High Field Plasmonics and Laser-Plasma Acceleration

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Photonics Ireland 2015, Cork, 1 September 2015

Outline

- Why laser-plasma accelerators?
- High-field femtosecond "relativistic" plasmonics
  - laser-plasmon coupling in grating targets
  - electron acceleration by surface plasmons
  - enhancement of proton acceleration
- Unipolar picosecond surface waves
  - generation and observation
  - application to proton post-acceleration
- "Light sail" acceleration (with plasmonic effects)

Many collaborators will be introduced later . . .

Lasers for particle acceleration?

Current intensity record: $I \simeq 10^{25}$ W m^{-2} with $\lambda \simeq 0.8\ \mu$m

$\rightarrow$ $eE \simeq 0.85$ PeV m^{-1} $\sim 10^6$ times the value in a particle accelerator!

Electron dynamics is strongly relativistic

$(a_0 = \frac{p_{\text{osc}}}{m_e c} = \frac{eE}{m_e \omega c} \simeq 22)$

BUT: direct laser acceleration is not easy, because

- laser field is (mainly) transverse
- laser pulse travels at c: dephasing with massive particles moving at $\lesssim c$

$\rightarrow$ use plasma as a transformer into accelerating electrostatic fields

The principle of collective acceleration

Early vision and definition:
"coherent" acceleration
V. I. Veksler, At. Energ. **2** (1957) 525

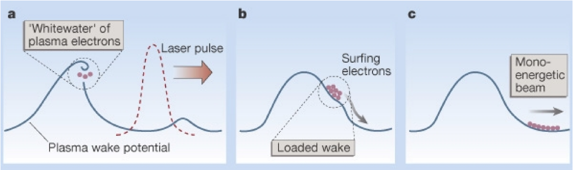
- accelerating field on each particle proportional to the number of accelerated particles
- automatic synchrony between the particles and the accelerating field
- field localization in the region where the particles are

Realization in a plasma: accelerating field created by collective charge displacement

Example: electron acceleration in laser wakefields

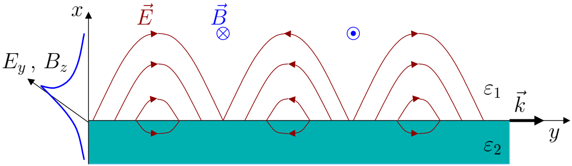
An intense laser pulse traveling at
$v_g = c(1 - \omega_p^2/\omega^2)^{1/2}$
creates a wake of
longitudinal plasma oscillations
with phase velocity $v_f = v_g \lesssim c$
$\rightarrow$ relativistic electrons may "surf"
the wake wave with little
dephasing

Figures from:
T.Katsouleas,
Nature **431** (2004) 515;
444 (2006) 688



Surface plasmons for electron acceleration?

Surface plasmons (aka surface waves) propagate along the interface between vacuum and simple metal or plasma



$$\varepsilon_1 = 1 \quad \varepsilon_2 = 1 - \frac{\omega_p^2}{\omega^2} = 1 - \frac{n_e}{n_c(\omega)} \qquad \left(n_c = \frac{m_e \omega^2}{4\pi e^2} \right)$$

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

The longitudinal field component (E_y) can accelerate electrons!

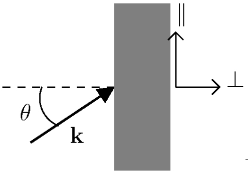
How to excite intense SP with laser pulses?

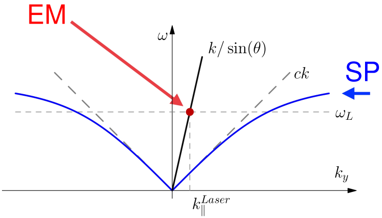
Issue 1: coupling with EM wave requires phase matching:

$\varphi_{\text{EM}} = \varphi_{\text{SP}}$ where $\varphi = \mathbf{k}_{\parallel} \cdot \mathbf{r} - \omega t$

No matching with EM wave at a plane interface:

$$\omega = ck = \frac{ck_{\parallel}}{\sin\theta}$$





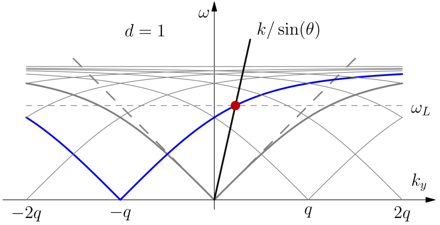
Issue 2: a theory of relativistic SP is not known - and longitudinal waves may “break” at high amplitudes!

