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Laser-based ion acceleration: experimental evidences and introduction to a theoretical comprehension.

M. Passoni
Dipartimento di Ingegneria Nucleare, Politecnico di Milano
Milan, Italy.

M. Lontano
Istituto di Fisica del Plasma-CNR
Milan, Italy.

Laser-based ion acceleration:
experimental evidences and introduction to a theoretical comprehension

Matteo Passoni[1,2], Maurizio Lontano[2]

[1] Dipartimento di Ingegneria Nucleare, Politecnico di Milano, Milan, Italy
[2] Istituto di Fisica del Plasma-CNR, Milan, Italy

matteo.passoni@polimi.it
www.polimi.it

"Summer College on Plasma Physics", 30 july - 24 August 2007 , ICTP, Trieste Italy

General Summary

1st lecture: - an overview of experimental evidences of laser-based ion acceleration interaction

- ion acceleration mechanism

- theoretical models I
  - ➡ quasi-neutral, self-similar plasma expansion

2nd lecture: - theoretical models II
  - ➡ effects of non-neutrality
  - ➡ hydrodynamic models
  - ➡ quasi-static isothermal models

- "hot" research issues

Outline of the 1st lecture

- Introduction:
  ultraintense ultrashort (UU) laser pulse interaction with matter

- charged particle acceleration in plasmas:
  electrons, protons, heavy ions

- laser-ion acceleration:
  main experimental evidences, potential applications

- physics of the laser-based ion acceleration:
  ion acceleration mechanism, need of theoretical understanding

- theoretical preliminaries:
  quasi-neutral self-similar plasma expansion in vacuum

Introduction: laser-matter interaction

…long story, started after the invention of lasers…

Introduction of Chirped Pulsed Amplification (CPA) in 1985 determined a true revolution in the field

Basic principle of CPA:

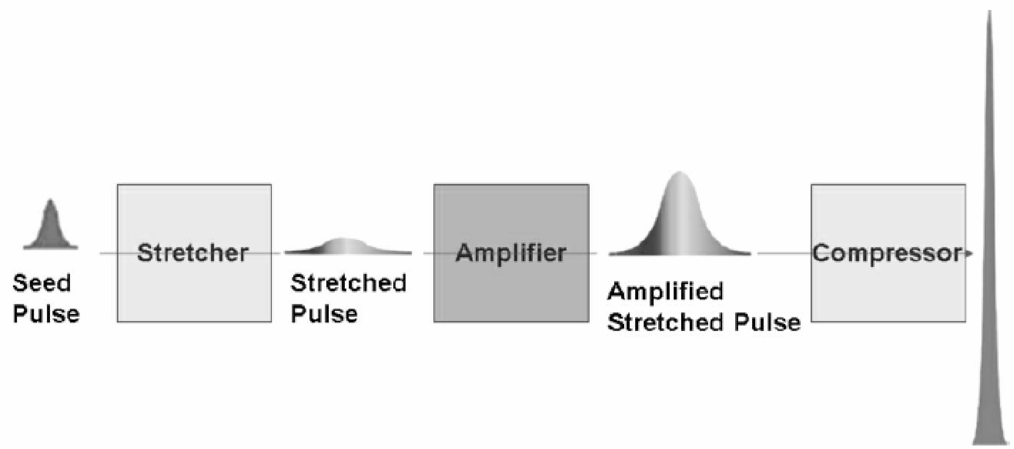


FIG. 4. Chirped pulse amplification concept. To minimize nonlinear effects the pulse is first stretched several thousand times lowering the intensity accordingly without changing the input fluence (J/cm^2). The pulse is next amplified by a factor of $10^6 - 10^{12}$ and is then recompressed by a factor of several thousand times close to its initial value.

"Optics in the relativistic regime"
G. Mourou, T. Tajima, S.V. Bulanov, *Rev. Mod. Phys.* **78**, 309 (2006)

Typical laser parameters with CPA

Laser wavelength (μm): 1 (Nd-Yag), 0.8 (Ti-Sa) 10.8 (CO_2)

Intensity (power per unit area): > few times 10^{18} W/cm^2
(5×10^{20} W/cm^2 , LLNL,'02)

Power: ≈ 100 TW - few PW (PW lines at LLNL and ILE)

Pulse duration: ≈ 10 - 10^3 fs (at λ = 1 μm, $\tau = c/\lambda$ = 3.3 fs)

Spot size at focus: down to diffraction limit → typically ø ≈ 10 μm

critical density →

$$\boxed{n_{cr} = \gamma \frac{1.1\times10^{21}}{\lambda^2(\mu m)}\text{cm}^{-3}}$$

γ : relativistic factor of the electron population

Physical fields vs. laser intensity

M. Lontano, M. Passoni, "Ultraintense electromagnetic radiation in plasmas",
Progress in Ultrafast Intense Laser Science, Springer's review book series, Vol I, (2006)

Electric field associated to the laser pulse: from $I = cE_{max}^2/8\pi$ → $\boxed{I\left(\frac{\mathrm{W}}{\mathrm{cm}^2}\right) \approx 1.4\times 10^{15} E^2\left(10^9\,\frac{\mathrm{V}}{\mathrm{cm}}\right)}$

- atomic field → $\frac{e}{a_0^2} \cong 5.15\times 10^9\,\frac{\mathrm{V}}{\mathrm{cm}} \Rightarrow I \cong 3.6\times 10^{16}\,\frac{\mathrm{W}}{\mathrm{cm}^2}$

- relativistic field → $\frac{m_e\omega c}{e} \cong \frac{3.2\times 10^{10}}{\lambda(\mu\mathrm{m})}\,\frac{\mathrm{V}}{\mathrm{cm}} \Rightarrow I \cong \frac{1.4\times 10^{18}}{\lambda^2(\mu\mathrm{m})}\,\frac{\mathrm{W}}{\mathrm{cm}^2}$

- limit for e^--e^+ equilibrium → $\nu^{cr}_{e^-,e^+} \approx \nu^{an}_{e^-,e^+} \Rightarrow I \approx 10^{20}\,\frac{\mathrm{W}}{\mathrm{cm}^2}$

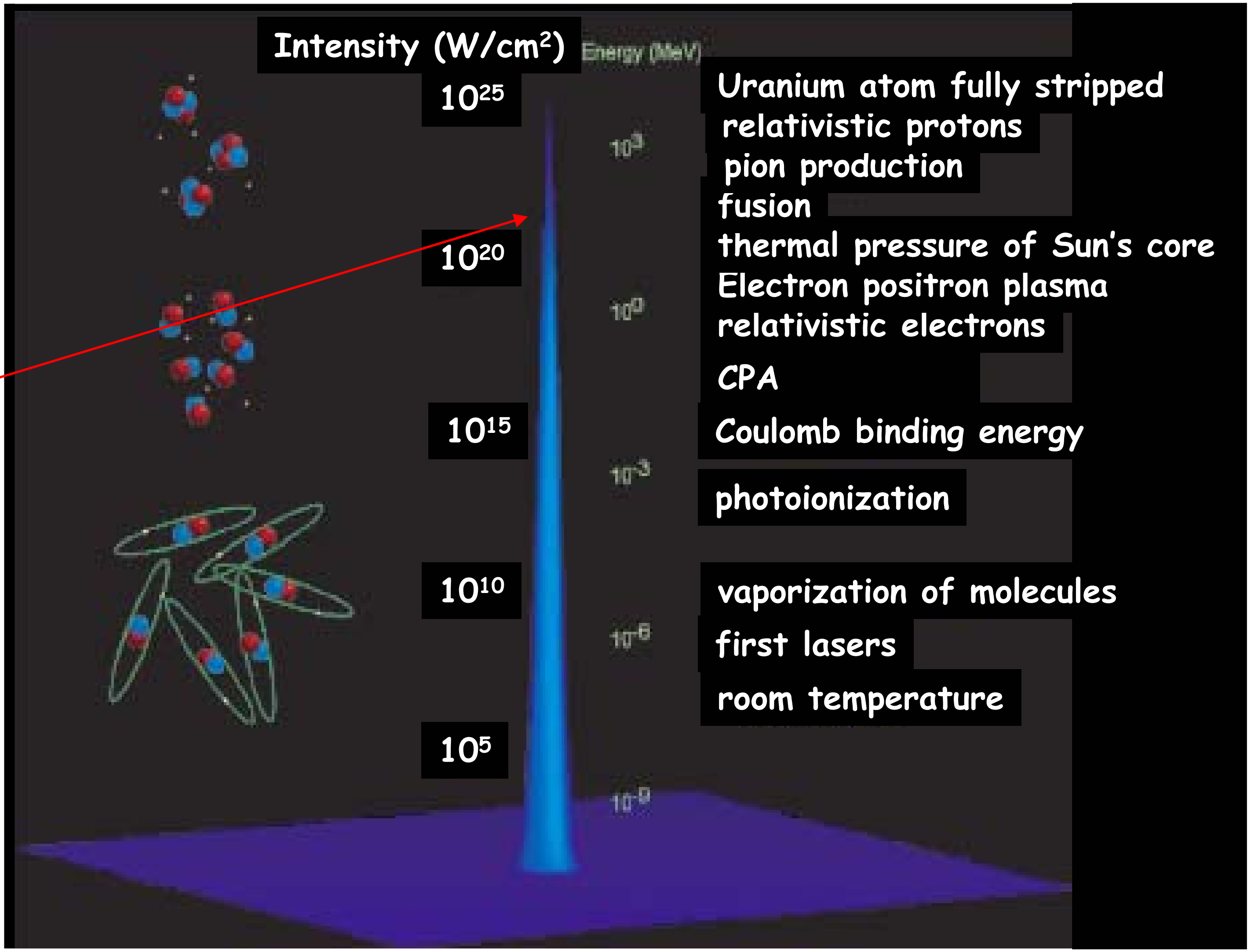
[$T_{e,hot} \approx 20\, m_ec^2$, BKZS limit in H: G.S. Bisnovaty, *et al.*, *Sov. Astr. Journal* **15**, 17 (1971)]

- Schwinger limit → $eE\lambda\!\!\!^{-}_C = 2m_ec^2 \Rightarrow E \approx 2.7\times 10^{16}\,\frac{\mathrm{V}}{\mathrm{cm}} \Rightarrow I \approx 10^{30}\,\frac{\mathrm{W}}{\mathrm{cm}^2}$

[Vacuum break-down: J. Schwinger, *Phys. Rev.* **82**, 664 (1951)]

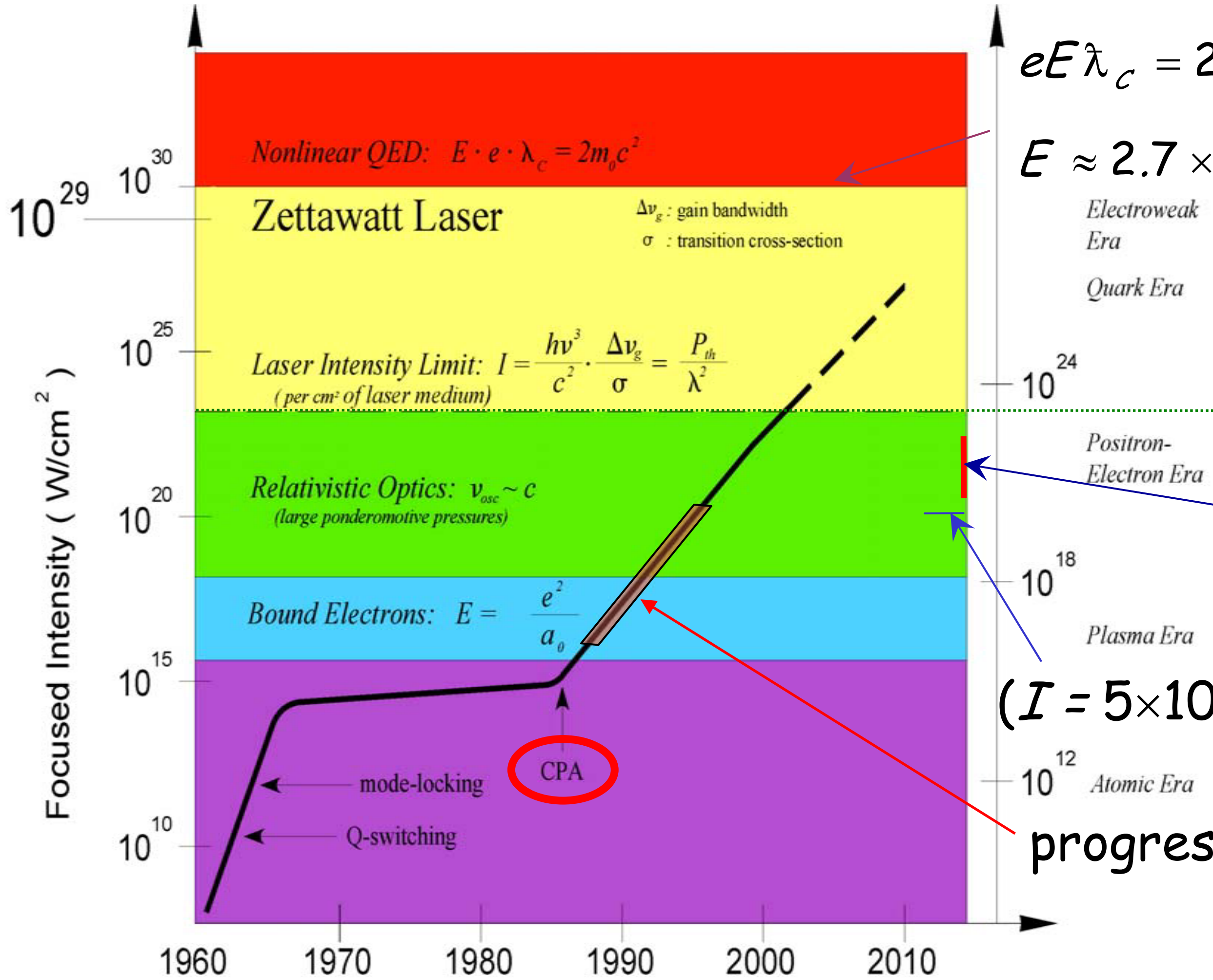
Physical regimes achievable - 1

today
$I \leq 10^{21}$ W/cm^2



D. Umstadter, *Relativistic laser-plasma interactions*, J. Phys. D: Appl. Phys. **36**, R151 (2006)

Physical regimes achievable - 2



$$eE\bar{\lambda}_c = 2m_ec^2 \Rightarrow$$

$$E \approx 2.7 \times 10^{16}\,\frac{V}{cm} \Rightarrow I \approx 10^{30}\,\frac{W}{cm^2}$$

($I = 10^{21}$-10^{22} W/cm^2, next few years)

($I = 5\times10^{20}$ W/cm^2 , LLNL,'02)

