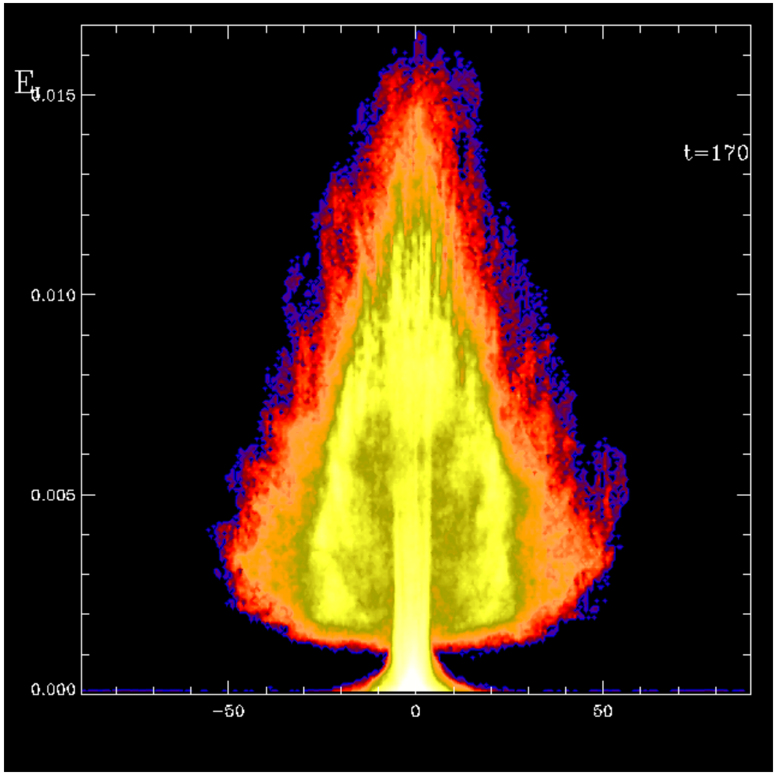
Superintense Laser Ion Acceleration and its Applications



Andrea Macchi

polyLab, CNR-INFM
Dipartimento di Fisica
Università di Pisa

Colloquium, INFN Pisa,
Tuesday, January 30, 2007

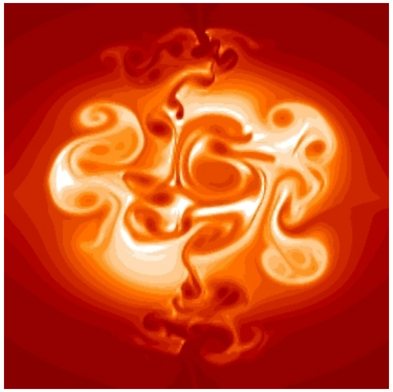
Research Group and Interests

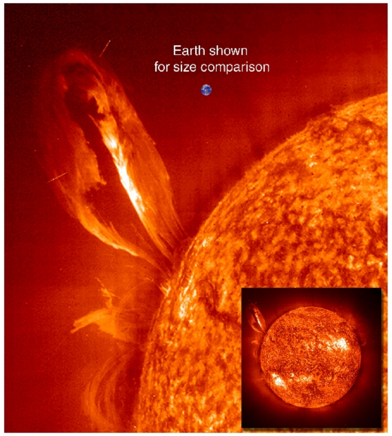
Staff: F.Pegoraro, F.Cornolti, F.Califano, A.Macchi, F.Ceccherini, T. V. Lyseikina, L.Galeotti,

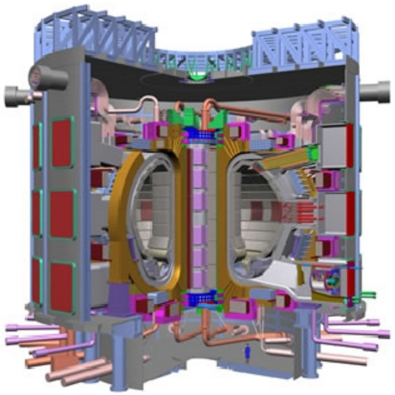
Students: 5 Ph.D. and 3 undergraduate

- *Theory of fundamental processes*: plasmas as macroscopical (relativistic) many-body systems in non-equilibrium, instabilities, coherent structures (solitons, vortices),...
- *Numerical simulations*: code and model development, supercomputing
- *Experimental collaborations*: modeling and interpretation of experiments

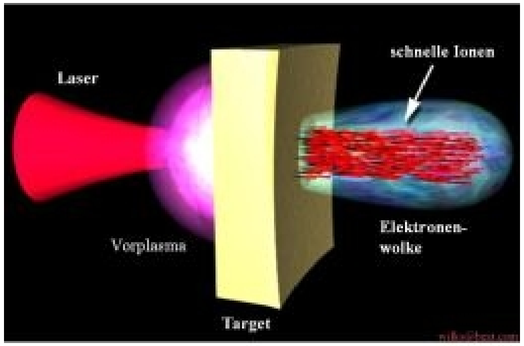
Collisionless Dynamics of Magnetized Plasmas
(kinetic effects, turbulence, ...)
Application: nuclear fusion, space plasmas, satellite observations

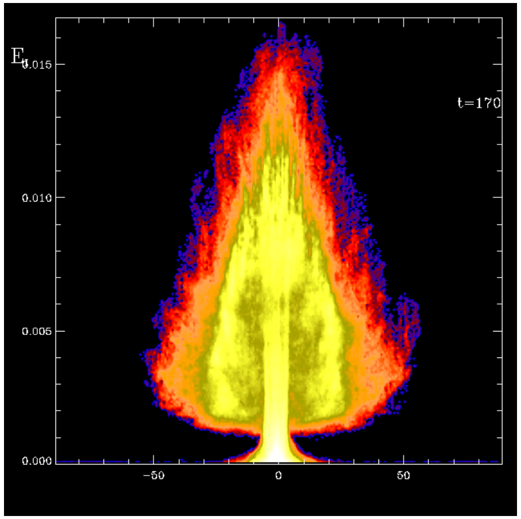






Superintense laser-matter interactions
(ultrafast and relativistic processes, ion acceleration, nonlinear optics)
Applications: ultrashort sources of radiation (ions, neutrons, photons), “fast ignition” for fusion





***Starting up*: “cold” plasmas for material processing**

Research Group and Interests

Staff: F.Pegoraro, F.Cornolti, F.Califano, A.Macchi, F.Ceccherini, T. V. Lyseikina, L.Galeotti,

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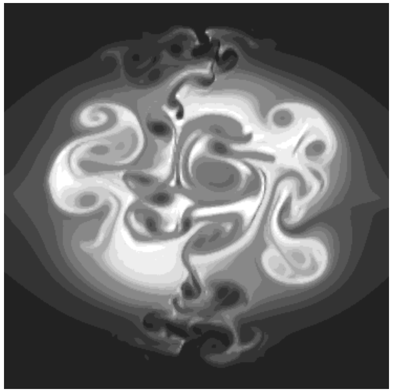

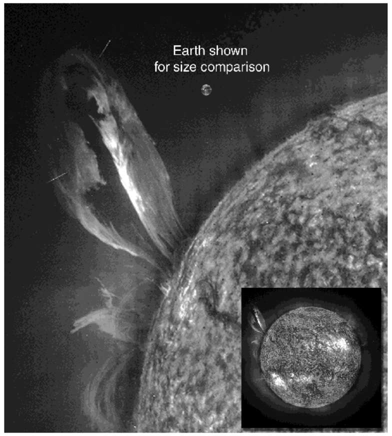

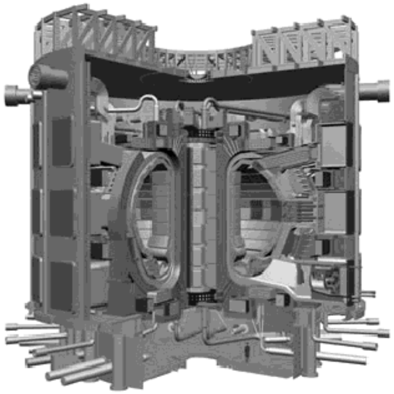

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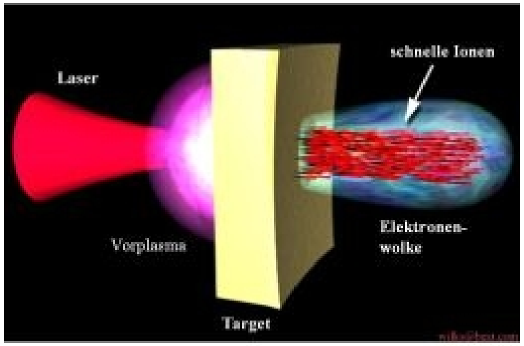
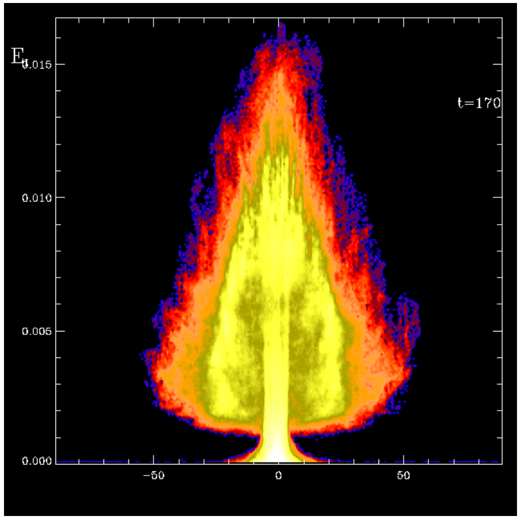




***Starting up*: "cold" plasmas for material processing**

Present funding and resources

Running projects:

- FIRB (2006-08) -> 1 PhD student
- PRIN (2005-06) -> 1 postdoc
- UK Royal Society project (07/2005-07/2007) -> travel & subsistence

Approved (but uncertain funding...):

- CNR “curiosity-driven” project

Stand-by:

- INFM-CINECA supercomputing initiative (CPU time on Linux cluster)

Future opportunities ?

- INFN PLASMON-X project
- ELI EU proposal (www.eli-laser.eu)
- HiPER EU proposal (www.hiper-laser.org)

Outline

- Outlook of high intensity laser-matter interaction
- The new era of Laser Ion Acceleration (mainly protons): discovery and applications
- Unfolding the physics of laser-plasma acceleration of protons (and using laser-accelerated protons to unfold the physics of laser-plasma interactions)
- Advanced schemes for Laser Ion Acceleration and future perspectives

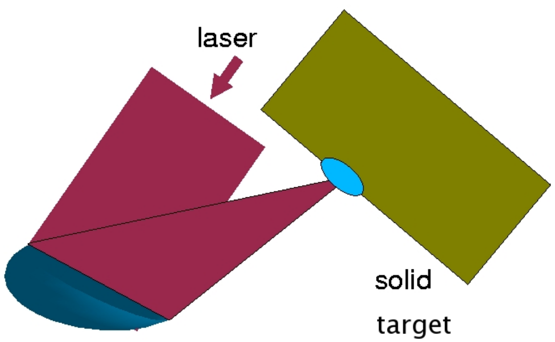
Outlook of high-intensity laser-matter interaction

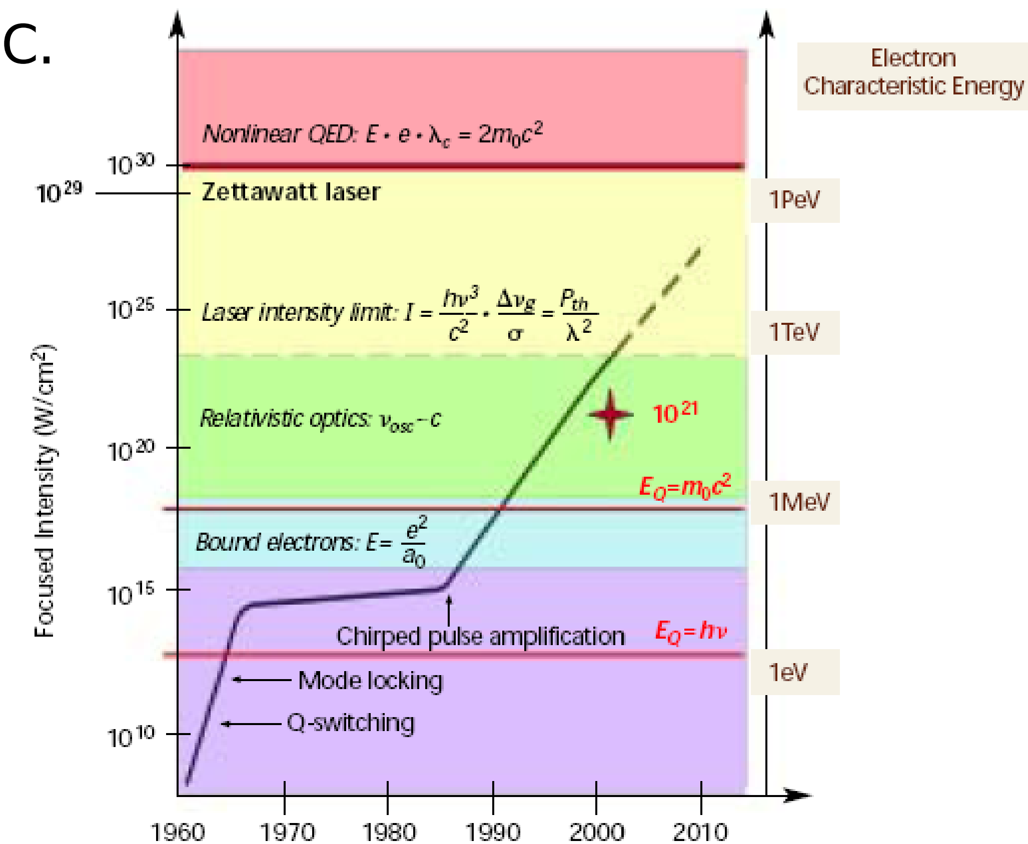
24 Centuries of Focused Light Interaction with Matter

Archimede, III century B.C.

