7th International Particle Accelerator Conference
May 8-13, 2016 Busan, Korea

Advanced Acceleration Mechanisms for Laser Driven Ions by PW-lasers

Stepan Bulanov, Qing Ji, Sven Steinke, Thomas Schenkel,
Eric Esarey, and Wim P. Leemans

Accelerator Technology & Applied Physics Division
Lawrence Berkeley National Laboratory

Work supported by Laboratory Directed Research and Development (LDRD) funding from Lawrence Berkeley National Laboratory, provided by the Director, Office of Science, of the U. S. Department of Energy under Contract No. DE-AC02-05CH11231.

In Collaboration with

D. P. Grote
R. Lehe
B. Loring
O. Rubel
C. B. Schroeder
J.-L. Vay
H. Vincenti

Japan Atomic Energy Agency
Kansai Photon Science Institute (KPSI)

T. Zh. Esirkepov
M. Kando
S. V. Bulanov

G. Korn
D. Margarone

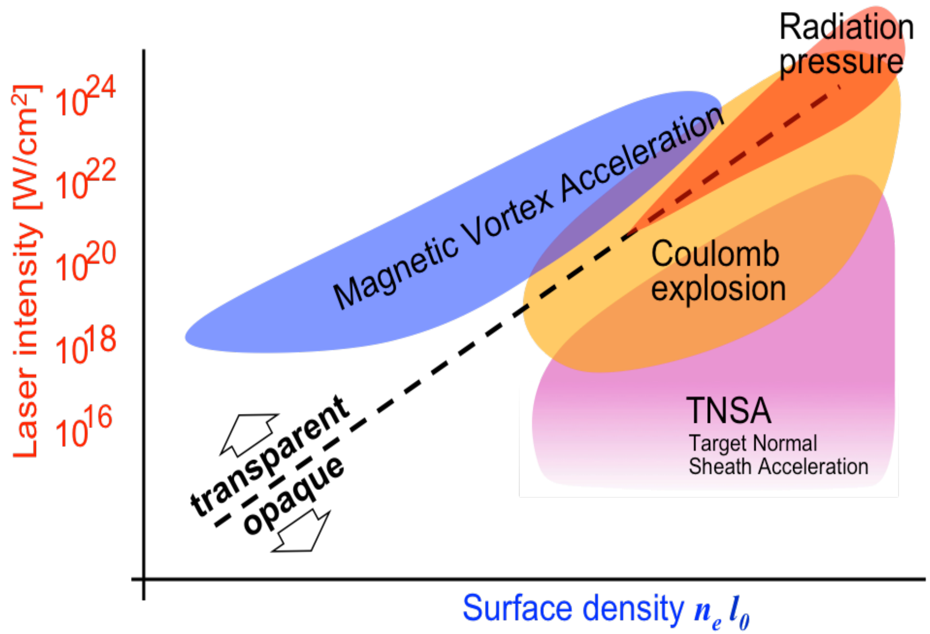
F. Pegoraro

Heidelberg Ionenstrahl-Therapie Centrum

T. Haberer

Laser plasma ion acceleration is of great interest to reduce the size and cost of future accelerators

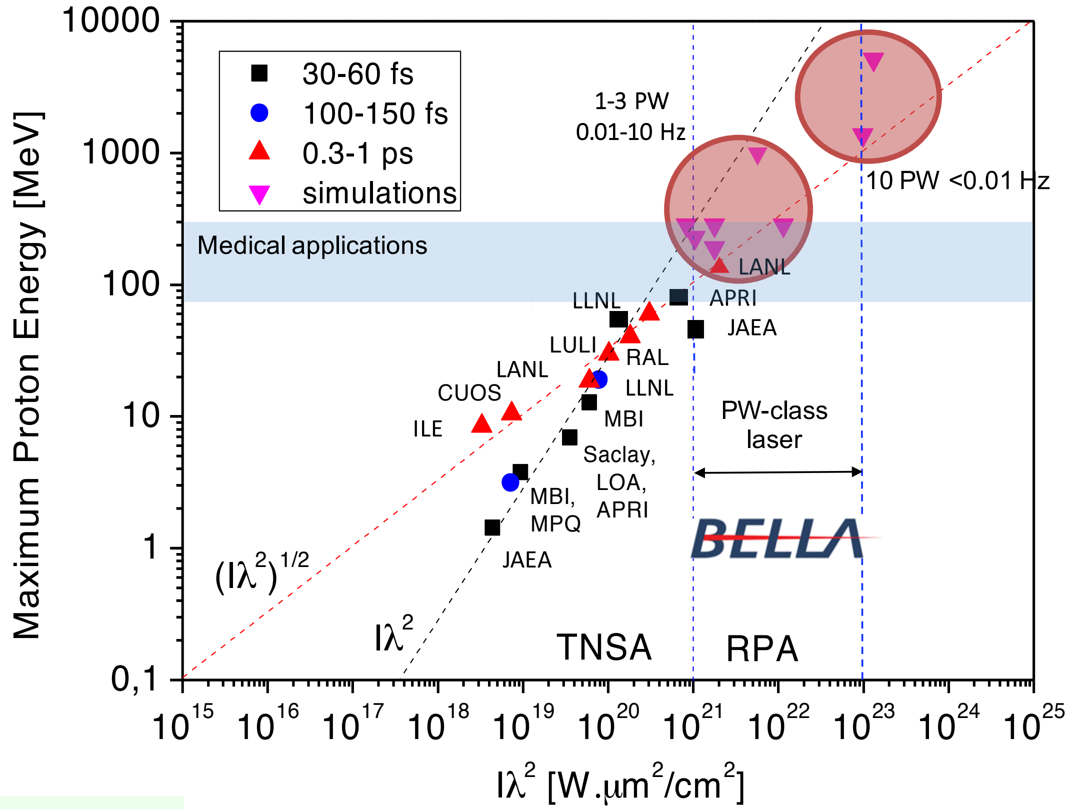
- The particle acceleration is one of the cornerstones of the fundamental physics.
- Conventional technology of particle acceleration leads to large scale facilities, high construction and operation costs.
- Advanced acceleration concepts are of great interest to reduce the size and cost of future accelerators.
- In laser plasma acceleration, particles are accelerated by strong electromagnetic fields generated by laser pulses in plasma.
- Application:
  - Injector of conventional accelerator
  - Hadron therapy
  - Radiography
  - Nuclear physics studies
  - Warm dense matter studies
  - … ...