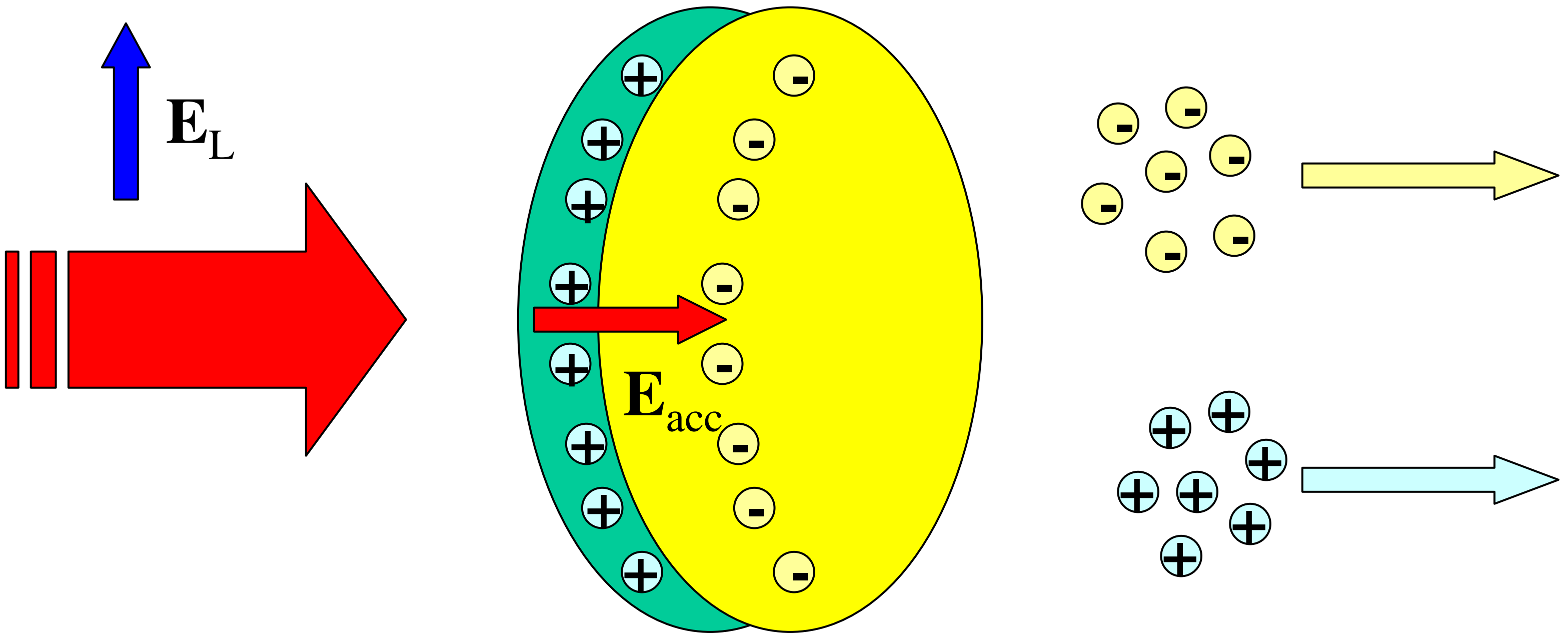
progress in the last 20 years

[G. Mourou, T. Tajima, S.V. Bulanov, *Rev. Mod. Phys.* **78**, 309 (2006)
M. Marklund, P.K. Shukla, *Rev. Mod. Phys.* **78**, 591 (2006)]

Accelerating fields due to charge separation

10 - 100 fs high-intensity laser pulse
causes strong charge separation

"electric field rectification" ($\tau_{1\mu m}$ = 3 fs)



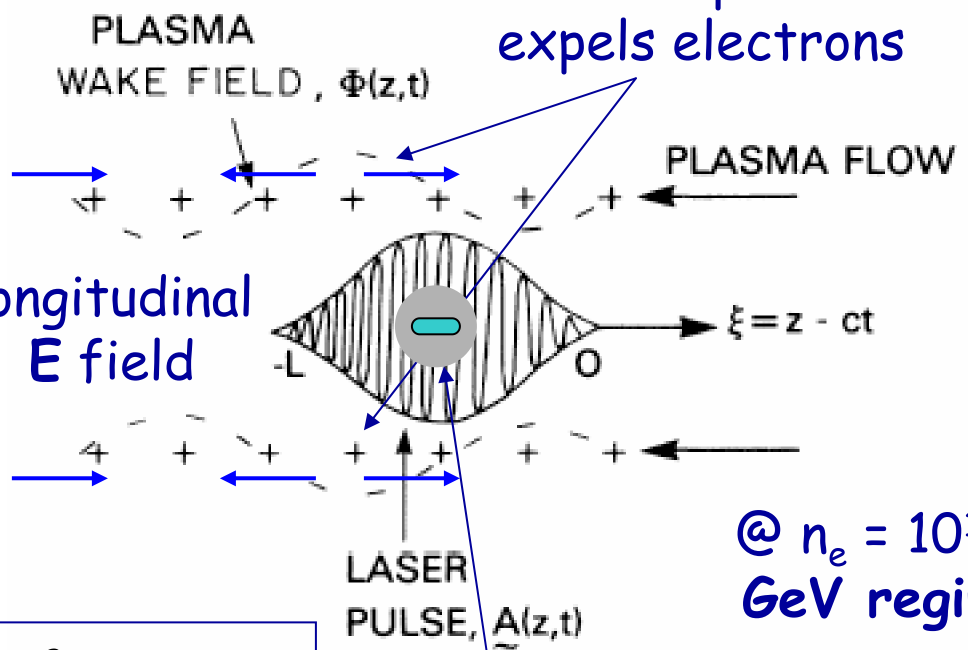
huge quasi-stationary electric (and magnetic) fields are produced
$E_L \approx E_{acc} \approx$ tens GeV/cm $\Rightarrow$ efficient charged particle acceleration

Electron acceleration

- **compact electron accelerators**

laser pulse into an underdense plasma ⇒ laser wakefield accelerator

radiation pressure expels electrons



longitudinal E field

effective negative bullet

$$\boxed{\frac{\partial \omega_L}{\partial k_L} \approx \frac{\omega_{pl}}{k_{pl}}}$$

-maximum s.s. electric field

A.I. Akhiezer, R.V. Polovin, *Sov. Phys. JETP* **30**, 915 (1956)

$$E_M = \frac{m_e \omega_{pe} c}{e}\left[2\left(\gamma_{ph} - 1\right)\right]^{1/2}$$

$$\cong 7.9 \times 10^9 \frac{n_e^{1/4}\left(10^{18}\,\mathrm{cm}^{-3}\right)}{\lambda^{1/2}(\mu\mathrm{m})} \frac{\mathrm{V}}{\mathrm{cm}}$$

@ $n_e = 10^{18}$ cm^{-3}, $\lambda = 1$ μm ⇒ $E_M \approx 8$ GV/cm

GeV regime experimentally approached!

T. Tajima, J. Dawson, *Phys. Rev. Lett.* **43**, 262 (1979)
J.M. Dawson, *Plasma Phys. Contr. Fus.* **34**, 2039 (1992)
C. Joshi, Th. Katsouleas, *Physics Today* **6**, 47 (2003)

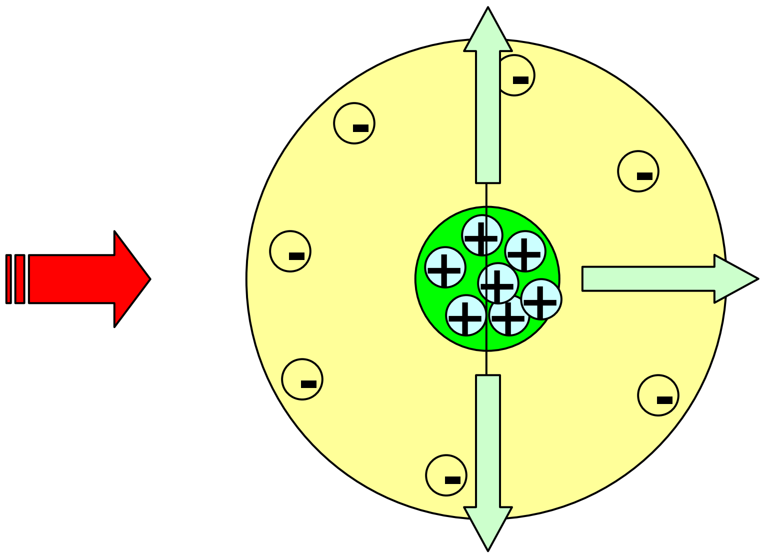
Laser-based ion acceleration in clusters

- **Laser irradiation of atomic clusters**

[T. Ditmire et al., *Phys. Rev. A* **53**, 3379 (1996)]

$I < 5\times10^{17}$ W/cm^2 in large Ar (1.8×10^5) and Xe (2.0×10^6) clusters

$\varepsilon_{max}^{(Ar)} = 50$ KeV , $\varepsilon_{max}^{(Xe)} = 1$ MeV



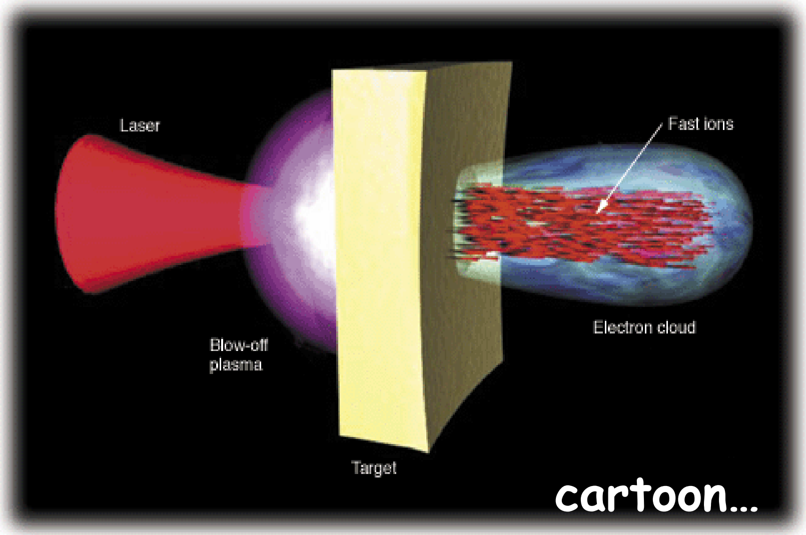
- local density: 3.5×10^{21} cm^{-3} (Xe)
  4.4×10^{21} cm^{-3} (Ar)

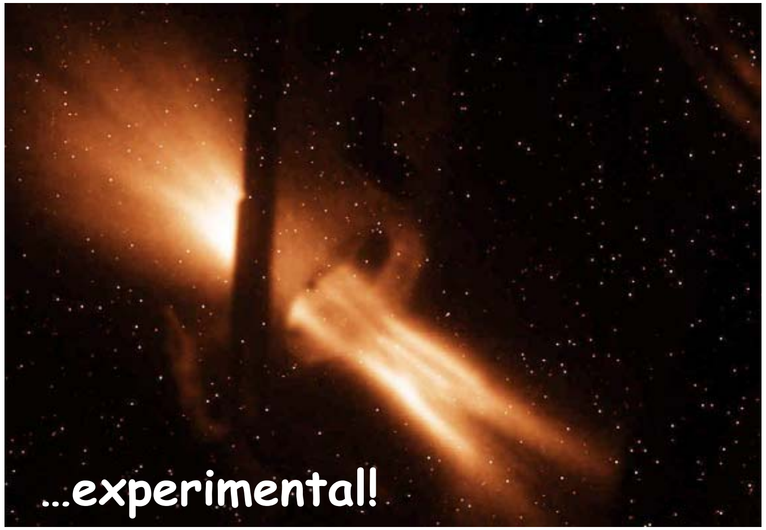
- pure Coulomb (Ar) or
  mixed Coulomb and hydro (Xe)
  expansion

  [M. Lezius, *et al.*, *Phys. Rev. Lett.* **80**, 261 (1998)]

Laser-based ion acceleration in solids targets

If an ultraintense and ultrashort laser pulse hit the surface of a thin solid film, intense and energetic ion beams are produced

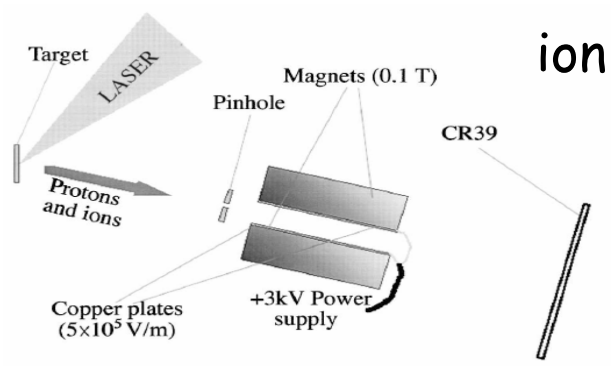




What kind of ions? Mainly PROTONS

Characteristics of ion emission: "front" vs. "rear" emission

…typical experimental setup to diagnose ion acceleration…from both sides of the target



E.L. Clark, *et al.*, *P.R.L.* **85**, 1654 (2000)

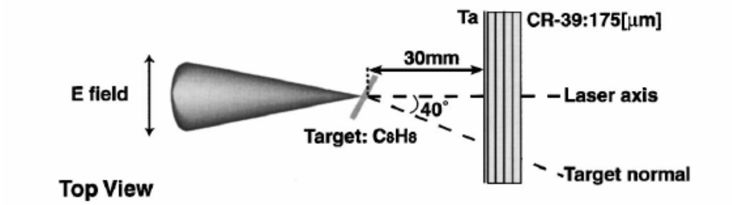


FIG. 1. CH target and CR-39 track detector setup. Target is 3 mm square in size and 5 to 100 μm in thickness. CR-39 film, stack of four layers, covered with Ta foil, is 6 cm in diameter, and is put 3 cm apart from target.

Y. Murakami, *et al.*, *Ph. Pl.* **8**, 4138 (2001)

Vulcan-Nd:Glass

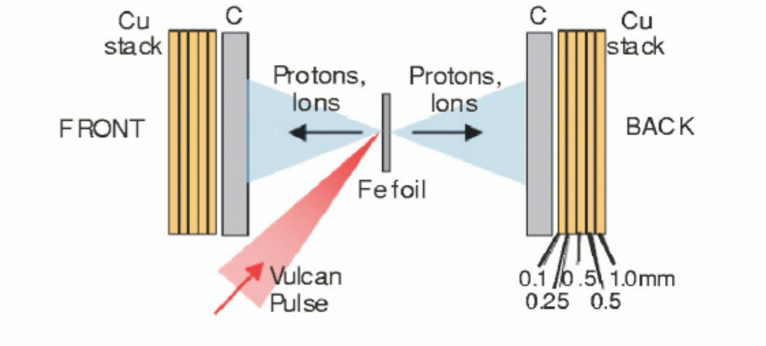
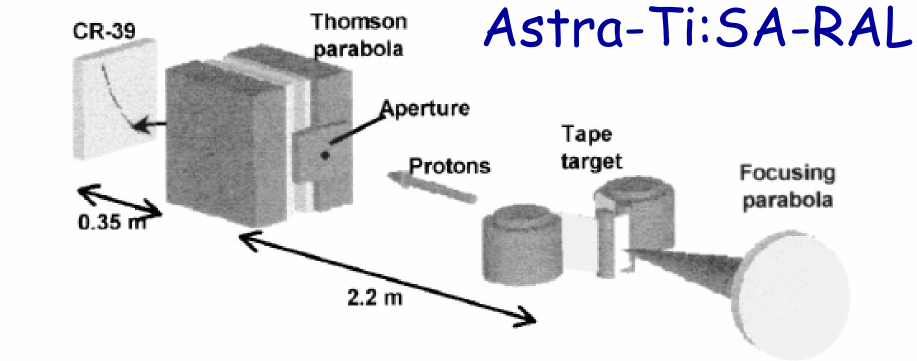


FIG. 1. (Color online) Experimental arrangement used for diagnosing ion acceleration using nuclear activation techniques.

