Superintense Laser-Plasma Interactions: Relativistic Condensed Matter Physics

Andrea Macchi

[1]Consiglio Nazionale delle Ricerche, Istituto Nazionale di Ottica (CNR/INO), Pisa, Italy

[2]Dipartimento di Fisica "Enrico Fermi". Università di Pisa, Italy

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Outline

Ultrashort introduction to "relativistic" laser-plasma physics and survey of recent results from our group:

- structured targets for high laser absorption
- resonant coupling in grating targets: "high field plasmonics"
- radiation pressure acceleration of thin targets: experiments and theory
- laser-plasma physics investigated by proton probing on picosecond scales
  - ultrafast discharge dynamics of a laser-irradiated target
  - dynamics of self-generated multi-MG magnetic fields

Additional aims

- Emphasize similar problems, analogies, interdisciplinary applications and relations between relativistic laser-plasma research and other fields in condensed matter physics and beyond
- Advocate the strategic placement in condensed matter physics of ultraintense laser-produced plasmas as collective, nonlinear many-body systems which can be controlled and diagnosed by laser light

Main coworkers for this talk

A. Sgattoni[1,2], M. Passoni[2], F. Pegoraro[1,3], T. V. Liseykina[4], S. Sinigardi[5], P. Londrillo[6], V. Floquet[7], T. Ceccotti[7], S. Kar[8], K. Quinn[8], M. Borghesi[8]

[1]CNR/INO, Pisa, Italy
[2]Dipartimento di Energia, Politecnico di Milano, Milan, Italy
[3]Dipartimento di Fisica "Enrico Fermi", Università di Pisa, Pisa, Italy
[4]Institut fuer Physik, Universitaet Rostock, Germany
[5]Dipartimento di Fisica, Università di Bologna, Bologna, Italy
[6]INAF and INFN, Bologna, Italy
[7]CEA/DSM/IRAMIS/SPAM/PHI, Saclay, France
[8]Center for Plasma Physics, Queen's University of Belfast, UK

The relativistic plasma

- Definition: a many-body system containing free charges, dominated by collective behavior and with a relevant population (typically the electrons) of particles with "relativistic" energy $\mathscr{E} > mc^2$.
- Production in the laboratory: generation and "heating" of a plasma by short duration $(10^{-12} - 10^{-15}$ s), high-intensity laser pulses focused on matter

$$p_{\text{osc}} = \frac{eE}{\omega} > m_e c \quad \Longrightarrow \quad I\lambda^2 > 1.4 \times 10^{18}\ \text{W cm}^{-2}\mu\text{m}^2$$

State of the art: $I > 10^{21}$ W cm^{-2} for $\lambda = 0.8\ \mu$m^2

Relativistic nonlinearity sources

- Nonlinear conductivity:

$$\mathbf{p}_{\text{osc}} = -i\frac{e\mathbf{E}}{\omega} \qquad \mathbf{v}_{\text{osc}} = \frac{\mathbf{p}_{\text{osc}}c}{(p^2 + m_e^2 c^2)^{1/2}}$$

$$\mathbf{J} = -en_e\mathbf{v} = \frac{in_e e^2}{m_e \omega c}\frac{\mathbf{E}}{(1 + (eE/\omega m_e c)^2))^{1/2}}$$

- Non-negligible $\mathbf{v} \times \mathbf{B}$ force
- Relativistic ponderomotive force (local light pressure per unit volume) and effective mass

$$\frac{d}{dt}\left(m_{\text{eff}}\langle\mathbf{v}\rangle\right) = -\nabla m_{\text{eff}}c^2 \qquad m_{\text{eff}} = m_e\left(1 + (e\langle\mathbf{A}\rangle/m_e c^2)^2\right)^{1/2}$$

