INO-CNR
ISTITUTO NAZIONALE DI OTTICA

October 3rd 2014

Laser-Driven Ion Acceleration, High Field Plasmonics, and Classical Instabilities

Andrea Macchi

Event:
INO Annual Symposium 2014

INO Sensor Lab Section
University of Brescia, Ingegneria Area
Via Branze, 38 – Brescia, Italy

Laser-driven ion acceleration, high field plasmonics, and classic instabilities

Andrea Macchi

Consiglio Nazionale delle Ricerche, Istituto Nazionale di Ottica (CNR/INO), research unit “Adriano Gozzini”, Pisa, Italy

(also Dipartimento di Fisica “Enrico Fermi”, Università di Pisa, Italy)

INO Annual Symposium, Brescia, Italy
Friday, October 3, 2014

Outlook

- Laser-plasma ion acceleration
- High field plasmonics for enhanced acceleration (and beyond)
  - surface wave coupling with grating targets
  - studies on tapered nanoguides
- Light sail acceleration: high gain and stability issues
  - observation in simulation and experiment
  - plasmonic effects on Rayleigh-Taylor instability

Main coworkers for this talk

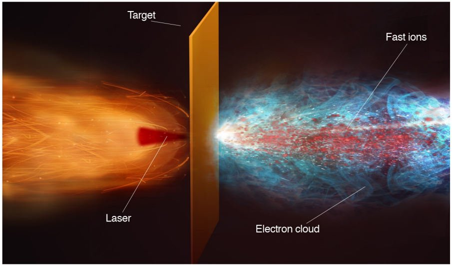
L. Fedeli[1], A. Sgattoni, S. Sinigardi[2], F. Pegoraro[1]

CNR/INO, Pisa, Italy
[1]Dipartimento di Fisica “Enrico Fermi”, Università di Pisa, Italy
[2]presently at Dipartimento di Fisica, Università di Bologna, Bologna, Italy

Plus colleagues from several institutes abroad (Queen’s University – Belfast, LULI Ecole Polytechnique – Palaiseau, CEA/LyDyL – Saclay, Technical University –Prague, . . .)

Laser-plasma acceleration of ions (2000–)

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



State of the art (2013):
- up to $\simeq 70$ MeV protons observed
(claims of > 100 MeV announced)
- $> 10^{13}$ protons, $> 10^{11}$ C ions accelerated in single shots
(as charge neutralized bunches)
- very low emittance measured ($< 0.1\pi$ mm mrad)
- proofs-of-principle of spectral manipulation and beam focusing

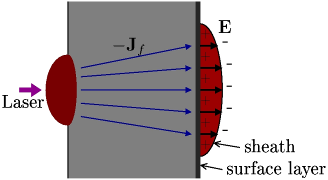
Applications

- Picosecond radiography of plasmas (sensitive to EM fields)
- Warm dense matter production and probing
- Short-lived isotope production
- Hadrontherapy
- High energy physics

  Need to increase energy and/or optimize energy spectrum and/or work at high repetition rate ...

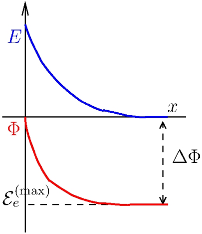
Sheath acceleration of protons

Target Normal Sheath Acceleration (TNSA) is driven by "fast" ($\mathscr{E}_e \sim \mathrm{MeV}$) electrons generated in thin targets: protons from surface contaminants are accelerated in the rear sheath



TNSA picture "for dummies":

Potential drop for static sheath $e\Delta\Phi = \mathscr{E}_e^{(\max)}$
(sheath potential must confine electrons)
Energy gained by "test" proton in the sheath

