Laser-Plasma Interaction and Target Coupling in the Intensity Regime relevant for Shock-Ignition

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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?

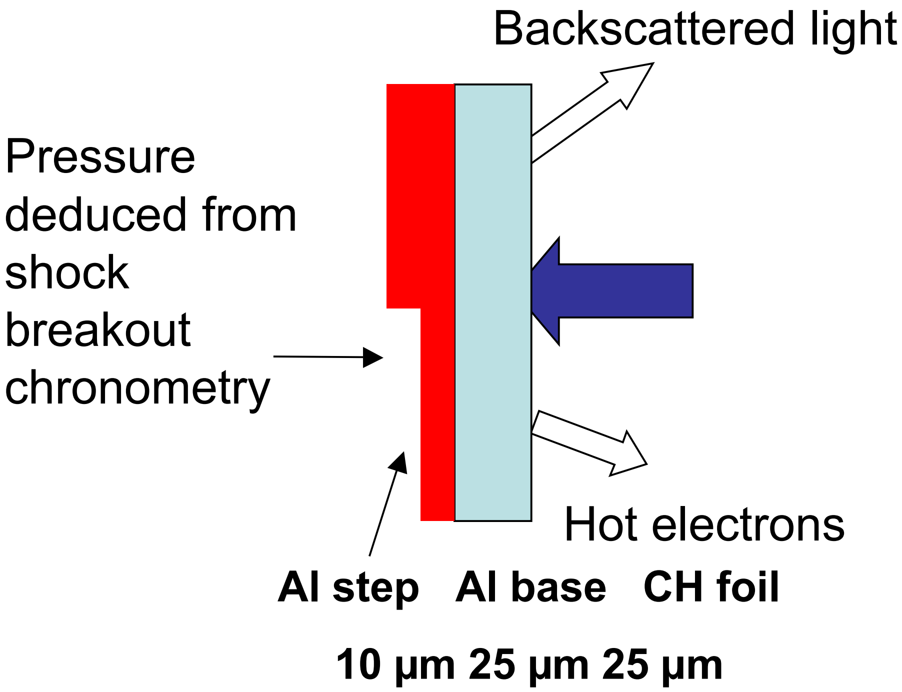
PALS experiment

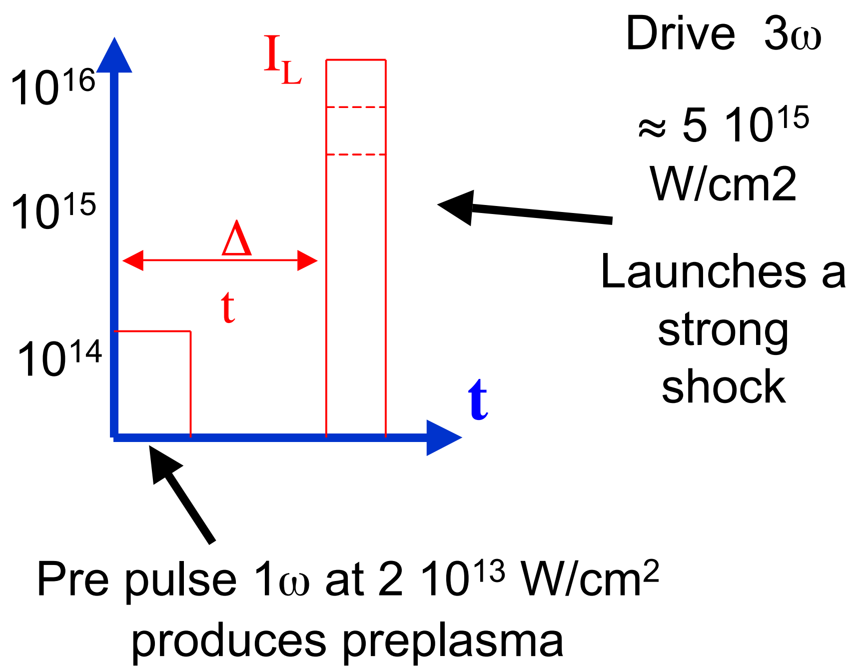
Iodine Laser
=1.3 μm τ = 300 ps E = 1500 J
3ω λ =0.44 μm E $\leq$ 500 J

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





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

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

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

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

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

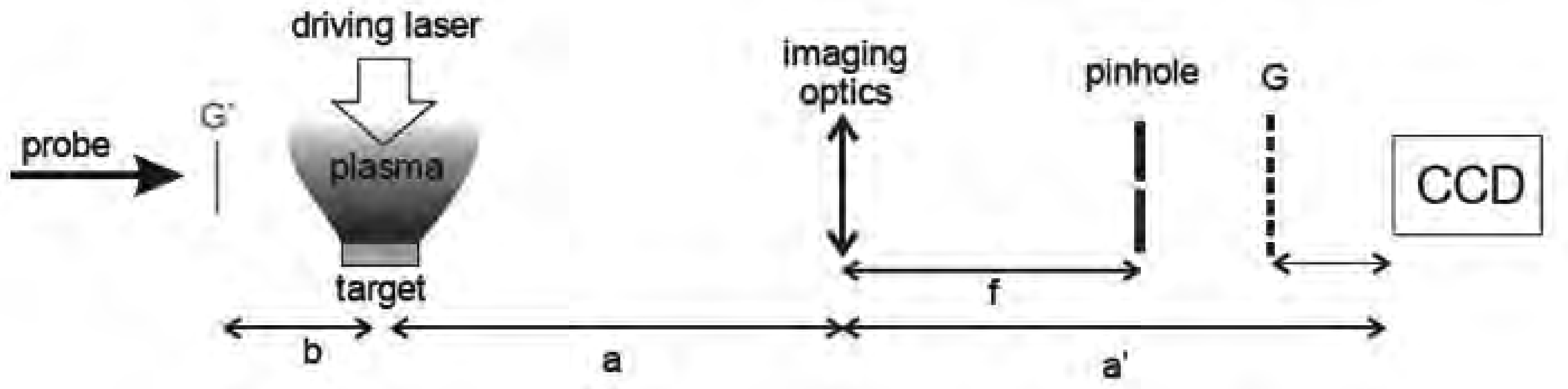
Phase 2
Characterization of shock formation and laser-plasma interaction with:

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

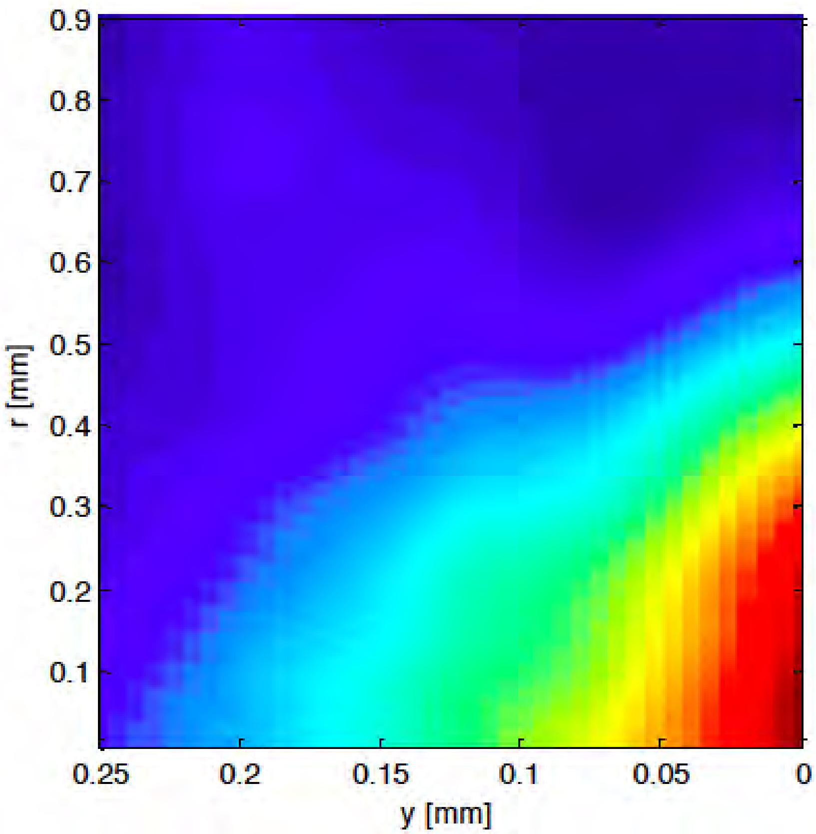


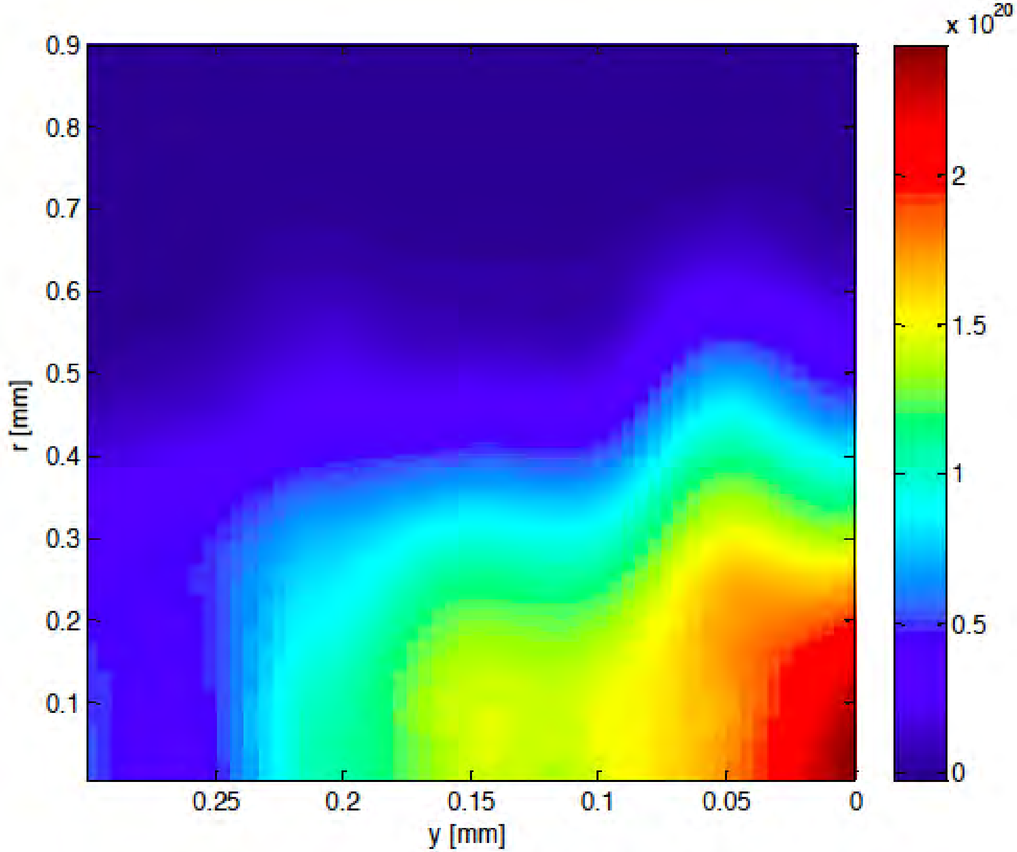
Ne-like zinc X-ray laser emitting at 21.2 nm, operated in single pass with 150-ps pulses of 200 μJ. Mo-Si multilayered spherical mirror with f=250mm used to image the plasma on back-illuminated X-ray CCD with M = 8.2. A pinhole of 0.5mm diameter was put to the image of the XRL source (2500 mm from the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