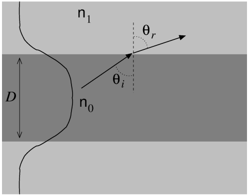
Relativistic nonlinear optics

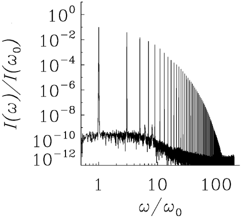
Relativistic Self-Focusing

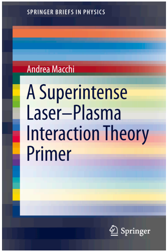
High harmonic generation

Self-induced transparency

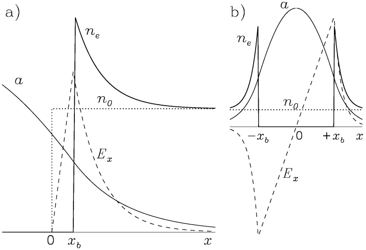
Electromagnetic solitons



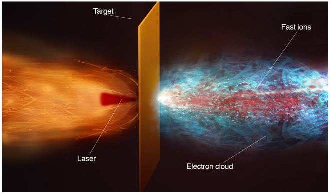




A. Macchi,
A Superintense Laser-Plasma Interaction Theory Primer
(Springer, 2013)



Focus on: ion accelerators



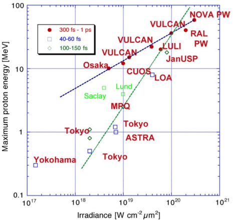
Pioneer vision of "coherent" particle acceleration
[V. Veksler, At. Energ. **2** (1957) 525]

- accelerating field proportional to number of particles
- automatic spatio-temporal synchrony between particles and accelerating field
- acceleration of quasi-neutral bunches with large numbers of particles

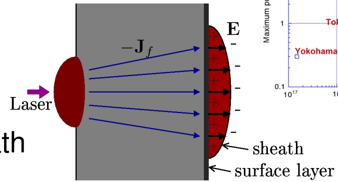
- All realized in laser-plasma acceleration of ions!

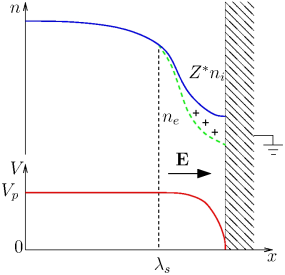
A. Macchi, M. Borghesi, M. Passoni,
Ion Acceleration by Superintense Laser-Plasma Interaction,
Rev. Mod. Phys. **85** (2013) 571

Target Normal Sheath Acceleration



TNSA is driven by “fast” electrons generated in thin solid targets: protons from surface contaminants are accelerated in the rear sheath





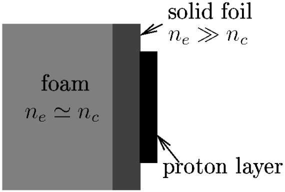
Connection with plasma discharge and AC/DC sheath physics:

- stochastic acceleration of electrons
- sheath formation and ion acceleration

Foam targets for low density-enhanced absorption

With low-density layer at near cut-off values $n_e \simeq n_c$ proton energy doubles in 3D simulations with 25 fs, 1 J energy pulse

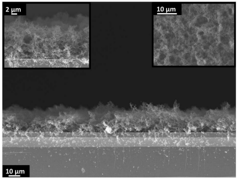
[Sgattoni, Londrillo, Macchi, Passoni, PRE **85** (2012) 036405]

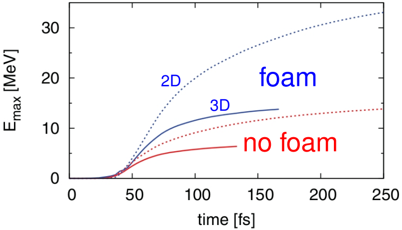


Foam target manufacturing:

