Study of laser matter interaction in an intensity regime relevant for shock ignition

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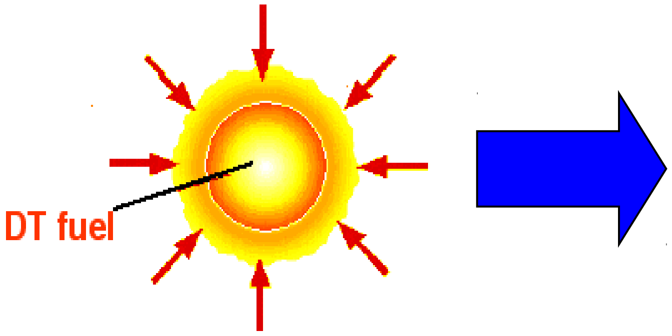
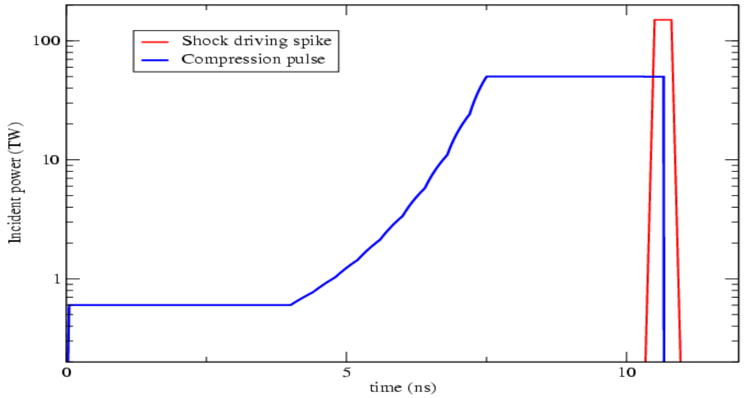
Experiment performed with the support of LASERLAB and HiPER

The concept of shock ignition

1: "normal" compression of a thermonuclear DT pellet with ns laser beams at I ≈ 10^{14} W/cm^2 (we are able to compress!)

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





Timing is essential

Goals of PALS experiment

We wanted to investigate:

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?

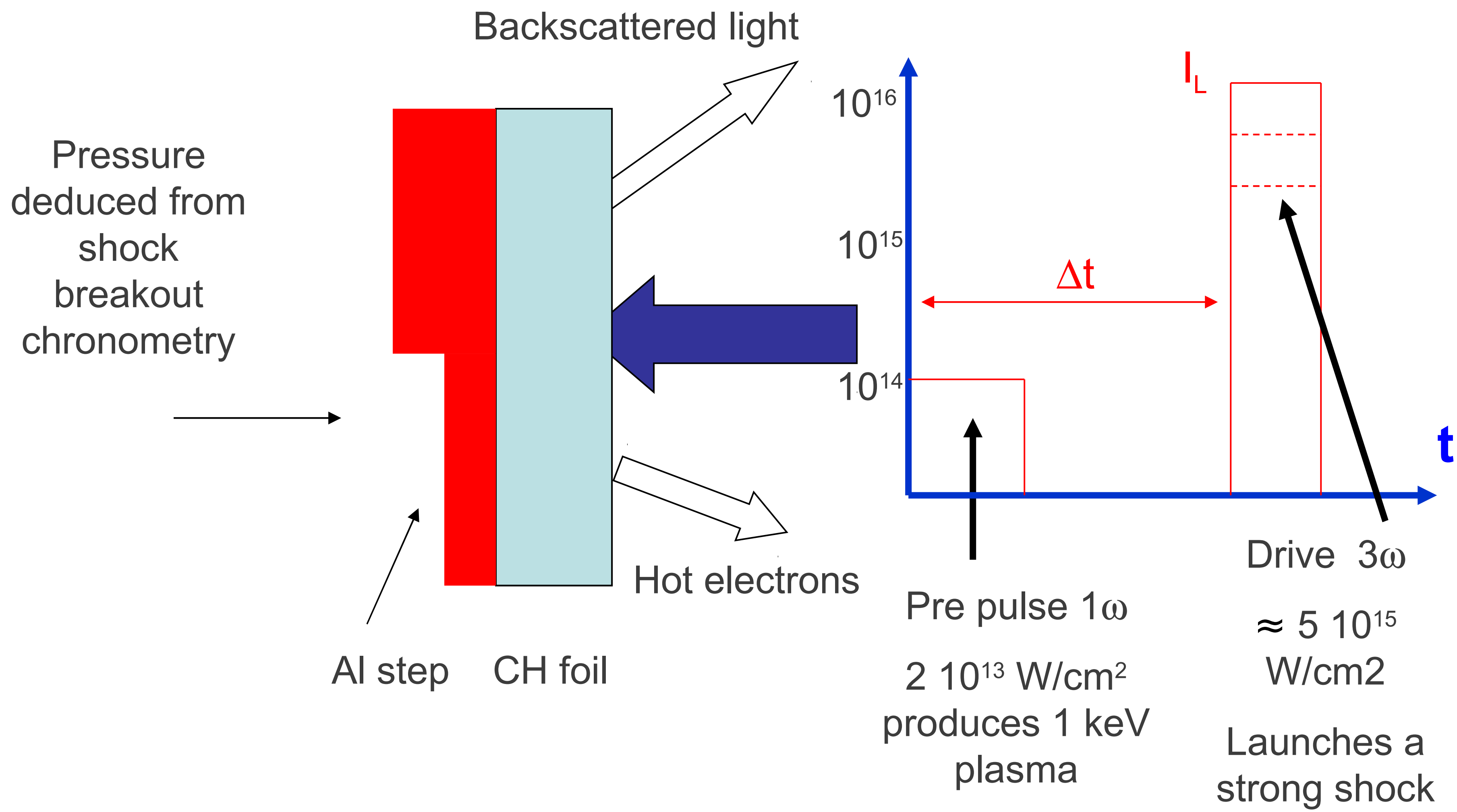
PALS experiment

Iodine Laser
=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

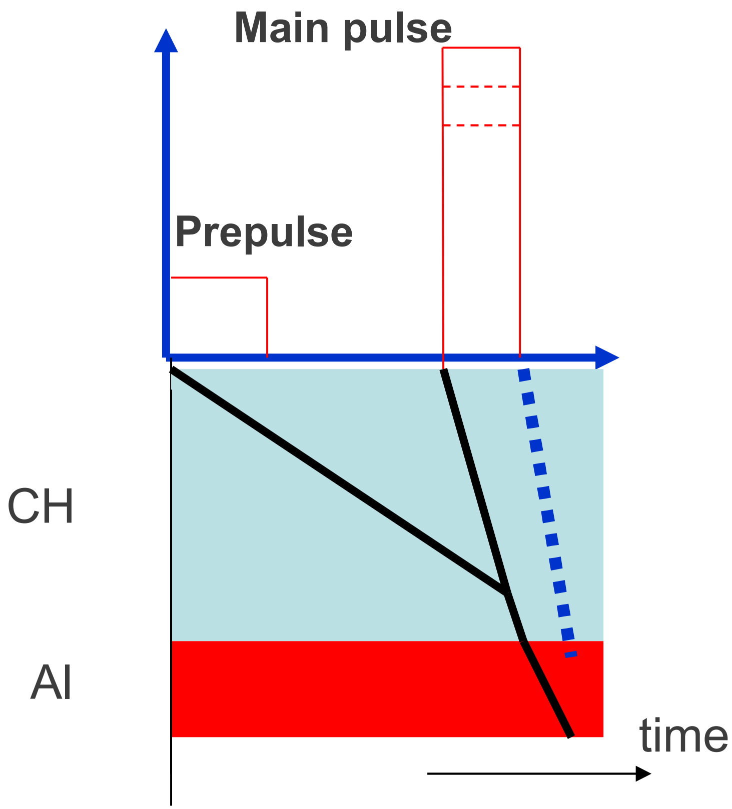
"Full" use of PALS laser facility:
Main beam at 3ω
Auxiliary beam creating extended plasma
XRL beam for diagnostics

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

Constraints on pulse and target



- Prepulse: produces 1keV, 1 mm plasma
- Drive : long enough to support pressure
- CH thickness : 2nd shock must catch up with 1st shock in CH
- Al thickness : trade off between
  - THIN Al : measurement must occur before the end of the main pulse (before the rarefaction wave lauched at the end of the pulse catches up with the shock) [actually this could NOT be realized in our conditions due to the short laser pulse…]
  - THICK Al increases the time resolution

Final target configuration:
25 µm CH layer (containing Cl to allow for X-ray spectroscopy)
25 µm Al layer plus 10 µm Al step (on some targets)

Targets produced by Ch.Spindloe and coworkers at the RAL Target Prep Lab

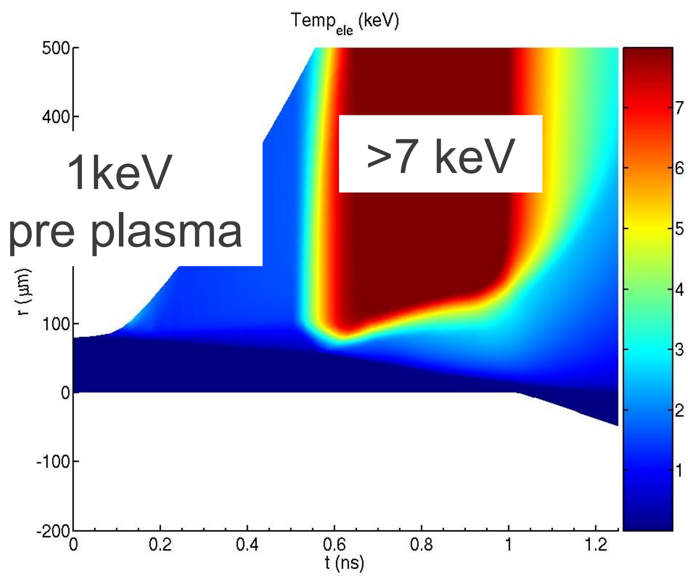
Target and Laser parameters

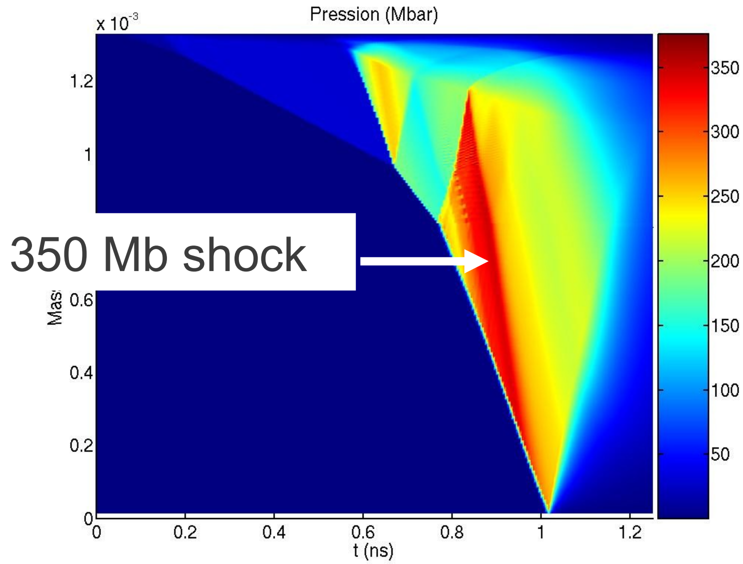
Prepulse - E = 30 J, λ = 1.3 µm, Φ = 1 mm, τ = 300 ps ⇒ I = 1.2 10^{13} W/cm²

Temperature $$T_e(eV) = 10^{-6}\left(I(W/cm^2)\,\lambda^2(mm)\right)^{2/3} \approx 750\,eV$$

Main Pulse - E = 250 J, λ = 438 nm, Φ =100 µm, τ = 300 ps ⇒ I = 10^{16} W/cm²

Pressure $$P(MBar) = 8.6\left(\frac{I(W/cm^2)}{10^{14}\lambda(mm)}\right)^{2/3}\left(\frac{A}{2Z}\right)^{1/3} = 320 \quad MBar$$