Leonardo Da Vinci,
XVI century A.C.

Progress in focused laser intensity
across the XX and XXI centuries A.C.





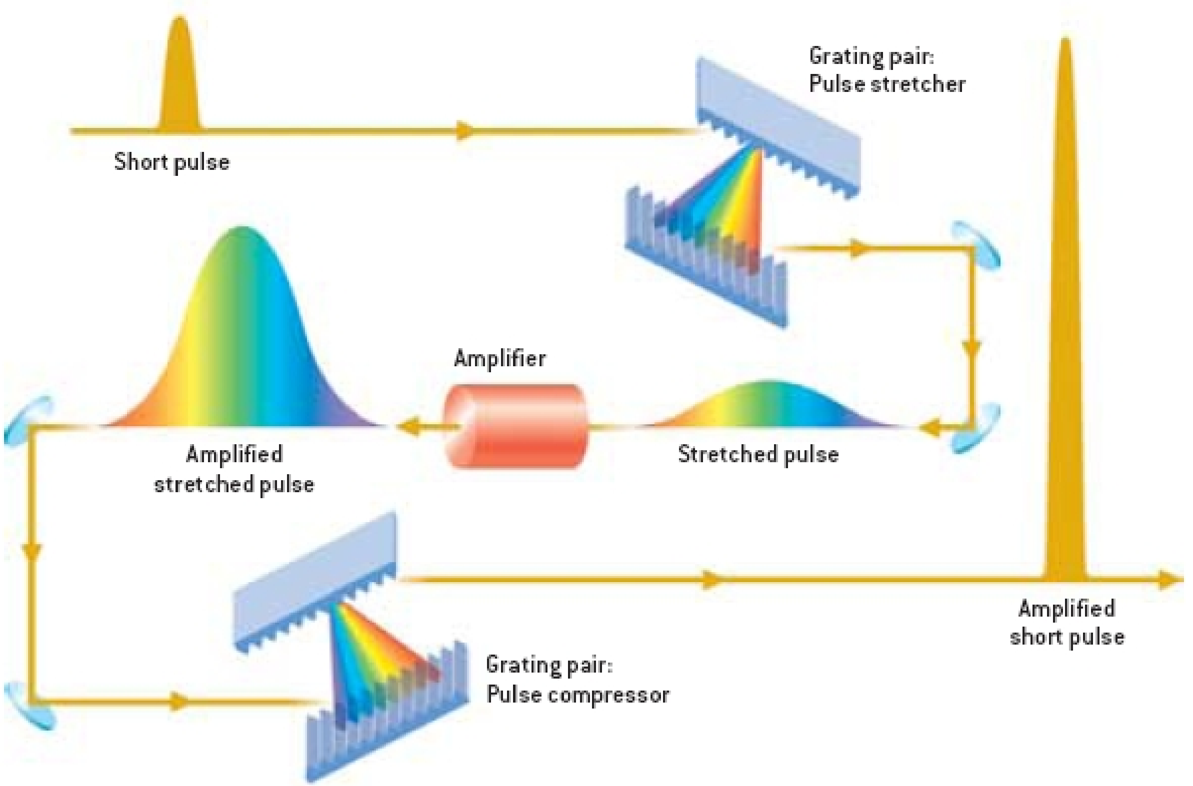
Highest intensity demonstrated:

10^{21} W/cm^2

(Center for Ultrafast Optical Science,
University of Michigan, 2005)

Chirped Pulse Amplification (CPA) technique

CPA concept: stretch the pulse in time by dispersion (chirping) to reduce power below the amplifier damage threshold



Donna Strickland & Gérard Mourou, Optics Communication (1985)

[Figure from: G. Mourou and D. Umstadter, Scientific American, May 2002, p.80]

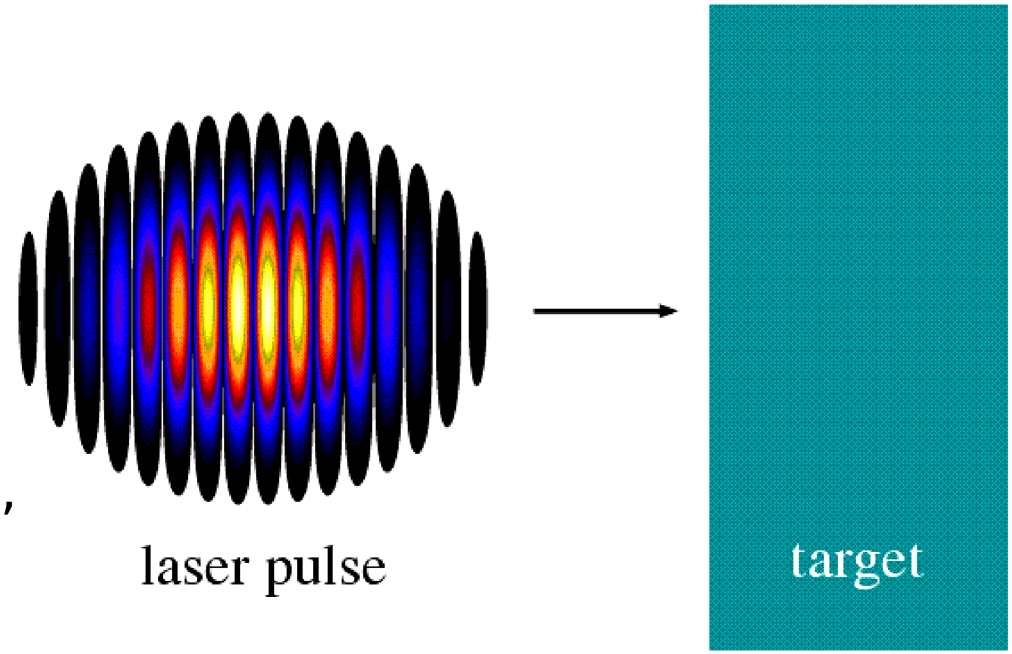
Laser-Matter Interaction Scenario @ I=10^{20} W/cm^2

Electric field $E=\sqrt{4\pi\frac{I}{c}}=2.7\times10^{13}\,V/m=53\frac{e}{r_B^2}$ → **ultrafast ionization and plasma production**

Electron momentum $p_{osc}=\frac{eE}{\omega}=8.5\,m_e c\ \ @\ \ \lambda=1\,\mu m$ → **electrons are strongly relativistic**

Radiation pressure $P_{rad}=\frac{I}{c}=3.3\times10^{15}\,N/m^2$ → **radiation pressure dominates hydrodynamics**

Pulse duration may be
< 10 laser cycles
(e.g. 30 fs=3 x 10^{-14} s)
i.e the focused “laser beam” is a
light bullet



Related Definitions:
“*Extreme Light*”, “*High Field Science*“,
“*Relativistic Optics*”,
“*High Energy Density Physics*” ...

G.Mourou, T.Tajima, S.V.Bulanov, Rev.Mod.Phys. **78** (2006) 309

Why is (super)intense laser-matter interaction interesting?

"The Laser is a solution looking for a problem" (anonymous)

General Physics:

"laser-plasma" as a macroscopical, many-body, collective *relativistic* system;
[See e.g. "special relativity in action" F.Pegoraro, T.Esirkepov, S.V.Bulanov, Phys.Lett.A **347**, 133 (2005)]

Applications:

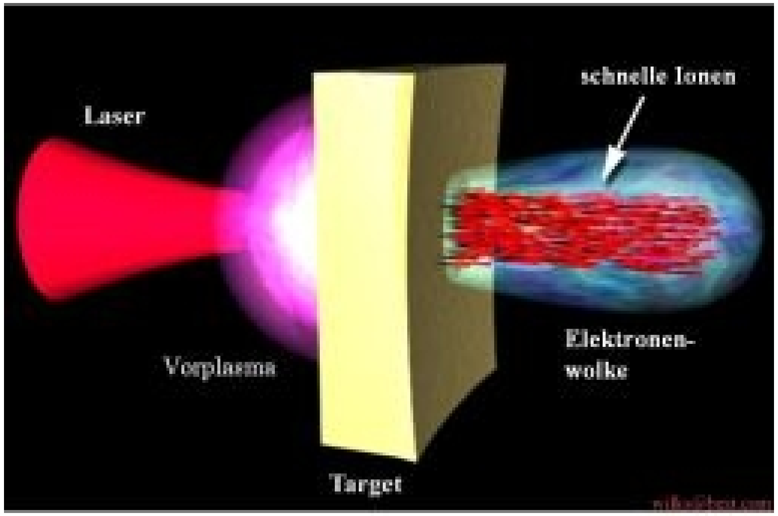
- controlled Thermonuclear Fusion ("Fast Ignition" Inertial Confinement scheme)
- nonlinear optics
- radiation sources (X, γ)
- particle acceleration

Experimental work @ DF :

- D. Giulietti (laser electron acceleration, X- and -ray sources, ...)
- F. Giammanco (nonlinear optics, multiphoton ionization ...)

The new era of
Laser Ion Acceleration
(mainly protons):
discovery and applications

The discovery of MeV proton emission in superintense interaction with *metallic* targets



Reported in 2000
by three experimental groups

[Clark et al, PRL **84** (2000) 670;
Maksimchuk et al, *ibid.*, 4108;
Snavely et al, PRL **85** (2000) 2945]

Question: origin of protons from metal?

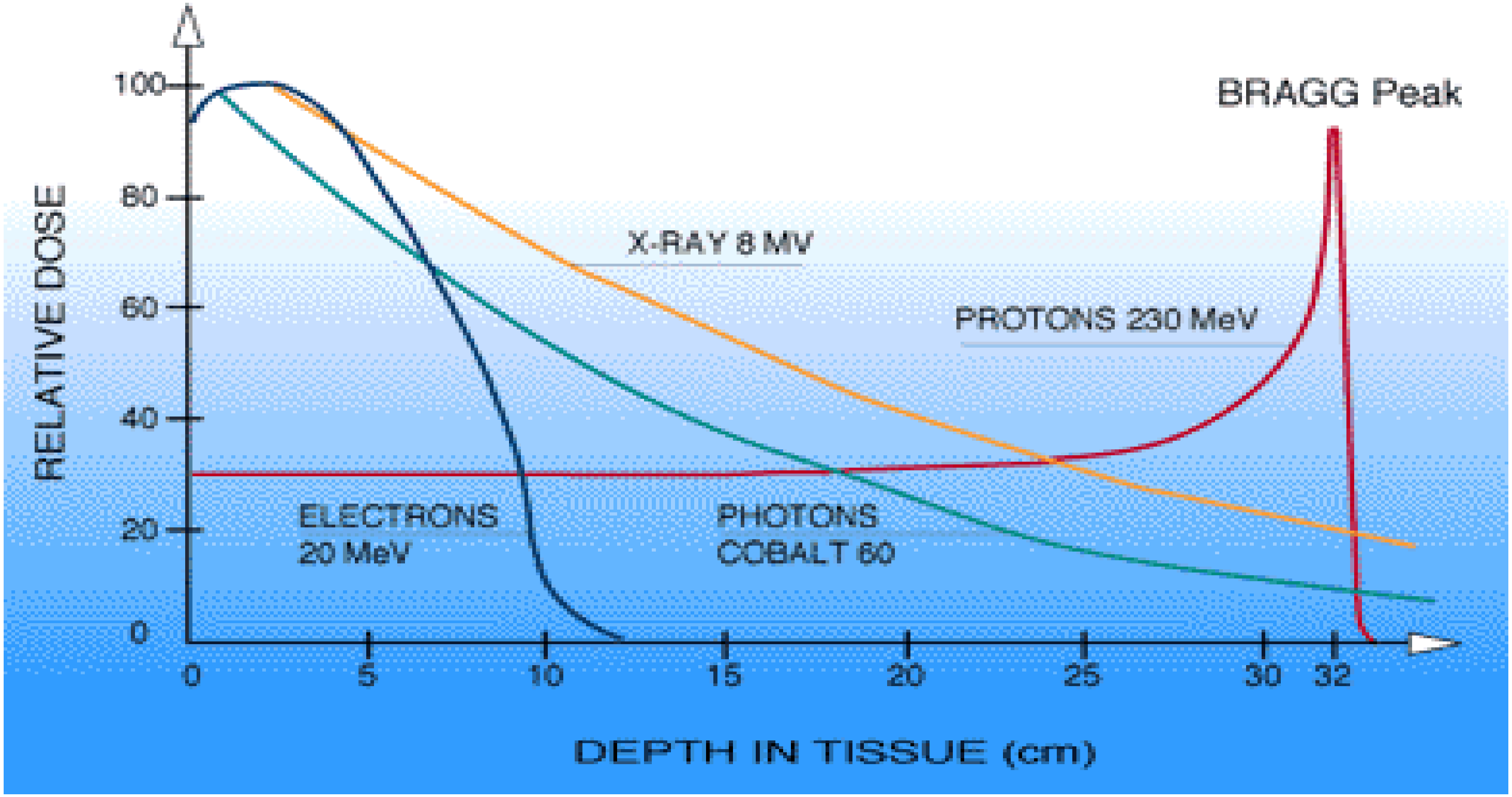
Answer: hydrocarbon impurities on the target surface (from vacuum pump oil ...)

