Giornate di Studio SPARX e Applicazioni
INFN-LNF, Frascati, 9-10 Maggio 2005

Caratterizzazione di radiazione X ad impulsi corti ed ultracorti con tecniche dirette ed indirette.

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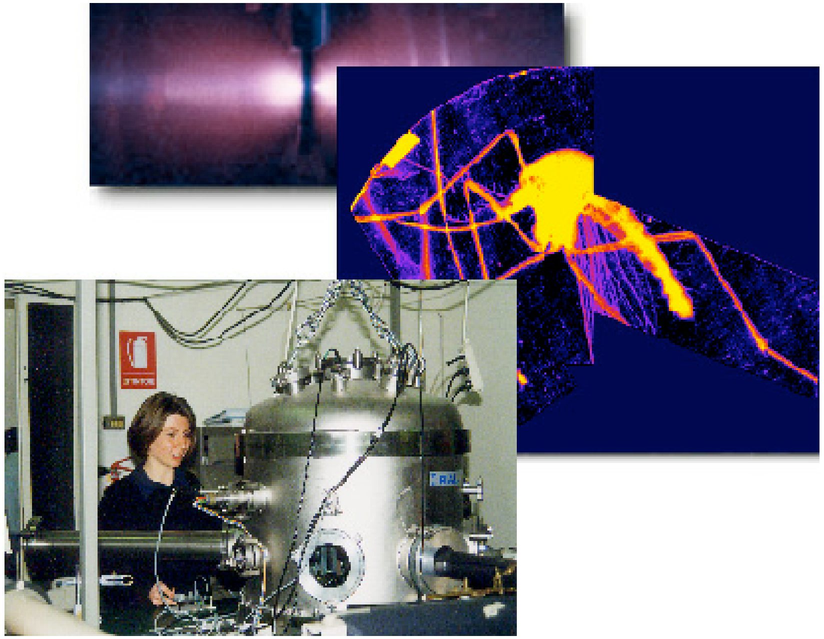
The ILIL GROUP



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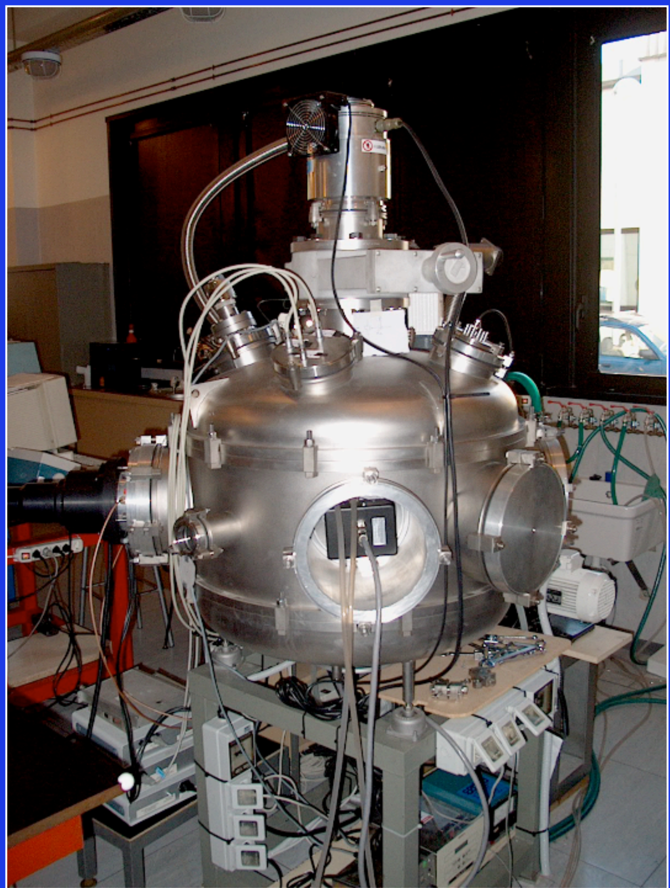
Area della ricerca CNR, Pisa

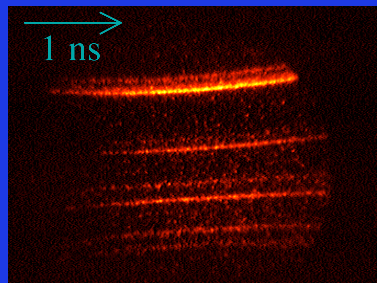
Items

- Direct measurements
  - Intro: sample experiments based on streak-cameras
    - Transient ionisation in Al plasmas
    - Radiative cooling
    - Thermal transport
  - Streak-camera basics
    - Temporal resolution limiting factors
    - Jitter-free and accumulation mode
- Indirect techniques: two examples
  - Cross-correlation technique
    - Bragg reflection in non-thermal melting experiments
  - Ionisation in gas
    - High sensitivity, high resolution probing
- **PROPOSALS OF FUTURE ACTIVITIES WITHIN *SPARKS***

X-RAY SPECTROSCOPY WITH TEMPORAL RESOLUTION

An X-ray streak-camera (no tube) equipped with a grating (soft X-rays) or a crystal spectrometer is used to perform temporal analysis of pulsed X-ray emission from plasmasb





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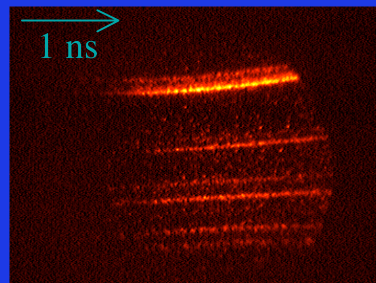

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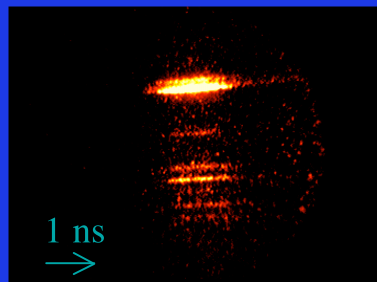
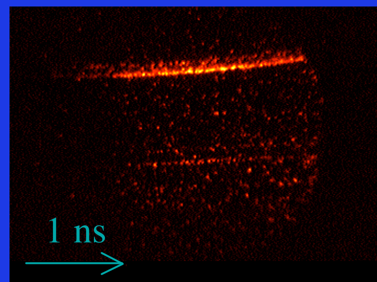


SILICIO



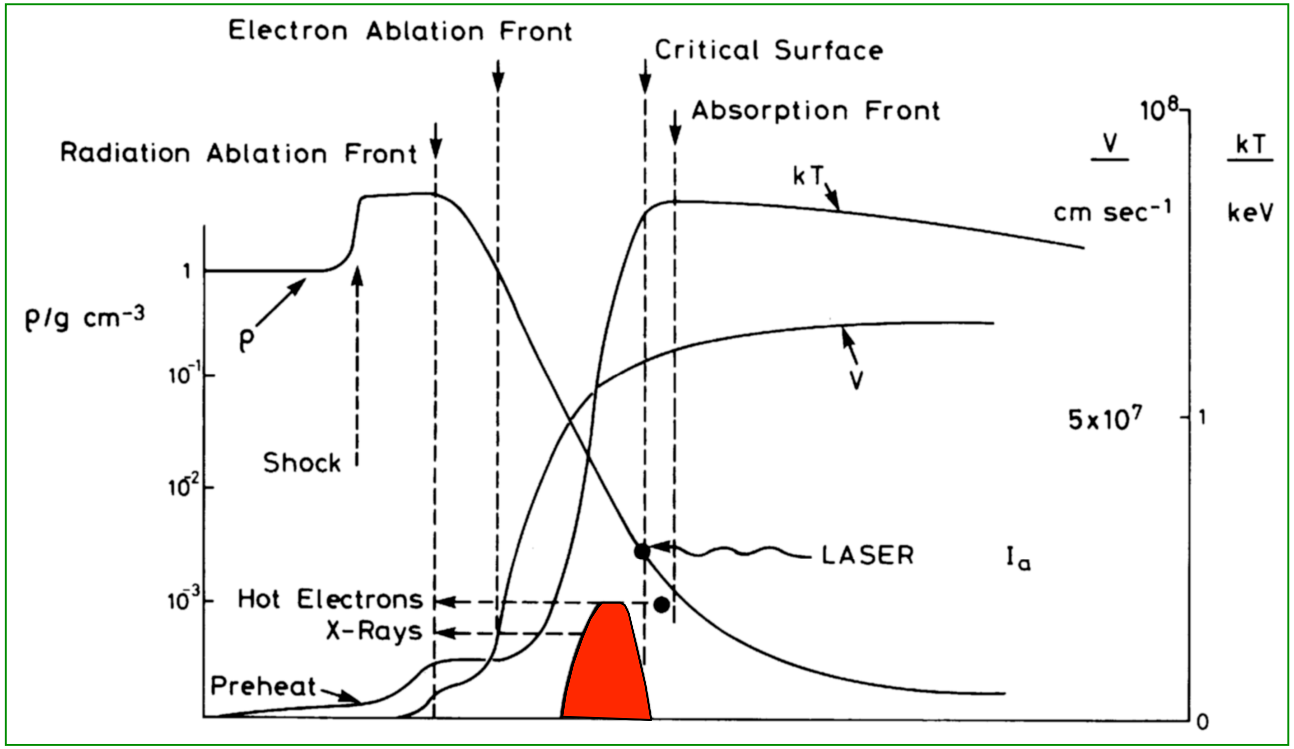
SILICIO

Transient ionisation in Al plasmas

Role of temporal resolution in modelling of X-ray spectra

BASIC HYDRODYNAMICS OF LASER-SOLID INTERACTIONS

Time resolved spectroscopy is widely used to investigate emission (optical through hard X-rays) from laser induced plasmas



