Principles of Laser-Plasma Acceleration

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The vision of “collective” acceleration

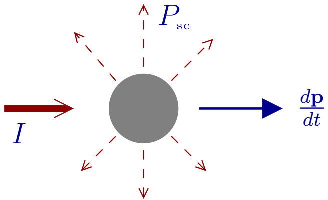
“The principles of coherent acceleration of charged particles”
V. I. Veksler, At. Energ. **2** (1957) 525

- accelerating field on each particle proportional to the number of accelerated particles
- automatic spatio-temporal synchronization between the particles and the accelerating field
- generation of quasi-neutral bunches with large numbers of particles
- the principles are largely realized in laser-plasma accelerators

Example: Coherent “Radiation Drag” Acceleration

A small particle (radius $a \ll \lambda$) undergoing Thomson Scattering of an EM wave absorbs momentum

[Landau & Lifshitz, *The Classical Theory of Fields*, ch.78 p.250 (1962)]



$$\frac{\mathrm{d}p}{\mathrm{d}t} = \sigma_T I \propto P_{sc}$$

(absorbed momentum $\propto$ scattered power in rest frame of particle)

For coherent scattering by a cluster with N $(\gg 1)$ particles

$$M \rightarrow NM$$
$$P_{sc} \rightarrow N^2 P_{sc}$$
$$\sigma_T \rightarrow N^2 \sigma_T$$

$\longrightarrow$ N-fold increase in acceleration (Veksler, 1957)

Does Ultrafast-Ultrahigh Dose Improve Therapy?

frontiers in Oncology

REVIEW
published: 17 January 2020
doi: 10.3389/fonc.2019.01563

Ultra-High Dose Rate (FLASH) Radiotherapy: Silver Bullet or Fool's Gold?

Joseph D. Wilson[1†], *Ester M. Hammond*[1†], *Geoff S. Higgins*[1†] *and Kristoffer Petersson*[1,2*†]

[1] *Department of Oncology, The Oxford Institute for Radiation Oncology, University of Oxford, Oxford, United Kingdom,*
[2] *Radiation Physics, Department of Haematology, Oncology and Radiation Physics, Skåne University Hospital, Lund, Sweden*

Laser-driven accelerators of electrons and ions provide ultra-high flux and may now test this regime

Introduction to Electron Acceleration by Plasma Waves

Plasma waves in a different frame

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A tutorial description of plasma waves in a cold plasma, with emphasis on their application in plasma-based electron accelerators, is presented. The basic physics of linear plasma oscillations and waves and the principle of electron acceleration in a plasma wave are discussed without assuming any previous knowledge of plasma physics. It is shown that estimating key parameters for plasma acceleration such as the maximum or "wave breaking" amplitude and the corresponding energy gained by electrons "surfing" the wave requires a relativistic and nonlinear analysis. This can be done with little mathematical complexity by using a Lorentz transformation to a frame co-moving at the phase velocity of the wave. The transformation reduces the problem to a second-order ordinary differential equation as originally found by Chian [Plasma Phys. **21**, 509 (1979)] so that the analysis can exploit the analogy with the mechanical motion of a particle in a potential well.

https://doi.org/10.1119/10.0001431

American Journal of Physics **88**, 723 (2020)

Nice Example of Acceleration by a Strong Wave

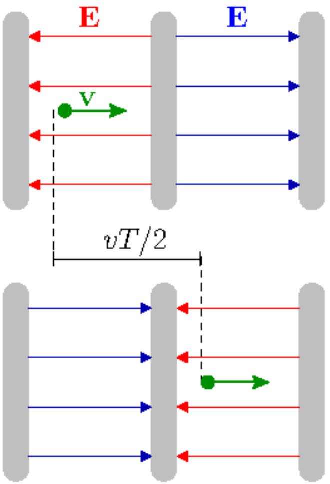
From: T.Katsouleas, *Nature* **444** (2006) 688

Looking for the Perfect Wave for Electrons

LINAC principle: a “fake” (non-propagating) wave created by localized oscillations in appropriate phase

An electron of velocity v crosses a cavity of length L within half the period T of $\mathbf{E}$-field so to “see” $\mathbf{E}$ as always accelerating

Idea: create a similar structure in a plasma where the maximum $\mathbf{E}$-field is not limited by electrical breakdown



Starting Point: Cold Plasma Oscillations

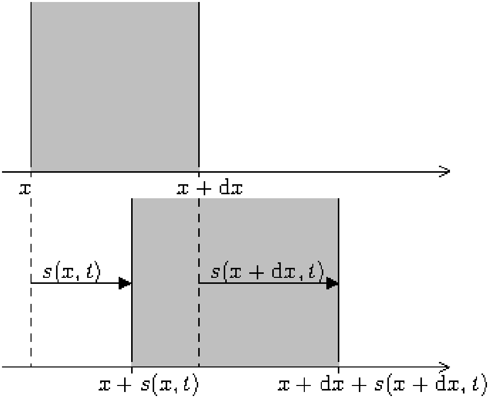
1D displacement of electrons $s(x,t)$

$v(x,t) = \partial_t s(x,t)$

Assumptions:

- $v(x,t) \gg$ thermal velocity
- immobile ions
- electrons do not overtake

General solution: localized oscillation at plasma frequency ω_p witi arbitrary profile $\tilde{s}(x)$



$$s(x,t) = \mathrm{Re}[\tilde{s}(x)\mathrm{e}^{-i\omega_p t}]$$

Starting point: cold plasma oscillations

$$n_0 \mathrm{d}x = n_e(x,t)\,[x + \mathrm{d}x + s(x+\mathrm{d}x,t) - x - s(x,t)]$$

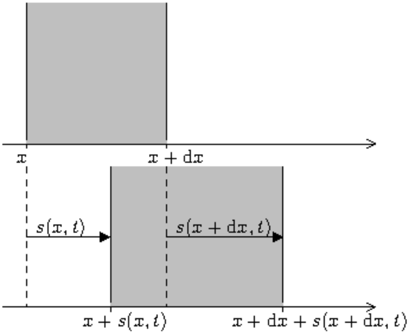
$$n_e(x,t) = \frac{n_0}{1 + \partial_x s(x,t)} \,.$$

assuming small displacements $|\partial_x s(x,t)| \ll 1$

$$n_e(x,t) \simeq n_0\,[1 - \partial_x s(x,t)] \,.$$

Electric field (from Gauss's law)

$$E_x = E_x(x,t) = 4\pi n_0 e s(x,t) \,,$$



Starting point: cold plasma oscillations

Equation of motion and its general solution

$$m_e \partial_t^2 s(x,t) = -eE_x(x,t) = -4\pi n_0 e^2 s(x,t) ,$$

$$s(x,t) = \mathrm{Re}[\tilde{s}(x)\mathrm{e}^{-i\omega_p t}] = \frac{1}{2}\left[\tilde{s}(x)\mathrm{e}^{-i\omega_p t} + \tilde{s}^*(x)\mathrm{e}^{+i\omega_p t}\right] ,$$

with the plasma frequency $\omega_p = \left(\frac{4\pi e^2 n_0}{m_e}\right)^{1/2}$

Oscillations are localized and do *not* propagate

From Fake Wave to Wake Wave

How to give a phase velocity to localized non-propagating oscillations?

