Laser-Plasma Accelerators of Ions: Advanced Schemes and Perspectives

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Gran Sasso Science Institute, INFN Center for Advanced Studies
L'Aquila, Italy, June 9, 2015

Outline

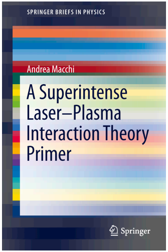
- The coherent (collective) acceleration paradigm (1957)
- The (re–)discovery of laser-driven proton beams (2000)
  - a “prompt” application: proton probing of laser-plasma interactions
  - *a framework for “laboratory astrophysics”*?
- Acceleration mechanisms: experiment & theory
  - Target Normal Sheath Acceleration (TNSA)
  - Radiation Pressure Acceleration (RPA)
  - Collisionless Shock Acceleration (CSA)
  - *a modeling issue: radiation friction*

Recent ion acceleration reviews (parochial selection)

A. Macchi, M. Borghesi, M. Passoni,
Ion Acceleration by Superintense Laser-Plasma Interaction,
Rev. Mod. Phys. **85** (2013) 571

A. Macchi, A. Sgattoni, S. Sinigardi, M. Borghesi, M. Passoni,
Advanced Strategies for Ion Acceleration using High Power Lasers,
Plasma Phys. Contr. Fus. **55** (2013) 124020

A. Macchi,
A Superintense Laser-Plasma Interaction Theory Primer (Springer, 2013)
Chap.5 "Ion Acceleration" (for absolute beginners)



Other ion acceleration reviews

H. Daido, M. Nishiuchi, A. S. Pirozhkov,
Review of Laser-Driven Ion Sources and Their applications,
Rep. Prog. Phys. **75** (2012) 056401

J.C. Fernández, B.J. Albright, F.N. Beg, M.E. Foord, B.M. Hegelich, J.J. Honrubia, M. Roth, R.B. Stephens, and L. Yin,
Fast ignition with laser-driven proton and ion beams,
Nucl. Fusion **54** (2014) 054006

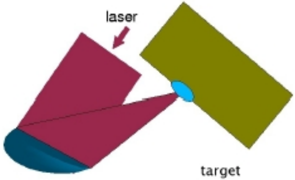
The vision of “coherent” acceleration: Veksler (1957)

V. I. Veksler, At. Energ. **2** (1957) 525

- accelerating field on each particle proportional to the number of accelerated particles
- automatic synchrony between the particles and the accelerating field
- field localization in the region where the particles are
- acceleration of quasi-neutral bunches with large numbers of particles

The dawn of laser-plasma physics (1964)

"*The laser is a solution looking for a problem*" (D'Haenens to Maiman, 1960)
Q-switched lasers (1962):
10 GW on $\sim 10^{-2}$ cm spot
$\rightarrow I \simeq 10^{13}$ W cm^{-2}



THE PHYSICS OF FLUIDS VOLUME 7, NUMBER 7 JULY 1964

On the Production of Plasma by Giant Pulse Lasers

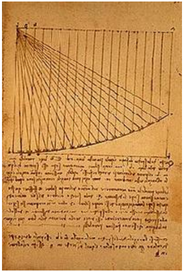
JOHN M. DAWSON
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey
(Received 10 October 1963; final manuscript received 10 March 1964)

Calculations are presented which show that a laser pulse delivering powers of the order of 10^{10} W to a liquid or solid particle with dimensions of the order of 10^{-2} cm will produce a hot plasma with temperatures in the range of several hundred eV. To a large extent the plasma temperature is held down by its rapid expansion and cooling. This converts much of the energy supplied into ordered energy of expansion. This ordered expansion energy can amount to several keV per ion. If the expanding plasma can be caught in a magnetic field and its ordered motion converted to random motion this might be utilized as a means for filling controlled thermonuclear fusion devices with hot plasma. Further, it should also be possible to do many interesting plasma experiments on such plasmas.

Focused light interaction with matter: an old story

Archimedes' mirror burning Roman ships. Giulio Parigi, ab. 1600. Uffizi Gallery, *Stanzino delle Matematiche*, Florence, Italy

Leonardo da Vinci: Studies on reflection by burning mirrors. Codex Arundel (1480-1518), British Library, London.



First attempts to "strongly" modify matter with intense light (heating, phase transition, ionization . . .)

Intensity of Sunlight: $I \simeq 1.4 \times 10^{-1}$ W cm^{-2}

with "ultimate" concentration $\sim 10^4 \rightarrow I \simeq 10^3$ W cm^{-2} at focus

Race to superintense lasers

Current intensity record: $I \simeq 2 \times 10^{22}$ W cm^{-2}
[HERCULES, Michigan University, 0.3 PW, 10 fs, diffraction-limited focus $w \sim 1$ μm: Yanovsky et al, Opt. Express **16** (2008) 2109]

Some 10 PW lasers in construction:
ELI (1.5 kJ/150 fs), APOLLON (150 J/15 fs), VULCAN (300 J/30 fs) ...
A future vision: multi-fibre laser for $I > 10^{23}$ W cm^{-2}
[Mourou et al, Nature Photonics **7** (2013) 258]

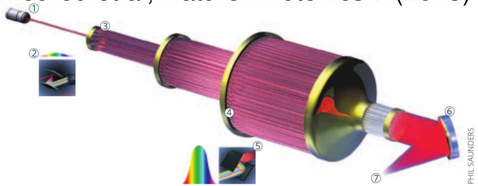
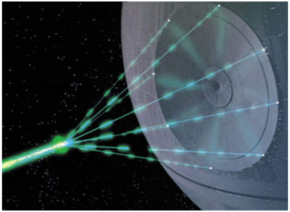
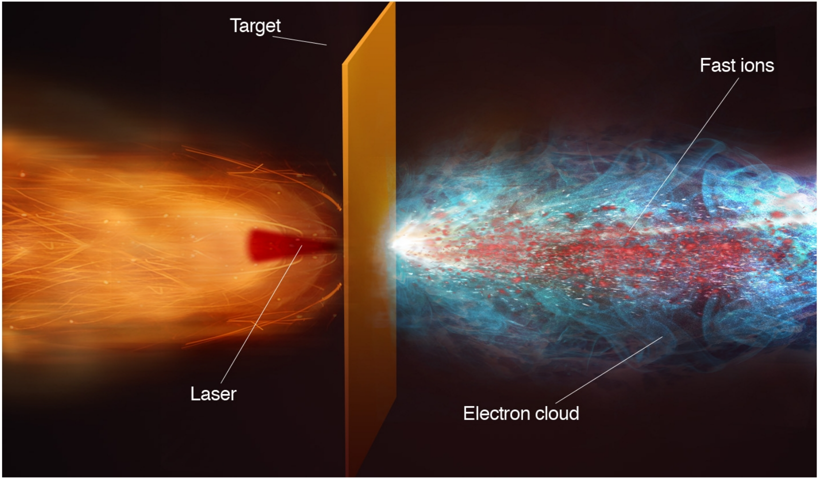


Figure 1 | Principle of a coherent amplifier network. An initial pulse from a seed laser (1) is stretched (2), and split into many fibre channels (3). Each channel is amplified in several stages, with the final stages producing pulses of ~1 mJ at a high repetition rate (4). All the channels are combined coherently, compressed (5) and focused (6) to produce a pulse with an energy of >10 J at a repetition rate of ~10 kHz (7).