Modelling of experimental spectra taken under "test conditions" can be used to benchmark hydrodynamics and atomic physics numerical codes

TRANSIENT IONIZATION IN LASER-PLASMAS

Ionization from a charge state *Z to a charge state Z+1*

$$\tau_{Z\rightarrow Z+1} = N_{Z+1}/|dN_{Z+1}/dt|$$

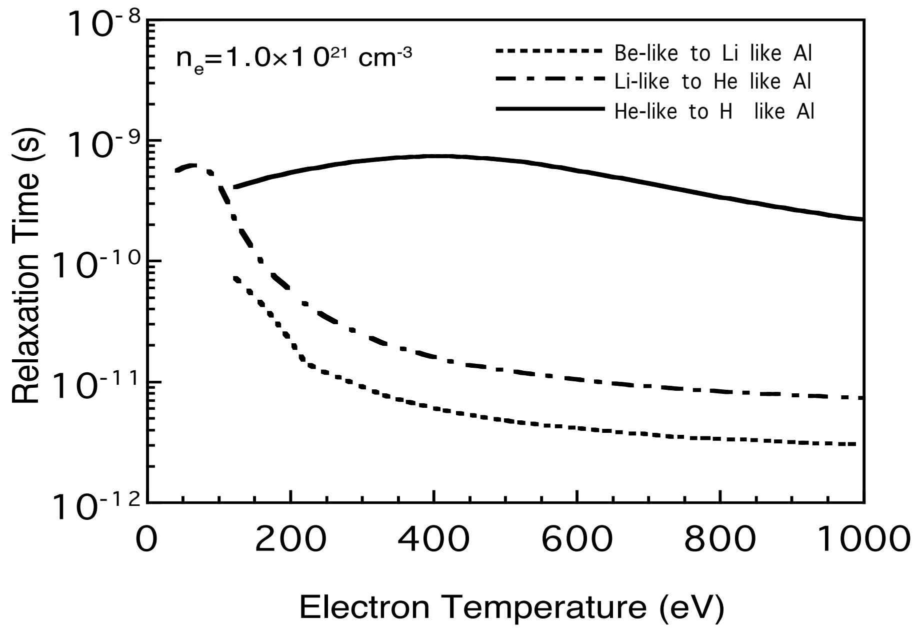
$$\frac{dN_{Z+1}}{dt} = n_e\left[(S_c^Z + S_R^Z)N_Z - (\alpha_{3B}^{Z+1} + \alpha_{RR}^{Z+1})N_{Z+1}\right]$$

N_Z : population of charge state Z

S_c^Z and S_R^Z : collisional and photo - ionisation rate from charge state Z

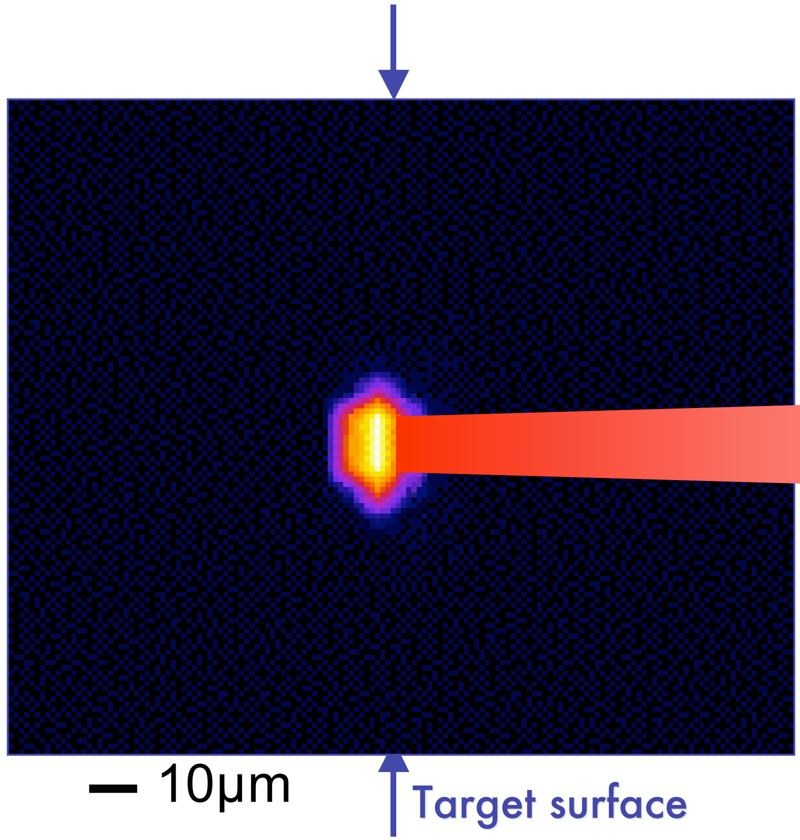
α_{3b}^{Z+1} and α_{RR}^{Z+1} : three - body and rad. rec. rate from charge state $Z+1$

Calculations show that relaxation time from He-like to H-like Al is comparable to the rise-time of nanosecond pulses

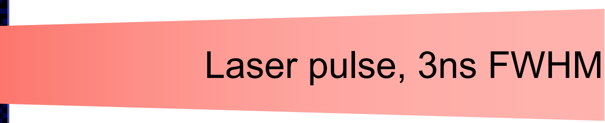


HYDRODYNAMICS AND X-RAY EMISSION

X-ray emission at 1.6 keV (He-like Al $1s^2$-$1s2p$) from a plasma produced by laser irradiation of an Al target



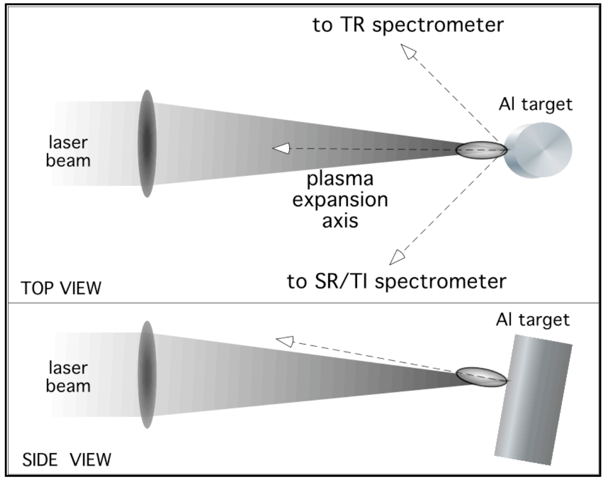
Total simulation time: 2 ns
Frame every 200 ps



Electron density and temperature maps obtained from hydrocode (POLLUX) are post-processed using time-dependent X-ray emission code (FLY)

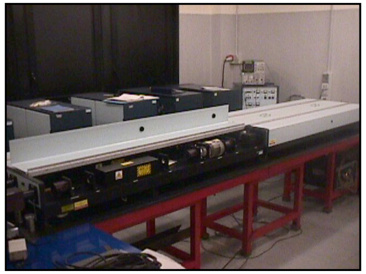
The experimental technique

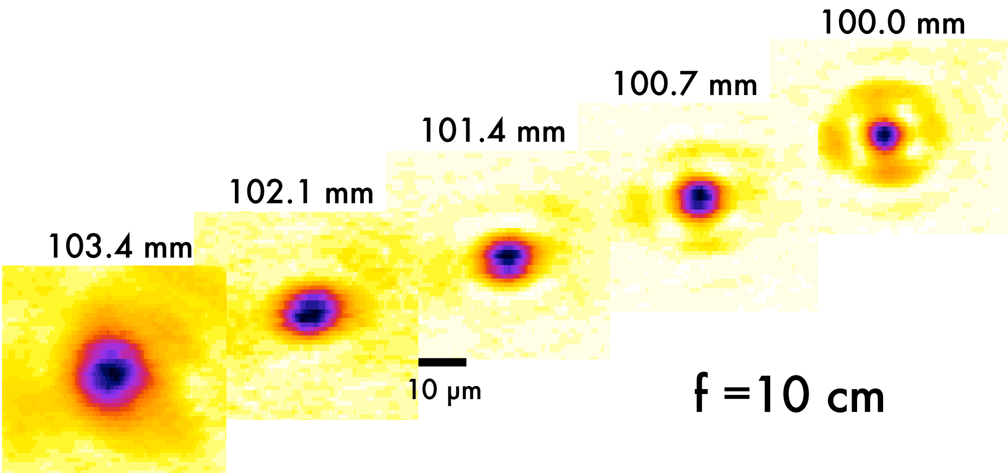
Tight-focus irradiation of solid target using *clean (temporally and spatially)* laser pulse