Some evidence for relativistic SP from simulations

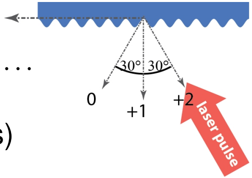
[Macchi et al, Phys. Rev. Lett. **87** (2001) 205004;
Raynaud et al, Phys. Plasmas **14** (2007) 092702]

Phase matching in periodic structures

In a spatially periodic medium (period d) the "replica"[1] of $\omega_{SP}(k_\parallel)$ allows phase matching
Resonant coupling with EM wave is possible in a grating at an angle of incidence



$$\frac{\omega}{c}\sin\theta_{res} \pm nq = k_{\parallel SP}(\omega) \qquad q = \frac{\pi}{d} \qquad n = 1, 2, \ldots$$

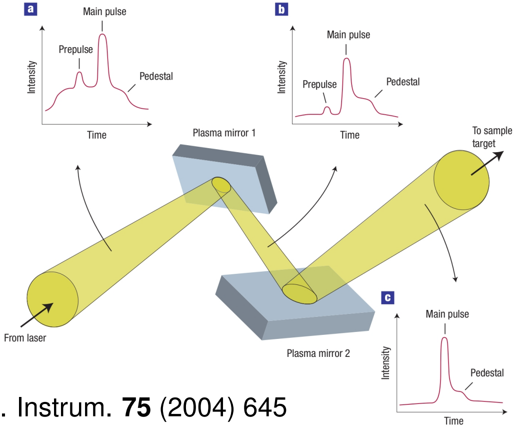


($\omega_{SP}(k_\parallel)$ weakly changes for shallow gratings)

[1] equivalent to folding in the Brillouin zone (Floquet-Bloch theorem)

Need for ultrashort and “ultraclean” pulses

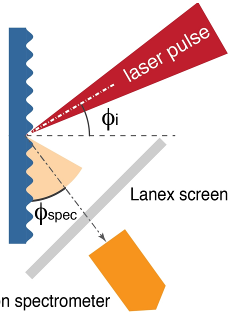
Ultrashort pulse duration (< 100 fs) and prepulse suppression by the use of ionization-based plasma mirrors are necessary to preserve grating surface until the short pulse interaction



Plasma mirrors:
B. Dromey et al, Rev. Sci. Instrum. **75** (2004) 645
C. Thaury et al, Nature Physics **3** (2007) 424
figure from P. Gibbon, *ibid.* 369

Experimental set-up for electrons

LaserLAB experiment at SLIC, CEA Saclay

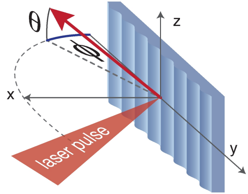


Laser UHI, 28 fs, 5×10^{19} W cm^{-2}
contrast $\sim 10^{12}$
Grating:
- $\theta_{\text{res}} = 15^\circ - 30^\circ - 45^\circ$
- depth $\delta = 0.3\ \mu$m

Diagnostics:
- CMOS-based electron spectrometer
- LANEX screen for electron imaging

L. Fedeli, A. Sgattoni, G. Cantono, D. Garzella, F. Réau, I. Prencipe, M. Passoni, M. Raynaud, M. Květon, J. Proska, A. Macchi, T. Ceccotti, "Electron acceleration by relativistic surface plasmons in laser-grating interaction", arXiv:1508.02328

Electron angular distribution

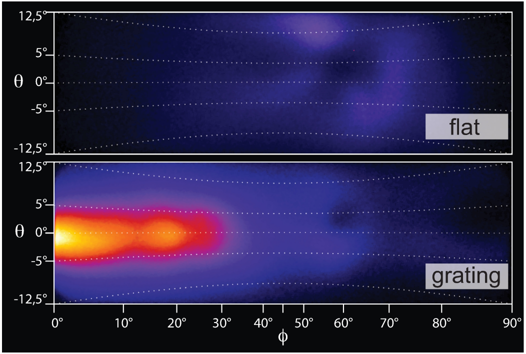


Target: 10 μm Mylar

$\phi_{\text{inc}} = \phi_{\text{res}} = 30^\circ$

Angular spread

$\Delta\phi \simeq 20^\circ$

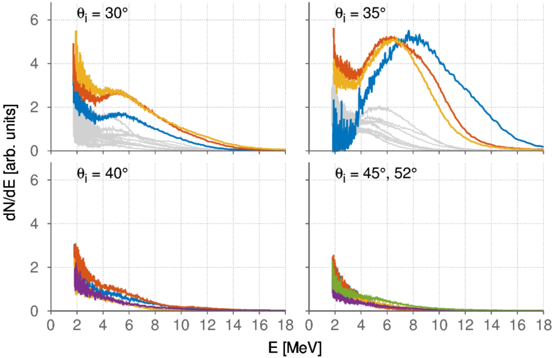


With gratings: collimated electron beam near the surface

Shot-to-shot fluctuations $\delta\phi \sim \delta\theta \simeq 5^\circ$ due to non-perfect planarity of foil target