M. Zepf, et al., Ph. Pl. 8, 2323 (2001)
P. McKenna, *et al.*, *Phys.Rev. E* **70**, 036405 (2004)

Astra-Ti:SA-RAL



I. Spencer, *et al.*, *Phys. Rev. E* **67**, 046402 (2003)

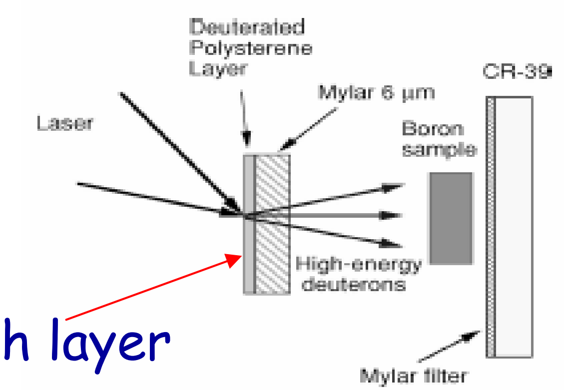
Characteristics of ion emission: "front" vs. "rear" emission

Spatial location of the ion source and region of acceleration

Front side source

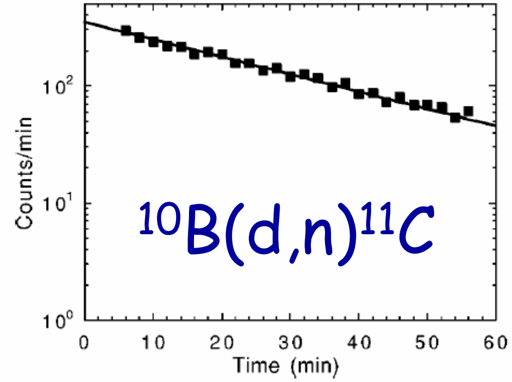
Ti:Sa/Nd:Gl-CUOS

A. Maksimchuk, *et al.*, *P.R.L.* 84, 4108 (2000)
K. Nemoto, *et al.*, *A.P.L.* 78, 595 (2001)



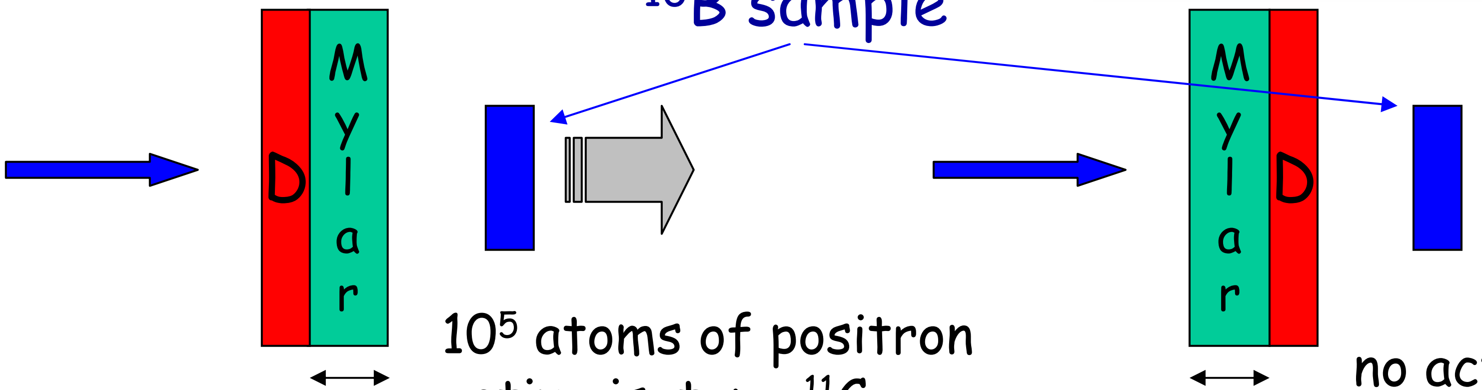
1μ D-rich layer

positron-active ^{11}C



$^{10}B(d,n)^{11}C$

^{10}B sample



6μ

10^5 atoms of positron active isotope ^{11}C

6μ

no activation !

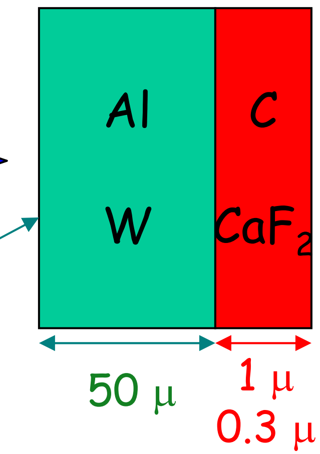
Characteristics of ion emission: "front" vs. "rear" emission

Rear side source

ion source

M. Hegelich, *et al.*, *P.R.L.* 89, 085002 (2002)
M. Allen, *et al.*, *Phys. Pl.* 10, 3283 (2003)

LULI



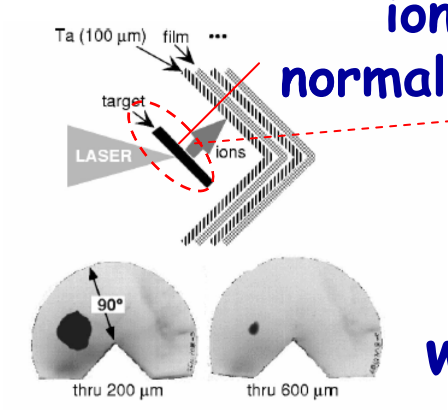
C^{4+}(11 MeV, > 1 MeV/u)

F^{7+} (100 MeV, > 5 MeV/u)

interaction material

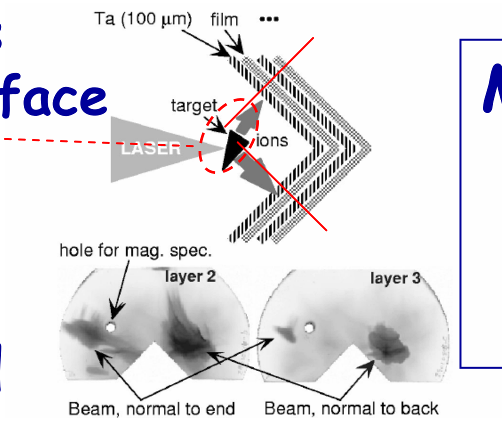
heated targets to prevent proton acceleration

Nova (Nd:Glass)-LLNL: S.P. Hatchett, et al., *Phys. Plasmas* 7, 2076 (2000)



ion emission always normal to the rear surface

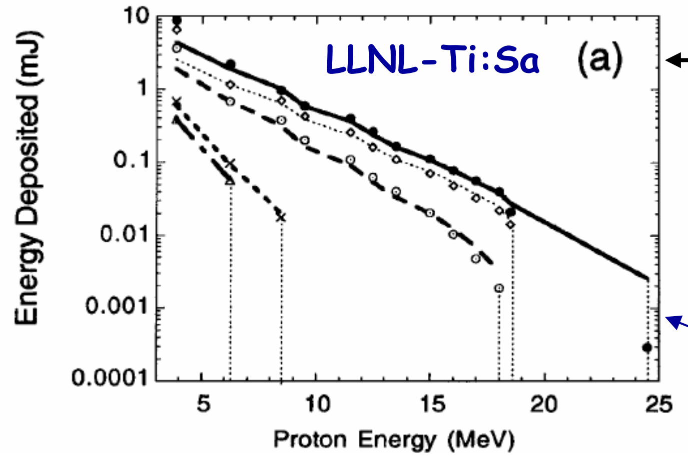
beam VERY well collimated



Many indications that ions come from the rear surface

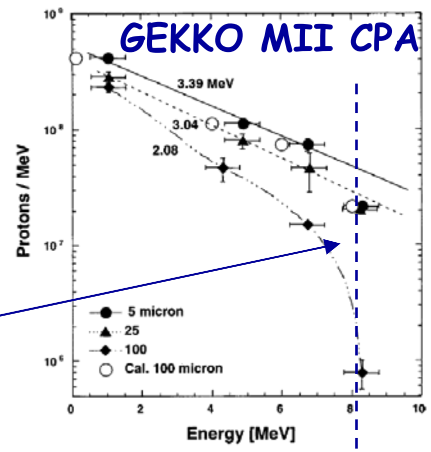
Characteristics of ion emission: ion energy spectra

high energy cut-off + plateau (sometimes)



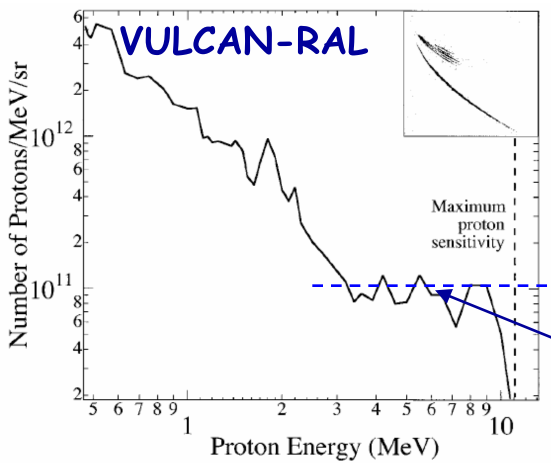
A.J. Mackinnon, *et al.*, *P.R.L.* **88**, 215006 (2002)

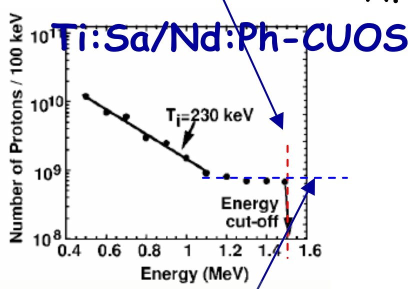
Y. Murakami, *et al.*, *Ph. Pl.* **8**, 4138 (2001)



high energy cut-off

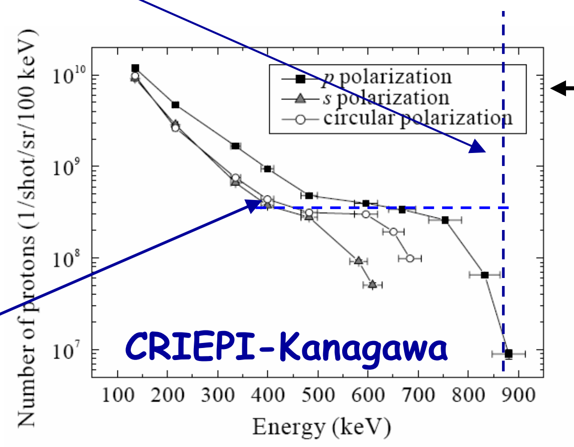
E.L. Clark, *et al.*, *P.R.L.* **85**, 1654 (2000)





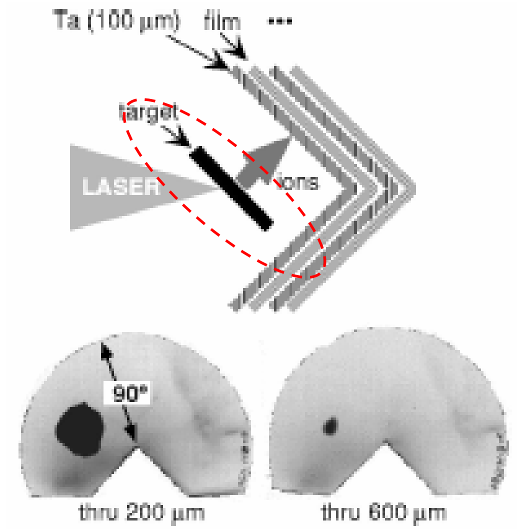
A. Maksimchuk, *et al.*, *P.R.L.* **84**, 4108 (2000)

A. Fukumi, *et al.*, *Ph. Pl.* **12**, 100701 (2005)



plateau

Characteristics of ion emission: direction, maximum energy



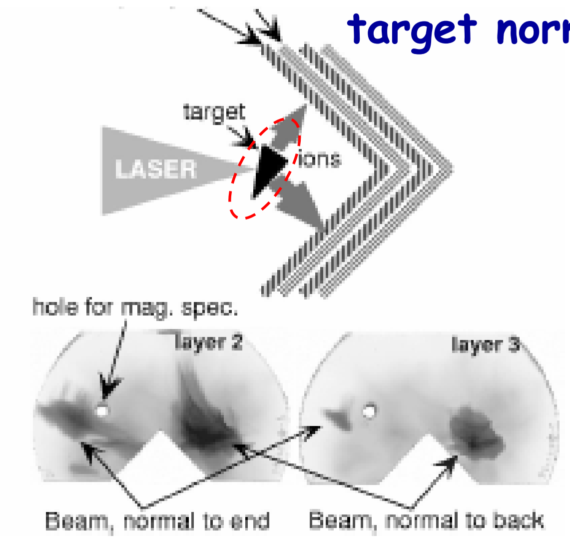
Laser: Nova (Nd:Glass)-LLNL. Parameters:
λ= 1.053 μm, $\tau_p \approx$ 1 ps, E < 700 J, $\varnothing \approx$ 8-9 μm,
I $\approx 3\times10^{20}$ W/cm^2

Au, CH targets, 50-125 μm thick

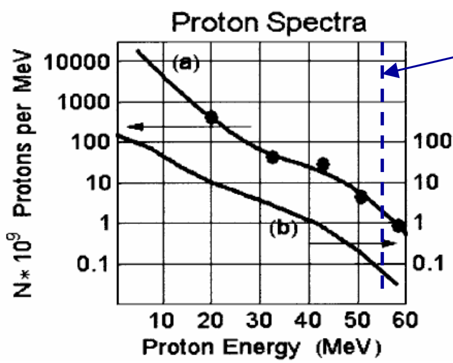
laser $\rightarrow$ hot electrons ($\eta_{l,e} \approx$ 40-50 %) $T_{hot} \approx$ 5-6 MeV

laser $\rightarrow$ protons ($\eta_{l,pr} \approx$ 7 %)
3×10^{13} prs.(>1 MeV), $T_{pr} \approx$ 6 MeV
$\varepsilon_{max} \approx$ 58 MeV