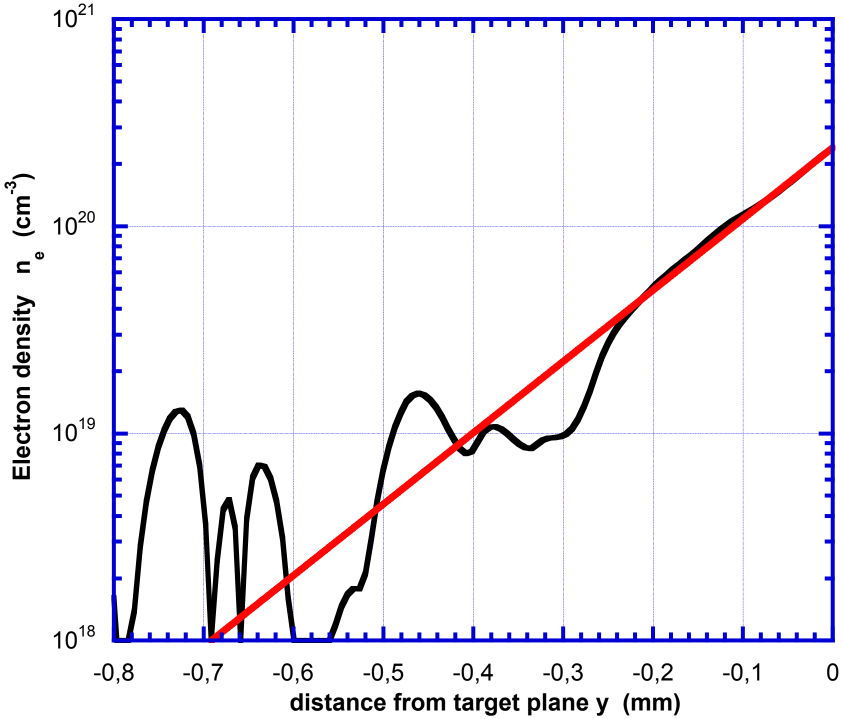


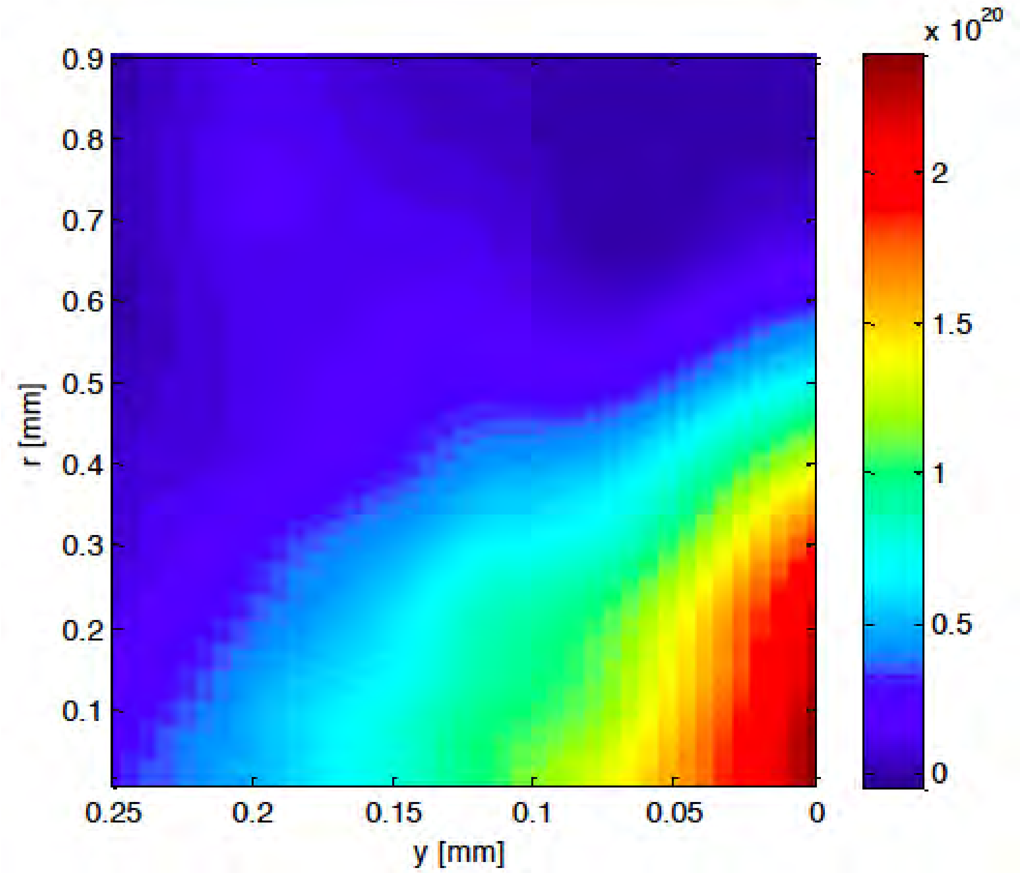


0.3 ns **0.9 ns**

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

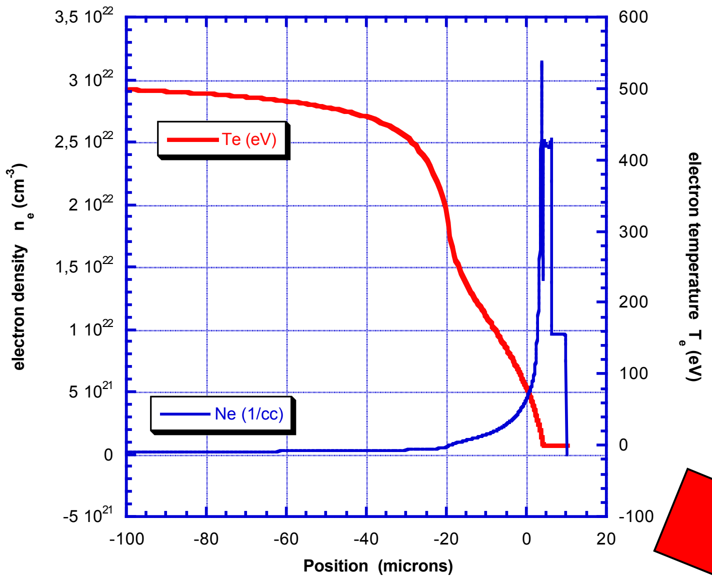




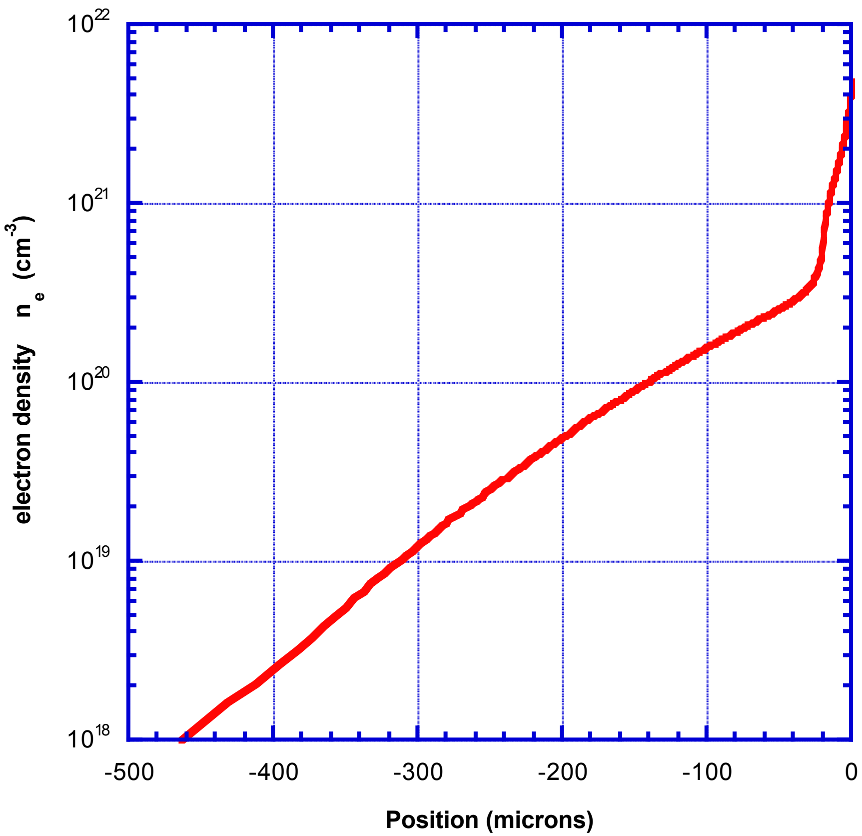
Max accessible density ≈ 2.4 $\times 10^{20}$ cm^{-3}

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}



Hydro simulations allow to recover the plasma temperature (between 300 and 500 eV depending on laser intensity)