Electron energy spectra

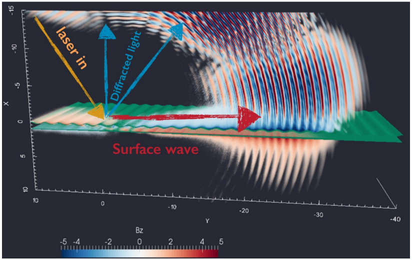
Near resonance ($\phi_{\text{inc}} = 30° - 35°$) with spectrometer close to tangent $\phi_{\text{spec}} \simeq 2°$: strongly non-Maxwellian spectrum with peak at $6-8$ MeV, cut-off at $15-18$ MeV

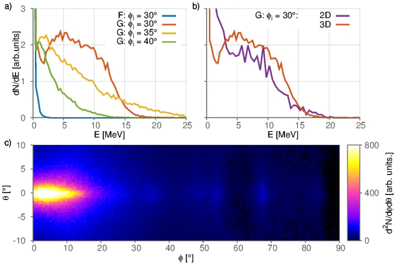


Spectrum variability (gray lines) related to beam direction fluctuations due to the small acceptance angle of the spectrometer

3D simulations of the experiment

Fully kinetic, EM Particle-In-Cell simulations with PICcante open source code[2] on 16384 cores of BlueGene/Q FERMI at CINECA, Italy



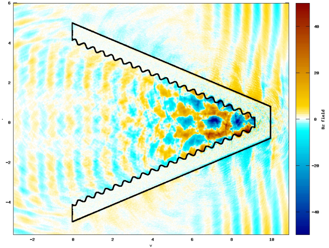


Simulations confirm excitation of relativistic SP and reproduce measurements quantitatively and in detail!

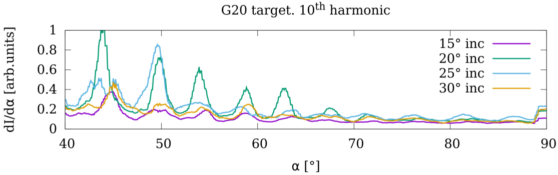
[2] available at http://aladyn.github.io/piccante

Perspectives for high field plasmonics

The experimental evidence for relativistic SP suggests applications also taking inspiration from “ordinary” (low field) plasmonics:
tapered waveguide for light
nano-focusing and amplification
(Original plasmonic concept:
M.Stockman, PRL **93** (2004) 137404)

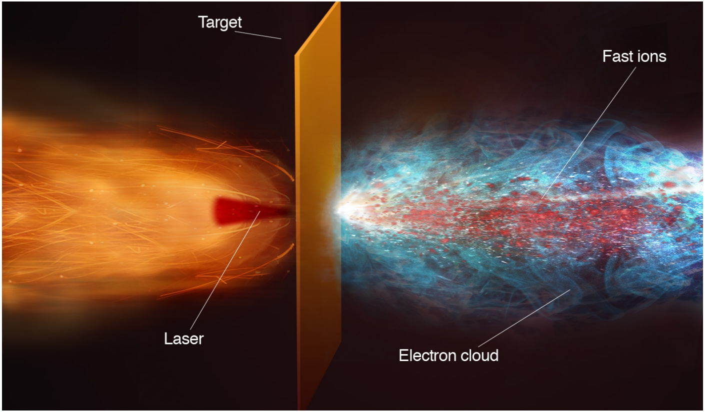


Plasmonic enhancement and angular selection of high harmonics from gratings



PICcante simulations by L. Fedeli

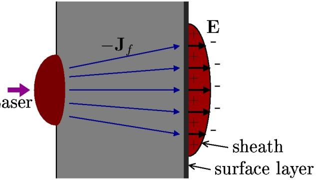
Proton acceleration from solid targets

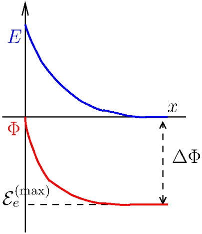


A. Macchi, M. Borghesi, M. Passoni, "Ion acceleration by superintense laser-plasma interaction", Rev. Mod. Phys. **85** (2013) 751-793

