Frequency-domain interferometry for laser-produced plasma diagnostics

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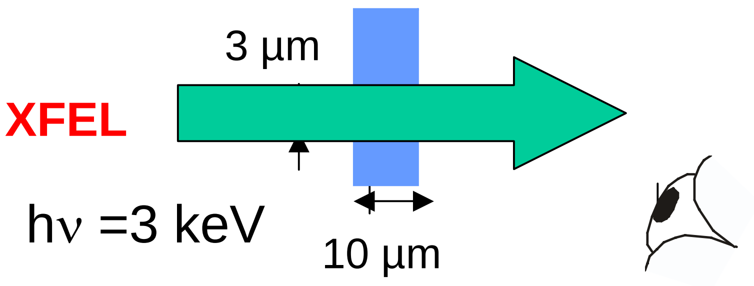
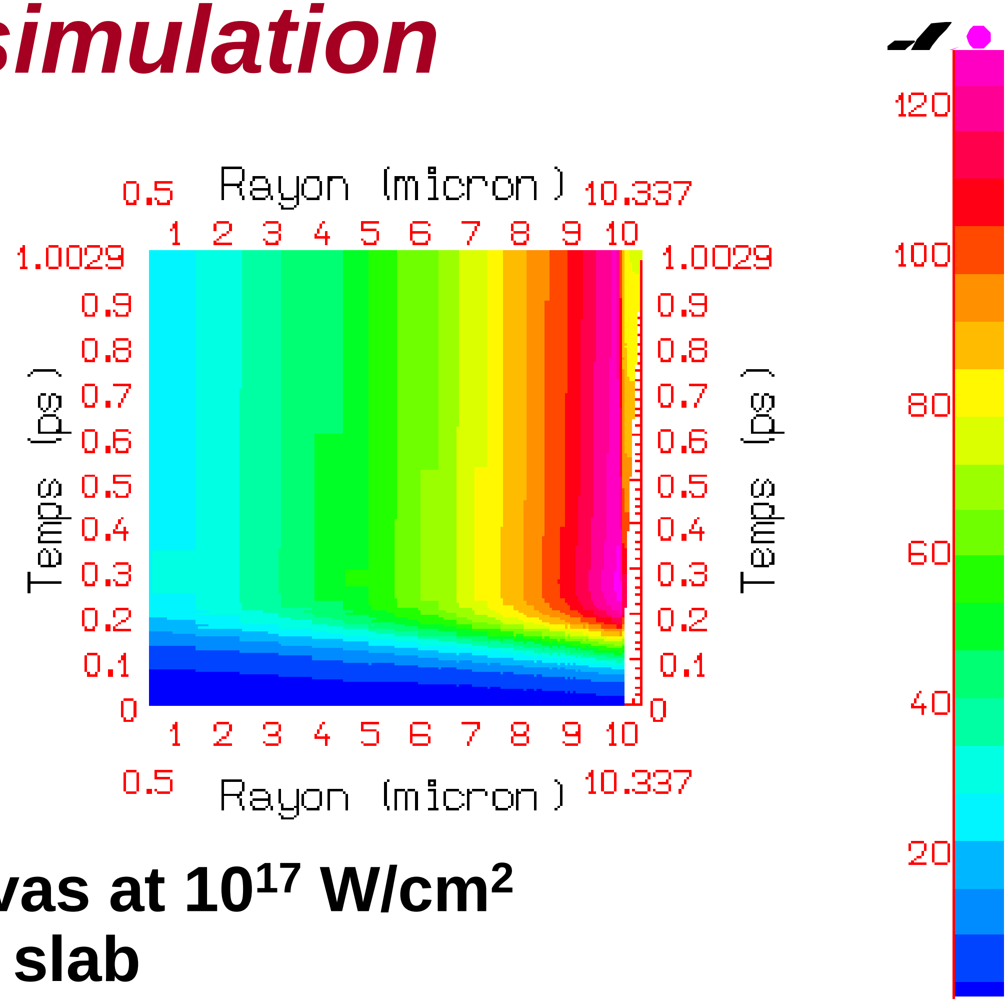
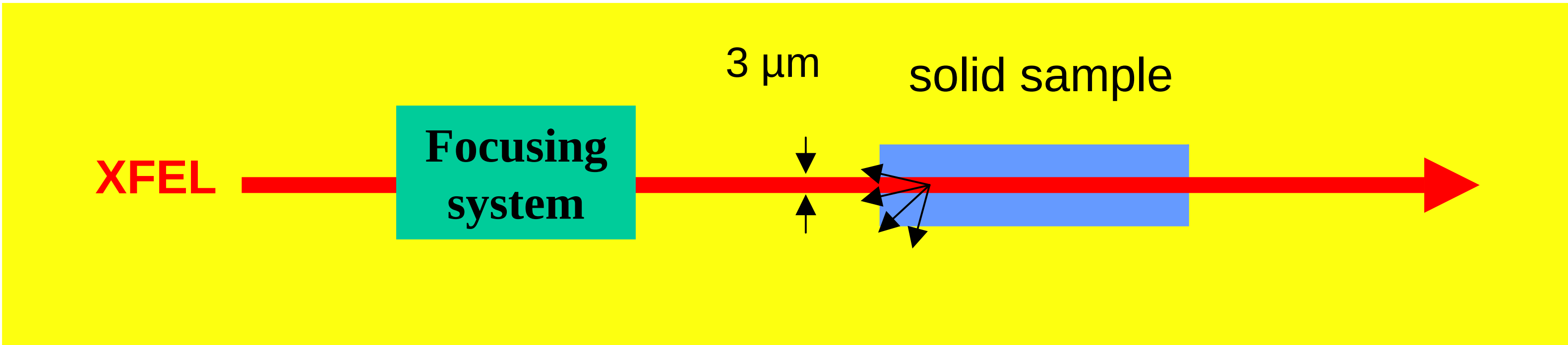
XFEL Preliminary simulation





- **Hydrodynamic 1D Code Chivas at 10^{17} W/cm^2 hν =3 keV, 100fs on 10µm Al slab**
- **Assuming we focus to a 3µm focal spot**
- **Target at solid density is heated up to 120 eV for more than a ps**

Single beam experiment



Measurement
- X-FEL Scattering spectrum (Thomson)
- Transmitted energy (absorption)
- Plasma emission spectrum X-ray, XUV
  time resolved (ps)

•**Reflectivity measurement**

•Pump probe experiment

Interferometry in Frequency Domain

- Plasmas produced by high intensity laser are characterized by very short lifetime, very steep gradients, and small lateral dimensions.
- Different techniques as been used to have information of the plasma in time and space

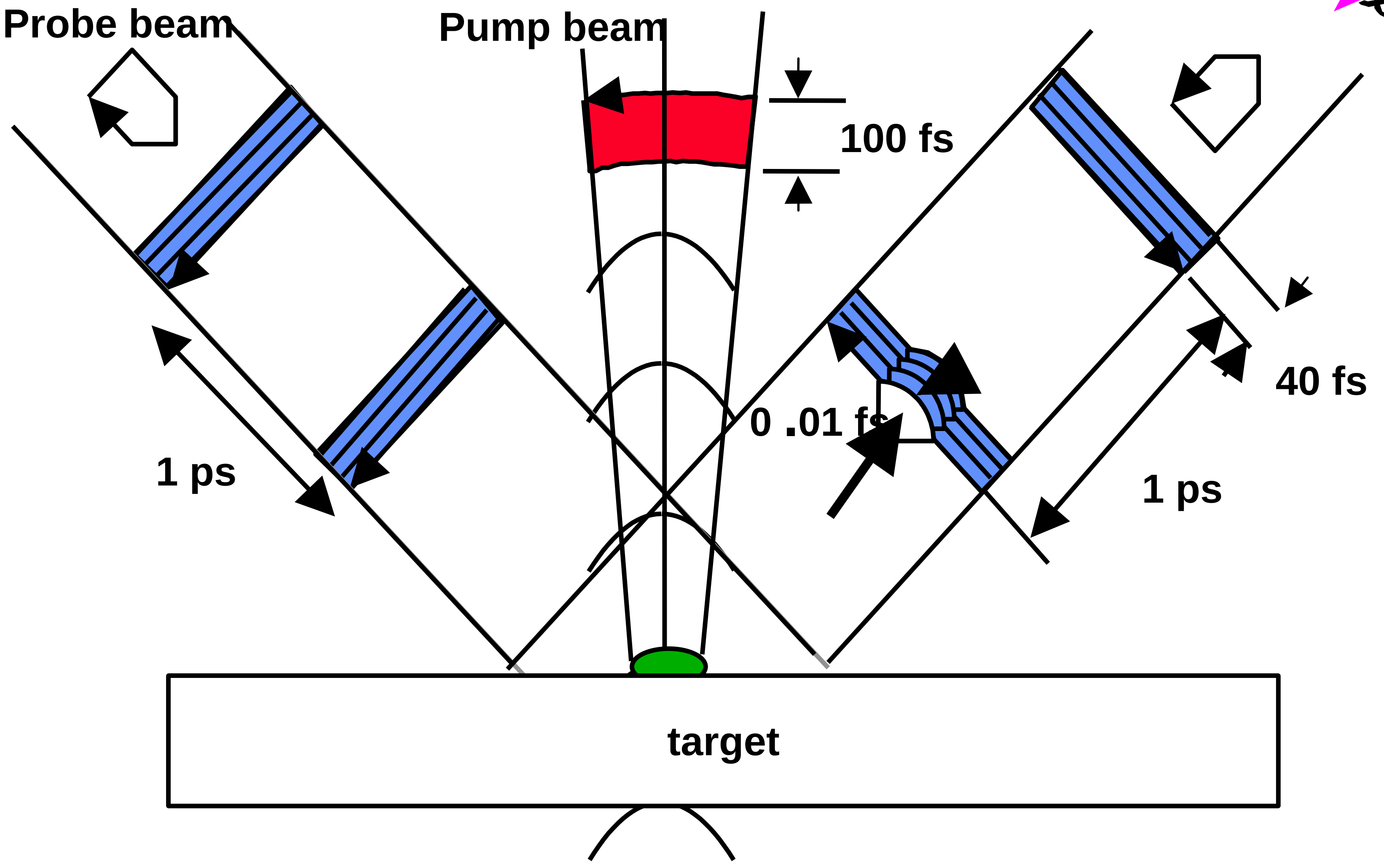
  reflectometry, Schlieren, ombroscopy, 2nd harmonic, spectral shifting ….

but record only change of amplitude of the probe.