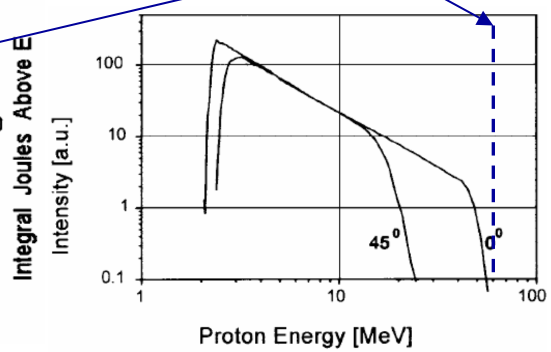
beam Direction: target normal!!



high energy cut-off



from RC films

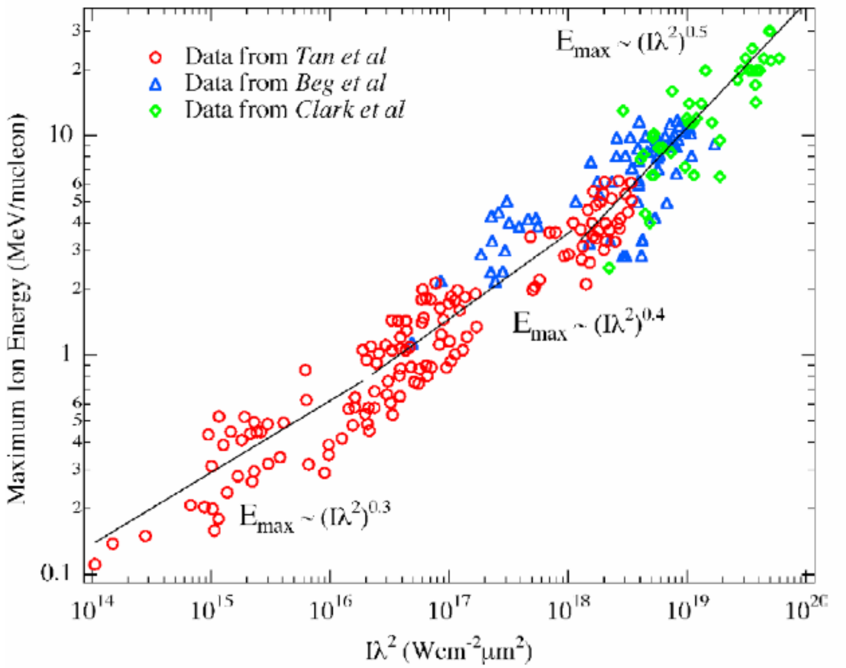


from magn. deflection spectrometer

[S.P. Hatchett, et al., *Phys. Plasmas* **7**, 2076 (2000)
R.A. Snavely, et al., *Phys. Rev. Lett.* **85**, 2945 (2000)]

Characteristics of ion emission: dependence on laser parameters

A large number of experiments have been performed to study the dependence of the accelerated ion properties on the laser parameters (rear side acceleration)



[K. Krushelnick, *et al.*, *Plasma Phys. Contr. Fus.* **47**, B451 (2005)]

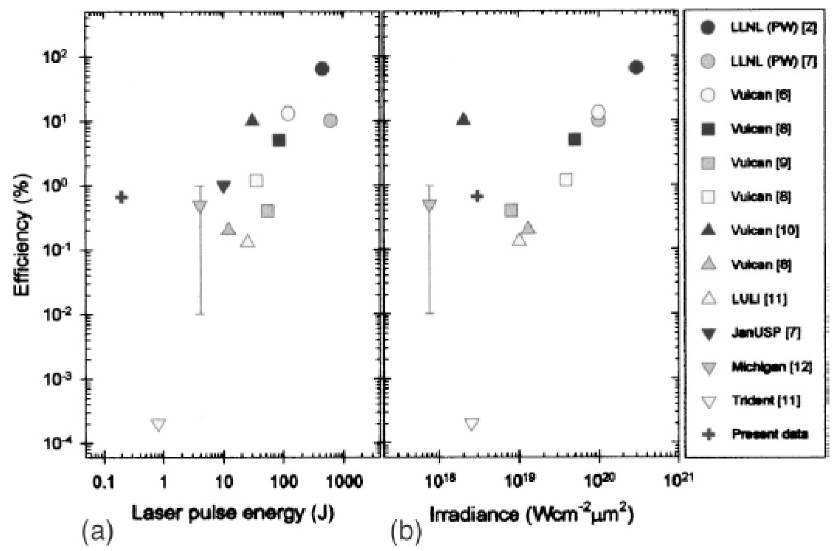


FIG. 1. Efficiency of laser-pulse energy conversion to protons as a function of (a) laser-pulse energy and (b) laser irradiance $I\lambda^2$.

[P. McKenna, *et al.*, *Rev. Sc. Instr.* **73**, 4176 (2002)]

Characteristics of ion emission: dependence on laser parameters

Experiments show that ion properties depend on

- laser intensity
- laser energy
- laser pulse duration

In particular some general features can be established:

- Maximum ion energy mainly depends on laser intensity: $E_{max} \sim I^{1/2}$

- Energetic spectrum depend also on laser energy

- Total number of ions increases with laser energy and pulse duration

- Total number with short pulses (10-50 fs) can be increased exploiting higher repetition rate (Hz)

Characteristics of ion emission: dependence on target composition

conducting *versus* insulating materials

Comparison between Au and CH targets: largest yield for normal incidence on 55-μm-thick CH targets; 5 times greater than with Au targets.
[Nova (Nd:Glass)-LLNL: R.A. Snavely, *et al.*, *P.R.L.* 85, 2945 (2000)]

Max proton flux with Mylar is an order of magnitude larger than that for metals.
[Astra: I. Spencer, *et al.*, *Phys. Rev. E* 67, 046402 (2003)]

→ "body" proton acceleration

	thickness	ε_{max}
Mylar	20-40 μm	1.5 MeV
Al	12 μm	950 keV
Cu	12.5 μm	850 keV

Proton beam quality much better in conducting materials than in insulating ones.
[LULI: J. Fuchs, et al., P.R.L. 91, 255002 (2003)
K. Krushelnick, *et al.*, *Plasma Phys. Contr. Fus.* 47, B451 (2005)]

→ role of e^- transport

Characteristics of ion emission: dependence on target thickness

several target thicknesses explored, from few μm (~ λ) to hundred μm…

indication of an optimal thickness depending on pulse properties

- evidences that 10-20 μm thickness maximizes proton energy

I. Spencer, *et al.*, *Nuc. Instr. Meth.* B **183**, 449 (2001)
P. McKenna, *et al.*, *Rev. Sc. Instr.* **73**, 4176 (2002)
I. Spencer, *et al.*, *Phys. Rev. E* **67**, 046402 (2003)

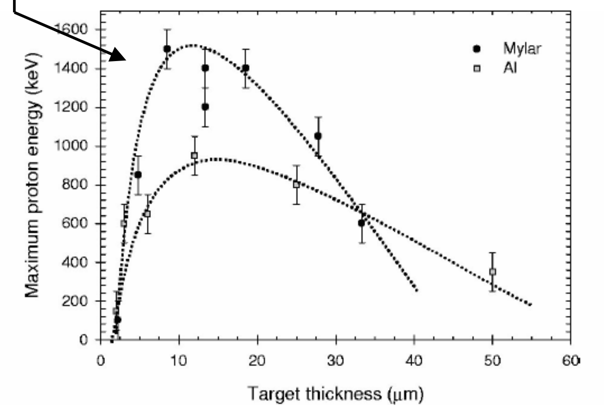
Vulcan-Nd:Glass
Astra-Ti:SA-RAL

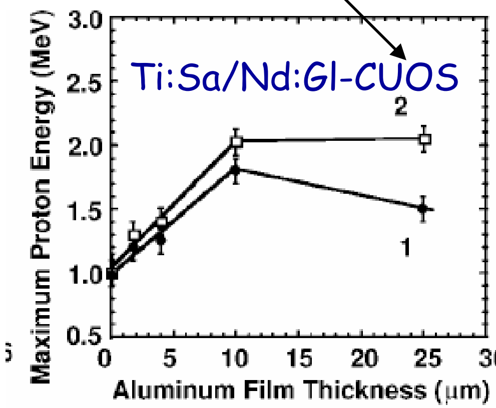
- evidences that thinner targets (< 50 μm) less divergent, more uniform, emission pattern, # protons increases

K. Krushelnick, *et al.*, *Plasma Phys. Contr. Fus.* **47**, B451 (2005)

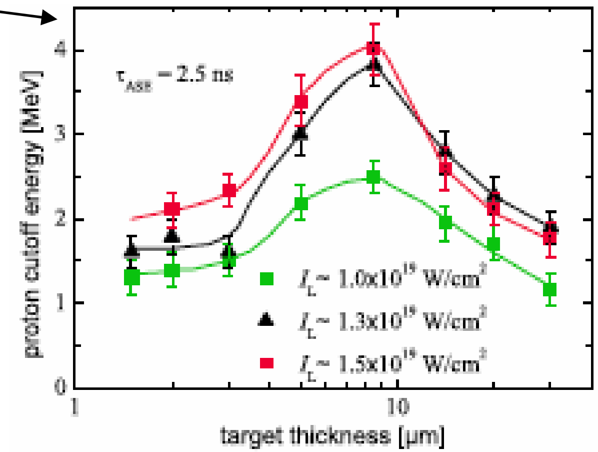
- evidences of optimal thickness of ~ 10 μm for rear acceleration

M. Kaluza, *et al.*, *P.R.L.* **93**, 045003 (2004)
A. Maksimchuk, *et al.*, *P.R.L.* **84**, 4108 (2000)





ATLAS-MPQ



Characteristics of ion emission: heavy ions

Vulcan (Nd:Glass)-RAL

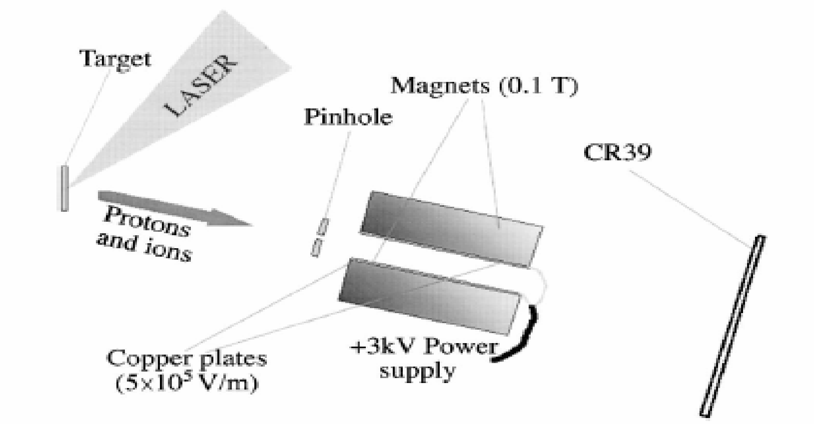
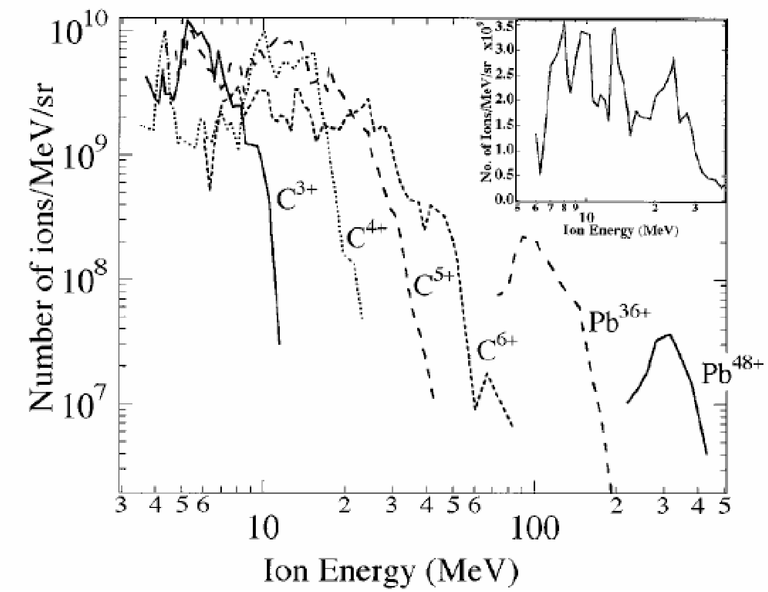


FIG. 1. Schematic of the experimental setup.