Multi-MeV protons from solid targets (2000)



Multi-MeV protons from solid targets (2000)

Up to 58 MeV protons observed at LLNL (Livermore) Petawatt

Snavely et al, PRL **85** (2000) 2945

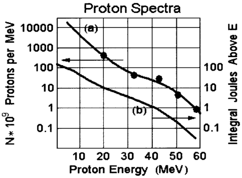
Other observations:

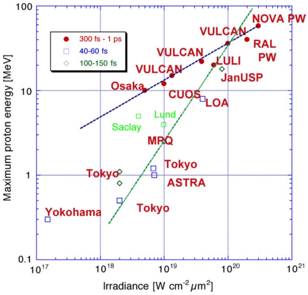
Clark et al, PRL **84** (2000) 670

Maksimchuk et al, PRL **84** (2000) 4108

Protons have been observed and characterized in a large number of laboratories and for different laser pulse regimes

Figure from Borghesi et al, Plasma Phys. Contr. Fus. **50** (2008) 124040





Features of protons from solid targets

- in metal targets proton originate from H impurities
- cut-off energy record: 67.5 MeV
  (Gaillard et al, Phys. Plasmas **18** (2011) 056710)
- mostly broad energy spectra (exponential-like)
- large numbers - e.g. $\sim 2 \times 10^{13}$ protons, ~kA current
  (Snavely et al, PRL **85** (2000) 2945)
- charge neutralization by comoving electrons ("plasma beam")
- good collimation with energy-dependent spread $\sim 10^\circ \div 30^\circ$
- low emittance $\sim 4 \times 10^{-3}$ mm mrad with cautious definition for broadband spectra
  (Nuernberg et al., Rev. Sci. Instrum. **80** (2009) 033301)
- ultrashort duration (~ pulse duration, $\sim 0.1 \div 10$ ps)

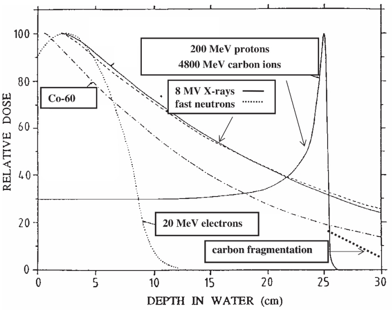
Interest in multi-MeV protons

Energy deposition dominated by Bragg peak: optimal for localized heating of matter

figure from:

U. Amaldi, G. Kraft,

Rep. Prog. Phys. **68** (2005) 1861

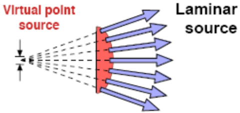


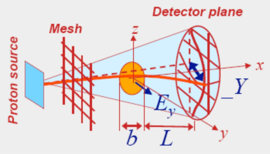
Foreseen applications:

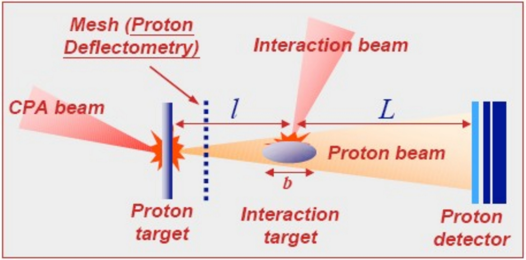
- oncology: hadrontherapy, ion beam therapy
- triggering of nuclear reactions, isotope production
- production of warm dense matter
- diagnostic of materials
- ultrafast probing of electromagnetic fields

Proton probing of laser-plasma interactions

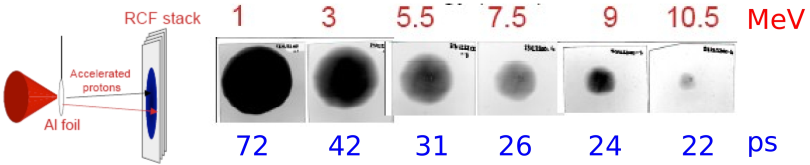
- charged beam:
  - field detection
- low emittance:
  - imaging capability
- laser driver:
  - easy synchronization
- broad spectrum:
  - time-of-flight arrangement
- short duration:
  - ultrafast resolution



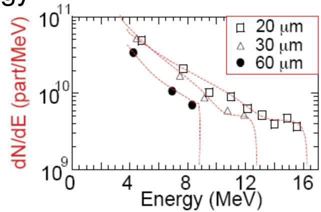




Achieving single-shot proton "movies"

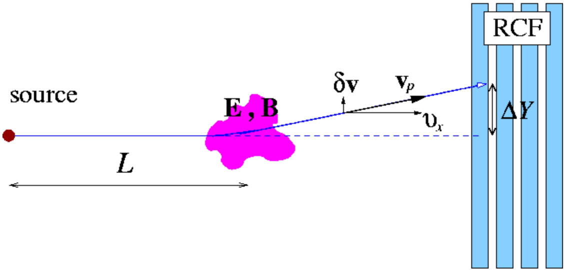


Radiochromic film (RCF) stack:
each layer a Bragg peak → a proton energy
Time-of-flight arrangement:
each layer → a probing time
(values refer to 1 mm flight distance)
Temporal resolution up to ~ 1 ps



Proton "image" formation

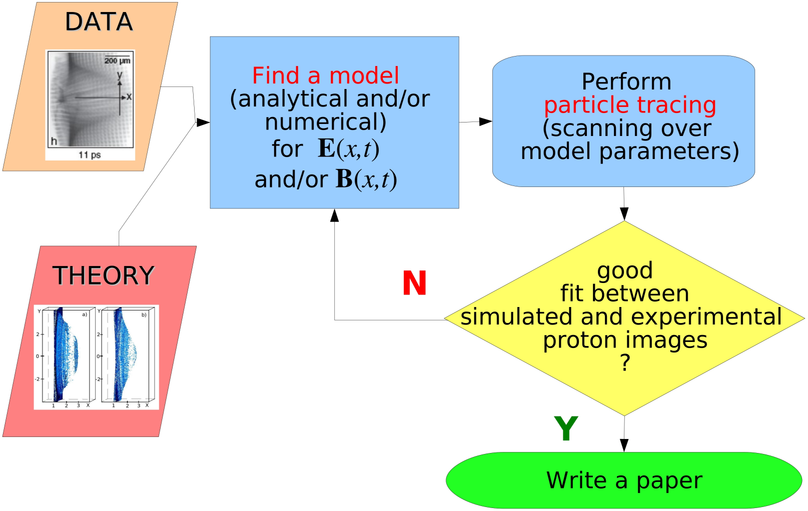
Small angle deflections by $\mathbf{E}$ and $\mathbf{B}$ distributions create a density modulation δn on the RCF detector plane producing an "image" (with magnification M)