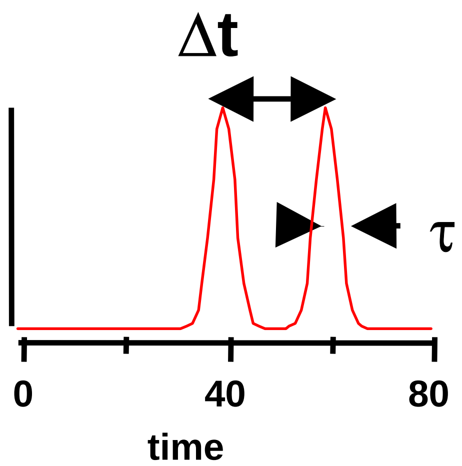
- We have developed a technique :

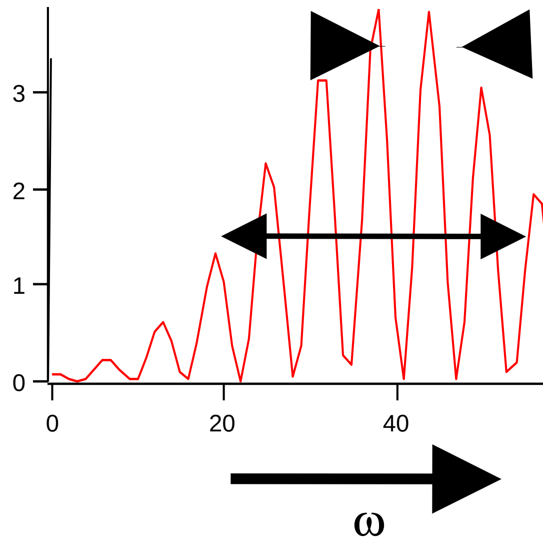
  the Interferometry in Fréquency Domain to access to both amplitude and phase of the probe.

Spectral interferometry



Phase-Space Interferometry





$\Delta\omega = 2\pi / \Delta t$

$\delta\omega = 1 / \tau$

$$\left.\begin{array}{l} E_1(t) = E_0 .\ e^{i\omega_0 t} \\ E_2(t) = R.\ e^{i\varphi}.E_0(t).\ e^{i\omega_0 dt} \end{array}\right\}$$

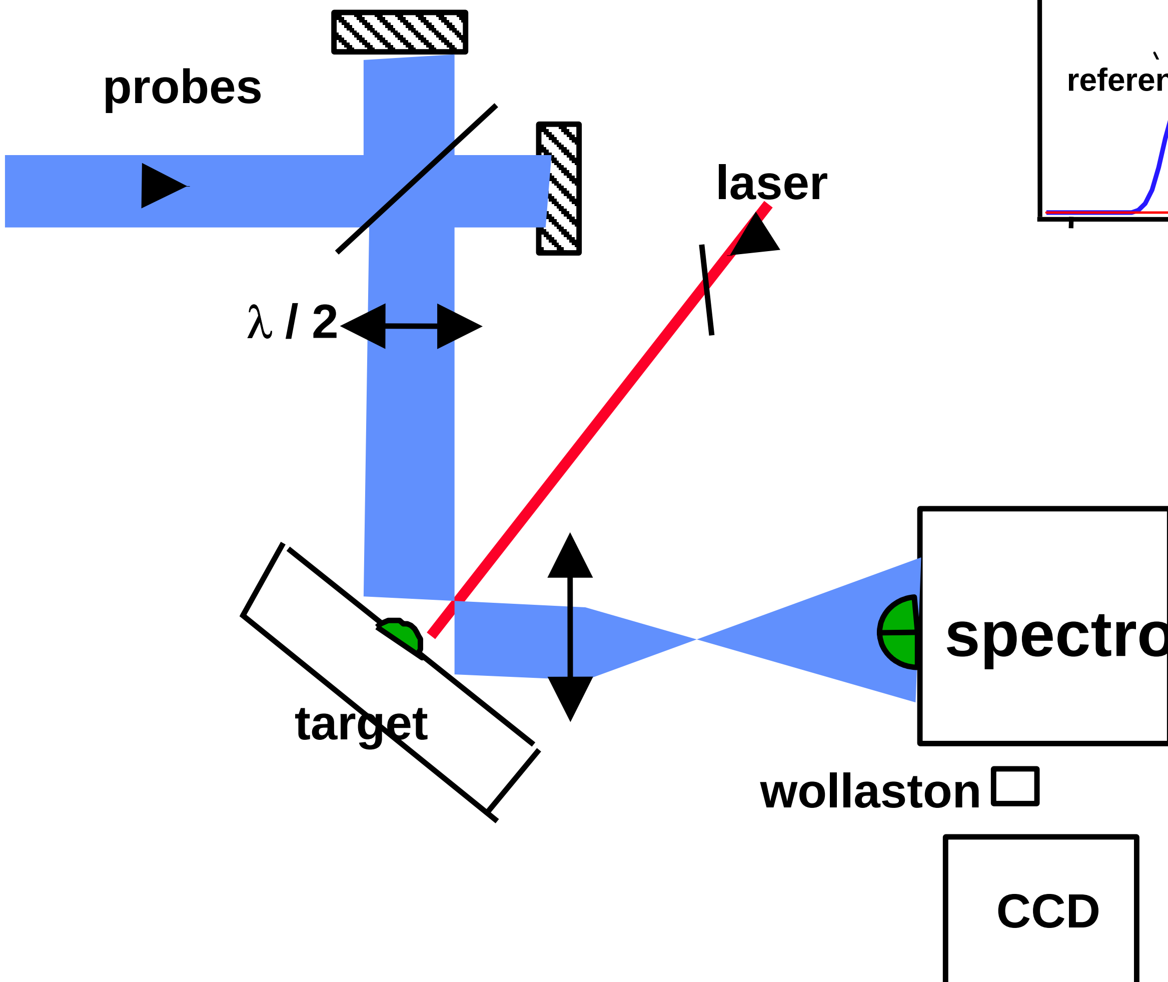
The Spectrum is

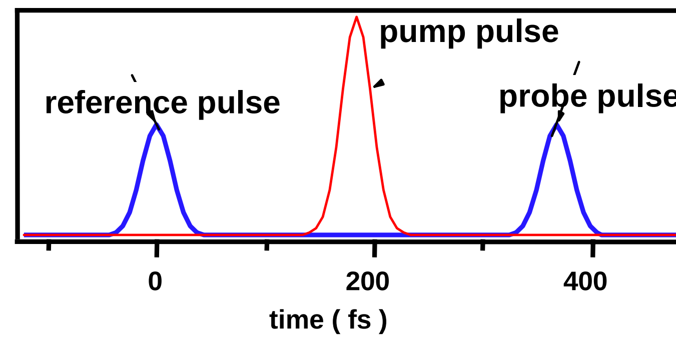
$$S(\omega) = I_0(\omega).\{1 + R^2 + 2R.\cos(\omega.\Delta t + \varphi)\}$$

the interfringe separation is inversely proportional to Δt where Δt is the time interval between the twin probe pulses

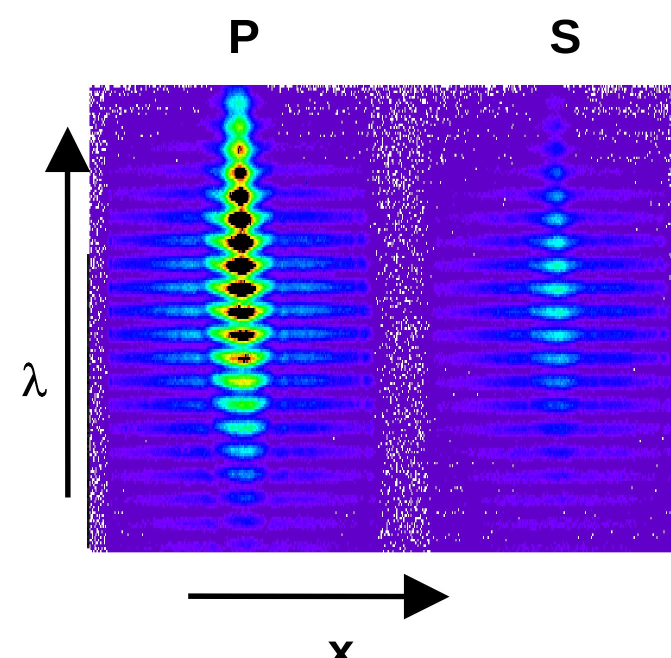
Experiment set up

Focal spot

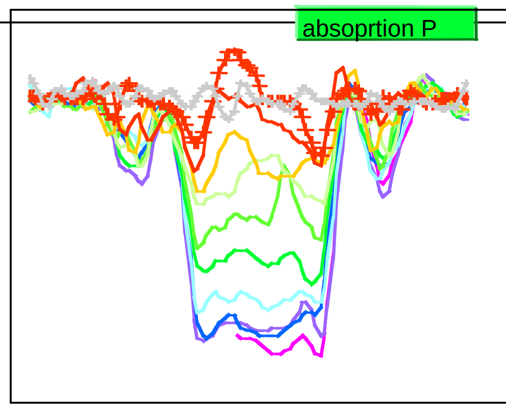




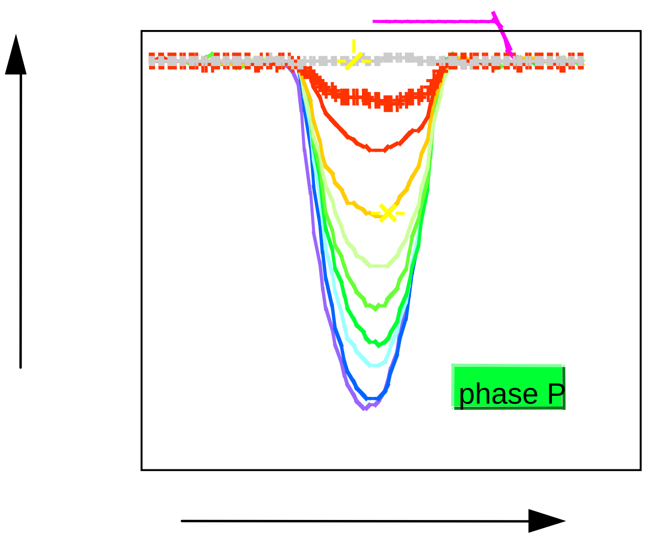
Polarization



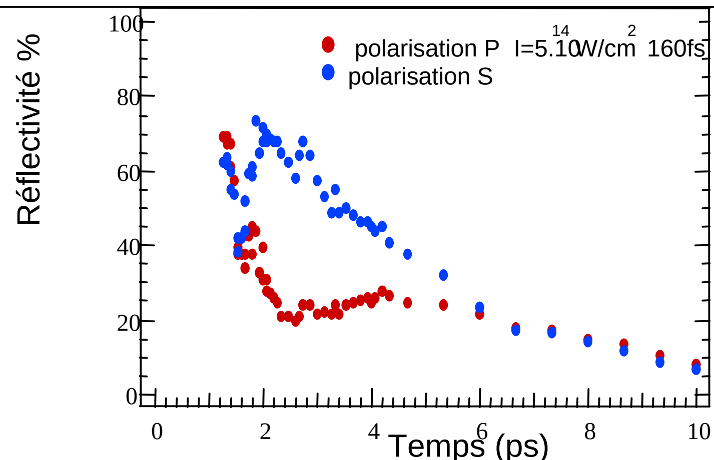
Experimentals RESULTS : time and space resolved for two polarisations

