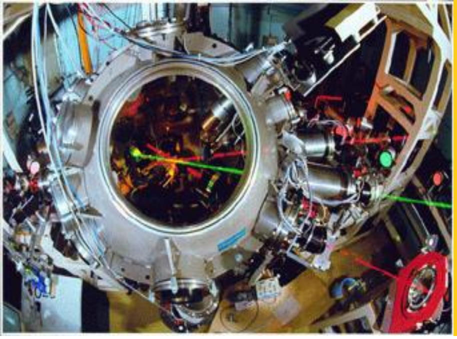


Radiative Shocks in the Laboratory

Jean Pierre Chièze

CEA / DSM / Irfu

Service d’Astrophysique - AIM

Radiative shocks in astrophysics

Planets:

Asteroïd entry in planetary atmospheres

Entry of various probes & vehicles

Stars:

Shocks in circumstellar envelopes

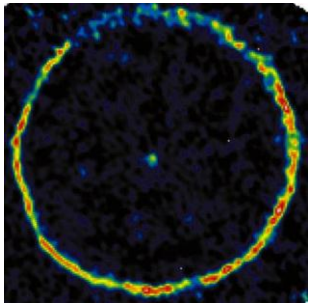
Pulsations of cepheids

Shocks in the solar chromosphere

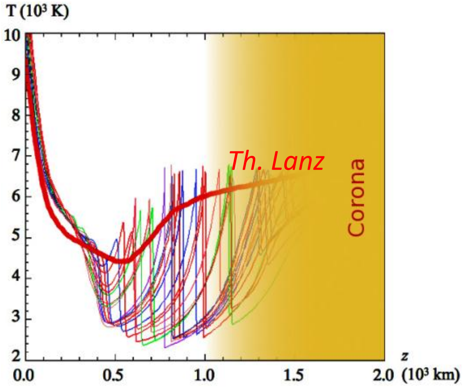
Supernova explosions,

Interaction of supernovae remnants with ISM.

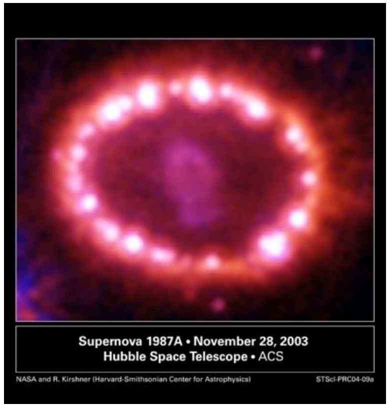
ISM: Interaction of jets with ISM (Bow shocks)



TT Cygni, (IRAM)



Chièze et al. 2012

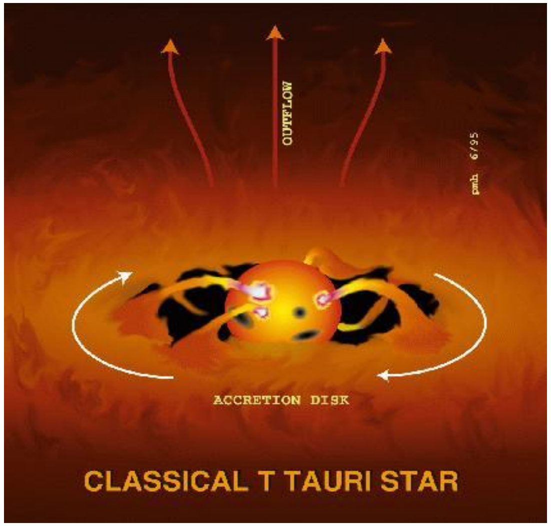


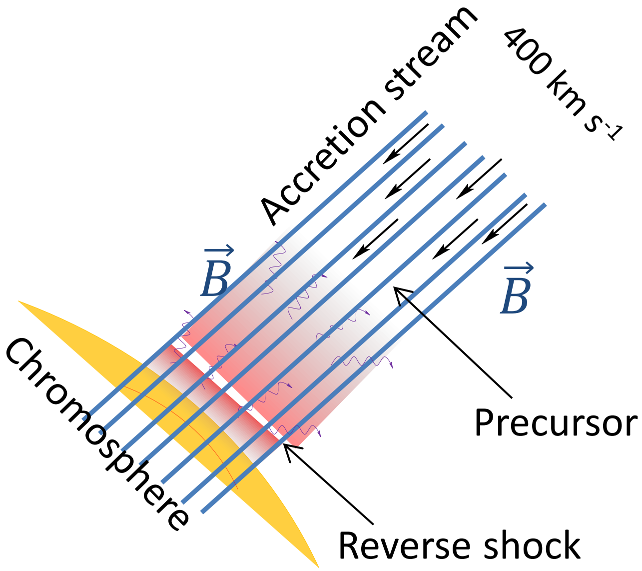
SNR 1987A with ISM november 2003, HST.

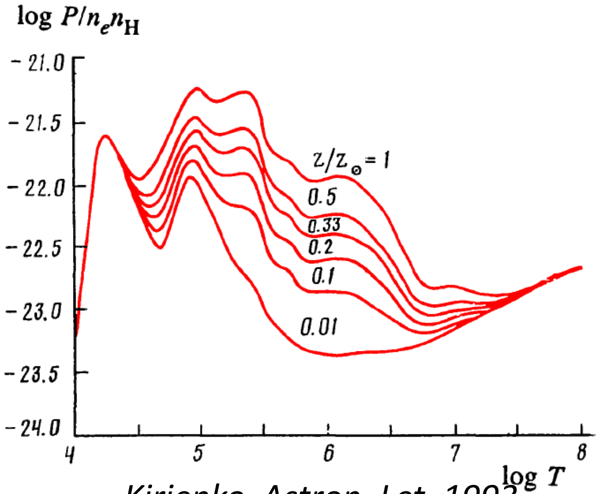
A Specific Example : Accretion on stars

Accretion from a disk around YSO

C. Stehlé & al. *ANR STARSHOCK*



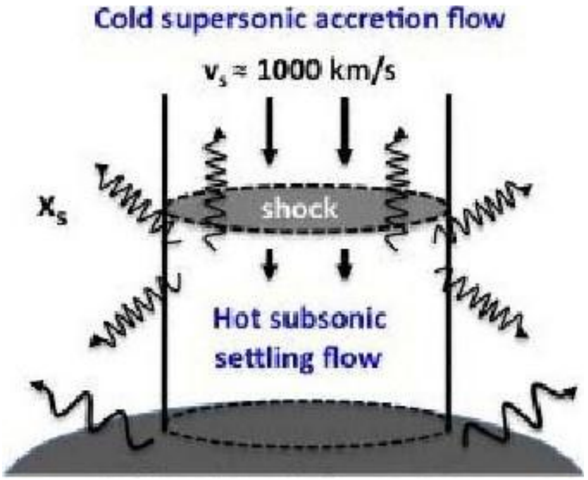


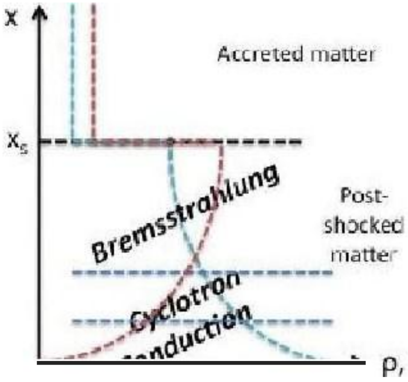


Kirienko, Astron. Let, 1993

Cataclysmic Variables POLARS

E. Falize & al. *POLAR project*





A Specific Example : Accretion on Young Stellar Objects

Astrophysical modelling

Observations + scenario + simulations

→ accretion rate from the shock signatures.
→ 1D hydro simulations + 1D radiative transfer
→ 3D hydro simulations + 3D radiative transfer

Experiments

Study the structure of shocks in regimes « similar » to their astrophysical analogues.

→ to understand their radiative signatures.
→ analyze with 1D /3D hydro-rad simulations
→ and thus provide benchmarks for codes which are used for astrophysical applications

Dual approach = numerical and experimental simulations

The nature of radiative shocks - 1

Two regimes

The so-called flux-dominated regime has a flux of radiation energy σT_s^4 that is non-negligible when compared with the flux of material energy $\rho_0 U_s^3$

As temperatures in the system increase, the radiation pressure, which is a factor $1/c$ smaller than the radiation flux, becomes comparable to or exceed the material pressure in the **pressure-dominated** regime.