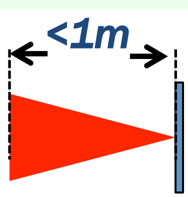
The laser ion acceleration mechanism is determined by laser Intensity and target surface density

S. S. Bulanov, et al., Physics of Plasmas 23 , 056703 (2016);

BELLA-I: A collaborative user facility for relativistic plasma physics and high energy density physics



Ion acceleration

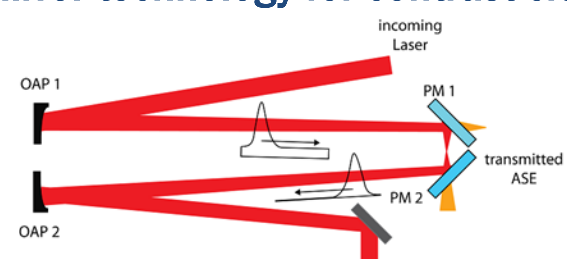


Intensity ~3-5x10^{21} W/cm^2
Acc. fields ~TV/m

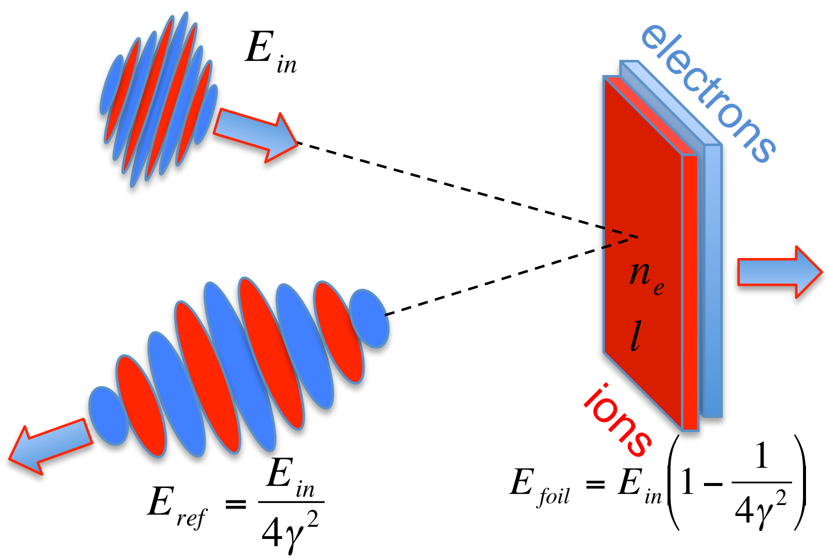
4-5 micron spot

+

Plasma mirror technology for contrast clean-up



Radiation Pressure Acceleration (relativistic receding mirror)



- Co-propagation configuration
- EM wave "pushes" relativistic mirror
- "Receding mirror": ions are accelerated by radiation pressure

Radiation Pressure Acceleration has a long history

The idea goes back to

P. N. Lebedev, Ann. Phys. (Leipzig) 6, 433 (1901);

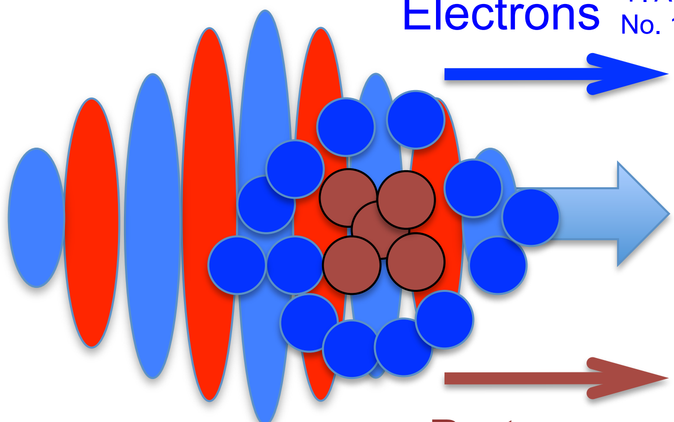
A. Einstein, Ann. Phys. (Leipzig) 17, 891 (1905);

A. S. Eddington, Mon. Not. R. Astron. Soc. 85, 408 (1925).

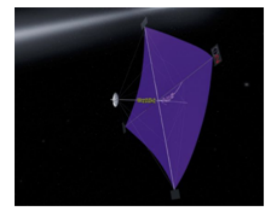
In the mid 1950's ion acceleration by strong electromagnetic wave was suggested by V. I. Veksler, Sov. J. Atomic Energy 2, 525 (1957).