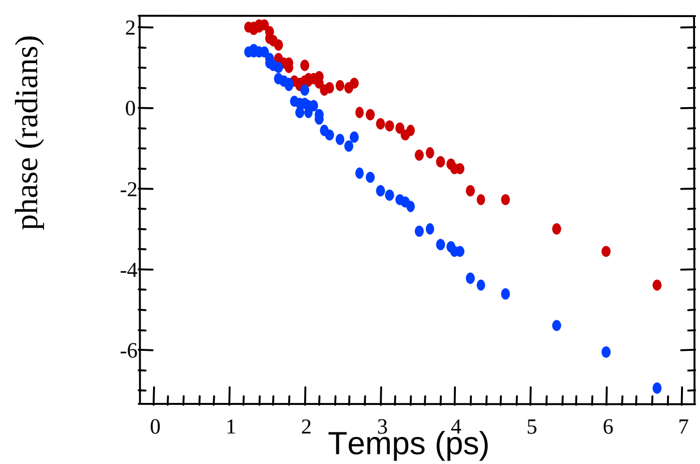


amplitude



spatial 1pixel=1.5 μm





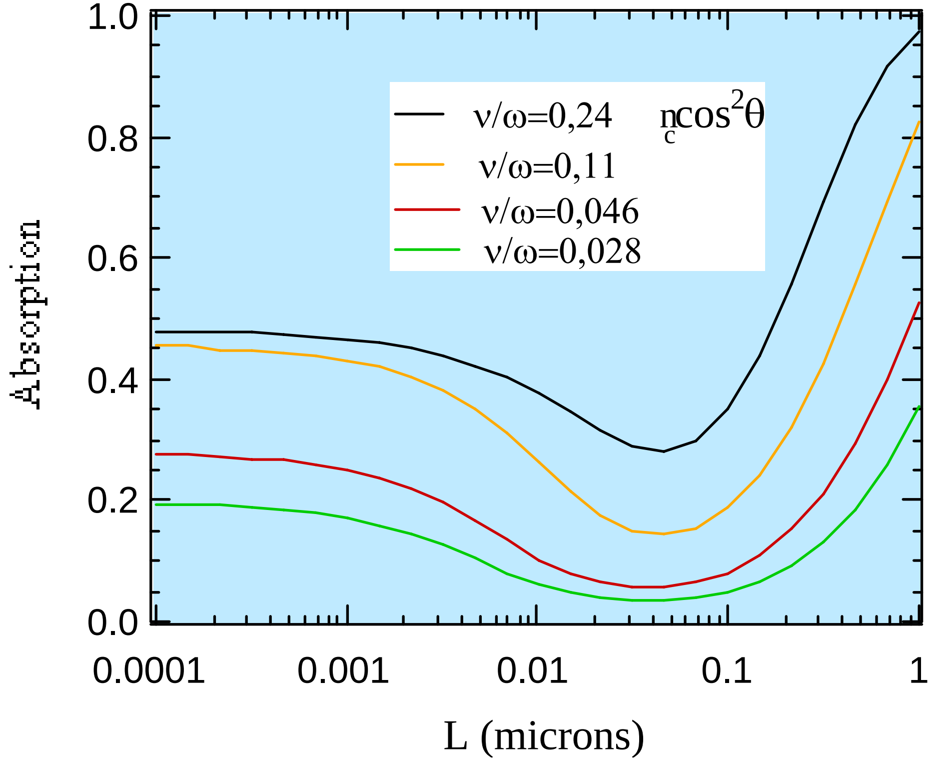
aluminium target

I = 5 10^{14} W/cm^2

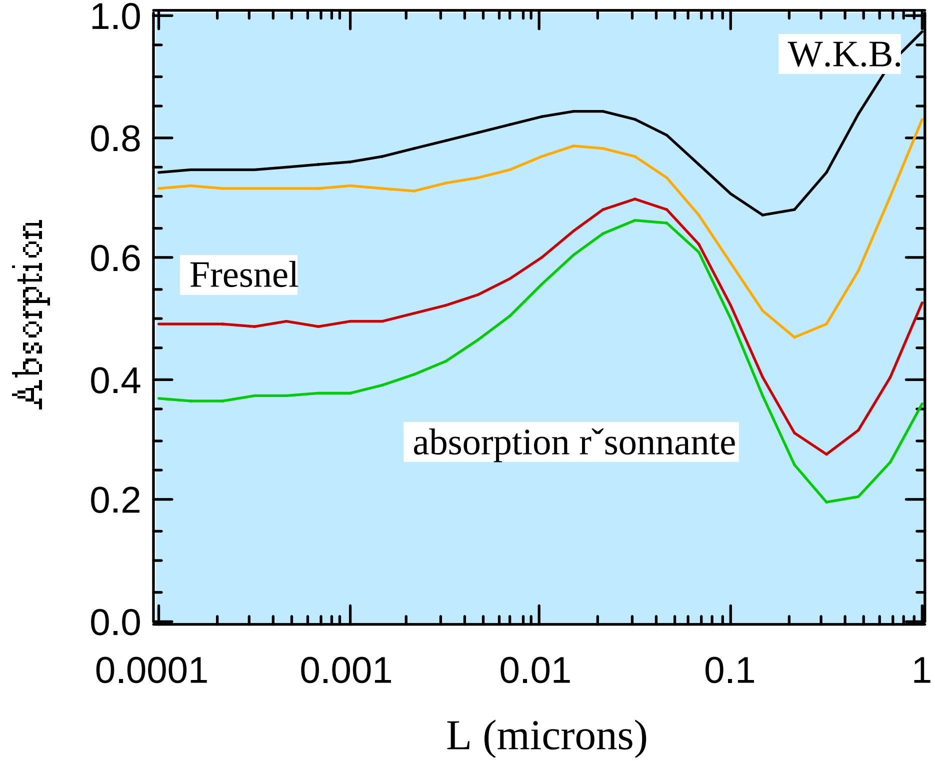
using an electromagnetic solver :
Drude Model

absorption **is function of:** **the electron density gradient L**
- collision frequency ν

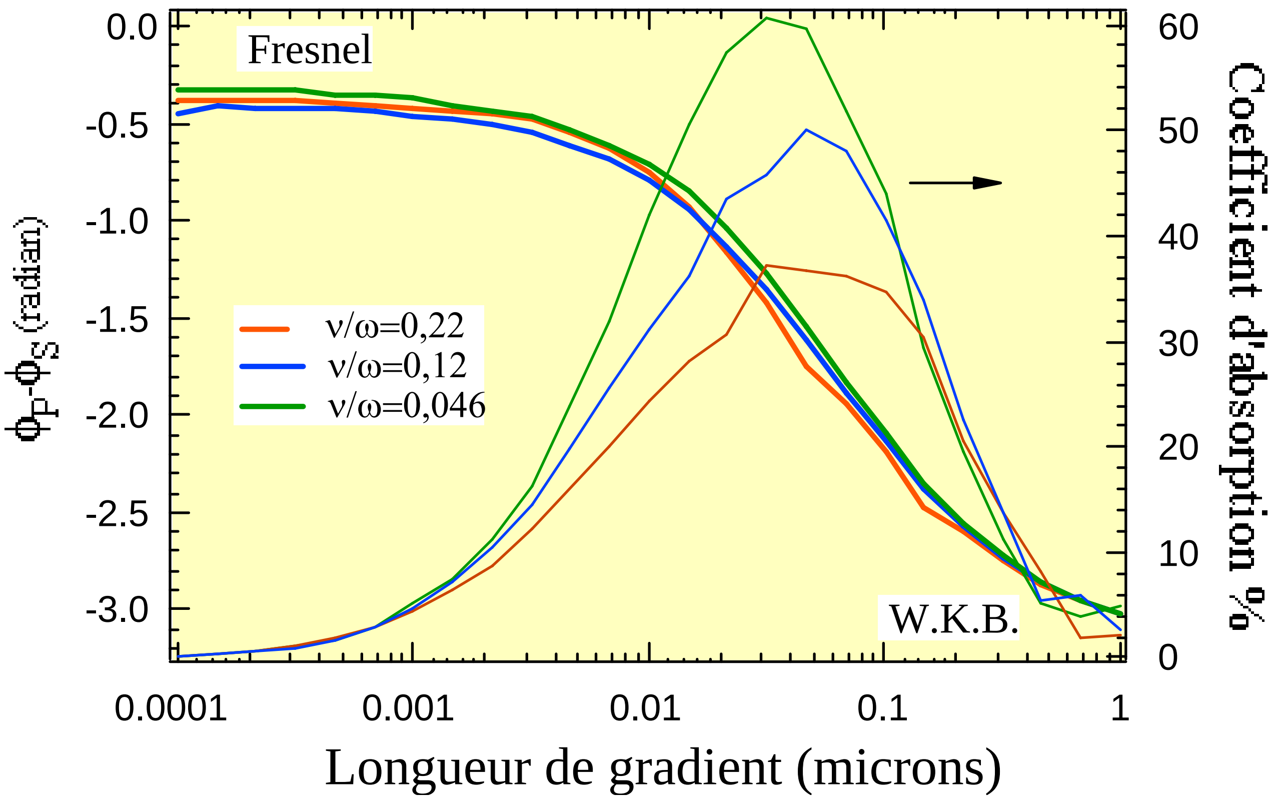
POLARISATION S



POLARISATION P



Gradient length measurement using polarisation phase difference



ϕ_P(t)-ϕ_S(t)=> density gradient L

mesure nearly independant of the collision frequency

Characterization of the hydrodynamique expansion

$\Phi_P(t)$ - $\Phi_S(t)$

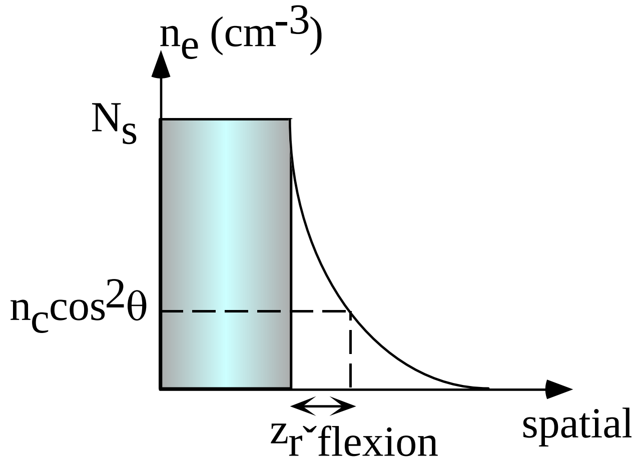
⇨

$$L = \left(-\frac{1}{n_e}\frac{dn_e}{dz} \right)^{-1}$$

Density gradient scale length

$\Phi_S(t)$

⇨



Position of critical density

$n_c\cos^2\theta$: $z_{réflexion}$

S and P polarisation phase measurement as function of time allow full characterization of the plasma

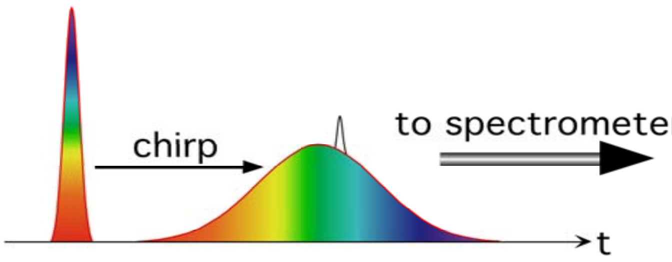
Spectral interferometry

- Spectral interferometry, also called Fourier-Domain Interferometry (FDI), is a well known linear optical technique for measuring the phase and amplitude modification of a laser pulse.
- This technique is now widely used in ultrafast laser-matter interaction experiments.

- But this pomp-probe technique give only one point in time for each shot

How to extend the twin pulses technique to single shot measurements?