Sheath acceleration of protons

Target Normal Sheath Acceleration (TNSA) mechanism: "fast" ($\mathscr{E}_e \sim \mathrm{MeV}$) electrons crossing the target generate a sheath where the charge-separation field $\mathbf{E}$ accelerates protons in a surface layer





- Potential drop is proportional to electron energy $e\Delta\Phi = \mathscr{E}_e^{(\max)}$ (sheath potential must confine electrons)

- Number of protons equals that of fast electrons (to restore charge neutrality)

$\rightarrow$ increase electrons energy and number to enhance TNSA

Experiment: TNSA enhancement in grating targets

PRL **111,** 185001 (2013) PHYSICAL REVIEW LETTERS week ending 1 NOVEMBER 2013

Evidence of Resonant Surface-Wave Excitation in the Relativistic Regime through Measurements of Proton Acceleration from Grating Targets

T. Ceccotti,[1,*] V. Floquet,[1] A. Sgattoni,[2,3] A. Bigongiari,[4] O. Klimo,[5,6] M. Raynaud,[7] C. Riconda,[4] A. Heron,[8] F. Baffigi,[2] L. Labate,[2] L. A. Gizzi,[2] L. Vassura,[9,10] J. Fuchs,[9] M. Passoni,[3] M. Květon,[5] F. Novotny,[5] M. Possolt,[5] J. Prokůpek,[5,6] J. Proška,[5] J. Pšikal,[5,6] L. Štolcová,[5,6] A. Velyhan,[6] M. Bougeard,[1] P. D'Oliveira,[1] O. Tcherbakoff,[1] F. Réau,[1] P. Martin,[1] and A. Macchi[2,11,†]

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[7]*CEA/DSM/LSI, CNRS, Ecole Polytechnique, 91128 Palaiseau Cedex, France*
[8]*CPHT, CNRS, Ecole Polytechnique, 91128 Palaiseau Cedex, France*
[9]*LULI, UMR7605, CNRS-CEA-Ecole Polytechnique-Paris 6, 91128 Palaiseau, France*
[10]*Dipartimento SBAI, Università di Roma "La Sapienza," Via A. Scarpa 14, 00161 Roma, Italy*
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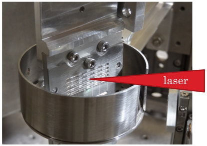
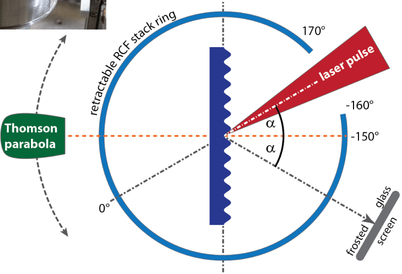
T. Ceccotti et al, Phys. Rev. Lett. **111** (2013) 185001

Experimental set-up for protons

LaserLAB experiment at SLIC, CEA Saclay
laser UHI, 28 fs, 5×10^{19} W cm^{-2}, contrast $\sim 10^{12}$



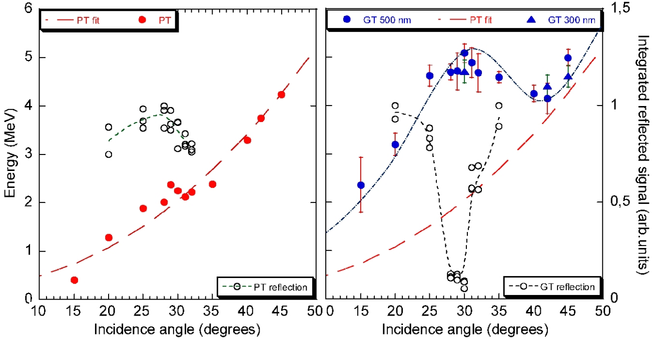


Grating:
- $d = 2\lambda \rightarrow \theta_{\text{res}} = 30^\circ$
- depth $\delta = 0.3 - 0.5\mu$m

Diagnostics:
- Thomson Parabola for proton detection
- Radio-Chromic Film (RCF) "ring" for radiation emission at any angle
- Reflected light

Plane target vs grating: resonant enhancement

Proton energy cut-off $\mathscr{E}_{\text{max}}$ and reflected light vs incidence angle:
- broad maximum (minimum) around SP resonance ($\theta_{\text{res}} = 30^\circ$)
- $\sim$2.5X enhancement in $\mathscr{E}_{\text{max}}$ at θ_{res}, $\sim$2 at small angles