λ = 1.053 μm, $\tau_p \approx$ 1 ps, ε < 50 J

$\varnothing \approx$ 10 μm, I < 5×10^{19} W/cm^2

$\varepsilon_{max} \approx$ 430 MeV Pb^{46+} ions

target heating to remove protons

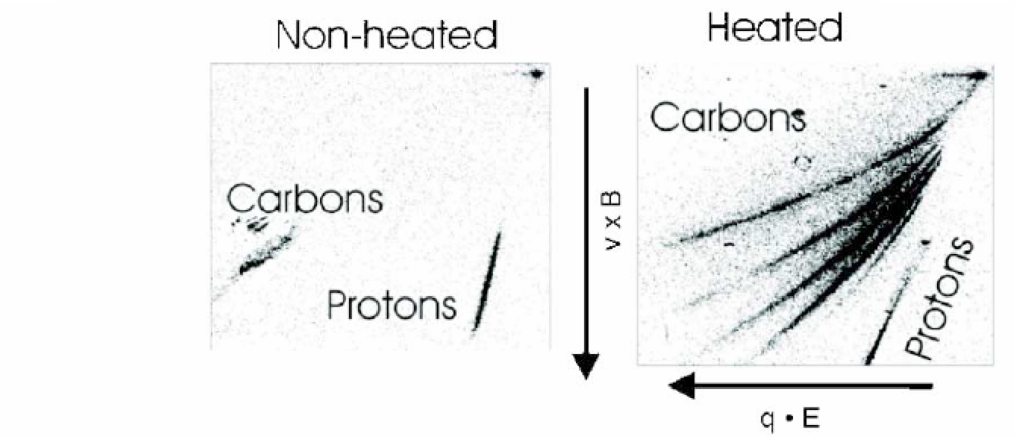
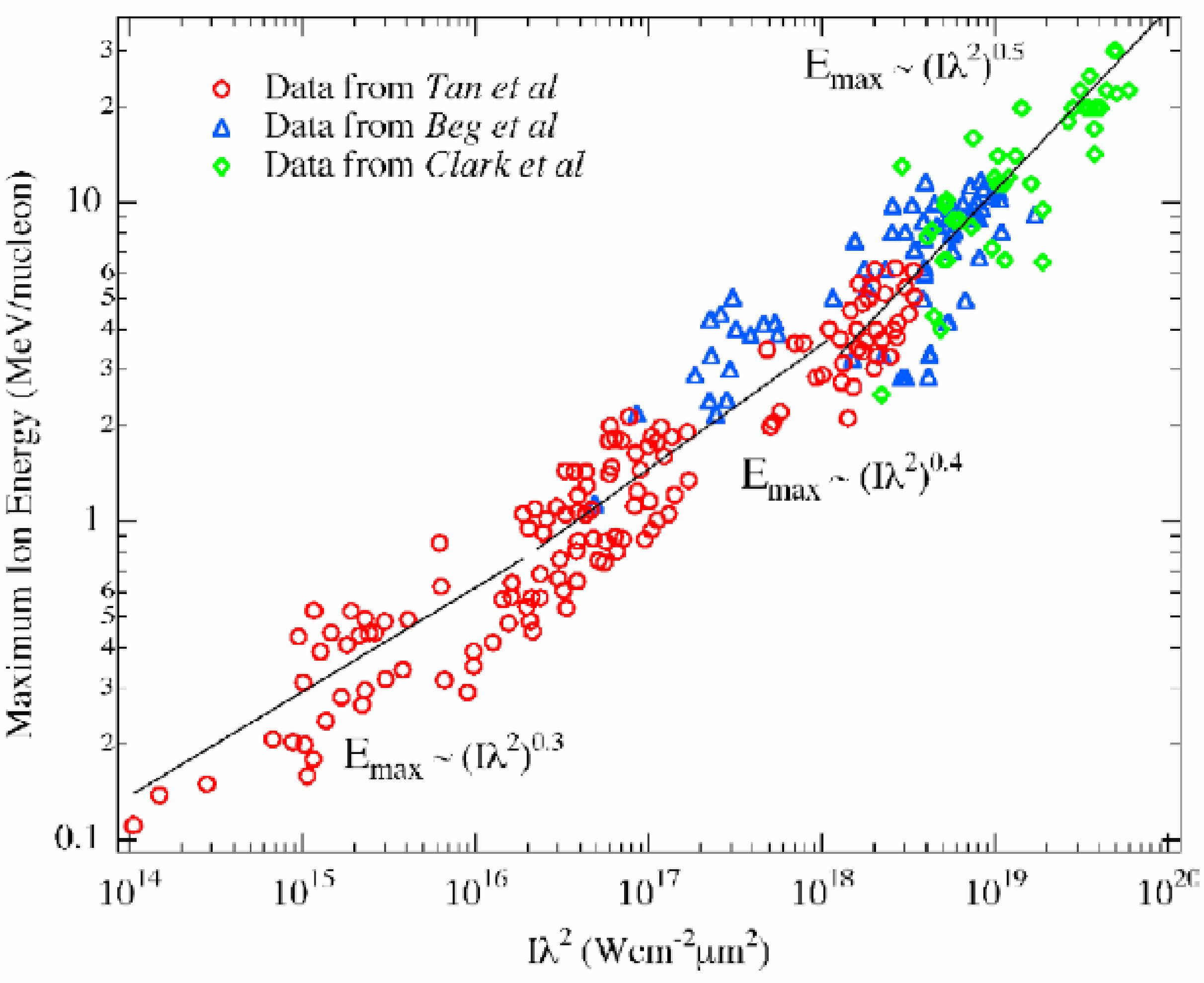


FIG. 5. Heavy ion beam production. In contrast to the strong proton signal (left), removing the hydrocarbons from the target rear surface results in a strong heavy ion (carbon) signal (right).

E.L. Clark, et al. *Phys. Rev. Lett.* **85**, 1654 (2000)

…a lot of experiments! - 1



[K. Krushelnick, *et al.*, *Plasma Phys. Contr. Fus.* **47**, B451 (2005)]

…a lot of experiments! - 2

Parameters of Some of the Laser Systems Used for High-Energy (>1-MeV) Proton Beam Acceleration Experiments and Typical Parameters of the Proton Beams Produced as Reported in the Quoted References*

Laser System	Reference	Laser Pulse Duration (ps)	Laser Energy (J)	Laser Intensity (W/cm^2)	Target Thickness (μm)	Maximum Proton Energy (MeV)	T (MeV)	Conversion Efficiency into Protons
LOA	90	0.04	0.8	6×10^{19}	6	8	—	—
CRIEPI, Tokyo	96, 99	0.06	0.1	0.7×10^{19} to 1×10^{19}	5	1.2	0.2	0.2%
ASTRA	97	0.06	0.2	7×10^{18}	20	1.5	—	0.7%
JanUSP	50	0.1	10	10^{20}	3	24	3.2	1%
MPQ	95	0.15	0.7	10^{19}	10	2.5	—	—
LULI 100 TW	82, 100	0.32	30	6×10^{19}	20	20	3	1% (> 5 MeV)
CUOS	94	0.4	5	5×10^{19}	12.5	12	—	—
GEKKO	75	0.45	25	5×10^{18}	5 to 25	10	3.4	—
NOVA PW	2	0.5	500	3×10^{20}	100	58	6	12% (>10 MeV)
RAL PW	92, 101	0.7	400	2×10^{20}	100	44	—	7% (>13 MeV)
RAL Vulcan	76	1	90	10^{20}	10	36	4.5	5%

*Some of the information was not provided in the references.

[M. Borghesi, *et al.*, *Fus. Science Techn.* **49**, 419 (2006)]

Characteristics of ion emission: summary of the main exp. results

- Ions can be effectively accelerated in laser-solid interaction

- Protons are mainly accelerated (from surface contaminants), unless the target is properly cleaned

- Ions are accelerated both at the front and at the rear surface

- In usual conditions, ions from the rear surface present better properties:
    - total number (depending on conditions, 10^{12} – 10^{13} protons)
    - maximum energy (uo to several tens MeV for protons)
    - energetic spectrum (wide spectrum with sharp cut -off)
    - beam properties (very well collimated ps bunches)

- There is a dependence on the target conditions
    - more protons from CH targets
    - much better properties from metallic targets (role of el. transport)

Potential applications

…many applications
of the UU laser-matter interaction are foreseen..

- intense X-ray sources

- relativistic nonlinear optics (underdense plasmas)

- electron/ion acceleration (several schemes):
  - ∴ diagnostics for laser plasmas (proton imaging)
  - ∴ "fast ignitors" (electron- or proton-driven)
  - ∴ laser-induced nuclear physics
  - ∴ medical applications (PET, hadrontherapy)

- laboratory astrophysics

- laboratory investigations of matter in extreme conditions

Potential applications: "proton imaging"

e.g.: ultrafast measure of localized transient electric fields

[M. Borghesi, *et al.*, *Phys. Plasmas.* **9**, 2214 (2002)]

Vulcan-RAL

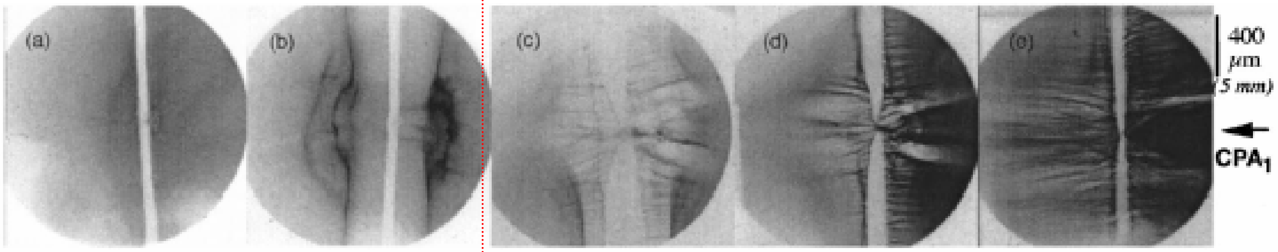
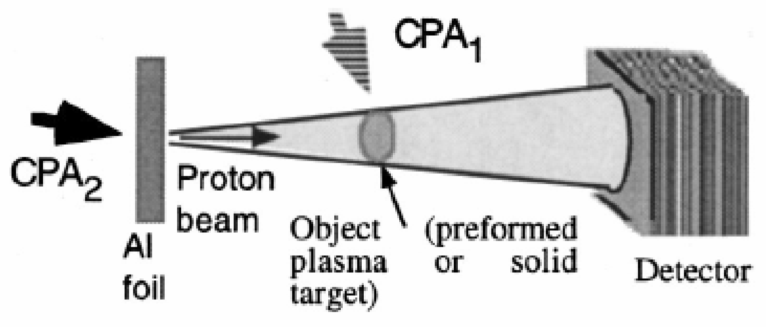
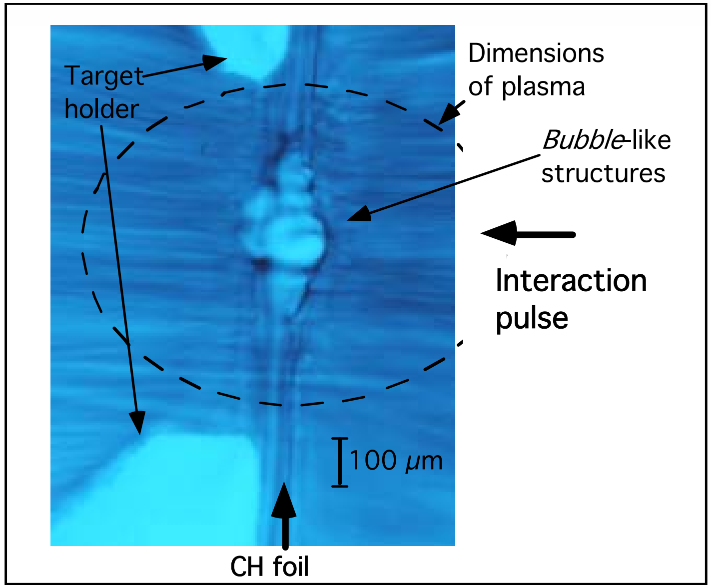


FIG. 3. Proton images of the interaction zone after irradiation with the CPA_1 pulse of a 50 μm Ta wire for different interaction-probing delays: (a) −15 ps; (b) −5 ps; (c) 5 ps; (d) 15 ps; (e) 25 ps. The energy of the protons employed was 6–7 MeV. Here and in the following figures spatial scales for both the target and the image plane (between bracket) are indicated.



Relativistic Electromagnetic Soliton ?

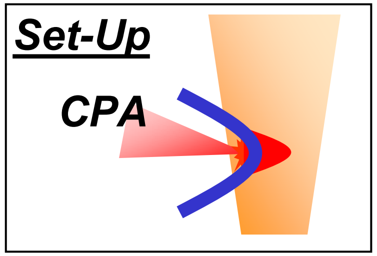


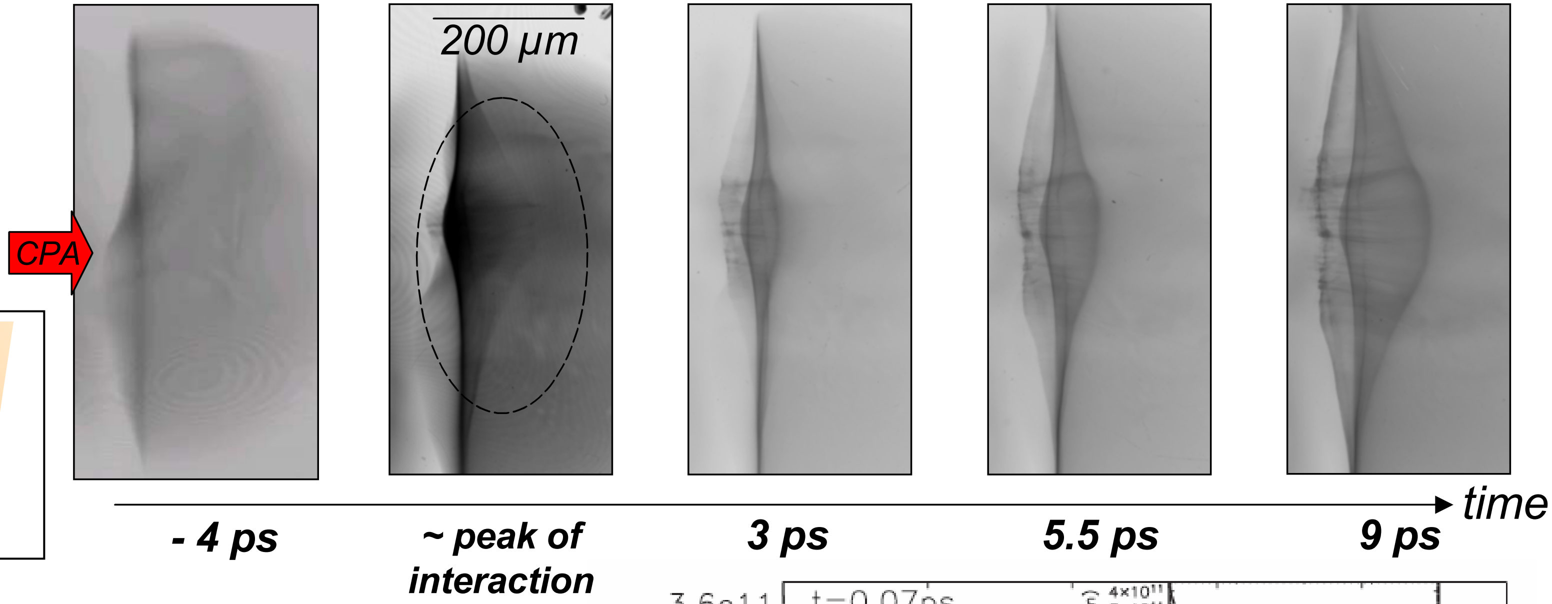
[M. Borghesi, *et al.*, *Phys. Rev. Lett.* **88**, 135002 (2002)]

Example? diagnostic of the accelerating electric field on the rear side!

[L. Romagnani, *et al.*, *P.R.L.* **95**, 195001 (2005)]

LULI





interaction CPA_1
$I \approx 3.5\times10^{18}$ W/cm^2
$\tau \approx 1.5$ ps
1 - 40 μm, Al, Au bent foils

diagnostic CPA_2
$I \approx 2\times10^{19}$ W/cm^2
$\tau \approx 300$ fs
10 μm, Au foil

$T_e \approx$ 500 keV
$\varepsilon_{int} \approx$ 6-7 MeV
$E \approx 3\times 10^{10}$ V/m

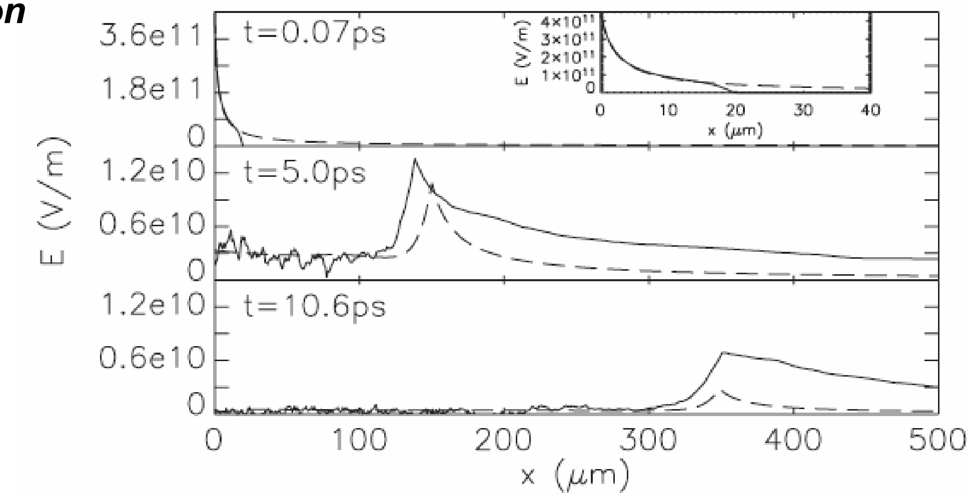


FIG. 3. Field profiles from PIC (solid line) and fluid (dashed line) simulations at three different times and for $T_{e0} = 500$ keV and $n_{e0} = 3 \times 10^{19}$ cm^{-3}.