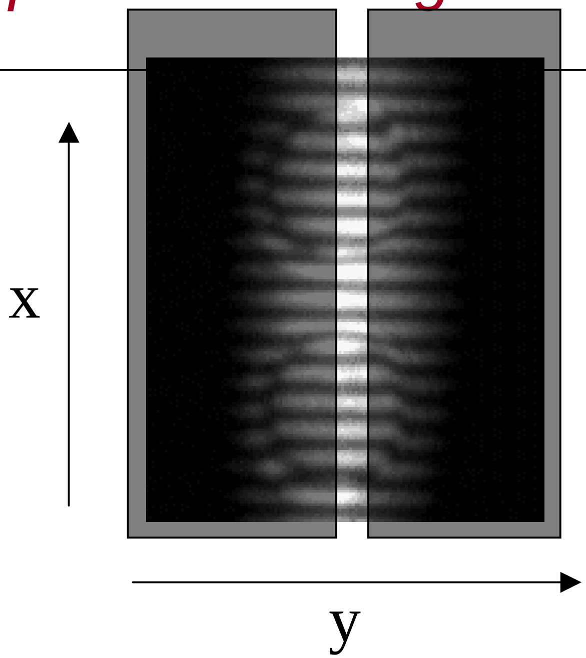
- The classical pump-probe method gives one point in time at each shot
- Single-shot measurements



FWHM Δt adapted to the temporal range

The phase and amplitude of the probe pulse are not independent any more

Single shot Fourier Domaine Interferometry: spatial interferogram



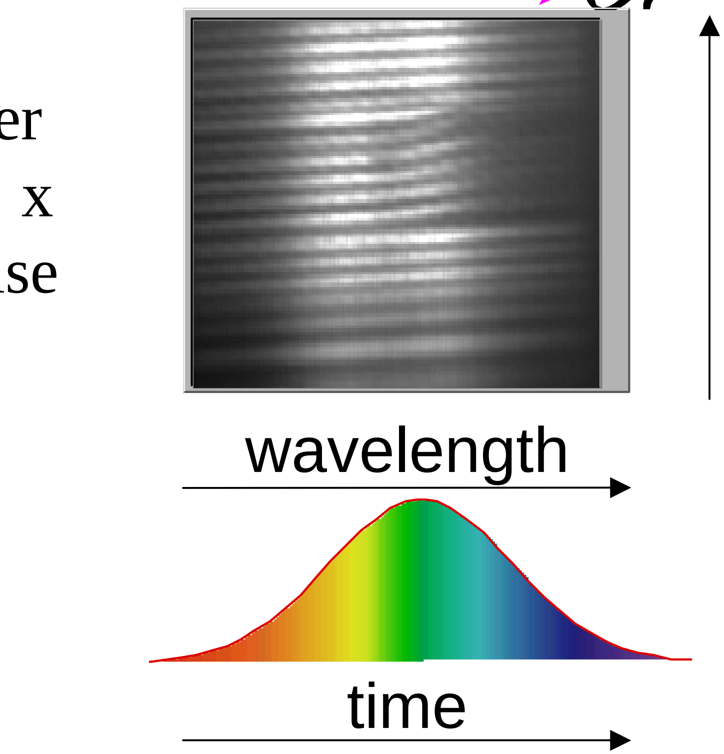
$\Phi(x,y)$

Spectrometer

$\Phi(x,\lambda)$

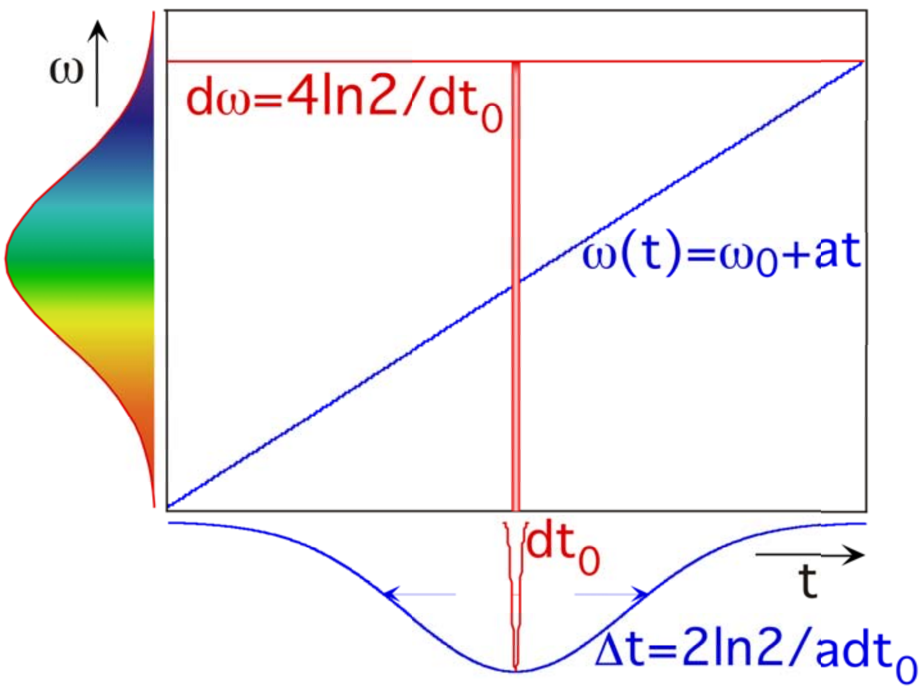
Chirped pulse

$\Phi(x,t)$



From the laser chirped interferogram image on a front of the spectrometer we get information of the phase of the probe pulse reflected on the plasma as function of time and space

Direct method :
Phase and reflectivity retrieval



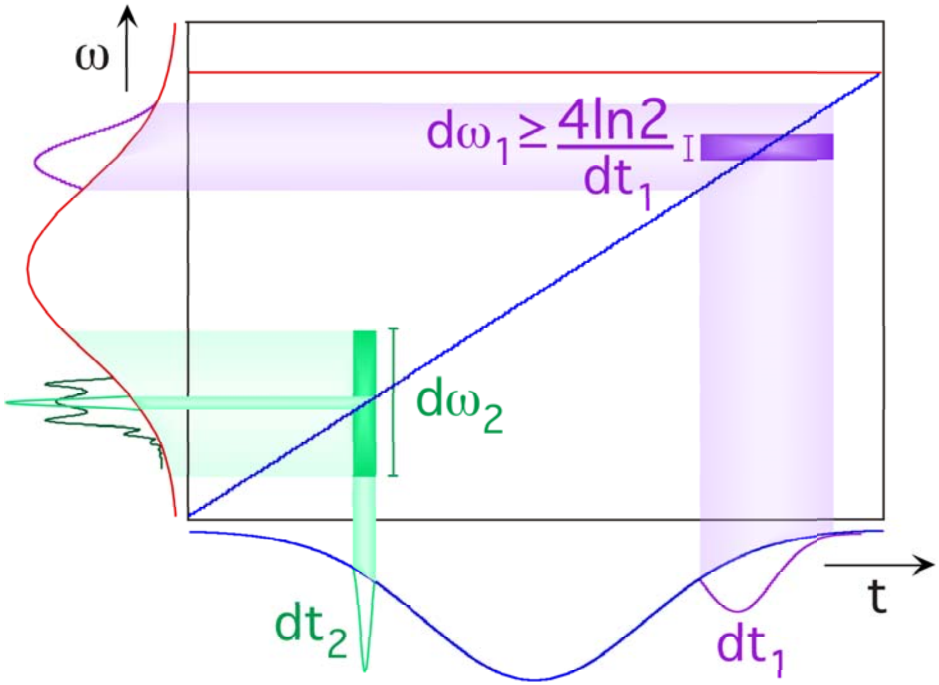
- **We measure the spectral phase and amplitude**
- **Reconstruction method when using chirped probe**
  - **Time-frequency relation**

$$\omega(t) = \omega_0 + at$$

- **Naïve way[1,2]**
  - **Spectral Frequency = Instantaneous Frequency**

[1] A. Benuzzi-Mounaix *et al.*, PRE **60**, n°3, 2488 (1999)
[2] C.Y. Chien *et al.*, Opt. Lett. **25**, n°8, 578 (2000)

Limits of the direct reconstruction
Need for a numerical method



- **Localization criteria of the perturbation dt**
  - ❖ given by the Fourier limit and the time-frequency relation

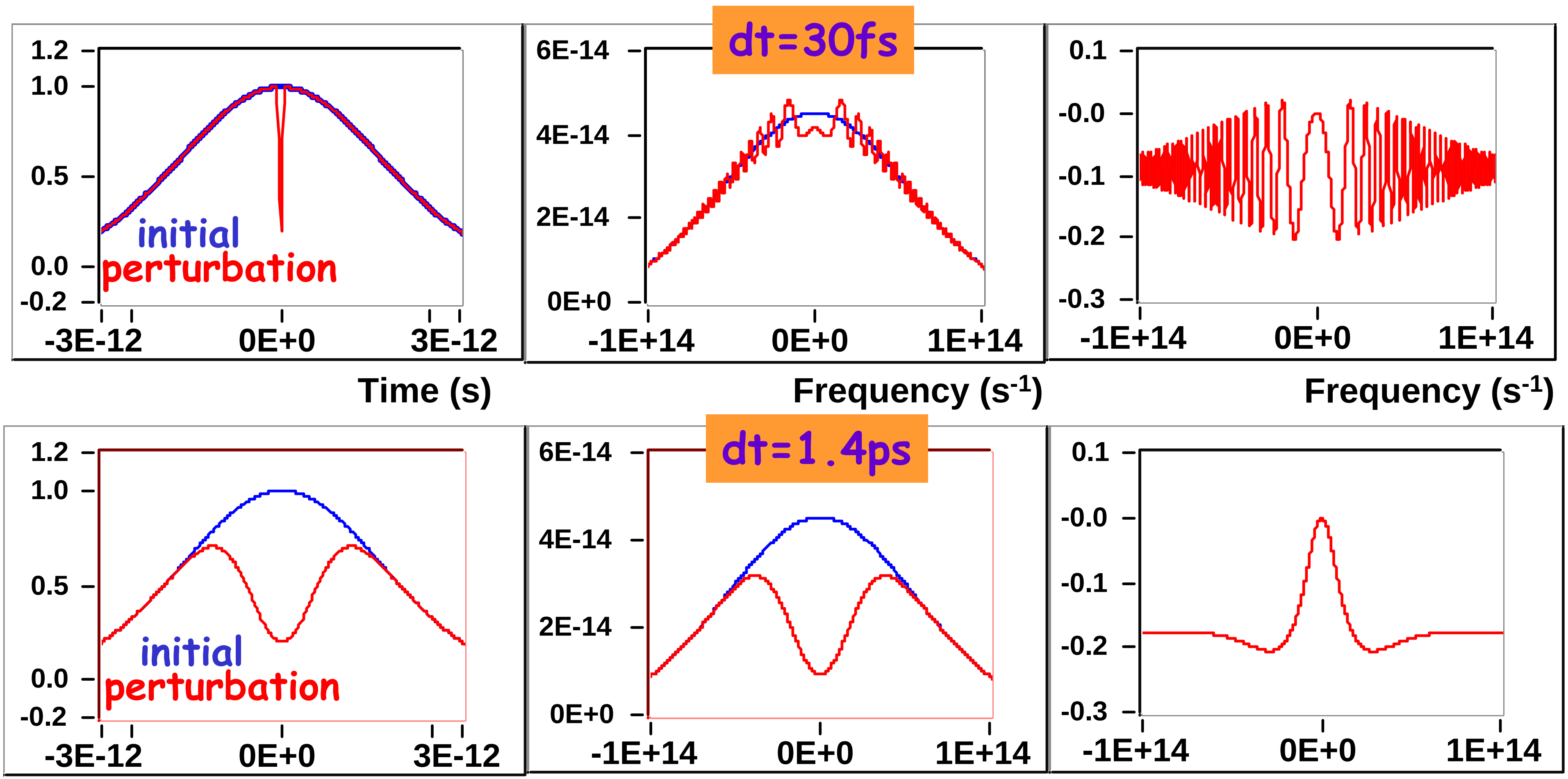
$$dt \,/\, dt_0 \geq \sqrt{2} \cdot \sqrt{\Delta t / dt_0}$$

