LL2 Meetings and PALS 10 Workshop
September 22-24 2010

Shock and hydro experiments at PALS

Dimitri Batani Università di Milano-Bicocca, Italy

Milan and Prague is an old history of friendship...
Our group has been one of the first and “most frequent” user of the PALS facility from the beginning of its activities.

- Shock Wave and Equation of State Experiments

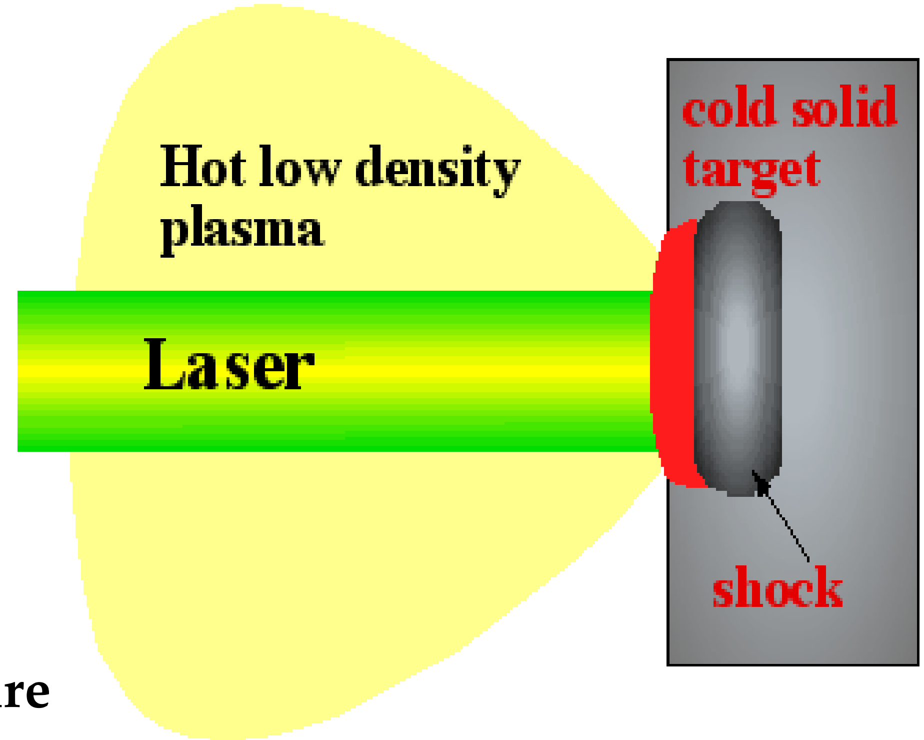
- Smoothing experiments

- Shock ignition experiments

We have also introduced new users to the “use” of the PALS facility, e.g.:
University of Rome Tor Vergata (Prof. Maria Richetta)
LOA Palaiseau (Prof. Victor Malka)
Milan, Faculty of Biology (Prof. Giulio Poletti and Franco Cotelli)
ILE, Osaka (Prof. Hiroaki Nishimura)
...

Equation of state Experiments (EOS)

High Power Lasers



Ablation pressure

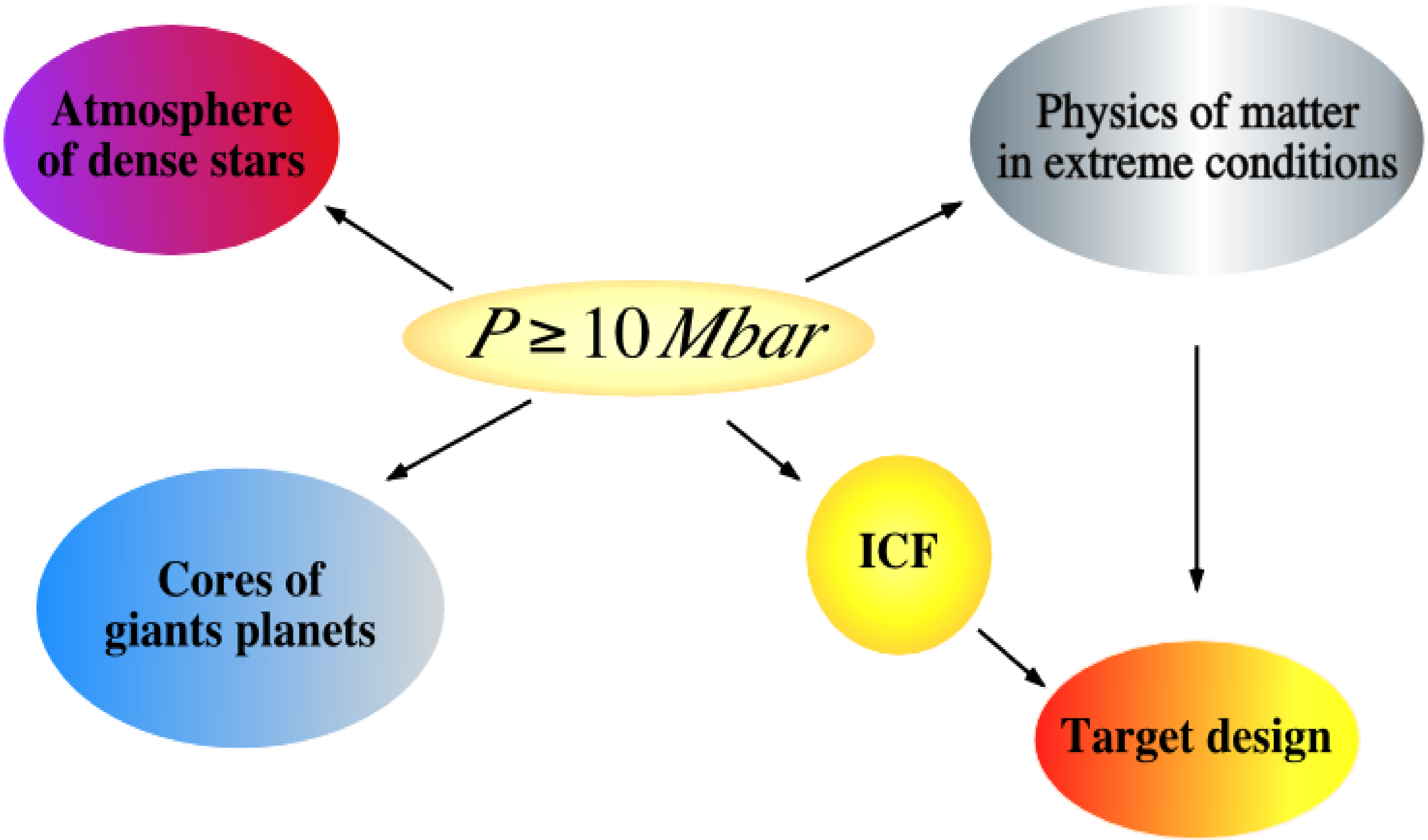
$$P(\text{Mbar}) = 11.6\ (I_L/10^{14})^{3/4}\ \lambda^{-3/4}\ (A/2Z)^{7/16}\ (Z^*\tau/3.5)^{-1/8}$$

I_L in W/cm^2, λ in μm, τ in ns

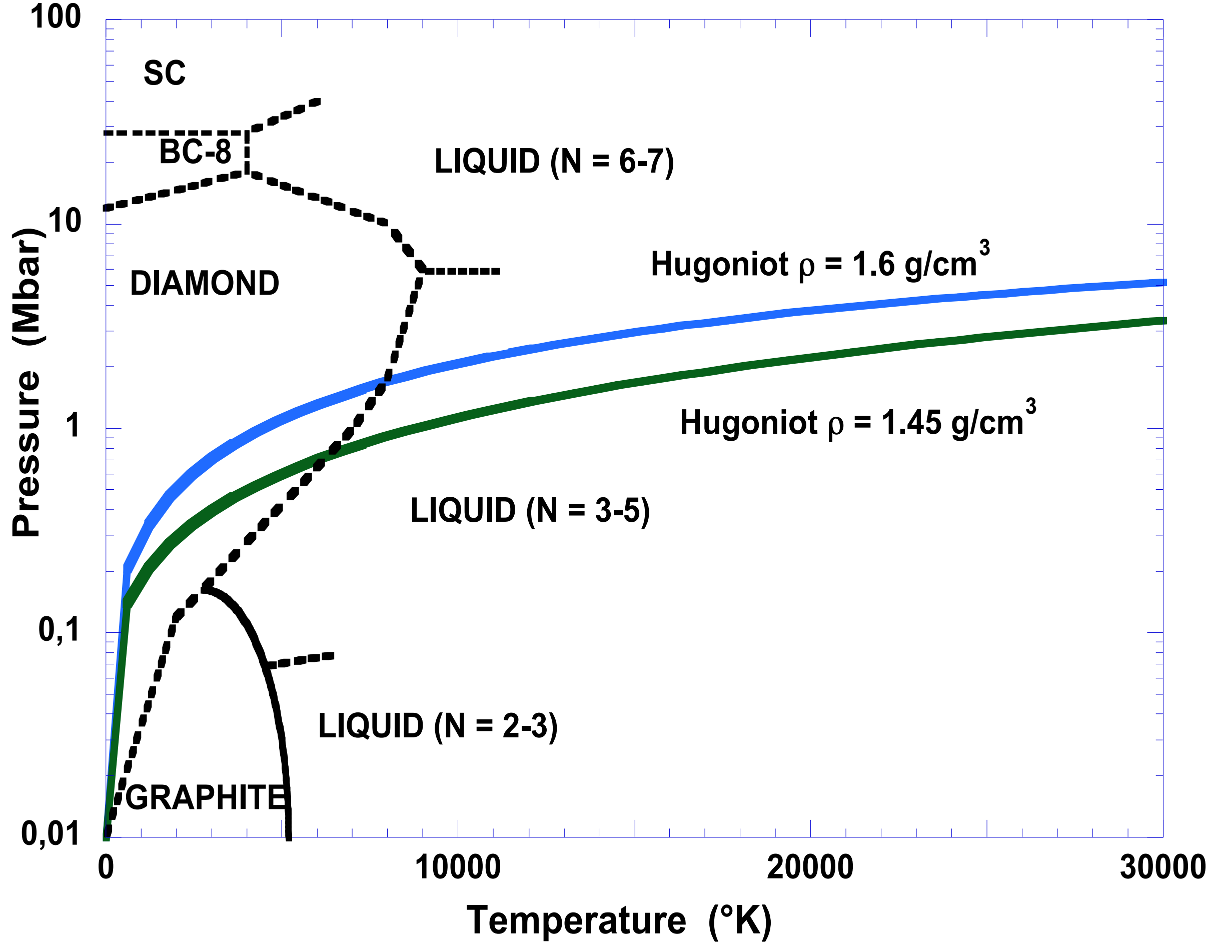
P.Mora "Theoretical model of absorption of laser light by plasma" Phys.Fluids, 1051 (1982)