Absorption on the critical surface

Diagnostics

Phase 1
Creation and characterization of preplasma with:

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

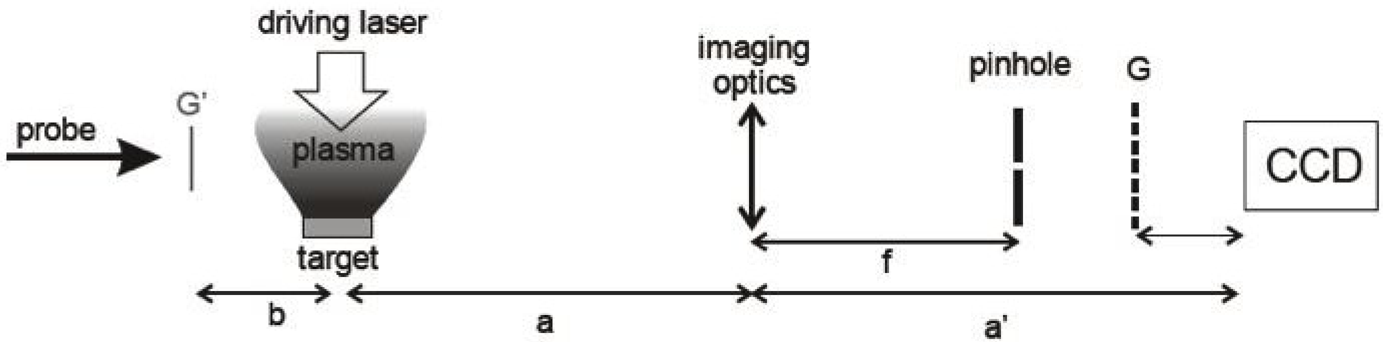
Phase 2
Characterization of shock formation and laser-plasma interaction with:

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 (Pisa group).
2) Shock chronometry (measuring the self emission from the target rear side with a streak camera) (Milan group)
3) 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) (Pisa group)

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

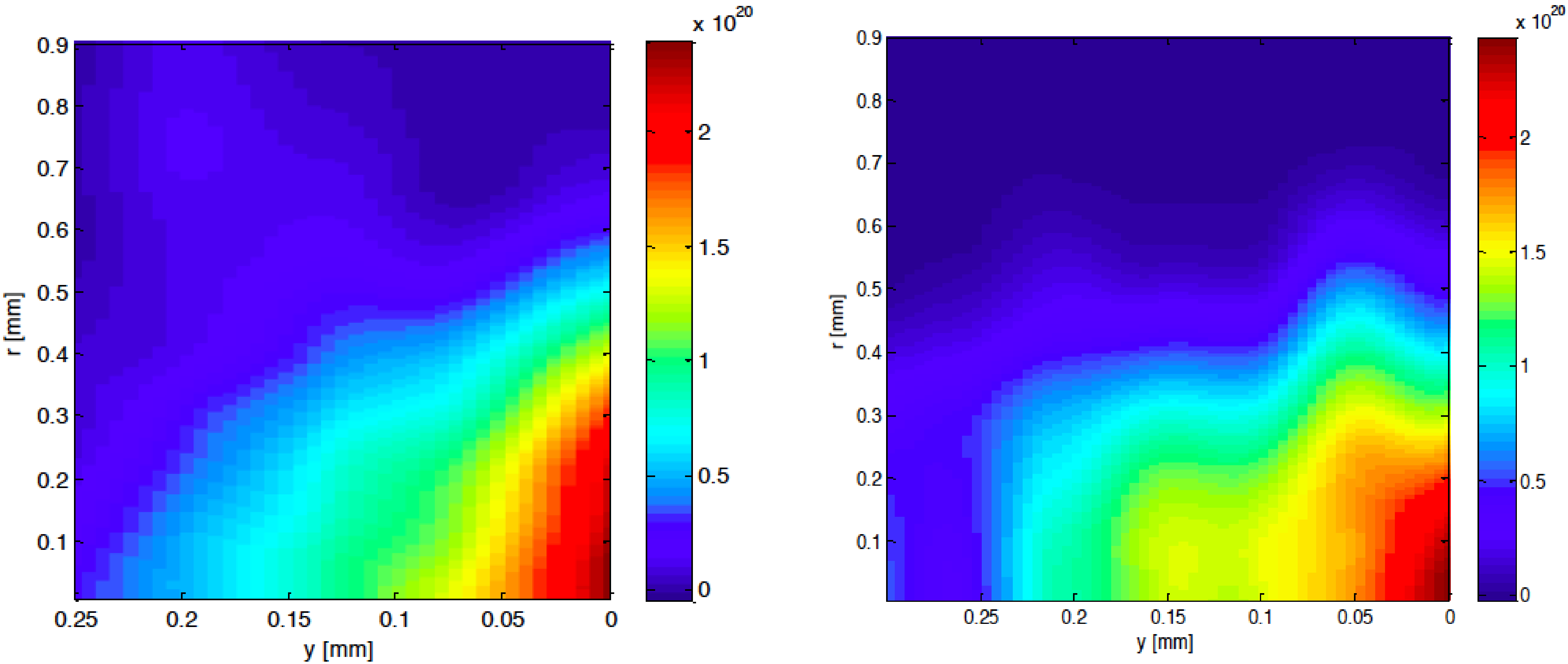


Ne-like zinc X-ray laser emitting at 21.2 nm, operated in single pass with 150-ps pulses of 200 µJ. Mo-Si multilayered spherical mirror with f=250mm used to image the plasma on back-illuminated X-ray CCD with M = 8.2. A pinhole of 0.5mm diameter was put to the image of the XRL source (2500 mm from the 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



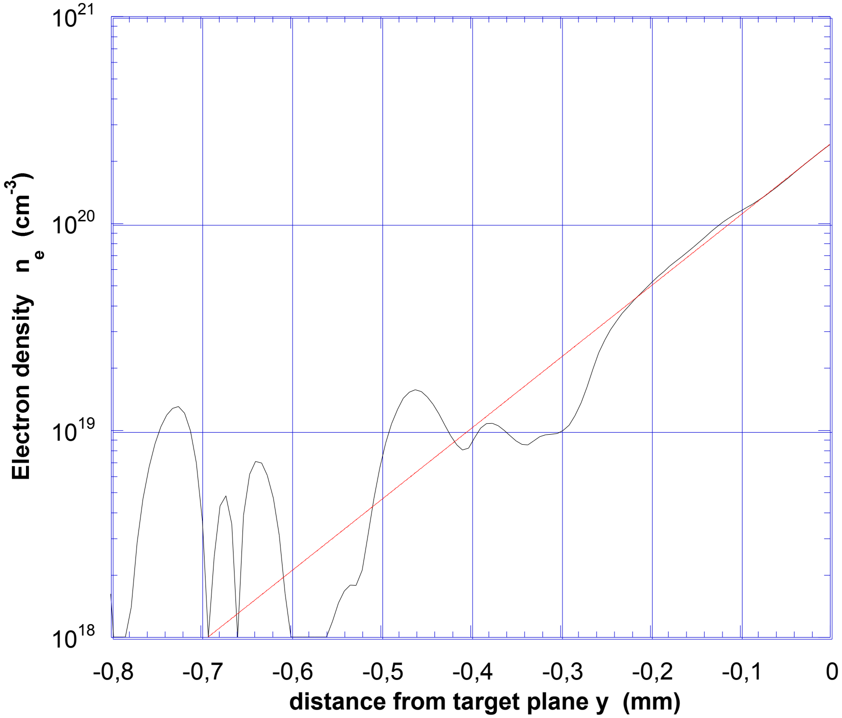
0.3 ns **0.9 ns**

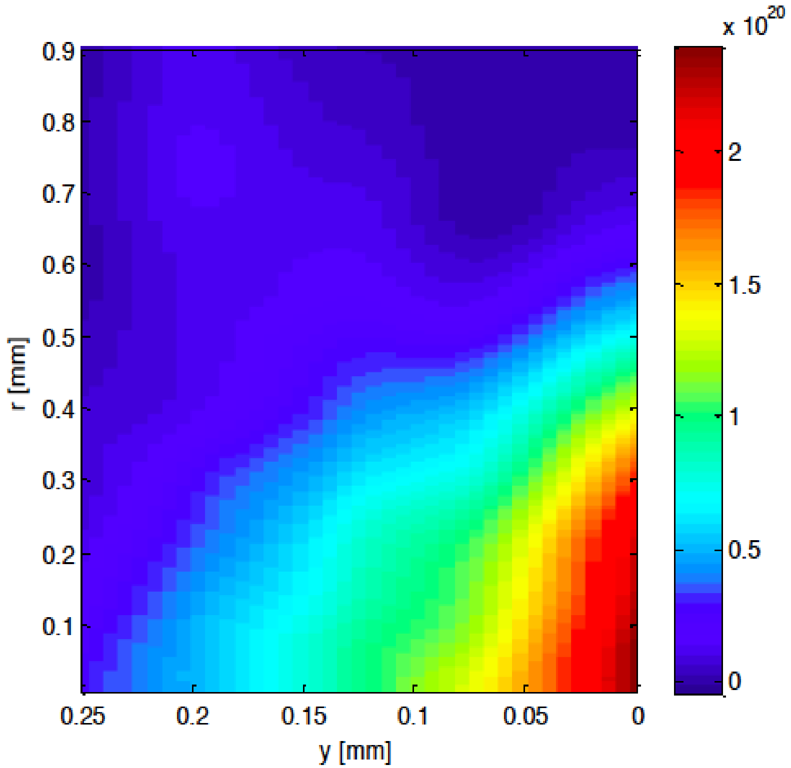
Probing of CH plasma by XRL beam 0.3ns after driving pulse arrival; a) reference pattern without plasma, b) signal recorded when probing the plasma, c) field of pattern deformation

Cylindrical symmetry allows resolving the electron density profile via inverse Abel transform

Density profiles of pre-plasma

Along the axis, plasma expansion is practically 1D and the profile is exponential (as expected) but with some “bumps” in density

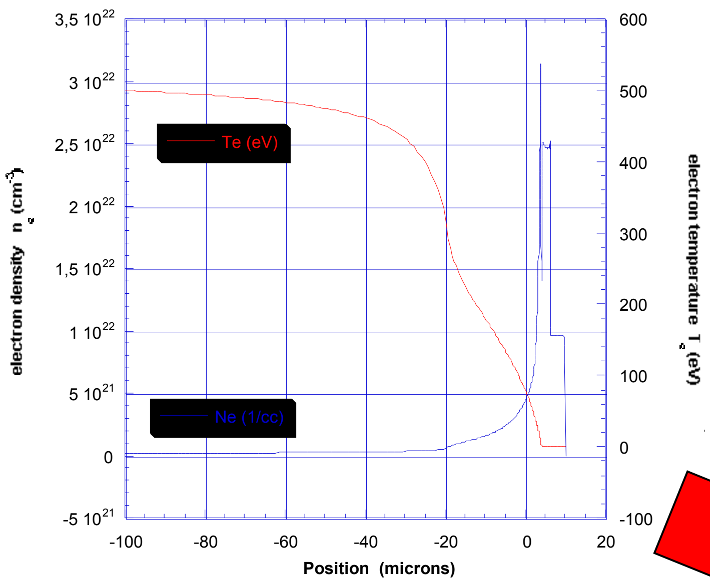




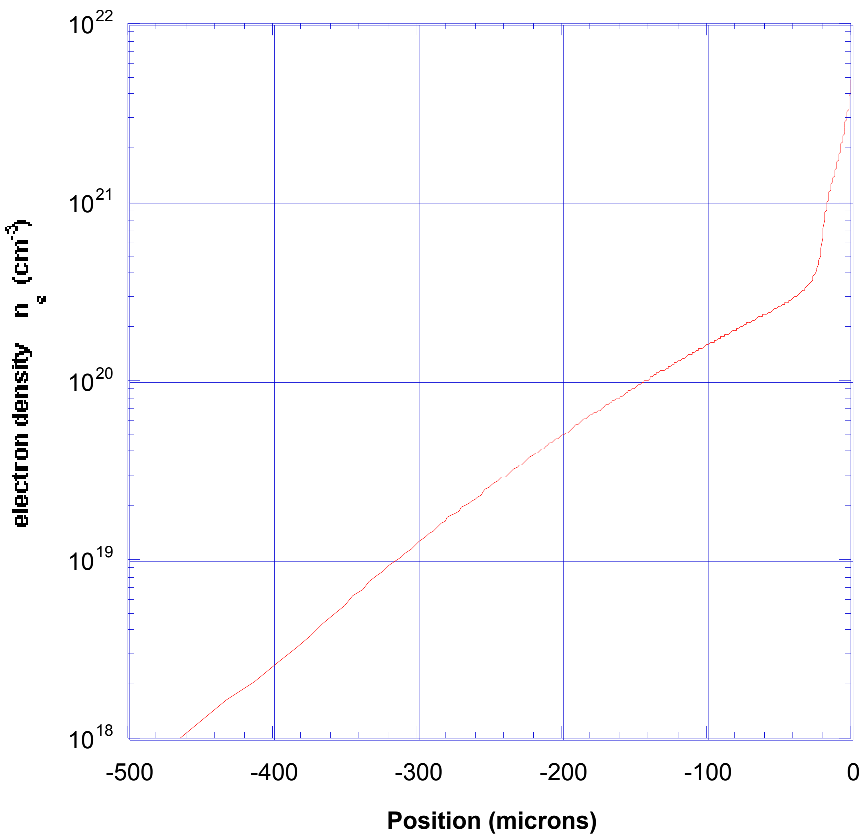
Max accessible density ≈ 2.4 ×10^{20} cm^{-3}