There is an analogy between the RPA mechanism and the “Light Sail” scheme for the spacecraft propulsion. This scheme, which uses the photon momentum transfer to the light-sail, was proposed by

F. A. Zander, Technika i Zhizn, No. 13, 15 (1924) [in Russian].

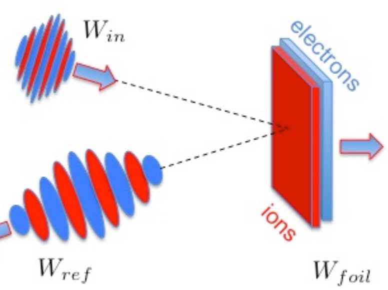


F. A. Zander (1887-1933)



The radiation pressure of a super-intense electromagnetic pulse on a thin plasma slab was studied in

T. Zh. Esirkepov, M. Borghesi, S. V. Bulanov, G. Mourou, T. Tajima, Phys. Rev. Lett. 92, 175003 (2004).



The use of lasers for propelling the sailcraft over interstellar distances has been considered in

R. L. Forward, Missiles and Rockets, 10, 26 (1962);
G. Marx, Nature, 211, 22 (1966);
J. L. Redding, Nature, 213, 588 (1967);
J. F. L. Simmons and C. R. McInnes, American Journal of Physics 61, 205 (1993)

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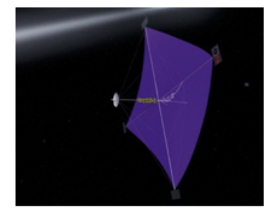

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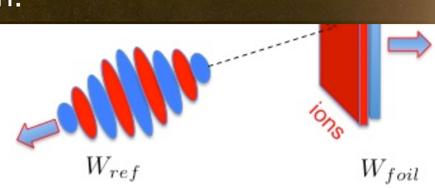

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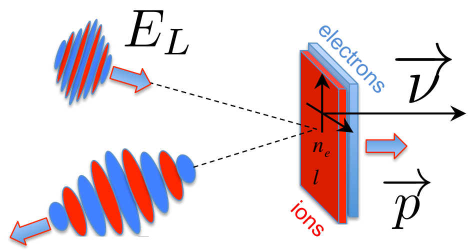
J. F. L. Simmons and C. R. McInnes, American Journal of Physics 61, 205 (1993)

Radiation Pressure Acceleration: Equation of Foil Motion

Lab Frame



$$\frac{d\vec{p}}{dt} = \frac{\mathcal{P}}{n_e l}\vec{\nu}$$

$\vec{\nu}$ - unit vector normal to the target surface

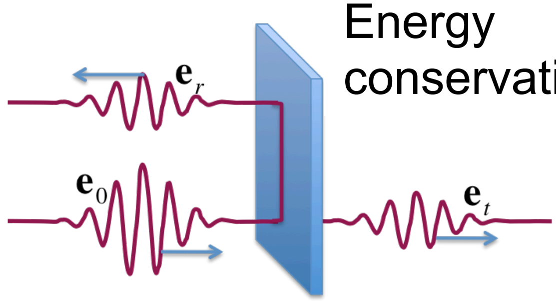
ρ - reflection coefficient

τ - transmission coefficient

α - absorption coefficient

Rest frame of the foil

to determine $\mathcal{P}$



Energy conservation: $|\rho|^2 + |\tau|^2 + |\alpha|^2 = 1$

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

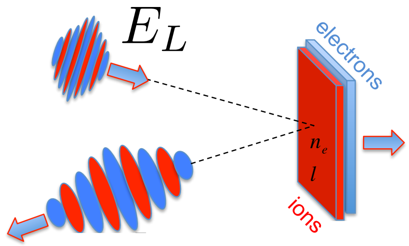
Lab Frame

$$\mathcal{P} = \left(\frac{E_L^2}{4\pi}\right)\left(\frac{\omega'}{\omega}\right)^2(2|\rho|^2 + |\alpha|^2)$$

$$\frac{dp}{dt} = \frac{K|E_L[t - x(t)]|^2}{4\pi n_e l}\frac{\gamma - p}{\gamma + p}$$

$$K = 2|\rho|^2 + |\alpha|^2$$

Radiation Pressure Acceleration demonstrates high effectiveness of energy transfer from the laser to the ions



$$\frac{dp}{dt} = \frac{K|E_L[t - x(t)]|^2}{4\pi n_e l} \frac{\gamma - p}{\gamma + p}$$

$$\gamma = \frac{2 + 2W + W^2}{2(1+W)} \qquad W = \frac{2}{n_e l} \int_{-\infty}^{t - x(t)} \frac{|\rho E_L(\eta)|^2}{4\pi} d\eta$$

$\gamma \sim 1 + \frac{W^2}{2}, \quad W \ll 1$ - non-relativistic case: ion energy ~ [laser energy]^2

$$\mathcal{E}_a = 8 \times (10^{11}/N_{tot})^2 (m_p/m_a)(\mathcal{E}_{las}/1 \text{ J})^2 \text{ MeV}$$

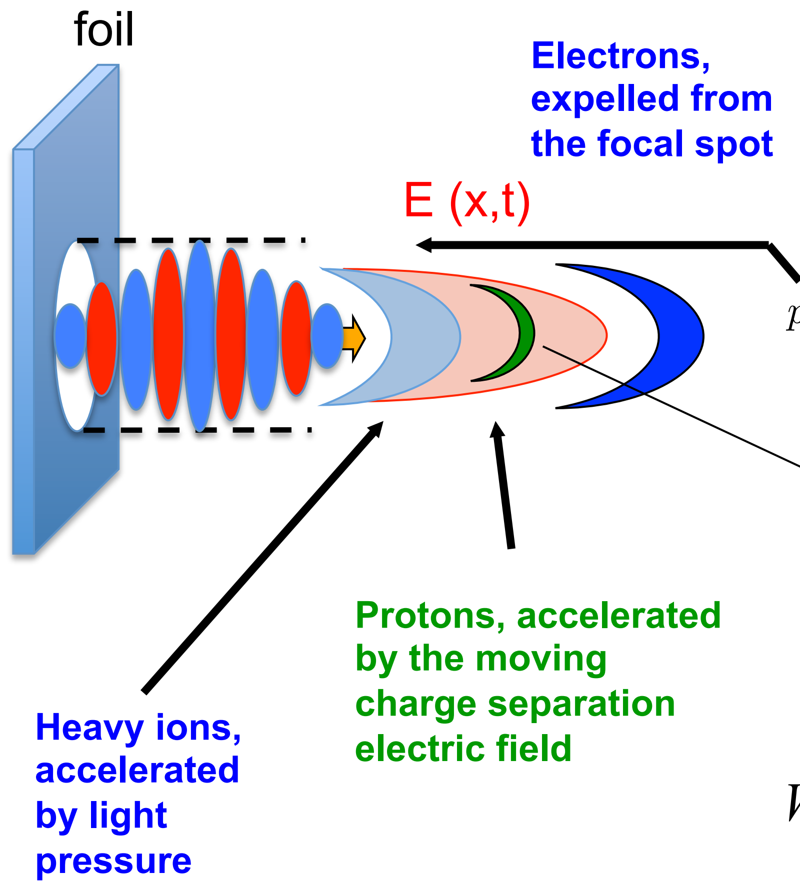
$\gamma \sim \frac{W}{2}, \quad W \gg 1$ - ultra-relativistic case: ion energy ~ [laser energy]