D.Batani, H.Stabile, J.Ullschmied, et al. "Ablation Pressure Scaling at Short Laser Wavelength" Physical Review E, 68, 067403 (2003)

High Pressures in Physics

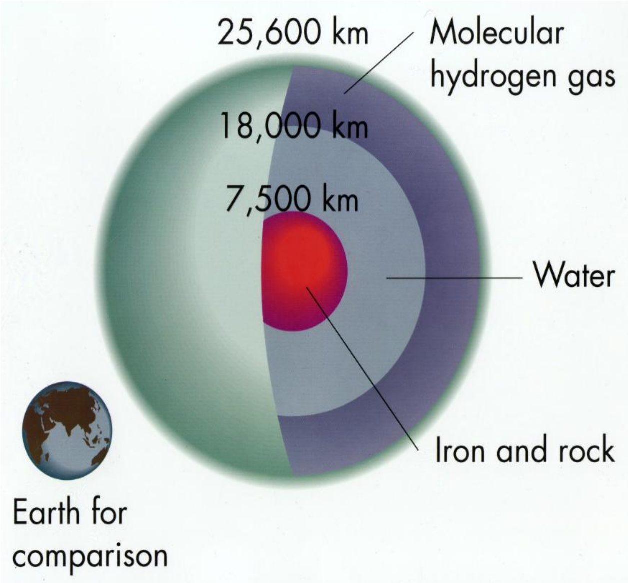


EOS of Carbon (theoretical model)



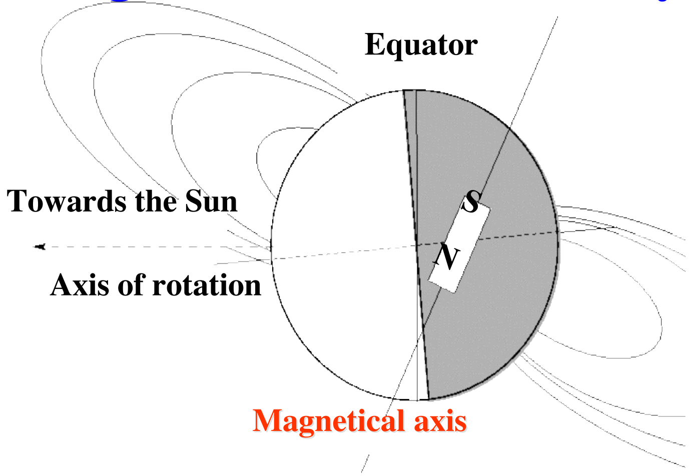
Grumbach and Martin's phase diagram and Hugoniot curves corresponding to initial densities ρ_o = 1.45 and 1.6 g/c

Astrophysical context



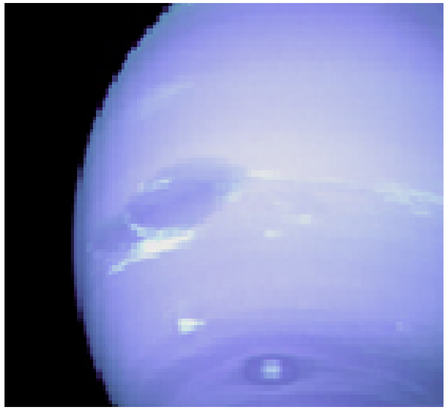
Neptune's internal structure

High magnetic fields measured by Voyager 2



Magnetic field of Uranus

- Mantle of Uranus and Neptune = «hot ices» of H_2O, NH_3, CH_4
- Intense, assymetrical magnetic field

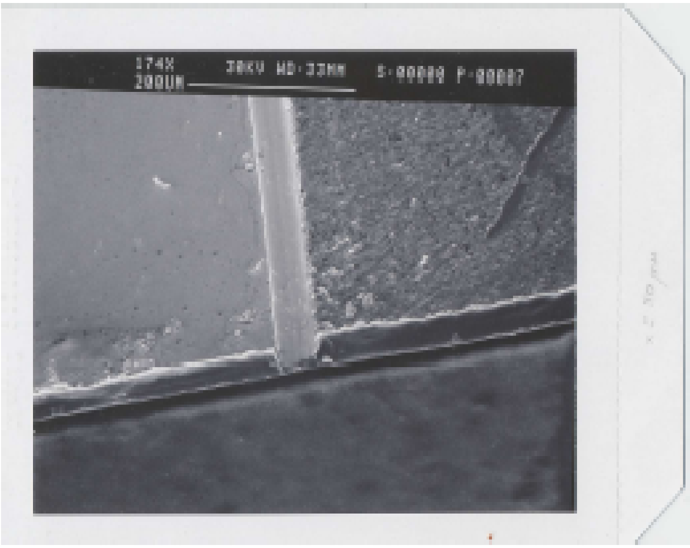


Pyrolisis of methane and separation of carbon?
Metallic liquid carbon or diamond layer?
Existence of a **fluid, conducting** region (based on water and carbon)?

PALS EXPT: Shock Chronometry

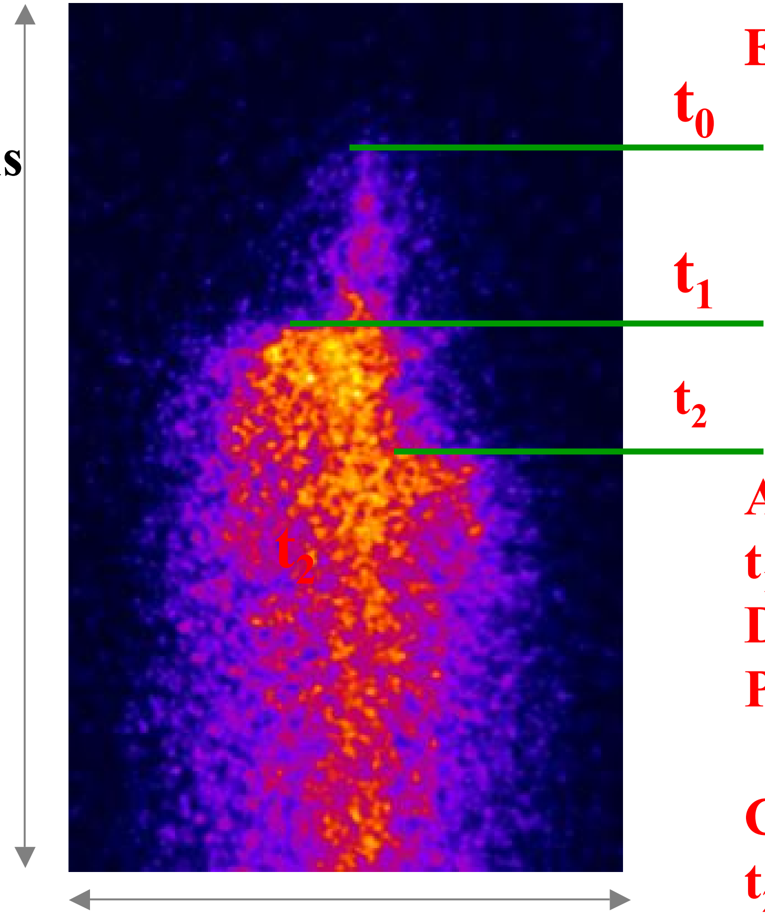
TARGETS PRODUCED AT GENERAL ATOMICS

$\rho_o = 1.6\ g/cm^3$



Two steps C / Al target

1.2 ns



0.7 mm

E = 108 J

Al step:

$t_1 - t_0 = 205$ ps

$D_{Al} = 38.8$ km/s

$P_{Al} = 33$ Mbar

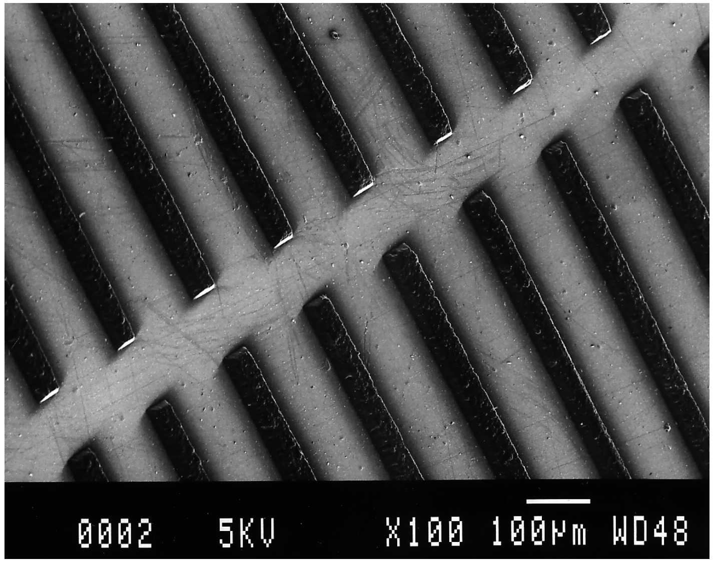
C step:

$t_2 - t_0 = 295$ ps

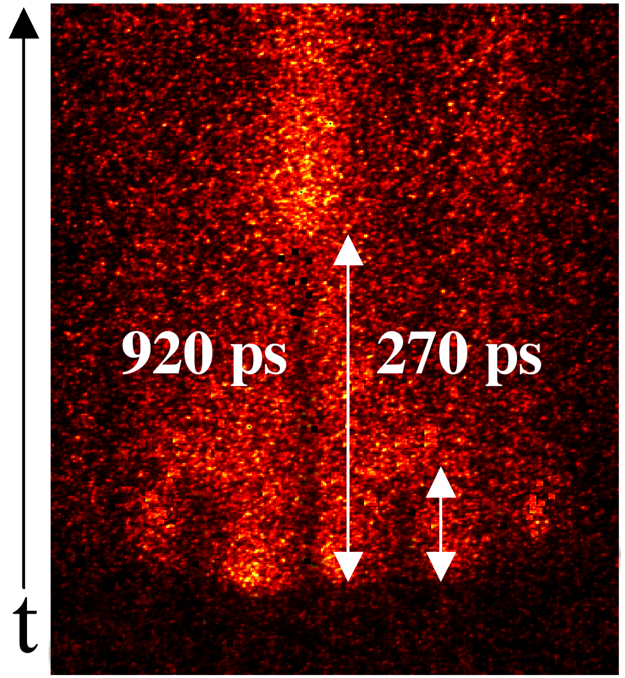
$D_c = 32.2$ km/s

$P_c = 18$ Mbar

Milan targets (ρ_o = 1.45 g/cm^3)