A shorter perturbation will alter the spectrum on a large zone
The phase and reflectivity temporal modulations will mix up on the spectrum

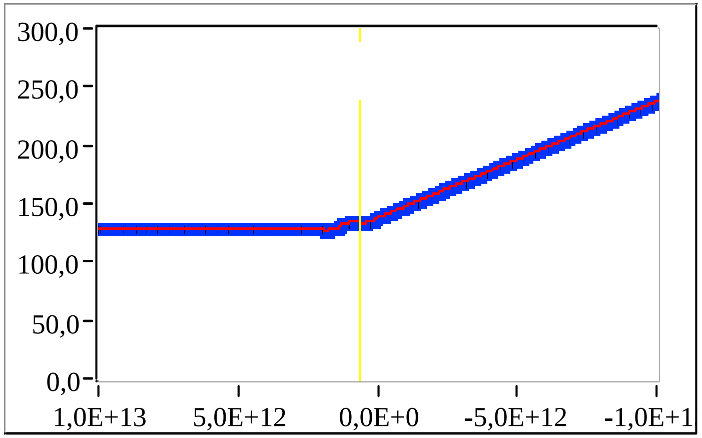
simulations

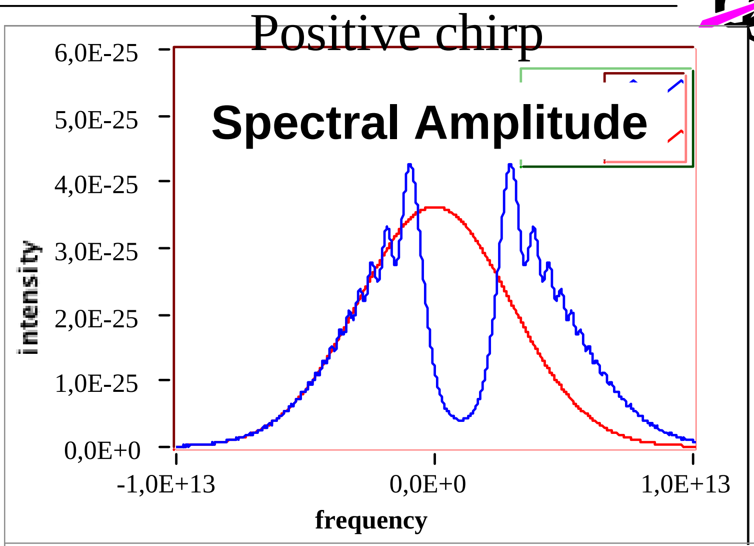
Amplitude Perturbation measure with a 30 fs probe chirp to 2.8ps

Time amplitude **Spectral Amplitude** **Phase spectrale**

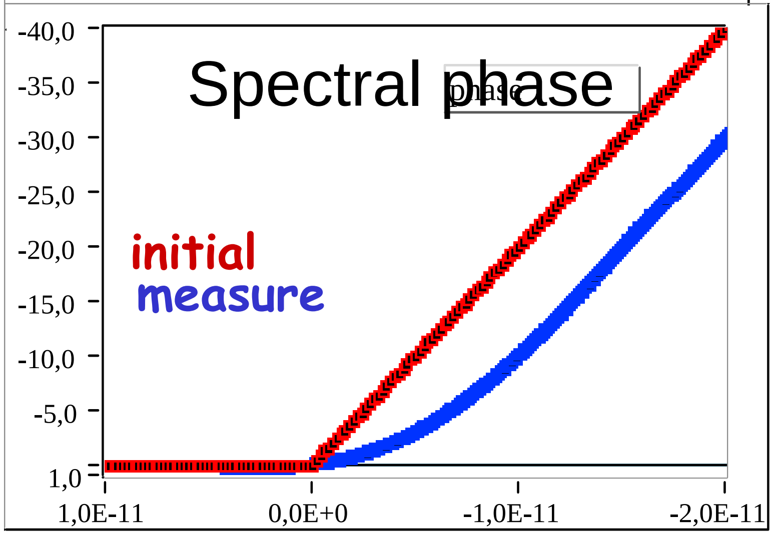


Simulations
Phase Perturbation measure with a 30 fs probe chirp to 2.8ps





When the phase perturbation is important there is a doppler effect which modify the measurement

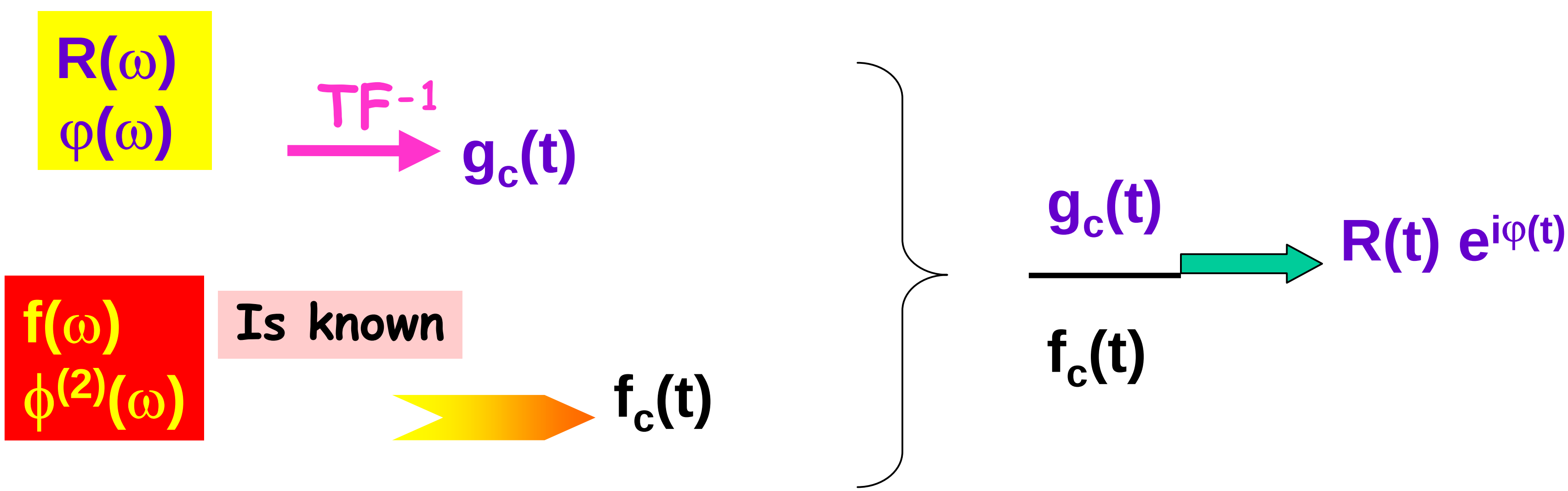


Amplitude and phase retrieval

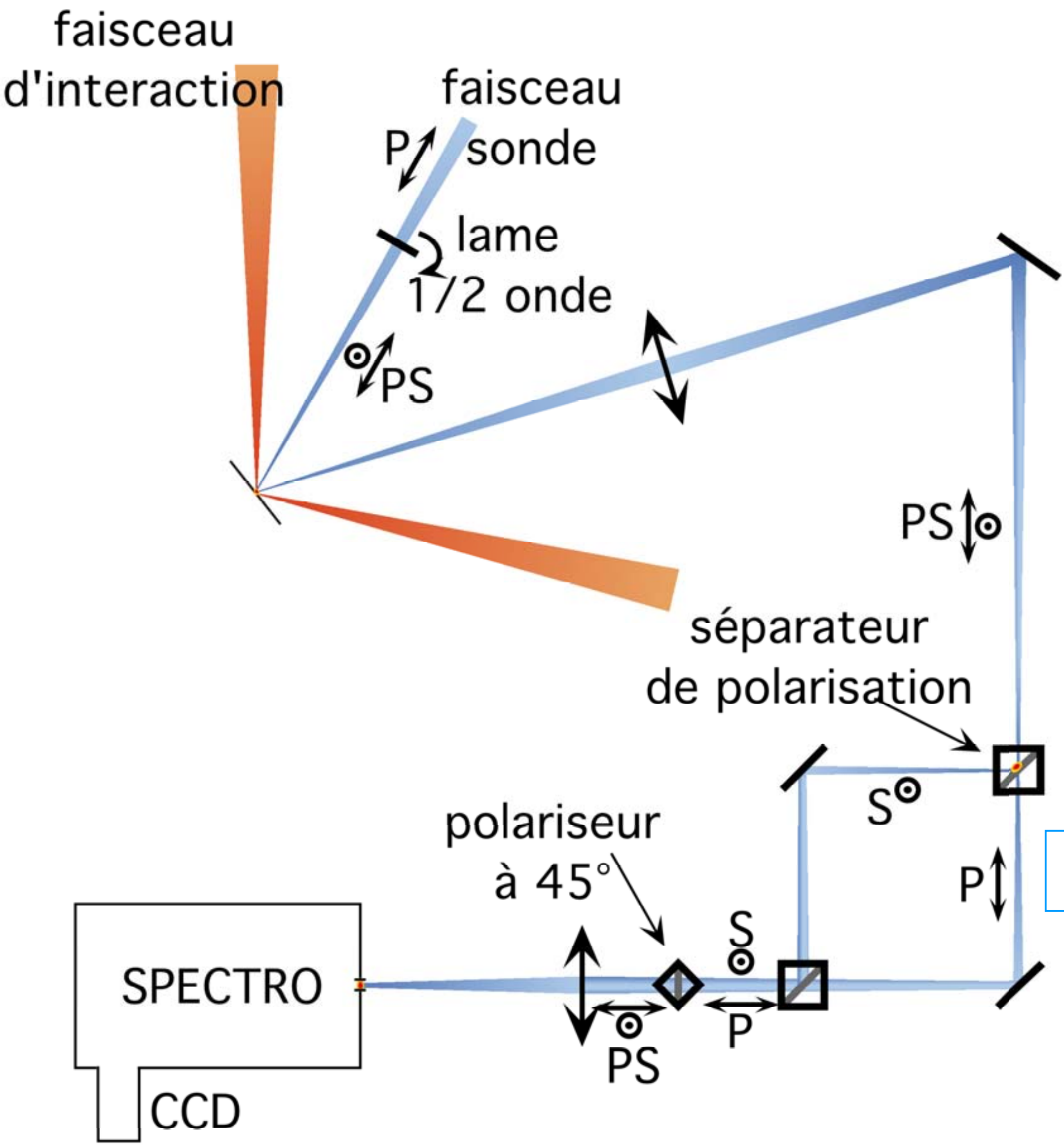
Initiale chirp probe $f_c(t) \Rightarrow f_c(\omega) = f(\omega).e^{i\phi^{(2)}\omega^2}$