PT: plane target
GT: grating target
- ● $\mathscr{E}_{\text{max}}$, GT, $\delta = 0.5\ \mu$m
- ▲ $\mathscr{E}_{\text{max}}$, GT, $\delta = 0.3\ \mu$m
- ● $\mathscr{E}_{\text{max}}$, PT
- ○ reflected light

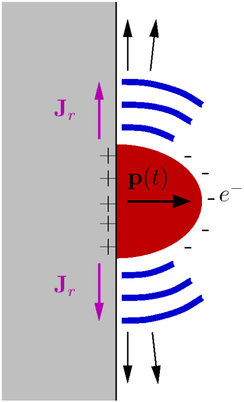
Generation of unipolar surface waves by fast electrons

TNSA scenario: fast-electron transient charge separation generates an electric dipole $\mathbf{p}(t)$

$\rightarrow$ generation of EM waves by the transient sheath as an antenna

Surface waves should drive return current J_f for neutralizing negative charge loss (some $\sim 10^{10} - 10^{12}$ electrons escape in vacuum)

$\rightarrow$ "unipolar" current pulses propagate on the surface



First observation of unipolar pulse

PRL **102,** 194801 (2009) PHYSICAL REVIEW LETTERS week ending 15 MAY 2009

Laser-Driven Ultrafast Field Propagation on Solid Surfaces

K. Quinn,[1,*] P. A. Wilson,[1] C. A. Cecchetti,[1,†] B. Ramakrishna,[1] L. Romagnani,[1] G. Sarri,[1] L. Lancia,[2] J. Fuchs,[2] A. Pipahl,[3] T. Toncian,[3] O. Willi,[3] R. J. Clarke,[4] D. Neely,[4] M. Notley,[4] P. Gallegos,[4,5] D. C. Carroll,[5] M. N. Quinn,[5] X. H. Yuan,[5] P. McKenna,[5] T. V. Liseykina,[6,‡] A. Macchi,[7] and M. Borghesi[1]

[1]*Department of Physics and Astronomy, Queen's University Belfast, Belfast BT7 1NN, United Kingdom*
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[7]*CNR/INFM/polyLAB, Dipartimento di Fisica "E. Fermi," Pisa, Italy*
(Received 28 January 2009; published 14 May 2009)

K. Quinn et al, Phys. Rev. Lett. **103** (2009) 194801

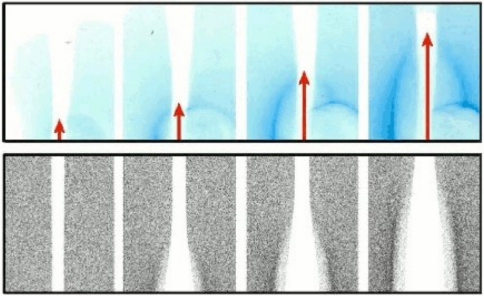
Imaging of field propagation along a wire target

Time-resolved imaging of the electric field via the proton probing technique

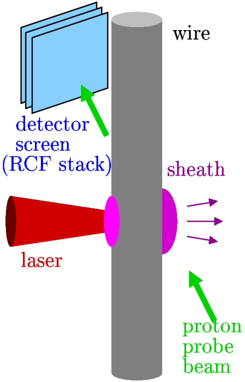
M. Borghesi et al, PoP **9** (2002) 2214

K. Quinn et al, RSI **80** (2009) 113506

Experimental proton images



Proton tracing simulations



Field front propagates along the wire with velocity $v_f = 0.96 \pm 0.04c$

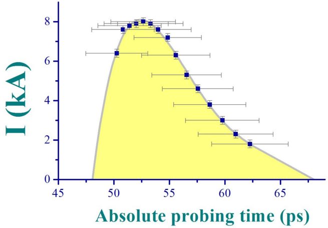
Electric pulse characterization

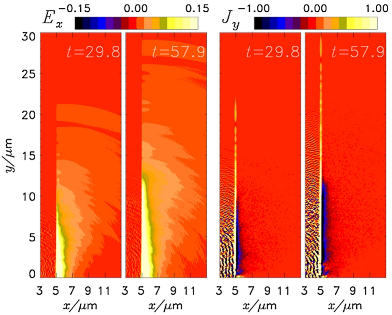
Measurement of radial field $E_s(t)$ and propagation velocity brings total current in the pulse

$$I(t) = \frac{\pi r_w^2}{2} \upsilon_f E_s(t)$$

$$I_{\text{peak}} \simeq 8\ kA\ , \qquad \tau_I \simeq 10\ \text{ps}$$

2D simulations of a model problem show that the pulse propagates as an unipolar surface wave spreading at $\upsilon \simeq c$ from sheath region