Remarkable properties of the proton beam:

- **high number** (up to 10^{14})
- **good collimation**
- **ultra-low emittance** (4×10^{-3} mm mrad)
- maximum energy and efficiency observed: **58 MeV** , **12% of laser energy** @ $I=3 \times 10^{20}$ W/cm^2

MeV protons (ions) are appealing for applications requiring localized energy deposition in matter

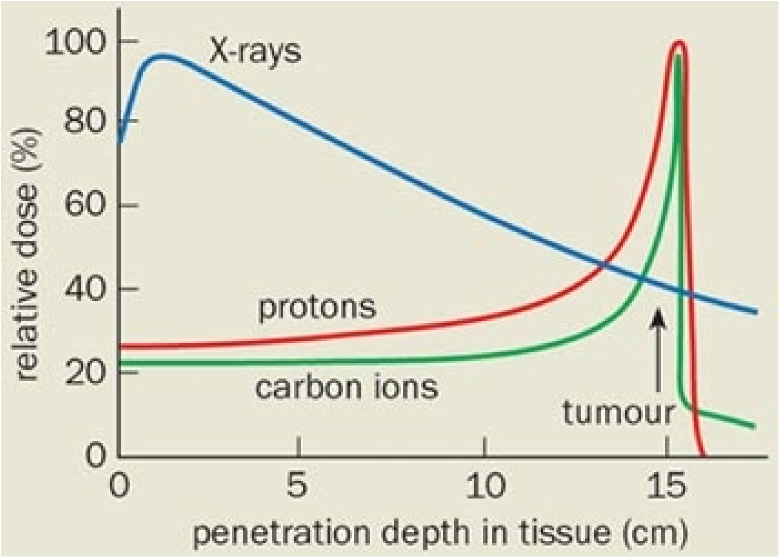
Sharp maximum of deposited energy
(Bragg peak)
Peak location depends on energy

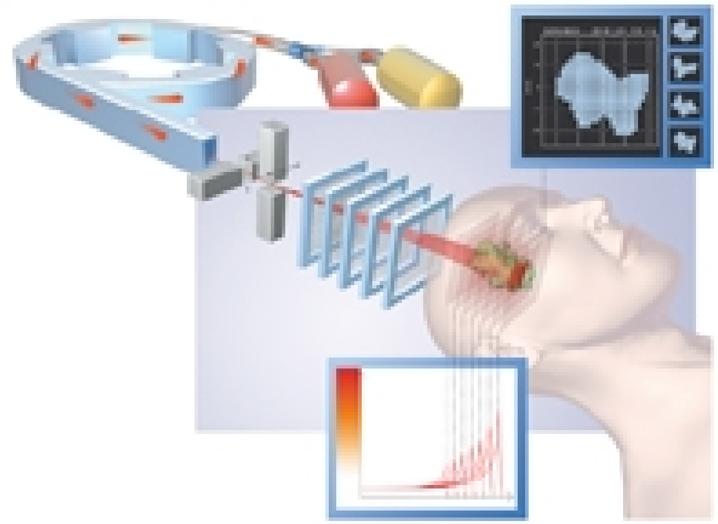


MeV protons (ions) are appealing for applications requiring localized energy deposition in matter

Medical Applications

ONCOLOGICAL HADRONTHERAPY





[K.Ledingham, Glasgow University, 2006]

If feasible with table-top, high repetition lasers,
cost can be reduced with respect to an accelerator facility

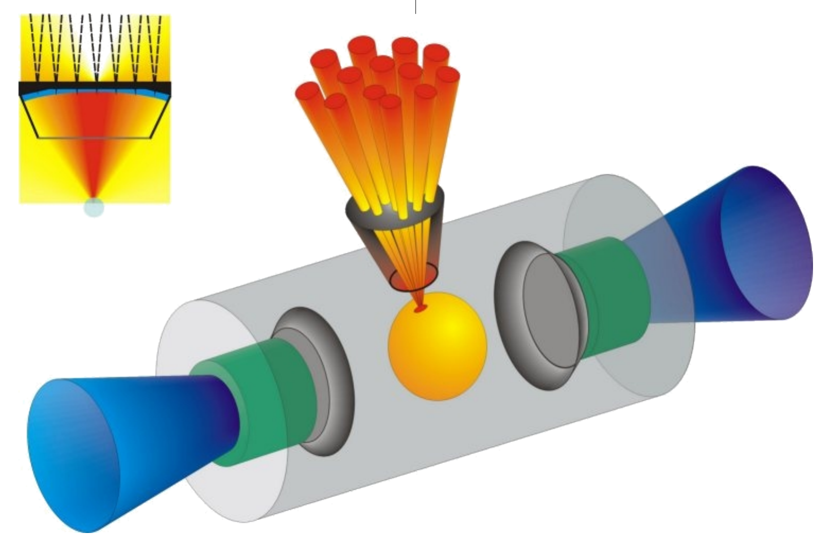
Other foreseen application in medicine:
isotope production (e.g. for Proton Emission Tomography)

MeV protons (ions) are appealing for applications requiring localized energy deposition in matter

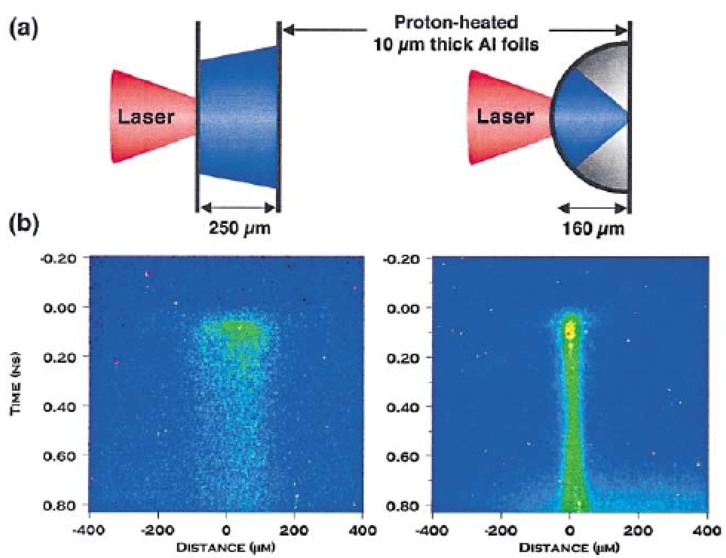
Inertial **C**onfinement **N**uclear **F**usion

FAST IGNITION

Protons can be used to create a "spark" in a pre-compressed ICF capsule achieving isochoric burn and high energy gain



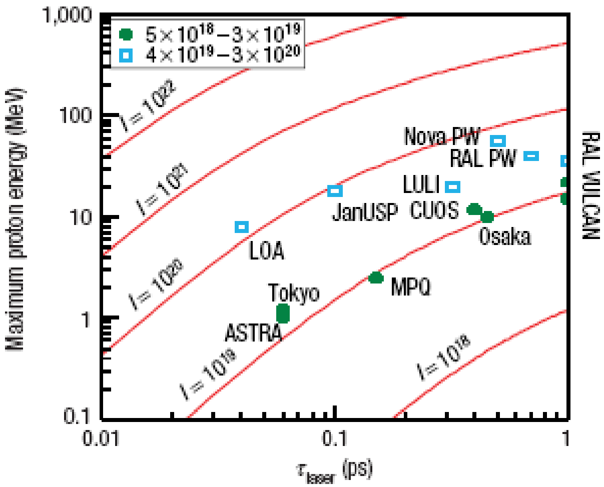
[Roth et al, Phys. Rev. Lett. **86** (2001) 436;
Atzeni et al, Nuclear Fusion **42** (2002) L1;
Macchi et al, Nuclear Fusion **43** (2003) 362]

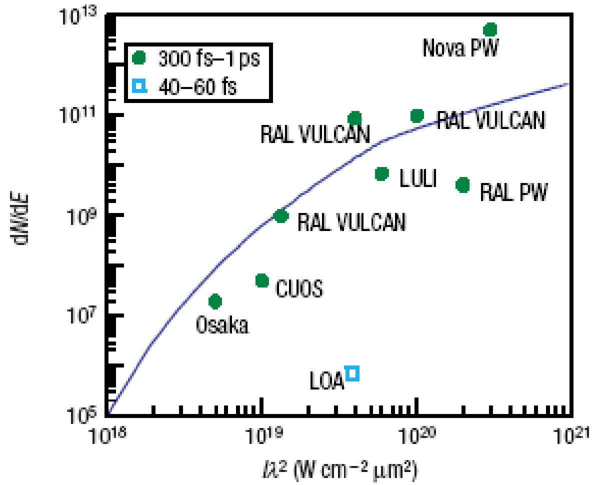


Geometrical focusing of laser-accelerated protons and localized isochoric heating has been demonstrated

[Patel et al, Phys. Rev. Lett. **91** (2003) 125004]

Experimental State of the Art (quick look)





Scaling of ion energy and number is promising for medical and fusion applications

From: M.Borghesi et al, Fusion Science & Technology **49** (2006) 412; J. Fuchs et al, Nature Physics **2** (2005) 48 .

Most recent results:

- narrow energy spectrum of protons from engineered double-layer target
[H. Schwoerer et al, Nature **439** (2006) 445]

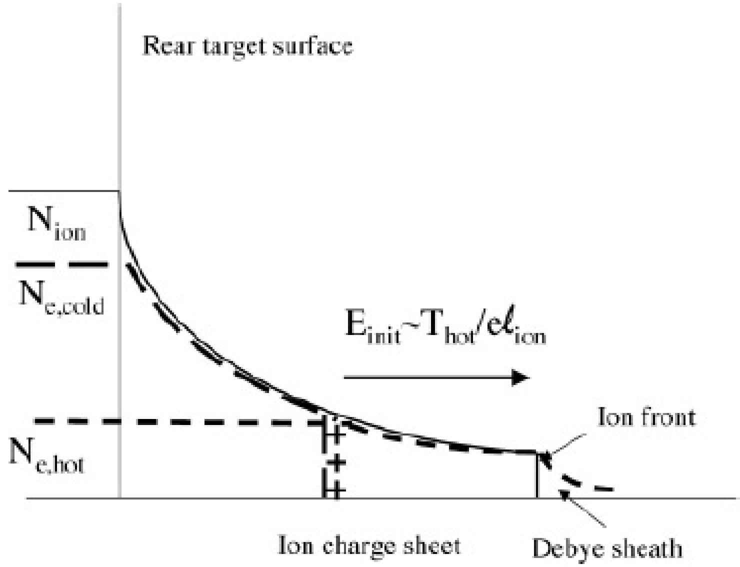
- MeV carbon ions from pre-heated (“decontaminated”) target
[B. Hegelich et al, Nature **439** (2006) 441]

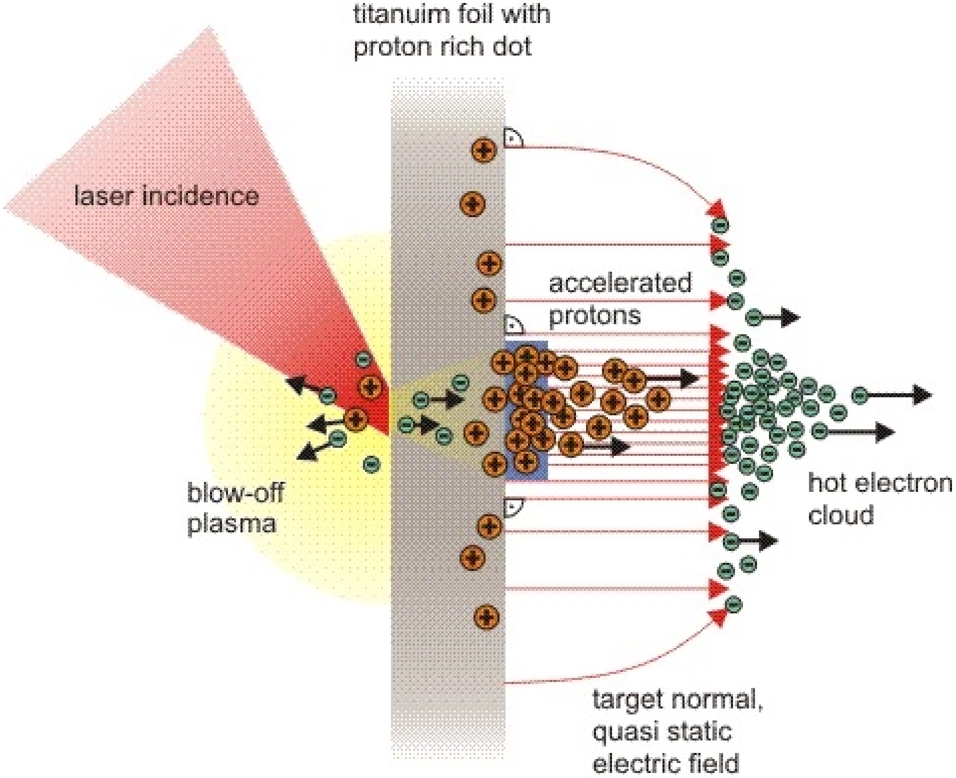
- Ultrafast “laser-plasma microlens” for ion beam focusing and energy selection
[Toncian et al, Science **312** (2006) 410]

Unfolding the physics of laser-plasma acceleration of protons (and using laser-accelerated protons to unfold the physics of laser-plasma interactions)

What are the ion acceleration mechanisms?