SEM image of carbon steps with ρ_o = 1.45 g/cm^3 deposited on a CH/Al substrate (P.Milani et al., Univ. Milan)



Shock breakout streak image of the target rear side in emission. Shot energy was 25.3 J. Arrows indicate the shock break-out from the Al step (right) and from the C step (left). The size of the image is 600 μm × 1.7 ns

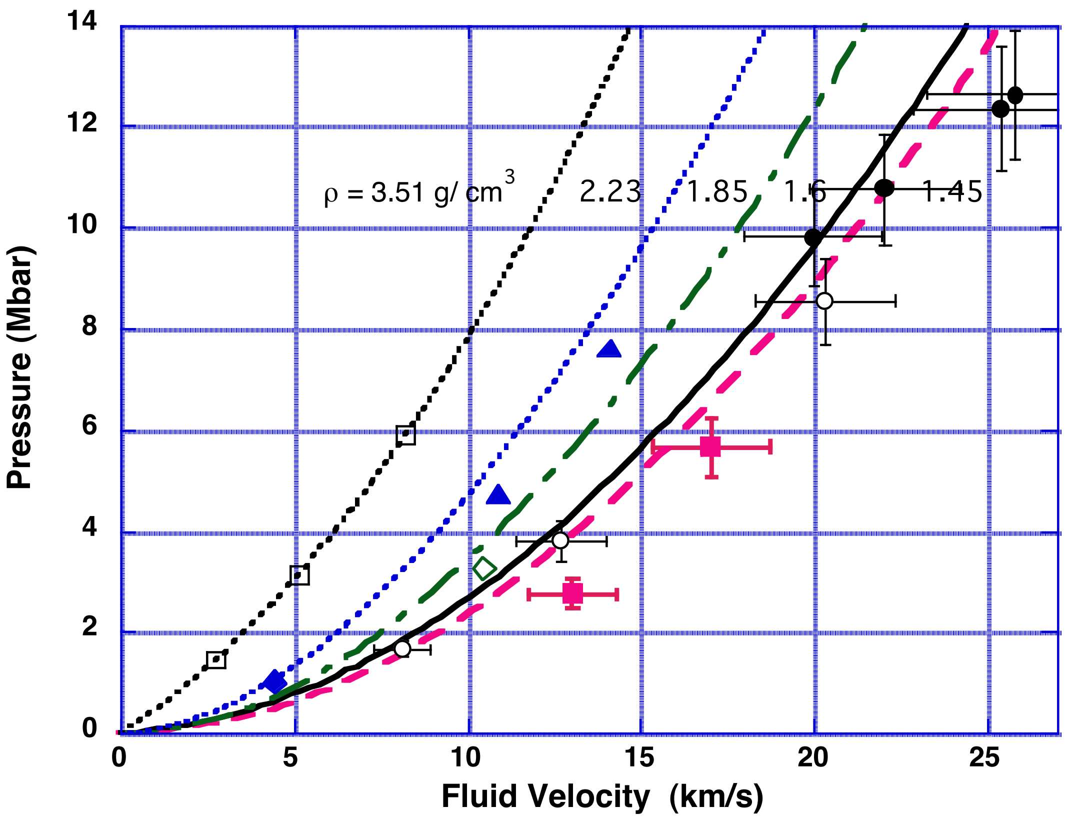
Carbon EOS: experimental results

Experimental EOS results from shock experiments:

Only data with pressures P ≥ 1.5 Mbar and corresponding Hugoniot are shown.

Our points:
full squares, 1.45 g/cm³ LULI;
empty circles, 1.6 g/cm³ LULI;
full circles, 1.6 g/cm³ PALS.

Previous points:
empty diamond, 1.85 g/cm³ Pavlovskii and Drakin;
triangles, 2.2 g/cm³ Nellis;
full diamond, 2.23 g/cm³ Pavlovskii et al.;
empty squares, 3.51 g/cm³ (diamond) Pavlovskii.



Carbon more compressible than what predicted by theoretical models

September - October 2002

shock wave and carbon EOS experiment

Alessandra Ravasio & Helise Stabile

June - July 2004

Shock-wave experiment (pressure scaling) and EOS of foams

LASERLAB 00933 (project leader D.Batani, Università Milano Biccoca)

(Federico Canova, Francesco Orsenigo, Renato Redaelli, DB)

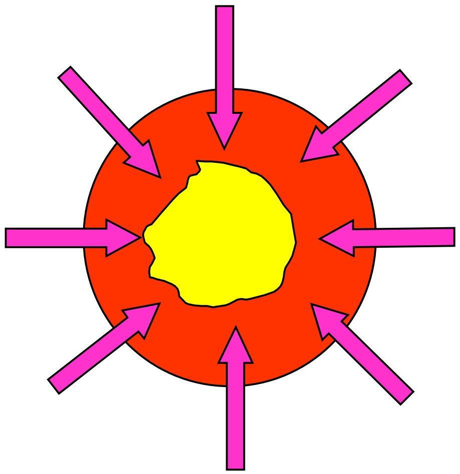
Smoothing Experiments

One of main problems in ICF

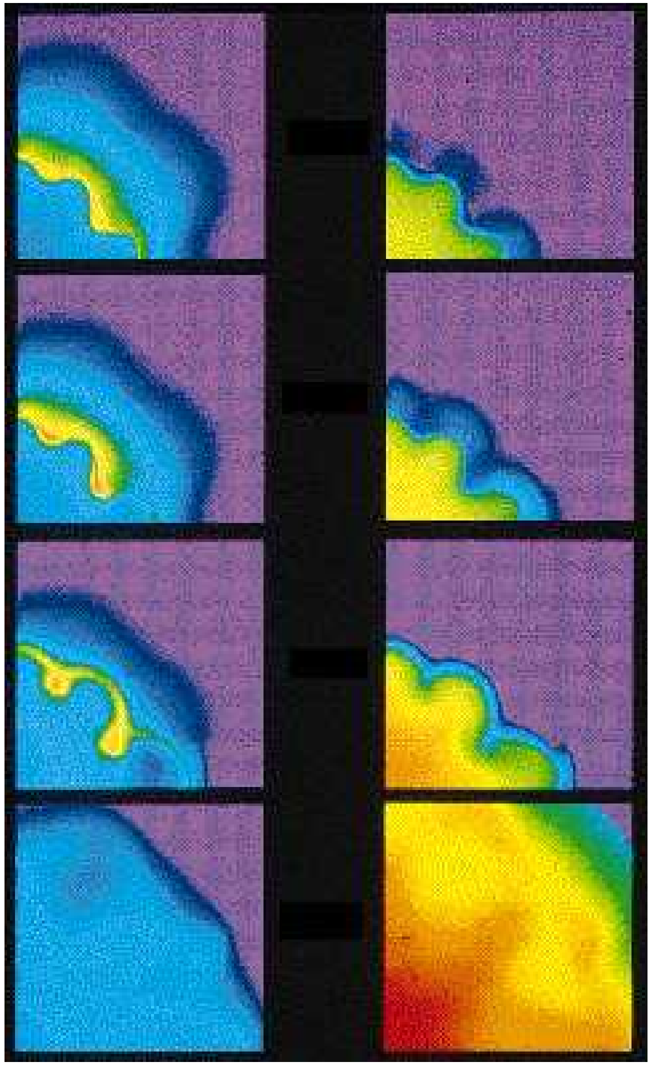
- non uniformity in laser or target
- Rayleigh Taylor hydrodynamic instability

These bring to:

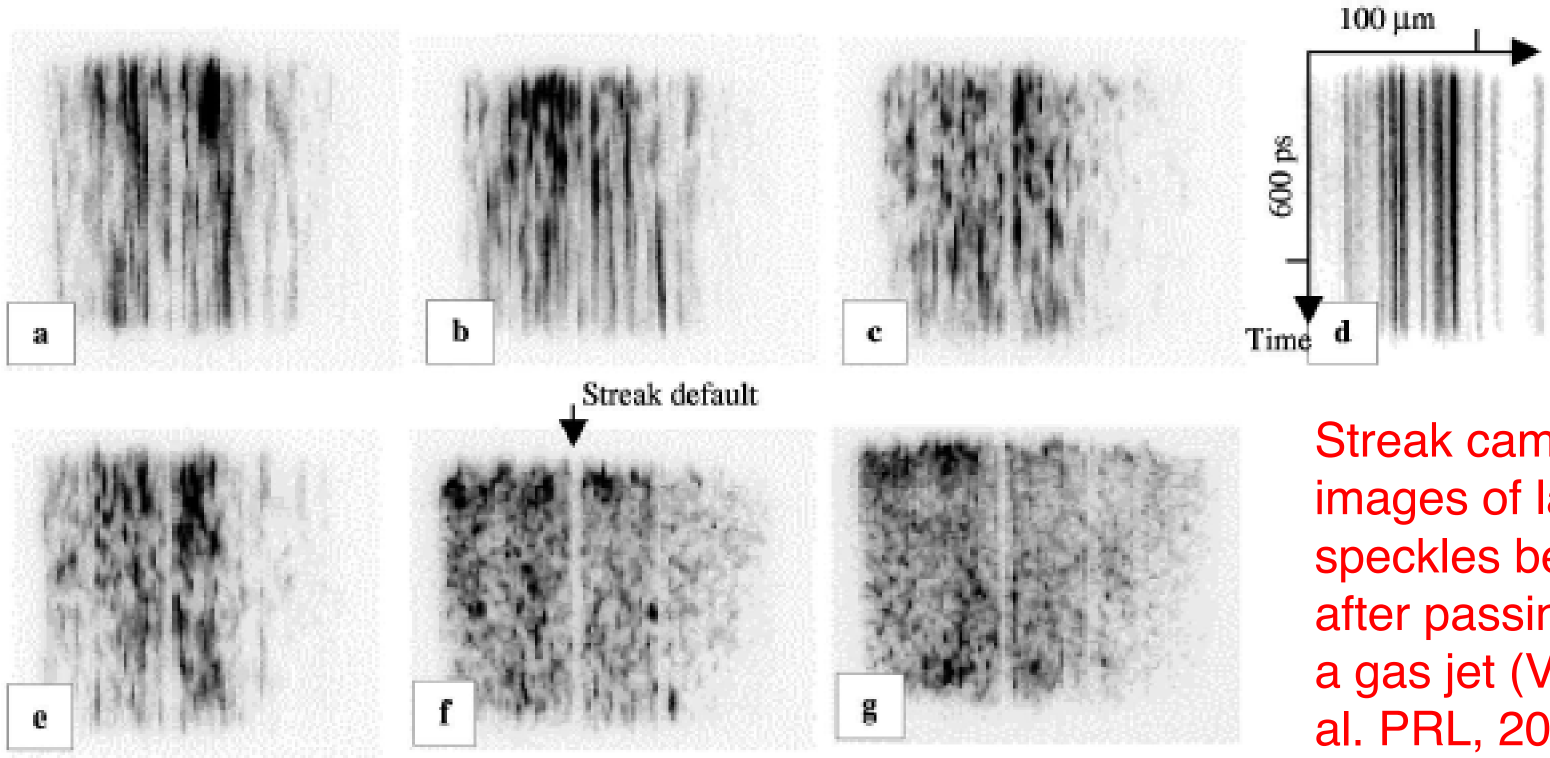
- Mixing of fuel and wall, higher Z*, increased emission and cooling
- The central hot spot is not generated



$$\frac{\Delta R_{fin}}{R_{fin}} \approx 50\% \Rightarrow \frac{\Delta I}{I} \approx 1\%$$