Zani et al, Carbon **56** (2013) 358

NEMAS lab, Politecnico Milano

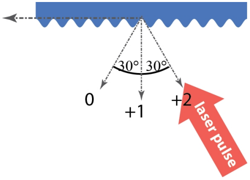




Grating targets for surface wave-enhanced absorption

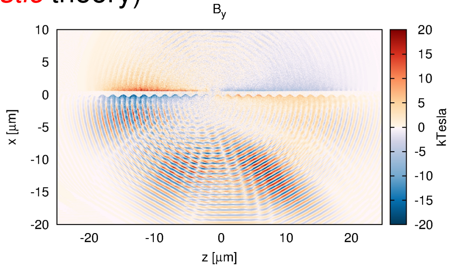
Irradiating grating targets at resonant angle

$$\sin \theta_{\text{res}} + \lambda/d = \left(\frac{1-n_e/n_c}{2-n_e/n_c}\right)^{1/2} \simeq 1$$



leads to surface wave (SW) excitation (according to *linear*, *non-relativistic* theory)

Simulations suggest SW excitation to occur also in the relativistic, nonlinear regime: perspectives for high field plasmonics?

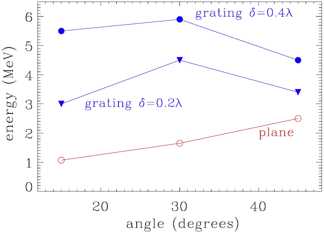


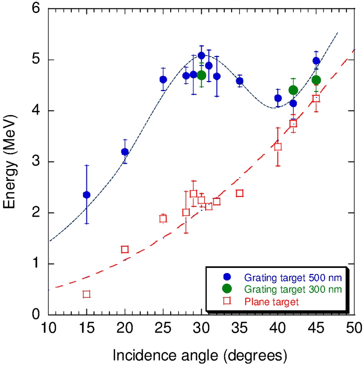
TNSA enhancement in grating targets: experiment

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

Proton energy peak around $\theta_{\text{res}} = 30^\circ$

Fair agreement with 2D simulations



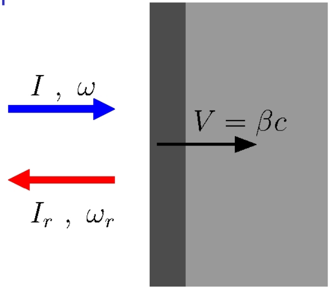


T. Ceccotti, V. Floquet, A. Sgattoni, A. Macchi et al, PRL (2013), submitted

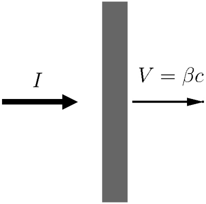
Radiation Pressure Acceleration

Accelerating mirror paradigm: momentum transfer to mirror from Doppler shift and photon number conservation

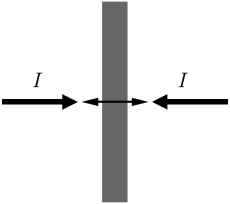
$$\frac{dP}{dt} = \frac{2I}{c}\frac{1-\beta}{1+\beta}$$



One beam: laser acceleration

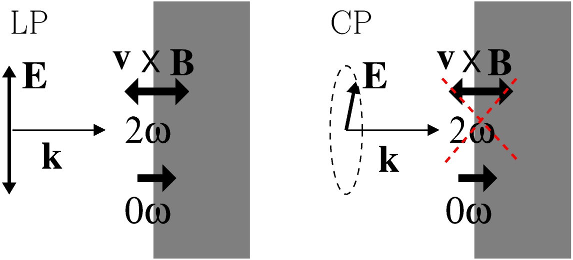


Two beams: laser cooling



Optimizing RPA using circular polarization

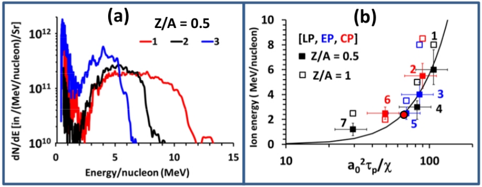
Suppress electron longitudinal oscillations and electron stochastic heating using normal incidence and circular polarization (CP) instead of linear polarization (LP)



[Macchi, Cattani, Liseykina, Cornolti, PRL **95** (2005) 185003]