Idea: let oscillations be excited by a moving perturbation (wake)

Bodensee at Bad Schachen, Lindau, Germany.
Photo by Daderot, Wikipedia, public domain.

Plasma Wake Waves

A traveling delta-kick force $f(x,t) = m_e u_0 \delta(t - x/V)$ displaces electrons by $s_0 = u_0/\omega_p$ at the overtaking time $t = x/V$
$\longrightarrow$ wake of plasma oscillations with phase velocity $v_p = V$

$$s(x,t) = \begin{cases} 0 & (t < x/V)\,, \\ s_0 \cos\left(\omega_p(t - x/V)\right) & (t > x/V)\,. \end{cases}$$

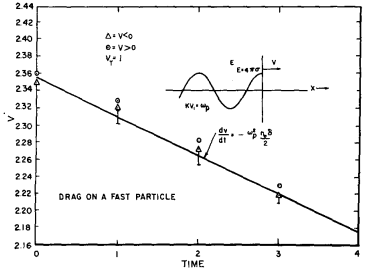


FIG. 6. The drag on a fast sheet.

Example: a charge bunch penetrating a plasma loses its energy to the wake (collective stopping)

J. Dawson, *Phys. Fluids* **5** (1962) 445

"Dawson's sheet" model - I

First plasma simulation model ever published!

J. Dawson, Phys. Fluids **5** (1962) 445

Figure from Birdsall & Langdon, *Plasma Physics via Computer Simulation* (Taylor & Francis, 1975/2004)

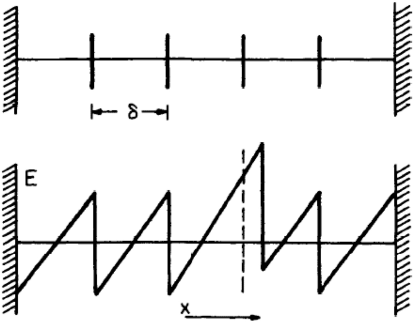
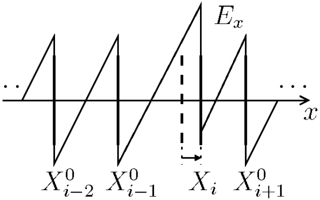


Figure 13-2a Original *Dawson* (1962) model, with thin electron sheets spaced $\delta = 1/n$ apart (in equilibrium) in a uniform positive ion background. The lower part shows $E(x)$ with one sheet displaced.

"Dawson's sheet" model - II

Each charged sheet (of position $X_i(t)$, $i = 1, \ldots, N$) is a "macro-electron" (over a neutralizing background of density n_0)



E-field on each sheet (Gauss):

$$E_i = E_x[x = X_i(t)] = 4\pi e n_0 \left[X_i(t) - X_i^{\mathrm{eq}}\right]$$

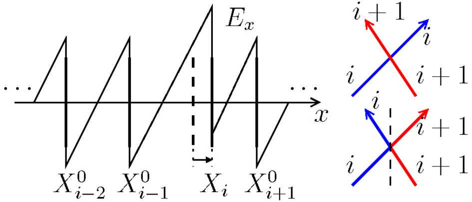
if $X_i < X_{i+1} \; \forall i$

Equation of motion (with external force f_{ext})

$$\frac{\mathrm{d}^2 X_i}{\mathrm{d}t^2} = -\frac{e}{m_e} E_x(X_i) + \frac{f_{\mathrm{ext}}}{m_e} = -\omega_p^2 \left(X_i - X_i^{\mathrm{eq}}\right) + \frac{f_{\mathrm{ext}}}{m_e}$$

"Dawson's sheet" model - III

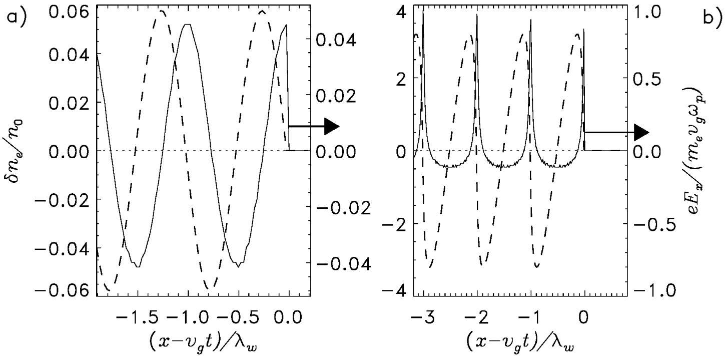
Sheet crossing is equivalent to a "reindexing" of sheets
$\longrightarrow$ swapping of indices at each timestep keeps the ordering



All nonlinear effects are in the swap!

Simulating wakes with Dawson's sheet model

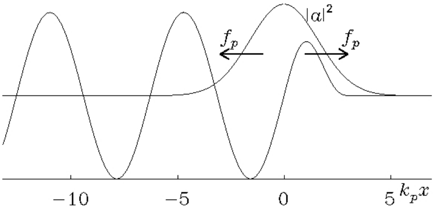
Simulation with impulsive force $f_{\text{ext}} = m_e u_0 \delta(t - x/v_g)$

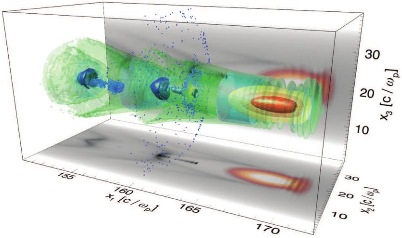


weak forcing strong forcing

Laser Wakefield

A short laser pulse
of duration $\simeq \pi/\omega_p$
excites a wake
with phase velocity
$v_p = v_{g\text{EM}} = c(1-\omega_p^2/\omega^2)^{1/2}$
T.Tajima & J.Dawson,
Phys. Rev. Lett. **43**, 267 (1979)