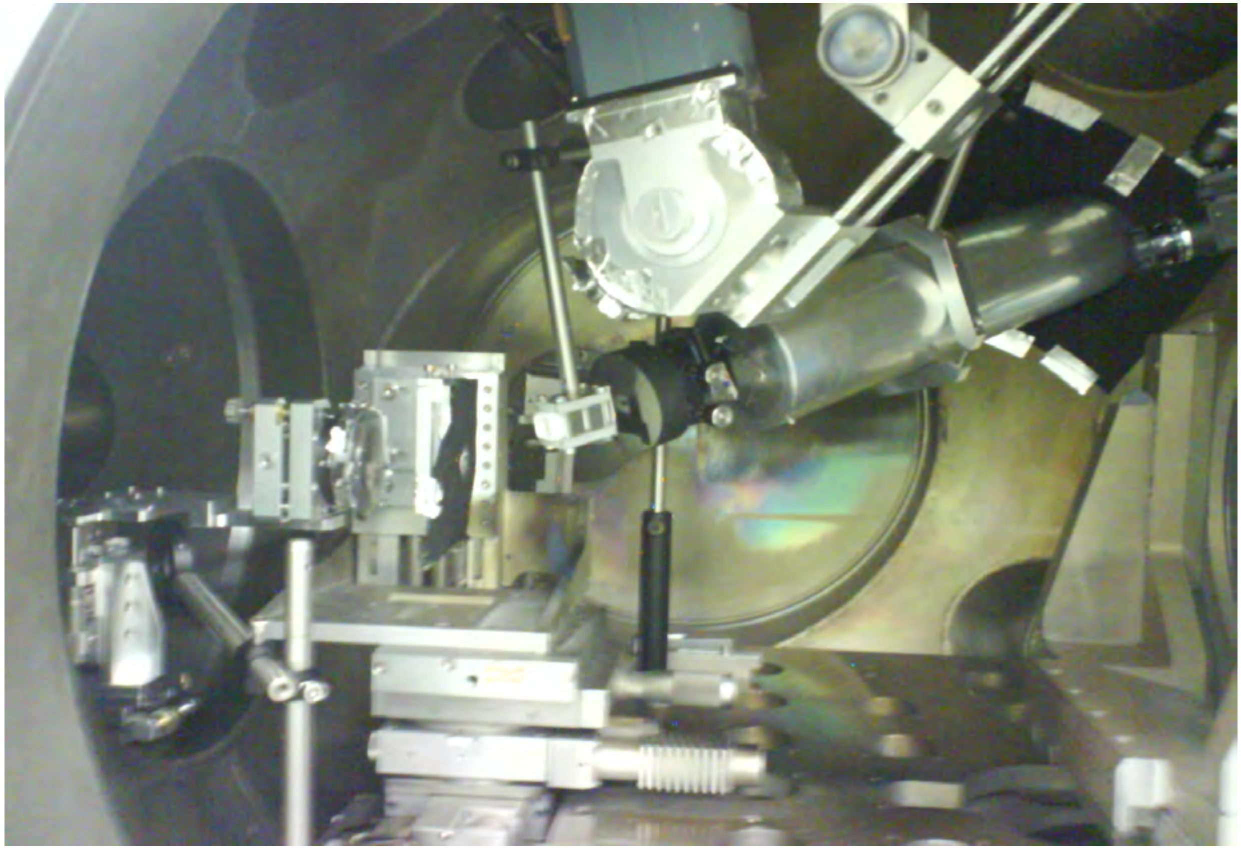
WORK IN PROGRESS...

keV Spectrometry of Cl ions

- ADP (ammonium dihydrogen phosphate) with $2d \approx 10.659$ Å, placed at ≈ 20 cm from the source and with a Bragg angle ≈ 19°
Observed range 2600 to 3600 eV

- Lines from Li-, He- and H-like Cl ions

- Temperature about 300 eV from X-ray spectroscopy



Preplasma characterization

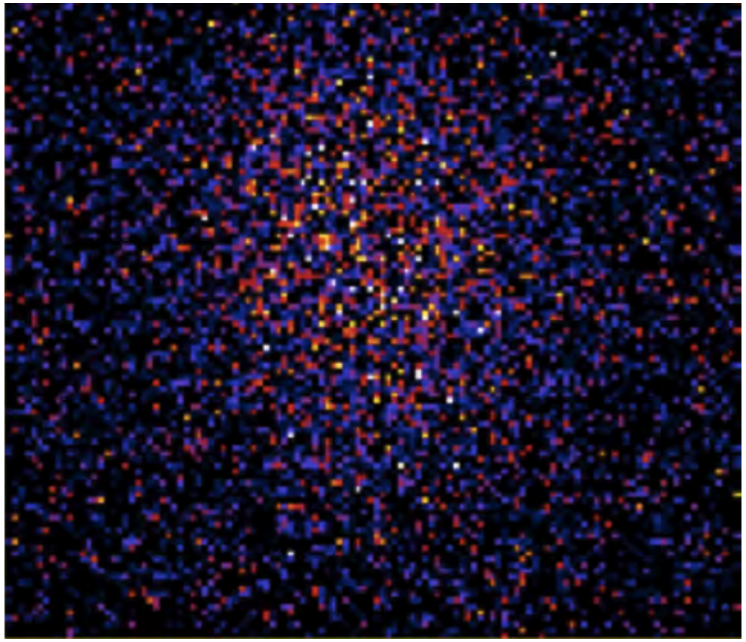
Plasma with $n_e > 10^{20}$ cm^{-3} extends over 200 μm (perpendicularly to target surface) and over 800 μm radially (expected spot size ≈ 1 mm)
Hydro compatible with plasma temperature of 300- 500 eV

(Size confirmed by X-ray PHC images)

Temperature about 300 eV from X-ray spectroscopy.