New approach gas jet smoothing



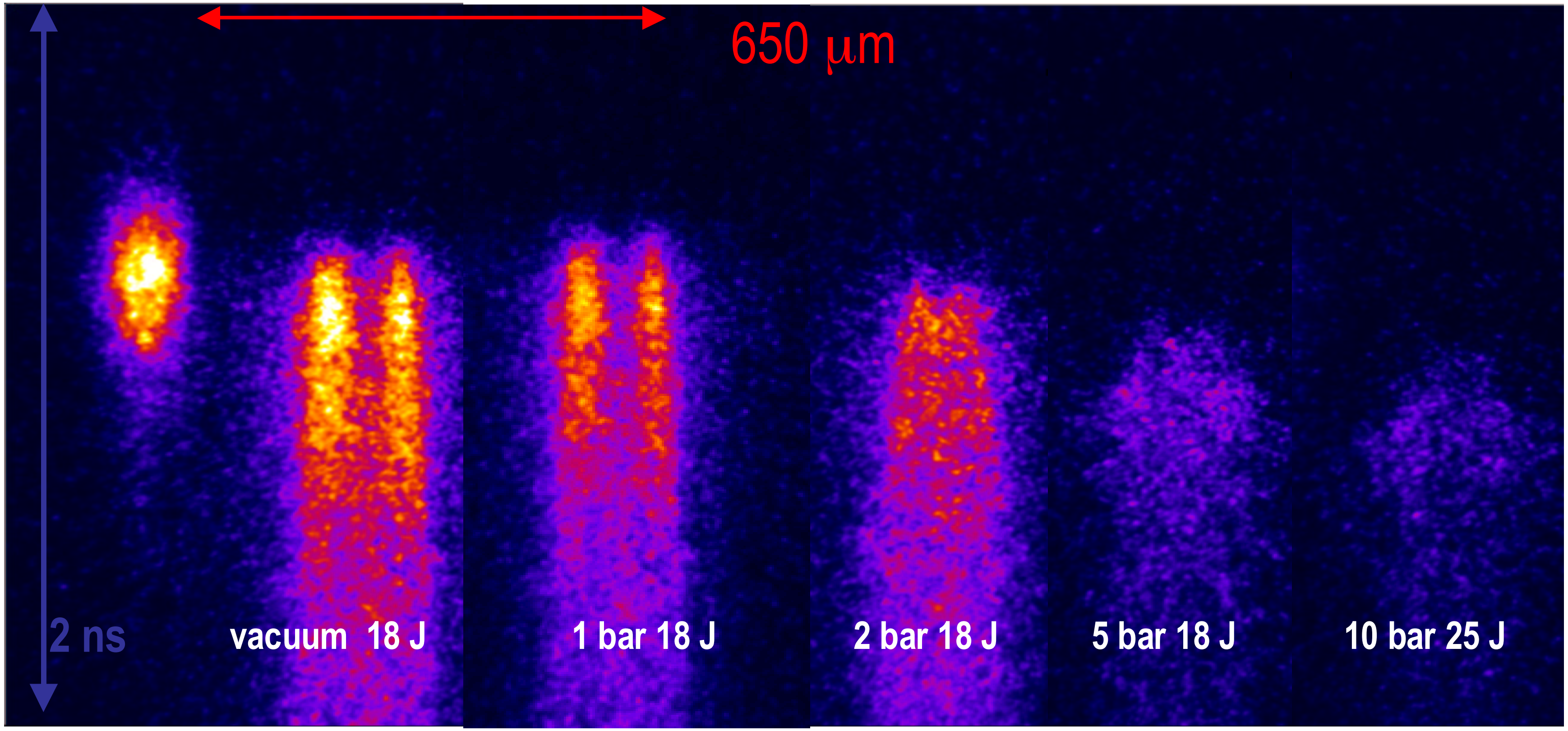
Streak camera images of laser speckles before and after passing through a gas jet (V.Malka et al. PRL, 2003)

FIG. 2. Time resolved images of the transmitted laser light in the PP (a)–(c) and NPP (e)–(g) cases for plasmas with the density of 0.2 (a),(e), 0.5 (b),(f), and 1% (c),(g) of the critical density. (d) Reference image for a vacuum shot without plasma. (h) Temporal dependence of the intensity for panels f (solid line) and d (dotted line).

New promising scheme. Interest of measuring the real effect on hydro and comparing with foam smoothing

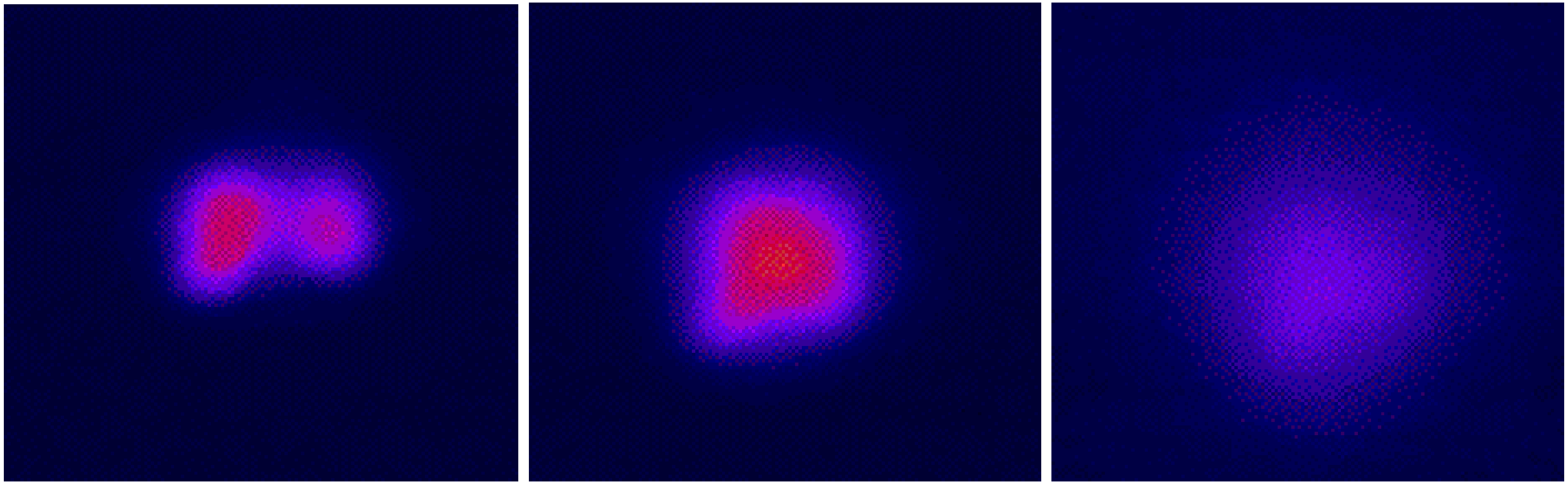
COUPLING TO PAYLOAD: Shock breakout

Coupling of the laser beam to a payload target (Al 10 μm) with Ar gas jet at different pressures



Very large non-uniformities seem to be smoothed very effectively.
Preliminary results. Need for further analysis and more measurements

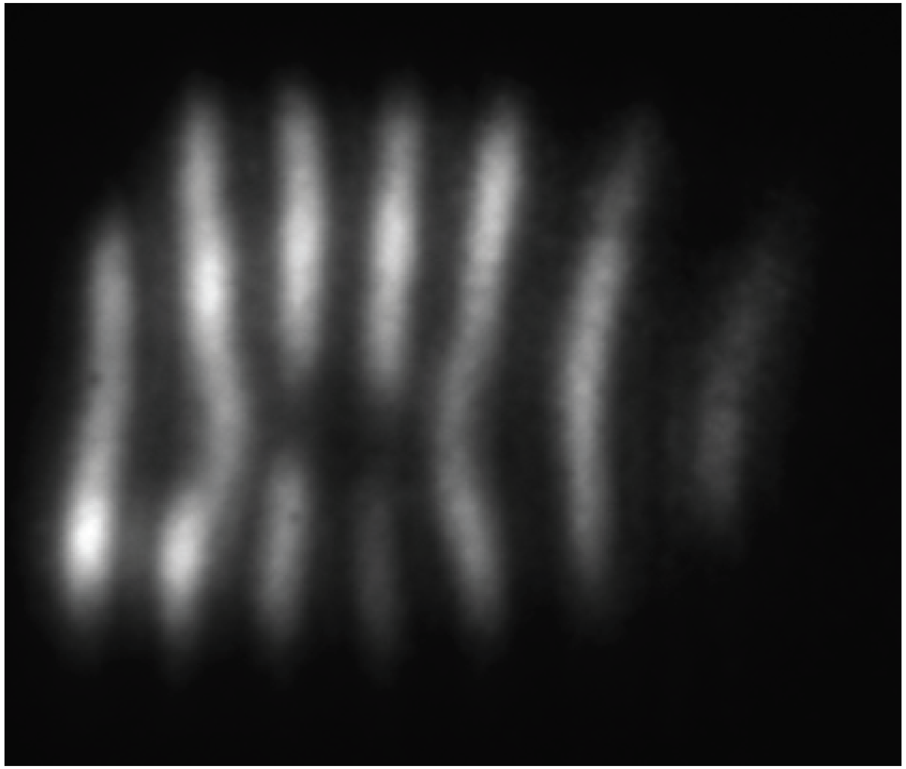
Results confirmed by X-ray pin-hole camera images