The flux-dominated regime is more readily accessible in the laboratory

Michaut & al. Astrophys. Space Sci. 322, 2009

The nature of radiative shocks - 2

Three opacity regimes

Thick-thick : In this case radiation energy from the downstream state heats the upstream material, forming a precursor. This returns radiative energy to the shock. The shock cannot loose energy radiatively, the maximum compression of a thick-thick shock is the same as for a non radiative shock.

At the other extreme, the theory of the **thin-thin** in which all of the energy leaves the system . Higher compression can be reached.

Downstream region optically thick and the upstream optically thin, this is a **thick-thin** radiative shock

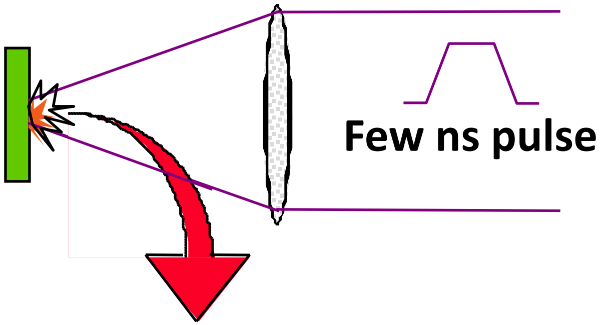
In the laboratory : the radiation is used up ionizing the upstream material and escapes in the upstream direction. The corresponding radiative energy does not return to the shock as it would if the upstream material were optically thick.

McClarren et al., PoP 17 2010

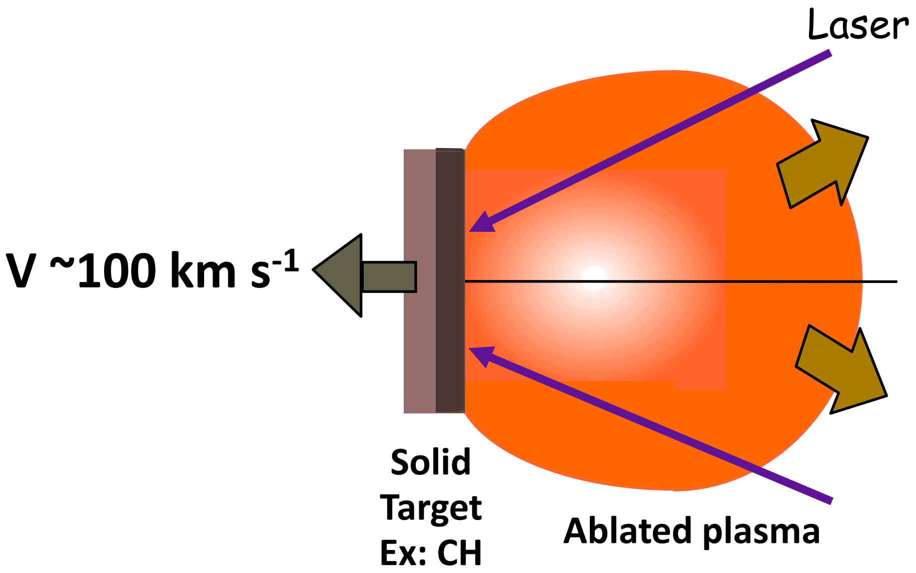
Plasma Created by Laser

Power deposited

10^{12}-10^{15} W cm^{-2}
up to 10^{20} W cm^{-2} with HE PW lasers



Rocket effect

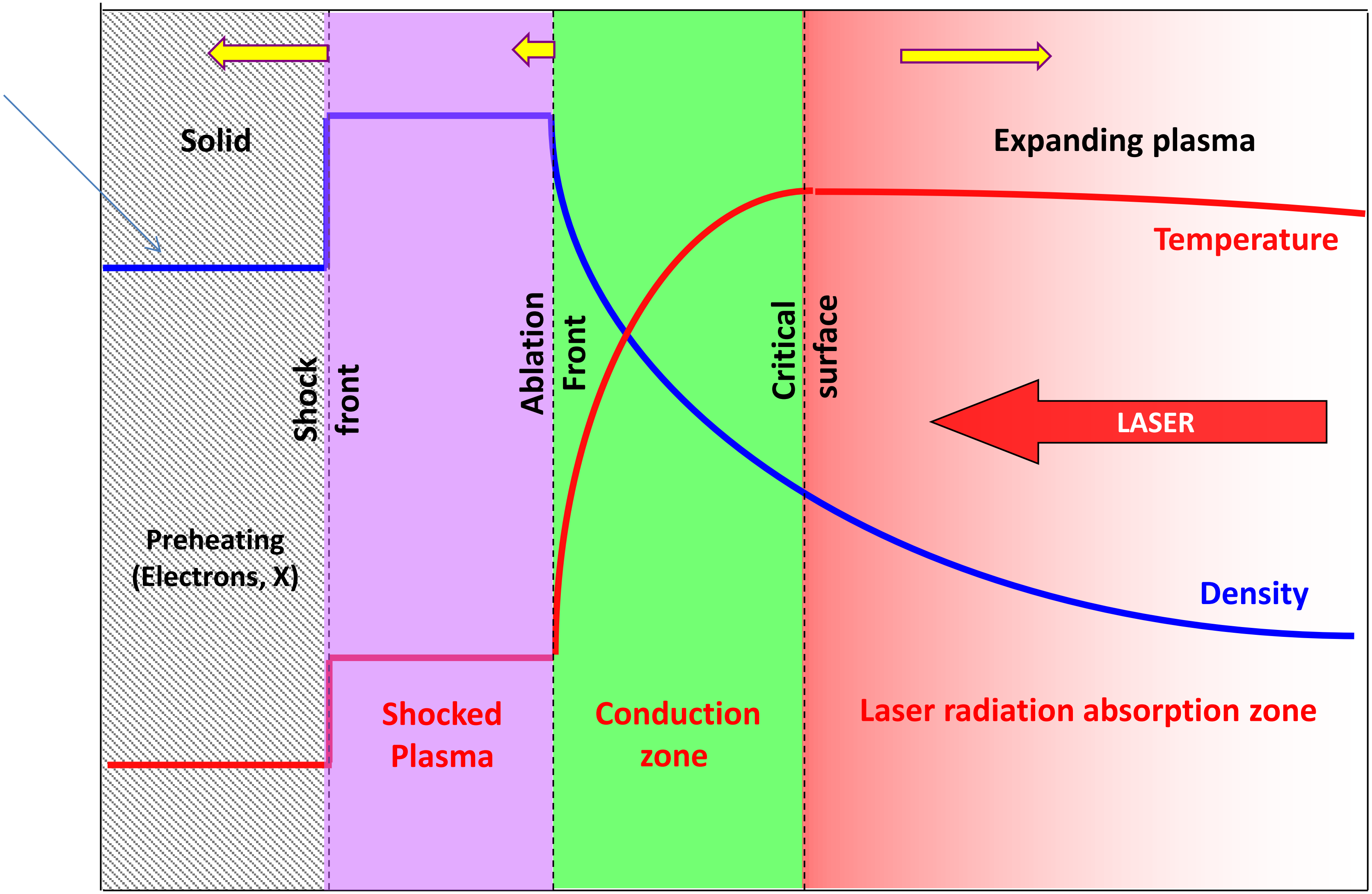


Temperature	**~ 10 - 50 MK (few 100 eV)**
Density	**~ 1 - 10^{-3} g cm^{-3}**
Pressure	**~ 10 - 100 MBars**

Short wave lengths (i.e. 0.35μm) have **high hydrodynamic efficiency** with a **small number of hot electrons.**

How to make a shock with a laser ?

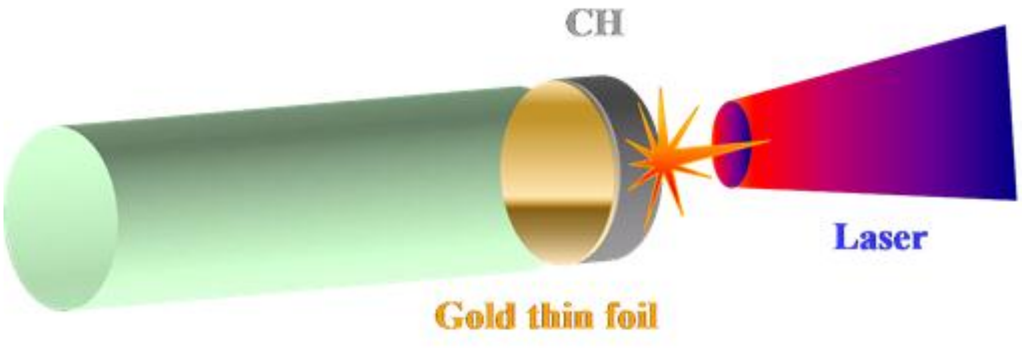
The laser is focalized on a foil, which converts the laser energy into mechanical energy.