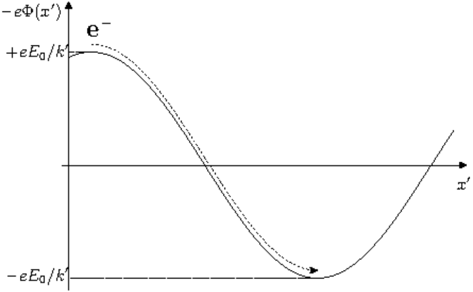


EM pressure force pushes electrons at the front and back slopes of the laser pulse

3D simulation of a laser wakefield
Fonseca et al, *Plasma Phys. Control. Fusion* **50**, 124034 (2008)

Energy Gain Estimate in the Wave Frame

In a reference frame S' moving with the phase velocity v_p with respect to the laboratory S the wave field is time-independent and can be derived by an electrostatic potential $\Phi(x')$



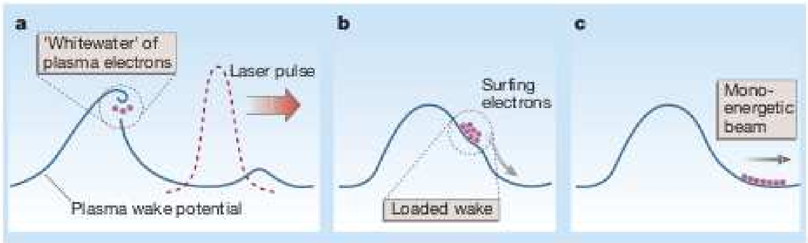
A "lucky" test electron moving from the top to the bottom of the potential hill with initial velocity $v'_{x0} = 0$ (hence $v_{x0} = v_p$ in the lab frame) will get the maximum energy gain possible $\mathscr{E}_{\max}$

Wave Amplitude Limit: Wavebreaking

The electron density must remain positive:

$$n_e = n_0 + \delta n_e > 0 \quad \Leftrightarrow \quad |\delta n_e| < n_0$$

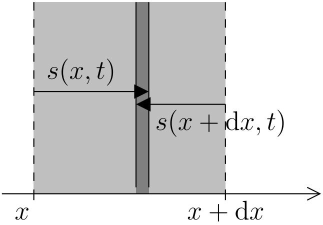
$\delta n_e \longrightarrow n_0$ as $u_0 \longrightarrow v_p$: "self-acceleration" of wave electrons
$\longrightarrow$ singularity in density profile, "breaking" of the wave
Onset of wavebreaking leads to self-injection of electrons



[T. Katsouleas, *Nature* **431** (2004) 515]

Plasma wave breaking

The electron density becomes singular when $\partial_x s(x,t) = -1$, i.e. the trajectories of electrons starting at x overlap with those starting at $x + \mathrm{d}x$



$$n_e(x,t) = \frac{n_0}{1 + \partial_x s(x,t)} \longrightarrow \infty\,.$$

The regular "hydrodynamic" structure is lost: the wave *breaks*

Note that $\partial_x s(x,t) = -1$ violates the assumption of small amplitude oscillations: a nonlinear analysis is required

Maximum Energy Estimate

- Assuming $v \simeq c$ and combining optimal injection ($v_{x0} = v_p$) with wavebreaking amplitude, Tajima & Dawson obtained

$$\mathcal{E}_{\max} = 4 m_e c^2 \gamma_p^2$$

$\gamma_p = (1 - v_p^2/c^2)^{-1/2} \gg 1$

- Objection! An incorrect wavebreaking threshold was used
- Using improved estimate from a fully nonlinear (but anlytically accessible ...) model:

$$\mathcal{E}_{\max} = 4 m_e c^2 \gamma_p^3$$

[Esarey & Pilloff, *Phys. Plasmas* **2**, 1432 (1995); Macchi *AJP* (2020)]

- Note the substantial increase by a factor γ_p

Issues: Acceleration Length, Injection, . . .

L_{acc} = how long must my plasma wave be to allow the maximum energy gain = (max energy)/(max force)

$$L_{\text{acc}} = \frac{W_{\max}}{eE_{\text{WB}}} \simeq 2\sqrt{2}\frac{c}{\omega_p}\gamma_p^{5/2} \quad \left(= \gamma_p L'_{\text{acc}} = \frac{1}{2}\lambda'_p \right) .$$

- Plasma wave length $\simeq L_{\text{acc}} \gg$ laser diffraction length: optical guiding needed (preformed channel, capillary tube, relativistic effect . . .)
- Self-injection and nonlinear regime not optimal for beam quality and mono-energetic spectrum: “external” injection needed
- . . .

The Dream Goes On . . .

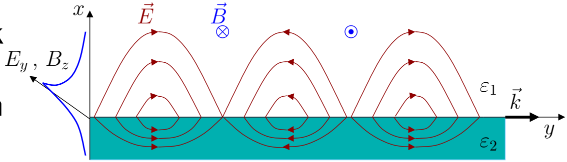
Nature **431**, issue 7008, 30 September 2004

Current energy record: 8 GeV [BELLA group at Berkeley: Gonsalves et al, *Phys. Rev. Lett.* **122**, 084801 (2019)]

Progress achieved by several groups in beam quality, stability and reproducibility, . . .

Surface Plasmon (aka Surface Plasma Wave)

SP: a building block of plasmonics (mostly studied in the *linear* regime)



SP excitation $\longrightarrow$ EM field confinement and enhancement

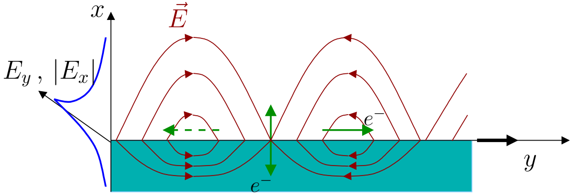
Interface between vacuum and "simple metal" (cold plasma):

$$\varepsilon_1 = 1 \qquad \varepsilon_2 = 1 - \frac{\omega_p^2}{\omega^2} = 1 - \frac{n_e}{n_c(\omega)} < -1$$

$$k = \frac{\omega}{c}\left(\frac{\omega_p^2 - \omega^2}{\omega_p^2 - 2\omega^2}\right)^{1/2} \qquad \omega < \frac{\omega_p}{\sqrt{2}} \qquad v_p = \frac{\omega}{k} < c$$

Surfin' the Surface Wave?

Can a SP accelerate electrons like a “bulk” plasma wave?