Potential applications: radiography of compound targets

Luli-Palaiseau
100 TW
≤ 30 J
@ 300 fs, 1.05 μm
≤ 5×10^{19} W/cm^2
$\varnothing \approx 8$ μm (FWHM)

$\varepsilon_{pr} \approx 7.5$ MeV

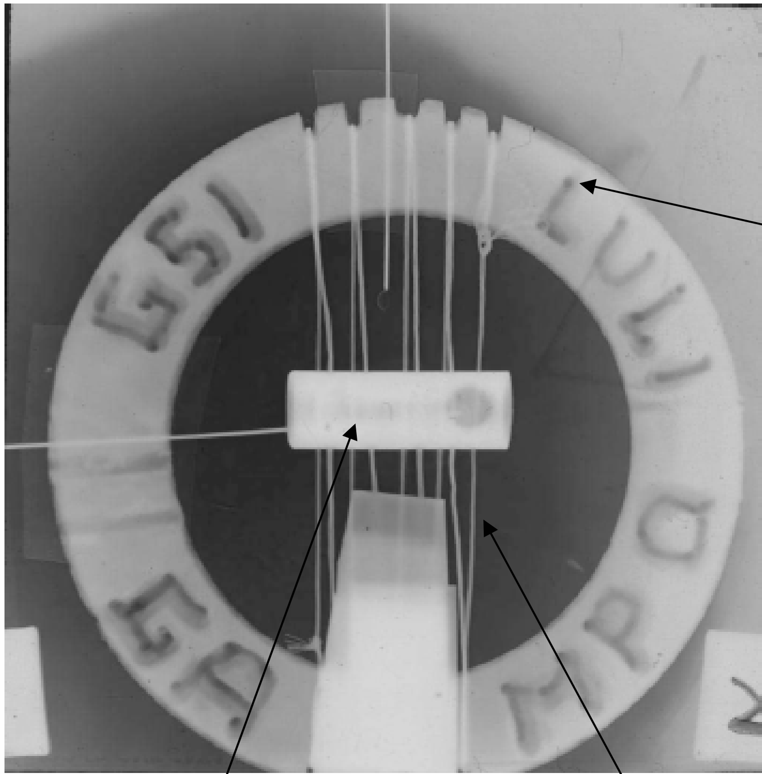


FIG. 6. Radiography of a compound target. Details of the target are given in the text.

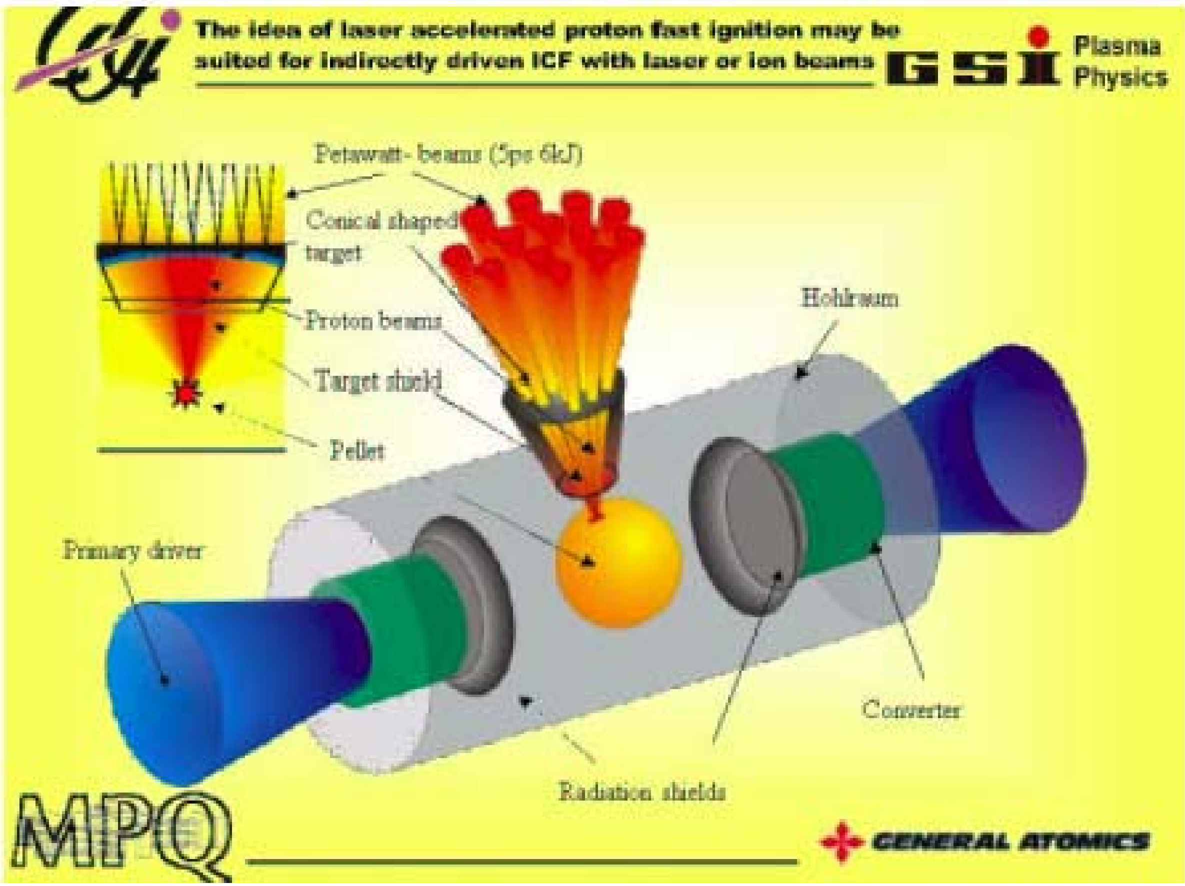
epoxy

steel hollow cylinder

copper wires

[M. Roth, et al., *Phys. Rev. Sp. Top.-Accelerator and Beams* **5**, 061301 (2002)]

Potential applications: Proton-based Fast Ignitor for inertial fusion



[M. Roth, *et al.*, *Nucl. Instr.Meth.* A **464**, 201 (2001)]

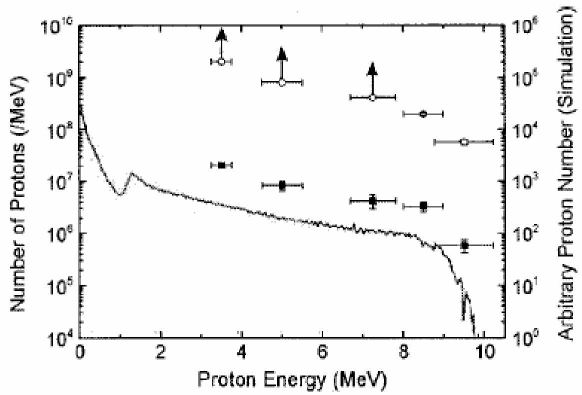
Potential applications: PET

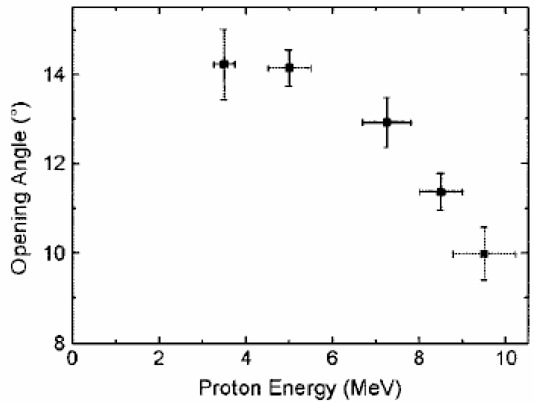
- production of positron active isotopes (^{18}F, ^{11}C, ^{13}N)
  (now: cyclotrons or Van de Graaff accelerators)

- Nd:Glass lasers (Vulcan) ⇒ 1 shot every 20 mins.!
  With table top Ti:Sa lasers ⇒ rep. rate ≈ 10 Hz

- potential advantages:
  - E > 100 GV/m ⇒ acceleration length ≈ fraction of mm
  - compact and cheap systems
  - no shielding for radioprotection is required up to the point where protons are generated

[S. Fritzler, *et al.*, *Appl. Phys. Lett.* **83**, 3039 (2003)]





Salle Jaune-LOA

TABLE I. Calculated activities for the minimum proton beam obtained with the 6 μm aluminum target. The secondary activation targets are chosen to have an areal thickness of 0.24 g/cm². The laser irradiation time would be 30 min.

Activation target	*Q*-value (MeV)	LOA laser at 10 Hz MBq (mCi)	LOA laser at 1 kHz MBq (mCi)
^{11}B	2.76	13.4 (0.36)	1340 (36.2)
^{18}O	2.44	2.9 (0.08)	290 (7.9)

Potential applications: production of PET isotopes

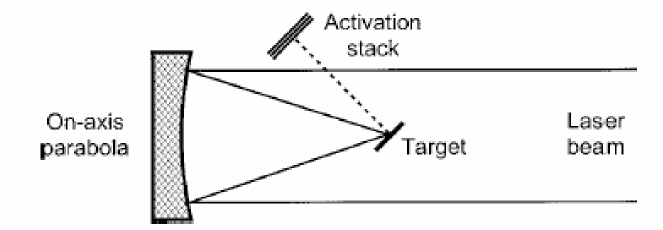
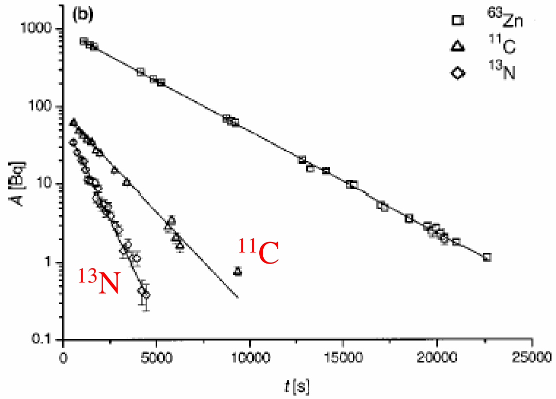


FIG. 1. Schematic experimental layout in the on-axis geometry. Laser beam entering from right-hand side is focused by the parabola (left-hand side) to target surface (middle). Blow-off plasma hits activation sample (top) in the target normal direction.



Vulcan-Nd:Glass

[M.I.K. Santala, *et al.*, *Appl. Phys. Lett.* **78**, 19 (2001)]

≈ 10^5 atoms of e^+ active ^{11}C from $^{10}B(d,n)^{11}C$

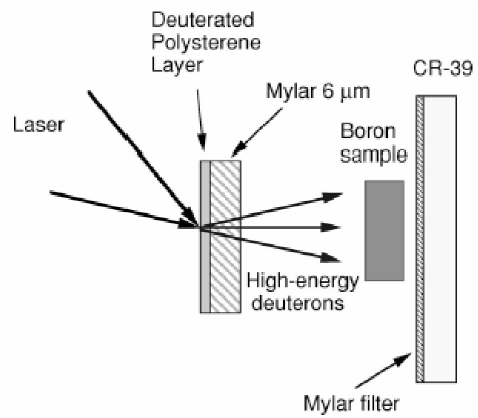


FIG. 2. Schematic diagram of the boron sample activation with high-energy deuterons.

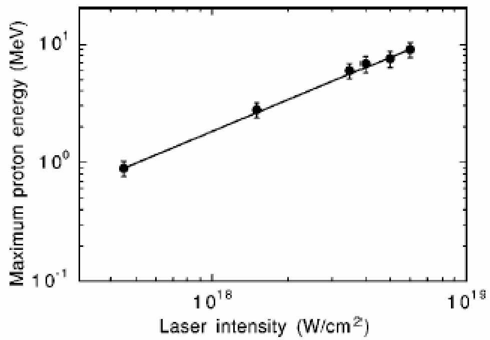


FIG. 1. Maximum proton energy in the forward direction as a function of laser intensity for 6 μm Mylar foil.

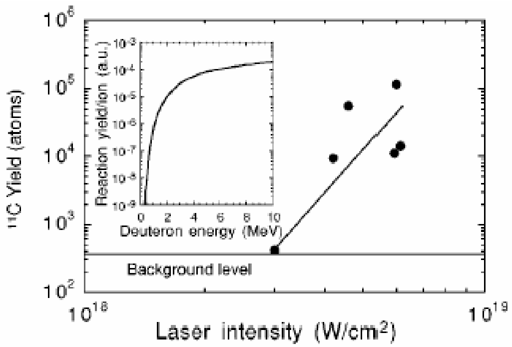
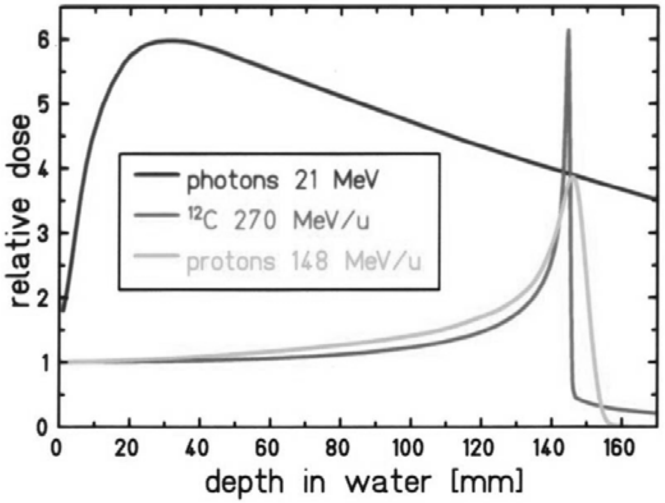


FIG. 4. Experimental yield of ^{11}C vs the laser intensity for the ^{10}B$(d,n)^{11}$C reaction. The inset shows calculated yield of ^{11}C per one deuteron as a function of energy cutoff E_{max} for a uniform distribution of deuterons in energy space.

