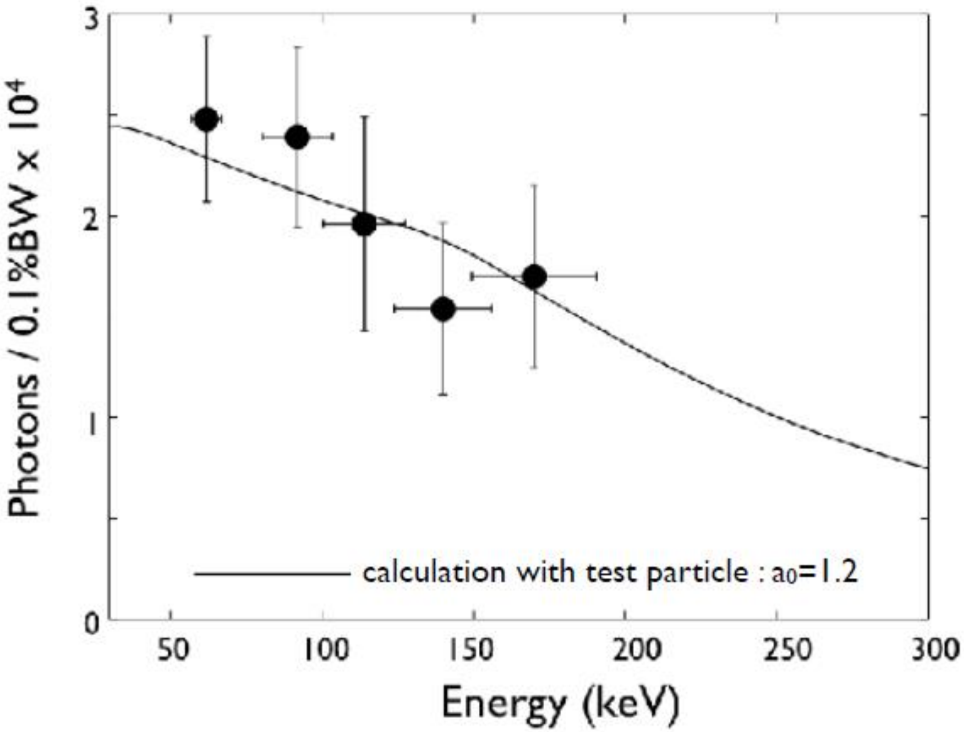
No alignement : the laser and the electron
beams naturally overlap

Save the laser energy !

Ta Phuoc, et al. Nature Photon 6 (2012)

Inverse Compton Scattering Spectra





- About 10^8 ph/shot, a few 10^4 ph/shot/0.1%BW@100 keV
- Source size less of 1.5 um
- Brigthness: 10^{21} ph/s/mm^2/mrad^2/0.1%BW @100 keV

K. Ta Phuoc *et al.*, Nature Photonics, May 2012