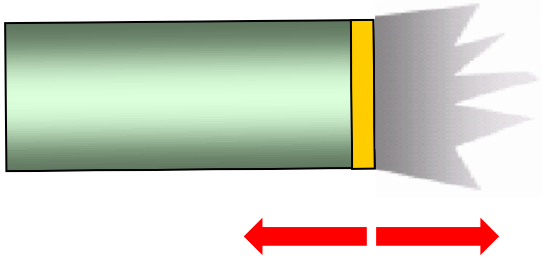


Launching a high velocity, high temperature shock

CH $(10\ \mu m)$ is ablated and pushes the Au foil $(0.5\ \mu m)$, which

- acts as a piston, launching the shock in the gas.
- protects from X rays





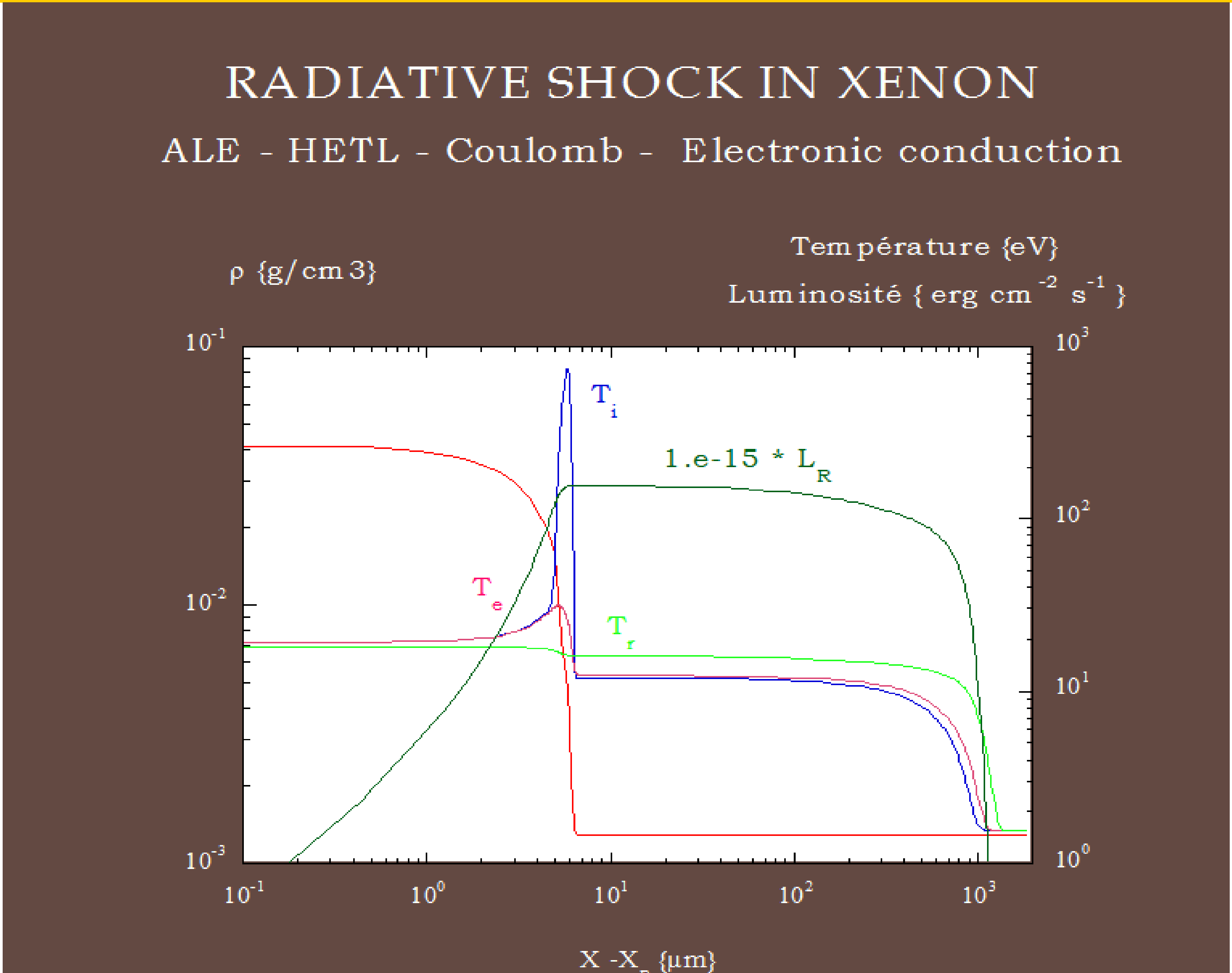
High atomic weight gas for high temperature

$$T = \frac{2(\gamma - 1)}{(\gamma + 1)^2}\frac{\boldsymbol{\mu}}{k}{U_s}^2 = \frac{1}{2C_v}{U_p}^2$$

$C_V(Xenon) \cong 1.8510^7 erg\ g^{-1}K^{-1}$ (varies by about × 2)

A theoretical view of radiative shock …

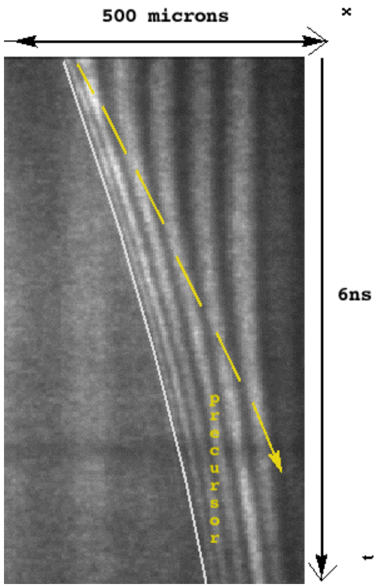
U_p = 63 km s^{-1} , ρ = 1.2 10^{-3} g cm^{-3}, T= 3.4 eV



Chièze, ASTROLABE Code

Bouquet et al. PRL 2004

Summary of the main achievements

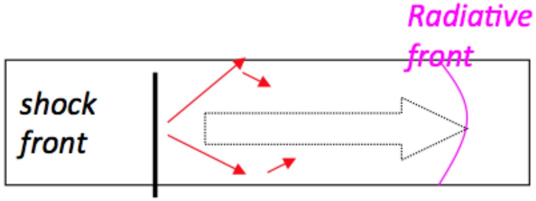


2000 @ LULI and after :

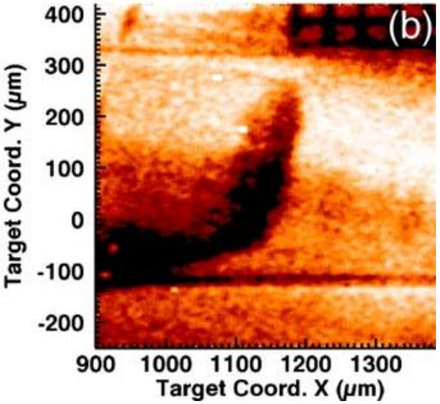
Precursor dynamics over 6 ns : visible time resolved interferometry

Shock velocity (60 km/s)

2D effects in the precursor : radiation losses through the windows reduce the velocity of the precursor



(Fleury et al, LPB 2002, Bouquet et al PRL 2005, Leygnac et al. 2005)



2006 @ Rochester :

Shock front :

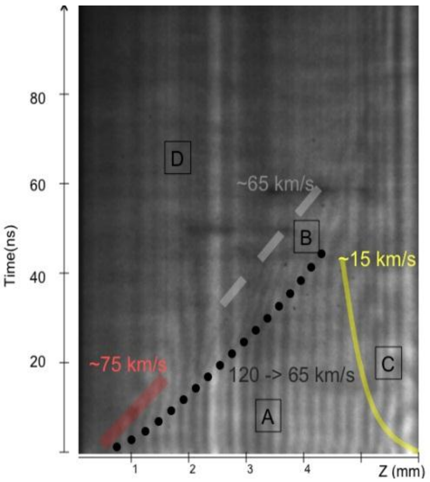
Shock velocity (~ 100-150 km/s)

Te (250 eV) ≠ Ti (700 eV) in the shock front: visible Thomson scattering

The shock front is plane : point source X ray imaging

(Reighard et al. POP 2006)

Summary of the main achievements



2005 and 2007 @ PALS :

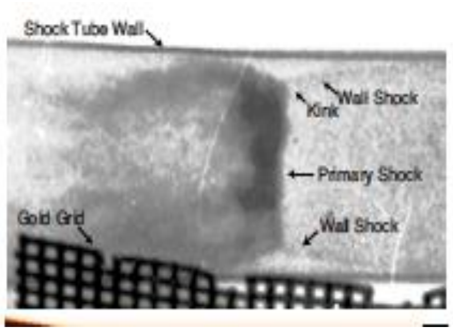
Precursor dynamics over 50 ns :

visible time resolved shadowgraphy & interferometry .