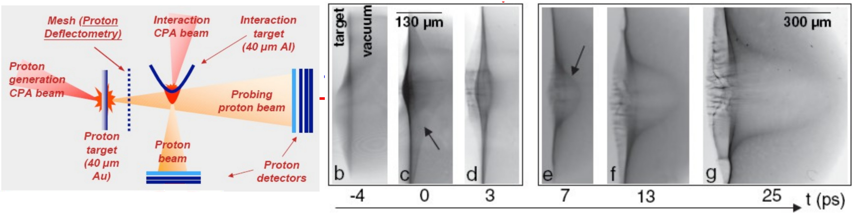
$$\Delta Y = |\delta \mathbf{v}| \Delta t \simeq \frac{eL}{2\mathcal{E}_p} \int (\mathbf{E} + \mathbf{v}_p \times \mathbf{B})_\perp dx$$

$$\frac{\delta n}{n_0} \simeq -\frac{1}{M} \nabla \cdot \Delta \mathbf{Y} \simeq \frac{-2\pi e L b}{\mathcal{E}_p M} \int_{-b/2}^{+b/2} \left(\rho - \frac{\mathbf{v}_p \cdot \mathbf{J}}{c^2} \right) dx$$

“Algorithm” for proton imaging analysis



Probing proton acceleration with accelerated protons



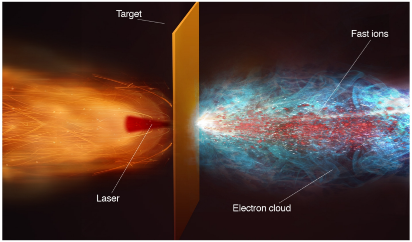
[L.Romagnani et al, Phys.Rev.Lett. **95** (2005) 195001]

Transverse probing of the target with a second proton beam: imaging of an expanding electric field front (bell-shaped contour) → confirmation that protons are accelerated at the rear surface of the target: TNSA (Target Normal Sheath Acceleration) model

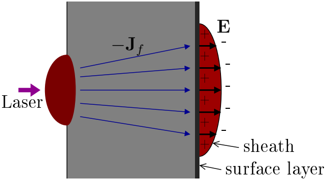
Target Normal Sheath Acceleration (TNSA) scheme

Physics: electric field generation in a cloud (sheath) of energetic "fast" electrons leaving the rear surface of the target

Sheath field back-holds electrons and accelerates ions



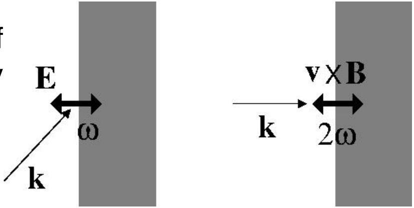
Protons mostly originate from a surface impurity layer at the rear: favorable initial position (at the peak of the sheath field) and highest charge-to-mass (Z/A) ratio (removing the layer → heavier ions acceleration)

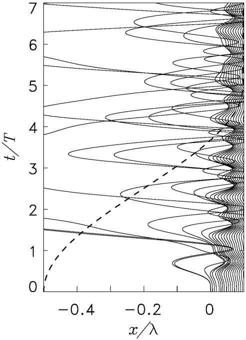


$\mathbf{J}_f$: fast electron current

Fast electron generation: a simplified picture

Needs laser-driven push-pull of electrons across the density gradient





Electrons perform "half-oscillations" in vacuum and re-enter in the plasma with approximately the "quiver" energy

Oscillations driven by:
- $\mathbf{E}$ for P–polarization
- $\mathbf{v}\times\mathbf{B}$ for S–polarization or normal incidence

Plasma Modeling: Maxwell-Vlasov Equations

$$\frac{df_a}{dt} = \frac{\partial f_a}{\partial t} + \frac{\partial}{\partial \mathbf{r}}(\dot{\mathbf{r}}_a f_a) + \frac{\partial}{\partial \mathbf{p}}(\dot{\mathbf{p}}_a f_a) = 0 \qquad f_a = f_a(\mathbf{r}, \mathbf{p}, t)$$

$$\dot{\mathbf{p}}_a = q_a(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \qquad \dot{\mathbf{r}}_a = \frac{\mathbf{p}_a}{\sqrt{\mathbf{p}_a^2 + m_a^2}} \qquad \mathbf{v} = \frac{\mathbf{p}}{\sqrt{\mathbf{p}^2 + m_a^2}}$$

$$\rho(\mathbf{r}, t) = \sum_{a=e,i} q_a \int f_a d^3p \qquad \mathbf{J}(\mathbf{r}, t) = \sum_{a=e,i} q_a \int \mathbf{v} f_a d^3p$$

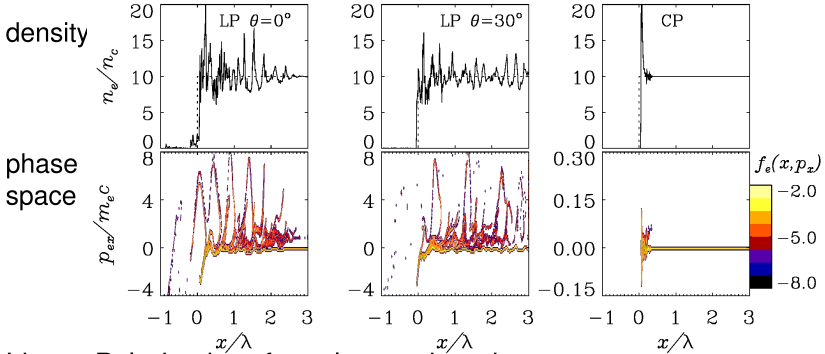
$$\nabla \cdot \mathbf{E} = \rho \qquad \nabla \cdot \mathbf{B} = 0 \qquad \nabla \times \mathbf{E} = -\partial_t \mathbf{B} \qquad \nabla \times \mathbf{B} = \mathbf{J} + \partial_t \mathbf{E}$$

Numerical solution: distribution function discretized over phase space trajectories of N particles (Particle-In-Cell method)

$$f_a(\mathbf{r}, \mathbf{p}, t) = \sum_{n=0}^{N-1} g(\mathbf{r} - \mathbf{r}_n(t))\delta(\mathbf{p} - \mathbf{p}_n(t)) \begin{cases} d_t \mathbf{p}_n = q_a(\mathbf{E}(\mathbf{r}_n, t) + \mathbf{v}_n \times \mathbf{B}(\mathbf{r}_n, t)) \\ d_t \mathbf{r}_n = \mathbf{v}_n \end{cases}$$

Fast electron generation: effect of polarization

1D simulations of laser interaction with solid-density plasma



Linear Polarization: fast electron bunches at rate ω (for $\theta = 30°$, P-pol.) or 2ω (for $\theta = 0°$)