Density profiles of pre-plasma

“Classical” exponential profile is well reproduced by 1D hydro simulations performed with the code MULTI



Exponential below a few 10^{20} cm^{-3}

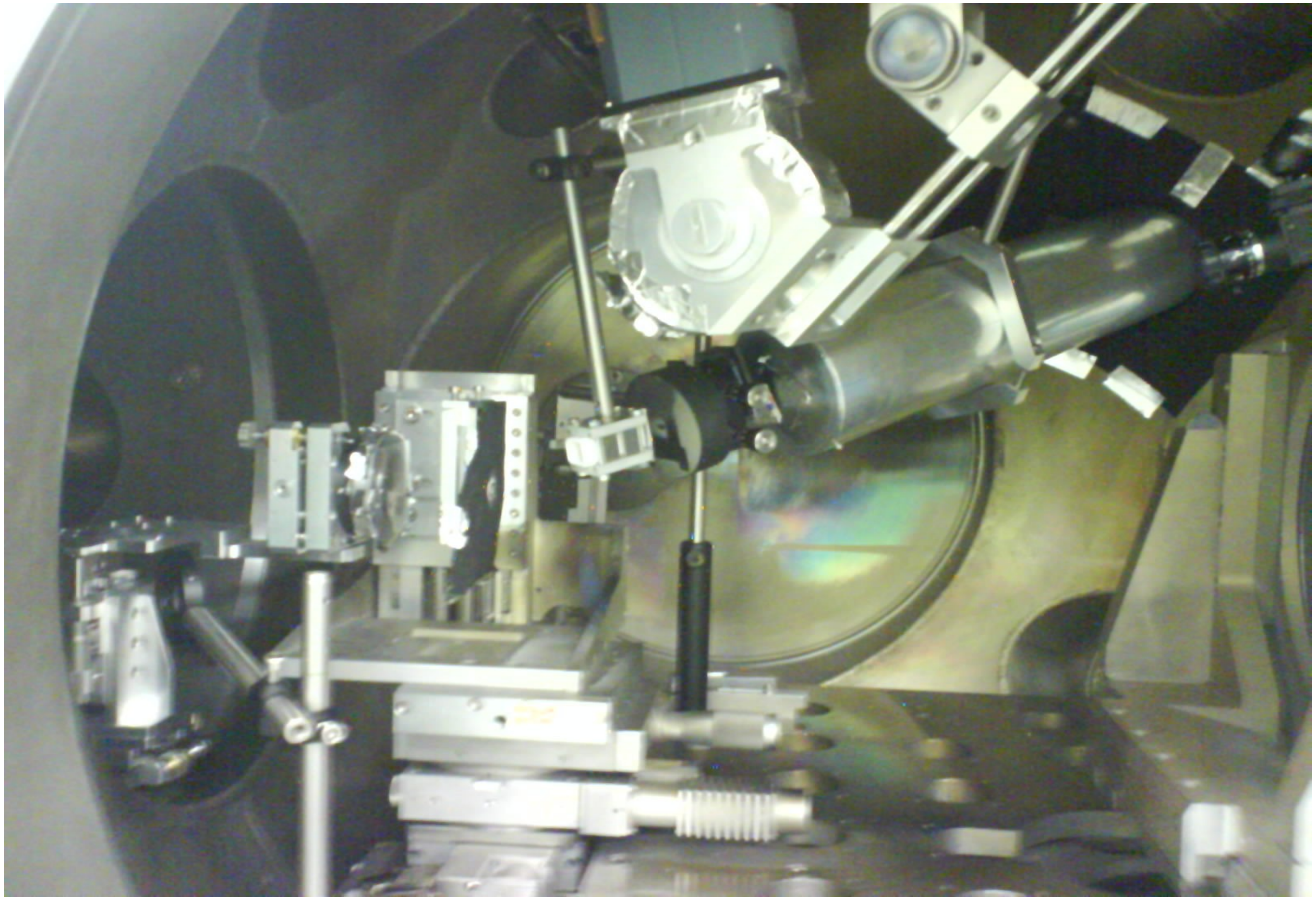


There is a coincidence in the exponential behavior between experimental and simulated data if we take in account of a prepulse of laser system. Hydro simulations allow to recover the plasma temperature (between 300 and 500 eV depending on laser intensity).

keV Spectrometer

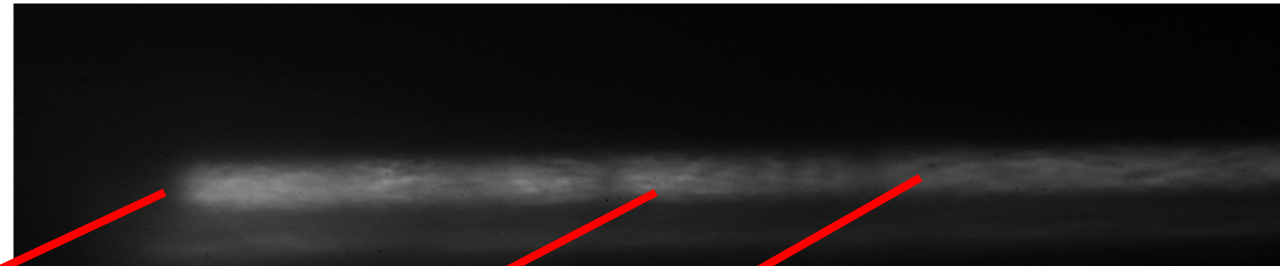
- ADP (ammonium dihydrogen phosphate) with 2d ≈ 10.659 Å
- Placed at ≈ 20 cm from the source and with a Bragg angle ≈ 19°

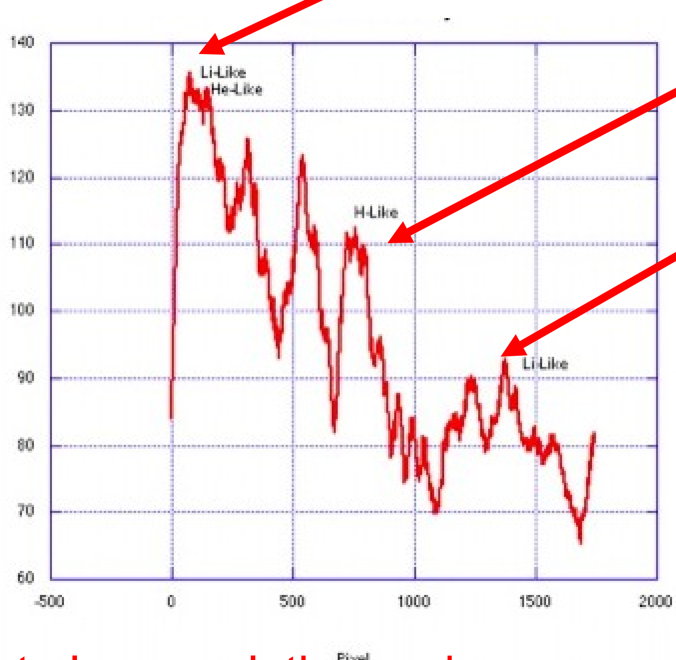
- Observed range from 2600 to 3600 eV



X-ray spectra from pre-plasma

Poor spectral resolution due to large source size (≈ 1mm) implying a line width ΔE ≈ 40 eV





Due to low resolution and presence of non-identified lines (from impurities?) this spectrum only allowed to estimate the order of magnitude for plasma temperature of the order of 500 - 1000 eV

Observed Li-, He- and H-like Cl ions

Cl	Li	3.8383	3p-1s
Cl	Li	3.8509	3p-1s
Cl	Li	3.8565	3p-1s
Cl	Li	3.862	3p-1s
Cl	Li	3.8701	3p-1s
Cl	Li	3.883	2s3d-1s2p
Cl	H	4.18518	2p-1s
Cl	H	4.1852	2p-1s
Cl	H	4.18533	2p-1s
Cl	H	4.19055	2p-1s
Cl	H	4.1906	2p-1s
Cl	H	4.19069	2p-1s
Cl	H	4.19074	2p-1s
Cl	He	4.4438	2p-1s
Cl	Li	4.4585	2p-1s
Cl	Li	4.463	2p-1s
Cl	He	4.4669	2p-1s
Cl	Li	4.4837	2p-1s
Cl	Li	4.4925	2p-1s
Cl	Li	4.497	2p-1s
Cl	Li	4.5215	2p-1s