→ Lateral radiative losses affect the long time dynamics of the precursor.

→ Bending of the ionisation front

(Gonzalez et al. 2005, Stehlé et al 2010)



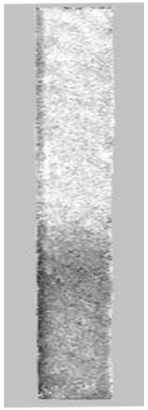
2009 @ Rochester :

Shock front: point source X ray imaging

Radiation from the front may ablate the window: this leads to perturbations near the front shock.

(Doss et al. 2009)

Summary of the main achievements



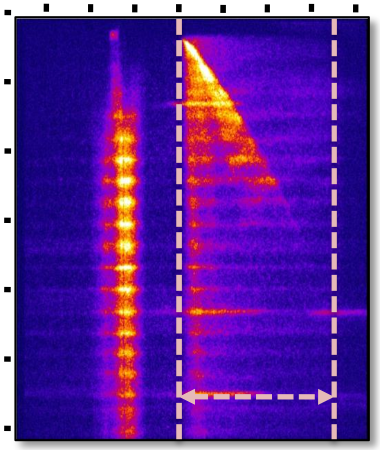
2010 and after @ PALS:

Completete structure

First XRL image of the full structure

Elongated precursor.

(Sthéle et al. 2012)



2011@ GEKKO XII

High velocity shocks

interferometry , self-emission

→ Transition towards the pressure regime.

(Dizière et al. 2011)

Experimental studies of radiative shocks with the PALS facility

Objectives

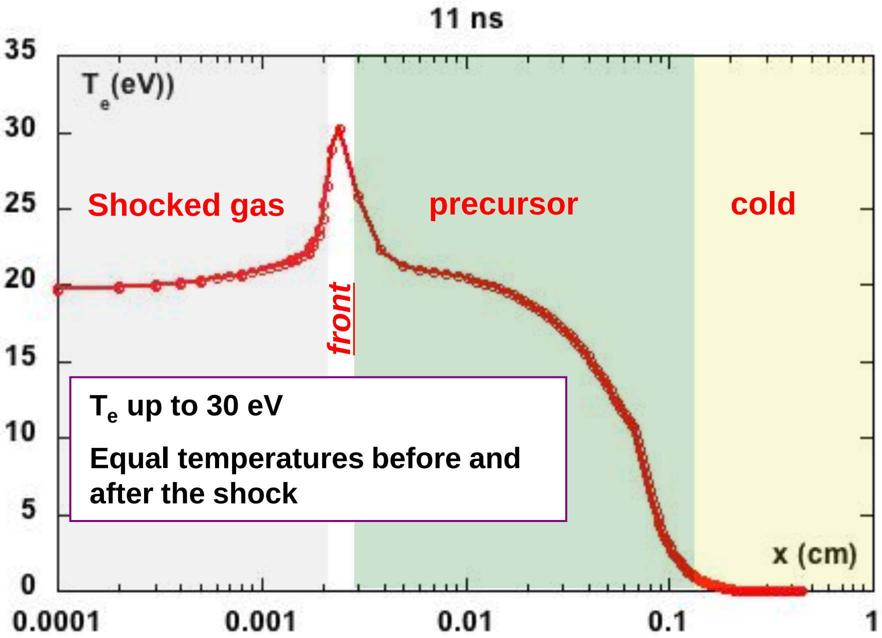
- strong sustained shocks (M>>1) in gases
- structured by radiation : *choice of Xenon at low pressure (<1 bar)*
- *simple geometries*

PALS installation : iodine laser up to 150 J at 438 nm, 0.3 ns.

Laser irradiance of ~ few 10^{14} W/cm^2 (ns pulse) allows to reach shock velocities V ~ 60 km/s

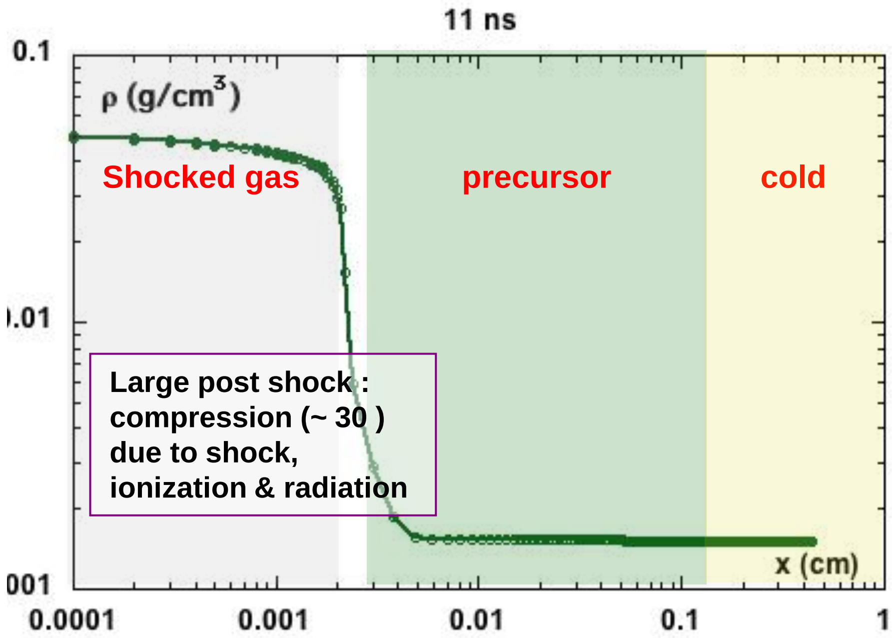
PALS iodine laser

Collaboration:
LERMA, SYRTE, GEPI, LPP, CEA, Imperial College
PALS team , C. Stehlé PI
Chantal Stehle, Michaela Kozlova, Jean Larour, Jaroslav Nejdl, Norbert Champion, Patrice Barroso, Francisco Suzuki-Vidal, Ouali Acef, Pierre-Alexandre Delattre, Jan Dostal, Miroslav Krus, Jean-Pierre Chièze, Matthias Gonzalez, Laurent Ibgui.