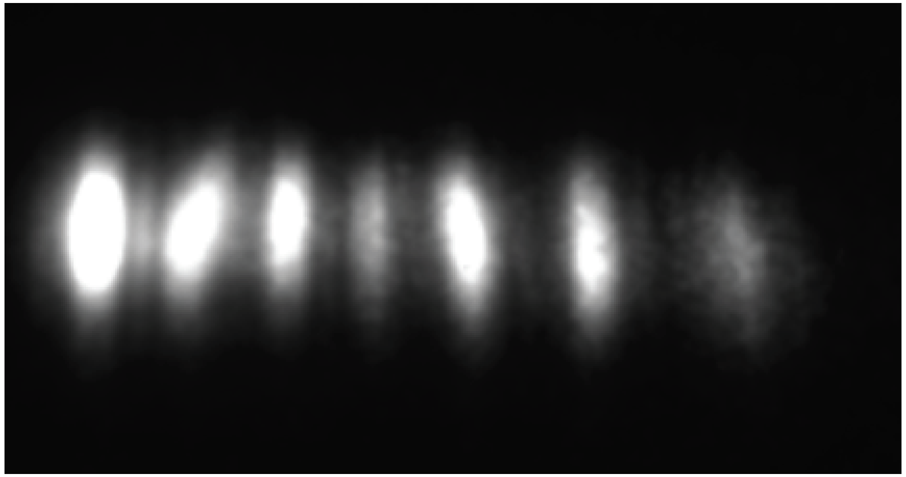


Pin hole camera images corresponding to previous figures b) c) and e), i.e. 1 bar 18 J; 2 bar 18 J; and 10 bar 25 J

The gas jets give good smoothing effect even for large scale disuniformities.

Next step: *stripy* focal spot





Static (CCD) and dynamic (streak camera) images of the stripy focal spot obtained with a mask. The horizontal linear dimension of the static image is about 500 μm.

13 February - 24 March 2006

Study of foam and gas smoothing of laser energy deposition

From the right: Riccardo Dezulian, DB, Michel Koenig, Adela Tumova, Miroslav Pfeifer, Eduard Krousky and Karel Masek

13 February - 24 March 2006

Study of foam and gas smoothing of laser energy deposition

From the right: Renato Redaelli, Helise Stabile (UMB) Victor Malka (LOA)

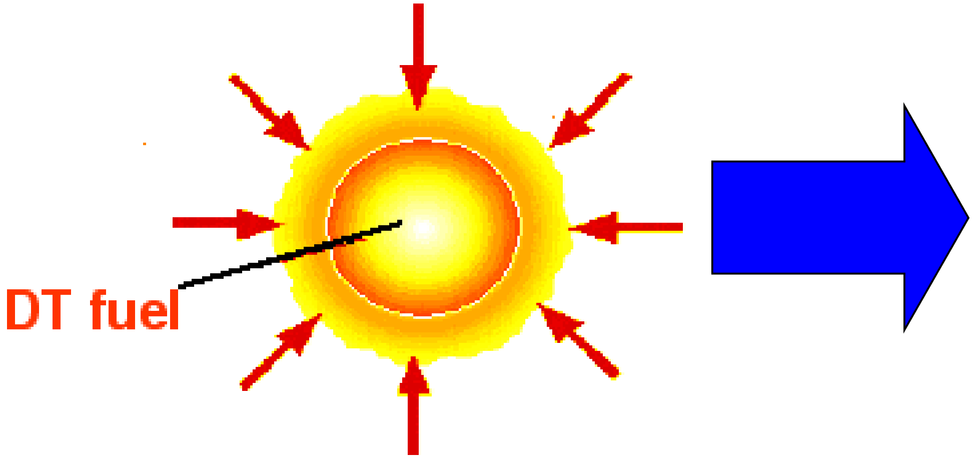
UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

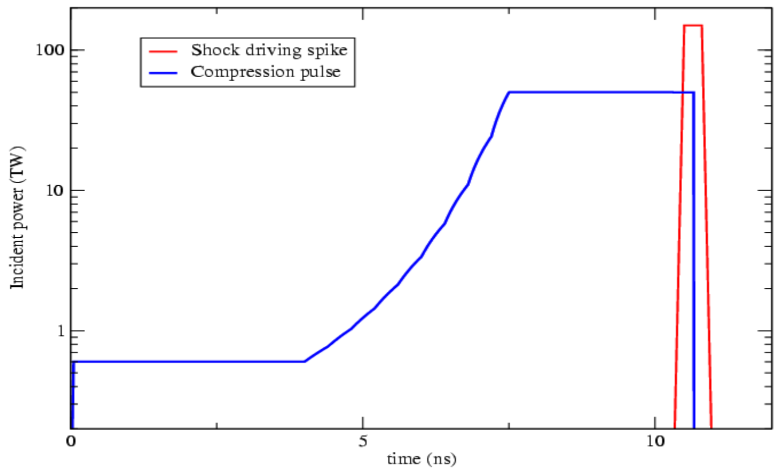
Shock Ignition Experiment (HiPER)

The concept of shock ignition

1: "normal" compression of a thermonuclear DT pellet with ns laser beams at $I \approx 10^{14}$ W/cm^2

2: a high-intensity pulse ($I \approx 10^{15}$ - 10^{16} W/cm^2) generates a strong shock ($P \approx$ several 100 Mbar) which heats the central spot and creates the conditions for ignition





Goals of PALS experiment:

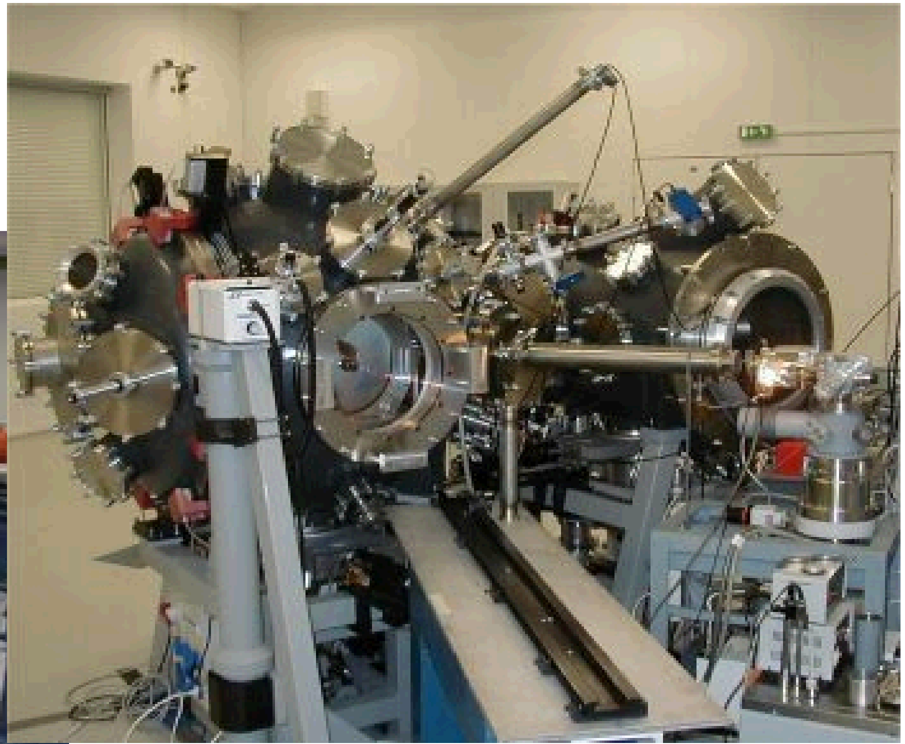
1) The effect of laser-plasma instabilities at $I \approx 10^{16}$ W/cm^2. Do they develop? How much light do they reflect? Do they create many hot electrons and at what energy?

2) Are we really able to couple the high-intensity laser beam to the payload through an extended plasma corona? Are we able to create a strong shocK?

PALS experiment

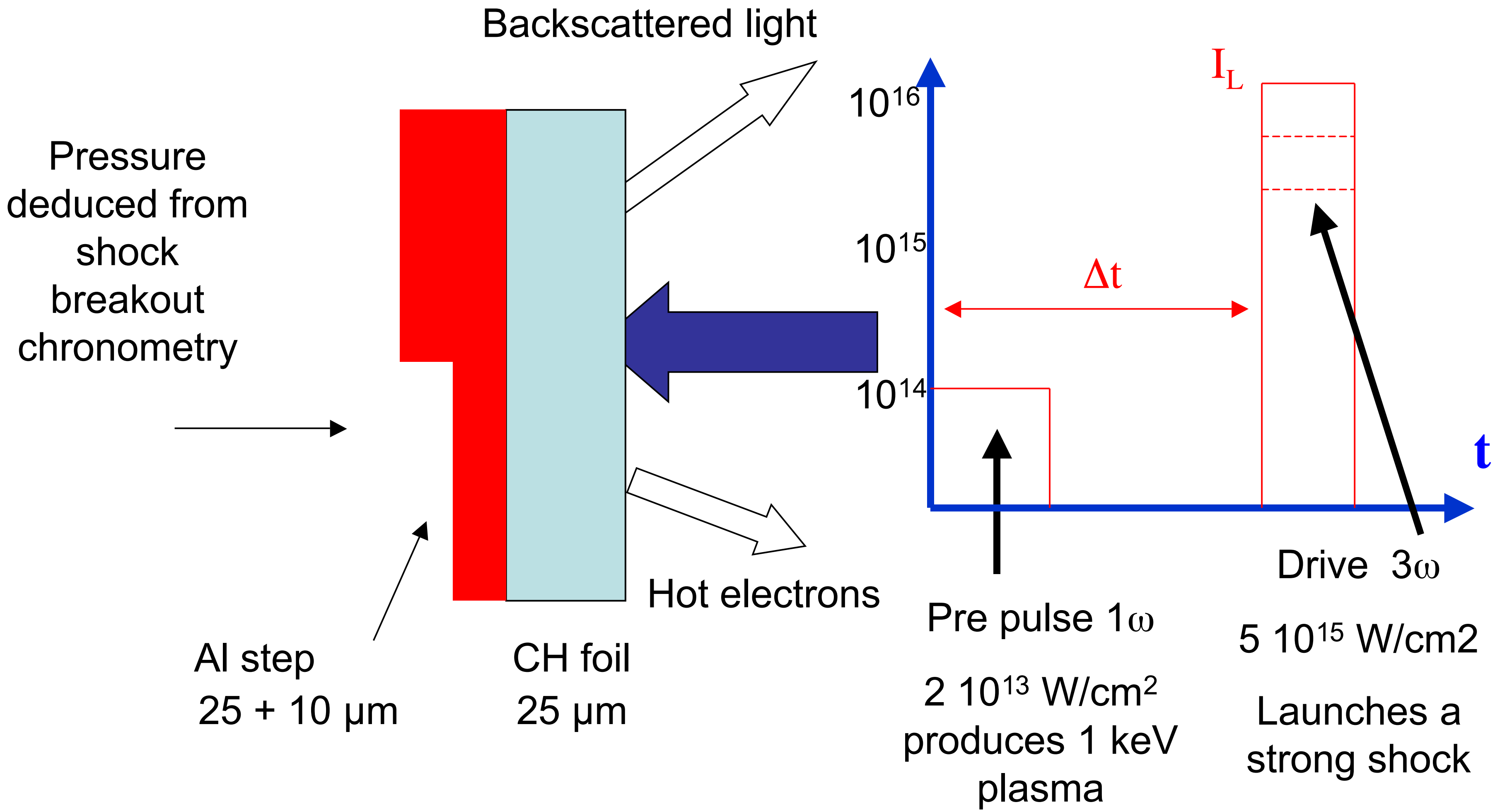
Iodine Laser
λ =1.3 μm τ = 300 ps E = 1500 J
3ω λ =0.44 μm E ≤ 500 J