$$\mathcal{E}_a = 6.25 \times (10^{11}/N_{tot})(\mathcal{E}_{las}/100 \text{ J}) \text{ GeV}$$

1 PW laser pulse:
E_{proton} ~ 300 MeV

O. Klimo, et. al., Phys. Rev. STAB 11, 031301 (2008)
S. V. Bulanov, et. al., Comp. Rendus Physique 10, 216 (2009)

Directed Coulomb Explosion = Radiation Pressure + Coulomb Explosion



$$\frac{dp}{dt} = \frac{K|E_L[t - x(t)]|^2}{4\pi n_e l}\frac{\gamma - p}{\gamma + p}$$

$$p_f = \frac{1}{2}\left(1 + W - \frac{1}{1+W}\right)$$

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

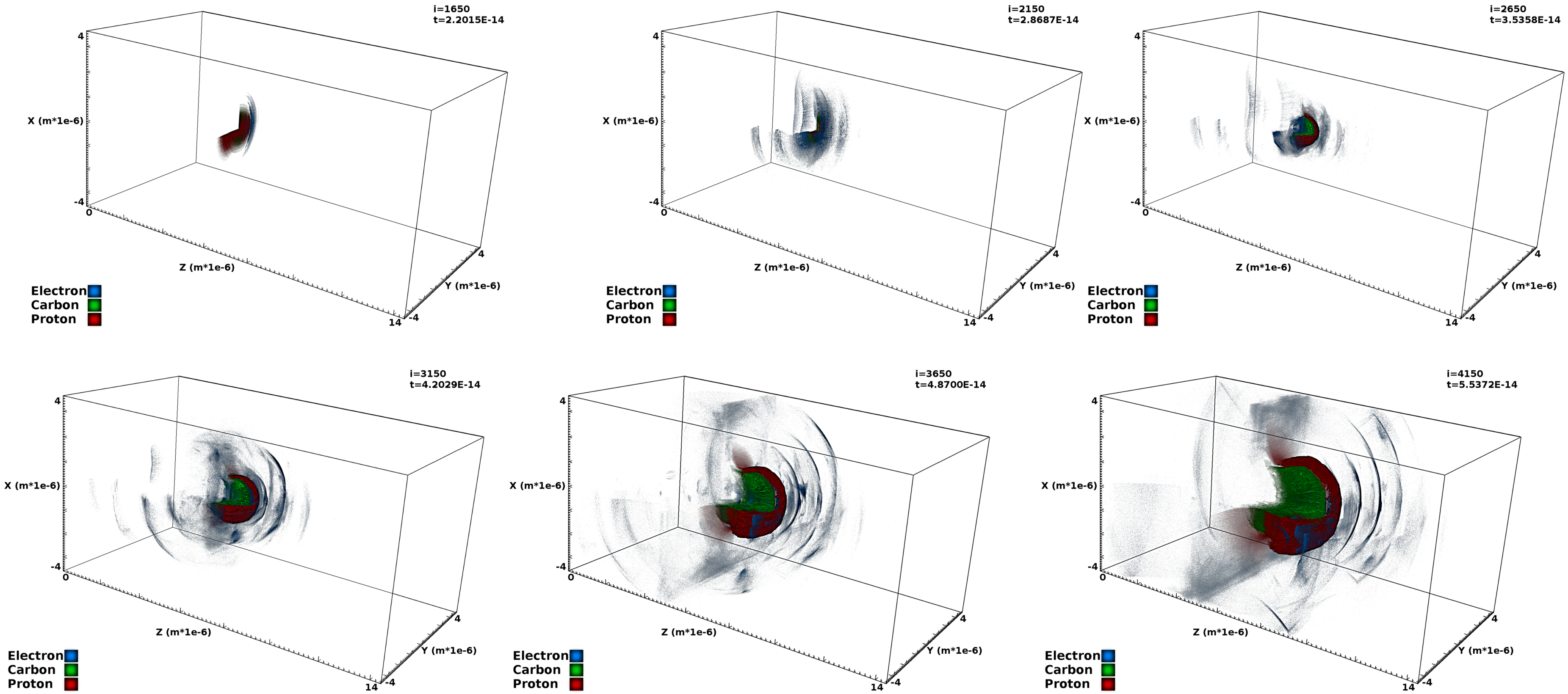
$$W_p = \frac{W_p' + Vp'}{\sqrt{1 - V^2/c^2}} = W_p' + (p_f / m_p c)\sqrt{2 m_p c^2 W_p'}$$

S. S. Bulanov, et al., Med. Phys. 35 (5), 2008.

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

3D PIC results: The protons are accelerated in front of the expanding carbon cloud