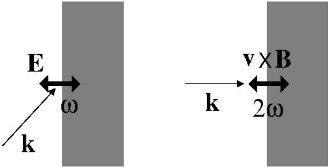


$$\mathscr{E}_p = e\Delta\Phi = \mathscr{E}_e^{(\max)}$$

Increasing electrons' energy $\longrightarrow$ increasing protons' energy

Fast electron generation: simple (rough) picture

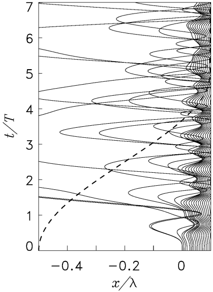
The Lorentz force of the laser wave (amplitude E_L, frequency ω) drives periodic "push-pull" of electrons across the density gradient



Electrons perform "half-oscillations" on the vacuum side and re-enter in the plasma (where the EM field is screened) and are "absorbed" keeping a net momentum

$$p_e \sim p_{\rm osc} \sim eE_L/\omega \equiv m_e c a_0$$

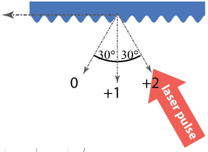
$a_0 = \left(\frac{eE_L}{m_e c\omega}\right) > 1 \longrightarrow$ relativistic electrons



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

Plasmonics at high fields for enhanced coupling

Concept: exploit collective electron excitation in sub-wavelength structures to concentrate light near the surface



Strategy: excitation of surface waves in periodic structures ("Catching light by a grating")

Phase matching possible at a plasma-vacuum interface if the shallow grating is preserved!

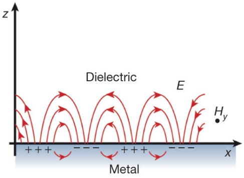
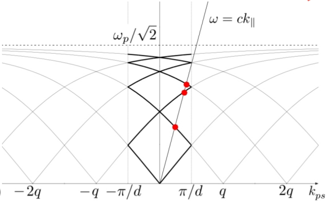


Fig.: O. Benson, Nature **480**, 193 (2011)



Question: is this possible in the high field, relativistic regime?

Coworkers

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,†]

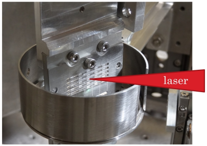
[1]*CEA/IRAMIS/SPAM, F-91191 Gif-sur-Yvette, France*
[2]*Istituto Nazionale di Ottica, Consiglio Nazionale delle Ricerche, research unit "Adriano Gozzini," 56124 Pisa, Italy*
[3]*Dipartimento di Energia, Politecnico di Milano, 20133 Milano, Italy*
[4]*LULI, Université Pierre et Marie Curie, Ecole Polytechnique, CNRS, CEA, 75252 Paris, France*
[5]*FNSPE, Czech Technical University in Prague, CR-11519 Prague, Czech Republic*
[6]*Institute of Physics of the ASCR, ELI-Beamlines project, Na Slovance 2, 18221 Prague, Czech Republic*
[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*
[11]*Dipartimento di Fisica "Enrico Fermi," Università di Pisa, Largo Bruno Pontecorvo 3, I-56127 Pisa, Italy*

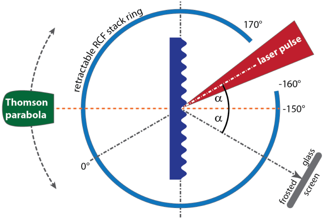
Experimental evidence: grating-enhanced TNSA

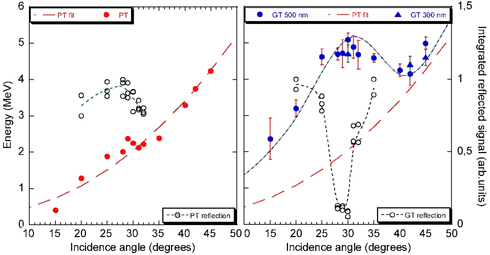
LaserLAB experiment at SLIC, CEA Saclay

laser UHI, 28 fs, 5×10^{19} W cm^{-2}

contrast $\sim 10^{12}$





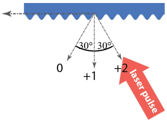


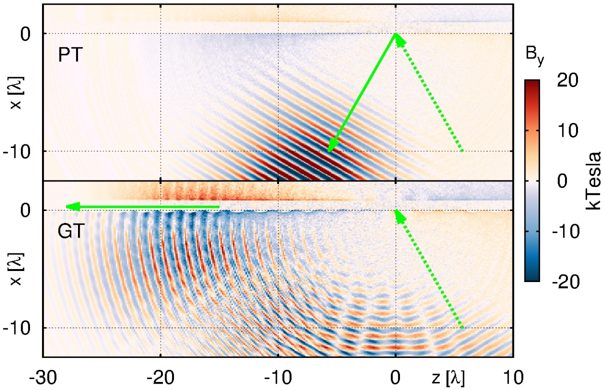
3X increase observed in proton energy at resonant angle