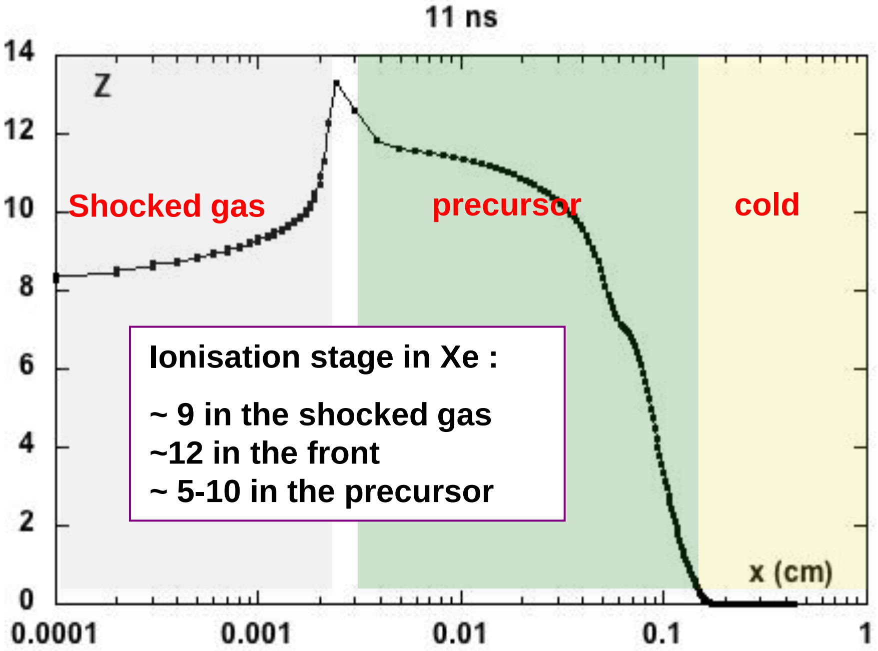
T_e up to 30 eV

Equal temperatures before and after the shock



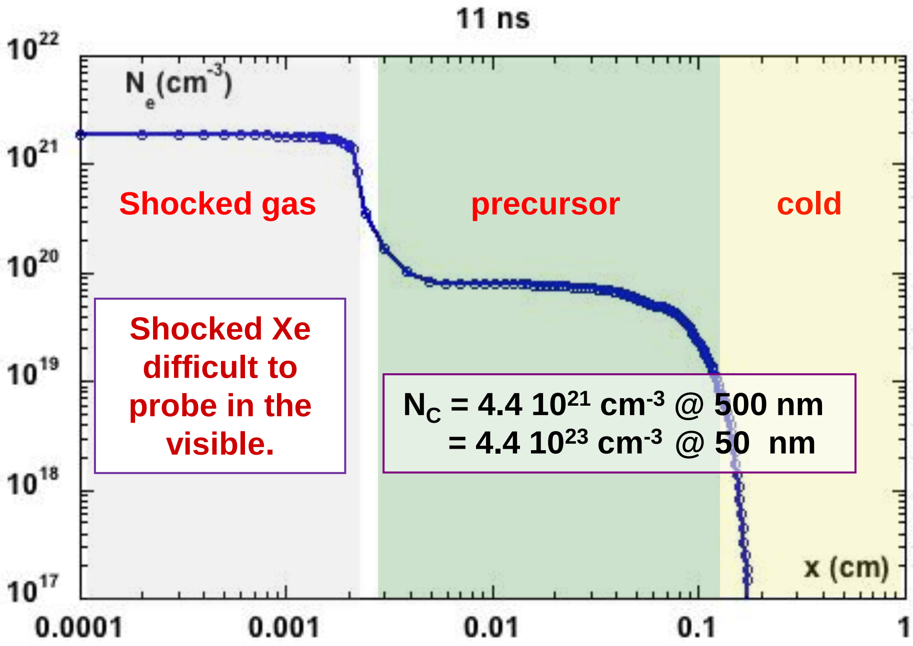
Large post shock : compression (~ 30) due to shock, ionization & radiation

Calculations with MULTI 1D (Ramis et al. 1988)



Ionisation stage in Xe :

~ 9 in the shocked gas
~12 in the front
~ 5-10 in the precursor



Shocked Xe difficult to probe in the visible.

$N_C = 4.4\ 10^{21}$ cm^{-3} @ 500 nm
$= 4.4\ 10^{23}$ cm^{-3} @ 50 nm

Example of Xe targets

Targets manufactured at Observatoire de Paris

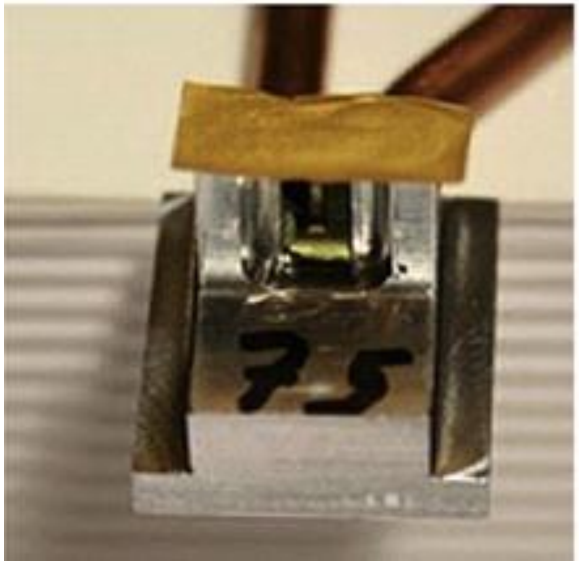
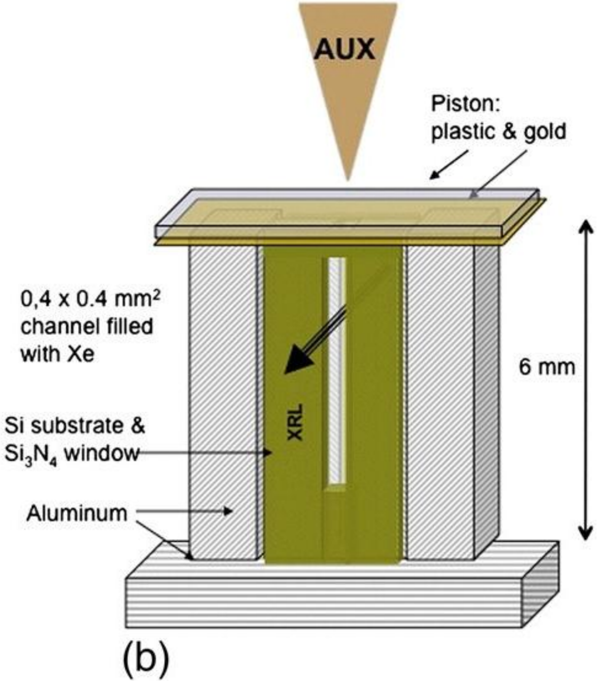
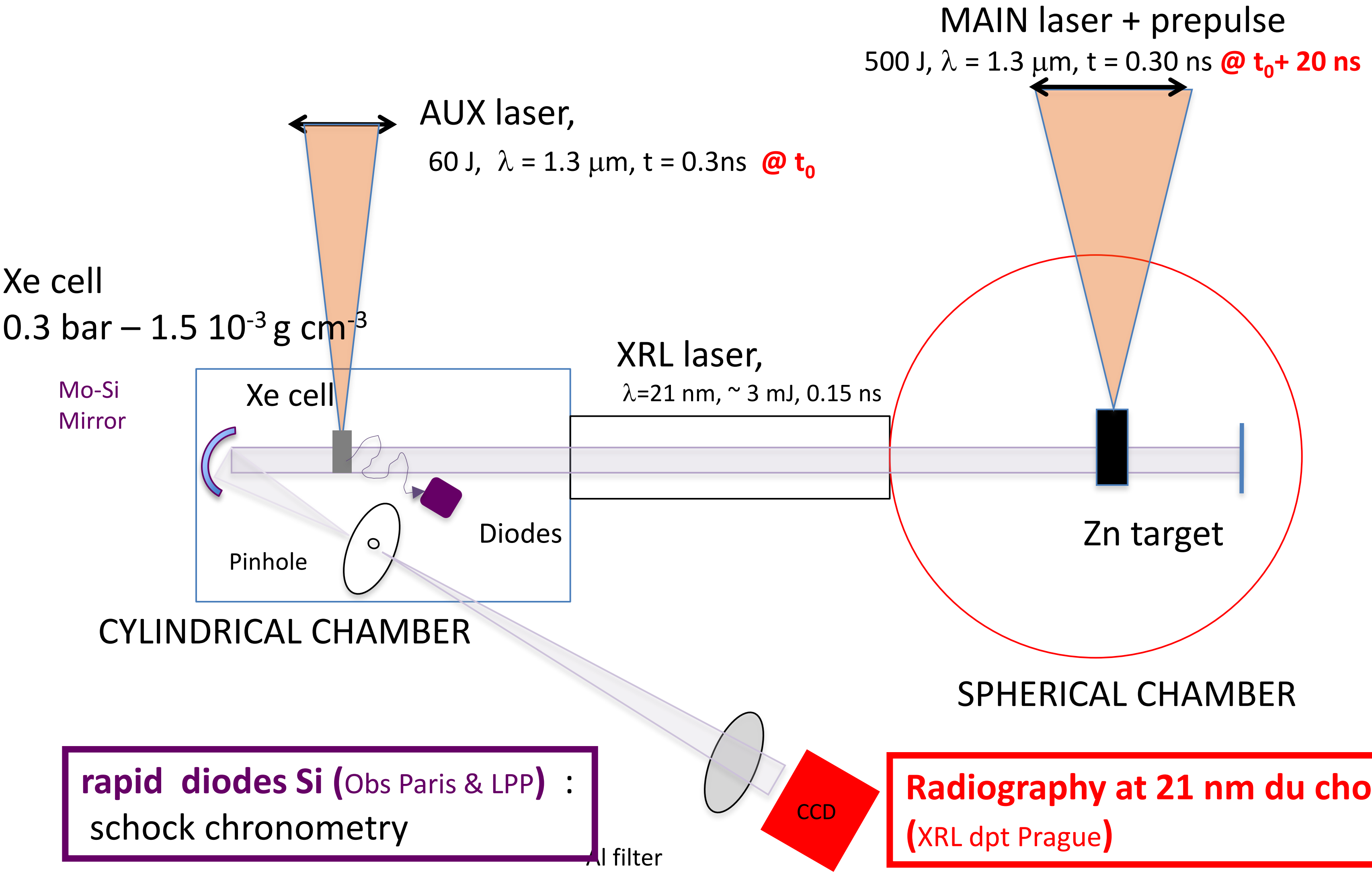