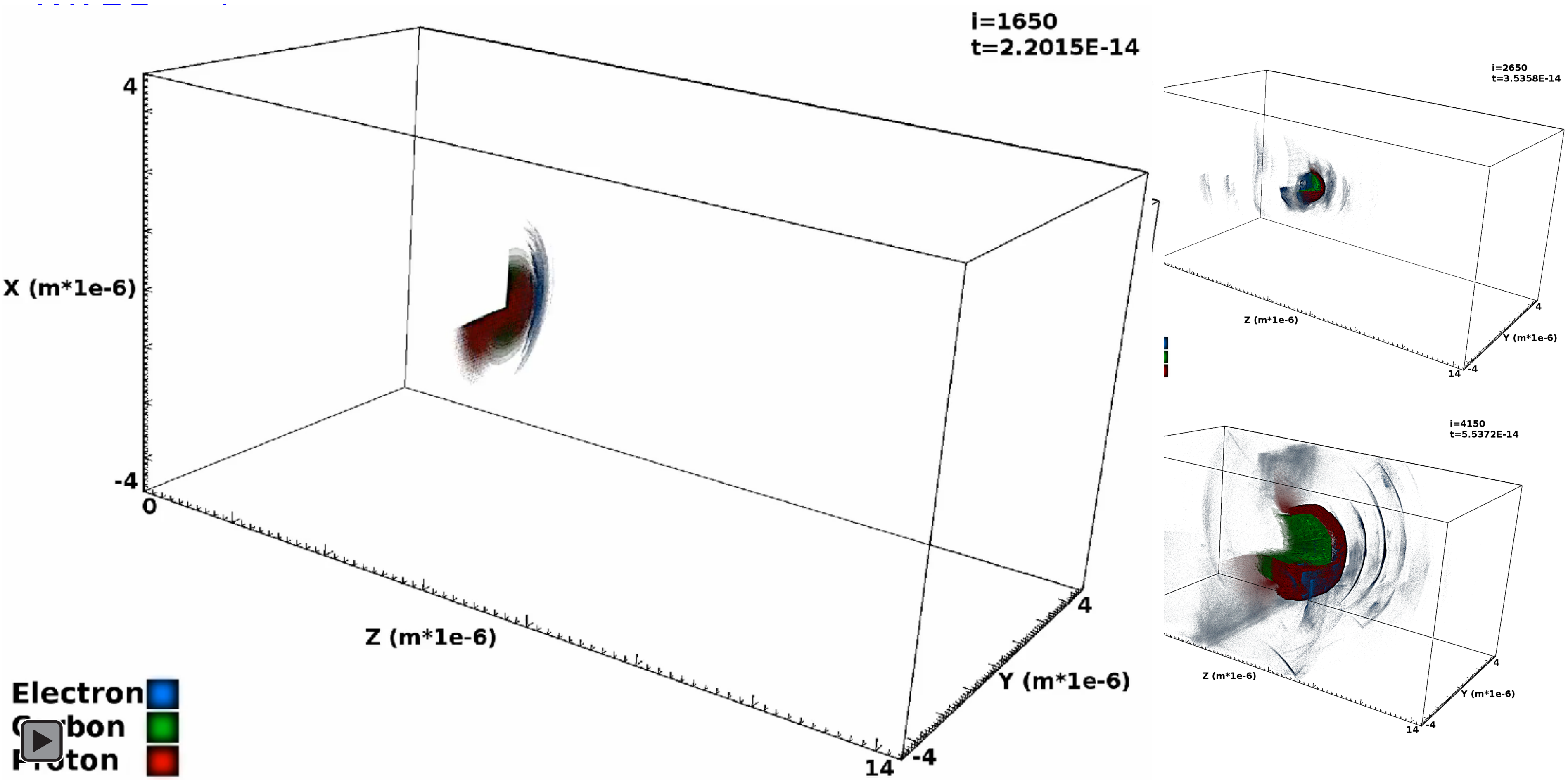
WARP code



Target: Carbon (75 nm, 400 n_{cr}) + Hydrogen (50 nm, 20 n_{cr})   Laser: 13 J, 27 fs, f/D=1.5

O. Rubel, B. Loring, J.-L. Vay, D. P. Grote, R. Lehe, S. S. Bulanov, H. Vincenti, submitted

3D PIC results: The protons are accelerated in front of the expanding carbon cloud