T.Ceccotti et al, PRL **111** (2013) 185001

Surface wave in PIC simulations

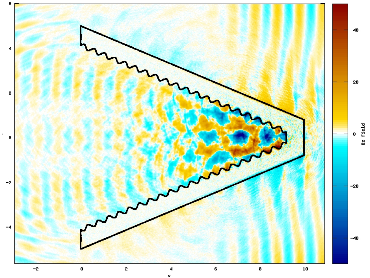
Snapshots of EM fields show localized wave propagating along the surface at resonant angle of incidence (plus reflection at various diffraction orders)





Exploring high field plasmonics with simulations

First PIC simulations of a tapered waveguide for light nano-focusing and amplification



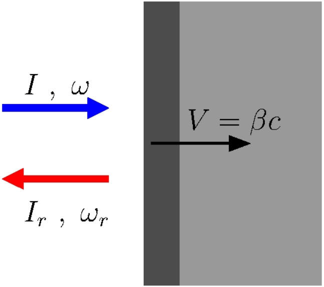
If 100X field amplification confirmed for ultraintense lasers, 10^{25} W cm^{-2} intensity is reached!

Simulations performed on FERMI super-computer with the Open Source Particle-In-Cell code PICcante originally developed by L.Fedeli, A.Sgattoni, S.Sinigardi

github.com/ALaDyn/piccante

Radiation Pressure Acceleration: "Light Sail"

Model:
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 ($\eta \rightarrow 1$) but slow gain ($dp/dt \rightarrow 0$) as $\beta \longrightarrow 1$

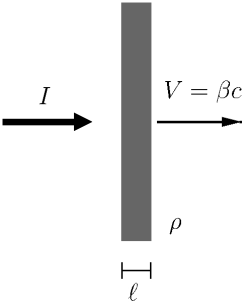
Light Sail formulas and scaling

$$\mathscr{E}_{\text{max}} = m_p c^2 \mathscr{F}^2/(2(\mathscr{F}+1))$$
$$\simeq m_p c^2 \mathscr{F}^2/2 \qquad (\mathscr{F} \ll 1)$$

$$\mathscr{F} = 2(\rho\ell)^{-1}\int_0^\infty I(t')dt' \simeq 2I\tau_p/\rho\ell$$

$$\mathscr{E}_{\text{ion}}(t) \propto \left(2It/\rho\ell c^2\right)^{1/3}$$

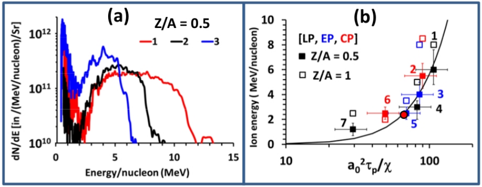
(for $t \gg \rho\ell c^2/I$, $\mathscr{E}_{\text{ion}} > m_p c^2$)



Favorable scaling with dimensionless laser pulse fluence $\mathscr{F}$
"Perfect" monoenergeticity for "rigid", coherent sail motion
Need of ultrathin (nm) foils and ultrahigh contrast pulses
Issues: slow energy gain, heating, transparency, deformation . . .