Laser Interaction Chamber at the PALS Laboratory in Prague



"Full" use of PALS laser facility:
Main beam at 3ω
Auxiliary beam creating extended plasma
XRL beam for diagnostics

Sketch of expt. set-up



The CH layer simulates the low-Z material of a pellet shell.
The Al layer is a standard material for shock measurements

Diagnostics

Phase 1
Creation and characterization of preplasma with:

1) X-ray deflectometry, using the PALS X-ray laser to obtain the density profile
2) X-ray spectroscopy, to obtain plasma temperature
3) X-ray pin-hole cameras

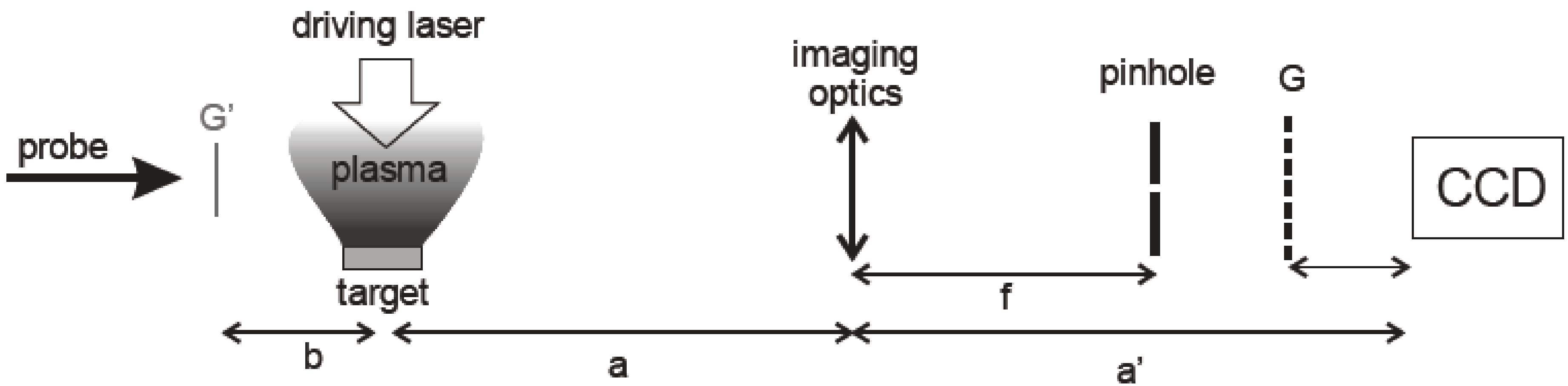
Phase 2
Characterization of shock formation and laser-plasma interaction with:

The interaction of the main pulse has been studied using:

1) EEPHC diagnostic (energy encoded X-ray pin-hole camera) to measure plasma extension and characterize its emission.
2) Ion diagnostics (ion collectors)
3) Shock chronometry (measuring the self emission from the target rear side with a streak camera)
4) Optical imaging, spectroscopy, and calorimetry of back reflected radiation to evaluate the onset and amount of back reflected light from parametric instabilities (SRS, SBS, TPD)

Density measurement - XRL deflectometry

The technique used for this measurement is based on the deformation of Talbot pattern of 2D grating caused by gradients of index of refraction (electron density) of plasma

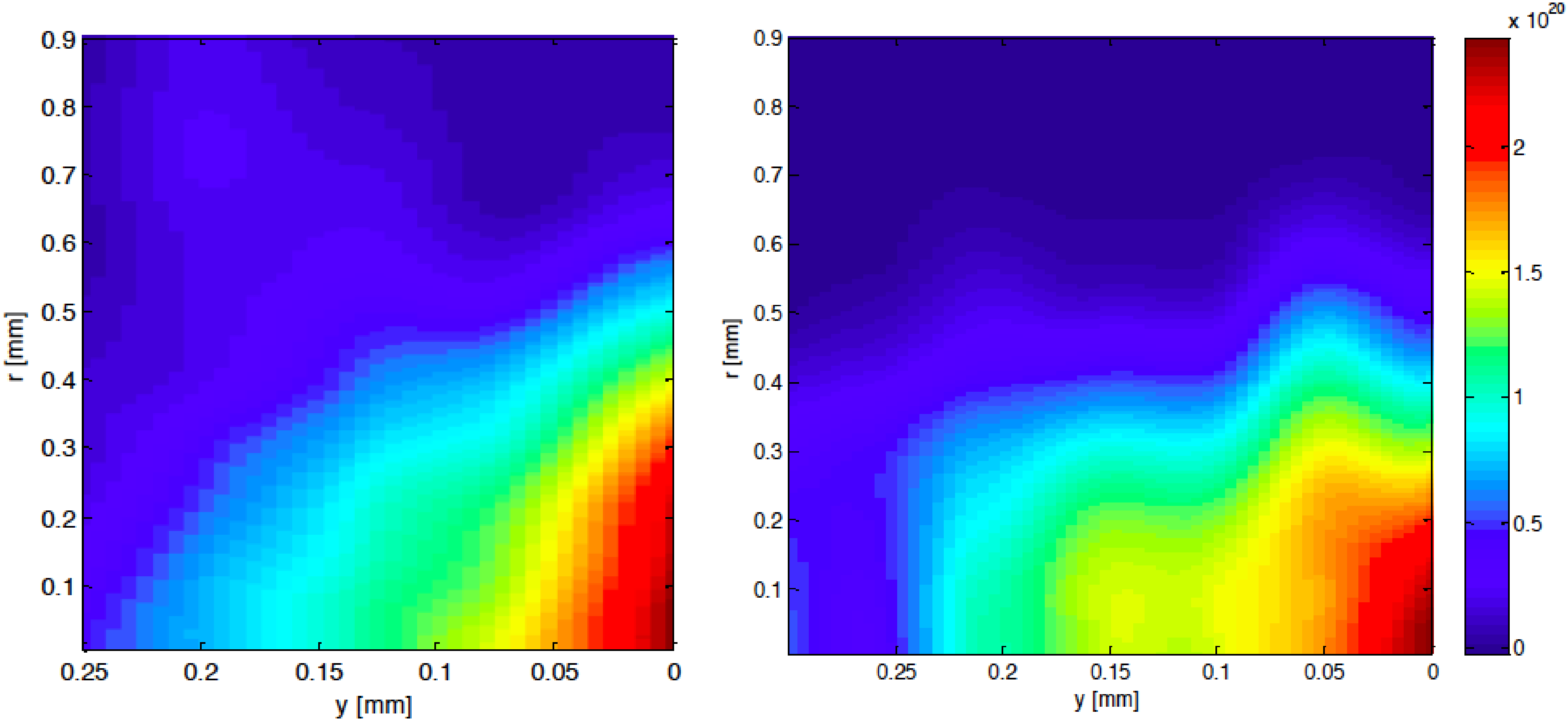


Ne-like zinc X-ray laser emitting at 21.2 nm, operated in single pass with 150-ps pulses of 200 μJ. Mo-Si multilayered spherical mirror with f=250mm used to image the plasma on back-illuminated X-ray CCD with M = 8.2. 0.5mm pinhole diameter was put to the image of the XRL source (2500 mm from the imaging mirror), to reduce the signal of plasma self-emission. The 100 μm period laser-drilled grid made of 5 μm thick steel was at 1275 mm from CCD.