- **YLF oscillator, 1053 nm**
- **Phosphate amplifiers**
- **3, 7, 20 ns, 2 beams**
- **Single longitudinal mode**
- **Intensity on target**
- **up to:** 5 10^{15} Wcm^{-2}

High quality, near diffraction limited focal spot

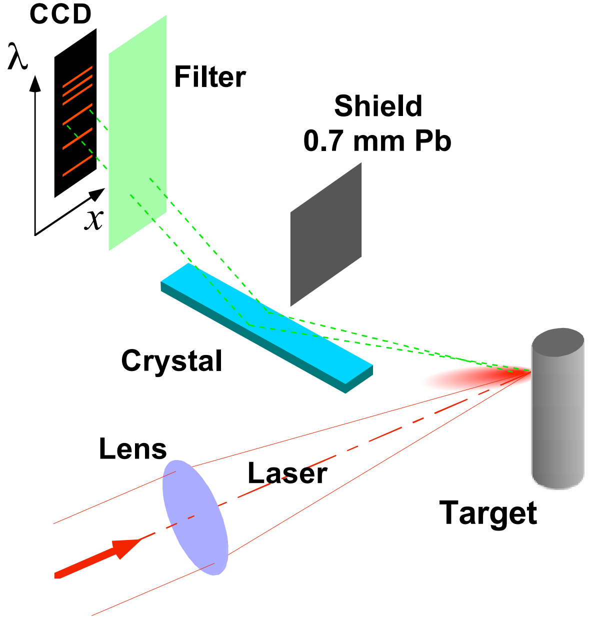


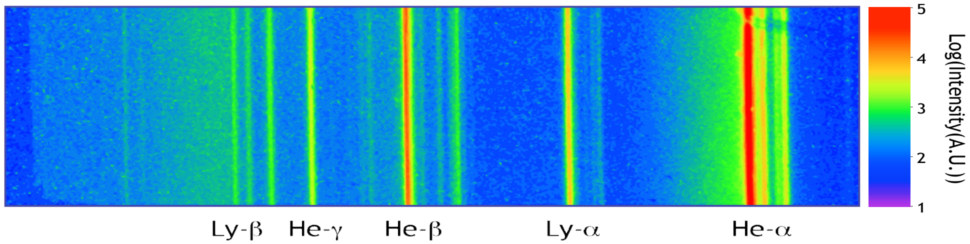


f =10 cm

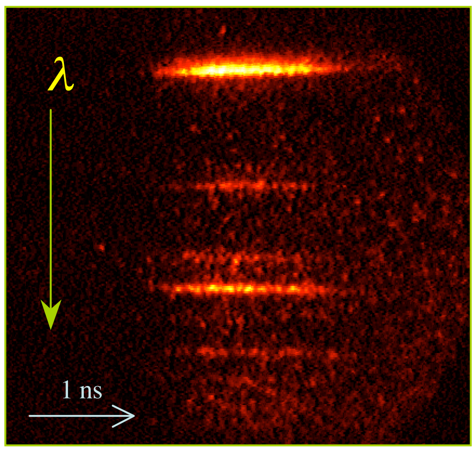
The X-ray spectra

X-ray spectroscopy of K-shell emission from H-like and He-like Al ions

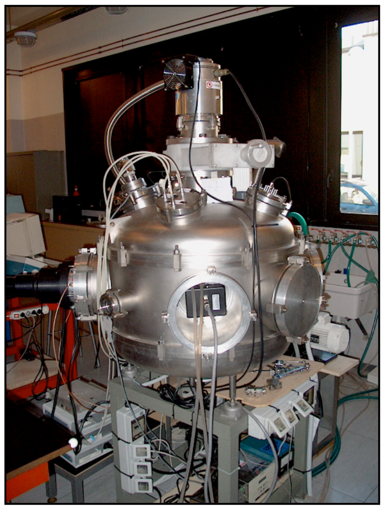




X-ray spectra must be resolved in time to obtain the temporal evolution of H/He line ratios early during irradiation. An X-ray streak-camera is used.

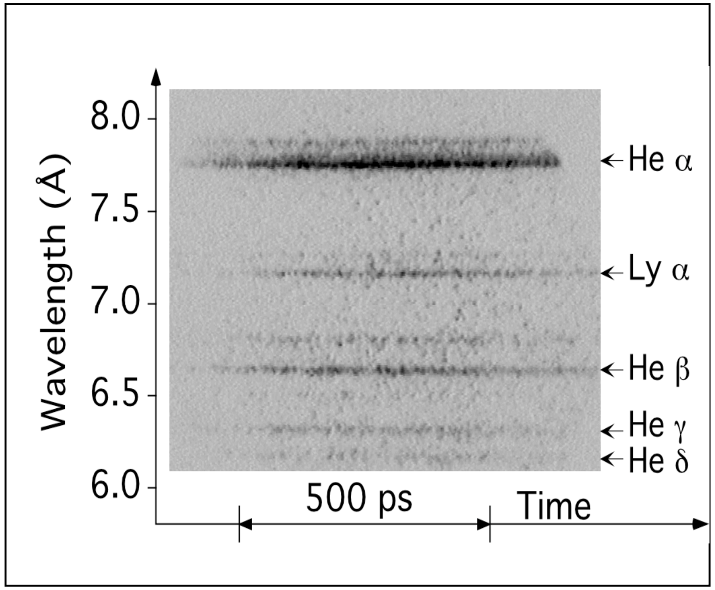


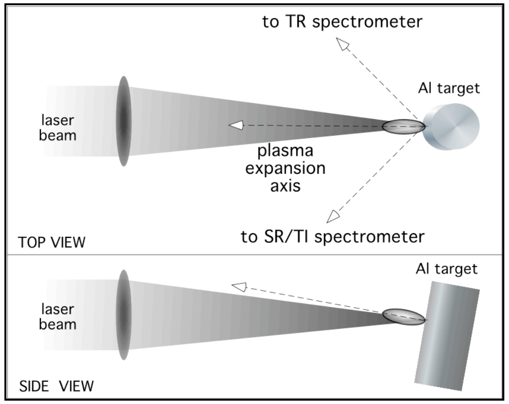
Raw data at low sweep speed



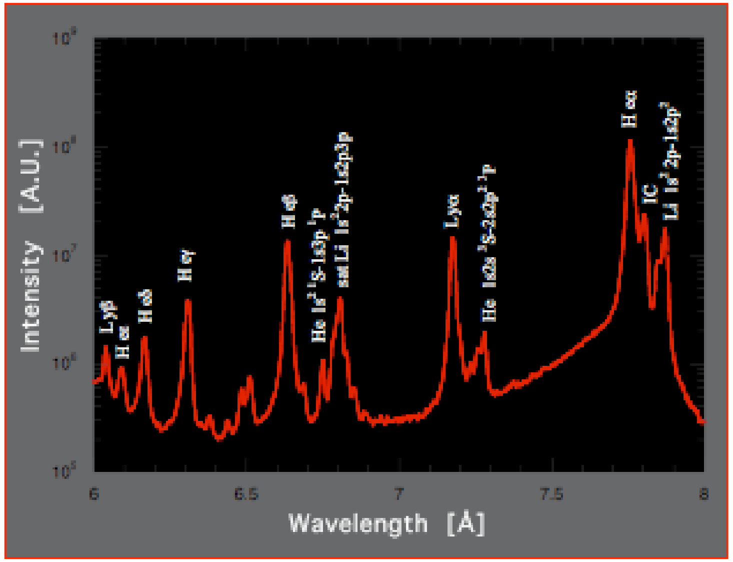
CROSS-CALIBRATION OF SPECTRA

Streak camera data are very difficult to calibrate due to the multi-stage detection process (photocathode, e-transport, phosphor, film/CCD)