$\mathscr{F}^2$ 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



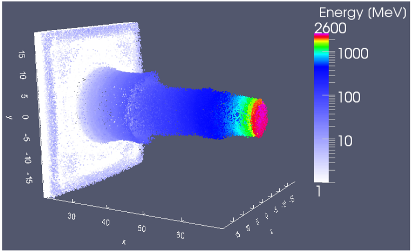
Multispecies ($Z/A = 1, 1/2$) peaks observed with $\Delta\mathscr{E}/\mathscr{E} \simeq 20\%$
Up to $\simeq 10$ MeV/amu observed at high flux
Simulations suggest > 100 MeV/nucleon are within reach

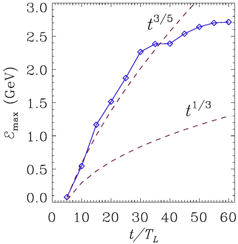
Kar, Kakolee, Qiao, Macchi, Borghesi et al PRL **109** (2012) 185006

Other recent expts: Steinke et al, PRST-AB **16** (2013) 11303;
Aurand et al, NJP **15** (2013) 33031

High energy gain in 3D simulation of ELI regime

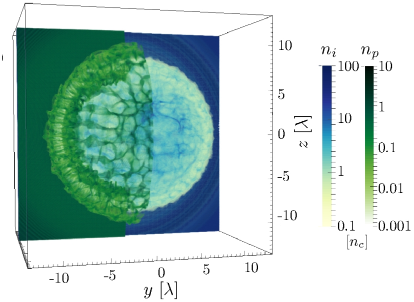
Laser: 24 fs, 4.8 μm spot, $I = 0.85 \times 10^{23}$ W cm^{-2} $\Longrightarrow$ **1.5 kJ**
Target: 1 μm foil, $n_e = 1.1 \times 10^{23}$ cm^{-3}, $\zeta \simeq a_0 \simeq 200$

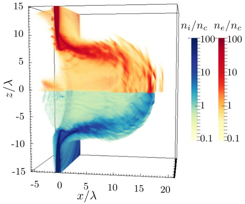




$\mathcal{E}_{\text{max}} \simeq 2.6$ GeV > 4 times 1D model prediction
Macchi et al, Plasma Phys. Contr. Fus. **55** (2013) 124020
Sgattoni et al, Appl. Phys. Lett. **105** (2014) 084105

Transverse Structures in 3D Simulation



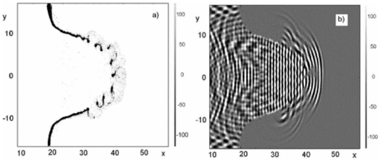


- Code: `ALaDyn` (originally developed by Benedetti, Londrillo, Sgattoni, Turchetti – Bologna University)
- Machine: FERMI BlueGene/Q at CINECA sponsored by PRACE
- Set-up: 4096×1792^2 grid points, 2×10^{10} particles, 16384 cores used
- 10^{23} W cm^{-2} laser pulse on solid target (sub-μm thickness)

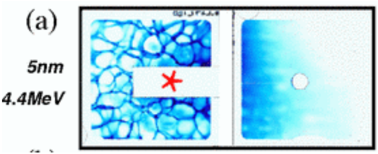
Formation of net-like structures with size $\sim \lambda$ (laser wavelength)
What is their orgin?
What sets the dominant scale?

Rayleigh-Taylor Instability in RPA?

Thin foil target of areal density σ accelerated by a laser of intensity I is unstable with growth rate $\gamma = (P_0 q/\sigma)^{1/2}$ with $P_0 = 2I/c$ and q the wavevector [Ott, PRL **29** (10972) 1429]



2D simulation [F.Pegoraro & S.V.Bulanov, PRL **99** (2007)065002]

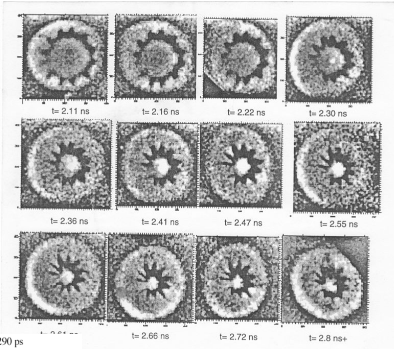


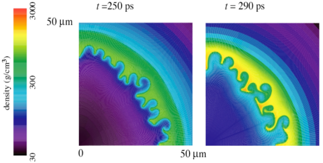
Experimental indication from accelerated ion beam profile structures [Palmer et al, PRL **108** (2012) 225002]