Circular Polarization at $\theta = 0°$: no fast electrons ($(\mathbf{v} \times \mathbf{B})_{2\omega} = 0$)

Fast electron generation: typical parameters

- Typical energy ("ponderomotive scaling")

$$\mathcal{E}_f = m_e c^2(\gamma - 1) \sim m_e c^2\left(\sqrt{1 + a_0^2/2} - 1\right)$$

a_0: "relativistic" amplitude parameter

$$a_0 = \left(\frac{I\lambda^2}{10^{18}\ \text{W/cm}^2}\right)^{1/2} = \frac{eE_L}{m_e\omega c} = \frac{p_{\text{osc}}}{m_e c}$$

- conversion efficiency $\eta_f \simeq 10^{-2} - 10^{-1}$
- density $n_f \simeq 10^{20} - 10^{21}\ \text{cm}^{-3}$
- current density $\sim 10^{12}\ \text{A/cm}^2 \rightarrow 10\ \text{MA}$ over the laser spot

Static modeling of TNSA

Assume fast electrons in Boltzmann equilibrium with density n_e and temperature T_e as the only parameters to evaluate sheath extension L_s and potential drop $\Delta\Phi$

$$L_s \simeq \lambda_D = (T_e/4\pi e^2 n_e)^{1/2}, \qquad \Delta\Phi \simeq T_e/e$$

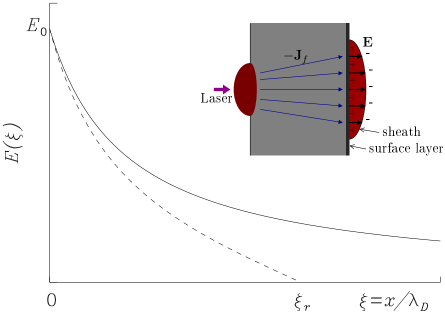
Energy gain by a "test" ion in the static sheath:

$$\mathcal{E}_{\mathrm{max}} = Ze\Delta\Phi \simeq ZT_e$$

⚠ : exact treatment yields

$$L_s \to \infty \qquad \Delta\Phi \to \infty$$

if Boltzmann's distribution is not "truncated" at high energy

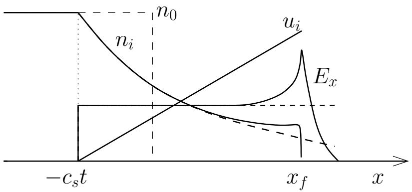


Dynamic modeling of TNSA

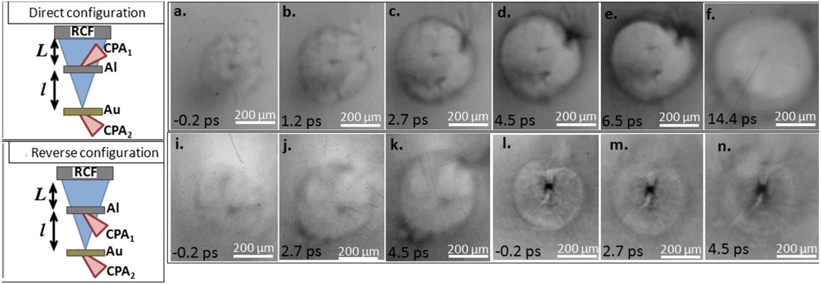
Plasma expansion model: isothermal rarefaction wave solution "patched" at the ion front where quasi-neutrality breaks down

$$c_s = \left(\frac{ZT_e}{m_i}\right)^{1/2}, \quad u_f \equiv u_i(x_f) = c_s[2\ln(\omega_{pi}t)+1], \quad \mathscr{E}_{\max} = \frac{m_i}{2}u_f^2 \propto ZT_e$$

⚠: ion energy diverges due to infinite energy reservoir!
assume finite model (e.g thin foil expansion) with $T_e(t)$
assume finite acceleration time (extra patch)

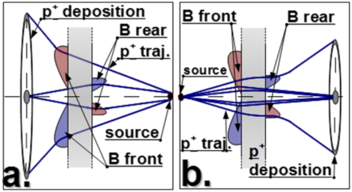


Magnetic fields around the sheath

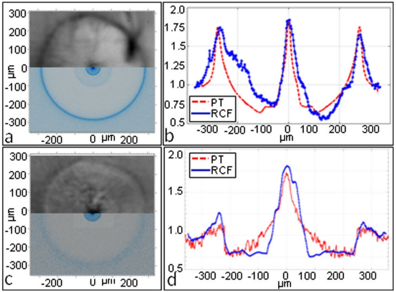


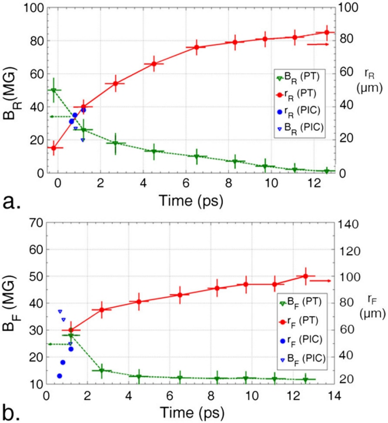
(**a-k**: *direct* config., **l-n**: *reverse* config.)

Front/rear side magnetic fields of opposite polarity cause probe proton focusing/defocusing → "double ring" [G.Sarri, A. Macchi, C.A.Cecchetti et al, PRL **109**, 205002 (2012)]



Sheath magnetization and self-confinement



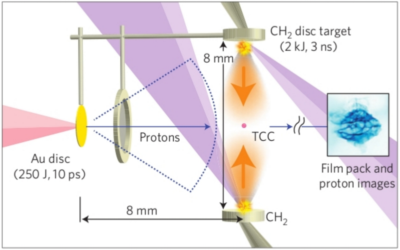


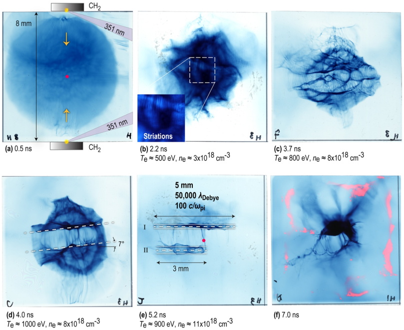
Estimated values $B \sim 80$ MG and temporal evolution of radius suggest that $\mathbf{B}$ confines the sheath

→ *a scaled-down laboratory environment for the study of astrophysical jets*?

A colliding plasmas experiment

Kugland et al, Nature Phys. **8** (2012) 809; Phys. Plasmas **20** (2013) 056313





Set-up on OMEGA EP laser
(Rochester, USA)
to study and probe
the generation of counterstreaming instabilities and collisionless shock waves with astrophysical interest
(assuming reliable scaling relations hold . . .)