Fast RPA scaling experimentally observed

VULCAN laser, RAL/CLF:
Laser pulse: $t_p \simeq 800\ fs$
3×10^{20} W cm^{-2}
$\sim 10^9$ contrast
Target: $\sim 0.1\ \mu$m metal foil

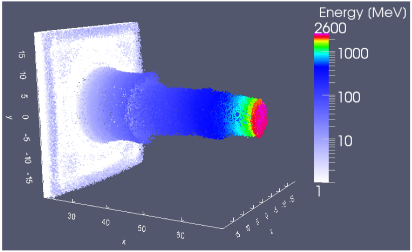


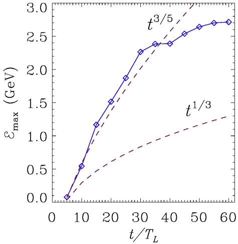
- Multispecies ($Z/A = 1, 1/2$) peaks observed with $\Delta\mathcal{E}/\mathcal{E} \simeq 20\%$
- Up to $\simeq 10$ MeV/amu observed at high flux
- Theoretical fast scaling of ion energy $\propto (I\tau_p/\rho\ell)^2$ confirmed
- Simulations suggest > 100 MeV/amu are within reach
- Foreseen applications: heating of warm dense matter, isotope production, hadrontherapy (but not anytime soon . . .)

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

3D simulations of future GeV ion accelerator

Laser: 24 fs, 4.8 μm spot, $I = 0.85 \times 10^{23}$ W cm^{-2} $\Longrightarrow$ **1.5 kJ**
Extreme Light Infrastructure (ELI) class laser

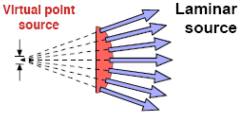


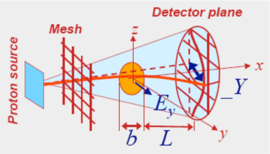


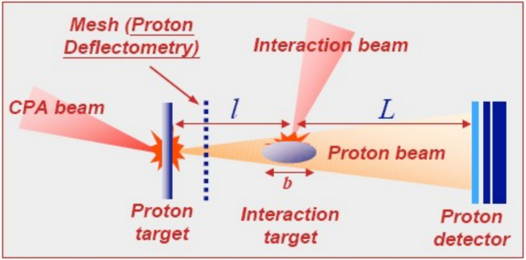
High gain RPA regime identified in 3D simulations on CINECA/FERMI BlueGene/Q^{TM}, sponsored by PRACE
Macchi, Sgattoni, Sinigardi, Borghesi, Passoni, arXiv:1306.6859

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

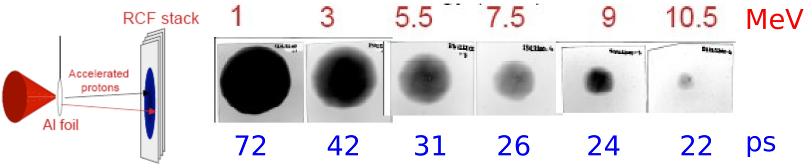




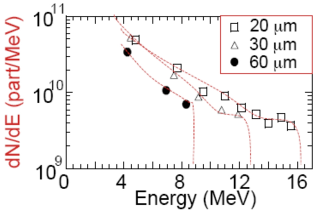


Borghesi et al, PPCF **43** (2001) A267

Achieving single-shot "movies"

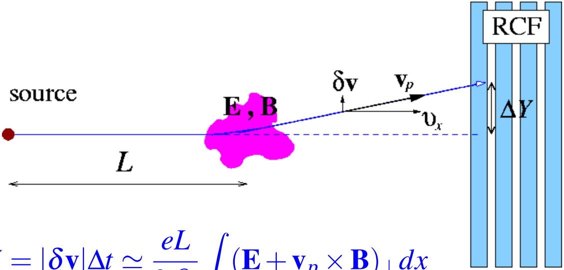


In a time-of-flight arrangement, each RCF layer produces a "snapshot" at a given proton energy $\rightarrow$ probing time (values refer to 1 mm flight distance)
Achievable resolution up to ~ 1 ps