Rayleigh-Taylor Instability in space and lab plasmas

Crab Nebula, Hubble Space Telescope

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

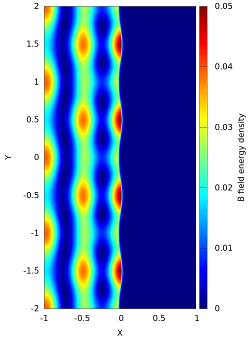


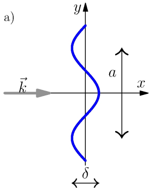


RTI simulation GAPS group, Roma (S.Atzeni et al)

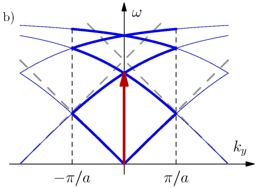
Plasmonic modulation of radiation pressure

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





Geometry



Matching with surface plasmons

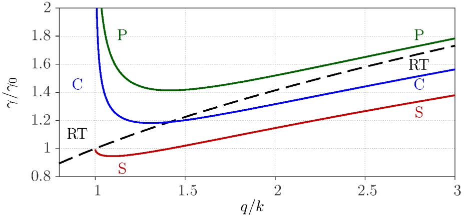
The resulting modulation of laser light pressure provides a spatial seed for RTI [A.Sgattoni et al, arXiv:physics/1404.1260]

Thin foil RTI with self-consistent pressure modulation

Model: reflection from shallow 2D grating of depth δ (first order in δ/λ) + modified Ott's theory with modulated pressure:

$$P \simeq P_0(1+K(q)\delta\cos qy)\,, \qquad K(q) = \begin{cases} -(q^2-k^2)^{1/2} & (S) \\ k^2 q(q^2-k^2)^{-1/2} & (P) \\ (k^2-q^2/2)(q^2-k^2)^{-1/2} & (C) \end{cases}$$

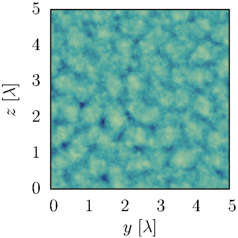
$$\gamma = (P_0/\sigma)^{1/2}\left[\left(q^2+K^2(q)/4\right)^{1/2}+K(q)/2\right]^{1/2}$$



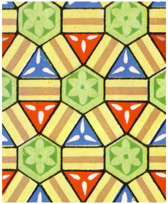
S-polarization
P-polarization
C-ircular polarization
RT: no modulation ($\delta = 0$)

Symmetry of RTI structures

Nonlinear hexagonal-like structures generated by RTI have “wallpaper” p6m symmetry



3D sim. (plane wave)



Persian glazed tile

An example of spontaneous symmetry breaking in a classical system (there’s not only quantum physics and the Higgs . . .)

EXTRA SLIDES

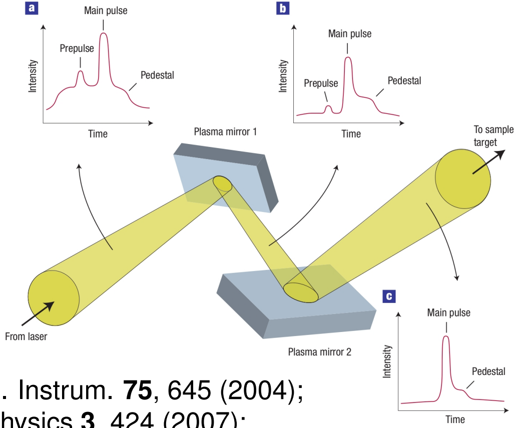
The paradigm of “coherent” acceleration

Early vision: V. 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
- challenge: control of the dynamics of the plasma (complex many-body system, leaning to instability)

Need for ultraclean pulses: plasma mirrors

Plasma mirrors yielding $\sim 10^{12}$ pulse-to-prepulse contrast allow to preserve target structuring until the short pulse interaction



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