Preplasma characterization

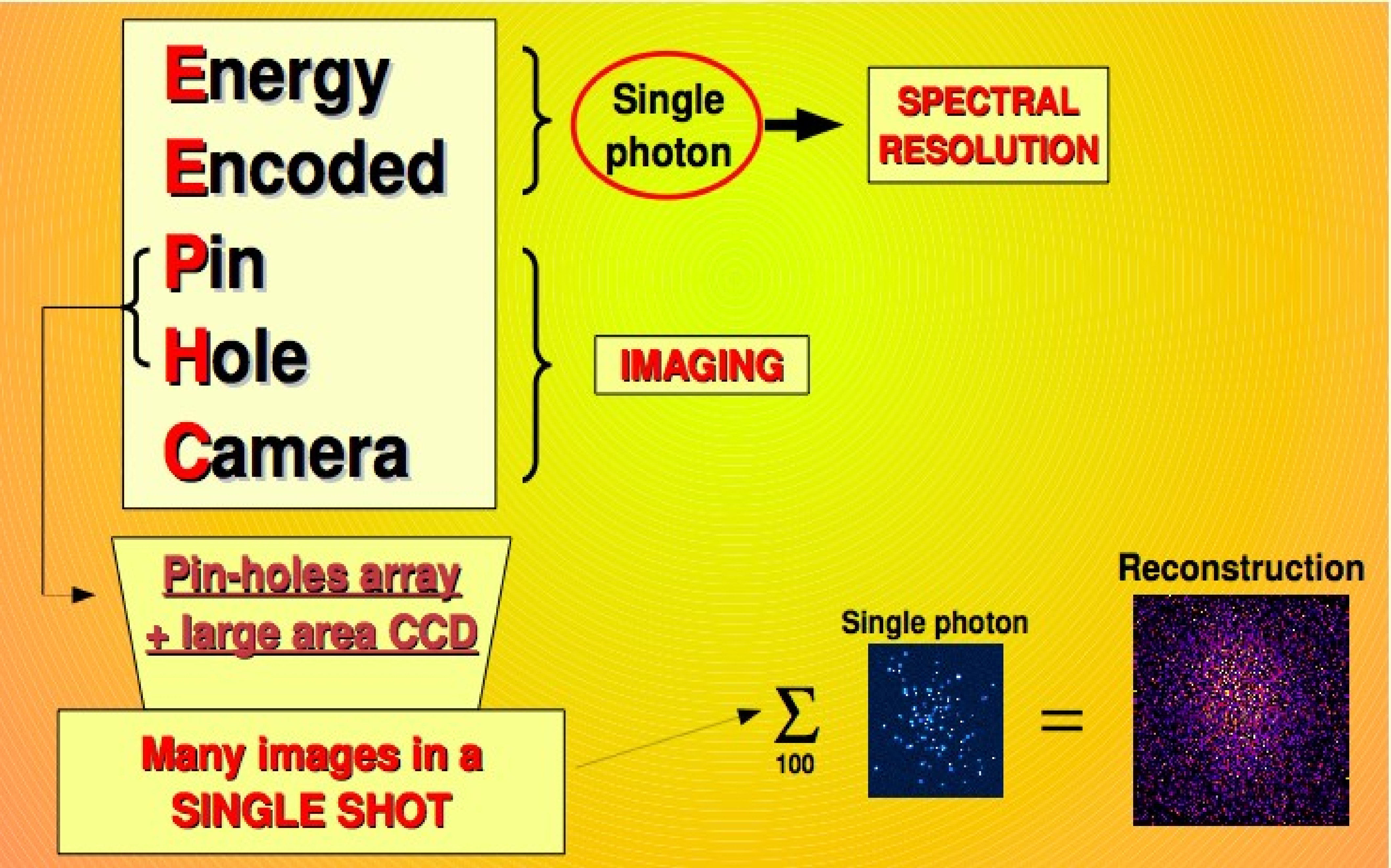
Plasma with $n_e > 10^{20}$ cm^{-3} extends over 200 μm (perpendicularly to target surface) and over 800 μm radially (expected spot size ≈ 1 mm)

Hydro compatible with plasma temperature of 300-500 eV

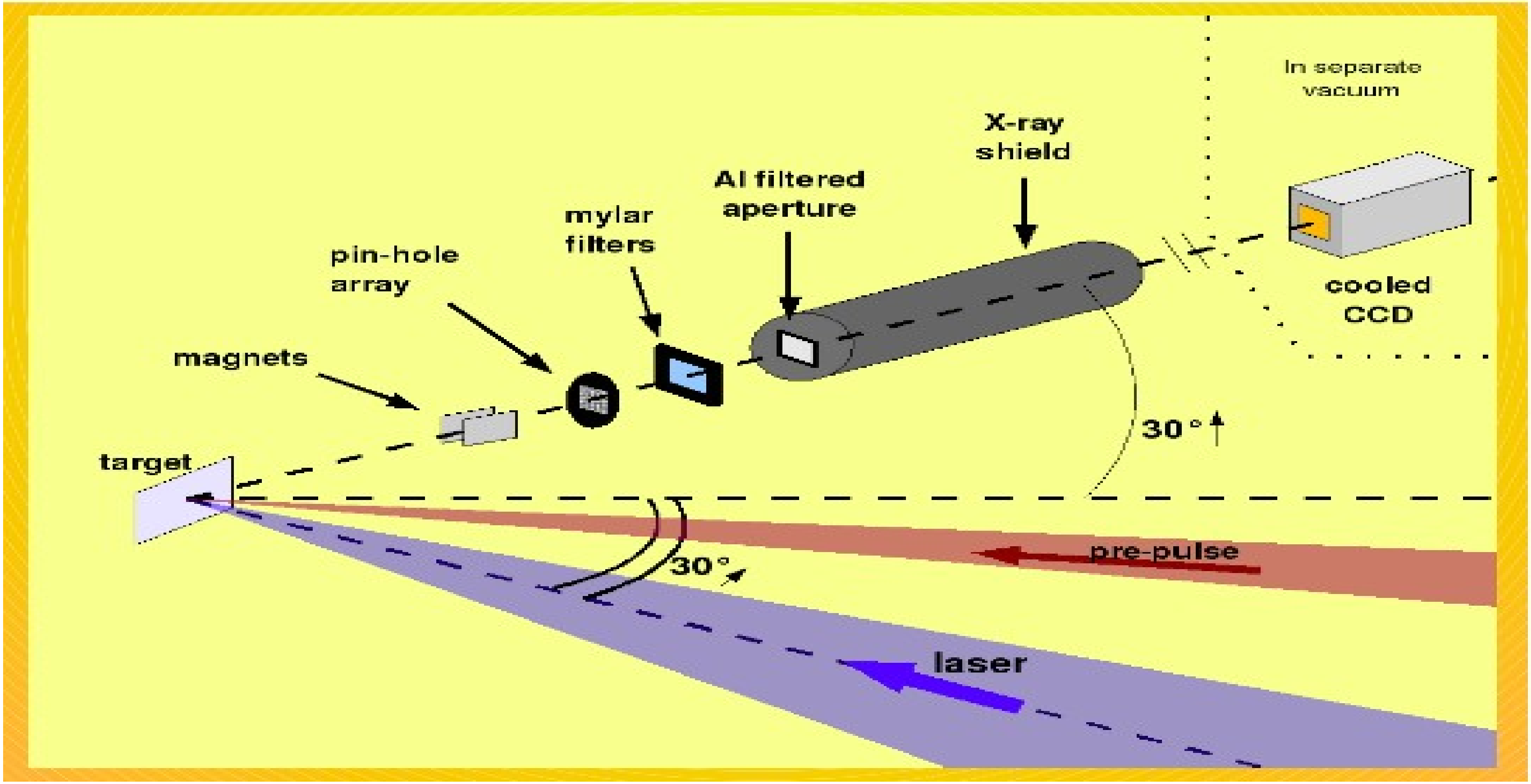
(Size confirmed by X-ray PHC images)

Shock Ignition on PALS: Phase 2

Energy encoded X-ray PHC



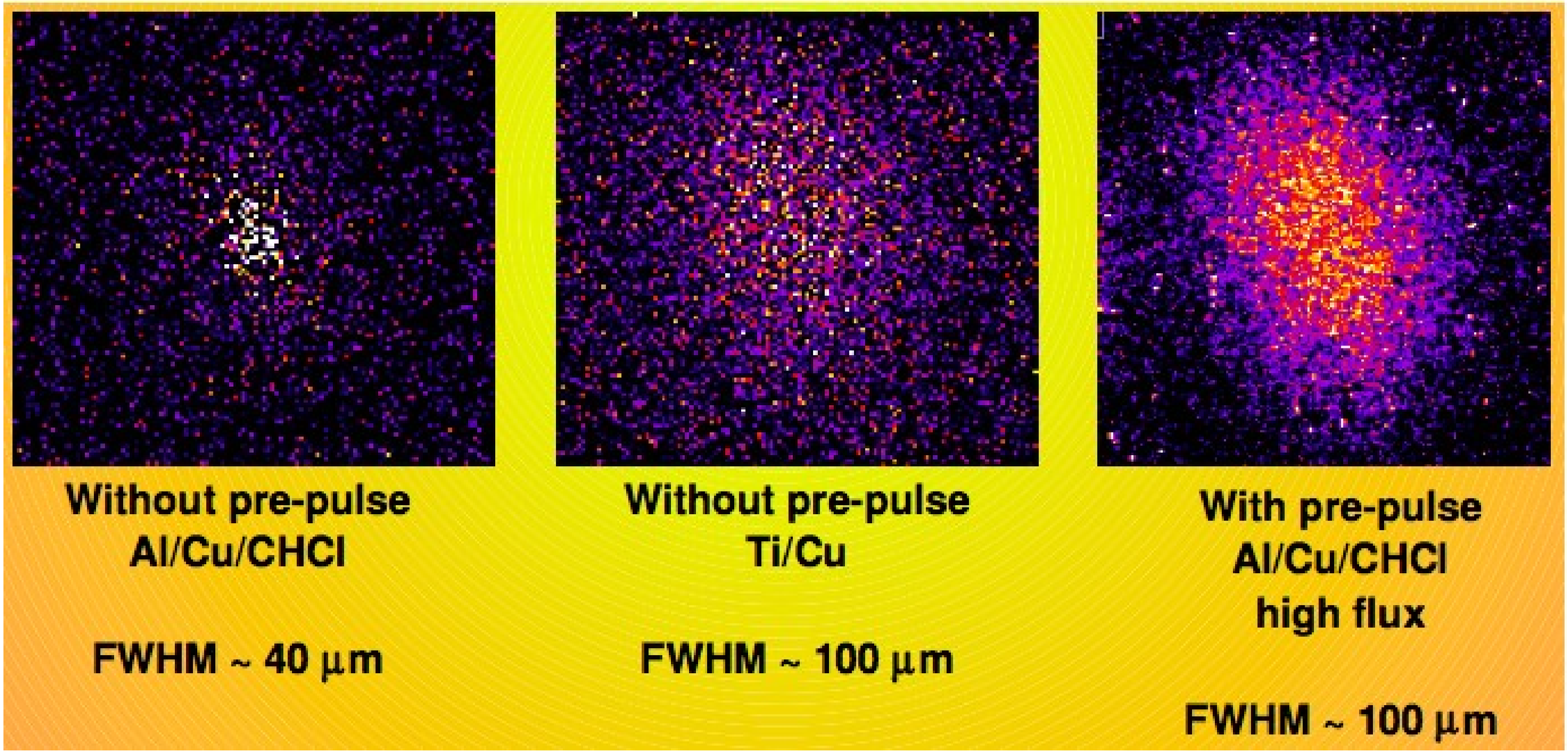
EEPHC Set-up



When using such a diagnostics we added a thin (1 μm) Cu layer between Al and CH. We also used Ti/Cu targets