Probe after the plasma $g_c(t) = f_c(t).R(t)\, e^{i\varphi(t)}$

- From the spectral interferometry we measure



Expérimental set up at LOA

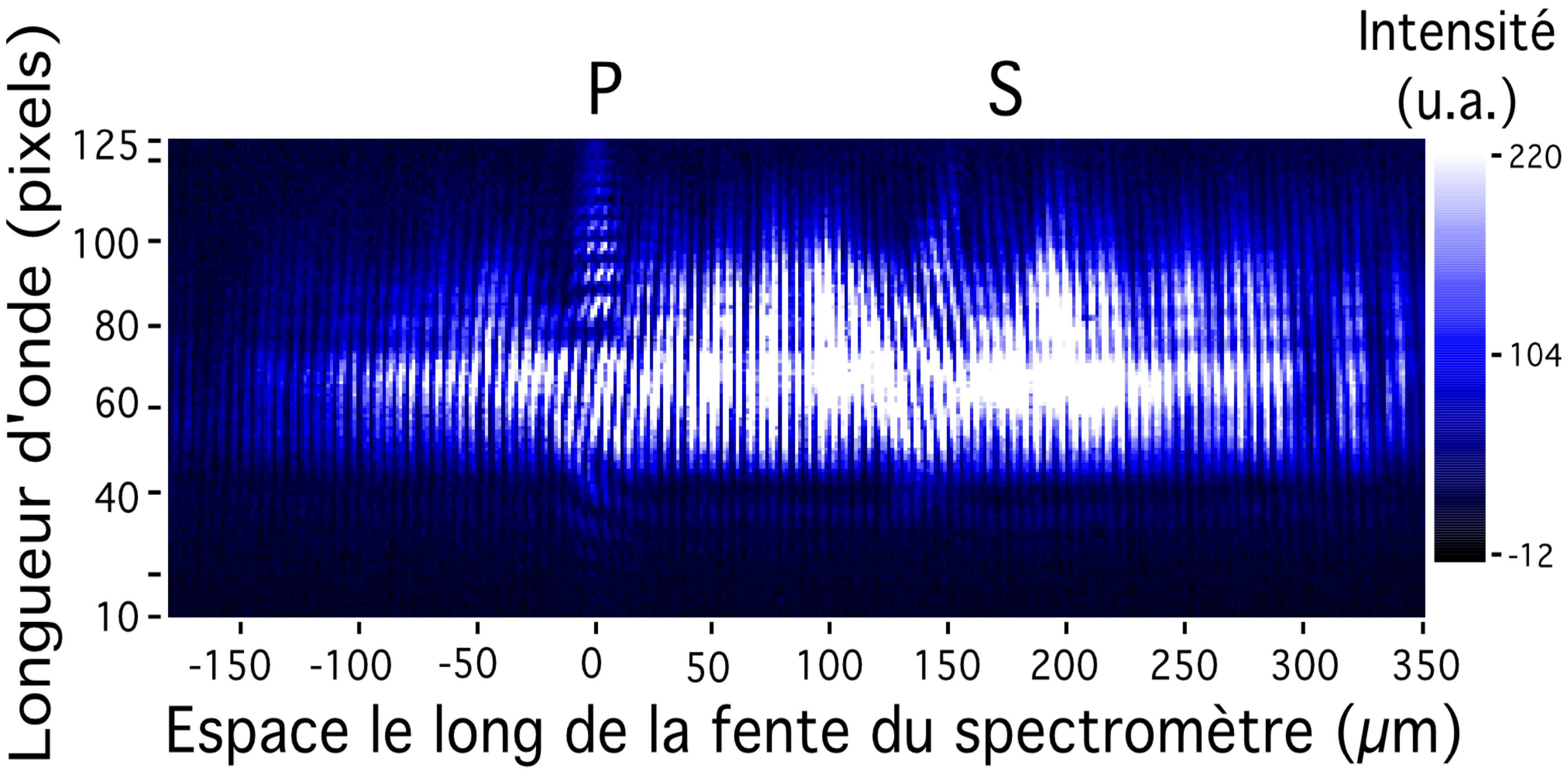


Faisceau principal
51,5°
polarisation P

Faisceau sonde
22,5°
polarisé à 45°

Mach-Zehnder

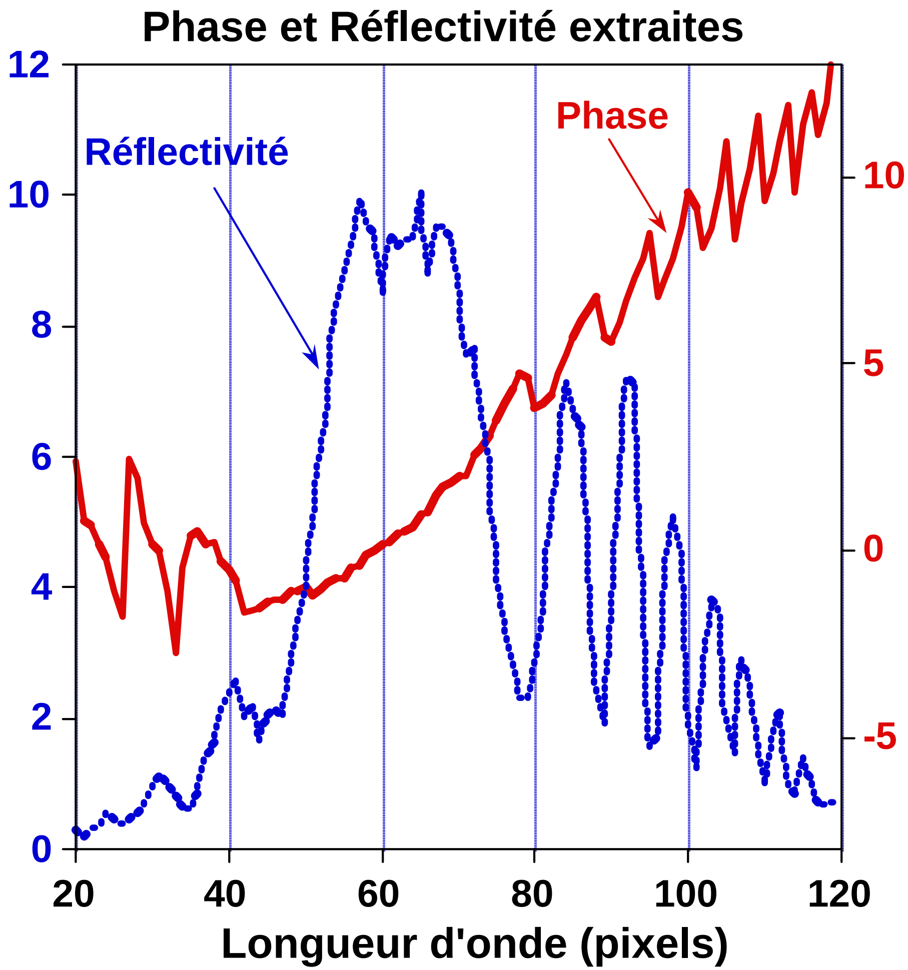
Interférogramme brut

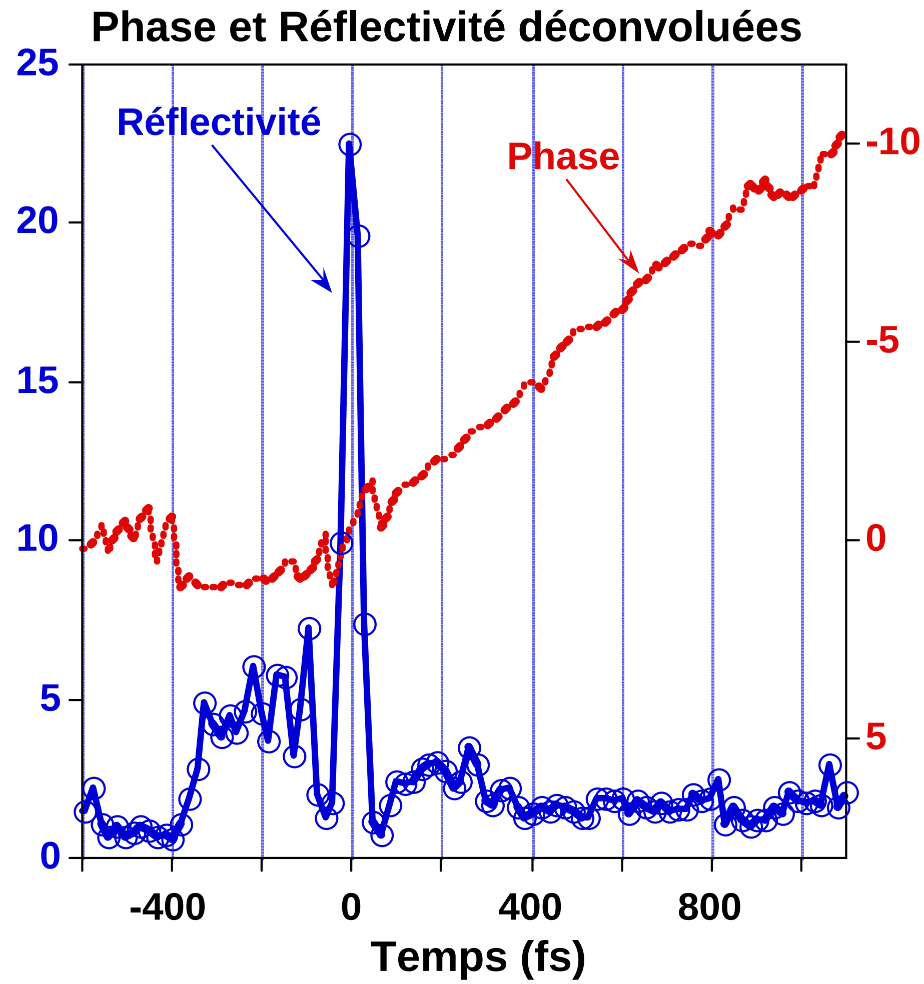


Le processus de reconstruction

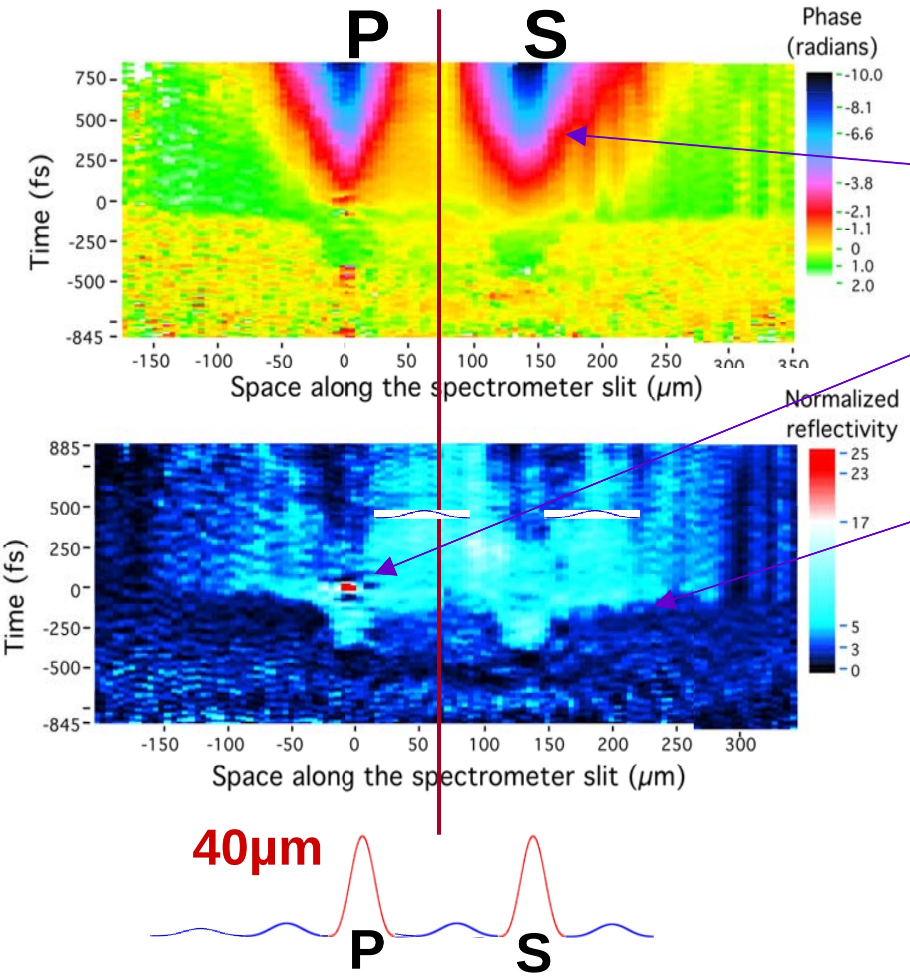
Exemple

Centre de la tache focale, polarisation P





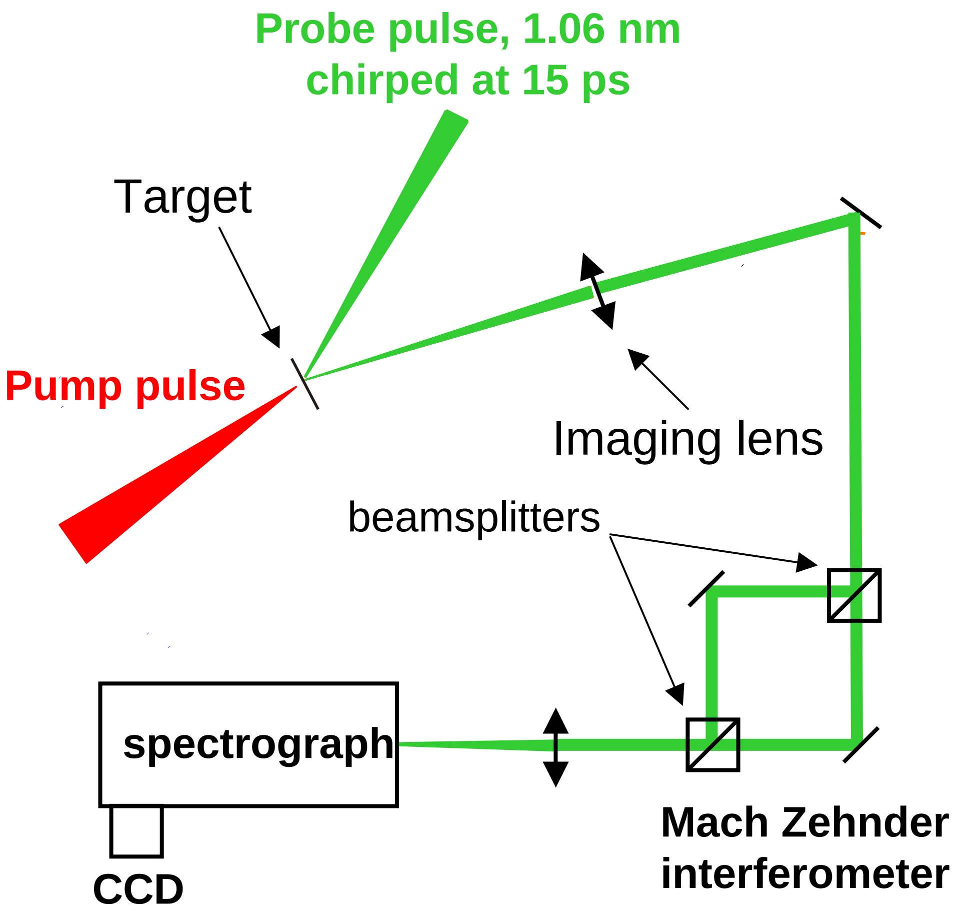
Phase and amplitude maps after deconvolution



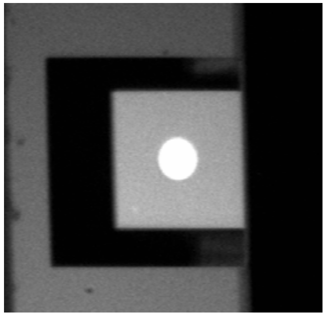
- Doppler phase
  - Hydrodynamic expansion
- Scattering peak in P-polarization
  - Scattered light has the same polarization than the laser