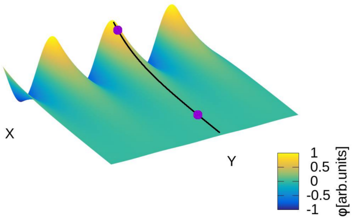


- longitudinal E-component (E_y)
- sub-luminal phase velocity $v_\mathrm{p} < c$

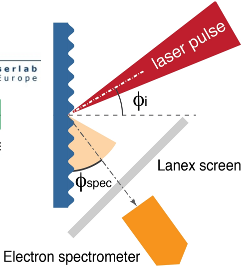
  (with $v_\mathrm{p} \to c$ when $\omega_p \gg \omega$)

→ electrons may “surf” the SP

The energy can be estimated in the wave frame as for a “bulk” plasma wave but accounting for 2D motion



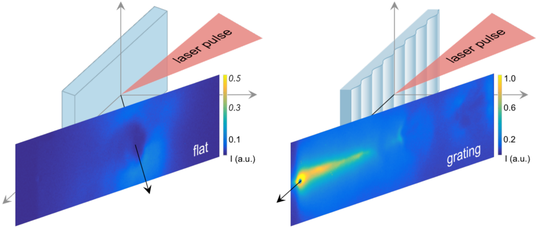
Observation of Surface Plasmon Acceleration

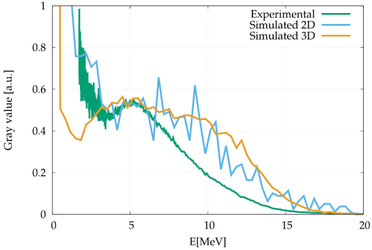


collimated ($\simeq 20^\circ$ cone) electron emission near the surface tangent ($\phi \simeq 2^\circ$)

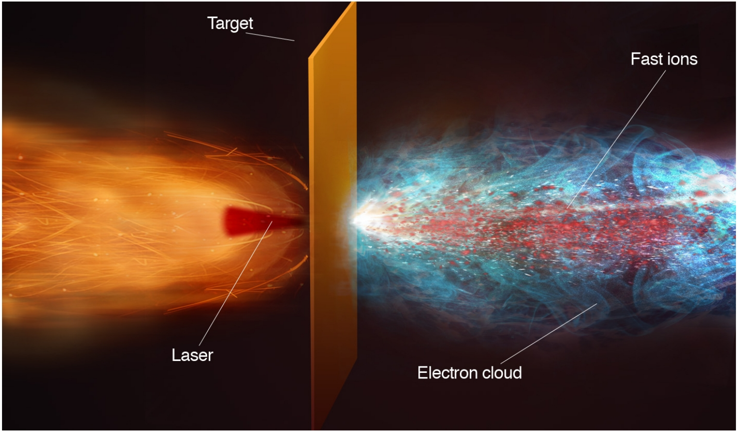
multi-MeV energy, total charge $\simeq 100$ pC (value allowed by high plasma density)

L. Fedeli et al, *Phys. Rev. Lett.* **116** (2016) 015001





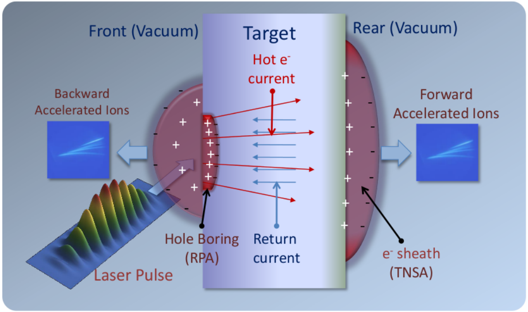
Artist's View of Ion Acceleration



A. Macchi, M. Borghesi, M. Passoni, *Rev. Mod. Phys.* **85** (2013) 571

Several mechanisms (and acronyms) are at play

Example of a thick solid target with ion acceleration on both sides because of
- Target Normal Sheath Acceleration (TNSA)
- Radiation Pressure Acceleration (RPA)



Different laser and target conditions activate new mechanisms: Relativistic Induced Transparency Acceleration (RITA), Collisionless Shock Acceleration (CSA), Magnetic Vortex Acceleration (MVA), Direct Coulomb Explosion (DCE), Break-Out Afterburner (BOA), ...

. . . and complementary efforts are required

- laser development
- target engineering
- advanced diagnostics
- massive simulation
- theory

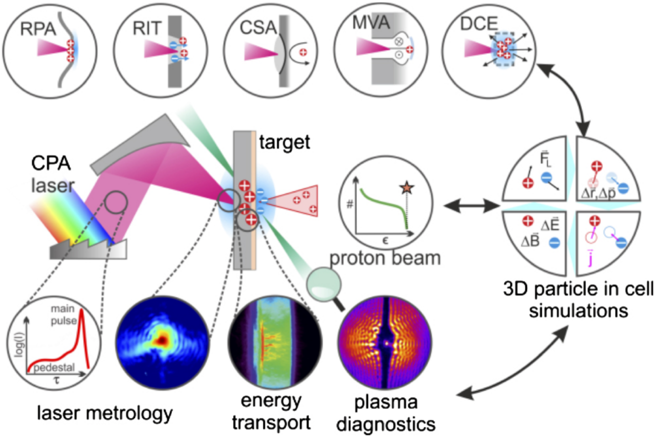


Figure: F. Albert et al, “2020 roadmap on plasma accelerators”, New J. Phys. **23** (2021) 031101

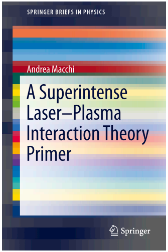
Reviews on ion acceleration (a selfish selection)

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

M. Borghesi, A. Macchi,
Laser-Driven Ion Accelerators: State of the Art and Applications,
in: *Laser-Driven Particle Acceleration Towards Radiobiology and Medicine* (Springer, 2016)

A. Macchi,
Laser-Driven Ion Acceleration,
in: *Applications of Laser-Driven Particle Acceleration*
(CRC press, 2018), arXiv:1711.06443

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



Other ion acceleration reviews

J. Schreiber, P. R. Bolton, K. Parodi,
“Hands-on” laser-driven ion acceleration: A primer for laser-driven source development and potential applications,
Rev. Sci. Instrum. **87** (2016) 071101