The dominant mechanism in present-day experiments is "sheath acceleration": "hot" relativistic electrons escaping from the rear side electrostatically drag ions (mostly protons at the surface)





- replacing surface impurities with hydrogen-rich dot increases yield and leads to narrower spectrum

[H. Schwoerer et al, Nature **439** (2006) 445]

- removing impurities lead to acceleration of heavier ions

[B. Hegelich et al, Nature **439** (2006) 441]

Basis of theoretical and numerical modeling

"Plasma physics is just waiting for bigger computers"

Vlasov-Maxwell system for *collisionless*, *classical* plasmas: kinetic equations are coupled to EM fields

$$\frac{df_a}{dt}(\mathbf{x},\mathbf{p},t) = \frac{\partial f_a}{\partial t} + \dot{\mathbf{x}}_a \frac{\partial f_a}{\partial \mathbf{x}} + \dot{\mathbf{p}}_a \frac{\partial f_a}{\partial \mathbf{p}} = 0, \quad a = (e, i)$$

$$\dot{\mathbf{p}}_a = q_a(\mathbf{E} + \mathbf{v} \times \mathbf{B}), \qquad \dot{\mathbf{x}}_a = \frac{\mathbf{p}_a}{m_a \gamma_a},$$

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

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

Mostly used numerical approach: particle-in-cell (PIC) method
[Birdsall & Langdon, *Plasma Physics via Computer Simulation* (IOP, 1991)]

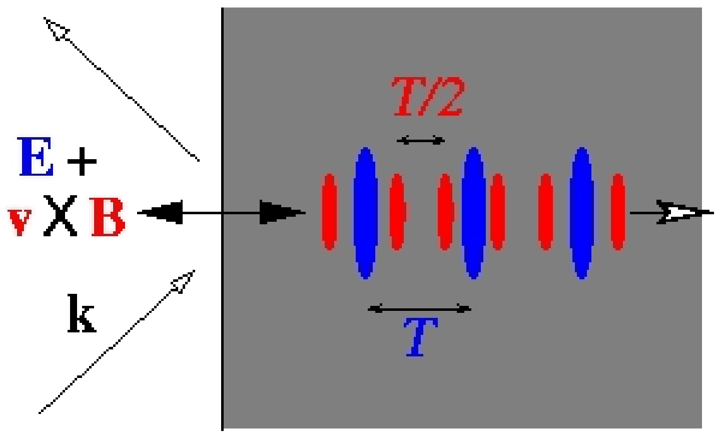
3D numerical simulations of "realistic" experimental conditions is most of the times beyond present-day supercomputing power

Models are needed to interpretate experiments and unfold the underlying physics

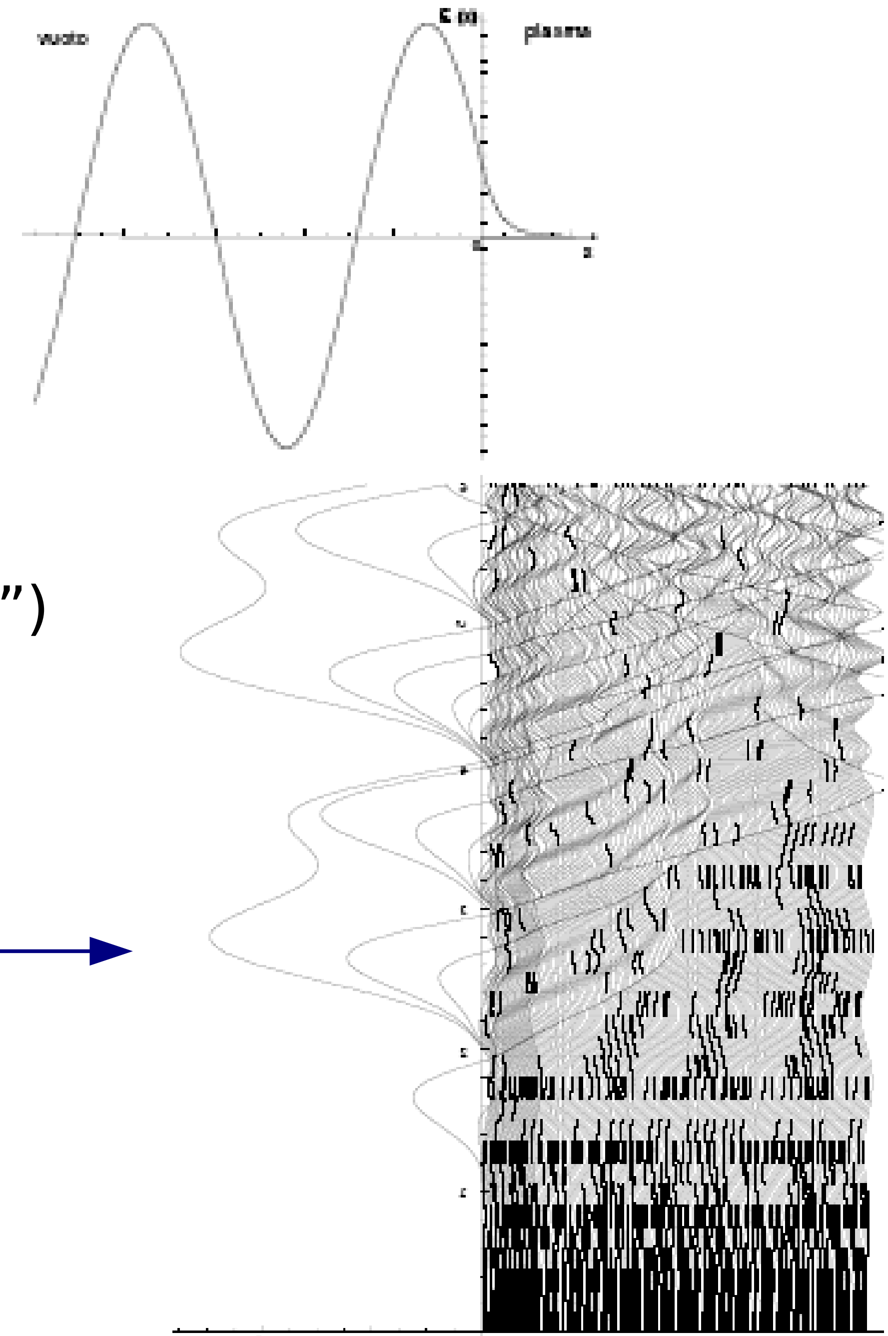
On the origin of “fast” electrons

Forced oscillations of electrons across a sharp plasma interface *($L << \lambda$)* are strongly non-adiabatic and lead to energy absorption from the EM (laser) wave

As can be shown with a simple electrostatic model at each cycle electron bunches are ejected into the vacuum region and re-enter the plasma with high momentum (“vacuum heating”)
[Brunel, PRL **59** (1987) 52]



The **E**$_\perp$ and **v**X**B** components drive electron bunches with different periodicity ($T=2\pi/\omega$ and $T/2$)



S. Tuveri, thesis, 2006

Modeling of sheath acceleration: the problem of plasma expansion in vacuum

Analytical approach:

- electrostatic approximation
- fluid ions
- electrons in Boltzmann equilibrium

$$n_e = n_0 \exp\left(\frac{e\Phi}{k_B T_e}\right), \qquad \nabla^2\Phi = Zen_i - en_e$$

$$M_i \frac{d\mathbf{v}_i}{dt} = Ze\mathbf{E} = -Ze\boldsymbol{\nabla}\Phi, \quad \partial_t n_i = \boldsymbol{\nabla}\cdot(n_i \mathbf{v}_i)$$

Numerical PIC approach:

- electrostatic approximation
- kinetic ions and electrons
- “fast” electron temperature and density as input parameters

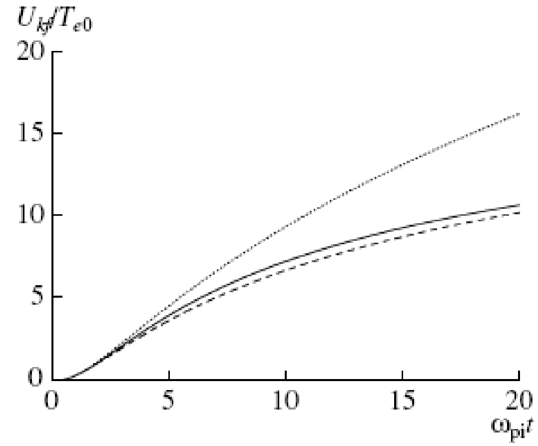


Fig. 3. The kinetic energy acquired by the fastest ion during the expansion of a slab of total thickness $2a = 40$ as predicted by the numerical simulations (solid line), by the analytical model (dashed line), and by the semi-infinite model [11] (dotted line).

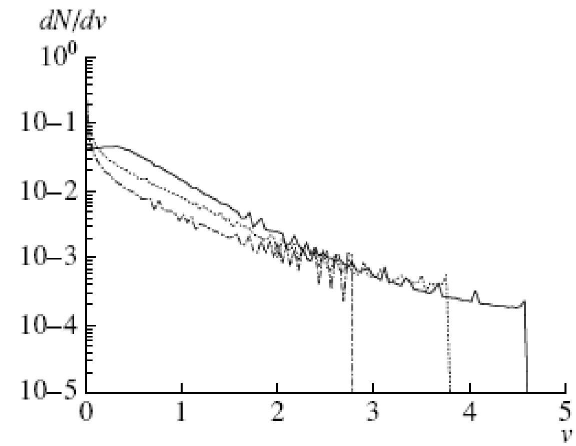
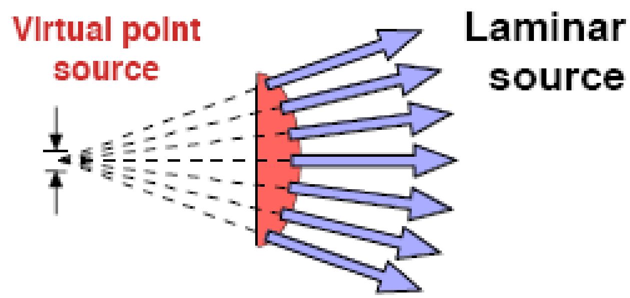


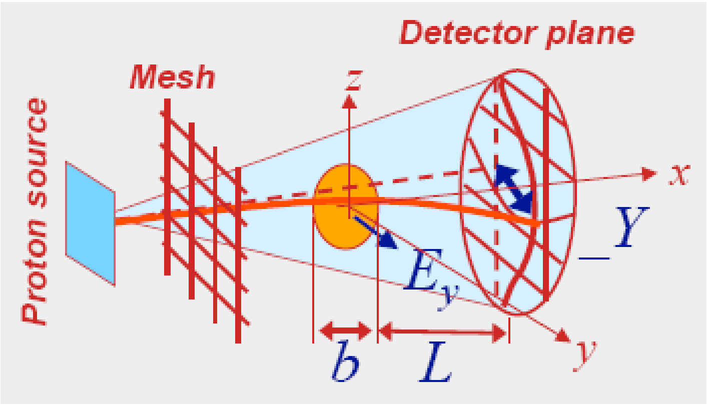
Fig. 4. Ion velocity spectrum at $\tau = 5$ (dashed line), $\tau = 10$ (dotted line), and $\tau = 20$ (solid line). The initial slab total size is $2a = 40$ and v is normalized to the initial sound speed.

S.Betti, F.Ceccherini, F.Cornolti, F.Pegoraro, Plasma Phys. Control. Fusion **47** (2005) 521
F.Ceccherini, S.Betti, F.Cornolti, F.Pegoraro, Laser Physics **16** (2006) 1

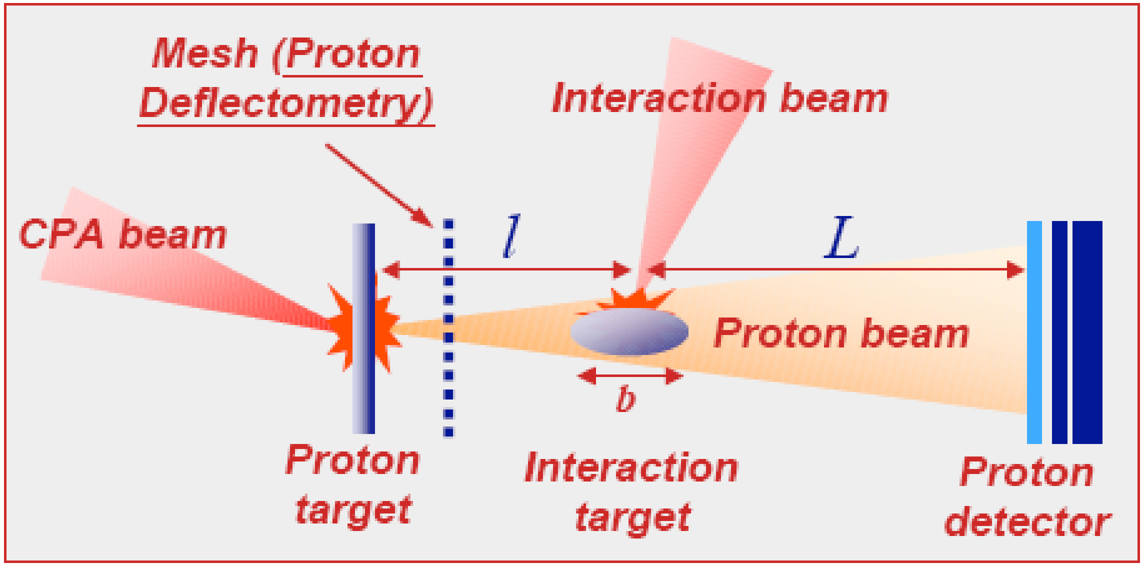
How to diagnose the electric fields directly?
Idea: use the protons as a probe