- Phase jump of 1 radian outside of the focal spot, with sharp increase of the reflectivity

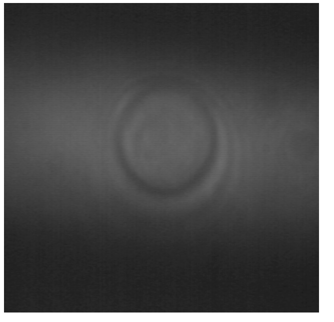
Single-shot Frequency Domain Interferometry

Of thin foil expansion heated by short pulse laser



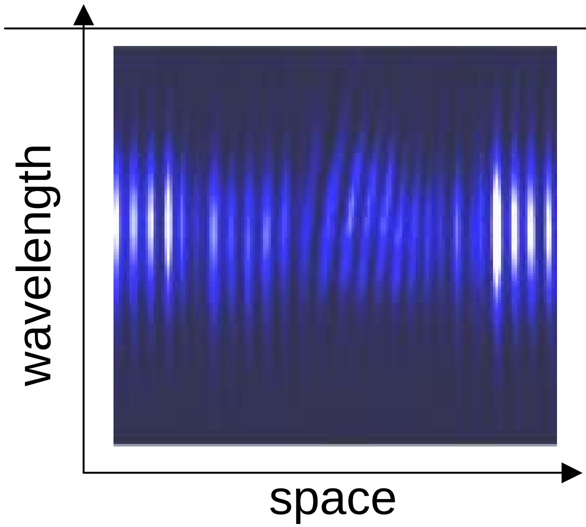
500 Å Thin Aluminium foil target

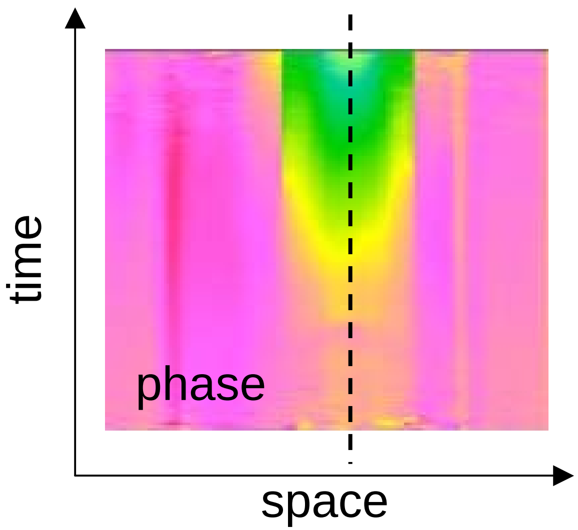




* Geindre et al., Optics Letters 26, 1612 (2001)

Single-shot FDI on 500 thin foil heated by 300fs laser at 3 10 ^{15}W/cm^2-



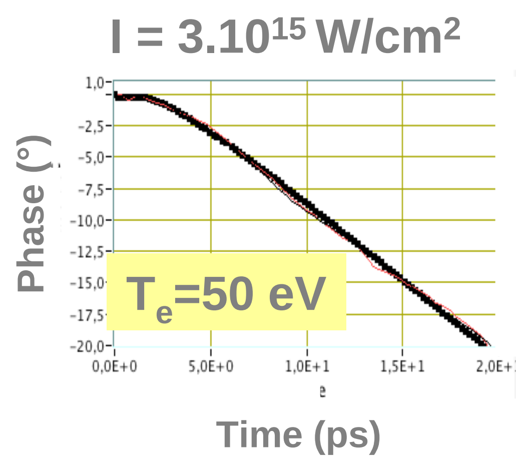


Simple model of hydrodynamic expansion

- **total energy is constant (adiabatic expansion)**

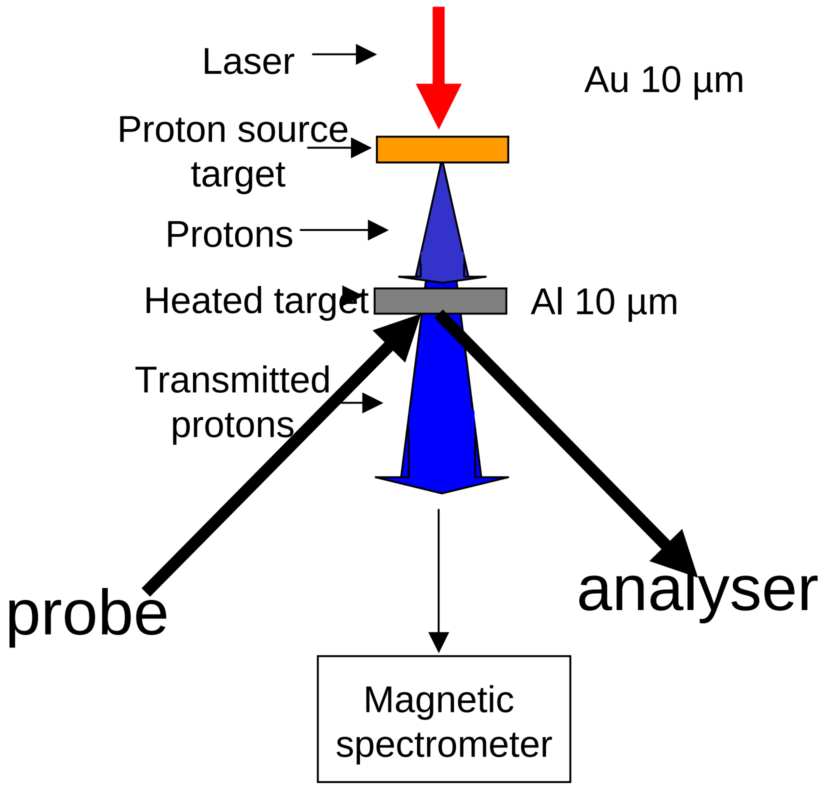
⇩

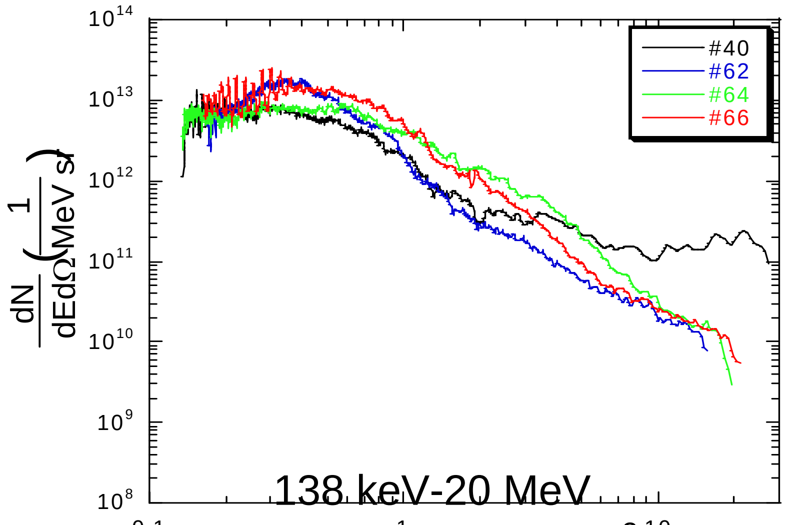
The phase variation depends only on the max temperature*