Possible applications of unipolar surface waves

- Picosecond duration of transient antenna fields $\rightarrow$ intense THz pulse generation

  A. Gopal et al, Phys. Rev. Lett. **111** (2013) 074802
  S. Tokita et al, Sci. Reports **5** (2015) 8268
  A. Poye et al, Phys. Rev. E **91** (2015) 043106

- Active, dynamic control of ion acceleration by engineering transient fields in shaped targets

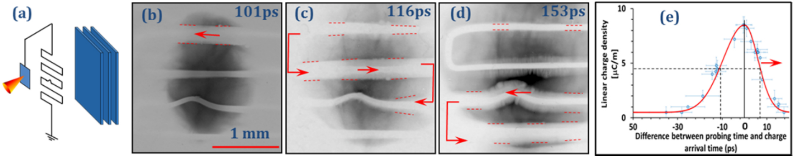
  S. Kar et al, Phys. Rev. Lett. **100** (2008) 105004

$\rightarrow$ Further developments of this approach in the following . . .

Propagation along a folded wire

"Self-probing" target: current pulse and probe protons generated from the same sheath field

Efficient propagation on long distances along a bent structure



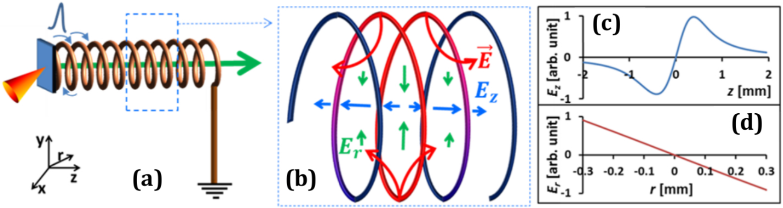
Idea: use current pulse as synchronized wave for proton focusing and (post-)acceleration

S.Kar, H. Ahmed, R. Prasad, M. Cerchez, S. Brauckmann, B. Aurand, G. Cantono, P. Hadjisolomou, C. L. S. Lewis, A. Macchi, G. Nersisyan, A. P. L. Robinson, A. M. Schroer, M. Swantusch, M. Zepf, O. Willi, M. Borghesi, "A laser-driven travelling-wave ion accelerator" (2015), submitted for publication

Application to post-acceleration of protons: design

Sending the pulse along a coaxial coil generates an electric field both re-accelerating and focusing a part of the protons

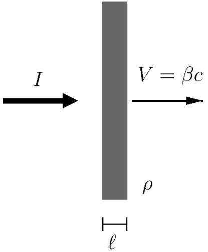
Coil can be designed to achieve phase matching



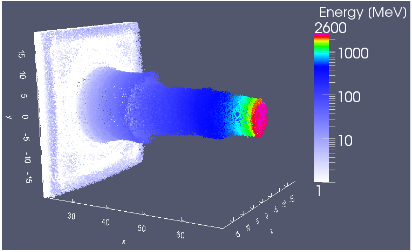
See **poster A30** by S. Kar et al (presented by M. Borghesi)

Light Sail acceleration

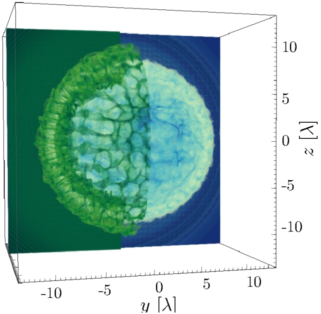
Concept: direct boost of an ultrathin target by light pressure ("accelerating mirror" model)
Very promising scaling and efficiency in the relativistic ion regime (GeV/amu) accessible with next generation lasers at $I > 10^{27}$ W m^{-2} (e.g. EU's Extreme Light Infrastructure)

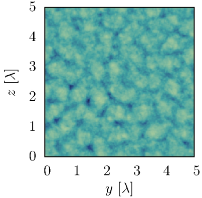


Theory and simulations:
T. Esirkepov et al, PRL **92** (2004) 175003
S. V. Bulanov et al, PRL **104** (2010) 135003
A. Sgattoni, S. Sinigardi, A. Macchi, Appl. Phys. Lett. **105** (2014) 084105



Light sail instability (3D simulations)





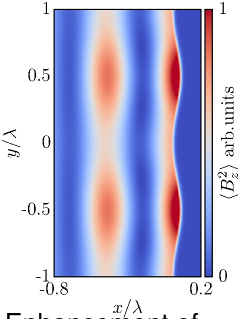
Formation of net-like structures in the ion density with size $\sim \lambda$ (laser wavelength) and $\sim$ hexagonal shape