No exploitable results withot main beam

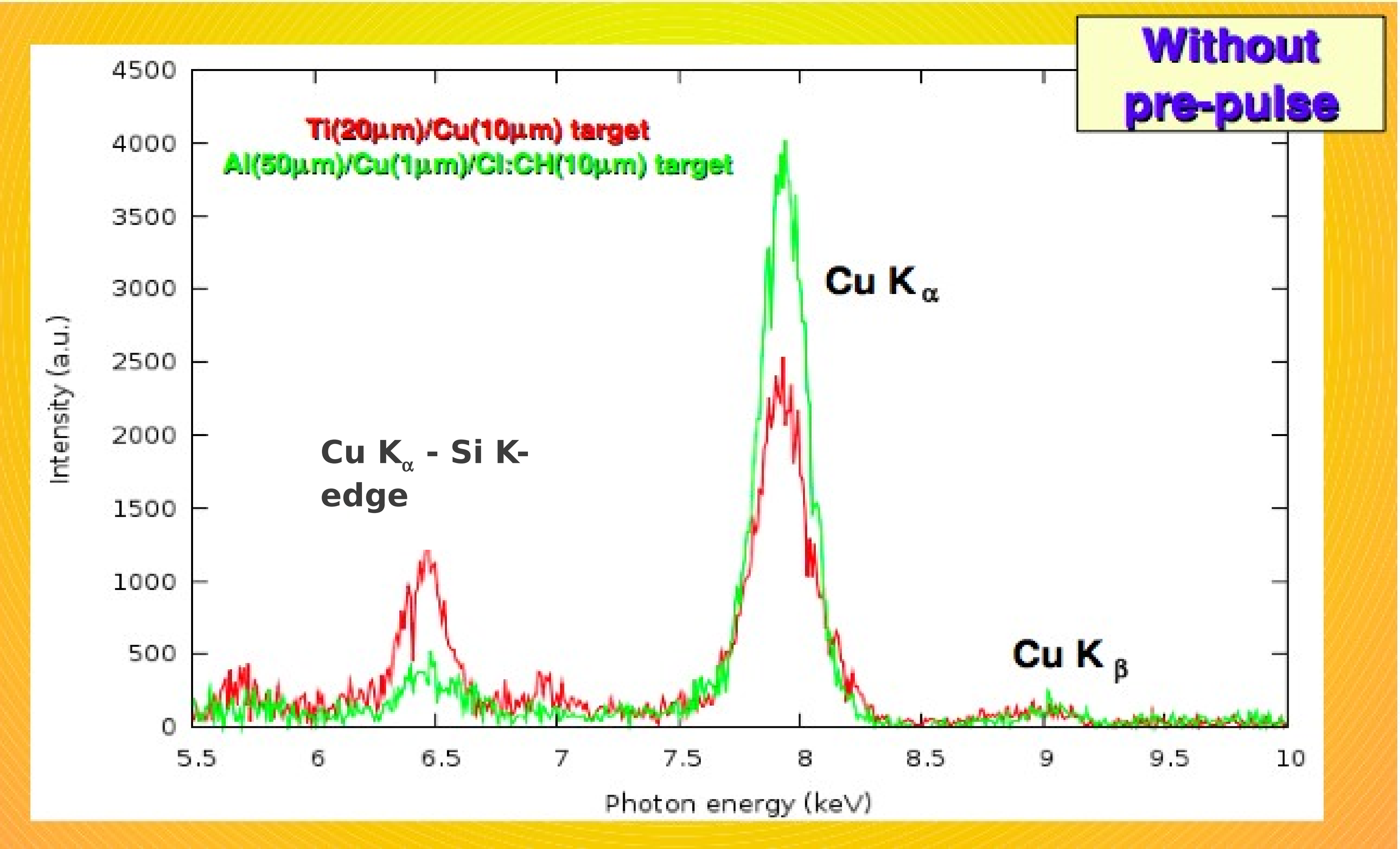
EEPHC results: imaging



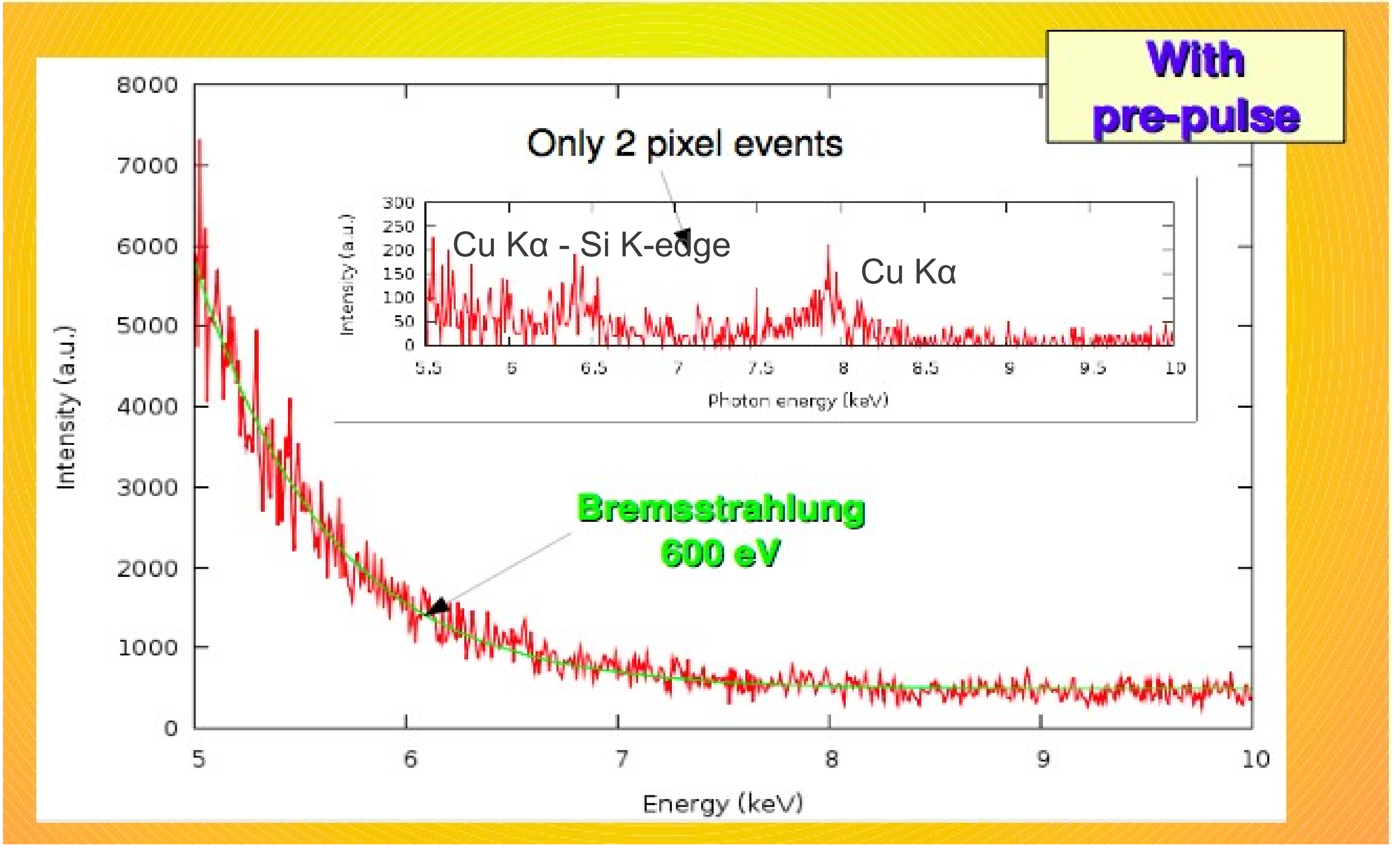
Focal spot size 100 μm (Range of 50 keV electrons in Cu 7 μm, in CH 40 μm)

Work in progress to retrieve hot electron energy. At 10^{16} W/cm^2 one expects $T_e = 100\ keV(I_{17}\lambda^2)^{1/3} \leq 30\ keV$ but higher energies may be produced by SRS

EEPHC results: imaging

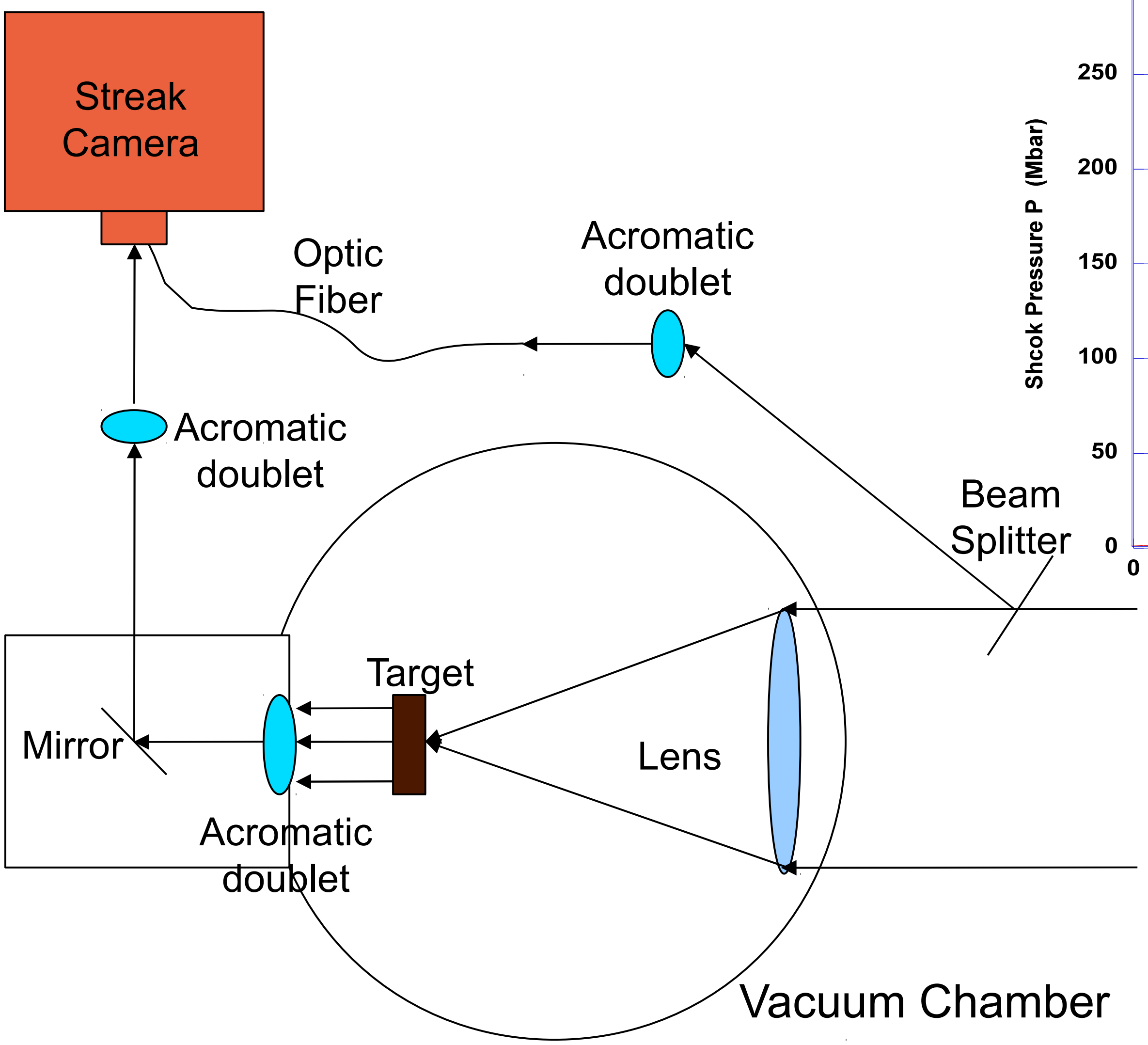


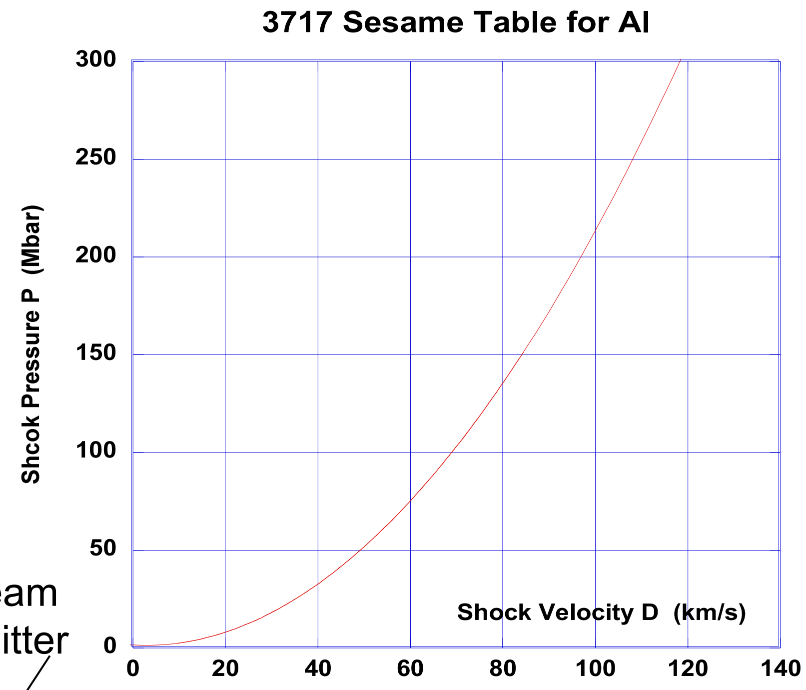
EEPHC results: spectroscopy



Is this representative of the true plasma temperature? Again detailed analysis in progress…