Proton "image" formation and analysis

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



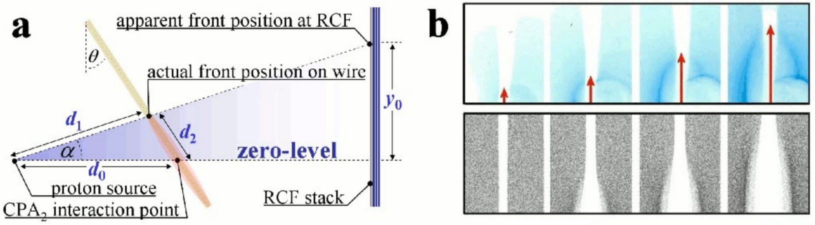
$$\Delta Y = |\delta \mathbf{v}|\Delta t \simeq \frac{eL}{2\mathscr{E}_p}\int (\mathbf{E} + \mathbf{v}_p \times \mathbf{B})_\perp dx$$

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

Structure and strength of probed fields inferred by comparison with synthetic images from particle tracing simulations

Imaging ultrafast charging and EM field propagation

Aim: shoot at some point a wire target to image (dis-)charging due to escaping fast electrons



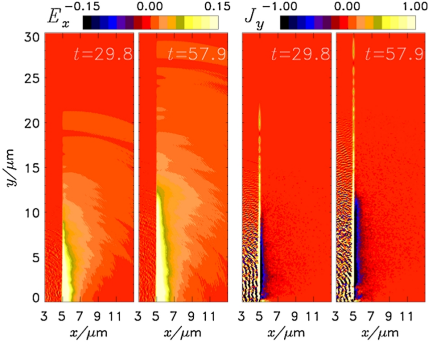
A field front propagates along the wire at $v_f = 0.96 \pm 0.04c$

[K.Quinn et al, PRL **102**, 194801 (2009)]

SUGGESTION

“Antenna” emission from transient charging

2D simulations of a model problem show return surface currents driven by an EM front at velocity $\sim c$
EM fields are generated by the transient charge distribution behaving as a dipole antenna

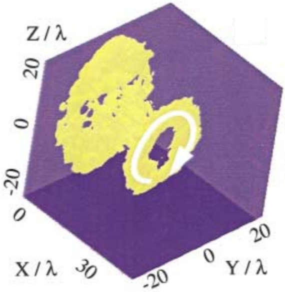


Corresponding THz radiation of GW power recenty measured [Gopal et al PRL **111** (2013) 074802]

[K.Quinn et al, PRL **102**, 194801 (2009)]

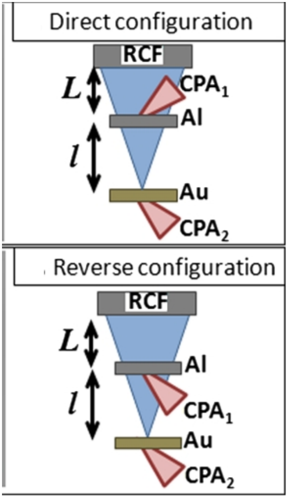
Probing magnetic fields

Purpose: detect magnetic fields "surrounding" the sheath region

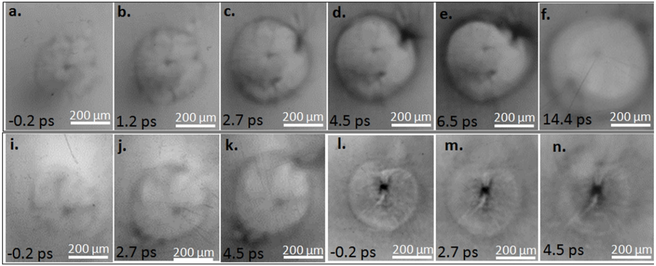


[**B**-field in 3D simulation - A.Pukhov, PRL **86**, 3562 (2001)]