Interpretation:
Rayleigh-Taylor instability
(light fluid accelerates heavy plasma fluid)
Crab Nebula image, Hubble telescope

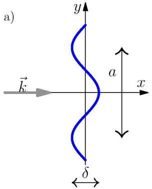
A.Sgattoni, S.Sinigardi, L.Fedeli, F.Pegoraro, A.Macchi, Phys. Rev. E **91** (2015) 013106

Plasmonic seed of Rayleigh-Taylor instability

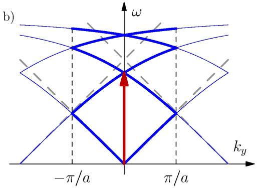
The EM field at a rippled surface (e.g. 2D reflecting, sinusoidal grating of period d) is modulated with plasmonic enhancement of the P-polarization component when $d \sim \lambda$



Enhancement of P-component in 2D simulations



Geometry



Matching with surface plasmons

The resulting self-modulation of laser light pressure provides a spatial seed for RTI

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

Conclusions

- Intense laser pulses can excite high field, relativistic Surface Plasmons
  - using grating targets (femtosecond SP)
  - by transient charge separation (picosecond unipolar SP)
- Applications for development of laser-driven electron and ion accelerators

  (possible detrimental role in Light Sail acceleration!)
- Other high field plasmonics applications under study . . .

EXTRA SLIDES

Simple model of electron acceleration in SP

- 2D extension of classic wakefield acceleration model
  [Tajima & Dawson, "*Laser Electron Accelerator*", PRL **43** (1979) 267]
- Plasmon field on the vacuum side is purely electrostatic in frame L' moving with phase velocity $\beta_f = v_f/c \lesssim 1$:

$$\Phi' = -(\gamma_f E_{\mathrm{SP}}/k)\,\mathrm{e}^{k'x}\sin k'y' \qquad k' = k/\gamma_f \qquad \gamma_f = (1-\beta_f^2)^{-1/2}$$

- "Lucky" electron injected with velocity v_f goes downhill the potential Φ' acquiring an energy $W' = eE_{\mathrm{SP}}\gamma_f/k$

$\rightarrow$ Energy ($\gg m_e c^2$) and emission angle in the lab (L) frame

$$\mathscr{E}_f \simeq eE_{\mathrm{SP}}\gamma_f^2/k \simeq m_e c^2 a_{\mathrm{SP}}(n_e/n_c)\ , \quad \tan\phi_e = p_x/p_y \simeq \gamma_f^{-1}$$

Highest energy electrons are closest to target tangent

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, $\sim$kA current
  (Snavely et al, PRL **85** (2000) 2945)
- charge neutralization by comoving electrons (“plasma beam”)
- good collimation with energy-dependent spread $\sim 10^\circ - 30^\circ$
- 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 ($\sim$ pulse duration, $\sim 0.1 - 10$ ps)

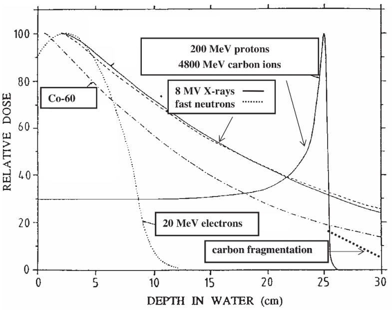
Interest in multi-MeV protons

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

figure from:

U. Amaldi, G. Kraft,

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

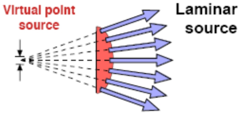


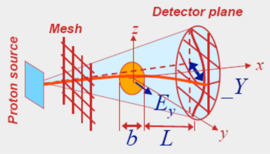
Foreseen applications:

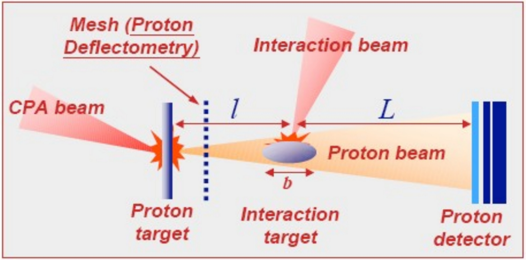
- oncology: hadrontherapy, ion beam therapy
- triggering of nuclear reactions, isotope production
- production of warm dense matter
- diagnostic of materials
- ultrafast probing of electromagnetic fields