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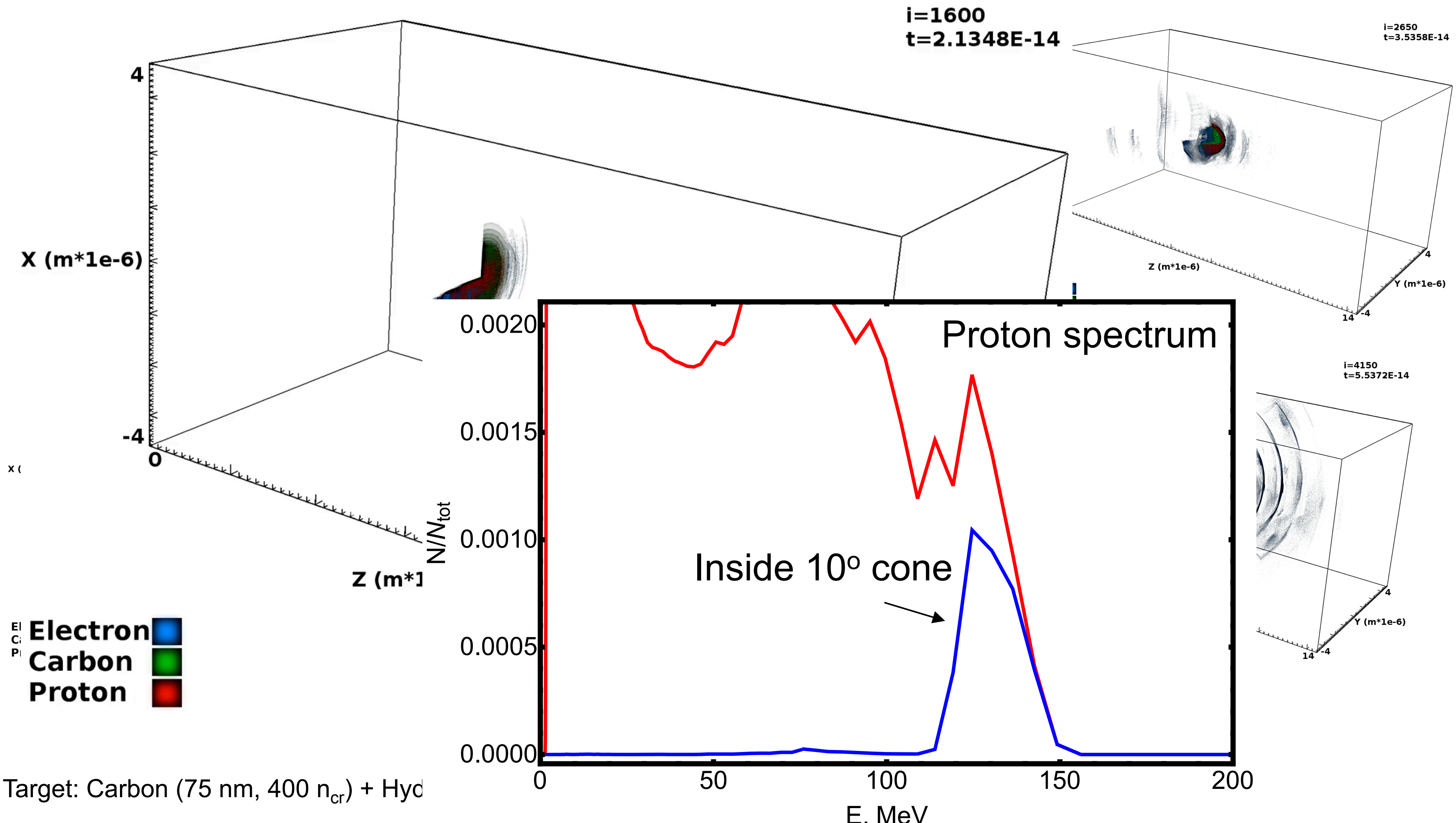
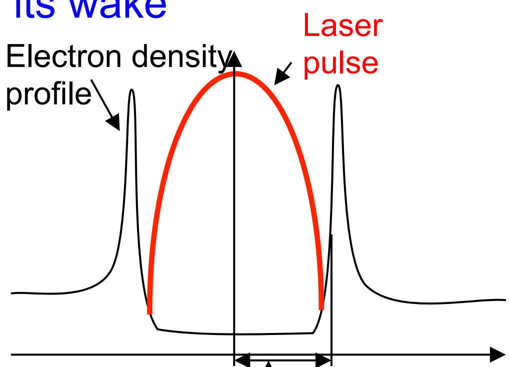


Target: Carbon (75 nm, 400 n_{cr}) + Hyd

O. Rubel, B. Loring, J.-L. Vay, D. P. Grote, R. Lehe, S. S. Bulanov, H. Vincenti, submitted

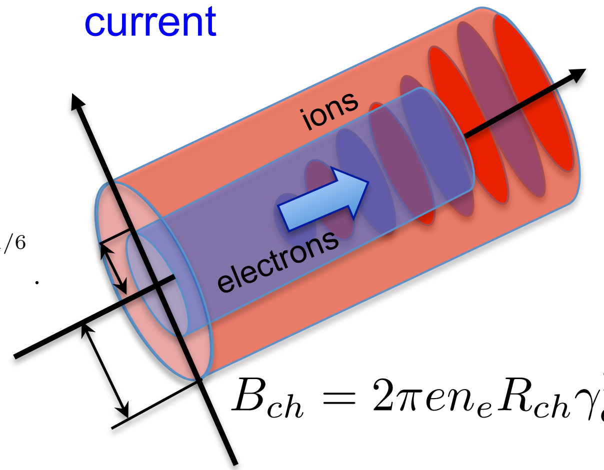
Magnetic Vortex Acceleration generates energetic ion beams from near critical density targets

Laser pulse in a self-generated waveguide accelerates electrons in its wake



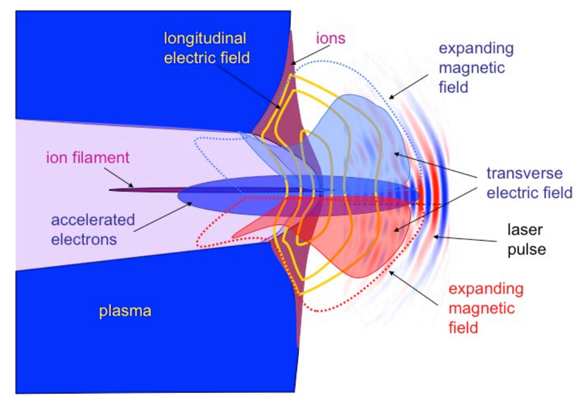
channel radius $R_{ch} = \frac{\lambda}{\pi}\left(\frac{n_{cr}}{n_e}\right)^{1/3}\left(\frac{2}{K}\frac{P}{P_c}\right)^{1/6}.$

Magnetic field is generated by the accelerated electron current



$$B_{ch} = 2\pi e n_e R_{ch}\gamma_e^2$$

Ion acceleration at the back of the target as the laser and electrons exit the target



The maximum helium ion energy

$$E_{He} = m_e c^2 2\pi^2 Z_{He}\frac{n_e}{n_{cr}}\left(\frac{R_{ch}}{\lambda}\right)^4$$