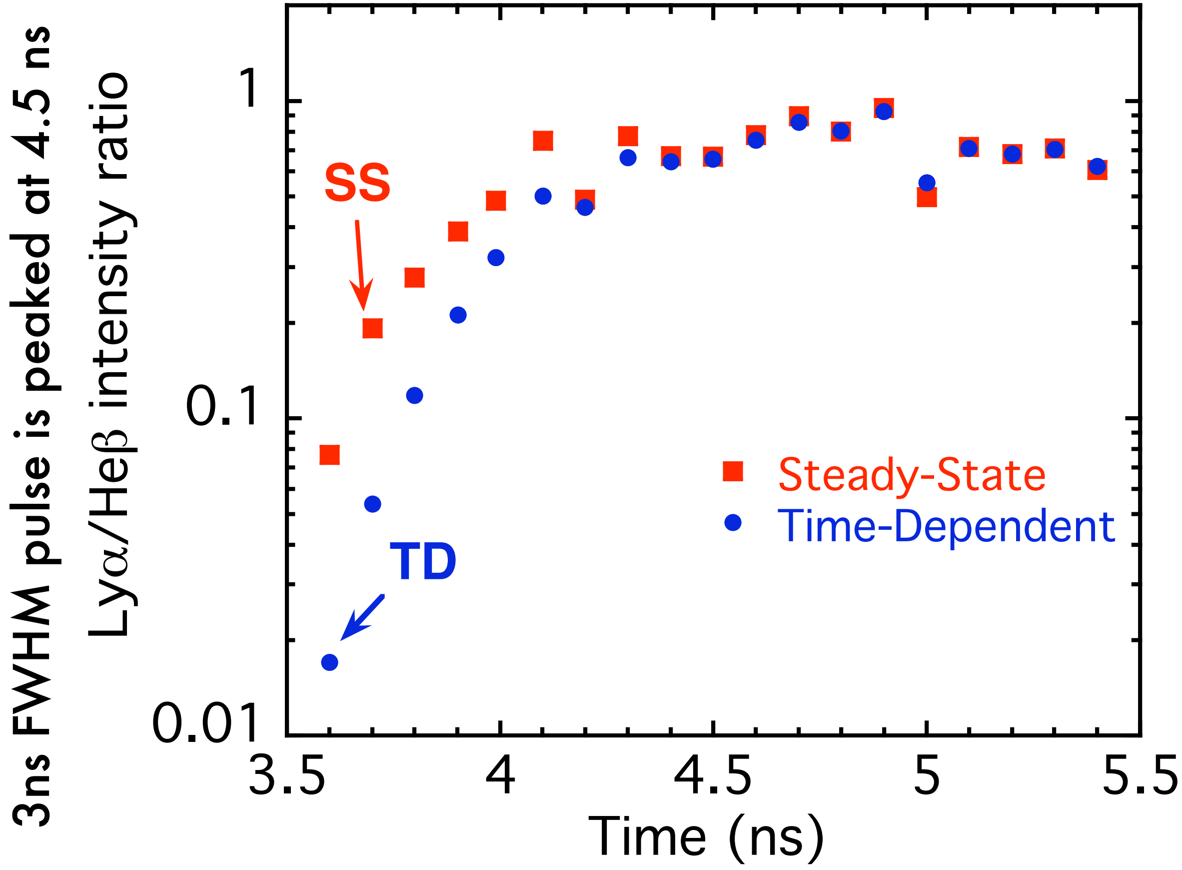
Cross-calibration



Simultaneous time integrated spectrum is taken along an equivalent line of sight

EVIDENCE OF TRANSIENT IONISATION

Temporal evolution of Lyα to Heβ intensity ratio: Steady-State *versus* Time-dependent modelling



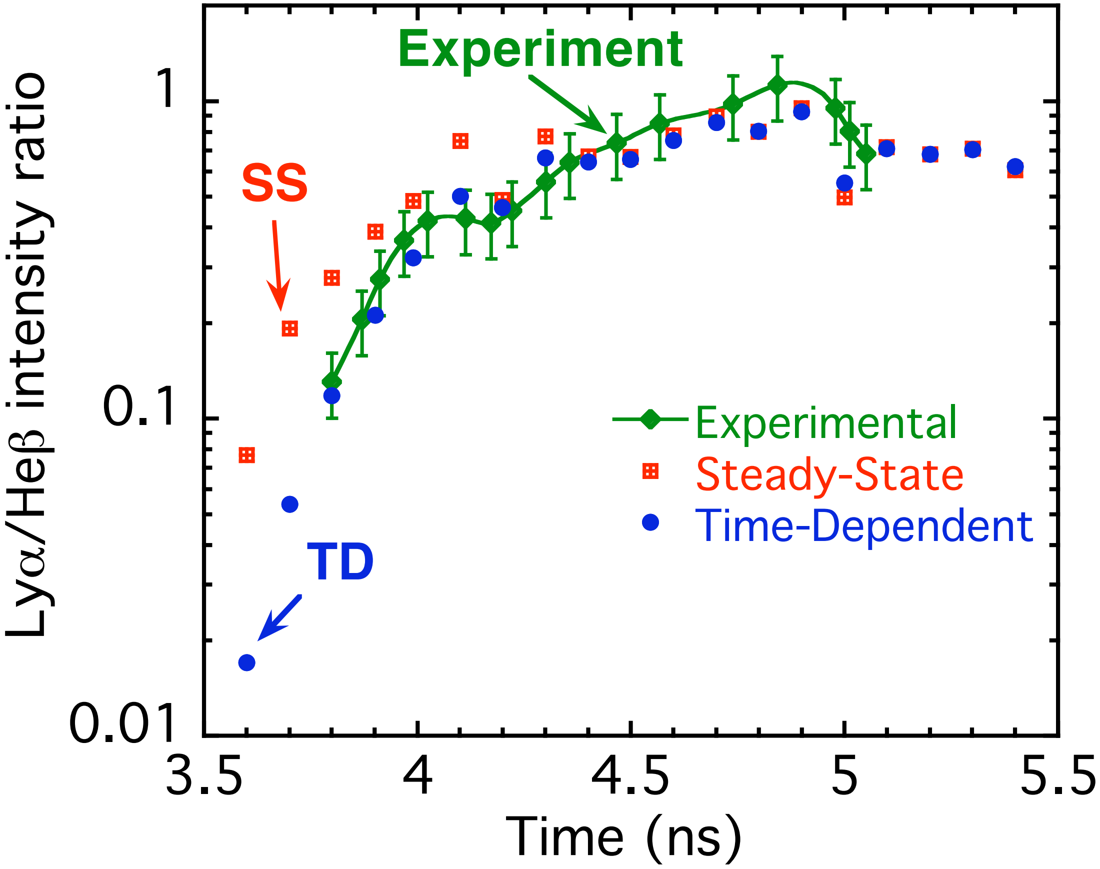
Early during the emission, time dependent and steady-state model show different results. Later on, both models give identical ratio.

EVIDENCE OF TRANSIENT IONISATION

Temporal evolution of Lyα to Heβ intensity ratio:

Experiment versus *SS/TD* modelling

3ns FWHM pulse is peaked at 4.5 ns



Early during the emission, time dependent and steady-state model show different results. Later on, both models give identical ratio. Early stage experimental ratio agrees well with *td* calculations.

L.A.Gizzi et al., Letter on Phys. Plasmas, (2003);
L.Labate et al; Submitted to Phys. Plasmas (2005).