Image of the target with the gilt polystyrene piston, an Si_3N_4 window (0.4×4 mm2) on its Si frame, the Al structure and the two filling capillaries;



The AUX laser comes from the top and is focused on the piston (yellow), whereas an XRL laser passes through Si_3N_4 windows and the channel filled with Xe. The opaque Si frame is shown in green and the Al structure in gray. The Xe gas is contained within a 0.4×0.4×6 mm^2 channel in the target center, delimited by the Al structure on two sides and by Si_3N_4 windows on the two perpendicular sides.

Experimental setup *PALS 2010*



MAIN laser + prepulse

500 J, λ = 1.3 μm, t = 0.30 ns **@ t_0+ 20 ns**

AUX laser,

60 J, λ = 1.3 μm, t = 0.3ns **@ t_0**

Xe cell

0.3 bar – 1.5 10^{-3} g cm^{-3}

XRL laser,

λ=21 nm, ~ 3 mJ, 0.15 ns

Mo-Si Mirror

Xe cell

Diodes

Pinhole

Zn target

CYLINDRICAL CHAMBER

SPHERICAL CHAMBER

rapid diodes Si (Obs Paris & LPP**)** :
schock chronometry

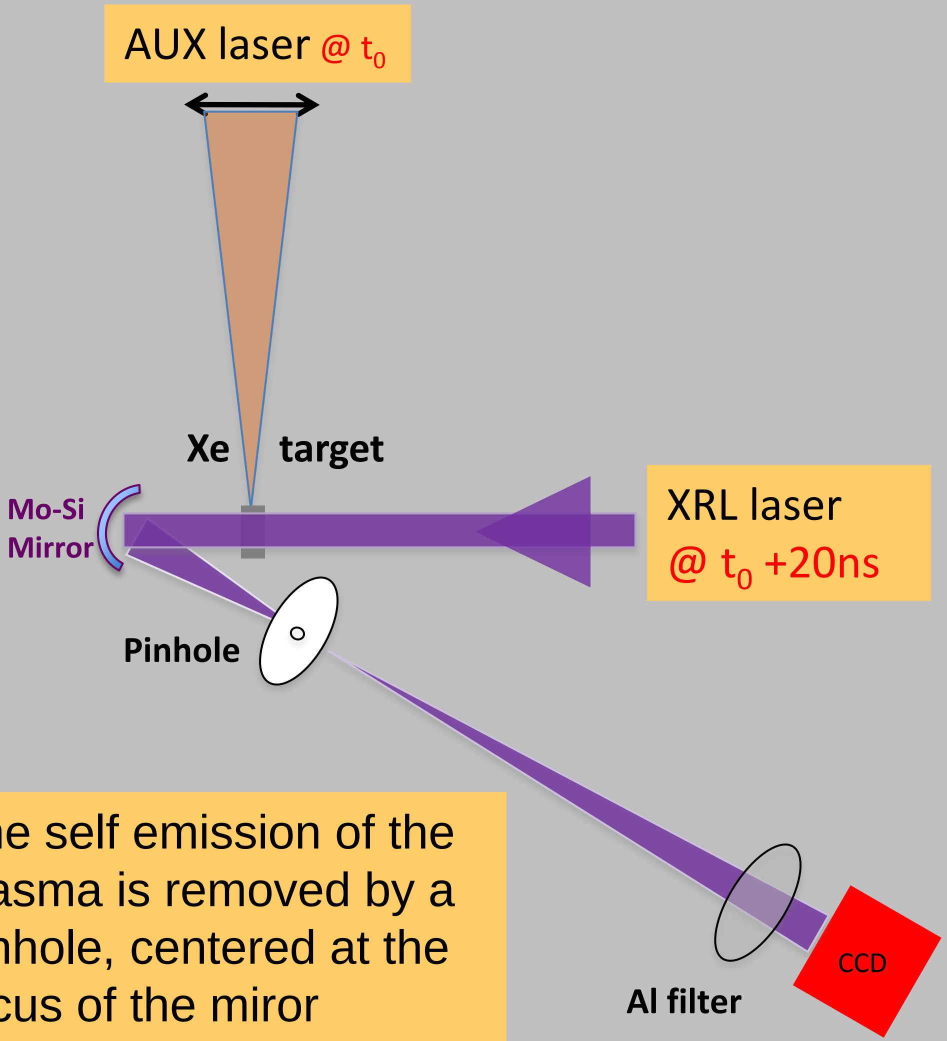
Al filter

CCD

Radiography at 21 nm du choc
(XRL dpt Prague**)**

NOT TO SCALE !

PALS 2010 : XUV Imaging



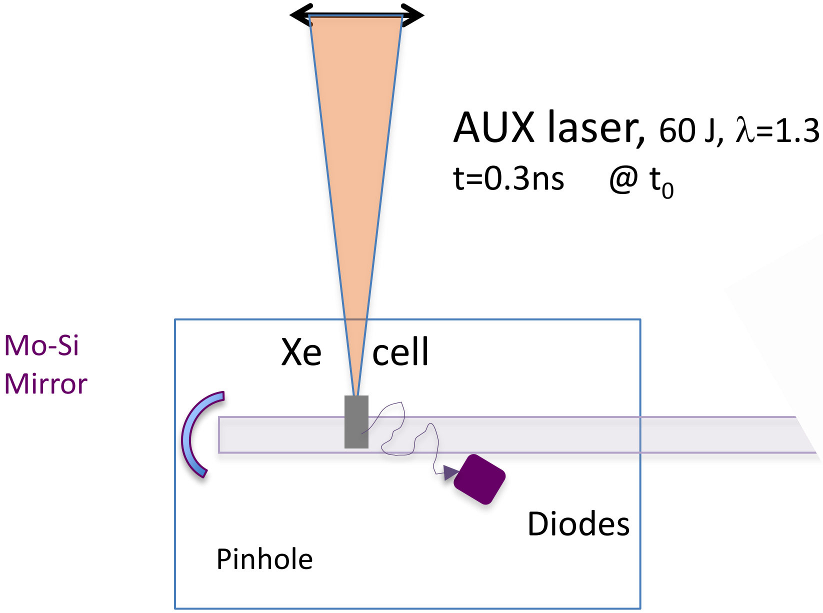
A MoSi miror forms an image of the cell on the CCD,
f= 300 mm

The xenon cell is illuminated by the 21 nm laser light

The self emission of the plasma is removed by a pinhole, centered at the focus of the miror

The parasite visible light is removed by an aluminium filter.