J. Nejdl, M. Kozlova, Plasma density-gradient measurement using x-ray laser wave-front distortion, Proc. SPIE Vol. 7451, 745117 (2009)

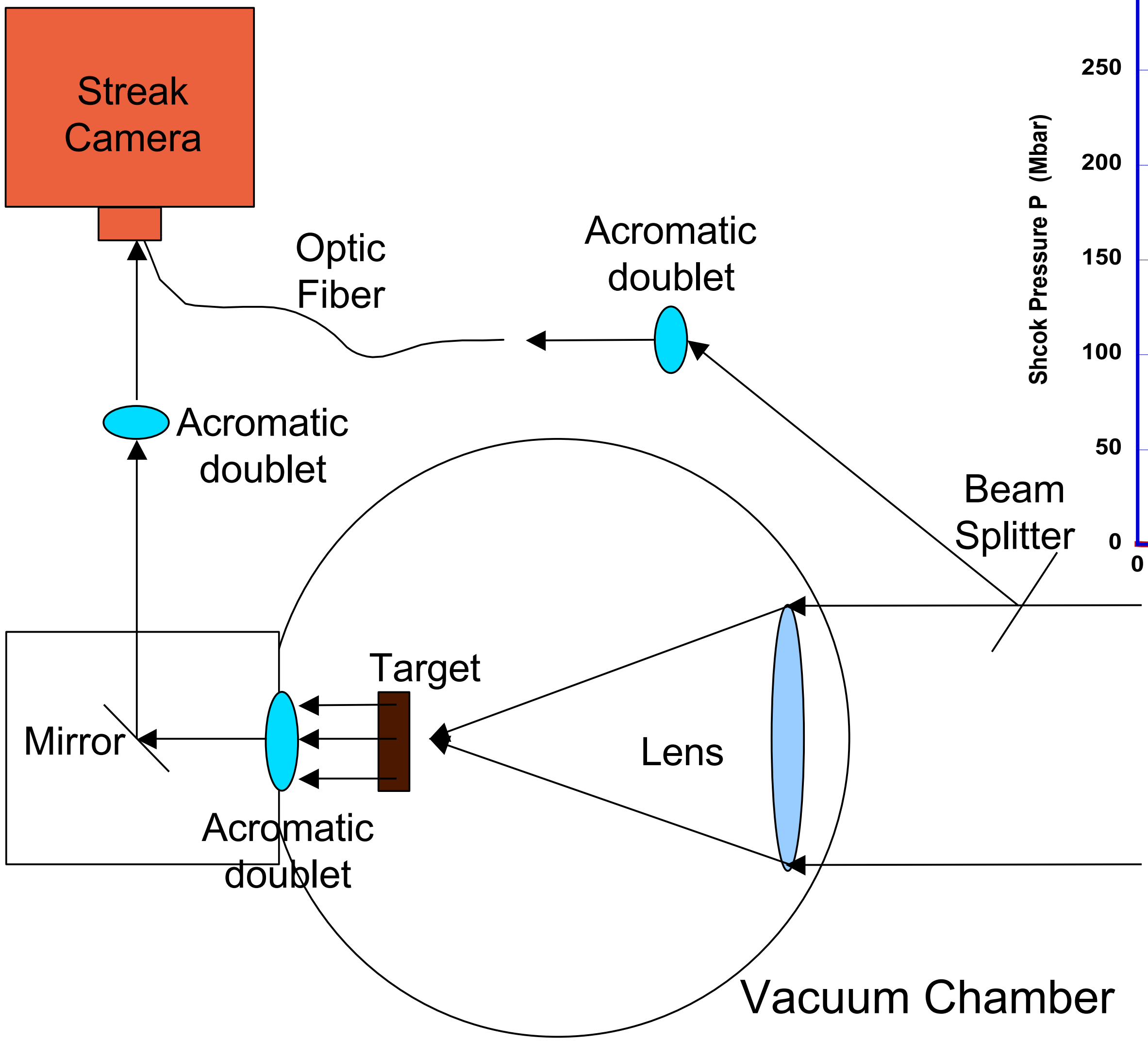
Density profiles of pre-plasma

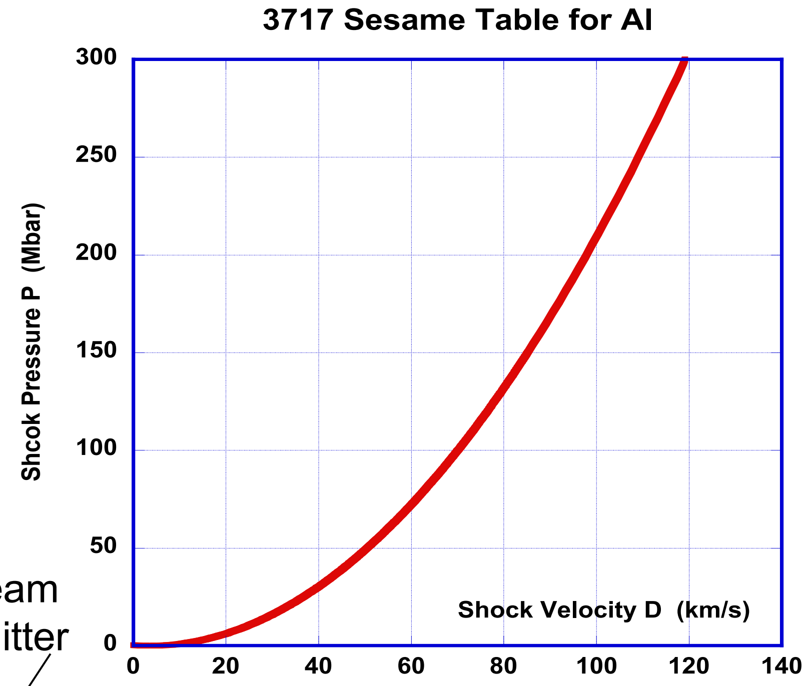
2D density profiles at different times after irradiation



0.3 ns **0.9 ns**

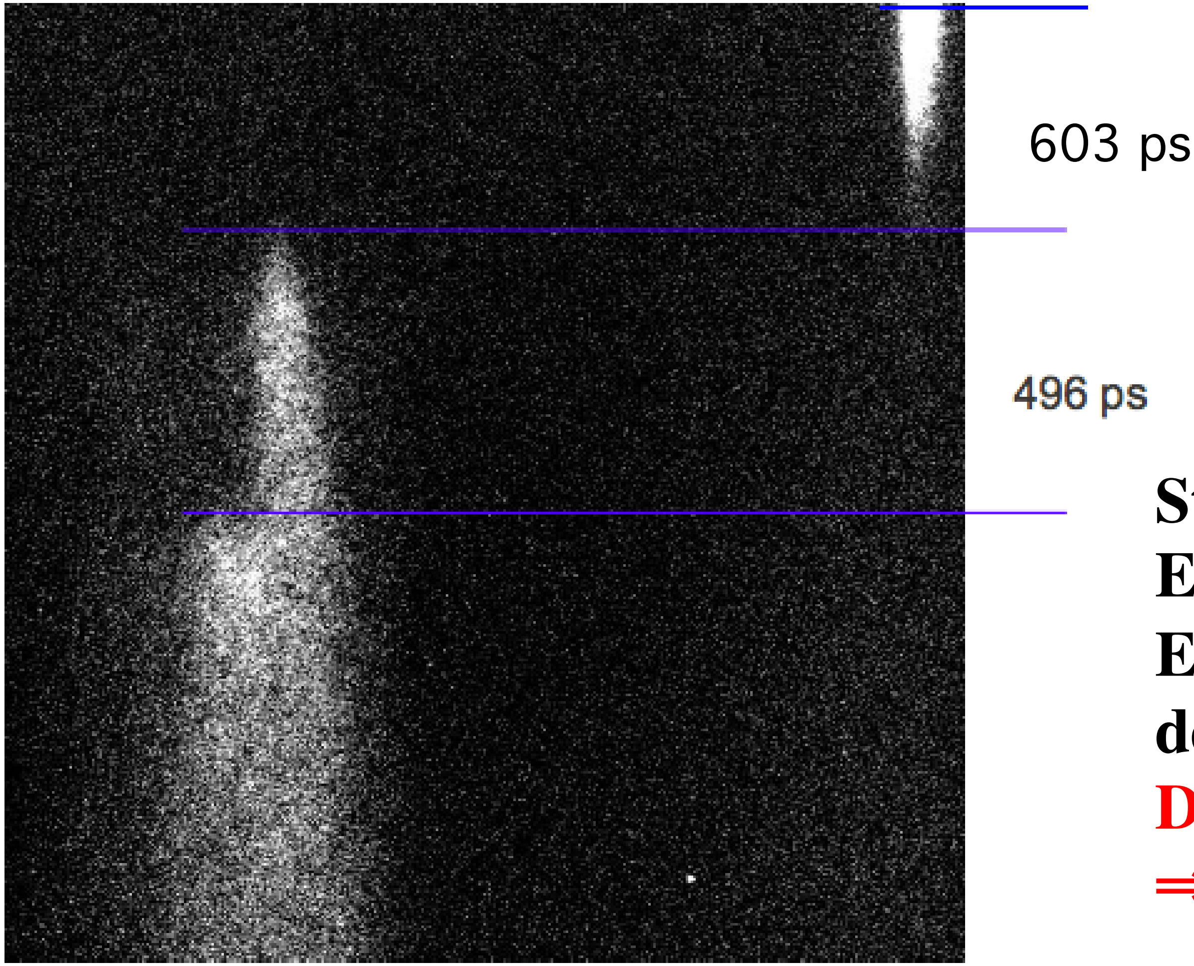
Shock chronometry: set-up





The measurement of shock velocity provides the value of shock pressure using an EOS

Shock chronometry



Stepped target with
E(3ω) = 245 J
E pre-pulse = 29 J,
delay prepulse 500 ps
D = 20.2 km/s
⇒ P = 6.3 MBar

Such pressure is compatible with initial P = 100 Mbar (due to 2D and relaxation effects)

Back scattering diagnostics

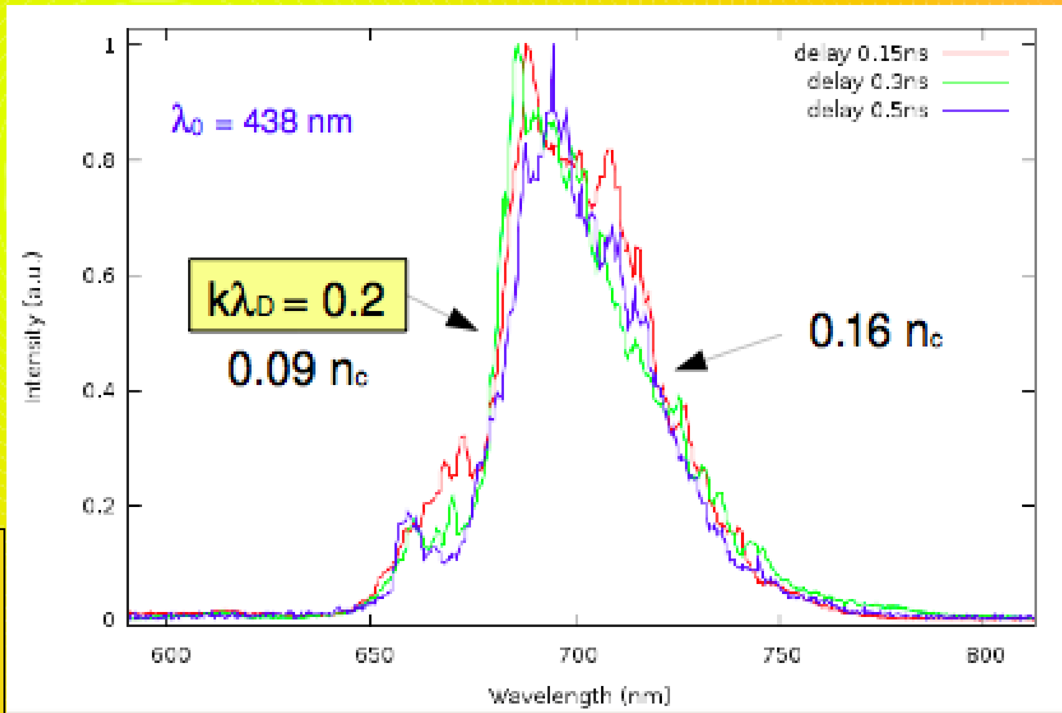
Results at Omega (Usa, 2009) give 33% back reflection at ≈ 8 10^{15} W/cm^2

A surprisingly small fraction of light (<5%) is backscattered in our experiment (≈ 10^{16} W/cm^2, $\lambda = 0.44\ \mu$m)

- **SRS**
  - **Emission between ω (n ~ 0) and $\omega/2$ (n= n_c /4)**

$$\lambda_{SRS} = \lambda_0 \left[1 - (n/n_c)^{1/2}(1+3k^2\lambda_D^2)^{1/2}\right]^{-1}$$

  - **Blue cut-off due to Landau damping**



kλD ← → n → nc/4

No SRS emission from $n_c/4$ layer. Depletion of laser beam due to delocalised collisional absorption?