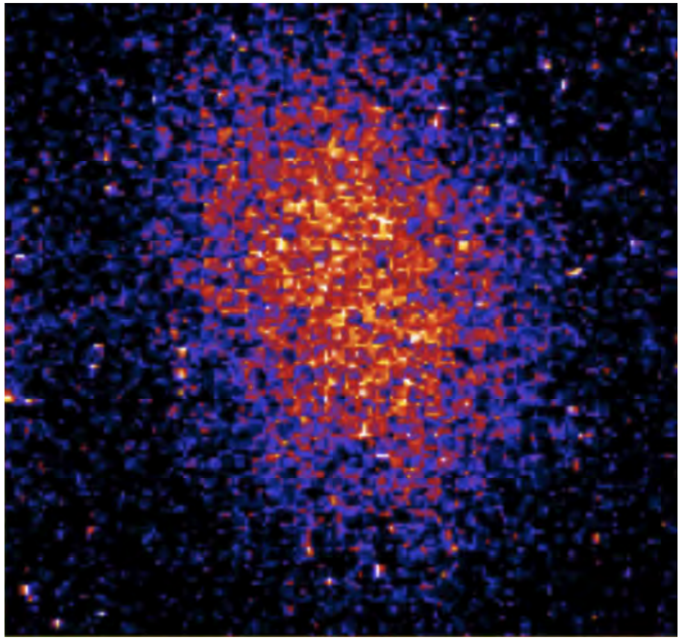
Shock Ignition on PALS: Phase 2

EEPHC results: imaging



Without prepulse Ti/Cu

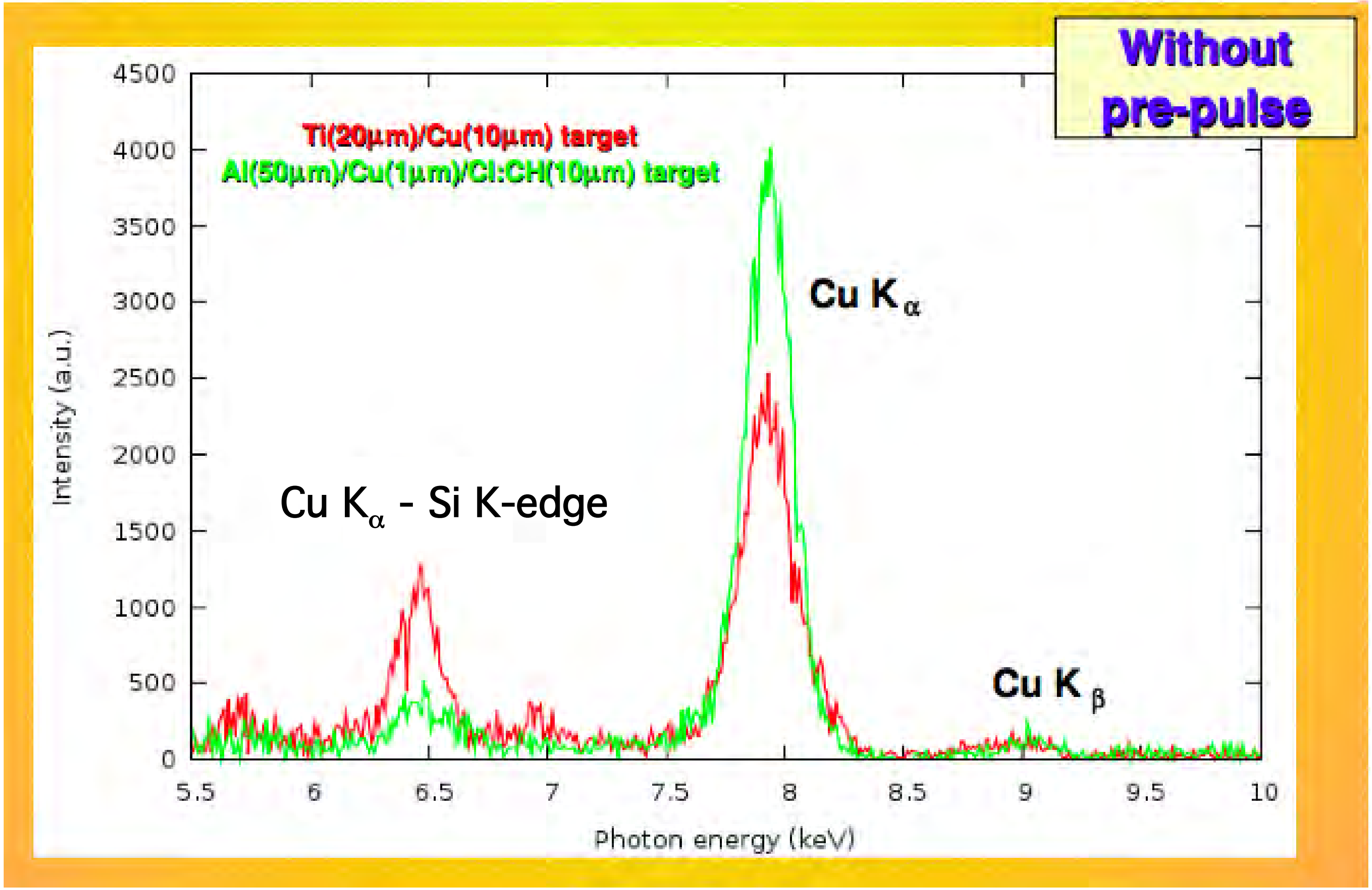
FWHM ≈ 100 μm



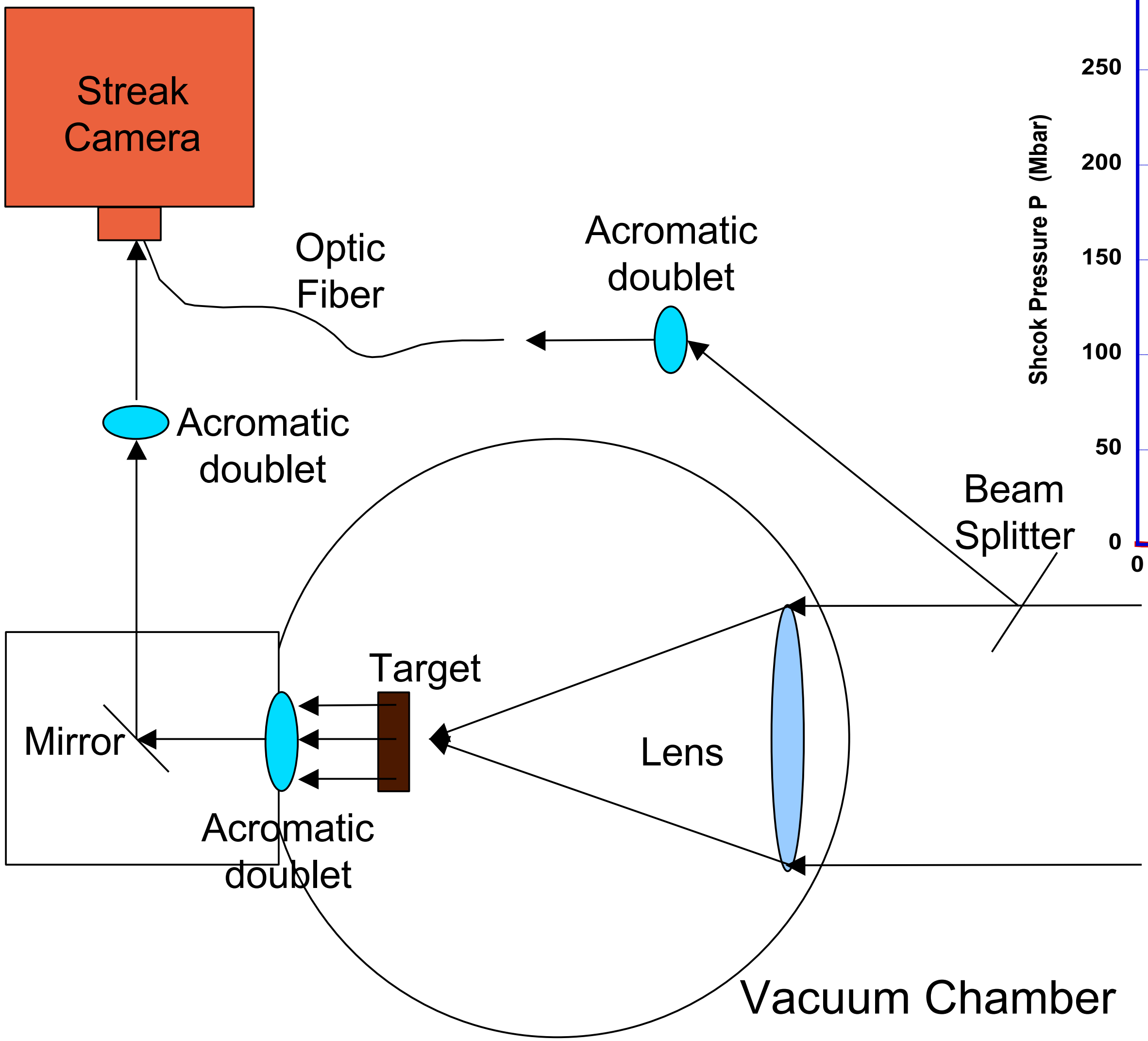
With prepulse CH/Cu/Al
High flux
FWHM ≈ 100 μm

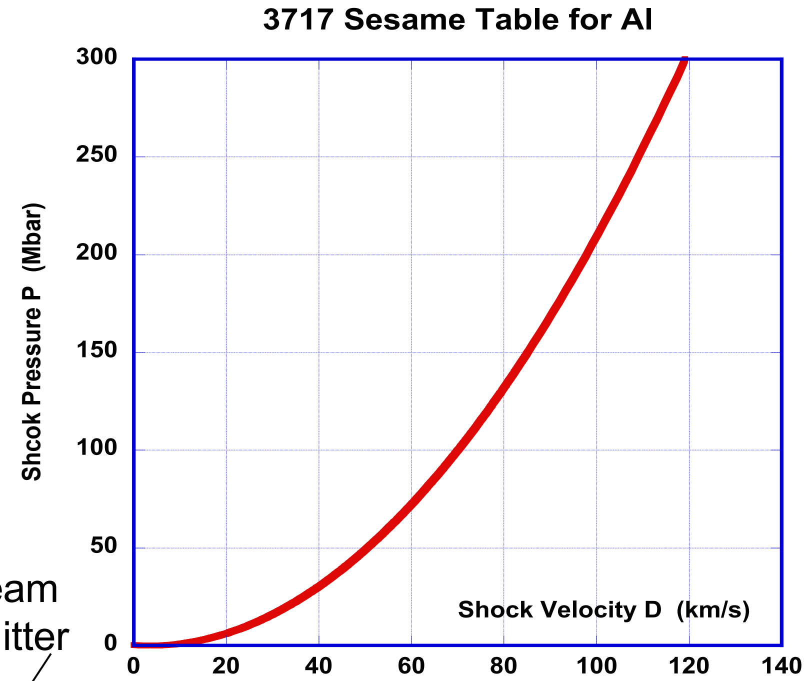
Range of 50 keV electrons in Cu 7 μm, in CH 40 μm
Work in progress to retrieve hot electron energy. At 10^{16} W/cm^2 one expects $T_e = 100$ keV$(I_{17}\lambda^2)^{1/3} \leq 30$ keV but higher energies may be produced by SRS

EEPHC results: spectroscopy



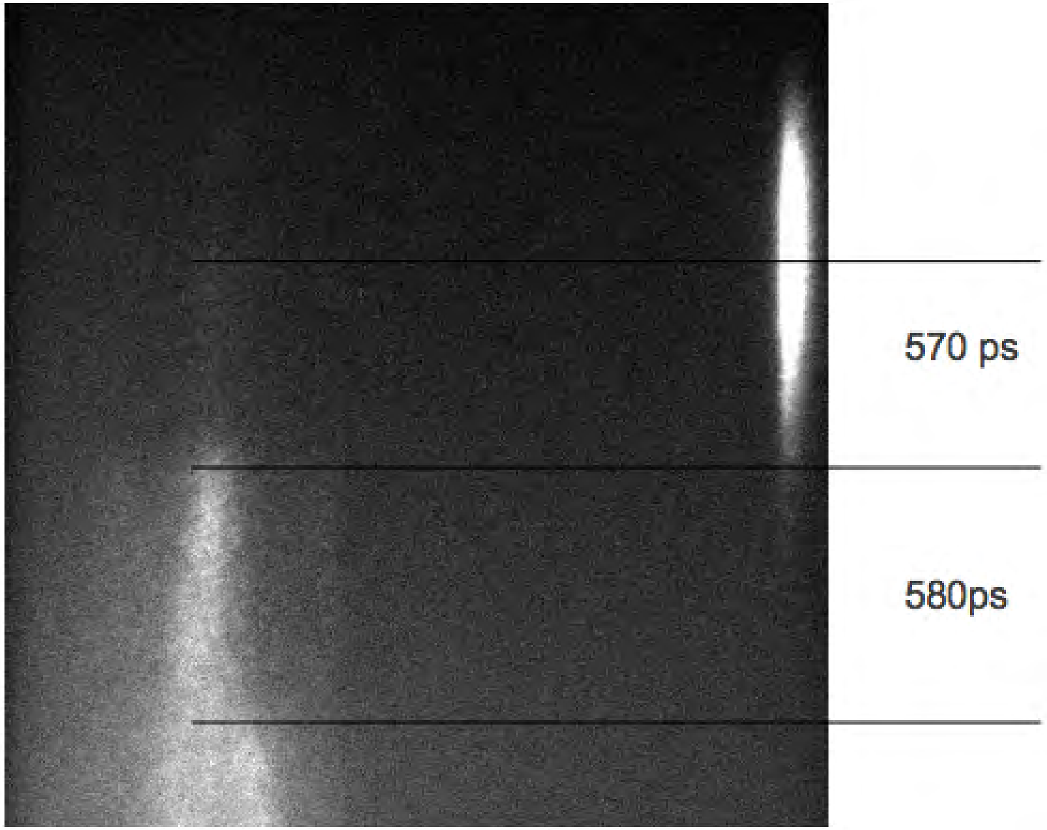
Shock chronometry: set-up





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

Shock chronometry



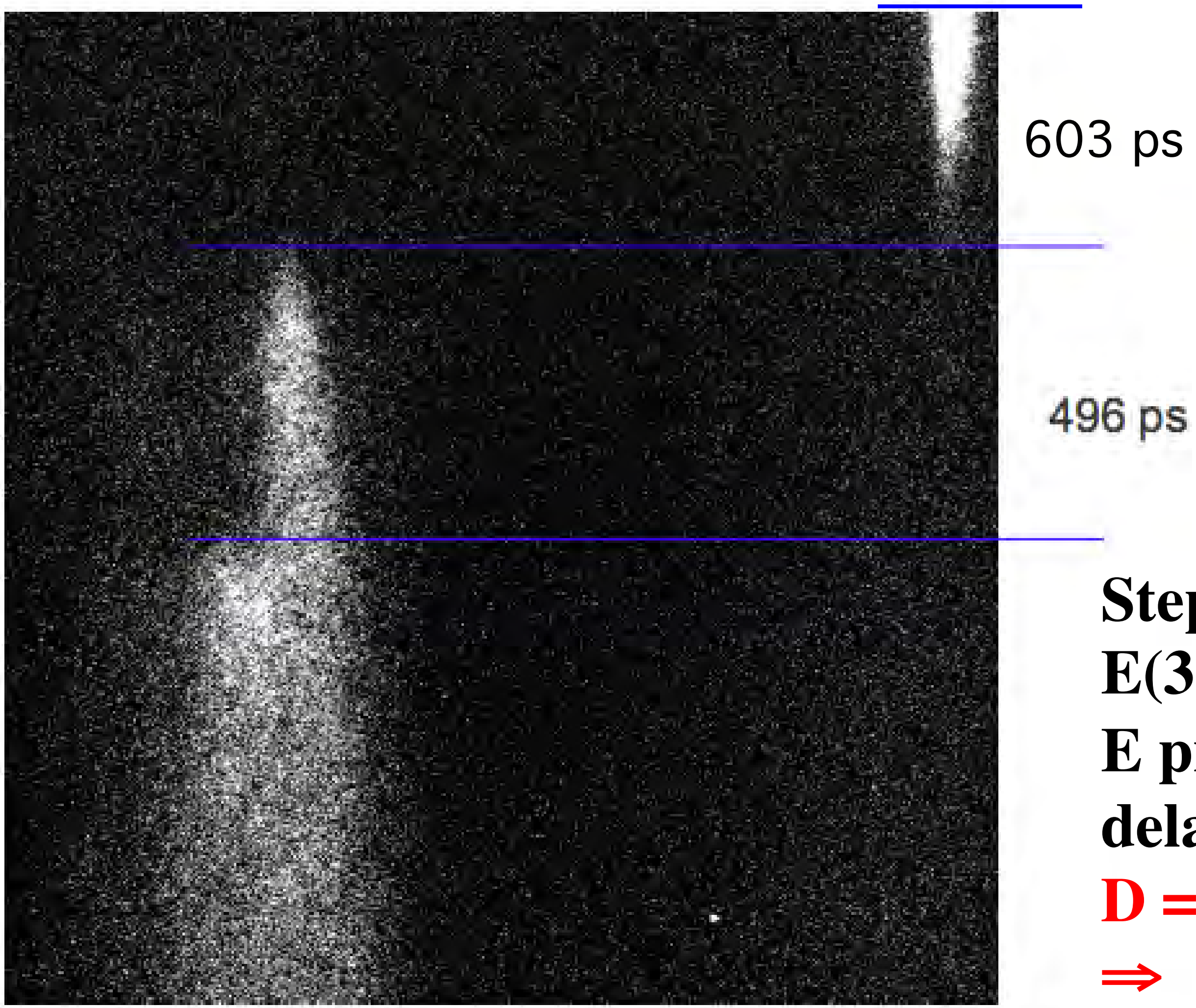
2 diagnostics per shot:

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

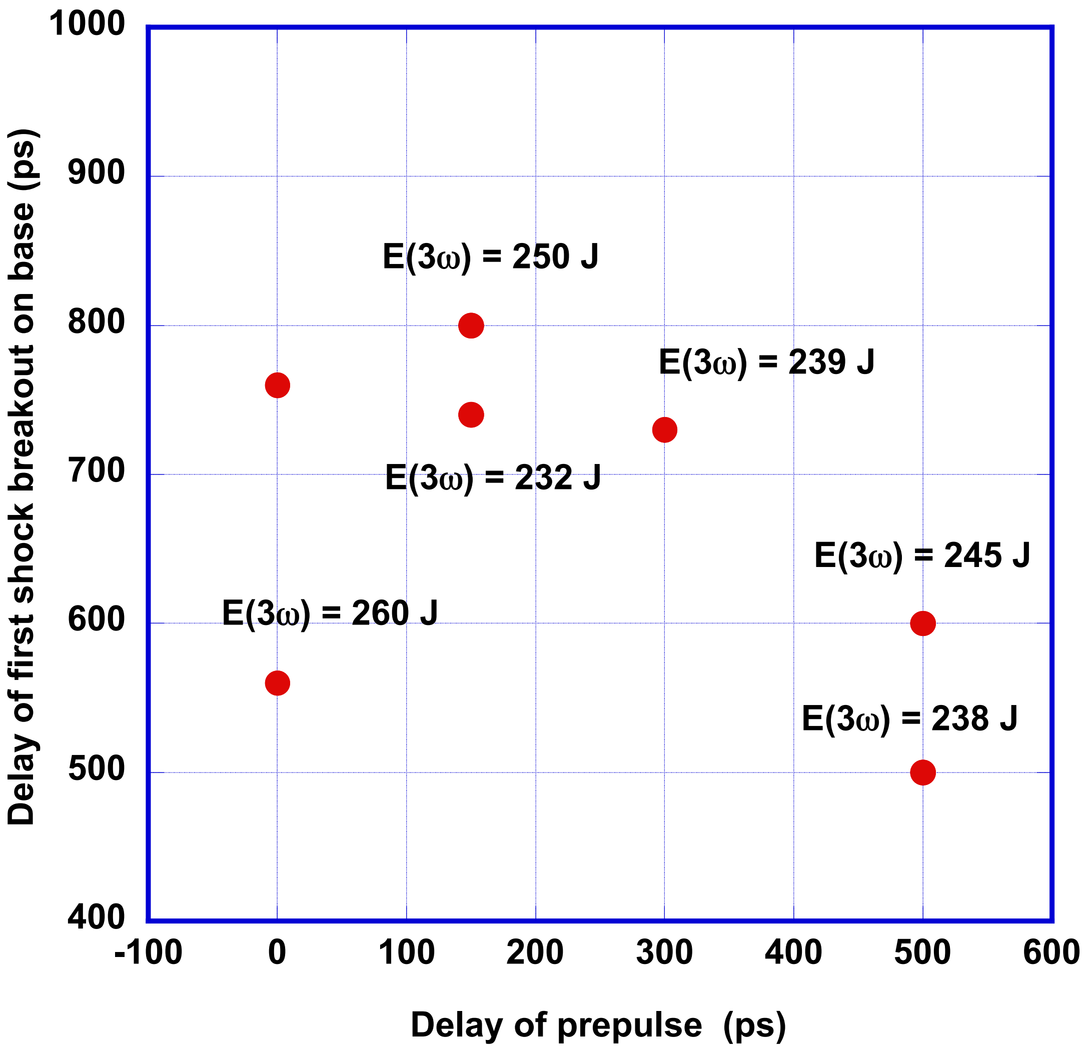
Shock chronometry



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.

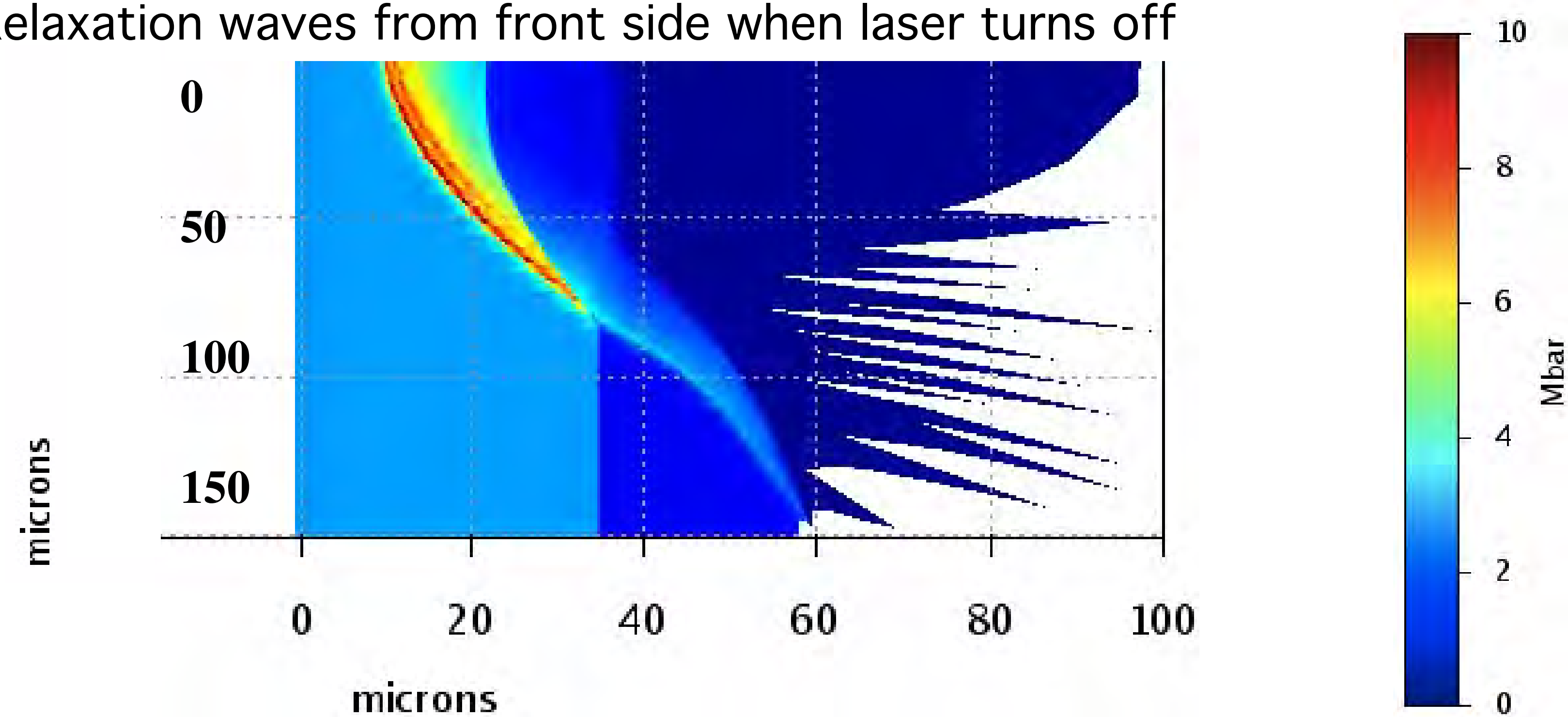
Value for $\Delta t = 500$ ps are every close to those without prepulse. The plasma is dispersed in 500 ps? (it does not seem to be supported by XRL deflectometry data nor by SRS data)

2D Hydro simulations

Low measured values of P is not in contradiction with expectations:

Shock pressure undergoes a rapid decrease due to:

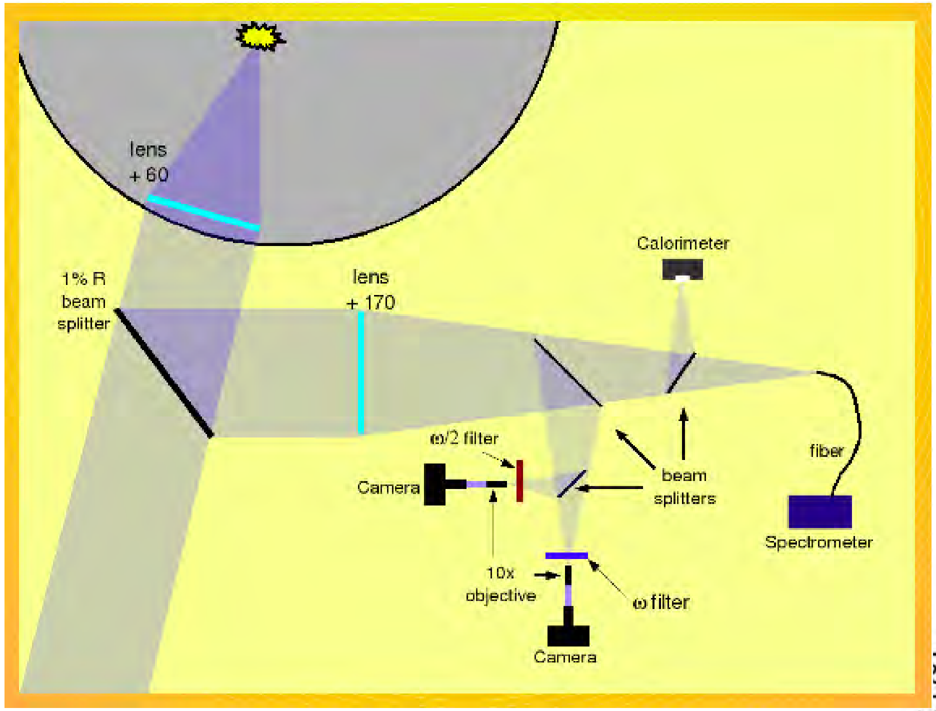
1) 2D effects during shock propagation
2) Relaxation waves from front side when laser turns off