[K. Nemoto, *et al.*, *Appl. Phys. Lett.* **78**, 595 (2001)]

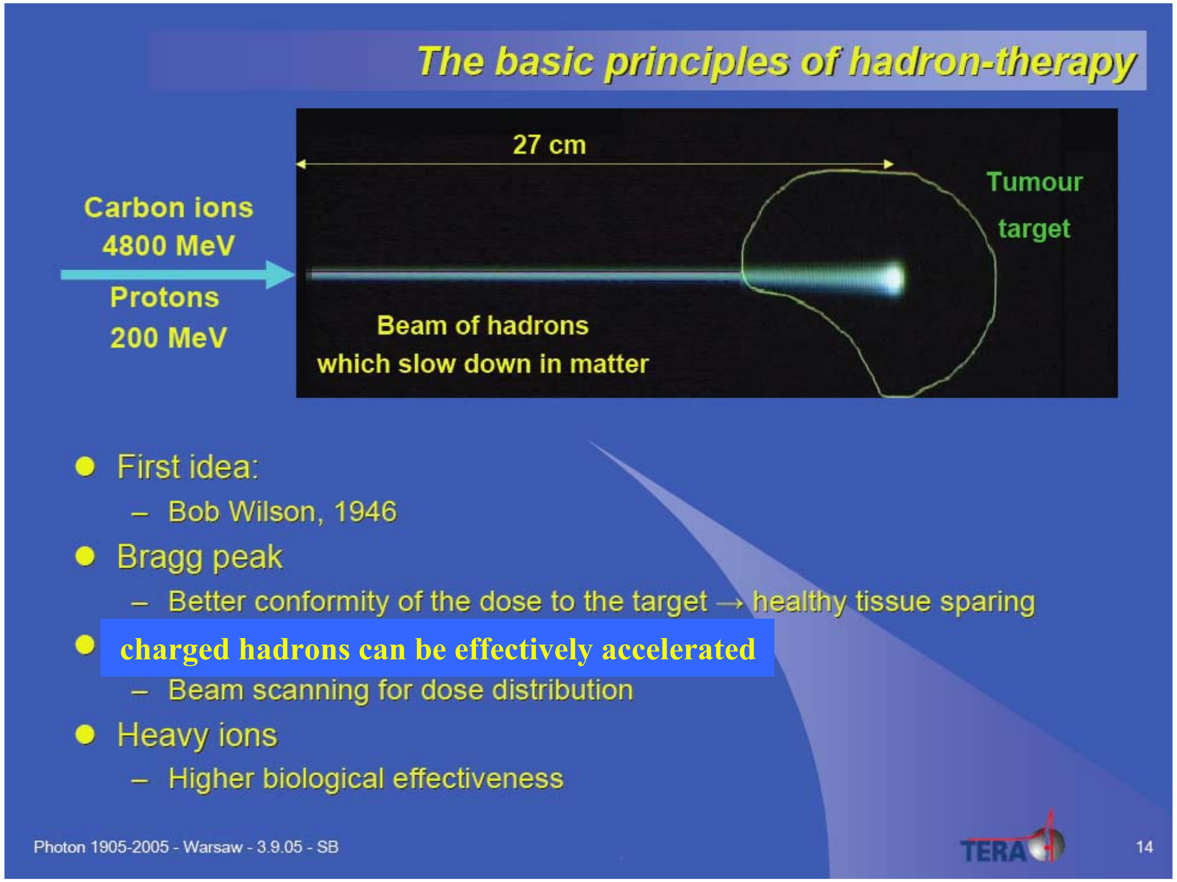
Potential applications: hadron-therapy

Using ions, the energy is released mostly in the region where the tumor is localized (Bragg peak)



Conventional method: syncrotron

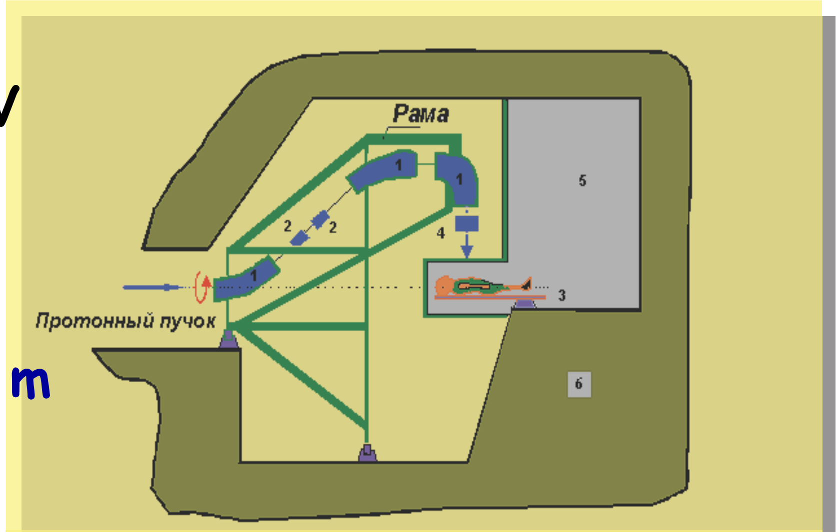
Courtesy of S. Braccini Foundation TERA



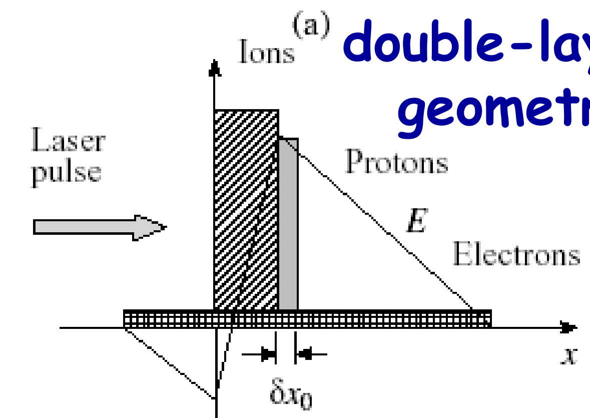
Potential applications: hadron-therapy

- beam requirements:
  $N = 1\text{-}5\times10^{10}$ pr/s, ε_M = 230-250 MeV
  $\Delta\varepsilon/\varepsilon \leq 10^{-2}$
- How to transport the proton beam ?

Gantry: $\varnothing$ = 6-8 m
D = 10-12 m
p ≥ 100 t

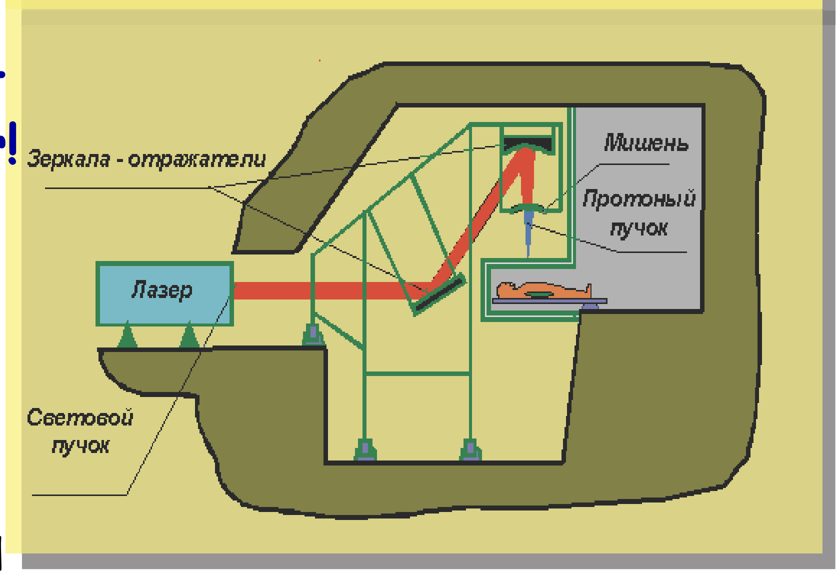


With laser:



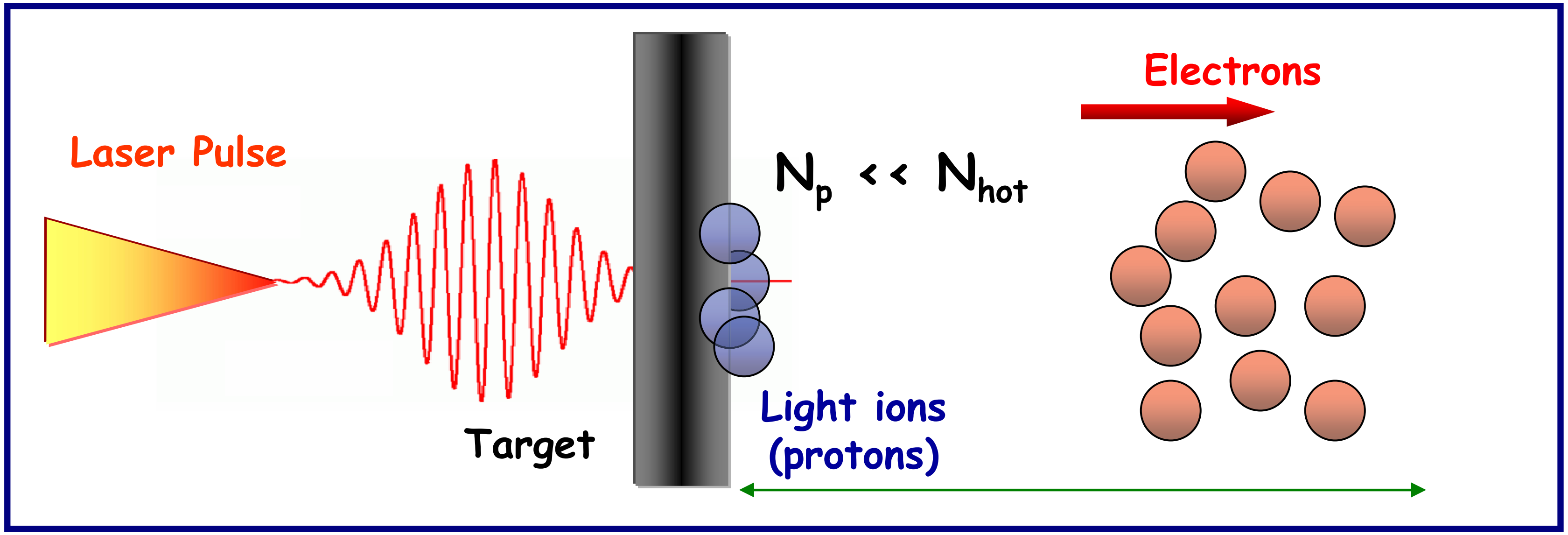
double-layer geometry

light transport is much easier!



[S.V. Bulanov, *et al.*, *Pl. Phys. Rep.* **28**, 453, 975 (2002)
T.Zh. Esirkepov, *et al. Phys. Rev. Lett.* **89**, 175003 (2002)
E. Fourkal, *et al.*, *Med. Phys.* **29**, 2788 (2002)
M. Passoni and M. Lontano, *Laser Part. Beam*, **22**, 163 (2004)]

Ion acceleration mechanism - 1

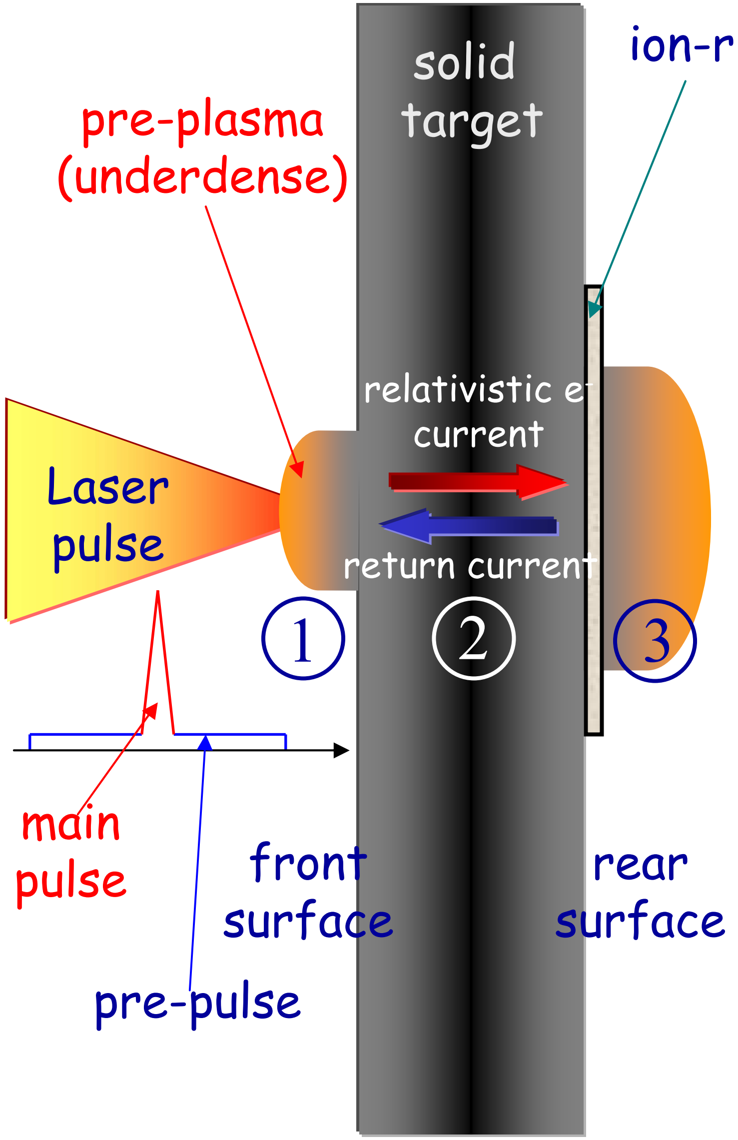


There is common agreement on the fact that the protons are accelerated by the electrostatic field set up by fast electrons propagating into or leaving the target.

Target Normal Sheath Acceleration mechanism (TNSA)

[S.C. Wilks, *et al.*, *Phys. Plasmas* **8**, 542 (2001)]

Ion acceleration mechanism - 2



1: laser pulse-front surface interaction;
generation of relativistic el. current

2: hot electron propagation in the target
possible if a return current is generated

3: expansion in vacuum;
charge separation at the rear surface;
generation of intense electric fields

Protons: bulk (CH) and/or contamination layers (oils, water vapour…)
and/or coated layers

Heavy ions: bulk and/or coated layers

Open problems

- which is the most effective laser absorption process at the front of the target? (resonant absorption, Brunel effect, ponderomotive electron acceleration…)

- role of pre-pulse/pre-plasma

- differences between front and rear acceleration

- How to describe the acceleration process theoretically?
  - (Realization of suitable numerical simulations – see ref. at the end of the two lectures)
  - Development of **analytical models**

Theoretical description of laser-based ion acceleration

How to develop analytical models of the acceleration process taking place at the rear side?