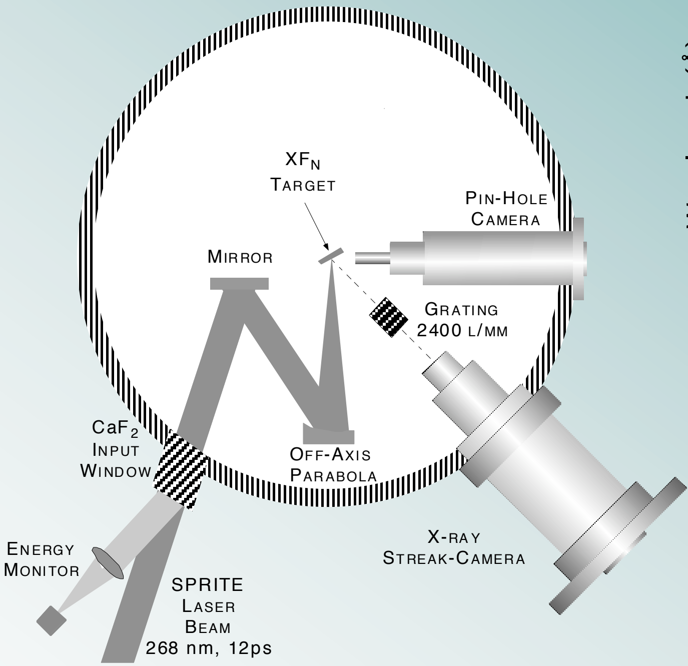
Example II

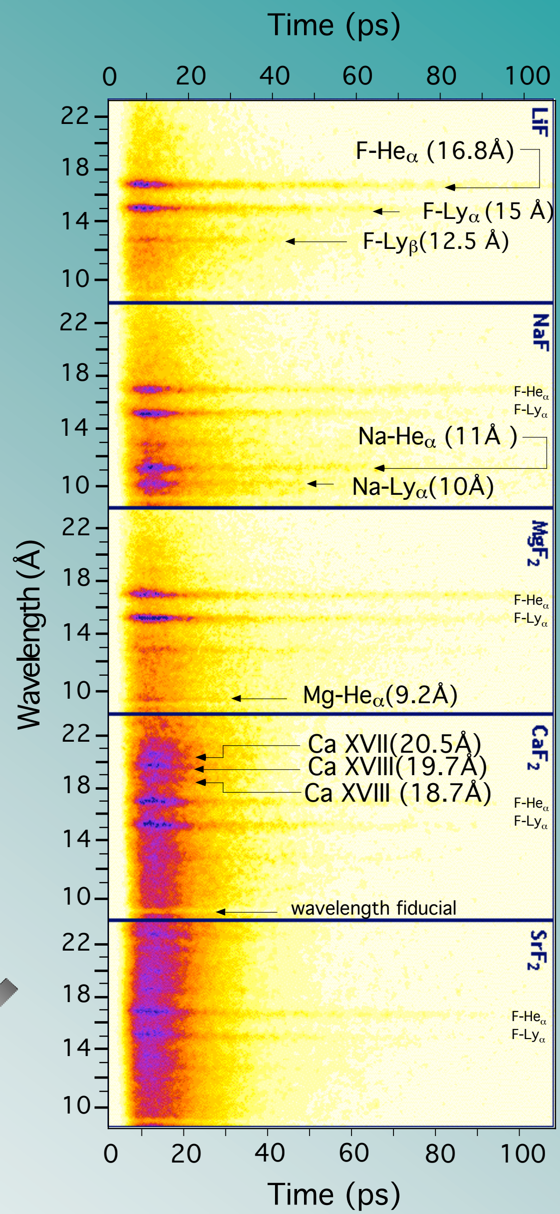
Radiative cooling of high density laser plasmas

RADIATIVE COOLING IN PS LASER PLASMAS

Cooling properties of plasmas play a key role in the achievent of efficient population inversion in short laser-pumped X-ray laser schemes. Plasma cooling can be investigated through time-resolved X-ray spectroscopy

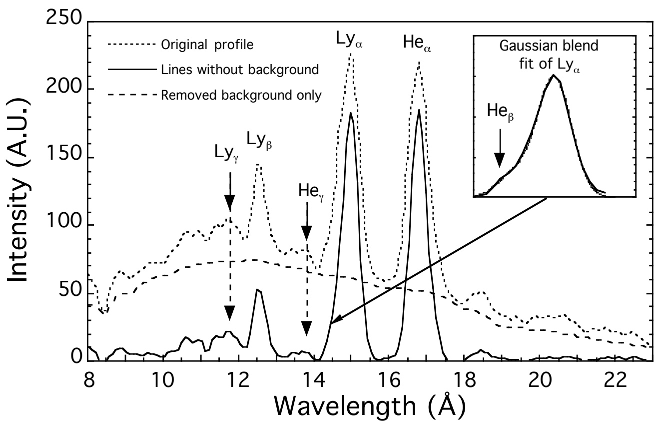
A high contrast 12 ps laser pulse is focused onto a solid target of Fluorine salts (LiF through SrF_2)

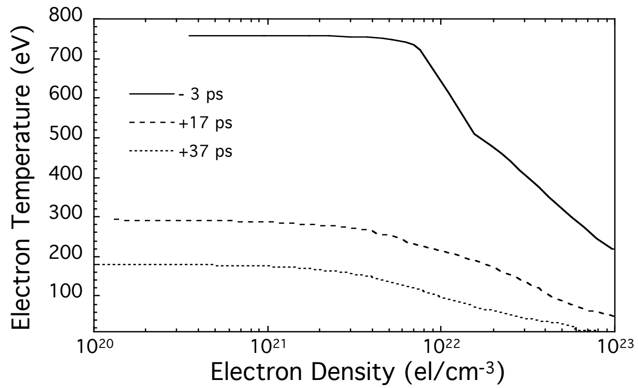


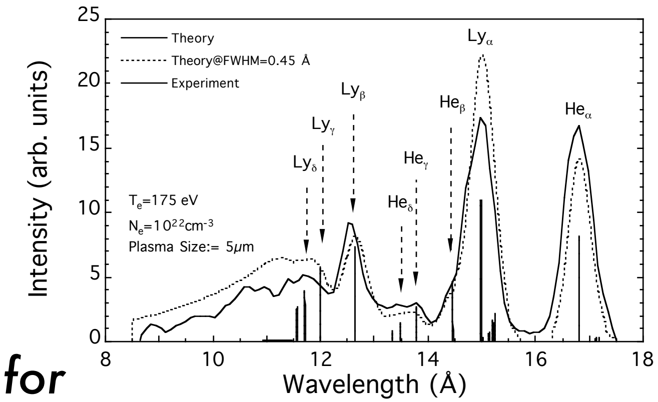


Leonida A. GIZZI - CNR

MODELLING OF PICOSECOND X-RAY EMISSION





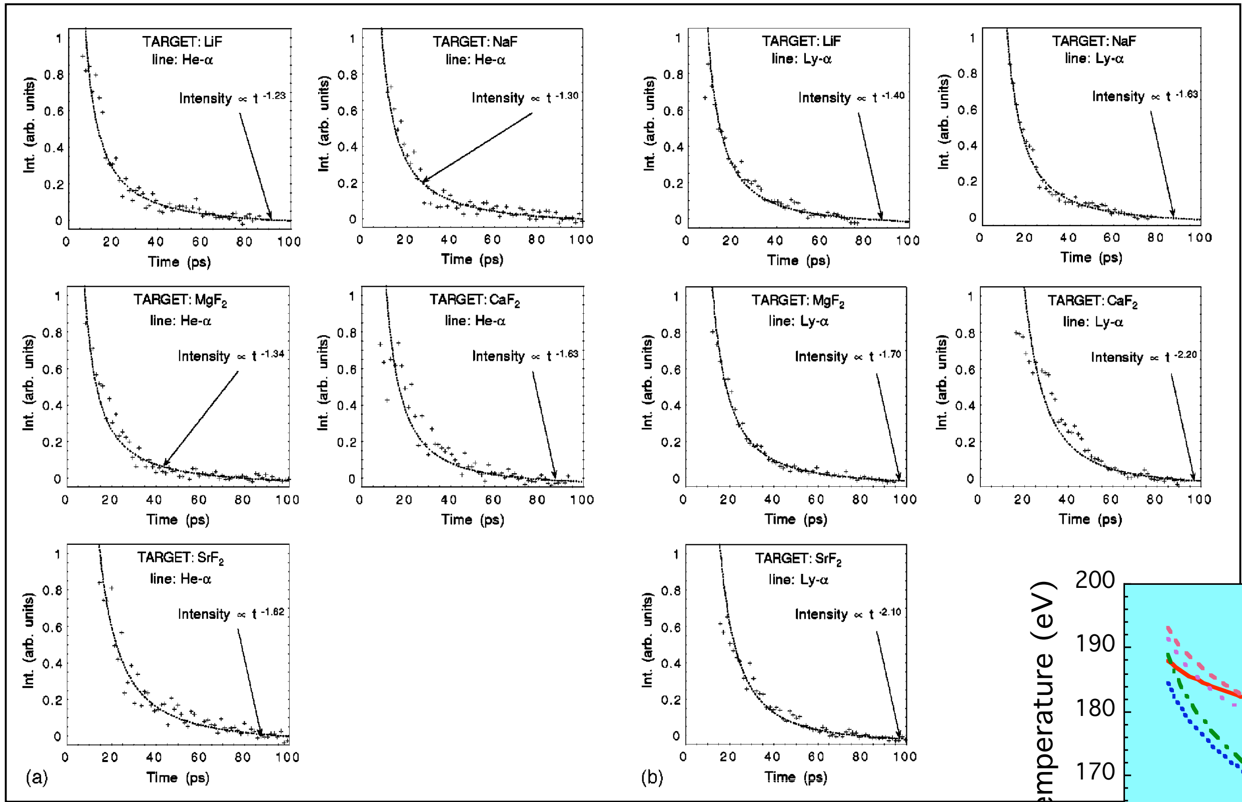


1D modelling provides satisfactory description of time-integrated K-shell spectra of Fluorine.

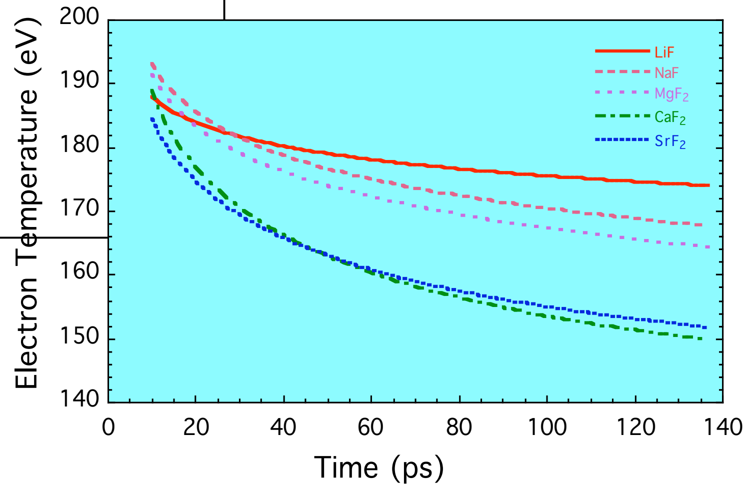
Line intensity ratios and electron temperatures at the peak of the emission for the five types of target.