Beyond TNSA: searching for other mechanisms

Unresolved issues and limitations of TNSA:

- broad ($\sim$ exponential) energy spectrum

→ not suitable for most application

- slow scaling of proton energy with laser intensity ($\mathscr{E}_{\text{max}} \sim I^{1/2}$)

→ hard to reach minimal requests for e.g. hadrontherapy (≥ 150 MeV)

- high repetition rate not easy with thin solid targets

Alternative regimes:

- Radiation Pressure Acceleration (RPA)
- Collisionless Shock Acceleration (CSA)

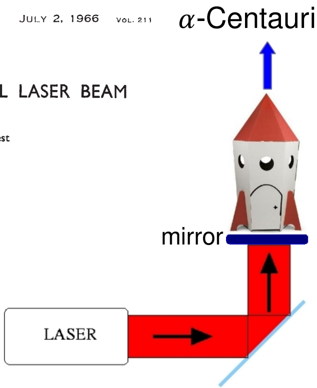
Early vision of radiation pressure acceleration (1966)

22 NATURE JULY 2, 1966 VOL. 211

INTERSTELLAR VEHICLE PROPELLED BY TERRESTRIAL LASER BEAM

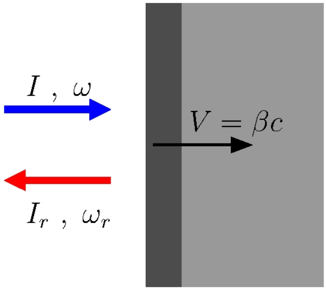
By PROF. G. MARX
Institute of Theoretical Physics, Roland Eötvös University, Budapest

A solution to "Fermi's paradox": "*Laser propulsion from Earth . . . would solve the problem of acceleration but not of deceleration at arrival . . . no planet could be invaded by unexpected visitors from outer space*"



The accelerating mirror model of RPA

Perfect mirror boosted by a plane wave: mechanical efficiency η and momentum transfer to mirror derived by Doppler shift and photon number conservation

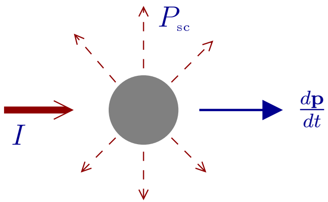


$$\frac{dp}{dt} = \frac{2I}{c}\frac{1-\beta}{1+\beta} \qquad \eta = \frac{2\beta}{1+\beta}$$

High efficiency ($\eta \to 1$) but slow gain ($dp/dt \to 0$) as $\beta \longrightarrow 1$

Analogy with Acceleration by Thomson Scattering

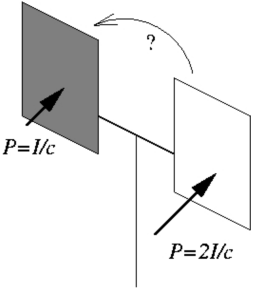
Light Sail equations of motion have the same form as those of a particle undergoing Thomson Scattering
Landau & Lifshitz, *The Classical Theory of Fields*, ch.78 p.250 (1962).



$$\frac{dp}{dt} = \sigma_T I \propto P_{sc}$$

Veksler's idea: coherent scattering by a cluster of radius $a \ll \lambda$ with N $(\gg 1)$ particles, $P_{sc} \to N^2 P_{sc} \Rightarrow \sigma_T \to N^2 \sigma_T$

How to make radiation pressure dominant?



The "Optical Mill" rotates in the sense *opposite* to that suggested by the imbalance of radiation pressure: *thermal* pressure due to *heating* dominates

Enforcing radiation pressure dominance requires to suppress heating of the surface

Possible solution for ultraintense lasers: circular polarization

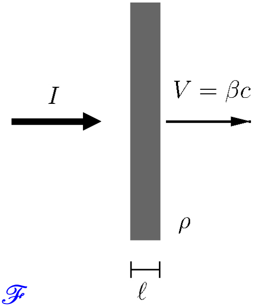
Macchi, Cattani, Liseykina, Cornolti, PRL **94** (2005) 165003

Light Sail acceleration

"Accelerated mirror" 1D model:

$$\mathscr{E}_{\max} = m_p c^2 \frac{\mathscr{F}^2}{(2(\mathscr{F}+1))}$$

$$\mathscr{F} = \frac{2}{(\rho\ell)} \int_0^\infty I(t')dt' \simeq \frac{2I\tau_p}{\rho\ell}$$



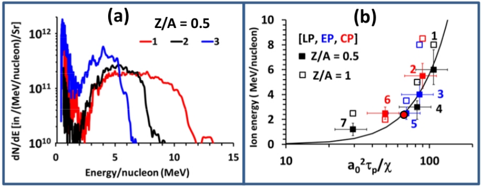
Favorable scaling with normalized fluence $\mathscr{F}$
100% efficiency in the relativistic limit (accessible with ELI)
"Perfect" monoenergeticity for "rigid", coherent sail motion

Issue: slow energy gain → stability, laser diffraction, . . .

$$\mathscr{E}_{\text{ion}}(t) \propto \left(\frac{2It}{\rho\ell c^2}\right)^{1/3} \qquad \left(t \gg \frac{\rho\ell c^2}{I}, \mathscr{E}_{\text{ion}} > m_p c^2\right)$$

$\mathscr{F}^2$ scaling experimentally observed

VULCAN laser, RAL/CLF:
Laser pulse: $t_p \simeq 800$ fs
3×10^{20} W cm^{-2}
Target: $\sim 0.1\ \mu$m metal foil



Multispecies ($Z/A = 1 \div 1/2$) peaks observed with $\Delta\mathscr{E}/\mathscr{E} \simeq 20\%$
Up to $\simeq 10$ MeV/nucleon observed with $\mathscr{F}^2$-scaling on average
Simulations suggest > 100 MeV/nucleon are within reach

Kar, Kakolee, Qiao, Macchi et al, PRL **109** (2012) 185006

Significant non-RPA effects observed: broad spectra, species separation, weak dependence on polarization . . .