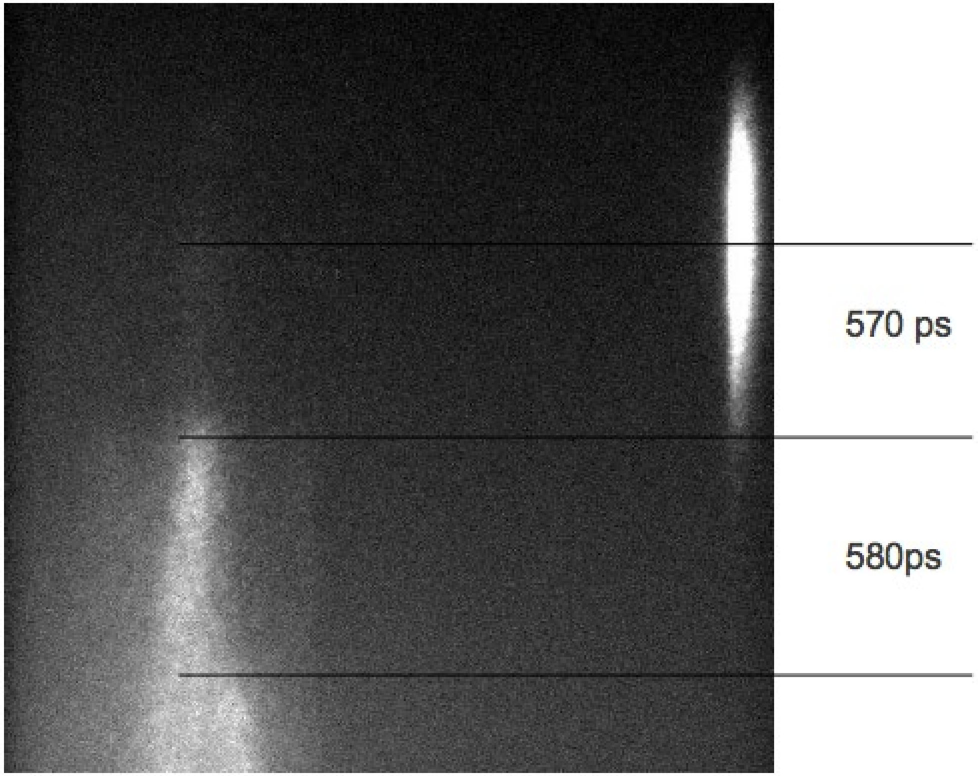
Shock chronometry: set-up





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

Shock chronometry



2 diagnostics per shot:

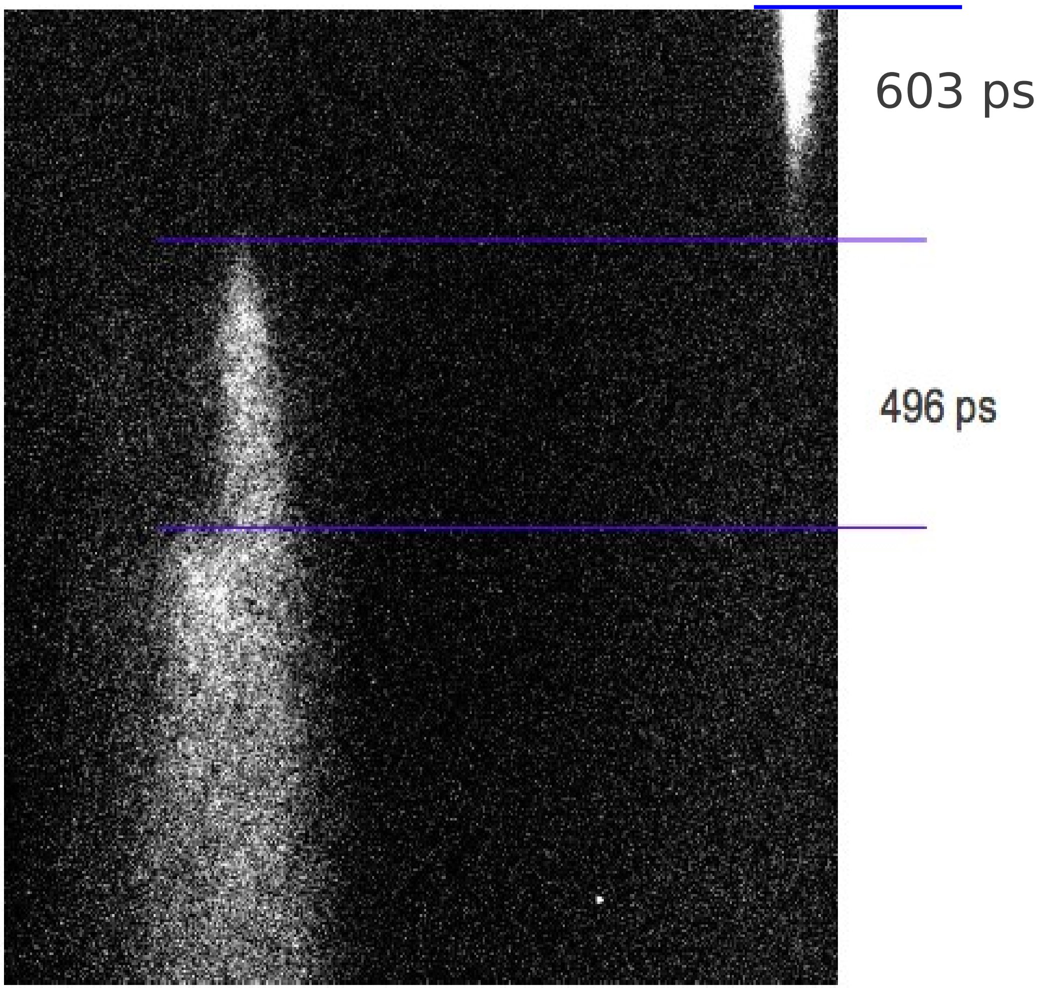
Δt between irradiation and first shock breakout

Δt between breakout on base and on step

Stepped target with E(3ω) = 260 J
Main only (shot 040110_03)

D = 17.3 km/s ⇒ P = 4.4 MBar

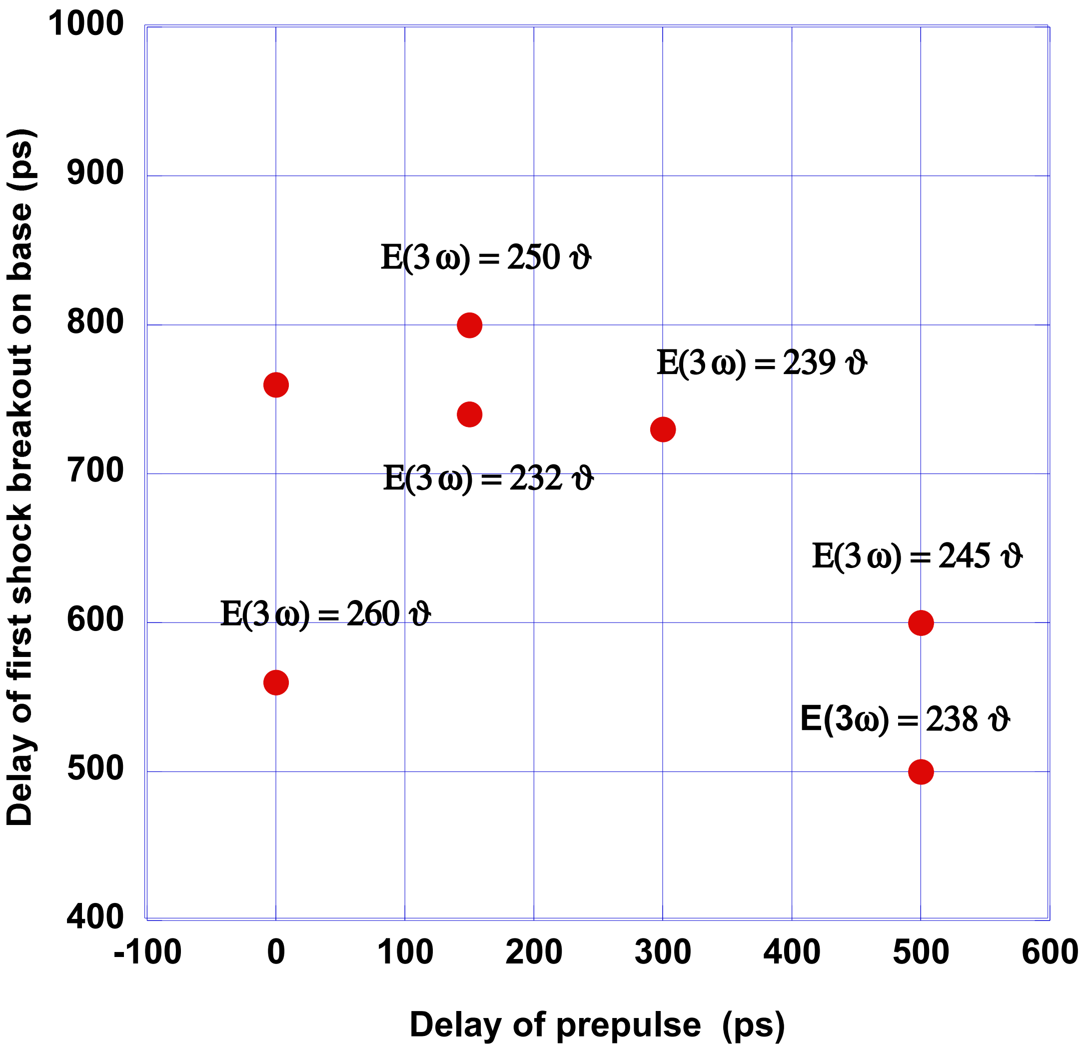
Shock chronometry



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

Shock chronometry: results

	240 J	120 J	60 J
150 ps Flat	040110_05 **740 ps**		
150 ps Step	040110_06 **804 ps**		
300 ps Flat	040110_07 **1023 ps**		040210_13 **856 ps**
300 ps Step	040110_08 **657 ps** 040110_12 **730 ps**		
500 ps Flat	040110_10 **498 ps**	040210_06 **764 ps**	
500 ps Step	040210_05 **603 ps**		

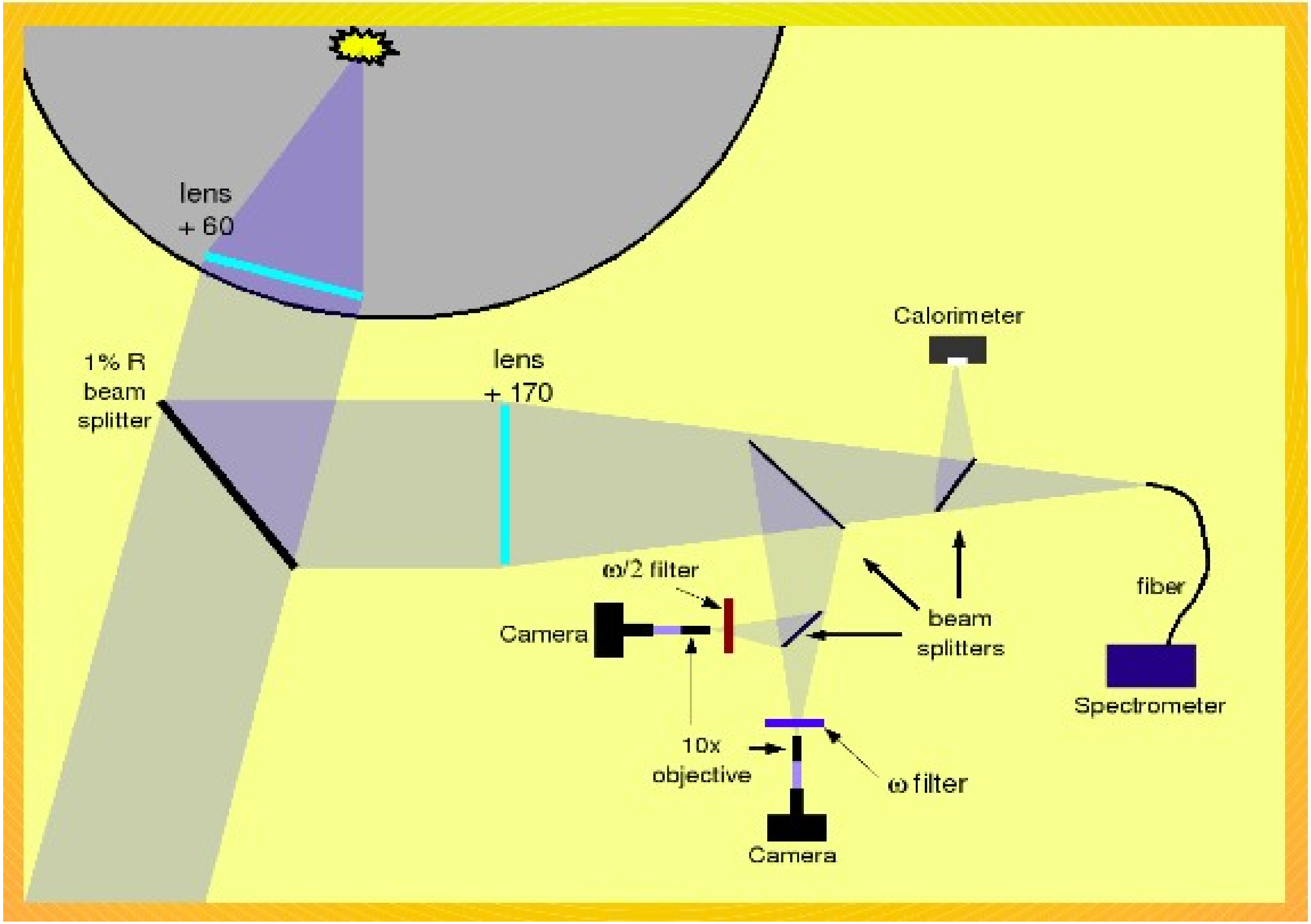


Same "bell shape" behavior of ion measurements.