Target	LiF	NaF	MgF_2	CaF_2	SrF_2
Ly_α/He_α ($\pm$10%)	0.94	1.10	1.05	0.97	0.84
Temperature (eV)	186–194	192–216	191–203	187–197	183–187

TEMPERATURE HISTORY VS. ATOMIC NUMBER



Electron temperature as obtained from H-like to He-like intensity ratio exhibits a faster decay for higher-Z targets as a result of stronger radiation cooling



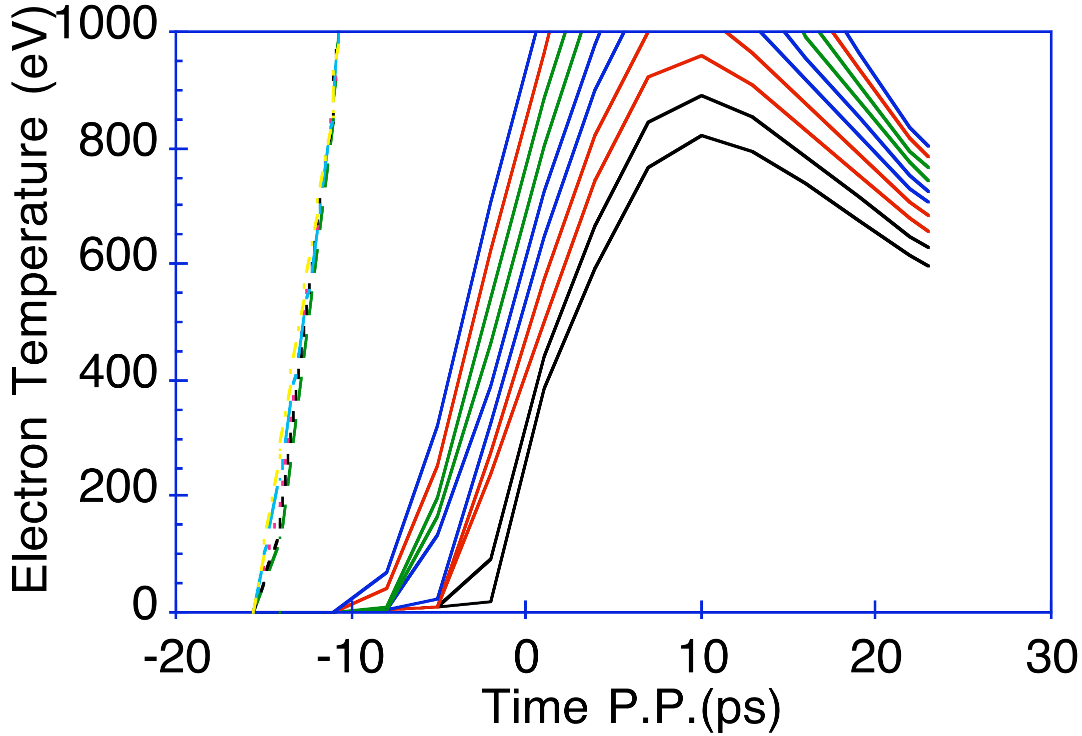
L.A.Gizzi et al., Phys. Rev. E, **52**, 2721 (2000).

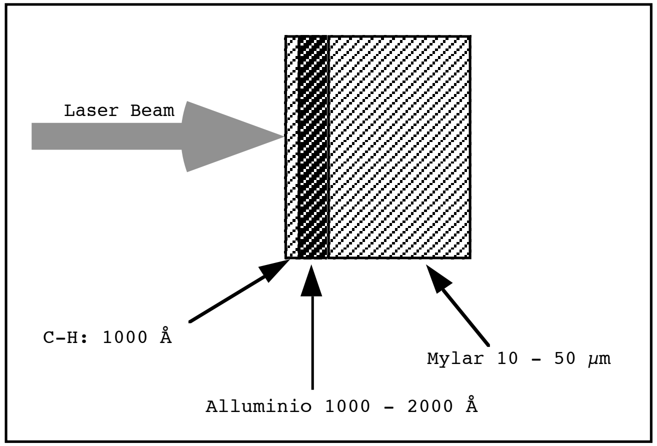
Example III

Thermal transport in solids

IONISATION OF MULTI-LAYERED TARGETS

Time-resolved spectroscopy of soft X-ray emission from laser irradiated layered targets is used to investigate thermal transport properties of solids under extreme conditions

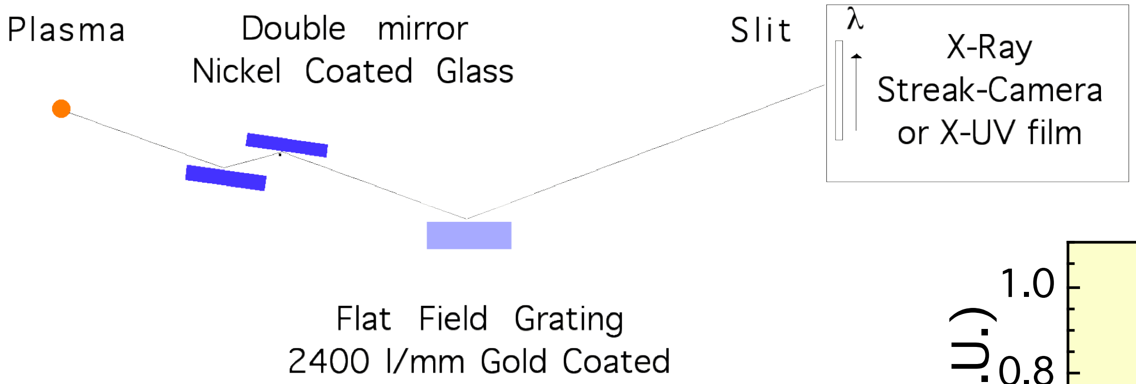




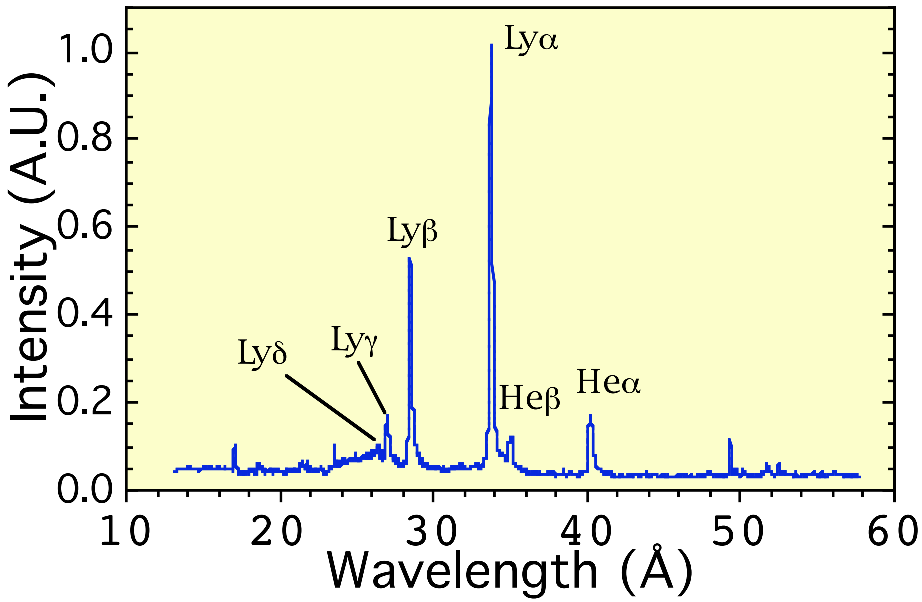
Numerical modelling shows that picosecond pulses are needed to resolve contribution from different layers

Spectroscopy in the 2-10 *nm* region

A grazing incidence flat-field spectrometer is used in combination with grazing incidence mirror filters. Due to the small incidence angle, grazing incidence grating suffer from a limited temporal dispersion