*** Audebert et al., JQSRT 81, 19 (2003)**

Target heated by laser accelerated protons

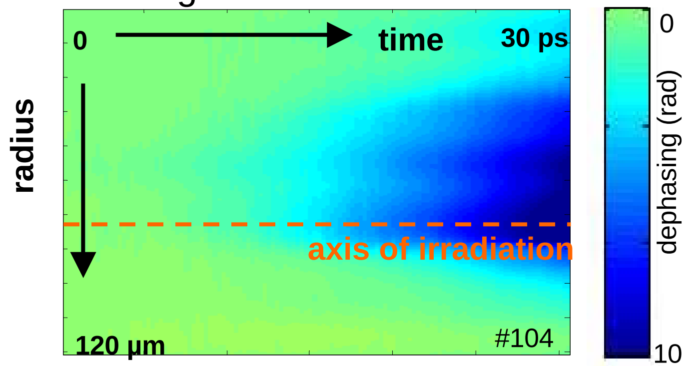




F=(1.6 – 3.2) e7 J m-2

Heated target: Al 5 µm

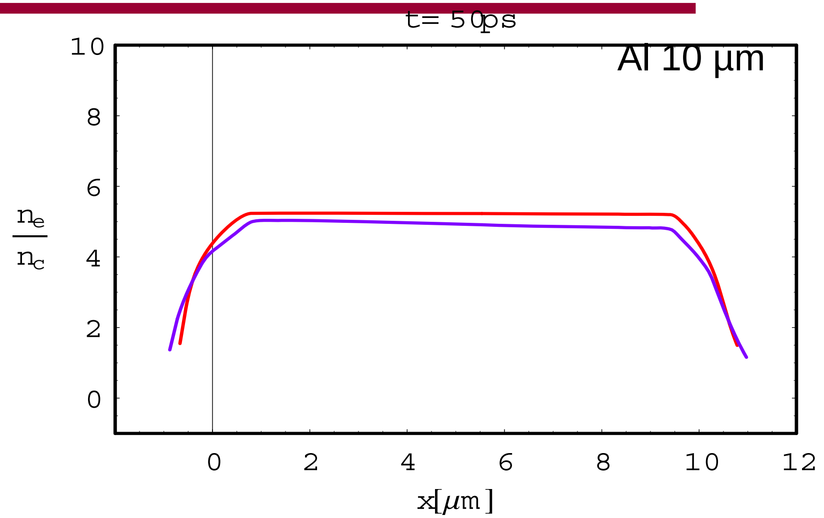
Single-shot measurement

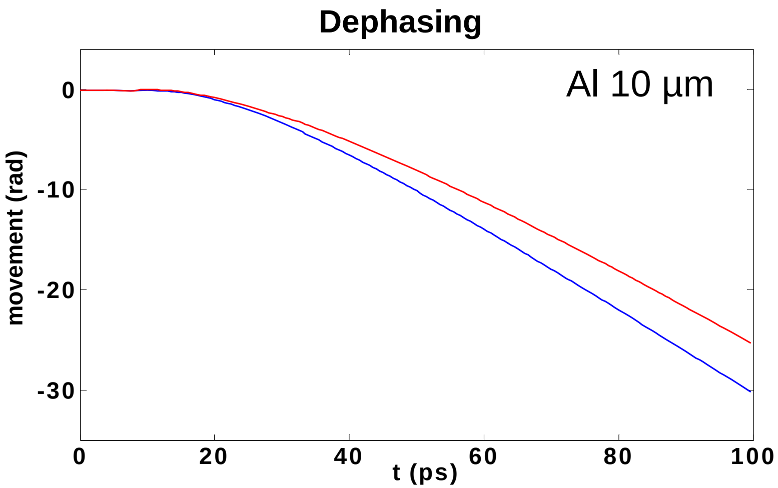


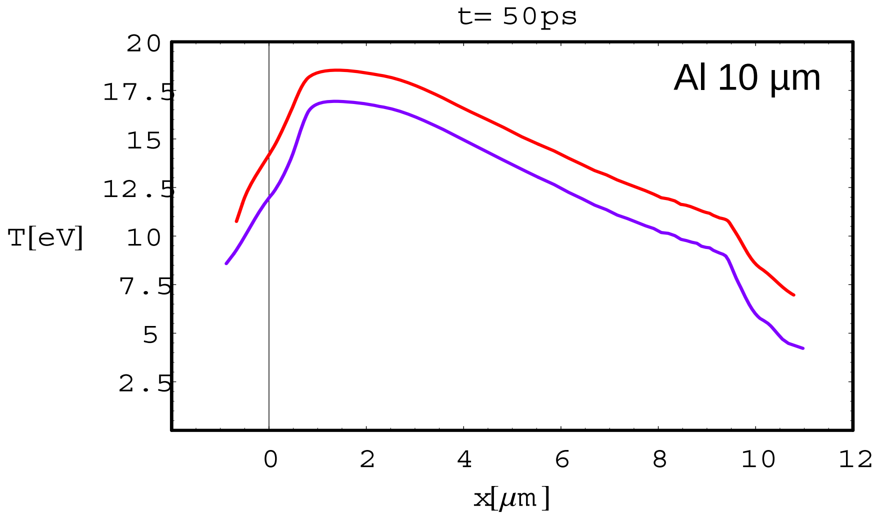
Simulation: with Different EOS on hydrocode

- **BLF** (Bushman-Lomonosov-Fortov)
  - more adapted for solids
  - take account of phase transitions

- **SESAME**
  - more adapted for plasma

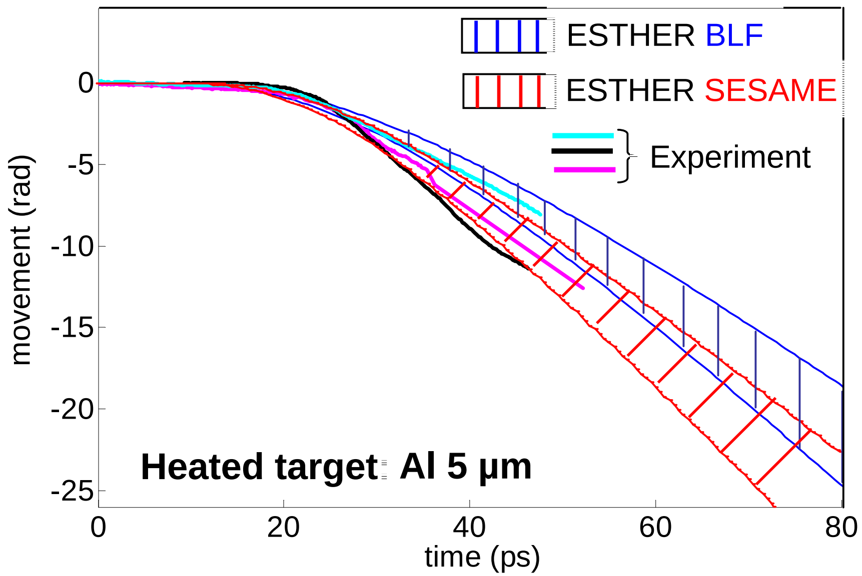


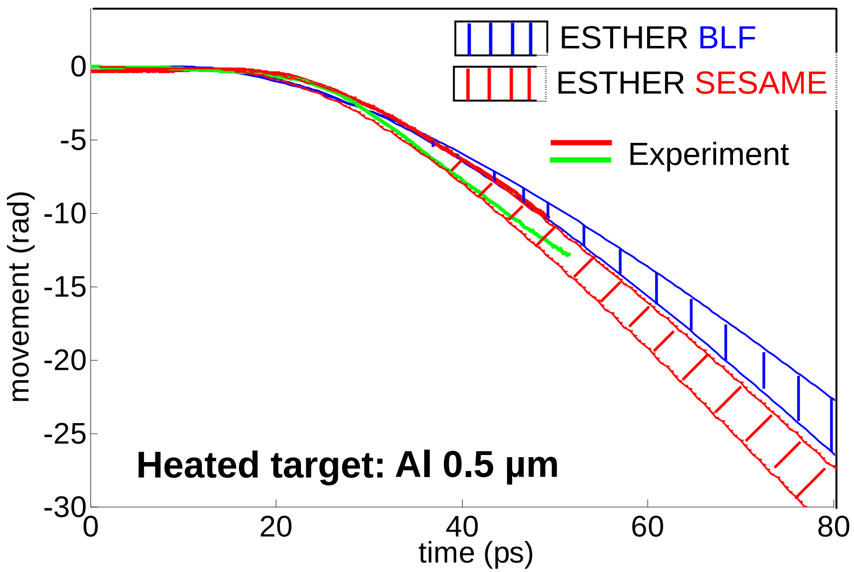


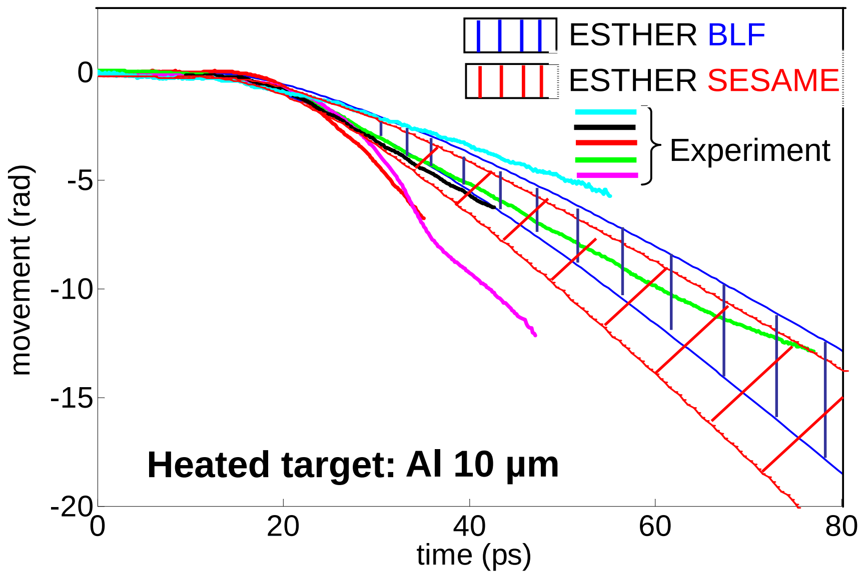


Comparison: Experiment – ESTHER output

- A laser probe diagnostic is implemented in the code
- The interaction between the laser field and the target – Helmholtz wave equation
- Conductivity: Eberling & Palik – solid phase, Spitzer formula – plasma phase







Conclusions

- FDI is a powerful technique to measure as function of space and time ultrafast-evolving laser-produced plasmas.

- We have implemented using chirp pulse a design for single shot frequency-domain interferometry .

- This technique as been used to fully characterized different type of plasma of varying electron density gradient scale-length.