Proton probing of laser-plasma interactions

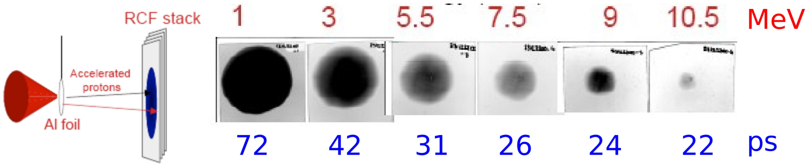
- charged beam:
  - ▶ field detection
- low emittance:
  - ▶ imaging capability
- laser driver:
  - ▶ easy synchronization
- broad spectrum:
  - ▶ time-of-flight arrangement
- short duration:
  - ▶ ultrafast resolution



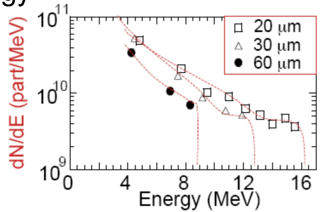




Achieving single-shot proton “movies”

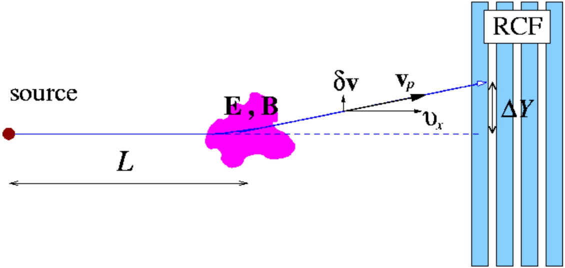


Radiochromic film (RCF) stack:
each layer a Bragg peak $\rightarrow$ a proton energy
Time-of-flight arrangement:
each layer $\rightarrow$ a probing time
(values refer to 1 mm flight distance)
Temporal resolution up to ~ 1 ps



Proton "image" formation

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

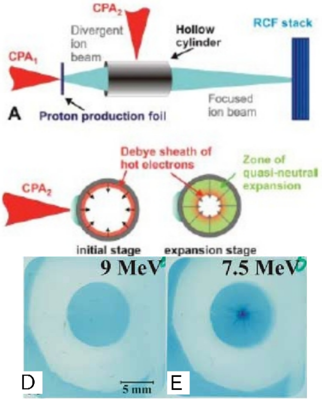


$$\Delta Y = |\delta \mathbf{v}|\Delta t \simeq \frac{eL}{2\mathcal{E}_p}\int (\mathbf{E} + \mathbf{v}_p \times \mathbf{B})_\perp dx$$

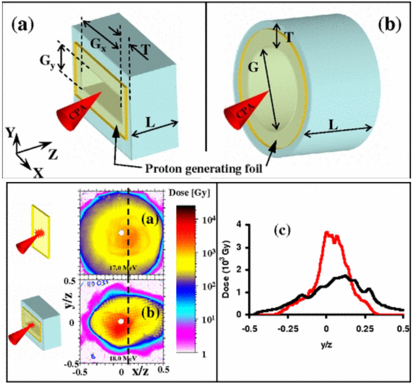
$$\frac{\delta n}{n_0} \simeq -\frac{1}{M}\nabla \cdot \Delta \mathbf{Y} \simeq \frac{-2\pi eLb}{\mathcal{E}_p M}\int_{-b/2}^{+b/2}\left(\rho - \frac{\mathbf{v}_p \cdot \mathbf{J}}{c^2}\right) dx$$

Proton beam focusing and manipulation

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



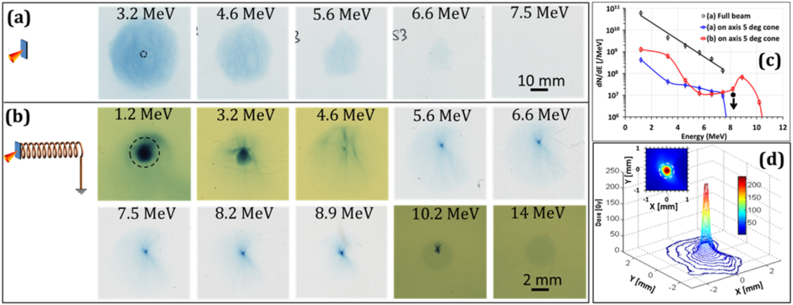
Toncian et al, Science **312** (2006) 410



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

Application to post-acceleration of protons: results

Tight beam focusing and 50% energy gain!



S.Kar, H. Ahmed, R. Prasad, M. Cerchez, S. Brauckmann, B. Aurand, G. Cantono, P. Hadjisolomou, C. L. S. Lewis, A. Macchi, G. Nersisyan, A. P. L. Robinson, A. M. Schroer, M. Swantusch, M. Zepf, O. Willi, M. Borghesi, "A laser-driven travelling-wave ion accelerator" (2015), submitted for publication