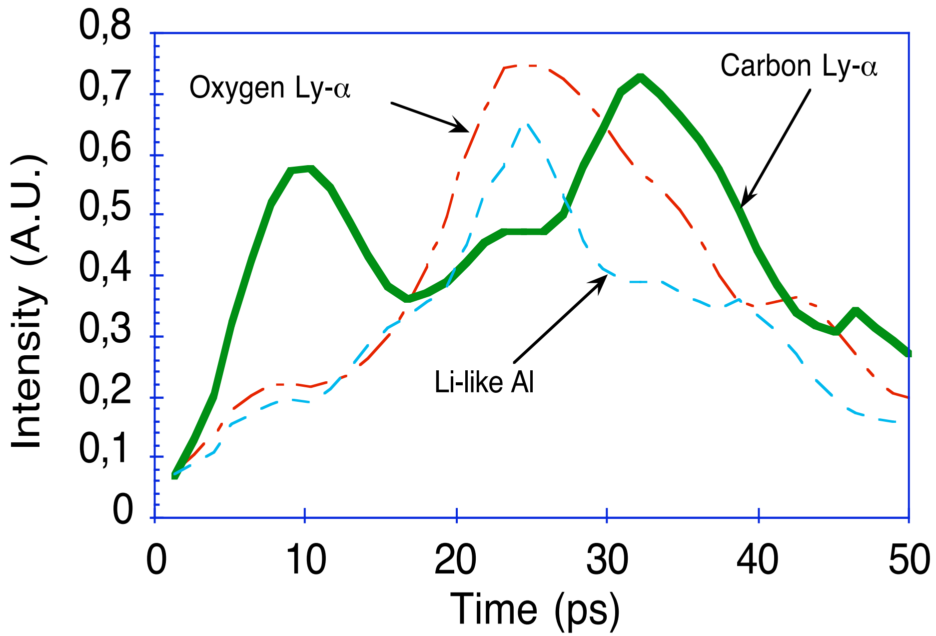


Spectrum from C plasma generated by irradiation of a solid target (mylar) with a 10ps (laser SPRITE-RAL) at 10^{17} W/cm²



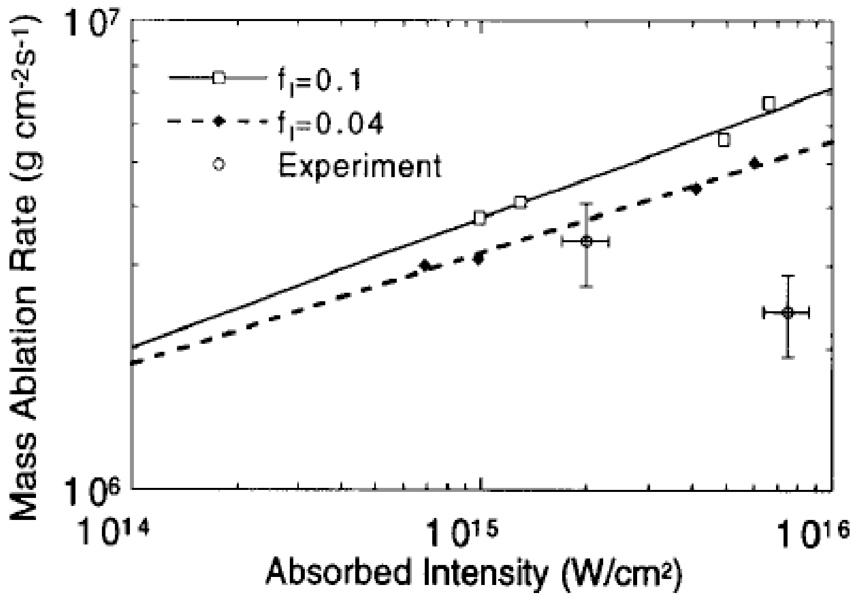
In the case of broad band X-ray emission (e.g. laser plasmas), multiple order diffraction may occur. Grazing incidence mirrors act as low-pass filters to reduce contribution from unwanted radiation.

TIME-RESOLVED EMISSION



Emission from H-like Carbon Ly-a line marks propagation of ionisation front in the CH (outer layer) and in the Mylar (substrate).

Peak-to-peak delay in the H-like emission from C gives a measurement of the mass ablation rate in the Al layer.

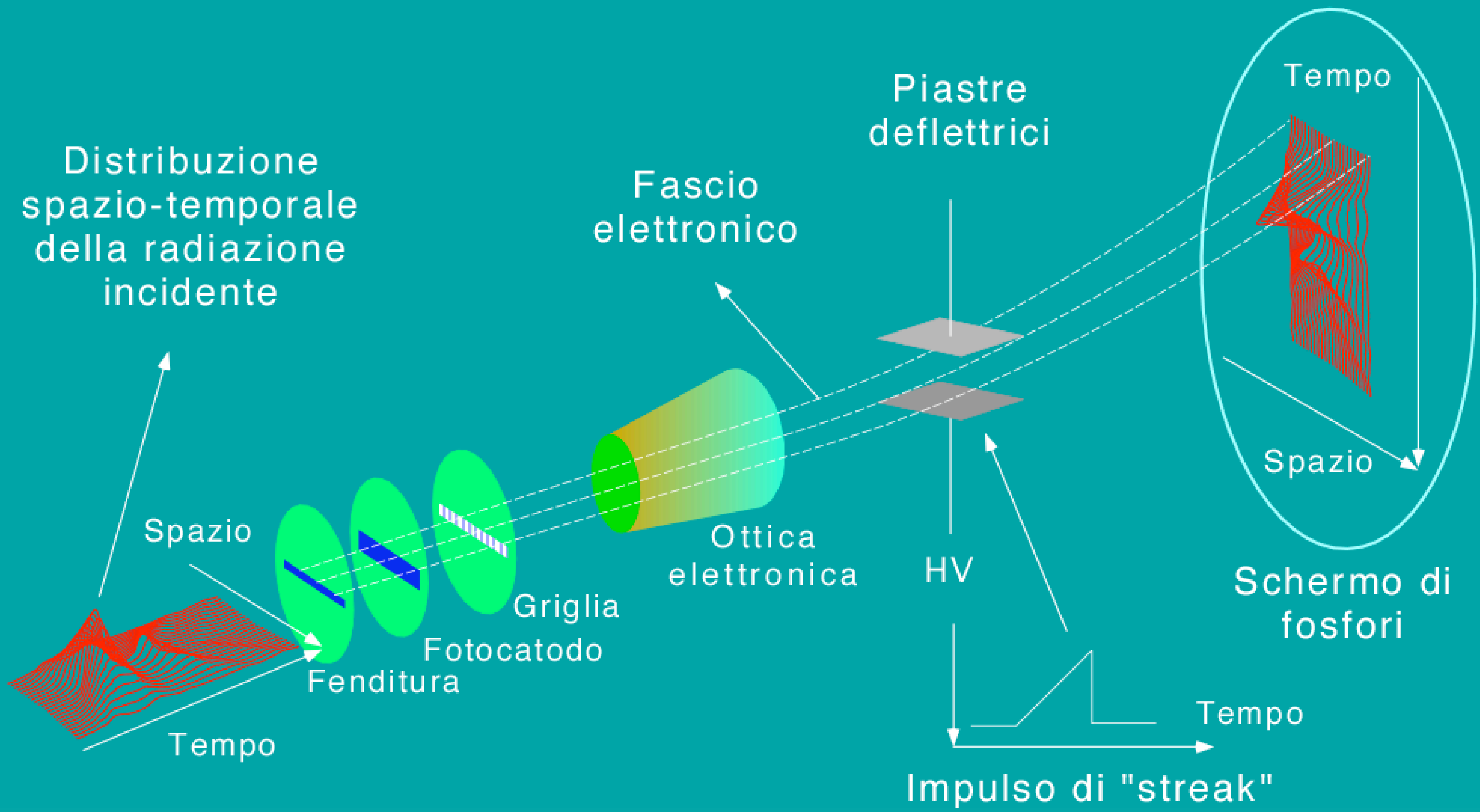


 L.A.Gizzi et al., Laser and Particle Beams,**13**, 511 (1995)

STREAK-CAMERA BASICS

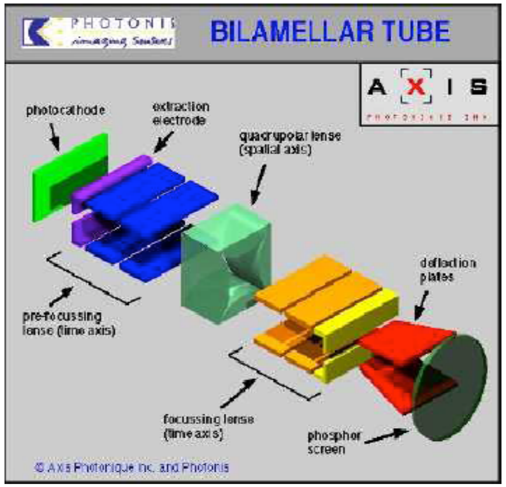
Commercial systems, time-resolution limiting factors and recent developments