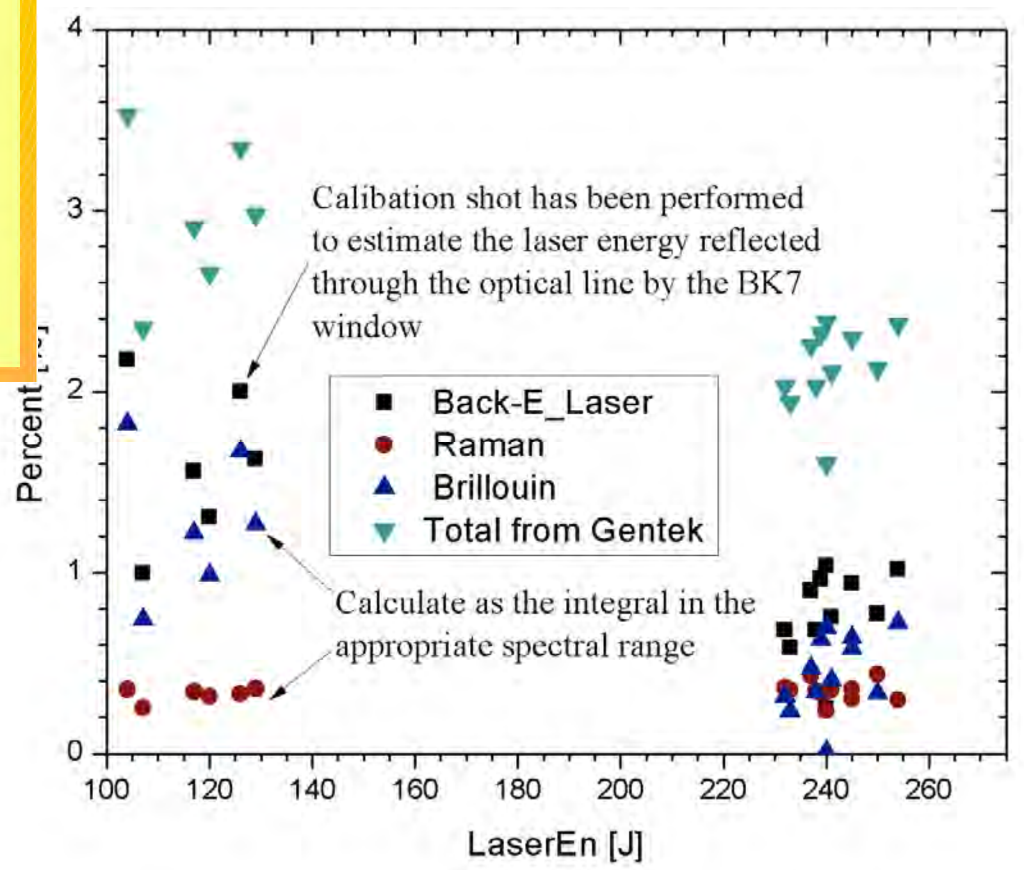


2D Simulation for I ≈ 2 × 10^{15} W/cm^2 and focal spot diameter ≈ 100 μm. Breakout time = 1 ns - 0.35 ns (time of laser max in simulation) = 650 ps [Tommaso Vinci, code DUED]

Final pressure ≈ 10 Mbar, Initial Pressure ≈ 100 Mbar, in agreement with laser intensity used in simulation

Back scattering diagnostics

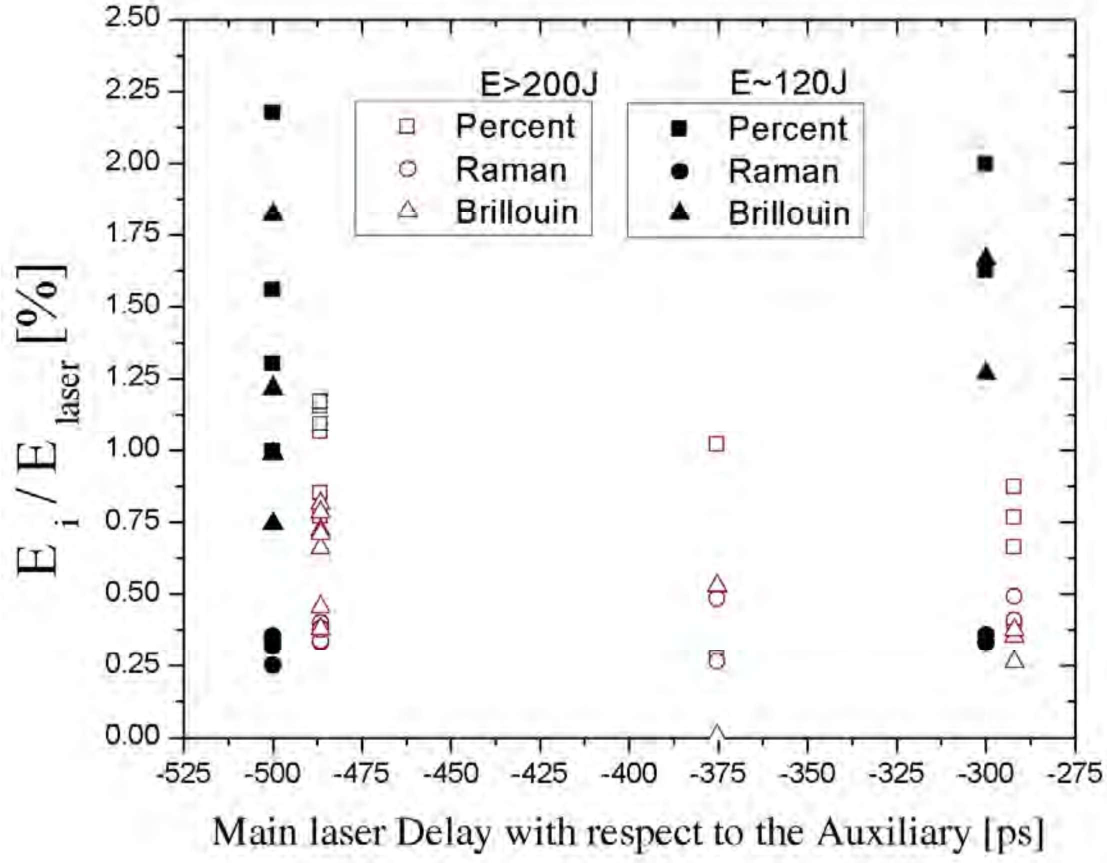




Back scattering: calorimetry

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

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



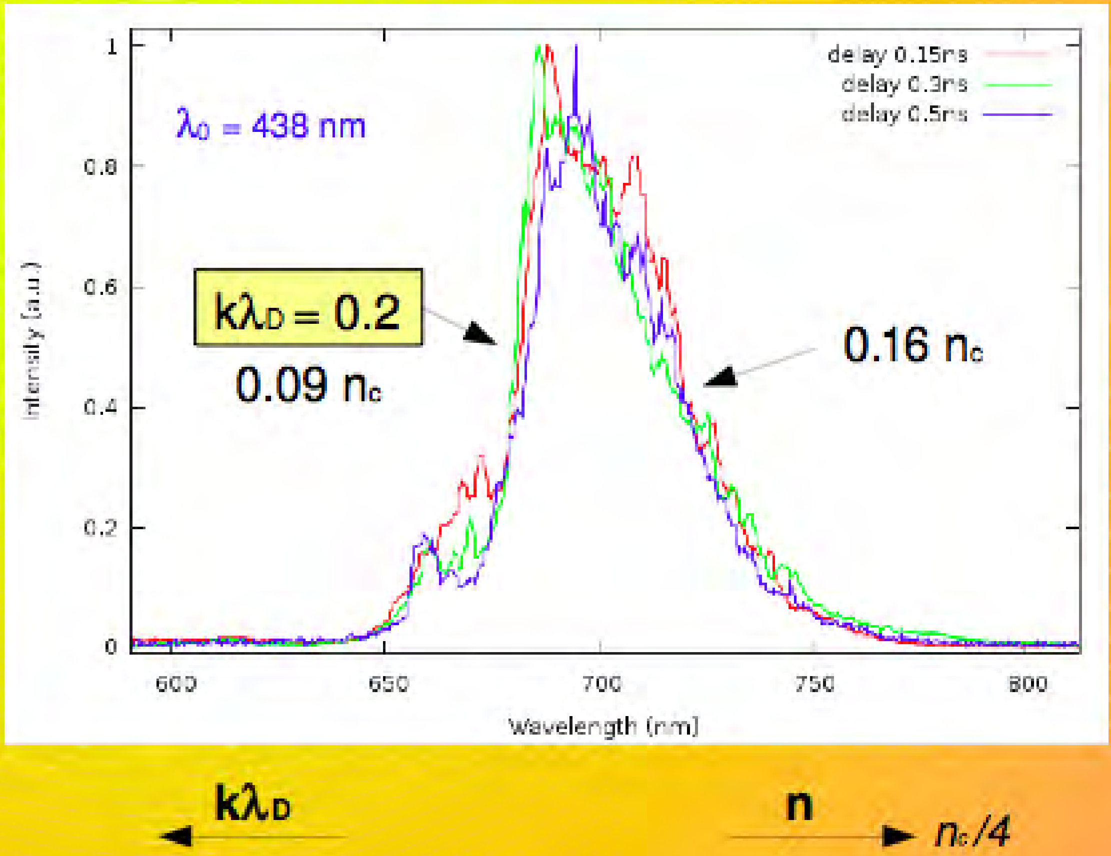
WORK IN PROGRESS...