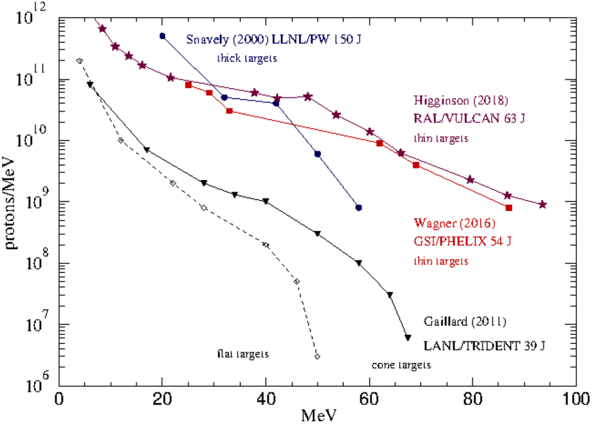
J.C. Fernández et al,
Fast ignition with laser-driven proton and ion beams,
Nucl. Fusion **54** (2014) 054006

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

M. Borghesi et al,
Fast Ion Generation by High-Intensity Laser Irradiation of Solid Targets and Applications,
Fusion Science and Technology **49** (2006), 412

The Race to Higher Proton Energy

History of highest cut-off energies observed 2000–2018



- Laser energy values given on target into focal spot (FWHM) (typically <50% of total available energy)
- pulse duration 0.5–1 ps
- different target types

Properties of Laser-Accelerated Protons

- mostly broad energy spectra (exponential-like)
- large numbers - up to 2×10^{13} protons, ~kA current
  Snavely et al, PRL **85** (2000) 2945
- charge neutralization by comoving electrons ("plasma beam")
- good collimation with energy-dependent spread (angular aperture $\sim 10° \div 30°$)
- 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 near source:
  3.5 ± 0.7 ps measured with TARANIS laser (600 fs pulse)
  Dromey et al., Nature Comm. **7** (2016) 10642

Proton Energy Deposition and Related Applications

Energy deposition by ions in matter is strongly localized at the stopping point (Bragg peak)

$\frac{d\mathscr{E}}{dx} \propto \frac{1}{\mathscr{E}^2}$ (Coulomb scattering)

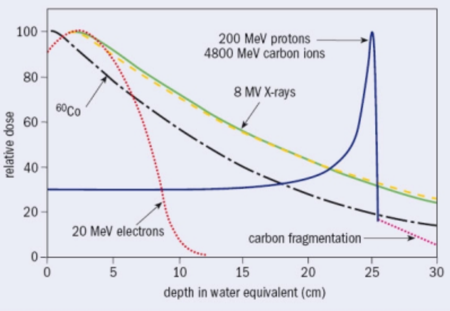


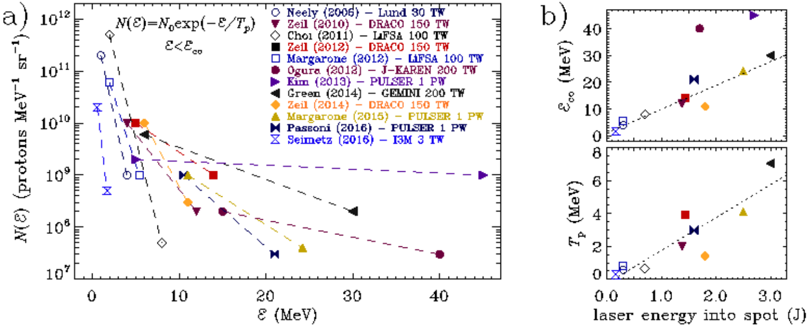
figure: Amaldi & Kraft, Rep. Prog. Phys. **68** (2005) 1861

(Foreseen) Applications:

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

A Selection of Short Pulse Results

Almost linear scaling of proton energy $\mathscr{E}$ with pulse energy



high contrast short pulses (25–40 fs) & solid targets (0.01–4.0 μm)

calibrated exponential spectra $N_p(\mathscr{E}) = N_{p0}\exp(-\mathscr{E}/T_p)$

$I = (1-5)\times10^{19}$ Wcm^{-2} (empty symbols)

$I = (0.3-2)\times10^{21}$ Wcm^{-2} (**filled** symbols)

$\mathscr{E}_{co} \simeq 9$ MeV/J

Understanding Target Normal Sheath Acceleration

TNSA is the most "robust" and investigated regime so far

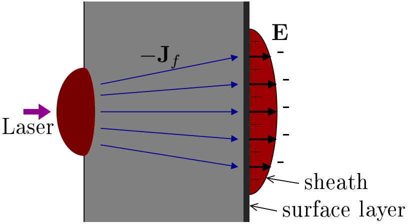
Although the sheath physics is highly complicated . . .

. . . reasonably simple models are needed to:

- infer scaling with laser & target parameters
- optimize performance

Basic "ingredients" of simple(st) model:

- fast electron generation
- sheath modeling



$\mathbf{J}_f$: fast electron current
$\mathbf{E}$: sheath field

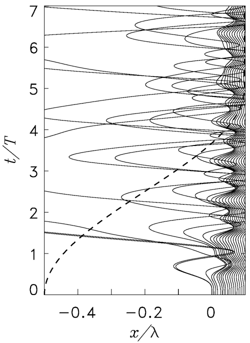
"*There are more things between cathode and anode that are dreamt in your philosophy*" (H. Raether)

Generation of “fast” electrons - 1

Short pulse interaction with solid targets

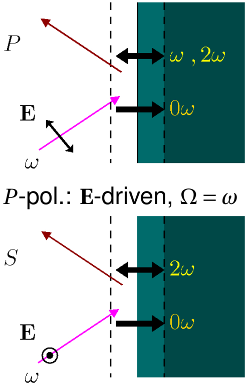
$$n_e \gg n_c = \frac{m_e \omega^2}{4\pi e^2} \text{ i.e. } \omega \ll \omega_p$$

ω_p plasma frequency, n_c cut-off or “critical” density



In the short gradient the laser-driven surface oscillations “break” and release energy to particles

Electrostatic simulation: trajectory self-intersection, *wavebreaking* and generation of “fast” electron bunches

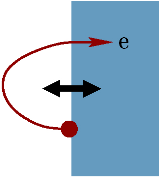


P-pol.: $\mathbf{E}$-driven, $\Omega = \omega$

S-pol.: $\mathbf{v} \times \mathbf{B}$-driven, $\Omega = 2\omega$

Generation of “fast” electrons - 2

Single particle picture: oscillating forces drag electrons into the vacuum side and push them back in the plasma after an half-cycle (strongly non-adiabatic motion)



Popular definitions:

“Vacuum heating” or “Brunel effect” if $\mathbf{E}$-driven at rate ω

[Brunel, Phys. Rev. Lett. **59** (1987) 52; Phys. Fluids **31** (1988) 2714]

“$\mathbf{J}\times\mathbf{B}$” heating if $\mathbf{v}\times\mathbf{B}$-driven at rate 2ω