Due to high laminarity the proton beam has **imaging properties**





The short duration of the proton burst allows **picosecond temporal resolution**

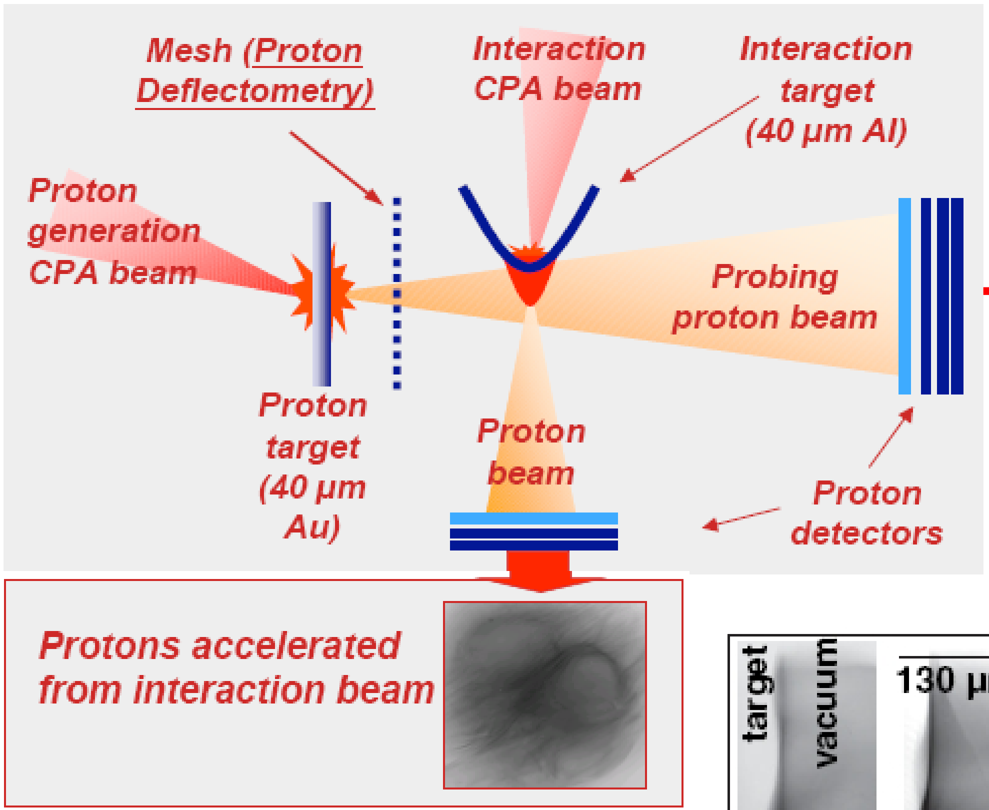


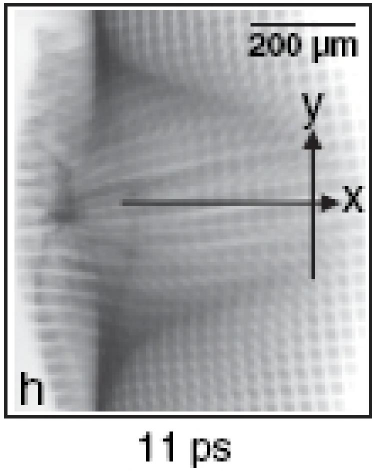
Borghesi et al, Phys.Plasmas **9** (2002) 2214
Borghesi et al, Phys.Rev.Lett. **92** (2004) 055003
Cowan et al, Phys.Rev.Lett. **92** (2004) 204851

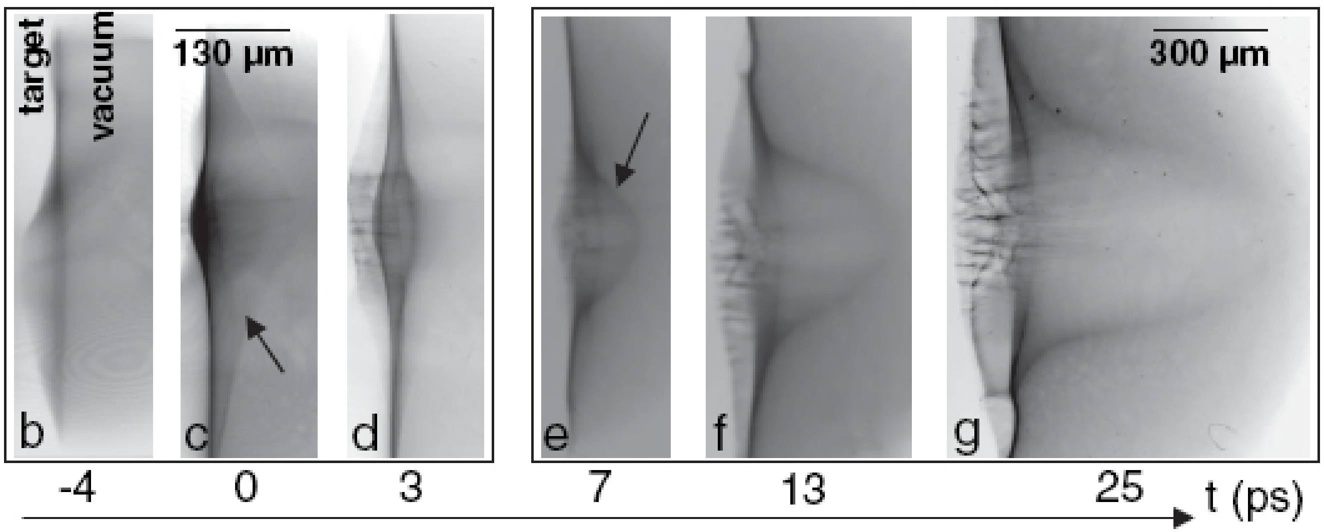
Protons of a given energy will cross the probed object at a particular time.
An energy-resolving detector (e.g. Radiochromic Film) thus provides **multiframe capability**

In a laser-plasma experiment the proton probe is easily **synchronized with the interaction**

Experimental detection of sheath fields using the proton diagnostic





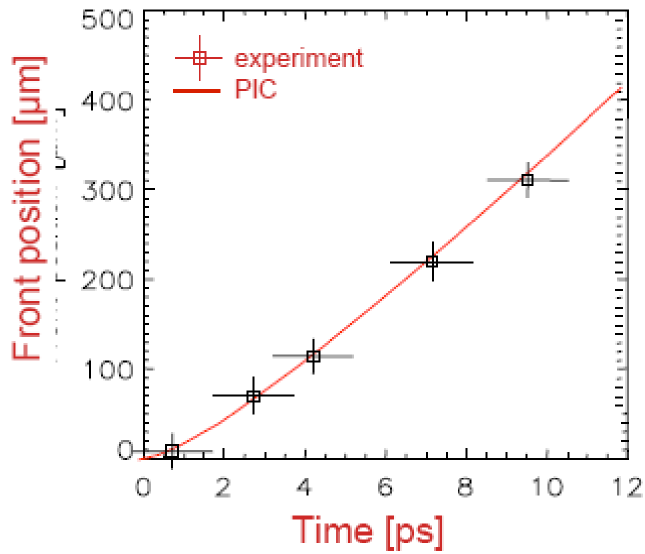


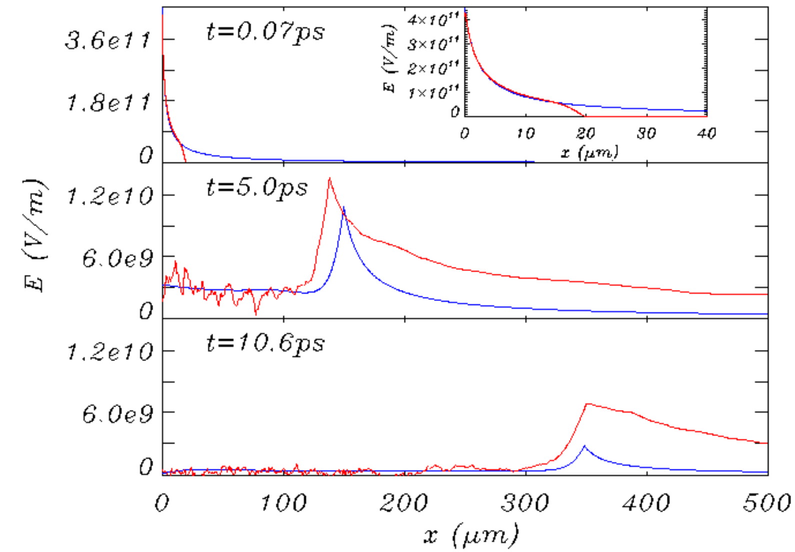
Expanding, bell-shaped electric field front observed in proton images and deflectograms

L. Romagnani, J. Fuchs, M. Borghesi, P. Antici, P. Audebert, F. Ceccherini, T. Cowan, T. Grismayer, S. Kar, A. Macchi, P. Mora, G. Pretzler, A. Schiavi, T. Toncian, O. Willi, Phys. Rev. Lett. **95** (2005) 195001

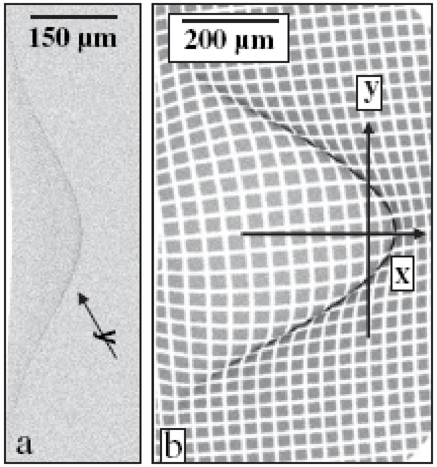
Experimental detection of sheath fields using the proton diagnostic

Experimental results have been compared with PIC simulations using the plasma expansion model.





Particle tracing simulations of proton deflection in the PIC fields well reproduce experimental images and deflectrograms



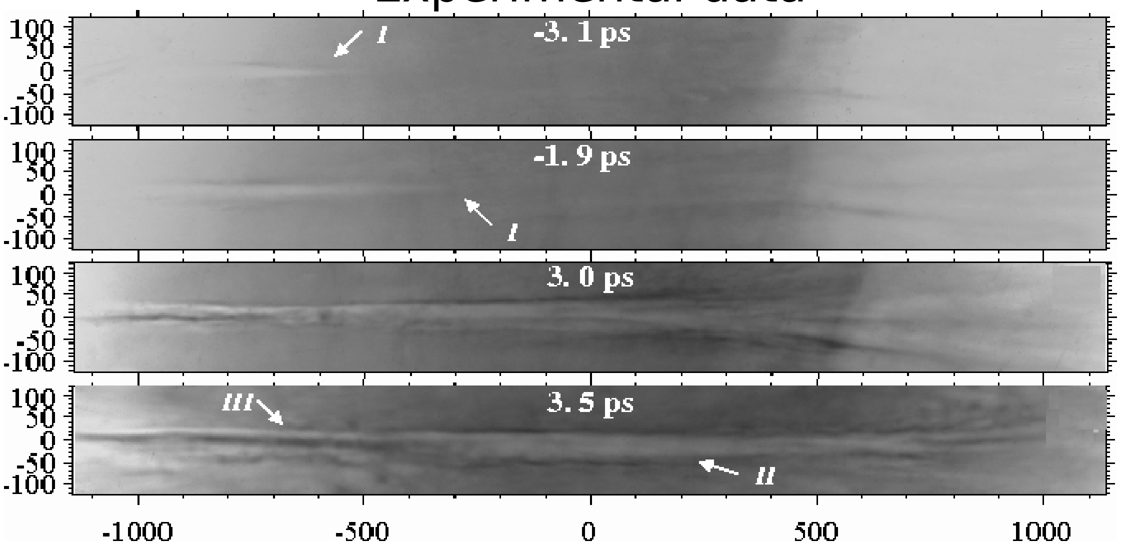
Comparison of fluid and kinetic (PIC) results show the importance of kinetic and non-thermal effects in the plasma expansion

L. Romagnani, J. Fuchs, M. Borghesi, P. Antici, P. Audebert, F. Ceccherini, T. Cowan, T. Grismayer, S. Kar, A. Macchi, P. Mora, G. Pretzler, A. Schiavi, T. Toncian, O. Willi, Phys. Rev. Lett. **95** (2005) 195001

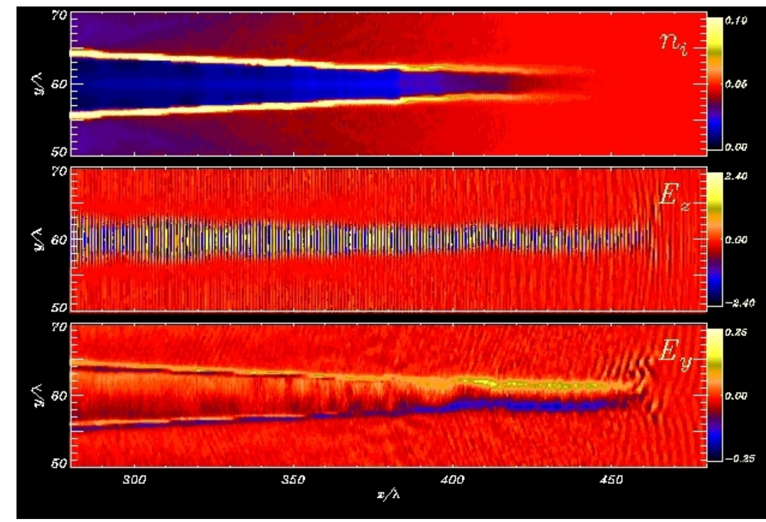
Study of charge-displacement self-channeling

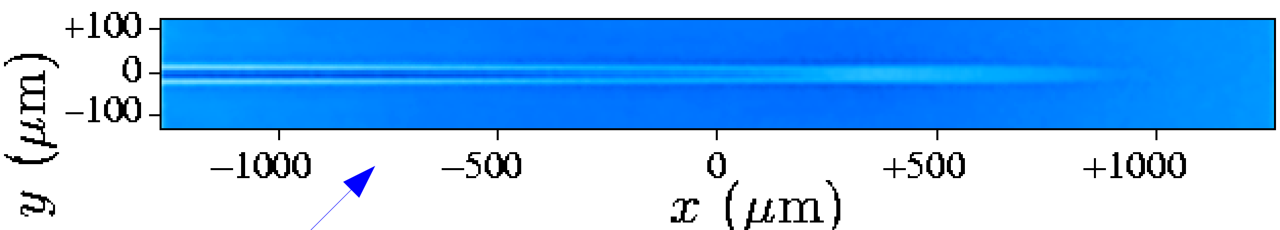
A superintense laser pulse propagating in a low-density gas jet pushes away electrons from the axis creating a charged channel