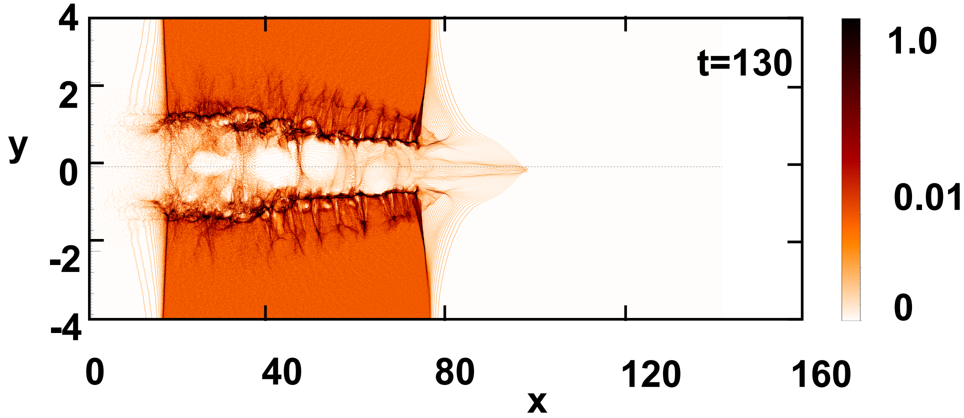
$$E_{He} \sim P^{2/3}$$

$$E_{He} \approx 3\ \mathrm{GeV}$$

for 1 PW laser pulse and $n_e = 3n_{cr}$

PIC simulations show the generation of a quasi-flat helium ion spectrum

He ion density distribution



Therapy relevant energy intervals:

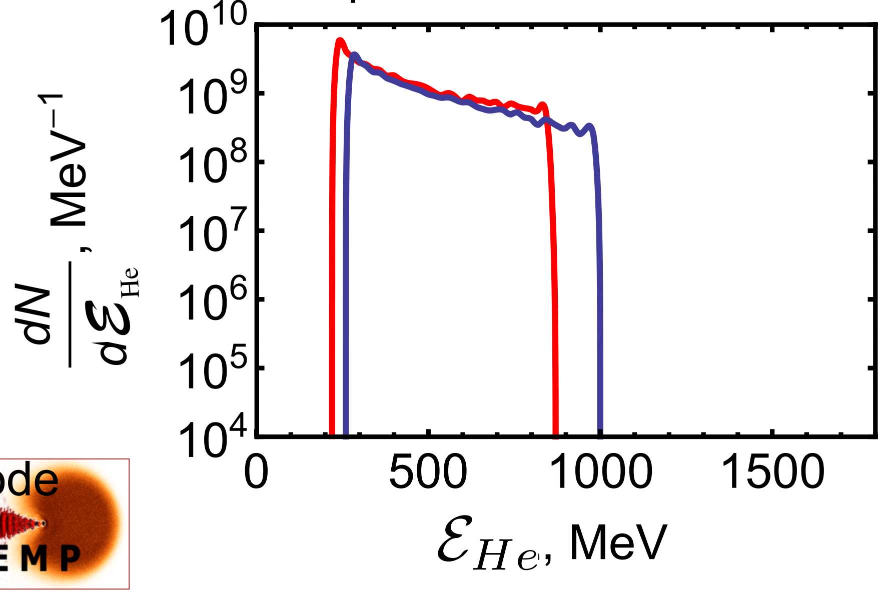
$$240 \text{ MeV} < \mathcal{E}_{He^3} < 860 \text{ MeV}$$

$$280 \text{ MeV} < \mathcal{E}_{He^4} < 1 \text{ GeV}$$

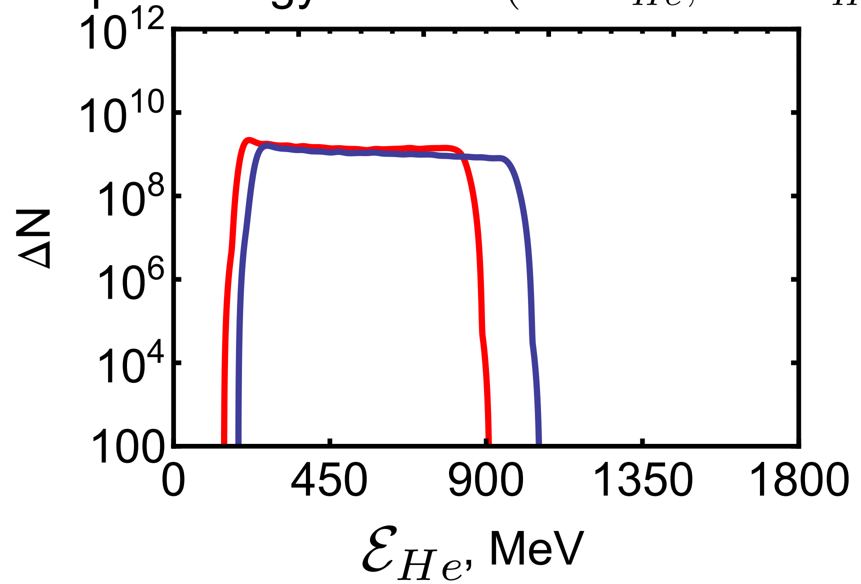
$$Target: \ n_e = (1-3)n_{cr}, \quad L = 60\lambda$$

$$Laser: \ f/D = 2, \ \tau = 30 \ fs$$

The spectra of He³ and He⁴ ions



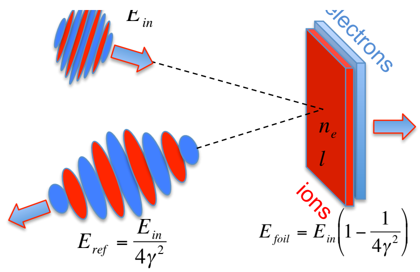
The number of He^3 and He^4 ions per energy interval $(0.98\mathcal{E}_{He}, \ 1.02\mathcal{E}_{He})$



code REMP

Summary

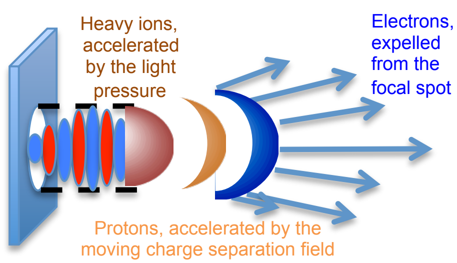
Radiation Pressure Acceleration



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

- Target: thin solid density foils
- Ion Energy ~ Laser Power
- 1 PW ⇨ 200 - 300 MeV