[Kruer & Estabrook, Phys. Fluids **28** (1985) 430]

Empirical “ponderomotive” scaling for fast electron temperature

$$T_{\mathrm{f}} = m_e c^2\left((1+a_0^2/2)^{1/2}-1\right) \qquad a_0 = 0.85\left(\frac{I_L\lambda_L^2}{10^{18}\ \mathrm{Wcm^{-2}}\mu\mathrm{m}^2}\right)^{1/2}$$

"Elementary" TNSA modeling: static case

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 $\Delta\Phi$

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

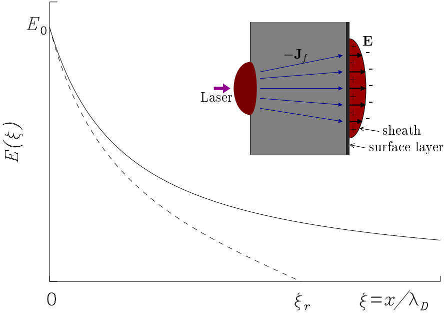
Energy gain by a "test" ion in the static sheath:

$$\mathscr{E}_{\text{max}} = Ze\Delta\Phi \simeq ZT_e$$

⚠ : exact treatment yields

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

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



Charging and “truncation” by electron escape

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

$$N_{\rm esc} = N_0 \exp\left(-\frac{U_{\rm esc}}{T_e}\right) \qquad U_{\rm esc} = \frac{e^2 N_{\rm esc}}{R}$$

- Message: cut-off energy $U_{\rm esc}$ (hence $\mathscr{E}_{\rm max}$) depends on target density, size, ...

⚠: the system is neither steady nor in Boltzmann equilibrium, the target is neither isolated nor grounded, ...

"Elementary" TNSA modeling: dynamic case

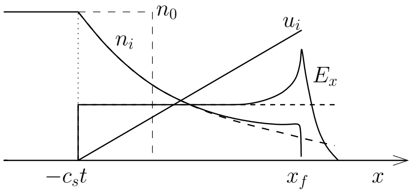
Plasma expansion model: isothermal rarefaction wave solution "patched" at the ion front where quasi-neutrality breaks down

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

⚠: 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)

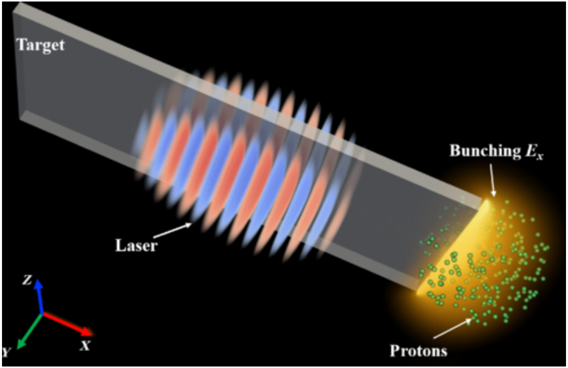


Open Issues with TNSA

- Need of “robust” models (not too empirical . . .) to explain scaling of cut-off energy (different for “long” (>ps) and “short” (<ps) pulses)
- Is $\sim$100 MeV reachable with “table-top” systems?
- spectrum is exponential-like despite initial “localization” of protons (low proton number at cut-off)
- solid targetry not optimal for high repetition rate
- . . .

SPW-based “Peeler” Proton Acceleration

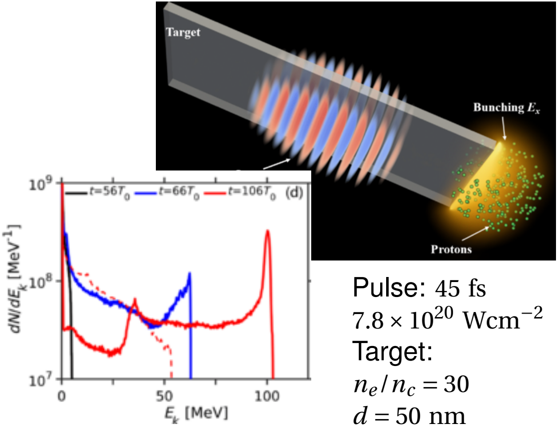
“A fs laser (red and blue) is incident on the edge of a micron-thick tape (grey) [. . .] Abundant electrons are trapped in the longitudinal potential well and accelerated by the SPW field”



X.Shen, A.Pukhov, B.Qiao, Phys. Rev. X **11** (2021) 041002

SPW-based “Peeler” Proton Acceleration

“[. . .] at the rear edge a longitudinal bunching field is established (yellow). Protons (green dots) are simultaneously accelerated and leading to a highly monoenergetic beam.”



Pulse: 45 fs

7.8×10^{20} Wcm^{-2}

Target:

$n_e/n_c = 30$

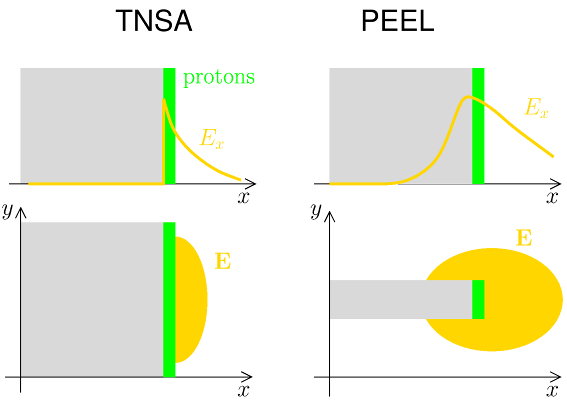
$d = 50$ nm

X.Shen, A.Pukhov, B.Qiao, Phys. Rev. X **11** (2021) 041002

Origin of Monoenergetic Proton Spectra

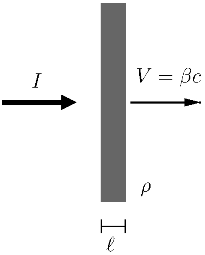
TNSA: fast electrons are less than protons in the layer which screen the $\mathbf{E}$-field producing a sharp gradient

PEEL: protons are less than fast electrons and the space charge $\mathbf{E}$-field on the proton layer is spatially "smooth".