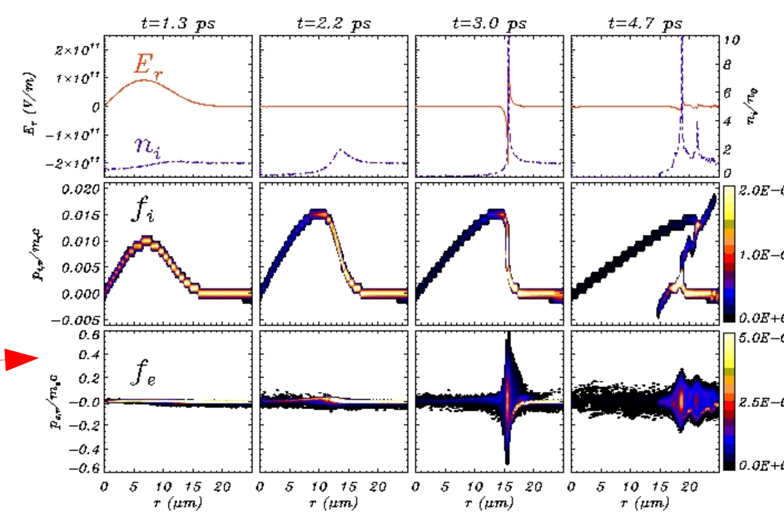
Experimental data



2D PIC simulations





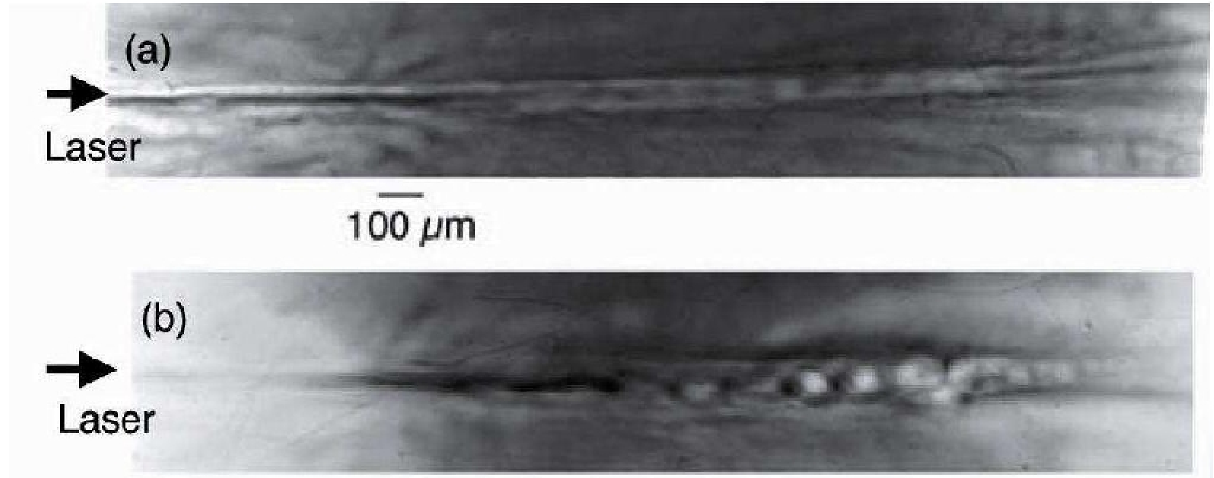


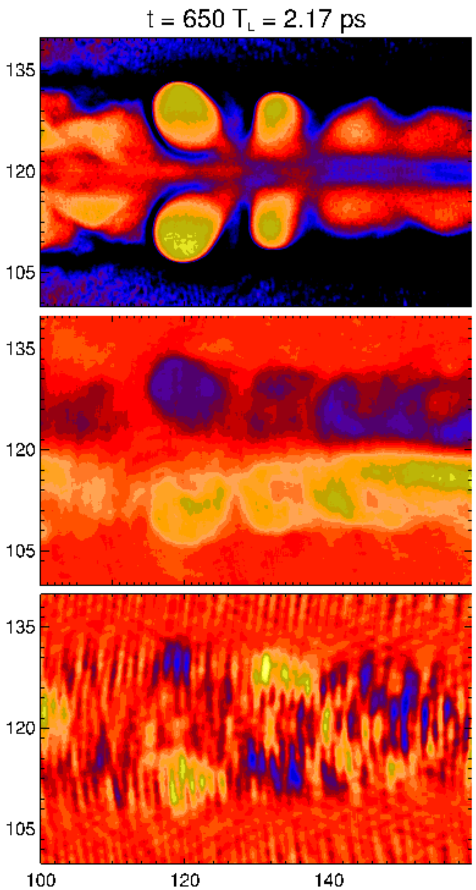
Simulated images using fields from a 1D PIC model agree well with experiment

- S.Kar, M.Borghesi, C.A.Cecchetti, L.Romagnani, F.Ceccherini, T.V.Lyseikina, A. Macchi, R.Jung, J.Osterholz, O.Willi, M.Galimberti, L.A.Gizzi, J.Fuchs, A.Schiavi, R.Heathcote, submitted to PRL (2006)

Study of coherent field structures

At late times regular, slowly evolving structures appear in the laser-drilled channel



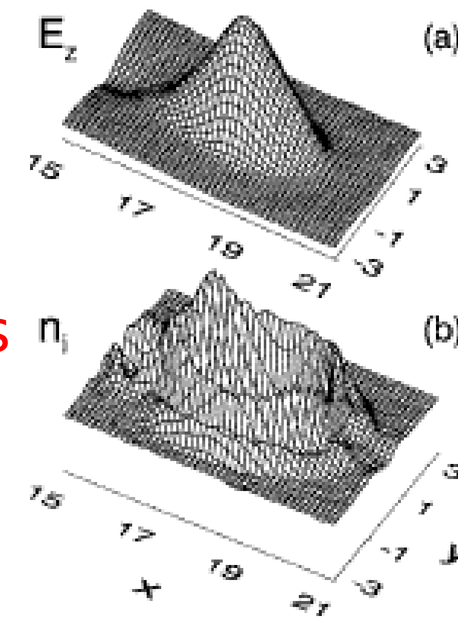


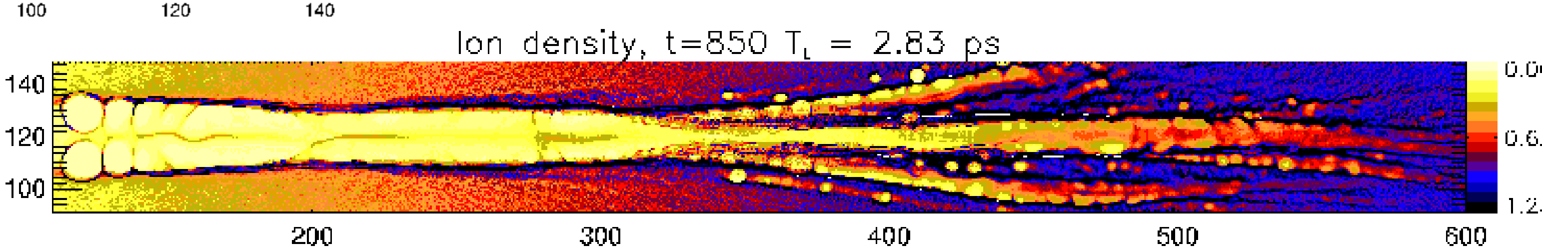
2D PIC simulations show the generation of coherent electromagnetic structures:

- sub-cycle EM **solitons** or cavitons

- magnetic **vortices**

- “hybrid” (mixed) structures?





Advanced schemes for Laser Ion Acceleration and future perspectives

What's next in Laser Ion Acceleration?

Goals:

- increase energy (can we go for **GeV** relativistic ions?)
- increase efficiency of laser energy conversion into ions
- improve spectrum, beam quality, repetition rate, ...

Three questions at least:

1 - Is the “fast electron” sheath mechanism the only route to LIA?

2 - If alternative routes exist, which is the best one for specific present applications and/or to achieve LIA in the relativistic ion regime?

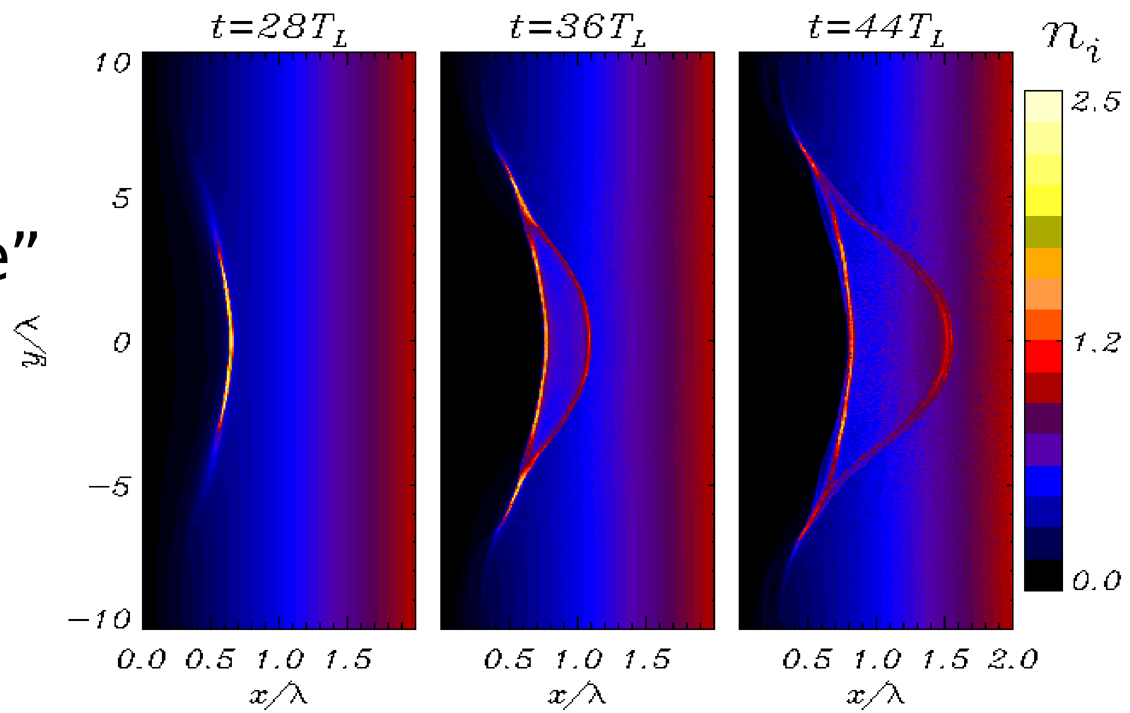
3 - Do we expect further progress in laser sources (higher intensity, higher repetition rate, ...) which can sustain novel advanced concepts of LIA and/or open a way to new applications?

Enough motivations for exploring “Advanced LIA Schemes”

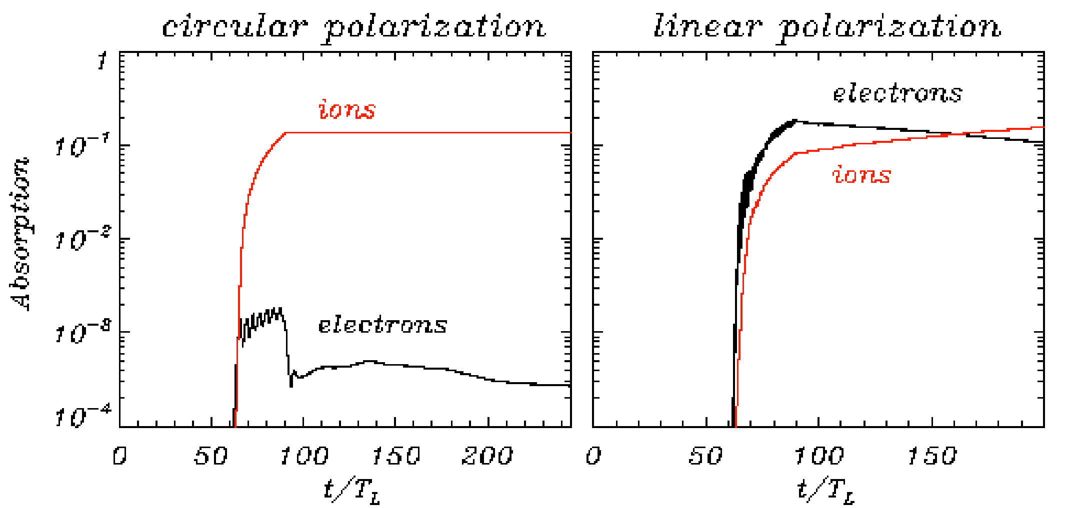
Proposed LIA with Circular Polarization ("*without fast electrons*")

[Macchi et al, Phys.Rev.Lett. **94**, 165003 (2005)]

Using circular polarization fast electron generation is inhibited: LIA is purely "ponderomotive" i.e. driven directly by the radiation pressure