Plasma self emission



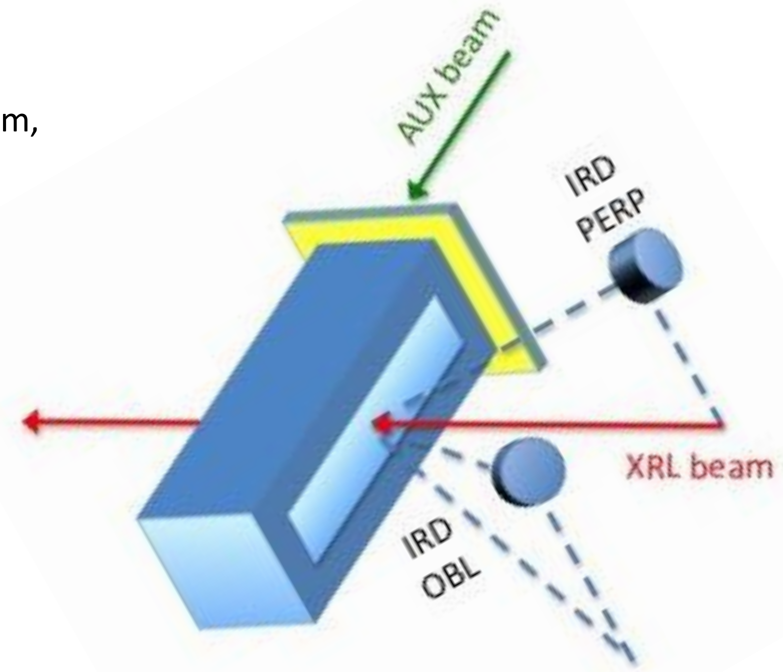
AUX laser, 60 J, λ=1.3 μm, t=0.3ns @ t_0

Mo-Si Mirror

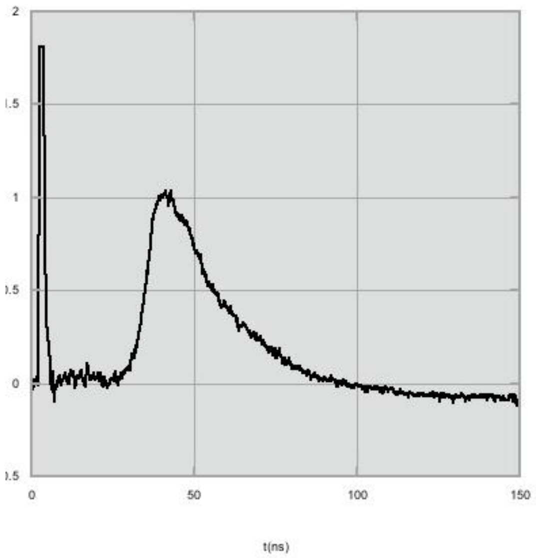
Xe cell

Diodes

Pinhole

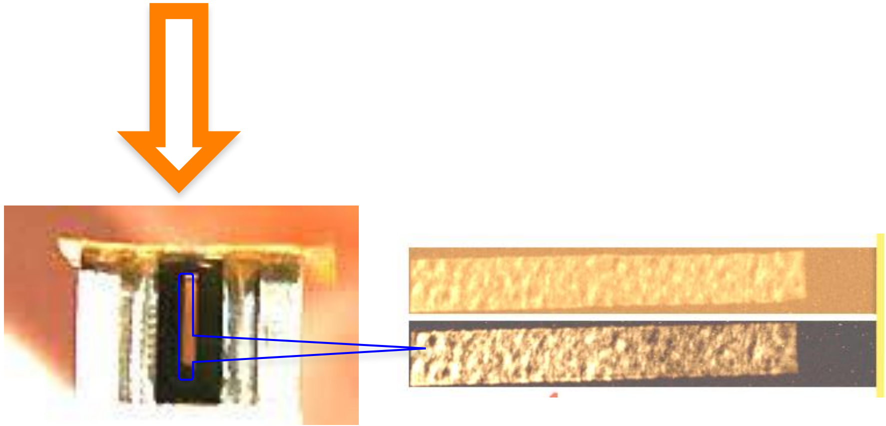


Two Si high speed diodes, for plasma self emission



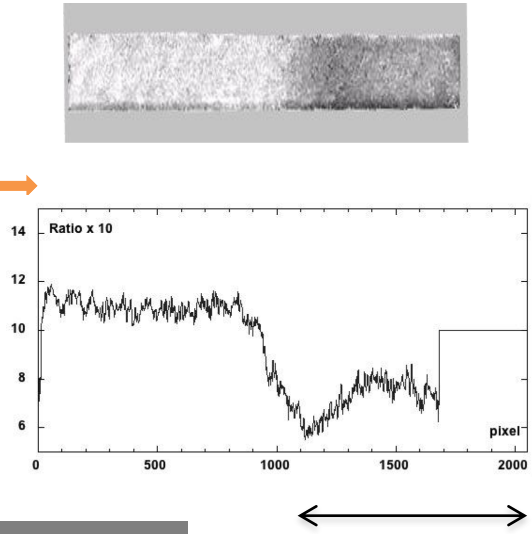
Lateral XUV self emission

PALS 2010/2011 : First XRL image of a the complete structure



Si$_3$N$_4$ windows

Ratio of the
2 images x 10



1.5 mm

Maximum absorption at ~ 1.5 mm from the piston
Shock velocity ~ 75 km/s

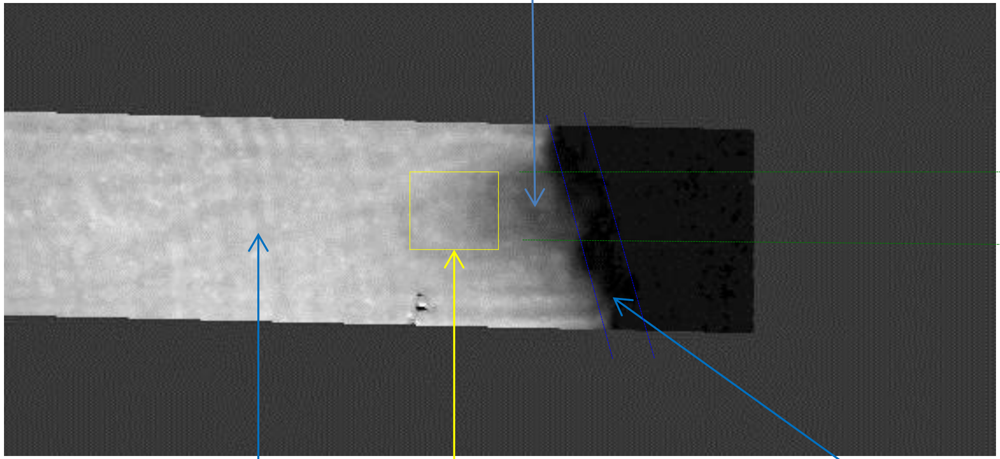
Transmission :
- 60 % near the shock front
- Absorption in the precursor (opacity varies with T)

PALS 2012 : more details

Uddhab Chaulagain Thesis

The shock front is thin ~ 50 µm
(blurring 0.15 ns x 40 km/s = 6 µm)

Distance between the shock and the initial position of the piston ~ 0.83 mm :
$U_S \sim 42$ km s



~ 150 µm

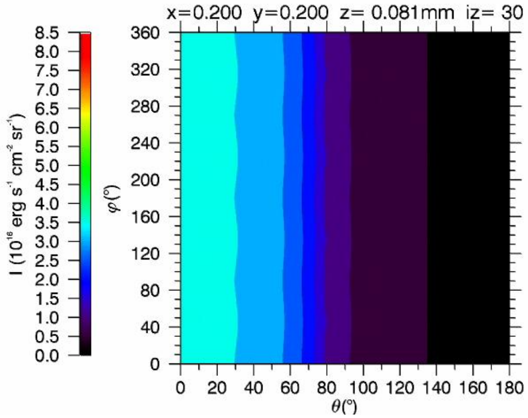
Focal spot ~ 200 µm
Difficult to estimate
(from craters and Kev image)

In flight CH/Au piston

Unperturbed xenon
at 0.3 bar

The precursor is elongated,
in accordance with simulations

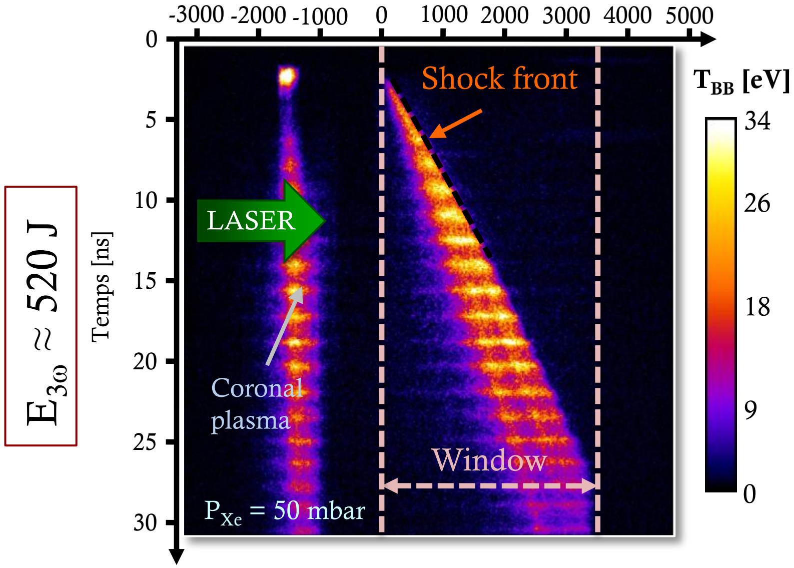
Specific intensity $I(\theta, \varphi)$ along the shock tube axis, calculated with the IRIS code (Laurent Ibgui).