All protons experience almost the same field
$\longrightarrow$ monoenergetic acceleration

Light Sail boosted by radiation pressure

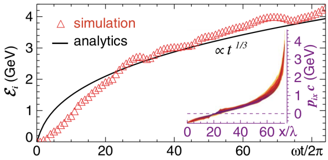


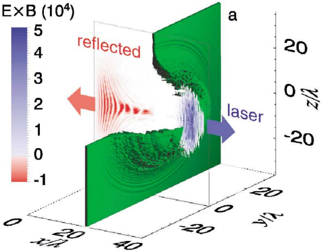
EoM for a plane mirror of finite mass

$$\frac{\mathrm{d}(\gamma\beta)}{\mathrm{d}t} = \frac{2}{\rho\ell c^2} I\left(t - \frac{X}{c}\right)\frac{1-\beta}{1+\beta} \qquad \frac{\mathrm{d}X}{\mathrm{d}t} = \beta c$$

Note: same equation as “radiation drag” motion

Analytical solution “observed” in simulations of thin foil acceleration at $\sim 10^{23}\ \mathrm{Wcm}^{-2}$

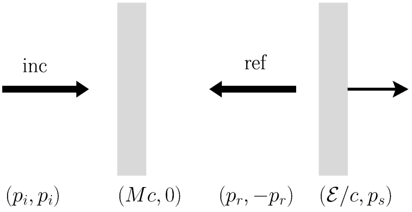




Esirkepov et al, *Phys. Rev. Lett.* **92** (2004) 175003

Light Sail energy from conservation laws

Conservation of 4-momenta in "collision" between laser pulse and moving mirror (mass $M = \rho\ell$)



$$\begin{aligned} p_i + mc &= p_r + \mathscr{E}/c \\ p_i &= -p_r + p_s \end{aligned}$$

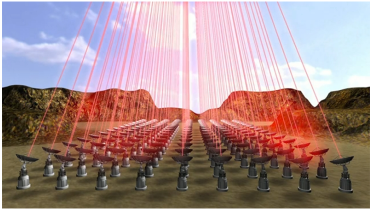
Using $\mathscr{E}^2 = M^2c^2 + p_s^2$ and $p_i = \int_0^\infty \frac{I(t')}{c} dt' \equiv \frac{Mc}{2}\mathscr{F}$

energy $\quad \frac{\mathscr{E}}{Mc^2} = \frac{\mathscr{F}^2}{2(\mathscr{F}+1)} \quad \left(\simeq \frac{\mathscr{F}^2}{2} \text{ for } \beta = \frac{p_s c}{\mathscr{E}} \ll 1\right)$

efficiency $\quad \eta = \frac{\mathscr{E}}{p_i c} = \frac{2\beta}{1+\beta} \longrightarrow$ 100% in the $\beta \to 1$ limit

Foreseen laser sailing . . .

R.Forward (1964)
G.Marx (1966)



Breakthrough Starshot (2016)

breakthroughinitiatives.org

Critical analysis of (un)feasibility:

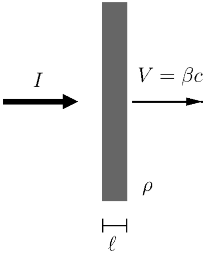
H.Milchberg, Phys. Today, 26 April 2016

Light Sail with extreme light on nanofoils

Energy/nucleon & efficiency from the 1D mirror model

(τ_p: laser pulse duration)

$$\mathscr{F} = \frac{2I\tau_p}{\rho\ell} = \frac{Z}{A}\frac{m_e}{m_p}\frac{a_0{}^2}{\zeta}\omega\tau_p \qquad \left(\zeta = \pi\frac{n_e}{n_c}\frac{\ell}{\lambda}\right)$$



Optimal thickness $a_0 \simeq \zeta$ at threshold of relativistic transparency

$$\mathscr{E}_{\max} \simeq 2\pi^2\frac{(m_e c)^2}{m_p}\left(\frac{Z}{A}\frac{c\tau_p}{\lambda}a_0\right)^2$$

$\ell \simeq 10$ nm , $I \simeq 1.6 \times 10^{21}$ W cm^{-2} ($a_0 = 22$) , $\tau_p = 40$ fs

$\longrightarrow \quad \mathscr{E}_{\max} \simeq 150$ MeV , $\eta \simeq 50\%$

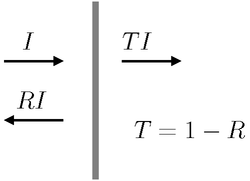
Coherent motion of the sail $\longrightarrow$ mononergetic ion spectrum

A dream ion beam? ...

Transparency of ultrathin plasma foil

1D model with relativistic nonlinearity

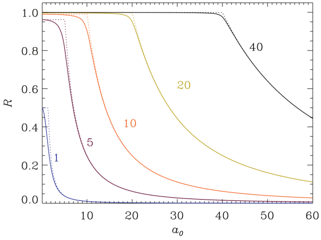
$$n_e(x) \simeq n_0 \ell \delta(x) \qquad (\ell\text{: foil thickness})$$



[V.A.Vshivkov et al, Phys. Plasmas **5** (1996) 2727]

Nonlinear reflectivity:

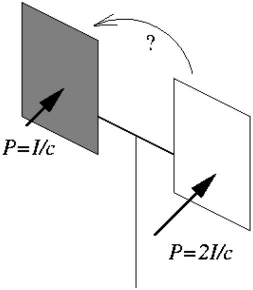
$$R \simeq \begin{cases} 1 & (a_0 < \zeta) \\ \dfrac{\zeta^2}{a_0{}^2} & (a_0 > \zeta) \end{cases} \qquad \zeta \equiv \pi \frac{n_0 \ell}{n_c \lambda}$$



The transparency threshold $a_0 \simeq \zeta$ depends on areal density $n_0 \ell$

(note: it is *not* $n_e < n_c \gamma$ with $\gamma = (1 + a_0^2)^{1/2}$)

Suppress heating to make light pressure dominant



The "Optical Mill" (Crookes radiometer) rotates in the *opposite* way to that suggested by the imbalance of light pressure between white (reflecting) and black (absorbing) faces

$$P = (1+R)\frac{I}{c}$$

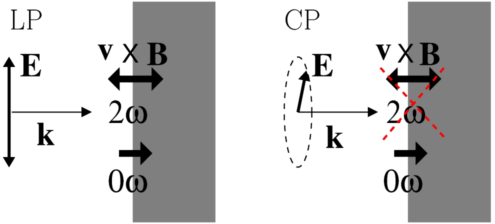
(white: $R \simeq 1$, black: $R \simeq 0$)

This is because the *thermal* pressure dominates due to stronger heating of the black face (in imperfect vacuum)
How to reduce heating in superintense laser interaction?