Features:
high efficiency,
large ion numbers,
good collimation,
narrow energy spectrum;



production of a single ultrashort ion bunch possible with femtosecond pulses

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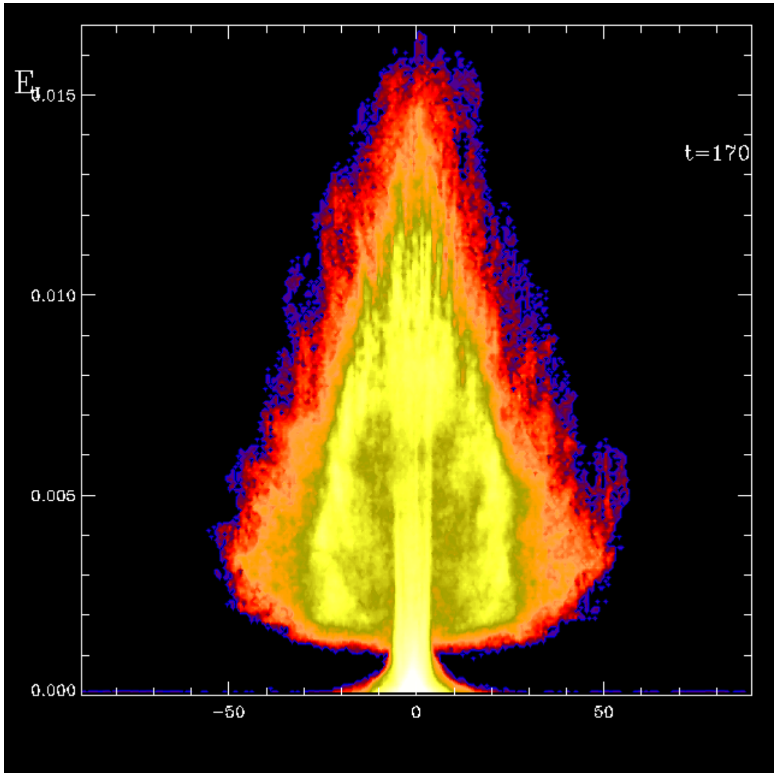
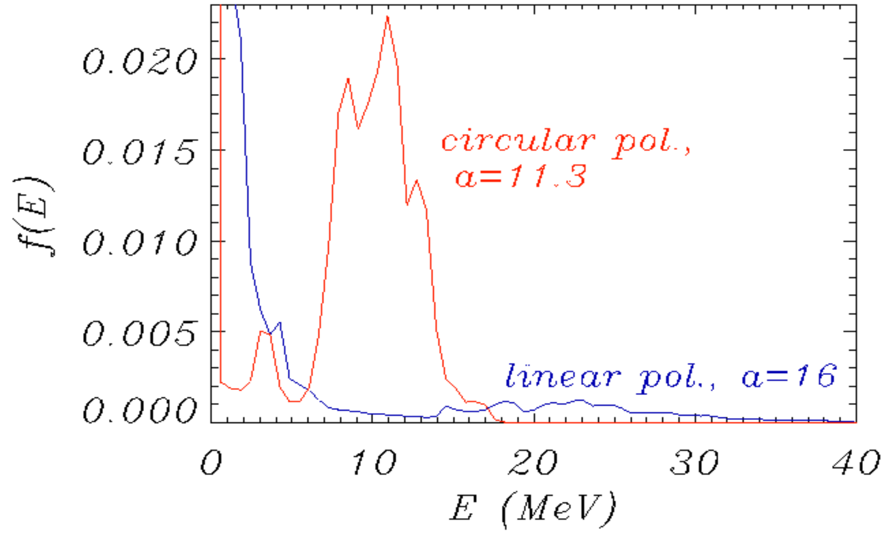
possible with
femtosecond pulses





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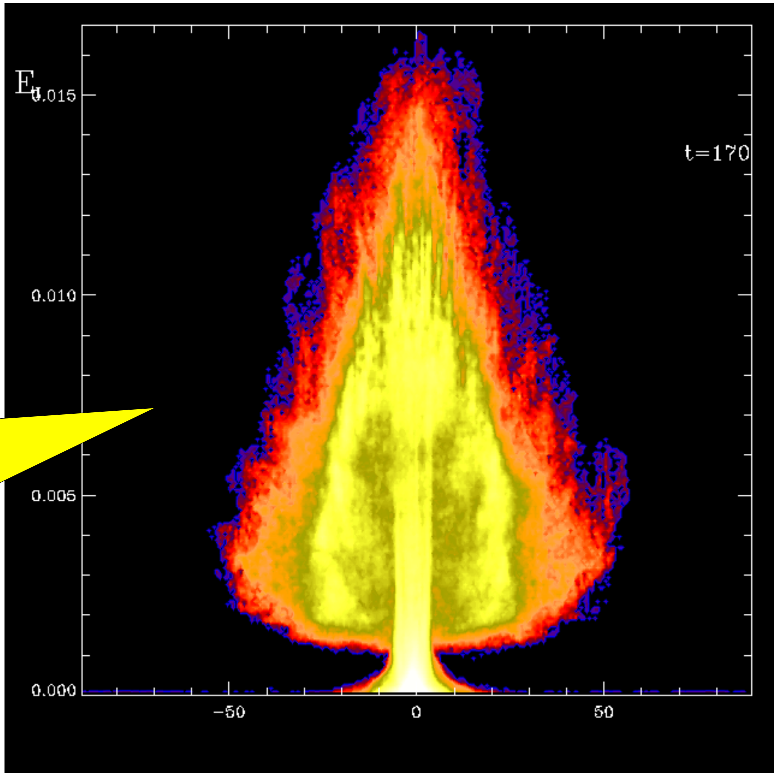
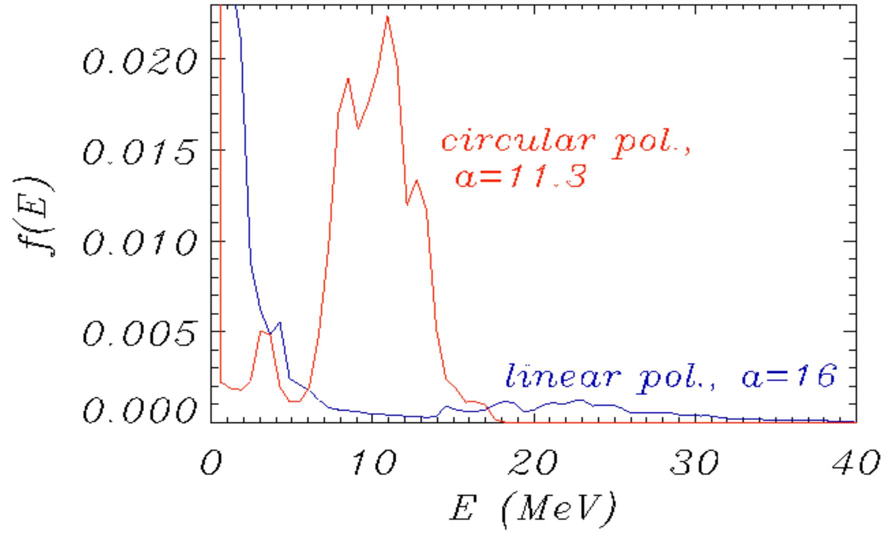
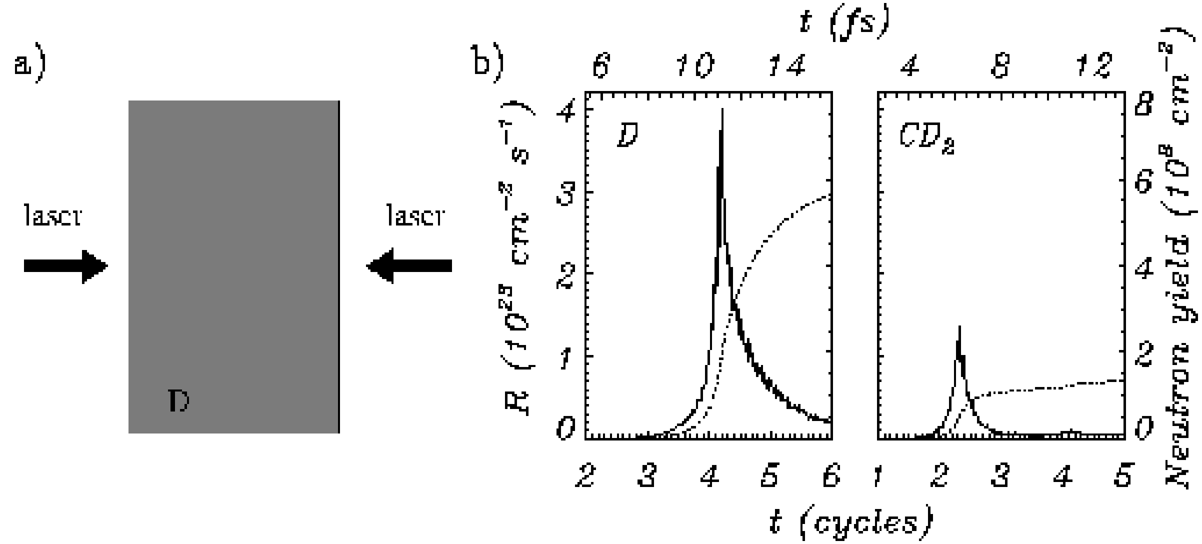
The “Xmas tree” is a contour plot of ion energy vs. emission angle, showing a high and energy-dependent collimation



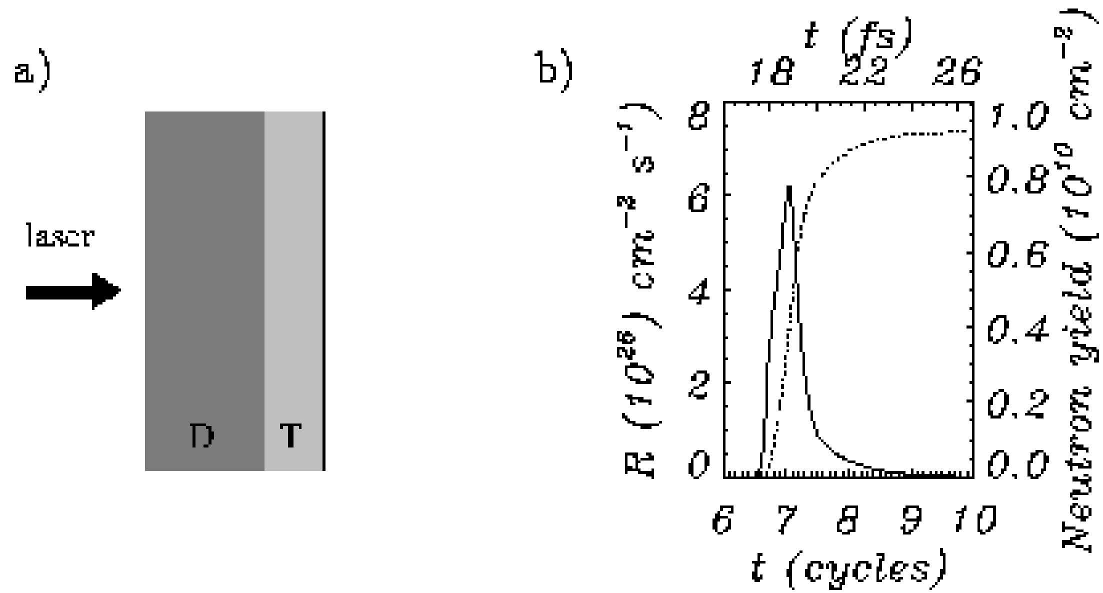


An application of circularly polarized LIA

Driver of beam fusion reactions in D or DT targets for a proposed scheme of a femtosecond source of MeV neutrons
[A. Macchi, Appl.Phys.B **82**, 337 (2006)]



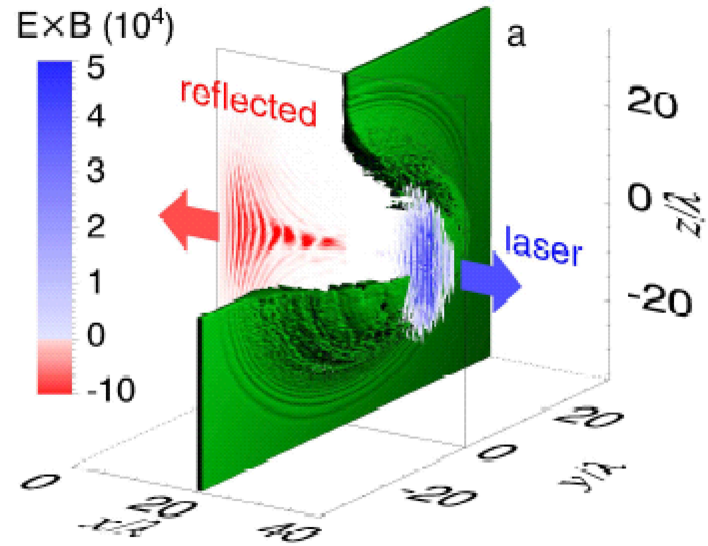
A source for ultrafast control of nuclear processes and time-resolved spectroscopy of nuclei?