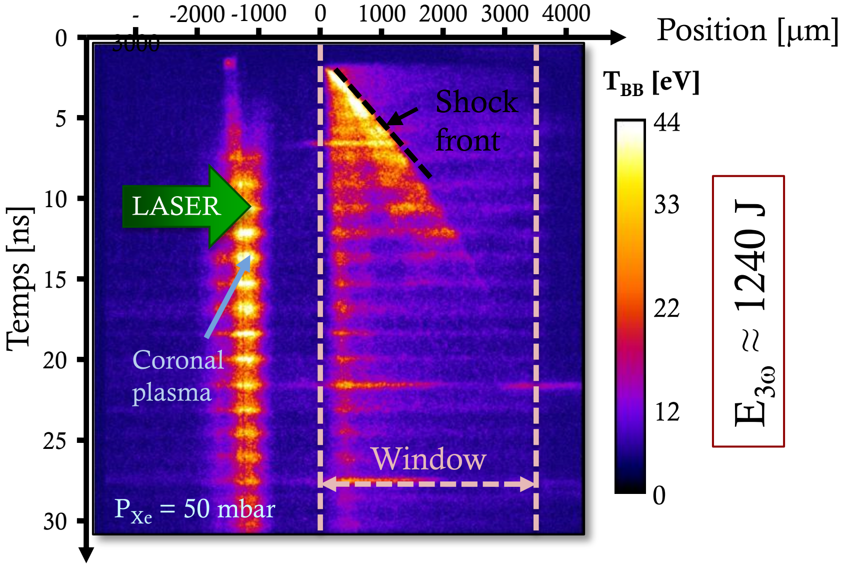


GEKKO XII – Shock velocity & temperature

A. Dizière · C. Michaut · M. Koenig · C.D. Gregory · A. Ravasio · Y. Sakawa ·
Y. Kuramitsu · T. Morita · T. Ide · H. Tanji · H. Takabe · P. Barroso · J.-M. Boudenne

Transverse SOP (Streaked Optical Pyrometry) : passive self-emission diagnostics, composed of an imaging system of the target on a visible streak camera, which collects all photons emitted within a selected wavelength range (here a blue filter 450 nm ± 15 nm).





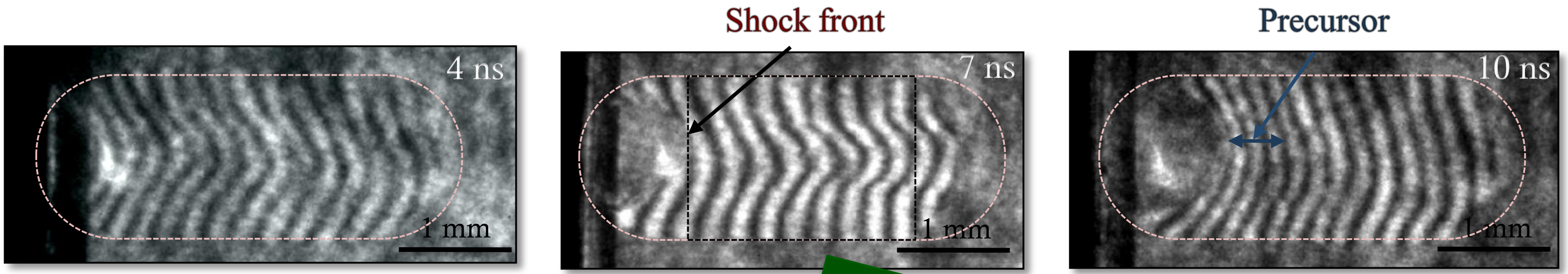
Precursor ? *highly emissive shock front too bright for the low dynamic range of the streak camera.*

Two shock behaviors observed at medium and high E_{las}

$2\ 10^{14} W\ cm^2$ **$E_{3\omega} \approx$ 520 J** : 30 – 35 eV for160 km/s

$2\ 10^{15} W\ cm^2$ **$E_{3\omega} \approx$ 1240 J** : 50 eV for 225 km/s (quickly opaque)

GEKKO XII – Morphology



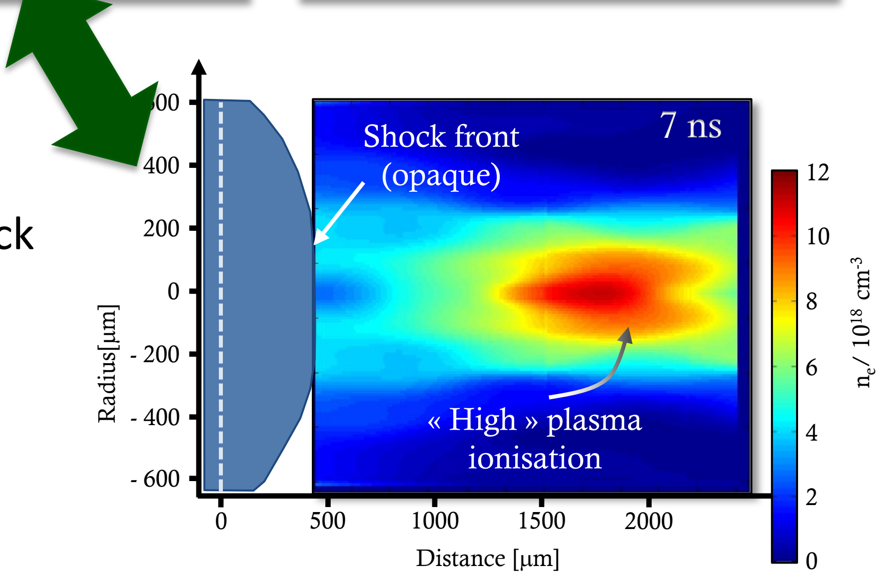
Presence of a radiative precursor (weaker interfringe)

Fringe shift collimated far upstream the shock (width similar to the focal spot size (around 400 µm)

Excluded …

Fast electrons (70 keV)

Preheating by hard X-rays (from corona)



Density map of the zone situated in the precursor zone, 7 ns after the main laser time (*t*0 + 7 ns)

$$3 \times 10^{18}\ \mathrm{cm}^{-3} < n_e < 1.2 \times 10^{19}\ \mathrm{cm}^{-3}$$

GEKKO XII – Partial conclusion

Production of high velocity shocks (150 to 225 km/s) at high temperature (up to 50 eV)

Partial characterization of the structure

Observation of a collimated, high velocity, perturbation upstream of the shock front (radiation + albedo ?)

Approaching the « radiative regime” with $R = P_{th} / P_{rad} \sim 12$

The study of this perturbation & the R < 1 frontier remains an experimental challenge!

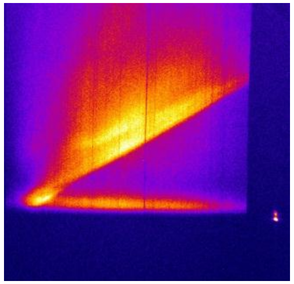
Conclusions

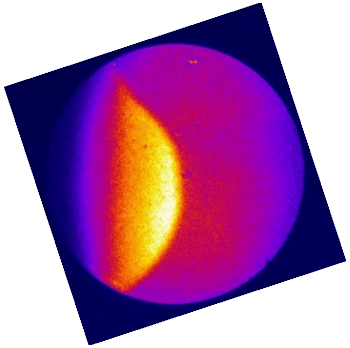
The regime of supercritical shock is now well probed in the laboratory

Most experiments are in the thick-thin regime

Increasing the energy opens the unexplored regime of pressure dominated radiative shocks

U_S = 146 km s^{-1}





10 ns

Experiment on LIL
Dec 2012
C. Michaut PI

… and may raise new questions

The development of numerical modeling of astrophysical objects is stimulated by laboratory experiments – and the reverse is also true!

Special thanks to Chantal Stehlé and Paul Drake