Circular polarization quenches heating

Radiation pressure must overcome the fast electrons pressure
Circular Polarization (CP) & normal incidence:
the 2ω component of the $\mathbf{v} \times \mathbf{B}$ force vanishes
→ longitudinal oscillations and electron heating are suppressed

Ions respond smoothly to steady force:
Radiation pressure dominates the interaction



[Macchi et al, Phys. Rev. Lett. **95** (2005) 185003]

Recent Results: Carbon Ion Acceleration

PHYSICAL REVIEW LETTERS **127**, 194801 (2021)

Featured in Physics

Selective Ion Acceleration by Intense Radiation Pressure

A. McIlvenny,[1,†] D. Doria,[1,2] L. Romagnani,[1,3] H. Ahmed,[1,4] N. Booth,[4] E. J. Ditter,[5] O. C. Ettlinger,[5] G. S. Hicks,[5] P. Martin,[1] G. G. Scott,[4] S. D. R. Williamson,[6] A. Macchi,[7,8] P. McKenna,[6] Z. Najmudin,[5] D. Neely,[4,*] S. Kar,[1] and M. Borghesi[1,‡]

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[8]*Dipartimento di Fisica Enrico Fermi, Università di Pisa, Pisa 56127, Italy*

GEMINI laser (RAL/CLF, UK) $\tau_p = 45$ fs, $I = 4.5 \times 10^{20}$ W cm^{-2}

$2-100$ nm thick C foils (H impurities removed)

33 MeV/nucleon C^{6+} energy ions observed

(only suitable driver for FLASH studies using C ions?)

Public Coverage

physicsworld

particle therapy

PARTICLE THERAPY | RESEARCH UPDATE

Intense radiation pressure enables selective acceleration of carbon ion beams

07 Dec 2021

Physics Today **75**, 1, 19 (2022); https://doi.org/10.1063/PT.3.4916

Mirror

Irish boffins' laser to help beat cancer

A laser selectively kicks carbon out of a foil

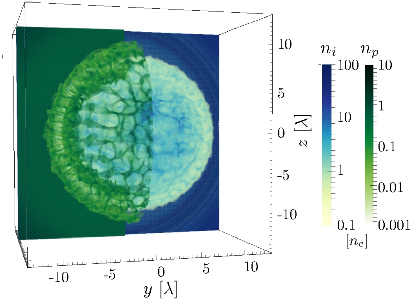
Experiments and simulations show how the shape of a laser's profile determines which target atoms make up the resulting ion beam.

Physics

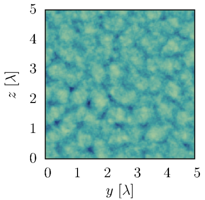
A New Trick to Make Short-Pulse Ion Beams

A new laser technique could lead to ultrashort-pulse, high-energy ion beams for medical use.

Light Sail Rayleigh-Taylor instability



3D light sail simulation: formation of net-like structures with size $\sim \lambda$ (laser wavelength) and $\sim$ hexagonal shape



two-species target: H^+, C^{6+}

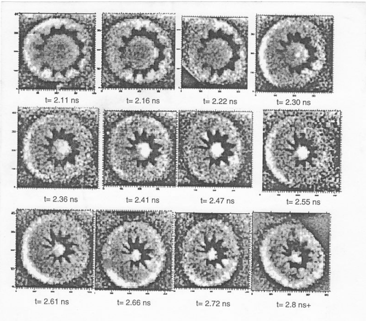
Interpretation: Rayleigh-Taylor instability driven by light pressure

Sgattoni et al, Phys. Rev. E **91** (2015) 013106

Rayleigh-Taylor Instability in space and lab

Crab Nebula (Hubble)

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



ICF implosion, 1995

Exagon formation in RTI is an example of “spontaenous symmetry breaking” in a classical system

S.I.Abarzhi, PRE **59** (1999) 1729

Relativistically Induced Transparency Acceleration

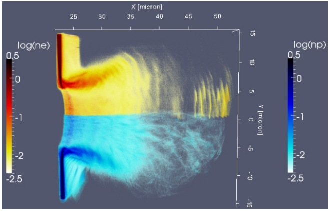
Many effects contribute to RIT: target heating & expansion, 3D bending & rarefaction, instabilities . . .

PIC simulations (*) are necessary for a complete picture

RITA is a complex scenario: several acceleration mechanisms are activated and may cooperate to yield high energy ions (typically with broad spectra and maximum energy off-axis)

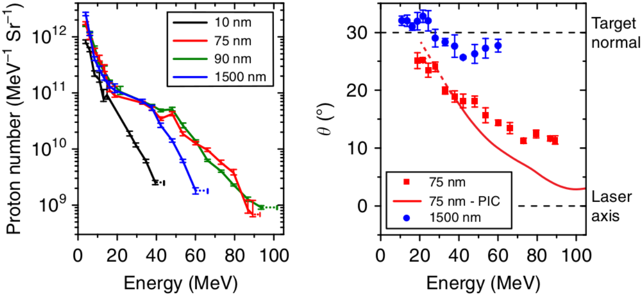
* Note: 3D is required for realistic predictions

3D PIC simulation of laser interaction with a thin target showing breakup to transparency
[A. Sgattoni, AlaDyn code]



Example: >94 MeV protons from RITA

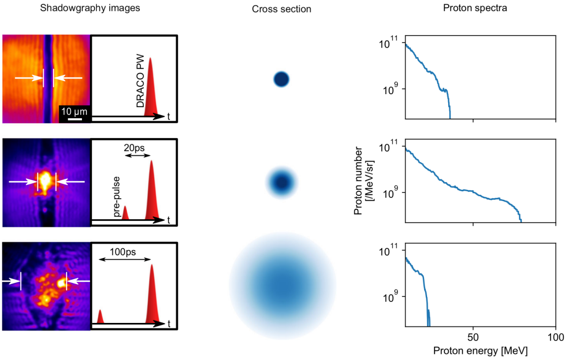
VULCAN laser, $I = 3 \times 10^{20}$ W cm^{-2}, $\tau_p = 900$ fs, plastic foil targets
Analysis based on simulations outlines a hybrid TNSA-RPA regime enhanced by magnetic collimation of fast electrons



Higginson et al. Nature Comm. **9** (2018) 724

Cryogenic hydrogen targets: experiments

- Continous “flowing” target ⟶ high repetition rate
- moderate density ⟶ enhanced laser coupling
- pure hydrogen content ⟶ pure proton beam



Optimizing jet width and prepulse for density shaping yields up to 80 MeV protons (DRACO laser, 30 fs, 5×10^{21} Wcm^{-2})

Rehwald et al, *Nature Comm.* **14** (2023) 4009

Conclusions & Outlook