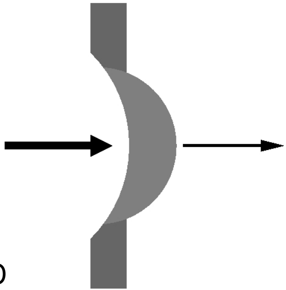
Fast gain Light Sail in 3D

Transverse expansion of the target reduces on-axis surface density $\rho\ell$

$\Rightarrow$ *light sail gets "lighter"*:

boost of energy gain

at the expense of the number of ions



Faster gain $E_{\text{ion}}(t) \simeq \left(\frac{2It}{\rho\ell c^2}\right)^{3/5}$ predicted in 3D

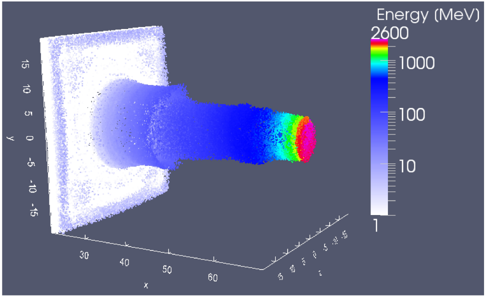
[S.V.Bulanov et al, "Unlimited ion acceleration by radiation pressure", PRL **104** (2010) 135003]

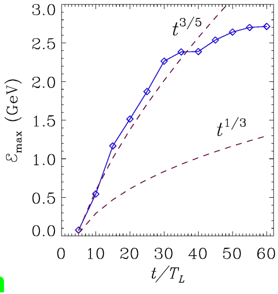
Mechanism is effective for *relativistic* ions ($\mathscr{F} \gg 1$)

Need to explore this regime (relevant for ELI project) with fully 3D simulations over long time scales

High energy gain in 3D LS simulations

Laser: 24 fs, 4.8 μm spot, $I = 0.85 \times 10^{23}$ W cm^{-2} $\Longrightarrow$ **1.5 kJ**
Target: $d = 1$ μm foil, $n_e = 10^{23}$ cm^{-3}

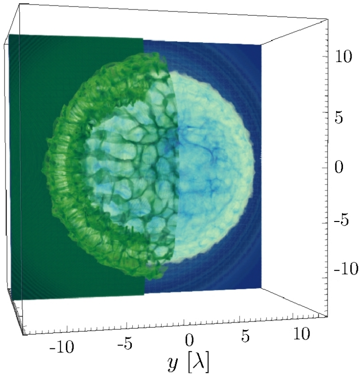




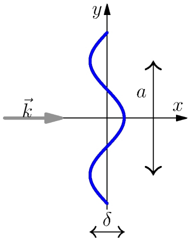
$\mathcal{E}_{max} \simeq 2.6$ GeV > **4X 1D model prediction**

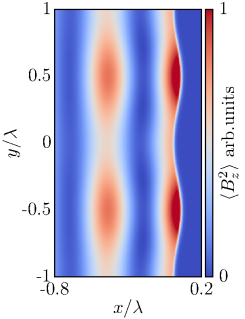
Macchi et al, Plasma Phys. Contr. Fus. **55** (2013) 124020;
Sgattoni et al, Appl. Phys. Lett. **105** (2014) 084105

Rayleigh-Taylor instability in LS acceleration



target breakup into net-like structures with size $\sim \lambda$ (laser wavelength) and $\sim$ hexagonal shape





Explanation: Rayleigh-Taylor instability stimulated by radiation pressure modulation
Sgattoni et al, Phys. Rev. E **91** (2015) 013106

field enhancement in surface ripple valleys

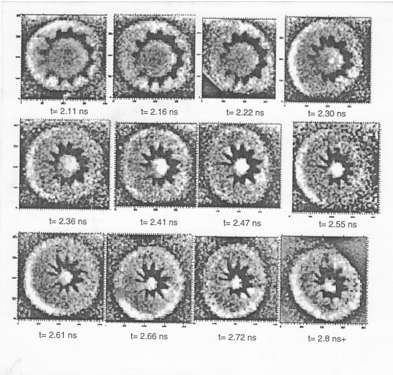
Rayleigh-Taylor Instability in space and lab

Crab Nebula, Hubble Space Telescope

Heavy fluid over a light fluid is unstable
(↑ gravity ↓ acceleration)

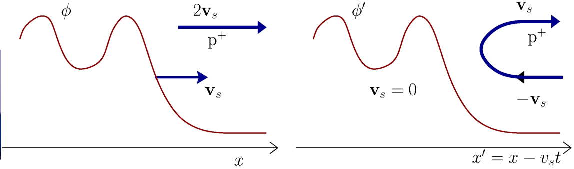
physicscentral.com

Laser-driven implosion for Inertial Confinement Fusion studies, 1995 (Wikipedia)



Collisionless Shock Acceleration

- Concept: shock wave of velocity $v_s = Mc_s$ ($M > 1$ Mach number, $c_s = \sqrt{ZT_e/Am_p}$ speed of sound) driven by the laser pulse into an ideal (collisionless) plasma (electric fields support the shock front rather than collisions)



- Shock front is a moving potential barrier → “moving wall” reflection of some ions: $v_i \simeq 2v_s$

→ acceleration of monoenergetic, multi–MeV ions if v_s is constant and $T_e \simeq T_{\text{fast}} >$MeV

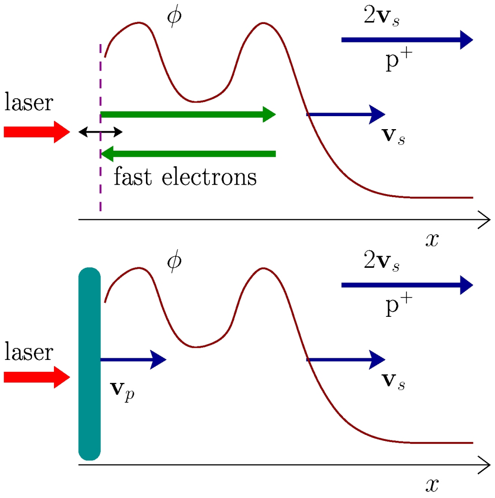
Laser-Driven Collisionless Shocks

Step 1:
- heating of "fast" electrons

Step 2:
- counterstreaming instabilities with "refluxing" electrons

OR

- radiation pressure acting as a "piston" (Need to characterize optimal laser and target conditions)



Monoenergetic CSA in CO_2 laser-H gas interaction?

UCLA experiment
Haberberger et al,
Nature Phys. **8** (2012) 95

Monoenergetic proton spectra:
$\mathscr{E}_{\text{max}} = 22$ MeV $\quad \Delta\mathscr{E} \lesssim 10^{-2}\mathscr{E}_{\text{peak}}$
Laser: 100 ps train of 3 ps pulses
$I = 6.5 \times 10^{16}$ W cm^{-2},
Target: H_2 gas jet
Interpretation: reflection from a shock driven by fast electrons

Number of protons is very low: is efficiency of CSA incompatible with monoenergetic spectra?

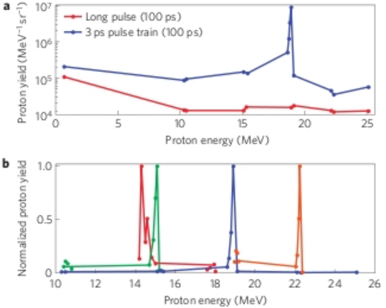
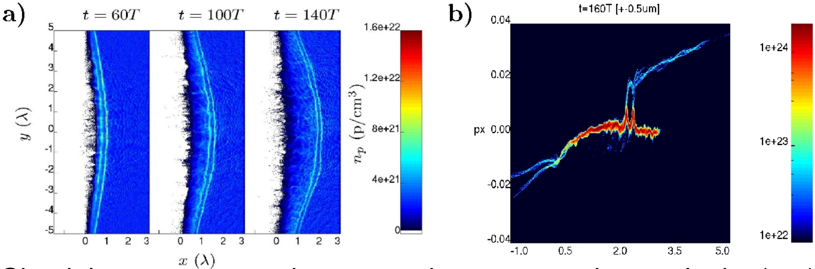


Figure 2 | Proton energy spectra. a, Proton spectra obtained with a 100-ps-long laser pulse (red) and a 100 ps macropulse consisting of a number of 3 ps micropulses (blue) both containing 60 J. The typical noise level on a single CR39 detector was 100 pits. The total number of protons contained within the monoenergetic peak was 2.5×10^5. **b**, The details of the energy spectra on four different laser shots with different macropulse structures (number of pulses and a_0 values ranging from 1.5 to 2.5).