Back scattering: spectroscopy

- **SRS**
  - **Emission between ω ($n \sim 0$) 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**



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

Conclusions

• The preplasma and the interaction of the main beam have been characterised using several diagnostics. Analysis of results still in progress

• 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. This could be in agreement with low laser wavelength,and coupling at low density

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

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

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

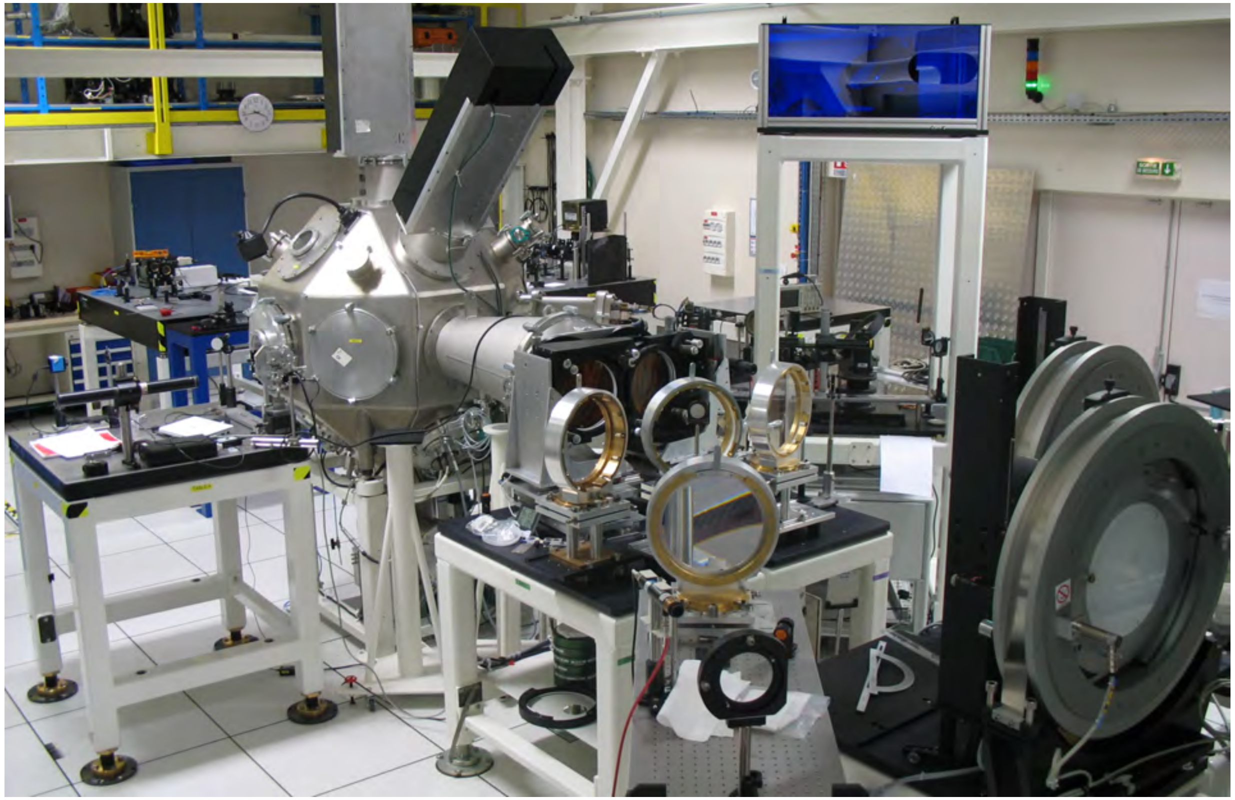
Do our results point out to the presence of different transport mechamisms and hence a different scaling of shock pressure vs. laser intensity?

FINALLY ...  WORK IN PROGRESS... !!

First experiment at LULI towards shock ignition feasibility

The new target area "Salle 2" at LULI gives the possibility to use two beams almost colinearly

- **experiment in a planar geometry**
  - **one beam to generate a first shock and create a large plasma**
  - **second beam for the "spike"**



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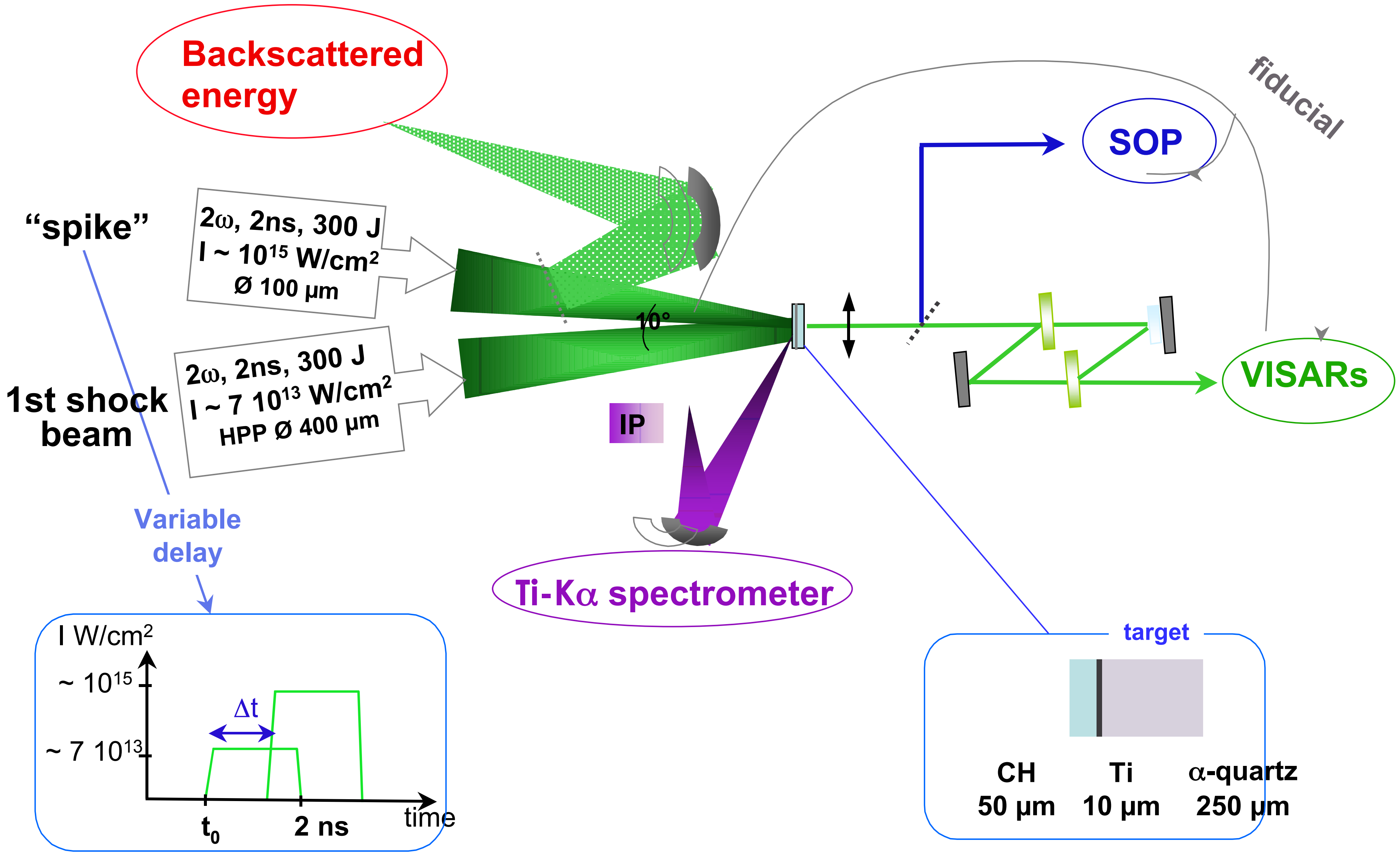
Set-up : rear side & backscattered diagnostics



2D hydro code to take into account 2D effects for the 2nd beam

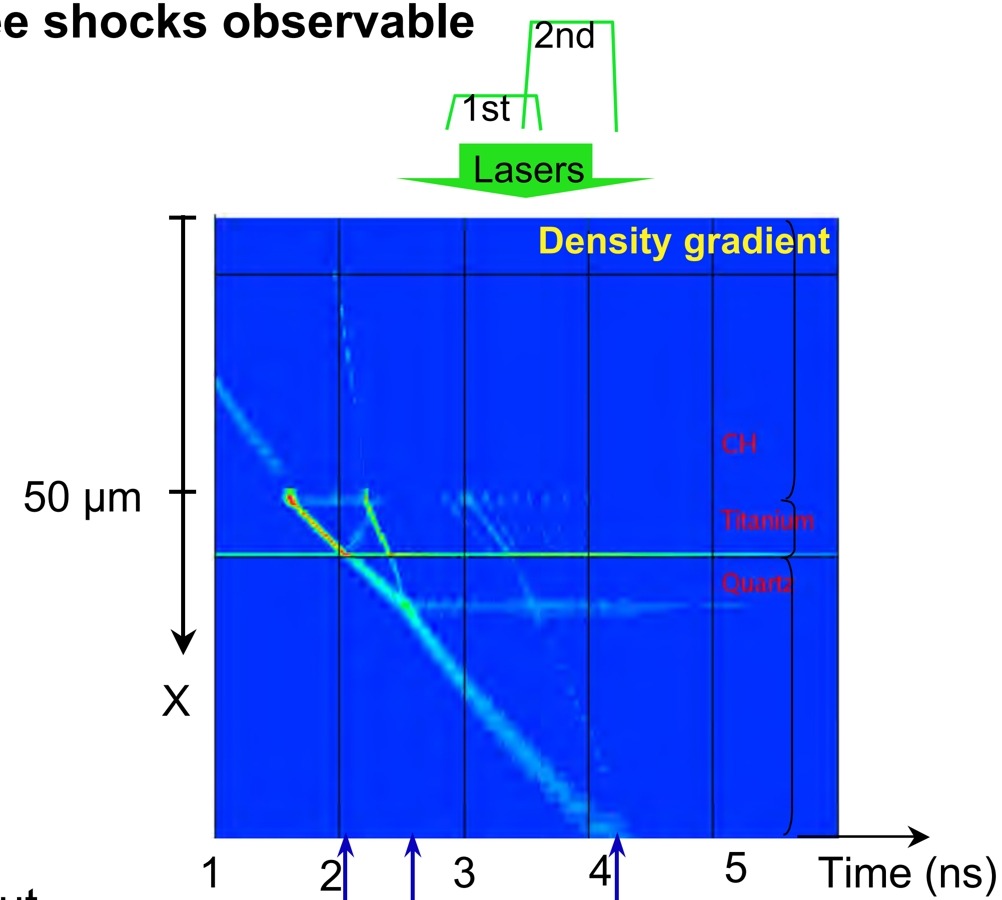
➡ **up to three shocks observable**

Laser parameters :