Relativistic ions: the Laser-Piston regime

Ultra-relativistic interaction regime dominated by radiation pressure

T.Esirkepov, M.Borghesi, S.V.Bulanov, G.Mourou, T.Tajima, PRL **92**, 175003 (2004)

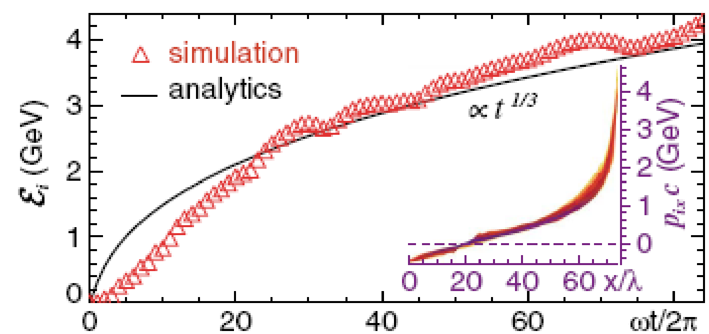


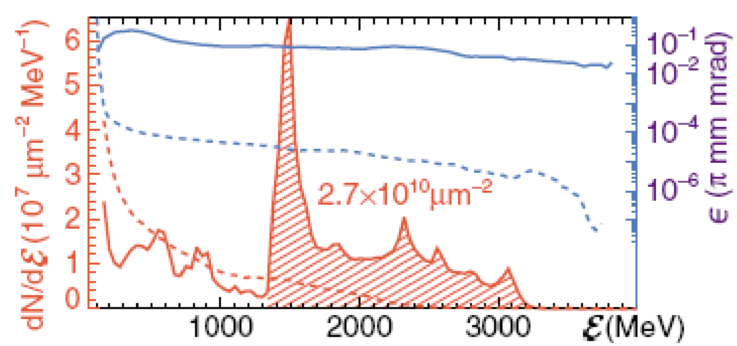
Required laser intensity

$I=10^{23}$ W/cm^2

The foreseen ion beam parameters make this attractive as a driver of low-energy neutrino sources for studies of CP violation

in $\nu_\mu \rightarrow \nu_e$ oscillations





S.V.Bulanov, T.Esirkepov, P.Migliozzi, F.Pegoraro, T.Tajima, F.Terranova, NIM A **540**, 133 (2005); F. Terranova, S.V.Bulanov, J.L.Collier, H.Kiriyama, F.Pegoraro, NIM A **558**, 430 (2006).

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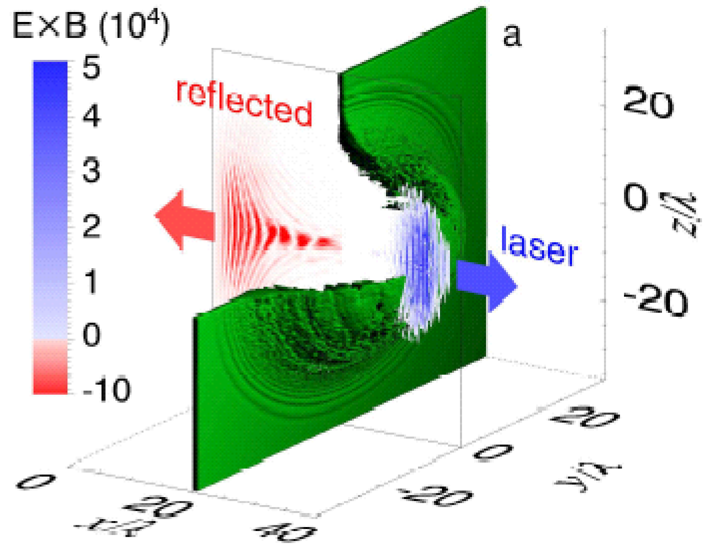
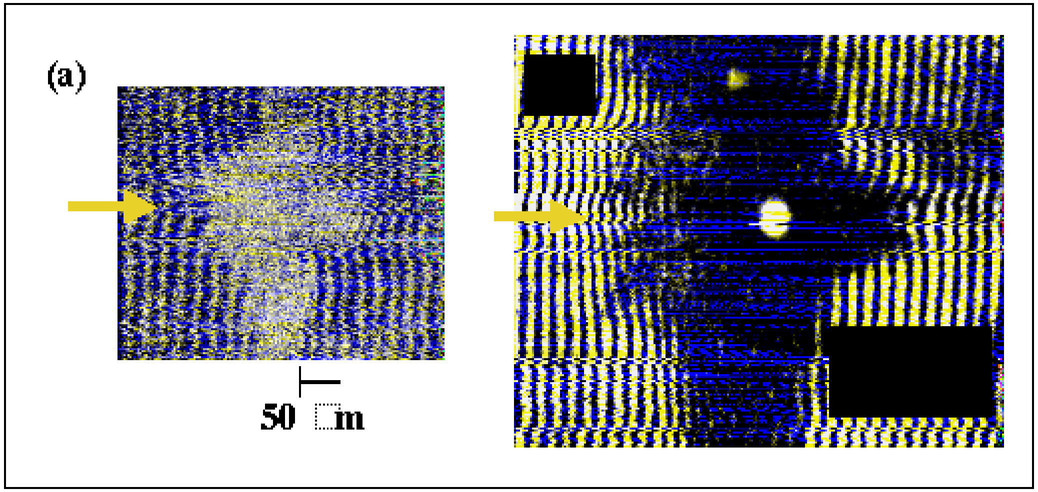


Required laser intensity for GeV ions

$I=10^{23}$ W/cm^2

Very preliminary indications of the onset of the "piston" regime were obtained in PW experiments ($I \sim 10^{20}$ W/cm^2) at Rutherford Laboratory, UK



S.Kar, M.Borghesi, L.Romagnani, A.J.MacKinnon, P.K.Patel, M.Key, A.Schiavi, O.Willi, A.Macchi, RAL CLF annual report 2003-2004, p.24
http://www.clf.rl.ac.uk/reports/2003-2004/pdf/16.pdf

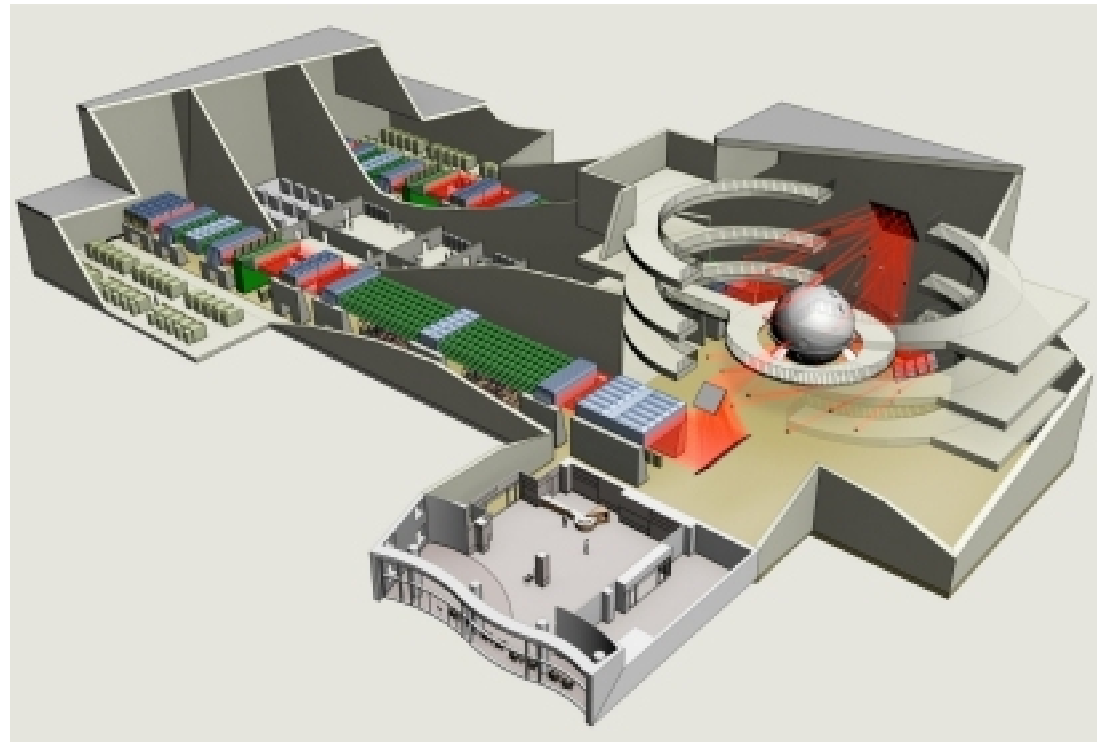
Two ultraintense laser facilities for the future?

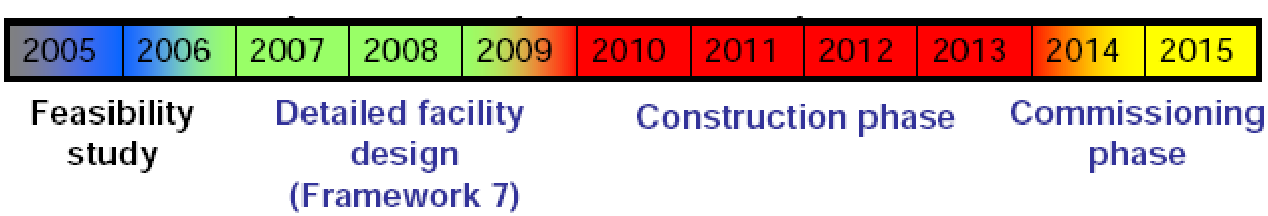
Two proposals have been accepted on the European (ESFRI) roadmap of future research infrastructures in October 2006:

HiPER -
High Power laser
Energy Research facility

Mission: demonstrating the feasibility of laser driven fusion as a future energy source

Laser Pulse:
10 ps = 10^{-11} s
7 PW = 7×10^{15} W





http://www.hiper-laser.org

Two ultraintense laser facilities for the future?

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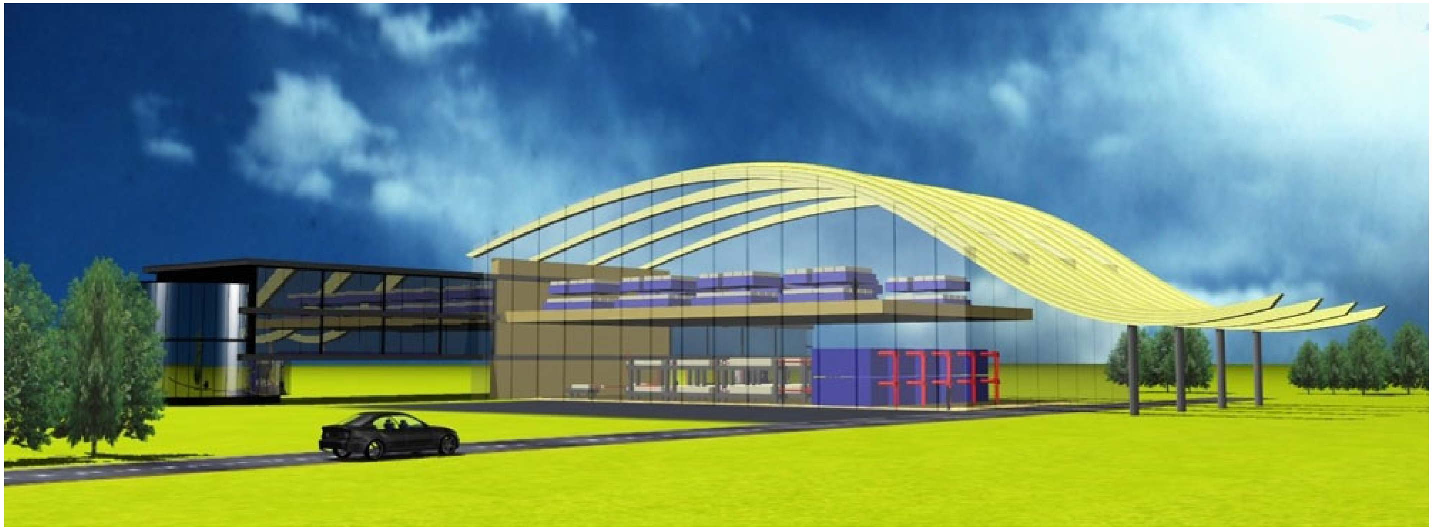
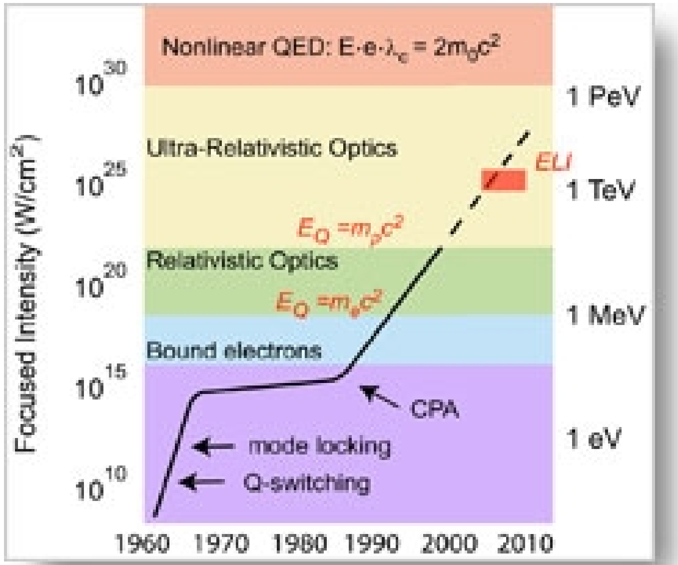
ELI -
Extreme Light
Infrastructure



Mission:
ultra-relativistic
interactions,
electron and ion
acceleration,
attosecond science,
fundamental physics ...



Laser Pulse:
~10 fs = 10^{-14} s
10^{23} W/cm^2 -> beyond **10^{26} W/cm^2**
(using laser-plasma compression techniques)

http://www.eli-laser.eu

What might be investigated with ultra-high intensities?

- *Nuclear and particle physics*: using ions to produce pions, neutrinos, and induce nuclear transmutations

- *QED physics*: approaching the Schwinger field

$$E = m_e c^2/\lambda_c = 1.3 \times 10^{18} \text{ V/m}$$

$$(I = 2.3 \times 10^{29} \text{ W/cm}^2)$$

for "vacuum breakdown" (pair creation)

- *General relativity tests*: driving extreme accelerations to generate Hawking-Unruh radiation

- ...

Conclusions

- Laser Ion Acceleration has emerged as one of the most active areas of ultraintense laser-matter interaction research

- The proton diagnostic technique allows unique capabilities to investigate laser-plasma physics: strong incitement for theory

- Several applications of laser-accelerated ions are foreseen

- Proposed ultraintense laser facilities may open new regimes of Laser Ion Acceleration and of laser-matter interaction in general

This talk may be downloaded from

www.df.unipi.it/~macchi/talks.html