November 2009 - April 2010

Shock-ignition experiment

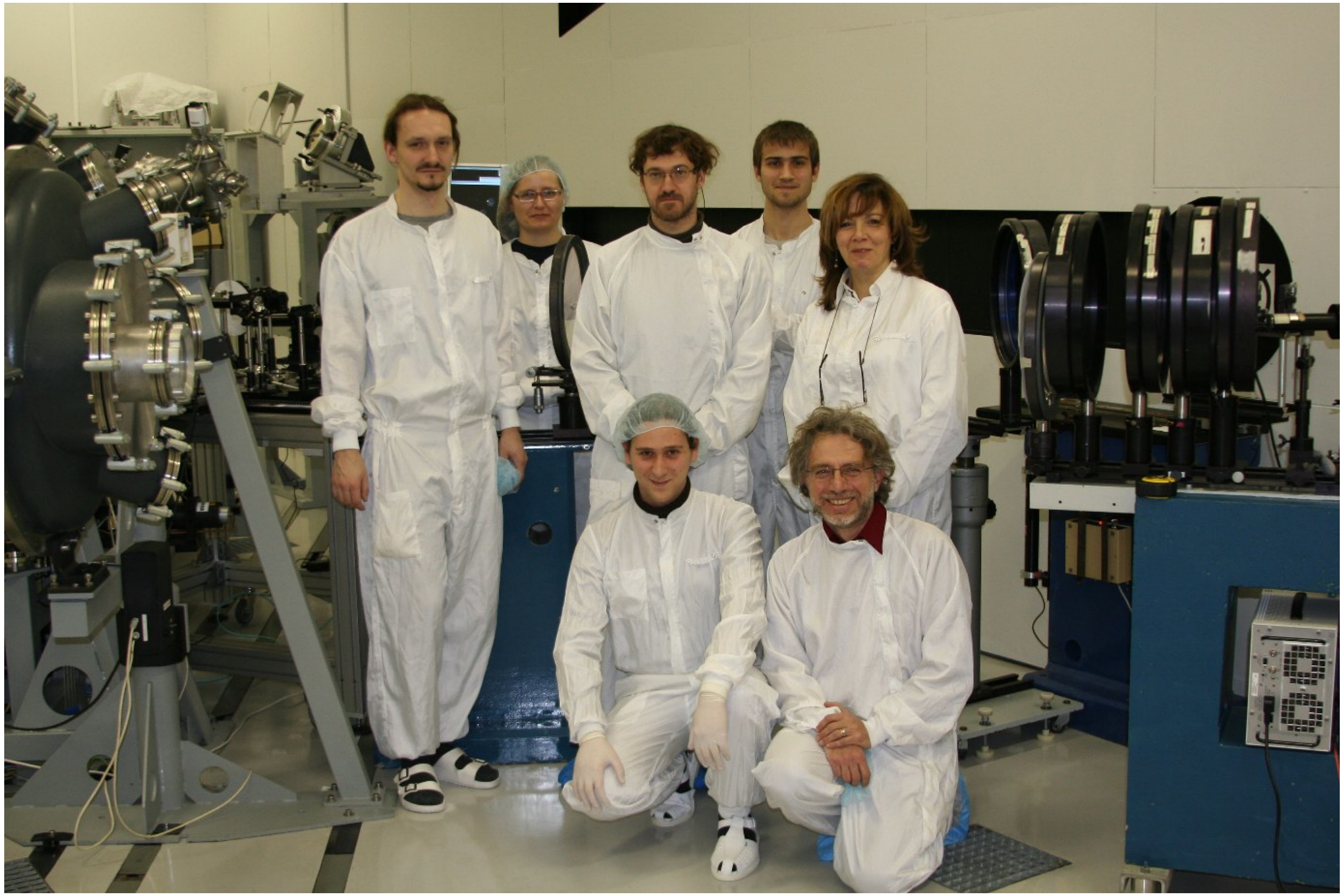
HiPER and LASERLAB project

From right: Mischa Kozlova, Jarda Nejdl, Mirek Krus (PALS), Carlo Cecchetti (CNR Pisa) Luca Antonelli (UMB Milano), Lorenzo Giuffrida (LNS Catania), Alessandro Moretti (Tor Vergata, Roma)

November 2009 -April 2010

Shock-ignition experiment

HiPER and LASERLAB project



From left: Jarda Nejdl (PALS), Petra Koester, Luca Labate (CNR Pisa), Andrea Patria (UMB Milano), Maria Richetta (Tor Vergata, Roma), bottom: Luca Antonelli, DB (UMB Milano)

Selected papers from PALS expts

D.Batani, H.Stabile, A.Ravasio, T.Desai, G.Lucchini, T.Desai, J.Ullschmied, E.Krousky, L.Juha, J.Skala, B.Kralikova, M.Pfeifer, C.Kadlec, T.Mocek, A.Präg, H.Nishimura, Y.Ochi "Ablation Pressure Scaling at Short Laser Wavelength" **Physical Review E**, 68, 067403 (2003).

D.Batani, H.Stabile. M.Tomasini, G.Lucchini, A.Ravasio, M. Koenig, A. Benuzzi-Mounaix, H.Nishimura, Y.Ochi, J.Ullschmied, J.Skala, B.Kralikova, M.Pfeifer, Ch.Kadlec, T.Mocek, A.Präg, T.Hall, P.Milani, E.Barborini, P.Piseri "Hugoniot Data for Carbon at Megabar Pressures" **Physical Review Letters**, 92, 065503 (2004).

G.Poletti, F.Orsini, D.Batani, A.Bernardinello, T.Desai, J.Ullschmied, J.Skala, B.Kralikova, E.Krousky, M.Pfeifer, Ch.Kadlec, T.Mocek, A.Präg, O.Renner, F.Cotelli, C.Lora Lami, A.Zullini "Soft X-ray Contact Microscopy of nematode *Caenorhabditis elegans*" **European Physical Journal D**, vol. 24, 84 (2004)

D.Batani, R.Dezulian, R.Redaelli, R.Benocci, H.Stabile, F.Canova, T.Desai, G.Lucchini, E.Krousky, K.Masek, M.Pfeifer, J.Skala, R.Dudzak, B.Rus, J.Ullschmied, V.Malka, J.Faure, M.Koenig, J.Limpouch, W.Nazarov, D.Pepler, H.Nishimura "Recent experiments on the hydrodynamics of laser-produced plasmas conducted at the PALS laboratory" **Laser and Particle Beams**, 25, March 2007, pp 127-141

R.Dezulian, F.Canova, S.Barbanotti, F.Orsenigo, R.Redaelli, T.Vinci, G.Lucchini, D.Batani, B.Rus, J.Polan, M.Kozlová, M.Stupka, A.R.Praeg, P.Homer, T.Havlicek, M.Soukup, E.Krousky, J.Skala, R.Dudzak, M.Pfeifer, H.Nishimura, K.Nagai, F. Ito, T.Norimatsu, A.Kilpio, E.Shashkov, I.Stuchebrukhov, V.Vovchenko, V.Chernomyrdin, I.Krasuyk "Hugoniot Data of Plastic Foams obtained from Laser-Driven Shocks" **Physical Review E**, 73, 047401 (2006)

Selected papers from PALS expts

D. Batani, H. Stabile, G. Lucchini, F. Canova, M. Koenig, A. Benuzzi, H. Nishimura, Y. Ochi, J. Ullschmied, J. Skala, B. Kralikova, M. Pfeifer, T. Mocek, A. Präg "High-Pressure Behavior of Carbon by Laser-Generated Shocks" **Russian Journal of Physical Chemistry A**, Vol. 81, No. 9, pp. 1360–1364. CONFERENCE: CHEMICAL THERMODYNAMICS AND THERMOCHEMISTRY (2007)

R.Benocci, D.Batani, R.Dezulian, R.Redaelli, G.Lucchini, F.Canova, H.Stabile, J.Faure, E.Krousky, K.Masek, M.Pfeifer, J.Skala, R.Dudzak, M.Koenig, V.Tikhonchuk, Ph. Nicolaï, V.Malka "Gas-induced smoothing of laser beams studied by interaction with thin foils" **Plasma Physics Contr. Fusion, 50** No 11 (November 2008) 115007 (2008)

R.Benocci, D.Batani, R.Dezulian, R.Redaelli, G.Lucchini, F.Canova, H.Stabile, J.Faure, E.Krousky, K.Masek, M.Pfeifer, J.Skala, R.Dudzak, M.Koenig, V.Tikhonchuk, Ph. Nicolaï, V.Malka "Direct evidence of gas-induced laser beam smoothing in interaction with thin foils" **Phys. Plasmas 16** 012703 (2009)

D.Batani, L.Antonelli, A.Patria, O.Ciricosta, C.Cecchetti, P.Koester, L.Labate, A.Giulietti, L.A.Gizzi, A.Moretti, M.Richetta, L.Giuffrida, L.Torrisi, M.Kozlová, D.Margarone, J.Nejdl, G.Schurtz, X.Ribeyre, M.Lafon[6], C.Spindloe, T.O'Dell « Laser-Plasma Coupling in the Shock-Ignition intensity regime" sub to **Acta Tecnica** (2010) [Proc. SPPT 2010 Prague]

Final remark:

We met a lot of difficult optical alignment problems. However, the technical skill of PALS staff has always helped us quite a lot!

Final remark:

Thank you!!