Shock Loading and Energy Chirping (2D Simulation)

density contours | phase space in beam direction



Shock loses energy to ions → v_s decreases → ions velocity ($2v_s$) decreases → spectrum broadens towards lower energies

Density profile and energy distribution of background ions are crucial for monoenergetic CSA (too many ions cannot be reflected anyway)

Macchi et al, PRE **85** (2012) 046402; Sgattoni et al, Proc. Spie **8779** (2013)

A modeling issue: radiation friction

- For ultra-relativistic electrons in super-strong fields the effects of radiation friction aka radiation reaction (back-action of the EM field generated by the electron on itself) become important:

$$\frac{d\mathbf{p}}{dt} = -e\left(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B}\right) + \mathbf{f}_{\text{rad}}$$

- Correct form of $\mathbf{f}_{\text{rad}}$: a >100 year-old controversial problem, revitalized by ultraintense laser interactions:
  - theoretical formulation
  - implementation in relativistic plasma modeling
  - observation of effects in experiments

Landau-Lifshitz approach

L.L.Landau, E.M.Lifshitz, *The Classical Theory of Fields* (Elsevier, 1975), 2nd Ed., par.76

$$\begin{aligned}\mathbf{f}_{\text{rad}} &= \frac{2r_c^2}{3}\left\{-\gamma^2\left[\left(\mathbf{E}+\frac{\mathbf{v}}{c}\times\mathbf{B}\right)^2-\left(\frac{\mathbf{v}}{c}\cdot\mathbf{E}\right)^2\right]\frac{\mathbf{v}}{c}+\right.\\ &\left.+\left[\left(\mathbf{E}+\frac{\mathbf{v}}{c}\times\mathbf{B}\right)\times\mathbf{B}+\left(\frac{\mathbf{v}}{c}\cdot\mathbf{E}\right)\mathbf{E}\right]-\gamma\left(d_t\mathbf{E}+\frac{\mathbf{v}}{c}\times d_t\mathbf{B}\right)\right\}\end{aligned}$$

- Dominant "dissipative" term $\mathbf{f}_{\text{rad}}^{(1)} \propto -\gamma^2\mathbf{v}$
- Implementation in PIC simulations of ultraintense laser-plasma interaction: Tamburini, Pegoraro, Di Piazza, Keitel, Macchi, New J. Phys. **12** (2010) 123005

Radiation Friction in Astrophysical Plasmas

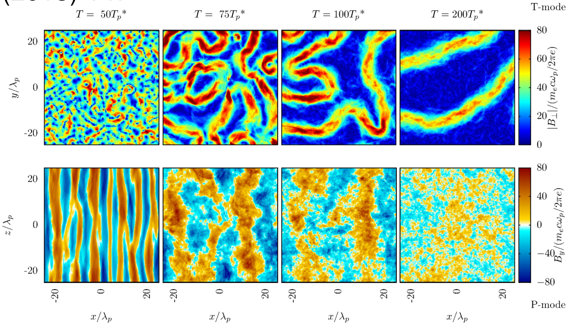
Kinetic modeling of ultra-relativistic e^+e^- plasmas including RF necessary to explain the origin of flaring from the Crab Nebula and similar objects (MHD modeling *not* adequate)

Jaroschek & Hoshino, Phys. Rev. Lett. **103** (2009) 075002;

Cerutti et al, ApJ **770** (2013) 147

Our contribution: PIC simulation of the e^+e^- current filamentation instability with RF included

M. D'Angelo et al, MNRAS (2015), in press

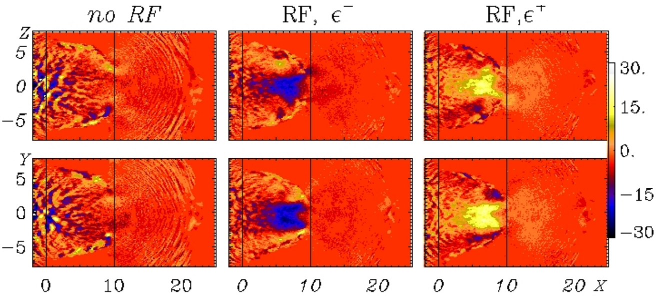


Magnetic Field Generation due to Radiation Friction

Absorption of a circularly polarized wave leads to angular momentum transfer to electrons with axial magnetic field generation (“Inverse Faraday effect”)

In superintense laser-plasma interaction RF provides friction mechanism → Gigagauss magnetic fields at $I = 10^{23}$ W cm^{-2}

Axial B-field in 3D simulations
T.Liseykina & A.Macchi, in preparation (2015)



Some conclusions and perspectives . . .

- Since 2000, progress in laser-driven ion acceleration has been obtained on various sides (cut-off energy, efficiency, energy spread . . .) in separate experiments with different mechanisms
- Laser-driven ion beams already used for ultrafast plasma diagnostic and warm dense matter production
- Reaching required performance for other applications is still challenging:
  - exploit new generation lasers (up to 10 PW power)
  - develop alternative concepts
- Experimental and theoretical research on ion acceleration has contributed to advances in plasma astrophysics ("scaled down" laboratory experiments, numerical modeling, . . .)

Funding acknowledgments

- MIUR (Italy):
  - FIR project SULDIS (“Superintense Ultrashort Laser-Driven Ion Sources”)
  - PRIN project LASHOW “Laser-Driven Shock Waves”
- supercomputing awards for access to FERMI BlueGene/Q™ supercomputer at CINECA (Italy):
- PRACE European projects LSAIL (“Large Scale Acceleration of Ions by Laser”) and PICCANTE (“Particle-In-Cell Code for AdvaNced simulations on TiEr-0 systems”)
- ISCRA Italian project TOFUSEX (“TOwards FUll-Scale simulations of laser-plasma EXperiments”)

EXTRA SLIDES

Charging and "truncation" by electron escape

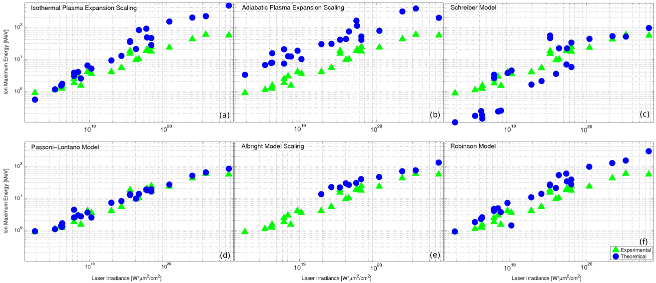
- An isolated, warm plasma in "real" 3D space gets charged due to the escape of N_{esc} electrons with energy $> U_{\text{esc}}$ (since the binding potential is limited)
- For a simple spherical emitter of radius R having N_0 electrons at T_e:

$$N_{\text{esc}} = N_0 \exp(-U_{\text{esc}}/T_e) \qquad U_{esc} = e^2 N_{\text{esc}}/R$$

- Message: cut-off energy U_{esc} (hence $\mathcal{E}_{\text{max}}$) depends on target density, size, ...
- ⚠: the system is neither steady nor in Boltzmann equilibrium, the target is neither isolated nor grounded, ...