$I_1 = 7 \times 10^{13}$ W/cm2

$I_2 = 1 \times 10^{15}$ W/cm2

$\Delta t = 1.7$ ns

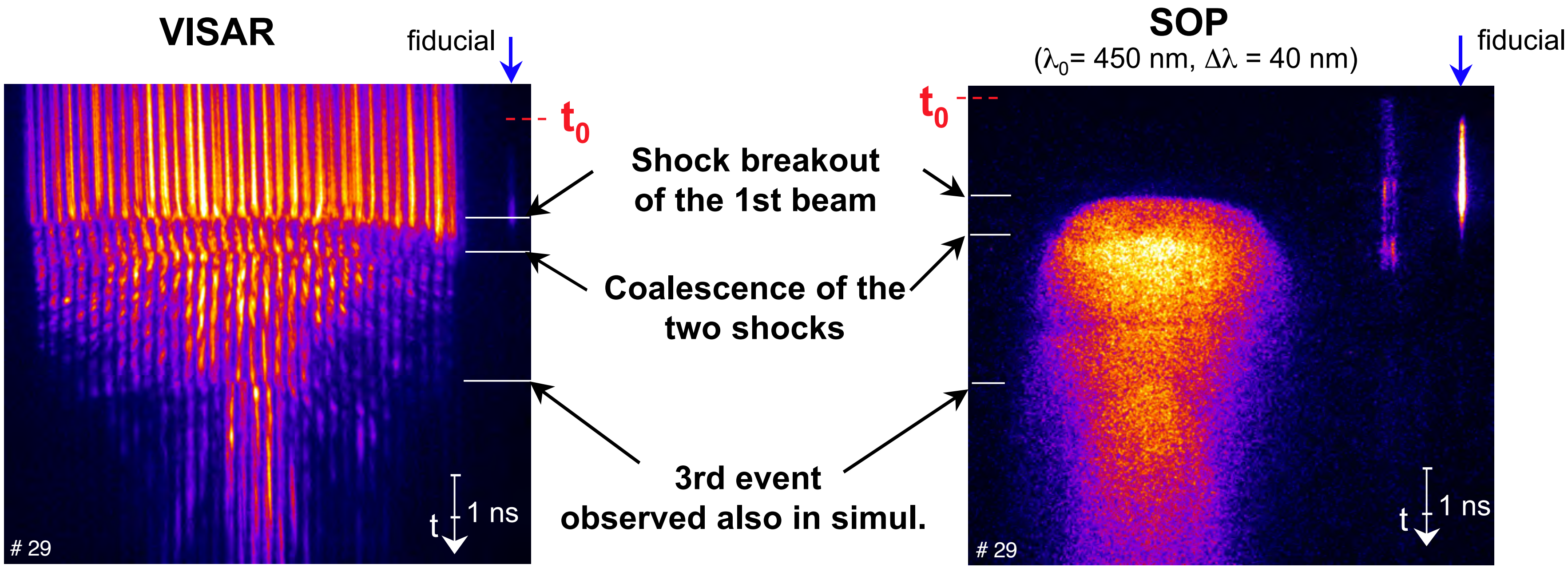


shock breakout of the first beam from Ti

Coalescence of the two shocks

3rd event due to reflection between Ti-Quartz interface and ablation front

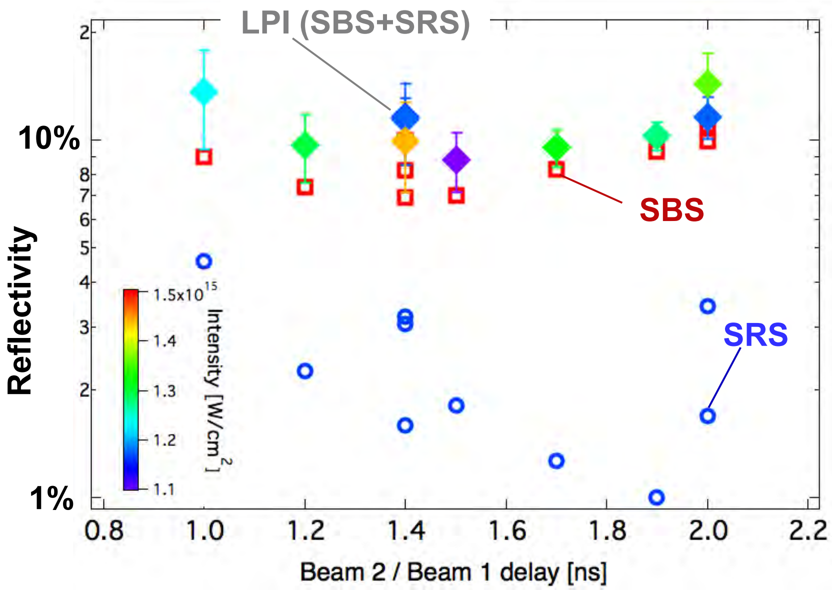
Experimental results and comparison with 2D code (FCI2)



	time / t_0	shock speed	*time / t_0*	shock speed
breakout	2.05 ± 0.05 ns	25 km/s	2.05 ns	25 km/s
coalescence	2.9 ± 0.1 ns	30 km/s	2.57 ns	32 km/s

- ✓ **Good agreement on the 1st shock breakout**
- ✓ **Coalescence time from code too early**
  => importance of backscattered energy ?

15% of backscattered energy (LPI) for the "spike"



Reflectivities ***(in focalisation cone)***

SBS : 7 - 11 %

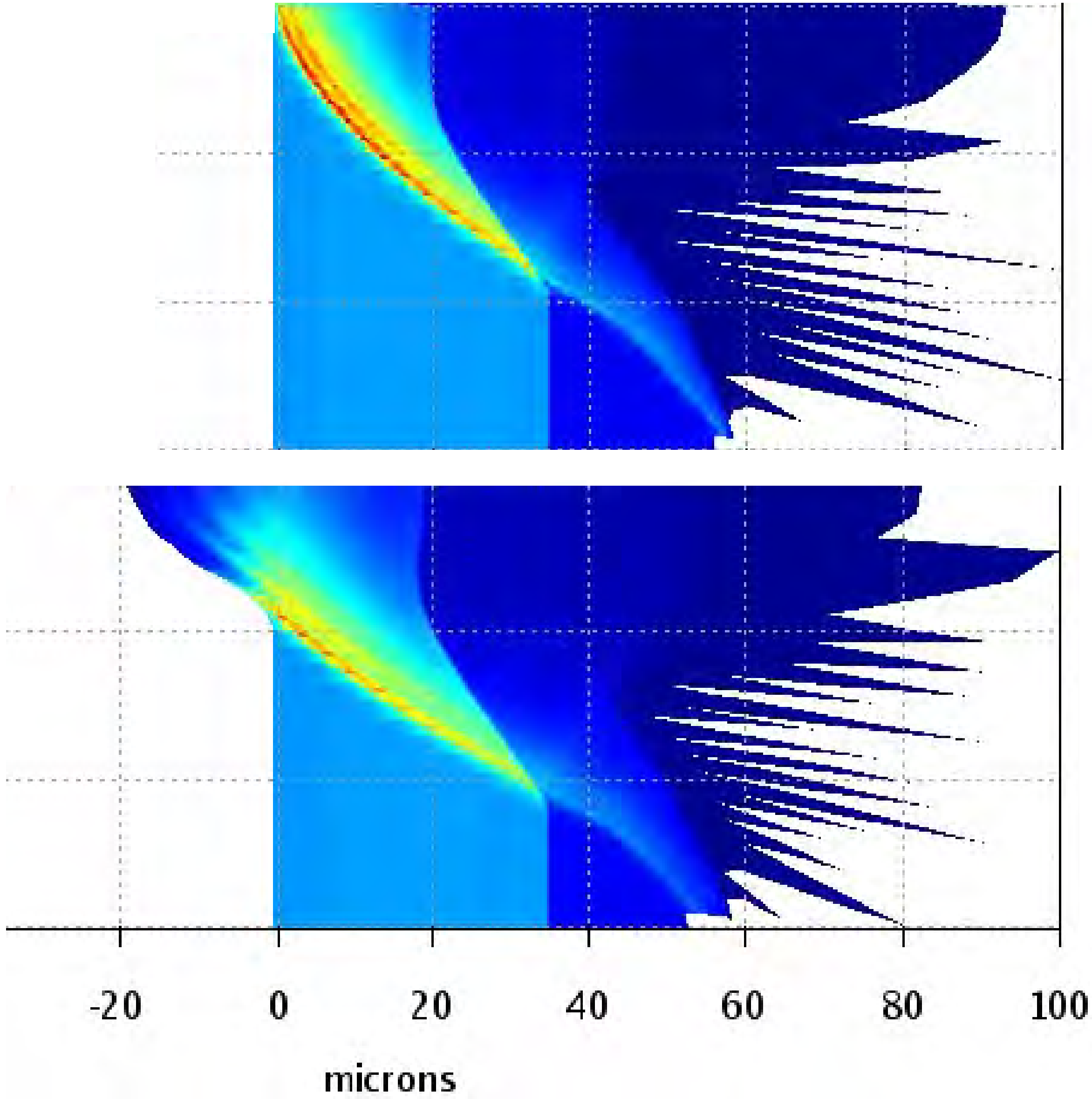
SRS : a few %

Backscattered energy from LPIs up to 15 % doesn't explain this slight discrepancy

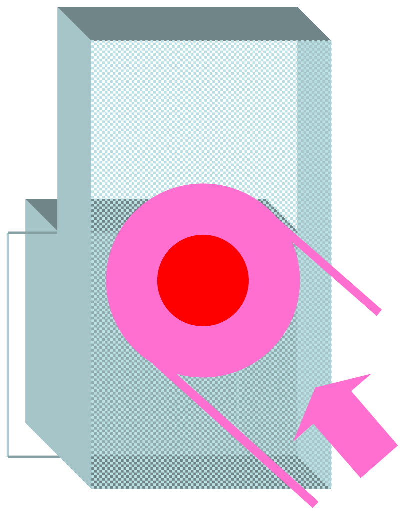
HiPER

Thank you!!

2D Hydro simulations



However break out of shock is not reproduced (too slow!!) unless we consider a displacement of laser focal spot with respect to step (as indeed observed in the experiment due to set-up problems...)



On axis
1290 ps ⇨
Δt = 290 ps

50 μm
off- axis
1710 ps ⇨
Δt = 710 ps