Value for Δt = 500 ps are every close to those without prepulse.

The plasma is dispersed in 500 ps? (it does not seem to be supported by XRL deflectometry data nor by SRS data)

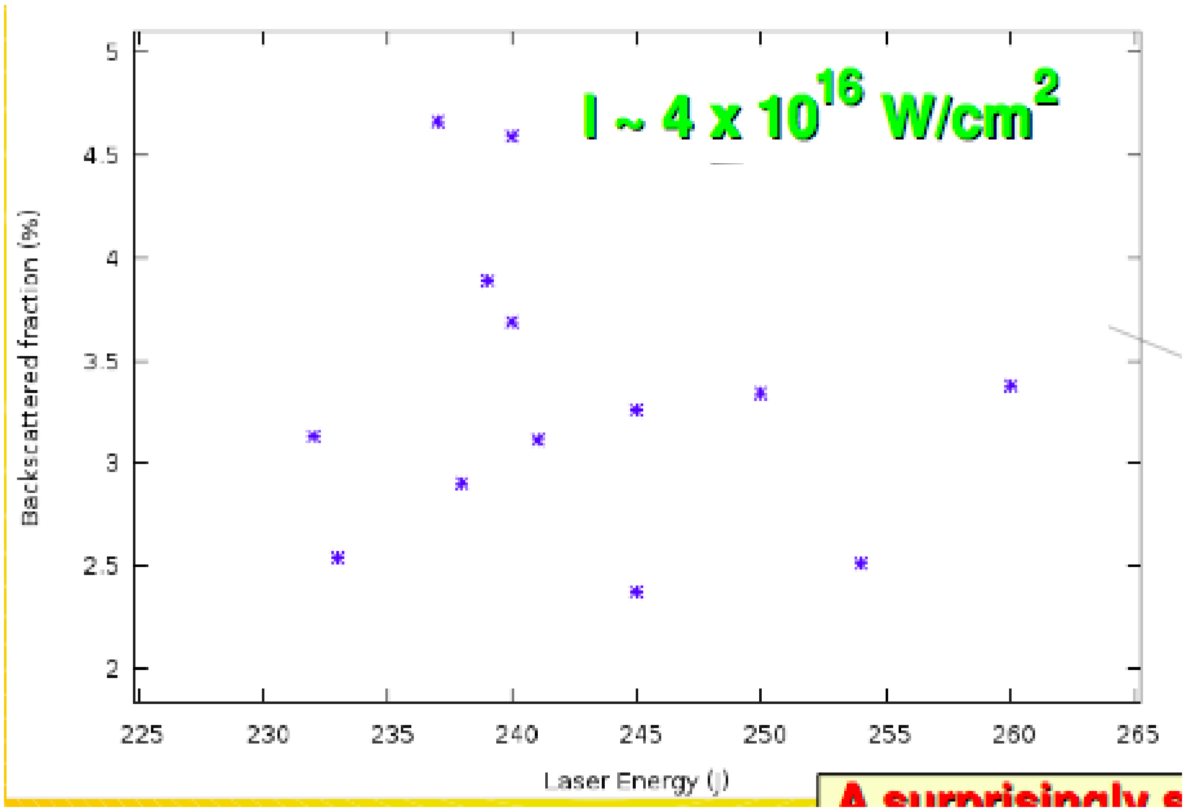
Back scattering diagnostics



Back scattering: calorimetry

Results at the Omega facility (Usa, 2009) give 33% back reflection at $I \approx 8\ 10^{15}$ W/cm^2

A surprisingly small fraction of light is backscattered in our experimenal conditions ($I \approx 10^{16}$ W/cm^2, λ = 0.44 µm)



Simulations (Klimo et al., PPCF, 52, 2010) also predict large SRS

Back scattering: spectroscopy

- **SBS**

$c_{i.a.}(1\,keV) \sim 3\times10^5\, m/s$

$$\omega_{i.a.} \ll \omega_{e.m.} \Rightarrow \omega_{scatt} \sim \omega_L$$

In detail $\left(\frac{\Delta\lambda}{\lambda}\right)_{SBS} \sim \frac{c_{i.a.}}{c} \lesssim \left(\frac{\Delta\lambda}{\lambda}\right)_{res}$ → Can't ditinguish SBS signal from scattered laser light

- **TPD**

$$\omega_L \rightarrow \frac{\omega_L}{2} + \frac{\omega_L}{2}$$

→ $+\omega_L^{back}$ → Tpical emission @ $\frac{3}{2}\omega_L$

No experimental evidence of TPD

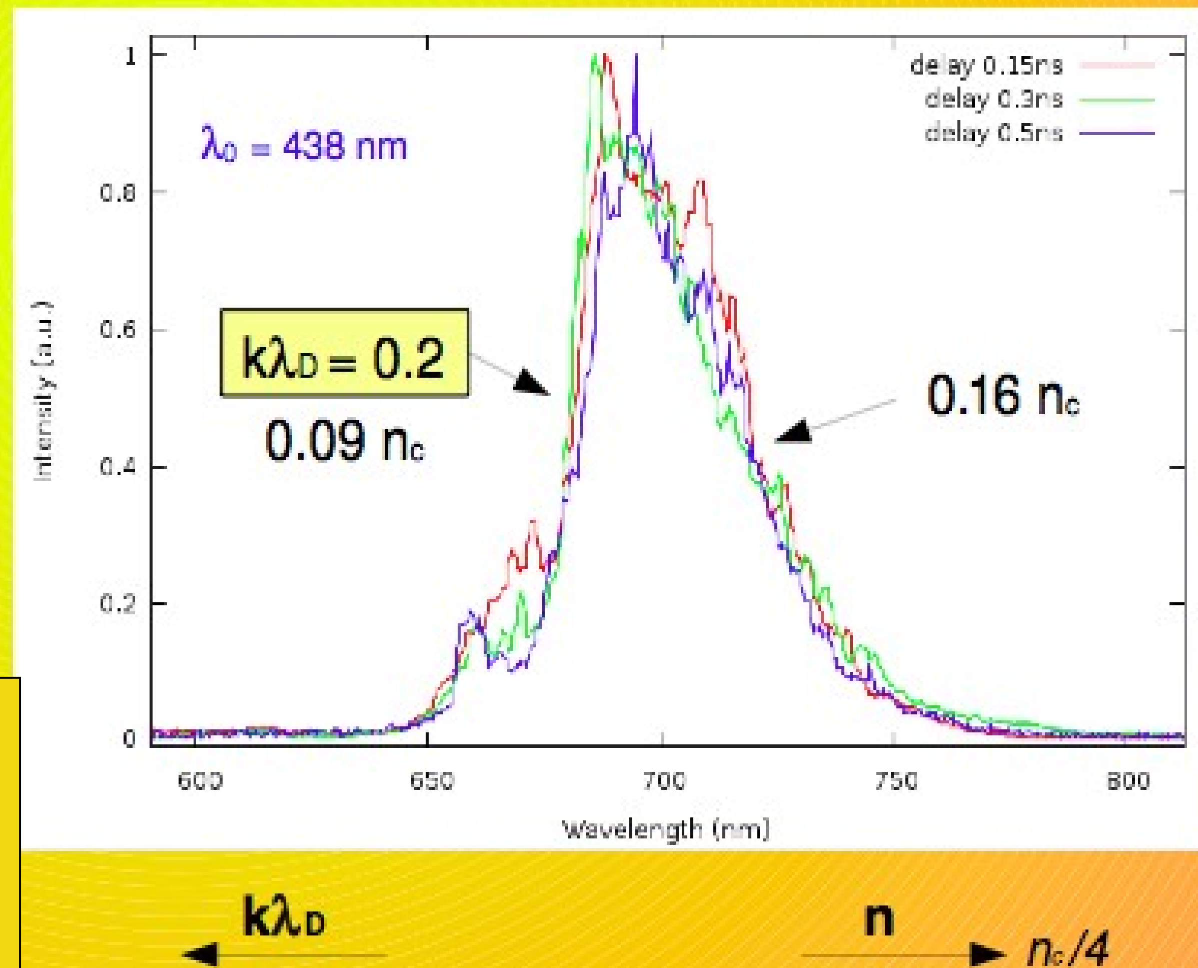
TPD cut by window transmission?

Back scattering: spectroscopy

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

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

  - Blue cut-off due to Landau damping



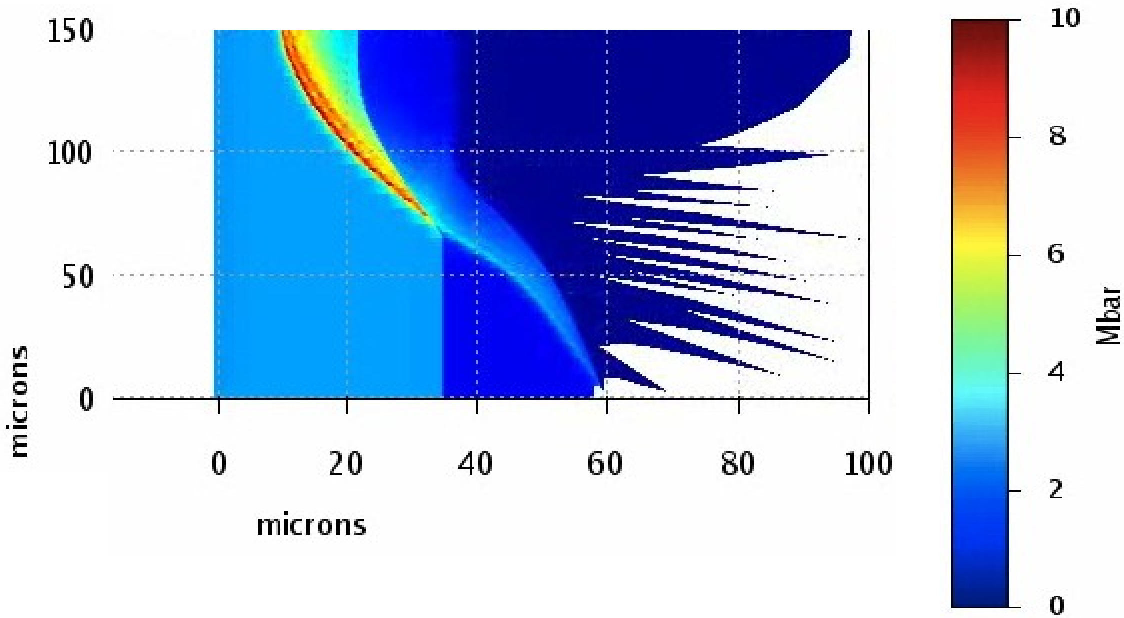
No SRS emission from n_c/4 layer. Depletion of laser beam due to delocalised collisional absorption?