Some models fit better than others

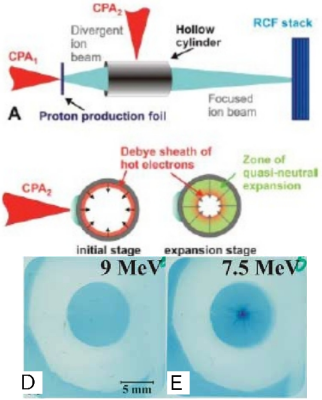
Comparison of several models with experimental energies
[Perego et al, Nucl.Inst.Meth.Phys.Res.A **653** (2011) 89]



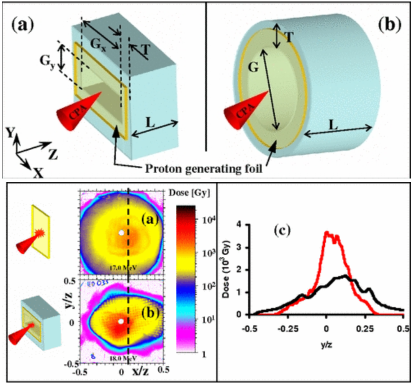
Fitting parameters: laser pulse energy, power, intensity, duration; fast electron energy, density, divergence; ion density and distribution; target thickness; . . . and various "phenomenological" quantities

Proton beam focusing and manipulation

TNSA-based “lenses” for spatial and spectral control of protons



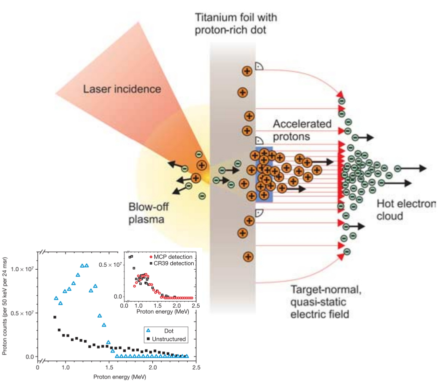
Toncian et al, Science **312** (2006) 410



Kar et al, PRL **100** (2008) 105004

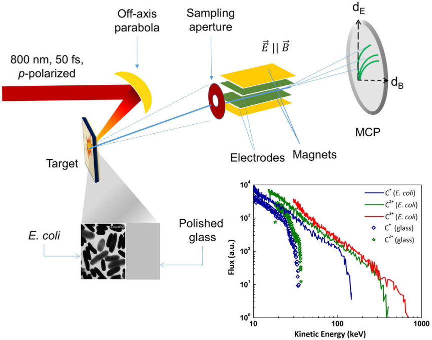
Engineering the initial distribution of ions

Hydrogen-rich microdot for monoenergetic acceleration



Schwoerer et al, Nature **439** (2006) 445

Use of *bacteria* as hydrogen-containing layer

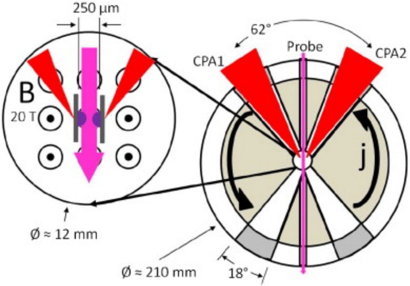


Dalui et al, Scient. Rep. **4** (2014) 1

Colliding plasmas in external magnetic fields

Higginson et al, High Energy Density Physics (2014)
doi:10.1016/j.hedp.2014.11.007

Set-up on TITAN laser (LLNL, USA) for collisions of “TNSA-like” plasmas with an external magnetic field



3D simulation campaign: LSAIL project

(Large Simulations of ion Acceleration by Intense Lasers)

- PRACE award for access to FERMI BlueGene/Q at CINECA, Italy
- Typical set-up: 4096×1792^2 grid points, 2×10^{10} particles, 16384 cores used
- Particle-In-Cell (PIC) codes:
  - ALADYN: C. Benedetti, A. Sgattoni, G. Turchetti, P. Londrillo, IEEE Trans. Plasma Science **36** (2008) 1790
  - PICCANTE: Open Source code (L.Fedeli, A.Sgattoni, S.Sinigardi, et al) `github.com/ALaDyn/piccante`

Relativistic transparency and optimal thickness

Thin plasma foil becomes transparent because of relativistic effects when

$$a_0 > \zeta \equiv \pi \frac{n_e}{n_c}\frac{\ell}{\lambda} \qquad n_c = \frac{m_e\omega^2}{4\pi e^2} \text{ (cut-off density)}$$

→ optimal thickness as trade-off between reduced mass and transparency: $a_0 = \zeta$

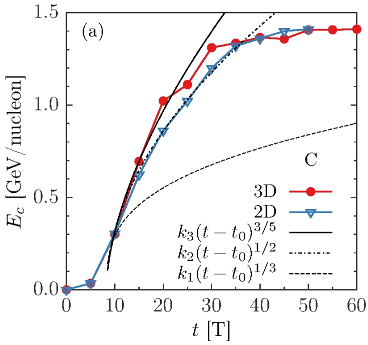
- Diamond-Like Carbon ultrathin (nm) targets

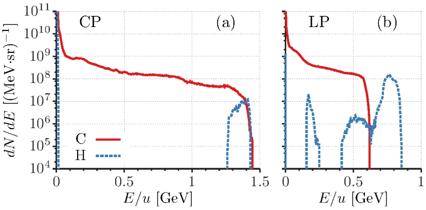
→ avoid “prepulses” to cause early target disruption

- ultrahigh-contrast systems
- wide spots (and large energy), supergaussian intensity profiles to avoid strong deformation ?

High energy gain in 3D LS simulations (CH foil)

C+H double layer foil , $n_C = (64/6)n_c$, $n_H = 8n_c$





Circular vs Linear Polarization: Higher energy and narrower H spectrum for CP

Onset of transparency stops acceleration and is faster in 3D than in 2D → similar final energy in 2D and 3D (∼1.4 GeV for CP)