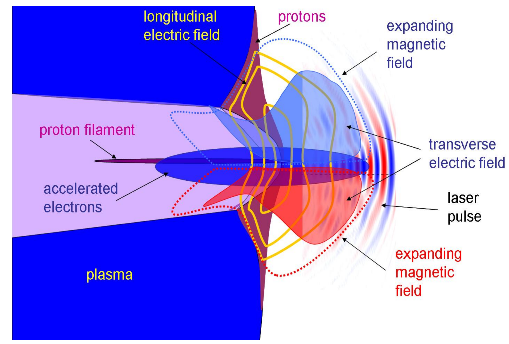
Directed Coulomb Explosion



S. S. Bulanov, et al., Med. Phys. 35, 1770 (2008)

- Target: thin solid density double layer foils
- Ion Energy ~ Laser Power
- 1 PW ⇨ 200 - 300 MeV

Magnetic Vortex Acceleration



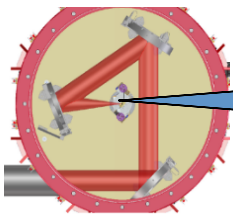
A. V. Kuznetsov, *et al.*,Plasma Phys. Rep. 27, 211 (2001).

- Target: plasma slab of near critical density
- Ion Energy ~ Laser Power$^{2/3}$
- 1 PW ⇨ GeV

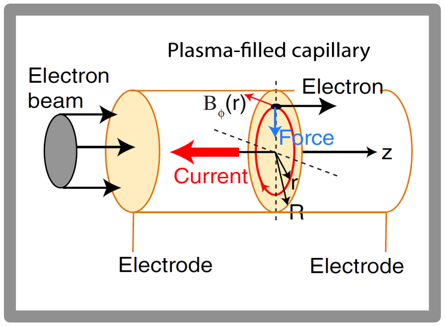
<u>Review papers on ion acceleration:</u>

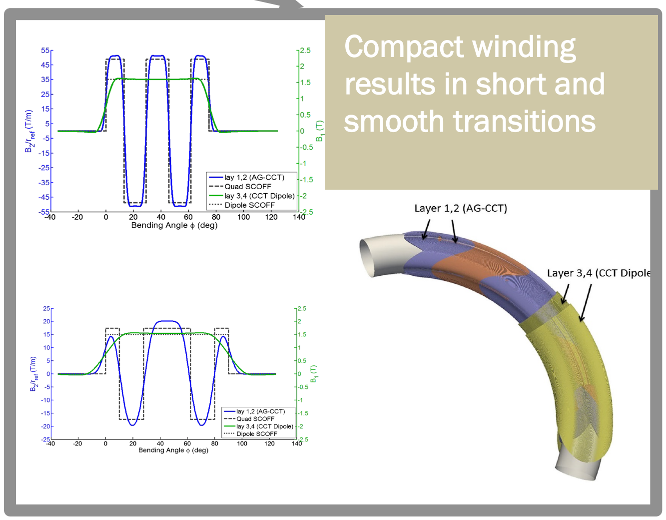
G. Mourou, *et al.*, Rev. Mod. Phys 78, 309 (2006)
H. Daido, *et al.*, Rep. Prog. Phys. 75, 056401 (2012)
A. Macchi, *et al.*, Rev. Mod. Phys. 85, 751 (2013).

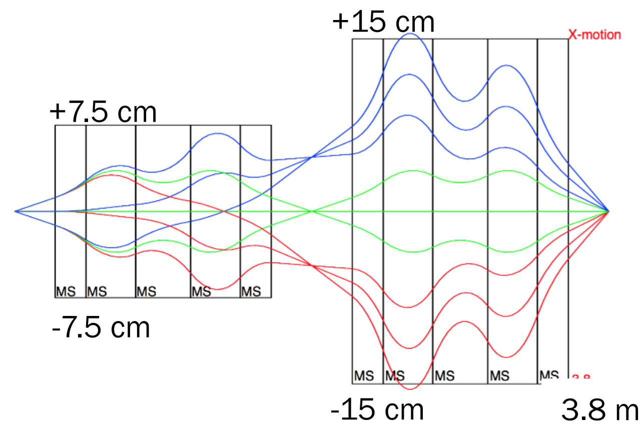
THPMR004: DESIGN OF A COMPACT ION BEAM TRANSPORT SYSTEM FOR THE BELLA ION ACCELERATOR (Q. JI *et al*)

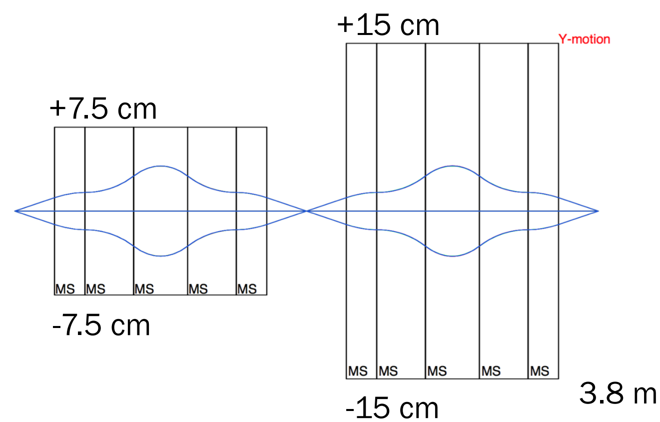


Discharge capillary as active plasma lens | AG-CCT super-conducting magnets → RF cavity bunch rotator → Beam Diagnostics









Ref: J. van Tilborg *et al*, Phys. Rev. Lett. **115**, 184802 (2015).

Ref: W. Wan *et al*, Phys. Rev. STAB **18**, 103501 (2015).