Laser-plasma coupling seems to occur at densities lower than critical

2D Hydro simulations

The measured values of P at target rear corresponds to higher values at front. Indeed shock pressure undergoes a rapid decrease due to:

1) 2D effects during shock propagation
2) Relaxation waves from front side when laser turns off



2D Simulation for I ≈ 2 × 10^{15} W/cm^2 and focal spot diameter ≈ 100 µm.
Breakout time = 1 ns - 0.35 ns (time of laser max in simulation) = 650 ps
[Tommaso Vinci, code DUED]

Final pressure ≈ 10 Mbar, Initial Pressure ≈ 90 Mbar, in agreement with laser intensity used in simulation

2D Hydro simulations

The expectation ≈ 300 Mbar is based on the classical model of laser absorption at the critical density

In our case the extended plasma corona likely implies delocalised absorption. Assuming absorption takes place at density ≈ 0.16 critical (as suggested by SRS spectra) we may expect ≈ 160 Mbar

However in order to reproduce the shock breakout time we need a pressure on front side P ≈ 90 Mbar and to get this we must either

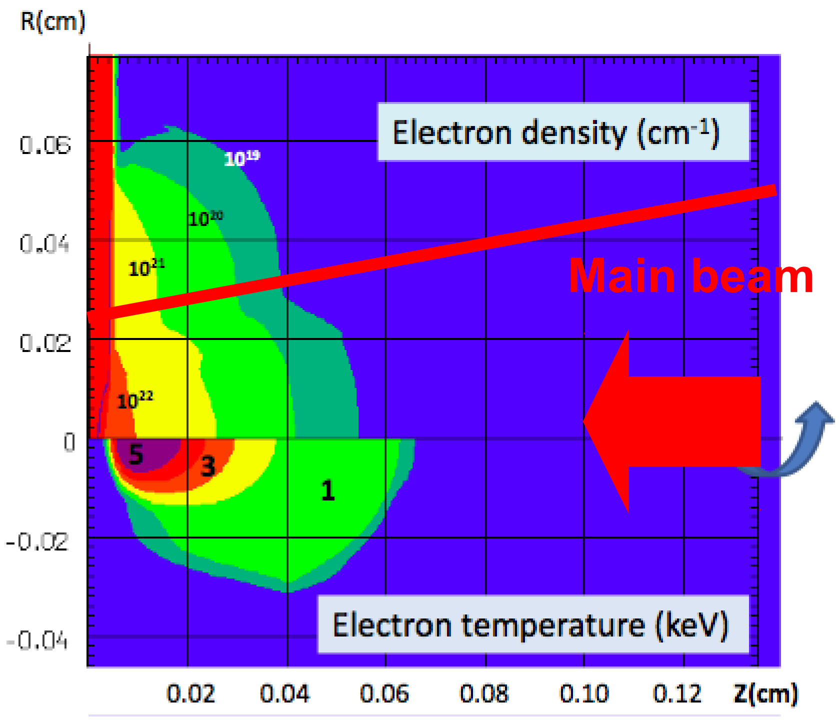
1) Reduce the laser intensity to $I \approx 2 \times 10^{15}$ W/cm^2 with the "normal" flux limiter $f = 0.06$
2) Use the nominal value 2D Simulation for $I \approx 10^{16}$ W/cm^2 with a reduced flux limiter $f = 0.01$

The flux limiter is a simple way to describe the physics of the transport of energy by electrons inside the target. Reducing f implies a different transport mechanism and an inhibition of thermal trasport

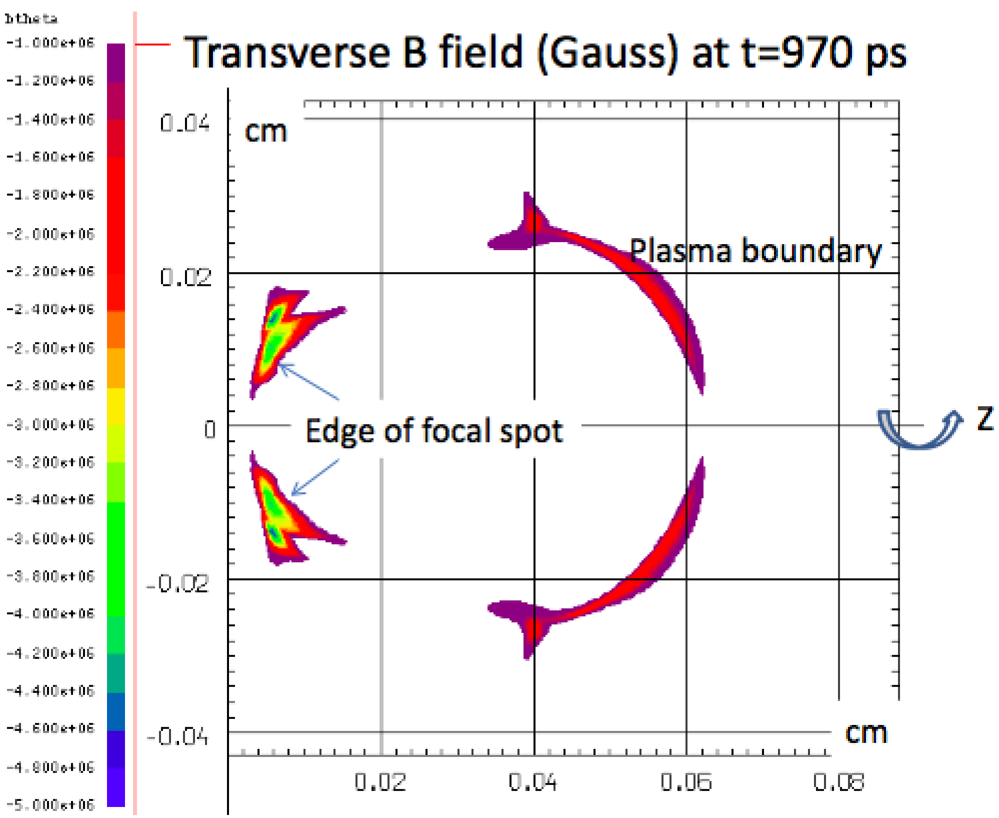
Is there any possible evidence of such inhibition in our experimetal situation?

Large magnetic fields

Very large magnetic fields (up to 5 Mgauss) are created due to the ∇n×∇T mechanism in our experimental conditions (simulations by Guy Schurtz, CELIA, using CHIC)



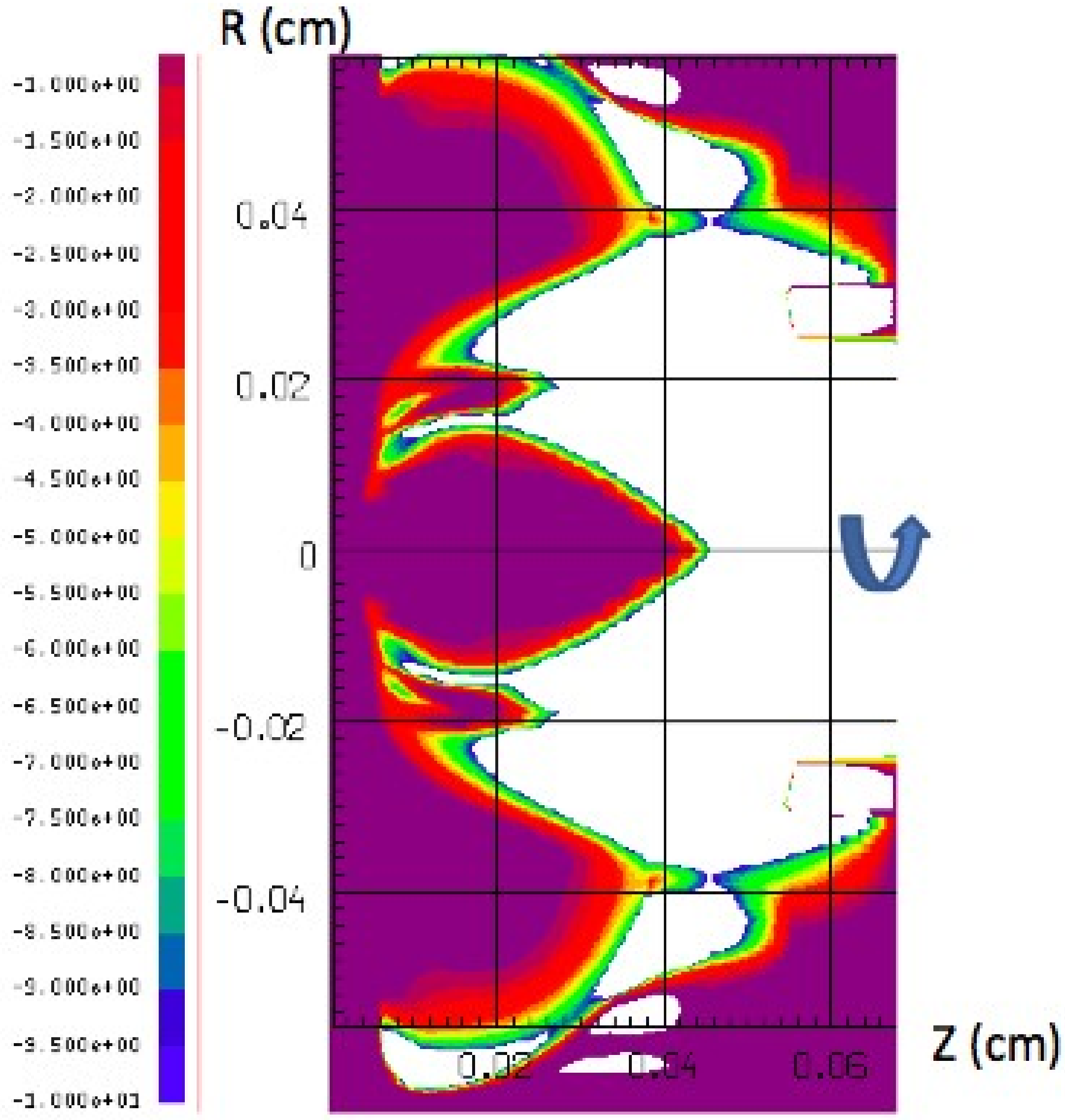
Plasma expansion at t=970 ps



Large magnetic fields

These imply a large value of $\omega\tau$, the Hall parameter, where $\omega = eB/mc$ is the electron cyclotron frequency and τ the collision time.

Therefore the motion of electrons is largely magnetized and the transport of heat towards the inside of the target may be inhibited



HALL PARAMETER $\omega\tau$

Conclusions

- **Analysis of results still in progress**

- **The preplasma and the interaction of the main beam have been characterised using several diagnostics.**

- **We are able to couple a strong which is initially strong (100 Mbar) corresponding to an effective laser intensity ≈ 2×10^{15} W/cm^2 . However we were expecting ≈ 10^{16} W/cm^2 and ≈ 300 Mbar. SRS spectra seem to suggest that laser couples to plasma at lower densities bringing to lower effectivness of shock generation**

- **It seems that light lost via PI is surprisingly low (however we need an accurate calibration of calorimetric data due to spectral response of the apparatus). This could be in agreement with low laser wavelength, relatively low effective intensity and coupling at lower density**

- **Some evidence of hot electron generation by Cu K_α emission (energy ≈ 50 keV). Need of more detailed characterization.**

- **SRS spectra are independent on prepusle delay, at least for $\Delta t \leq 500$ ps**

- **"Bell shaped" behavior from several diagnostics. Does the preplasma become transparent for $\Delta t = 500$ ps?**


Vielen Dank