…generally speaking, two approaches are possible:

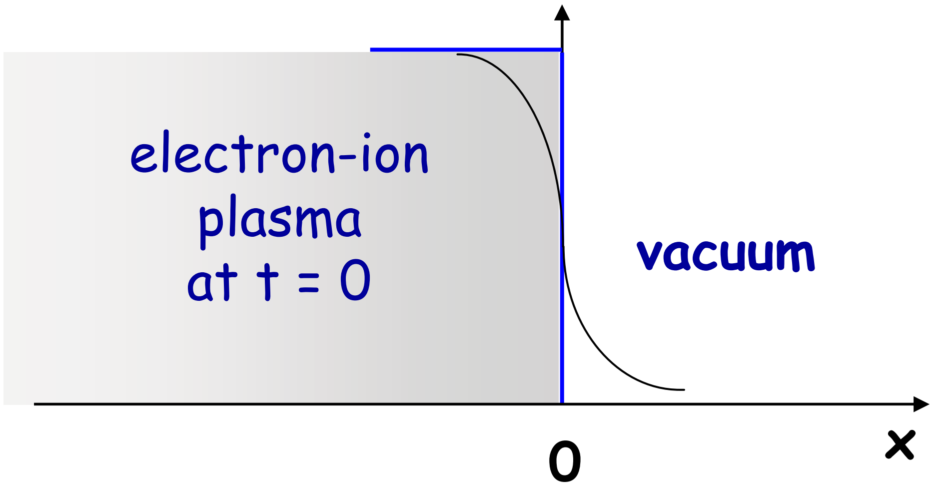
1) consider ions and hot electrons as an expanding plasma which is described with fluid or kinetic models

- ions are the positive component of a globally neutral plasma
- Focus on the collective time evolution of ion dynamics

2) describe in detail the accelerating field as a quasi-static electric field set up by the hot electrons

- ions treated as test particles forming a thin low-density layer
- focus on the accelerating field
- focus on the very early stages of ion acceleration (energetic ions)

Plasma expansion in vacuum - 1

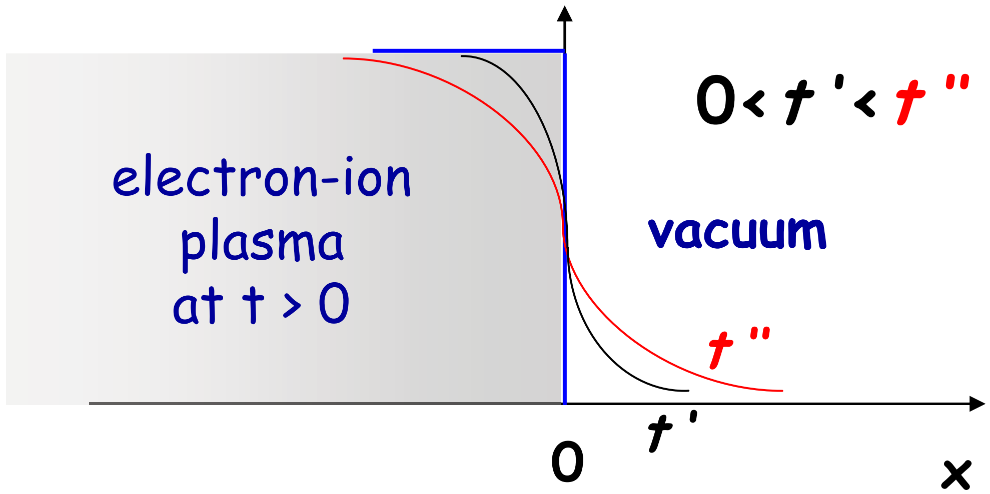


$t = 0$

- cold ions occupy a semi-infinite region ($x<0$)
- hot electrons, due to their thermal energy, are separated by the ions; an electric field is produced

$t > 0$

- hot electrons start to drag ions due to charge separation
- the whole plasma expands in a semi-infinite vacuum



Plasma expansion in vacuum - 2

1D fluid equations with T_i = 0 and $\boxed{T_e = \text{const.}}$ ion collisions are neglected

isothermal model

$$\frac{\partial N_i}{\partial t} + \frac{\partial}{\partial x}(N_i v_i) = 0 \qquad M\left(\frac{\partial v_i}{\partial t} + v_i \frac{\partial v_i}{\partial x}\right) = -Ze\frac{\partial \phi}{\partial x}$$

Poisson equation for the electrostatic field

$$E = -\frac{\partial \phi}{\partial x}$$

charge separation

$$\frac{\partial^2 \phi}{\partial x^2} = -4\pi e\left(N_i - N_e\right)$$

self-consistent electrostatic field

Equations for the electron dynamics are needed

If electrons can be assumed in equilibrium with the e.s. potential (see below): Boltzmann relation $\longrightarrow$

$$N_e = N_0 \exp\left(\frac{e\phi}{T_e}\right)$$

Plasma expansion in vacuum - 3

introduce normalization constants

$$\bar{x} \to \frac{x}{x_0}, \quad \bar{N} \to \frac{N}{N_0}, \quad \bar{\phi} \to \frac{e\phi}{T_e}$$

the dimensionless Poisson equation becomes

$$\frac{\partial^2 \phi}{\partial x^2} = -\boxed{\frac{x_0^2}{\lambda_D^2}}\left(ZN_i - N_e\right)$$ (overbars are removed)

there is a spatial scale implicit in the problem: the Debye length

$$\lambda_D = \sqrt{\frac{T_e}{4\pi e^2 N_0}}$$

(we then set $x_0=\lambda_D$)

generally speaking, the evolution is not "self-similar"; however …

Plasma expansion in vacuum - 4

$$t_1 = 2\pi \frac{\lambda_{De}}{V_{te}} = \frac{2\pi}{\omega_{pe}}$$

$$t_2 = 2\pi \frac{\lambda_{De}}{V_{ti}} = \frac{2\pi}{\omega_{pi}}$$

t

electrons and ions are separated on average by a distance ~ λ_{De}

an ambipolar electrostatic field arises, which opposes to further charge separation

over t >> t_3 slow expansion of the plasma as a whole at $v_{ti} = (ZT/M)^{1/2}$

$N_e = 10^{21}$ cm^{-3} T_e = 1keV
$t_1 \approx 3\times10^{-15}$ s $\lambda_{De} \approx 10^{-5}$ cm

$N_e = 10^{19}$ cm^{-3}
$t_3 \approx 10^{-12}$ s

the typical scale of the plasma inhomogeneity becomes $c_s t \gg \lambda_{De}$
the plasma maintains quasi-neutrality $|ZN_i - N_e|/N_0 \ll 1$

plasma moves slowly, at $(ZT_e/M)^{1/2} \Rightarrow$
electrons have time to reach an equilibrium

$$N_e = N_0 \exp\left(\frac{e\phi}{T_e}\right)$$

therefore, we can close the system

$$e\phi = T \ln\left(\frac{N_e}{N_0}\right) \cong T \ln\left(\frac{ZN_i}{N_0}\right)$$

Plasma expansion in vacuum - 5

Therefore, assuming

- quasi-neutrality: $N_e = N_i$ (strictly valid only for times $t \gg t_i$)
- cold ions: $T_i = 0$
- hot electrons in thermal equilibrium $N_e = N_0 \exp(e\phi)$

the expansion is governed by the system

$$\begin{cases} \dfrac{\partial N_i}{\partial t} + \dfrac{\partial}{\partial x}(N_i v_i) = 0 \\[2ex] M\left(\dfrac{\partial v_i}{\partial t} + v_i \dfrac{\partial v_i}{\partial x}\right) = -e\dfrac{\partial \phi}{\partial x} = -ZT_e \dfrac{\partial \ln N_i}{\partial x} \end{cases}$$

(also kinetic!) ⟵ "*Self-similar motion of rarefied plasma*"
A.V. Gurevich, *et al.*, *Sov. Phys. JETP* 22, 449 (1966)

Plasma expansion in vacuum - 6

The equations obtained resemble a formal analogy with the problem of the expansion of an ordinary 1D ideal fluid in a semi-infinite space:

$$\begin{cases} \dfrac{\partial \rho}{\partial t} + \dfrac{\partial (\rho v)}{\partial x} = 0 \\ \dfrac{\partial v}{\partial t} + v\dfrac{\partial v}{\partial x} = -\dfrac{1}{\rho}\dfrac{\partial p}{\partial x} = -c_s^2 \dfrac{1}{\rho}\dfrac{\partial \rho}{\partial x} \end{cases}$$

with $c_s = \left(\dfrac{\partial p}{\partial \rho}\right)^{1/2}$

sound velocity of the fluid

in particular, our system is equivalent to the expansion of an isothermal ideal fluid of particles of mass M, temperature ZT_e and constant sound velocity $c_s = (ZT_e/M)^{1/2}$

Plasma expansion in vacuum - 7

Such a system has fundamental properties:

- no characteristic length
- characteristic velocity (sound velocity of the system)

It admits a "self-similar" solution

- all quantities [$\rho(x,t)$, $v(x,t)$] must depend on x/t
- the spatial distribution of all quantities at various istants is similar, differing only in the scale which increases with time → ***self-similar flow***

Therefore, we conclude that
an isothermal quasi-neutral plasma
is characterized by a self-similar expansion

[Landau & Lifshitz, *Fluid Mechanics,* chapter X]

Plasma expansion in vacuum - 8

General technique of solution for this system:

introducing $\xi = x/t$ and observing that $\dfrac{\partial}{\partial x} = \dfrac{1}{t}\dfrac{d}{d\xi}$, $\dfrac{\partial}{\partial t} = -\dfrac{\xi}{t}\dfrac{d}{d\xi}$

the equations become

$$(v-\xi)\rho' + \rho v' = 0$$

$$(v-\xi)v' = -c_s^2\rho'/\rho$$

and eliminating ρ' and v' we have

choice of the sign is conventional

$$(v-\xi)^2 = c_s^2 \longrightarrow \boxed{\xi = \frac{x}{t} = v - c_s}$$

. Substituting, we have

$$\rho v' = -c_s\rho' \longrightarrow \boxed{v = -\int c_s d\rho/\rho}$$

Plasma expansion in vacuum - 9

It is possible to demontrate that for these solutions

$$d\rho / dt < 0$$
$$dp / dt < 0$$

$\longrightarrow$ **it is a non-steady rarefaction wave!**

In our case $c_s=(ZT_e/M)^{1/2}$=const. Therefore we easily obtain

$$N_i = N_0 \, exp(-v/c_s) = N_0 \, exp[-(1 + x/c_s t)] \cong N_0 \, exp(-x/c_s t)$$

$$(\xi \rightarrow +\infty)$$

$$v_i = c_s + \frac{x}{t}$$

$$E = -\frac{T_e}{e}\frac{N'}{N} = \frac{T_e}{ec_s t} = \frac{T_e}{eL_n}$$

$$N_e = N_0 \, exp(e\phi / T)$$

$$\boxed{E = \frac{T_e}{eL_n}}$$

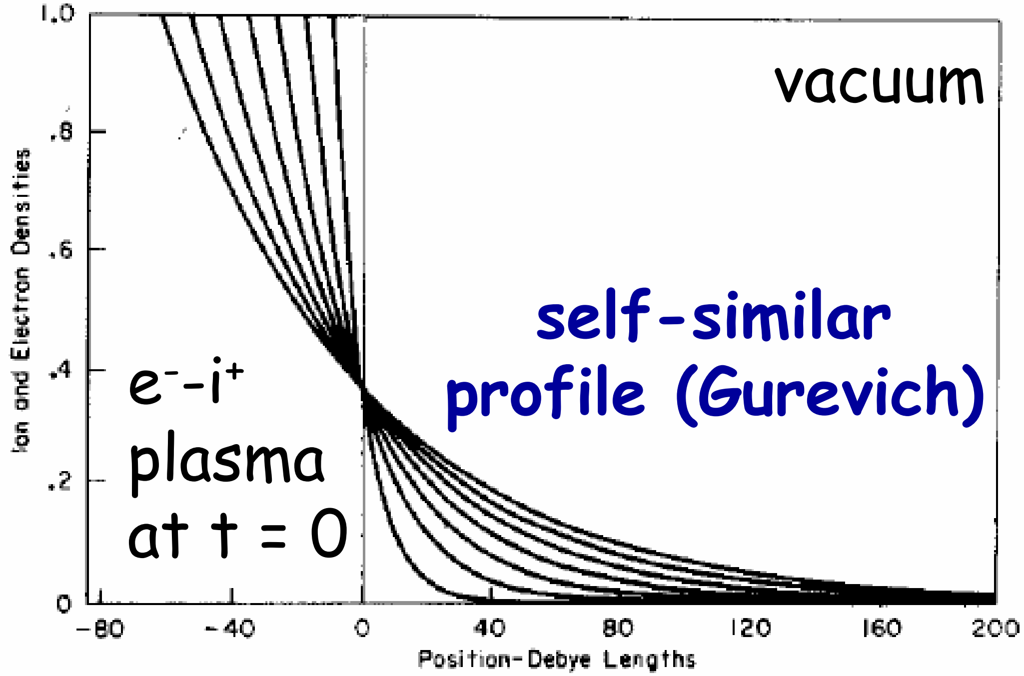
Accelerating field,
($L_n = c_s t$ =local plasma length)

[S.C. Wilks, *et al.*, *Phys. Plasmas* **8**, 542 (2001)]

Plasma expansion in vacuum - 10

for $\xi \gg 1$ $\quad e\phi = T_e \ln\left(\frac{N}{N_0}\right) \approx -\sqrt{2}T_e\xi + k \longrightarrow \frac{\partial^2\phi}{\partial x^2} \propto \frac{1}{t^2}\frac{d^2\phi}{d\xi^2} \approx 0$

quasi-neutrality ok!



Obs: this solution has several divergences, which require more physical considerations to be properly interpreted…

[Landau & Lifshitz, *Fluid Mechanics*, chapter X]

…more on quasi-neutral plasma expansion…

"*Self-similar expansion of a plasma into a vacuum*"
P. Mora, R. Pellat, *Phys. Fluids* **22**, 2300 (1979)
- extension of previous theories to non-equilibrium electron distribution function (first order in $(Zm/M)^{1/2}$); energy conservation

"*Exact solution of Vlasov equations for quasi-neutral expansion of plasma bunch into vacuum*"
D.S. Dorozhkina, V.E. Semenov, *Phys. Rev. Lett.* **81**, 2691 (1998)
- quasi-neutral approximation: electron and ion expansion in the presence of self-consistent electric field;
- arbitrary el-ion mass-ratio Zm/M, T_e/T_i, f_e, three-dimensional

"*Particle dynamics during adiabatic expansion of a plasma bunch*"
V.F. Kovalev, *et al.*, *JETP* **95**, 226 (2002)
- quasi-neutral approximation: renormalization-group approach ⇒ adiabatic expansion for arbitrary distribution functions;
- used for a 2-temperature e.d.f., and different ion species, one-dim.

Conclusions on quasi-neutral dynamics

- self-similar plasma expansion takes place for $t \gg t_2$
  (ok for pre-CPA experiments $\Rightarrow$ "long" laser pulses: $\tau \approx$ ns scale)

- the motion consists in an unsteady rarefaction wave
  (plasma expansion into vacuum over times $\gg 2\pi/\omega_{pi}$)

- The residual electric field E accelerates part of the ions flowing into vacuum:

$$E = \frac{T_e}{eL_n} \quad (L_n = c_s t \; = \text{local plasma length})$$

- the ion motion is characterized by $N_i = N_0 \, exp[-(1 + x / c_s t)]$

$$v_i = c_s + \frac{x}{t}$$

Open problems

The self-similar quasi-neutral model, if applied to describe the ion acceleration process induce by ultrashort lasers presents several important limitations:

- it is not valid on the time scale typical of ultrashort fs lasers

- on the relevant time scales, $c_s t \ll \lambda_D$
  quasi-neutrality brakes down!

- the typical scale length of the accelerating field becomes λ_D
  We must use Poisson equation

To overcome these difficulties and achieve a satisfactory theoretical description, we must go beyond our starting assumptions……

WENSDAY at 9 o' clock!!