Technique: probing perpendicular to the target surface, (anti/)parallel to the symmetry axis of **B**

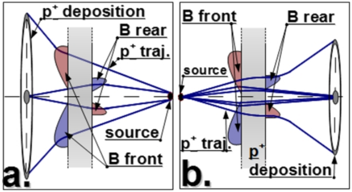


"Double-ring" pattern from magnetic field deflections

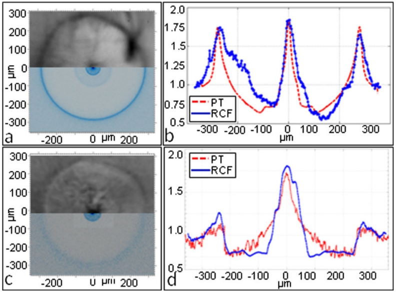


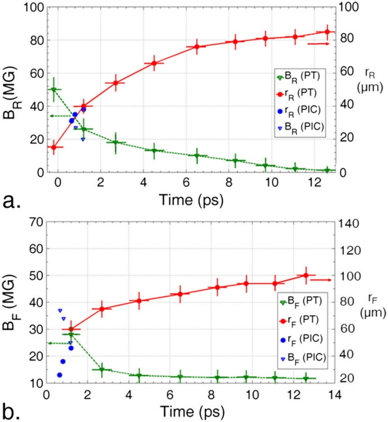
(**a-k**: *direct* config., **l-n**: *reverse* config.)

Front/rear side magnetic fields of opposite polarity cause focusing/defocusing of protons [Sarri, Macchi, Cecchetti et al, PRL **109**, 205002 (2012)]



Temporal evolution of magnetic fields

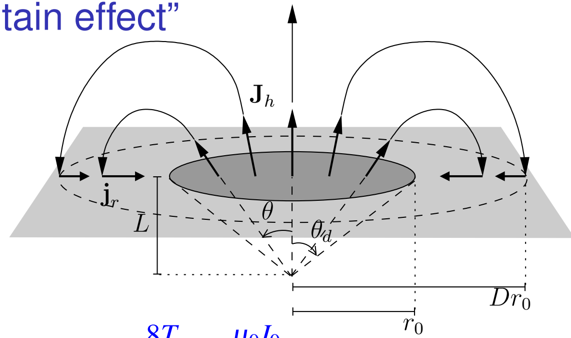




$\mathbf{B}$-field up to ~ 80 MG confines the sheath expansion

Generation of relativistic (MHD) plasmas for "laboratory astrophysics" scaled-down experiments?

Toy model of the "fountain effect"



The divergent flow of fast electrons from the rear side forms loops due to the "gravity" action of $\mathbf{E}$-field: a net current circulates

Proposed scaling for $\mathbf{B}$-field

$$B_{\text{max}} \simeq \frac{8T_e}{eEr_0}\theta_d \frac{\mu_0 I_0}{2\pi r_0}$$

Experimental value of B_{max} consistent with $T_e \simeq 0.5$ MeV, $E \simeq 10^{12}$ V/m, $r_0 = 15\ \mu$m, $\theta_d = 25^\circ$

A.Macchi, *Toy model of the 'fountain effect' for magnetic field generation in intense laser-solid interactions*, arXiv:1202.0389

Conclusions and comments

- "Relativistic" laser-plasma physics has citizenship rights in condensed matter physics

  Keywords: many-body physics, collective dynamics, nonlinear phenomena, self-organization, material science, ultrafast phenomena, high-field plasmonics ...
- At the same time it has bridges to high-energy physics (accelerator development) and astrophysics (modeling and scaled-down experiments on "extreme" phenomena)
- The present "abundance" of high power lasers is a solution looking for (more) problems

Acknowledgments

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  - FERMI BlueGene/Q^{TM}, PRACE award (project LSAIL – "Large Scale Acceleration of Ions by Lasers")