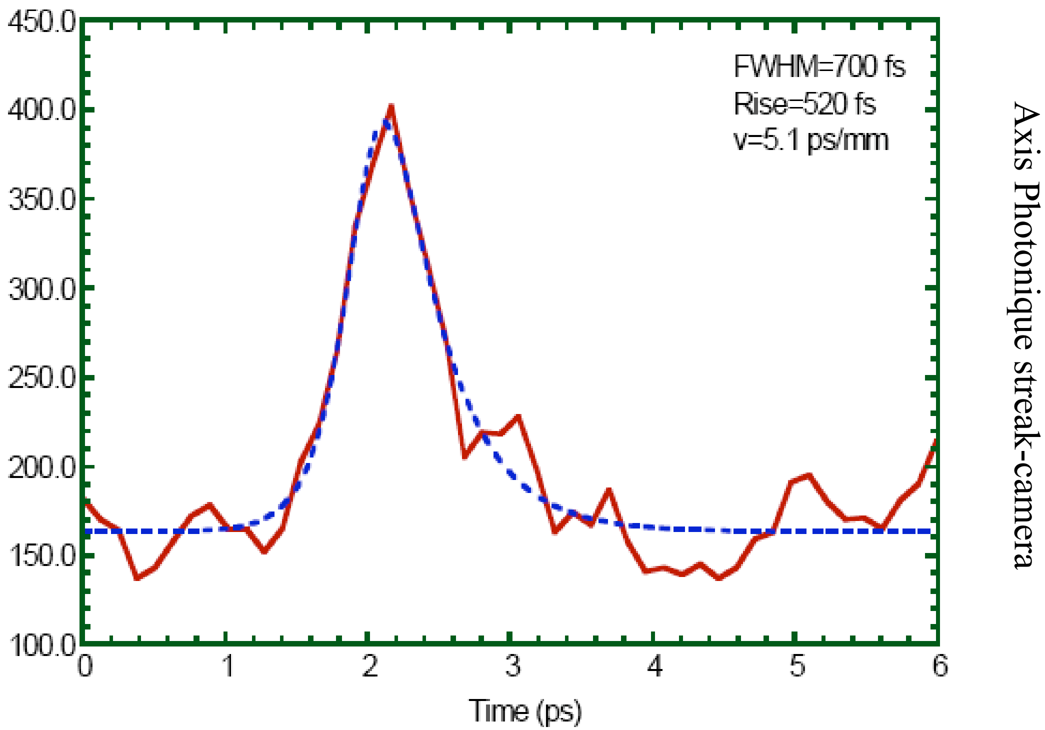
Streak-camera working principle



LATEST NEWS FROM COMMERCIAL STREAK-CAMERAS

Output signal with UV laser light of 60 fs duration laser pulse



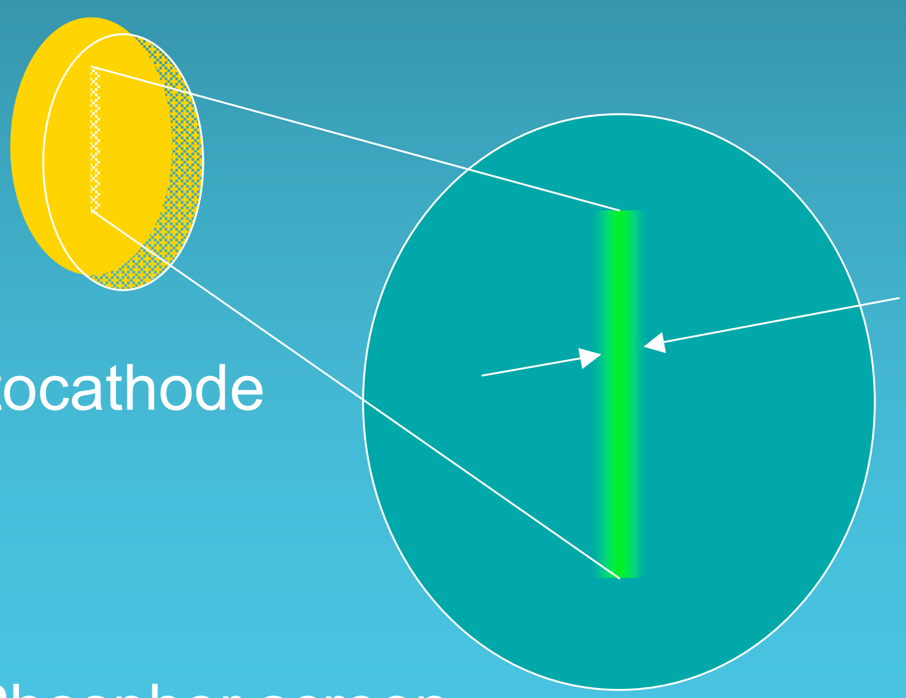


Temporal resolution on a single shot is 700 fs
Dynamic range is very low (approx. 4)

Courtesy of G. Tallents, U. of York

TIME RESOLUTION LIMITING FACTORS

- **SIZE OF UNSWEPT (STATIC) IMAGE OF THE INPUT SLIT (VS. TIME AXIS):**



$$t_s = \frac{\delta_{LSF}}{v}$$

t_s an be reduced using a narrow slit

TIME RESOLUTION LIMITING FACTORS

- **TRANSIT TIME DISPERSION***

$$t_{ph} \approx 3\times10^{-8}\ \frac{\left[\left(E_0+\Delta kT/2\right)^{1/2}-\left(E_0-\Delta kT/2\right)^{1/2}\right]}{E_{extract}}\ \text{(s)}$$

E_0 : average kinetic energy of photoelectrons (eV)

ΔkT : FWHM of the energy spread of the secondary electrons (eV)

$E_{extract}$: Extraction field (V/cm)

Typically: $E_0 = \Delta kT/2 \longrightarrow t_{ph} \approx 3\times10^{-8}\ \frac{\sqrt{\Delta kT}}{E_{extract}}\ \text{(s)}$

***t_{ph}* an be reduced using a high extraction field …**

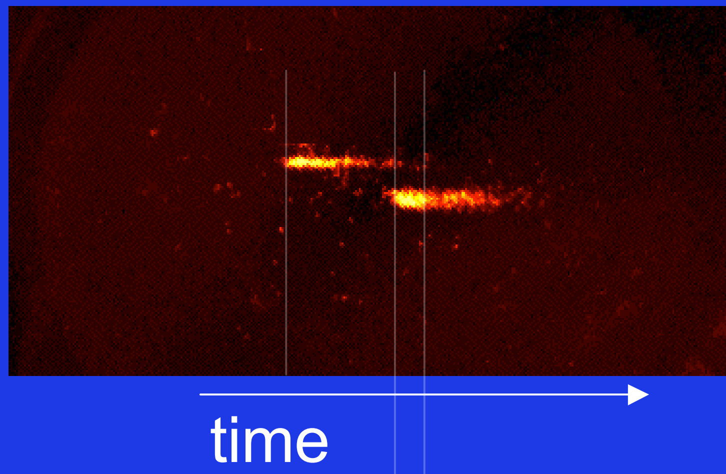
*M.M.Murnane et al., Appl. Phys. Lett. **56**, 1948 (1990)

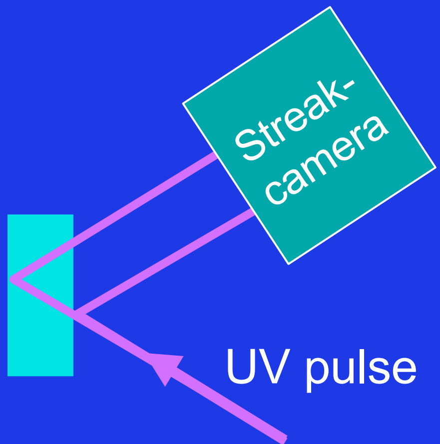
Comparing CsI and KBr

Camera	Photocathode	Gain (CCD electrons)	SNR_1	F^2	Electrons/event
Optical	S-20	108	2.56	1.15	1.0
X-ray/UV	Al	150	2.40	1.17	1.0
X-ray	Au(250 Å)	171	1.78	1.32	1.14
X-ray	KBr(1500 Å)	368	1.20	1.69	2.45
X-ray	CsI(1500 Å)	510	1.00	2.00	3.40

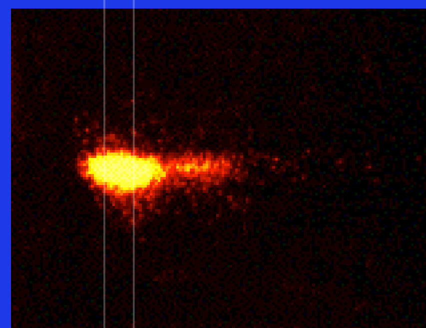
S. Ghosh et al., Rev. Sci. Instr. **75**, 3956 (2004)

CsI photocathode
4 ps (FWHM) UV (248 nm) pulse
Double pulse 30 ps delay





KBr photocathode
4 ps (FWHM)
UV (248 nm) pulse

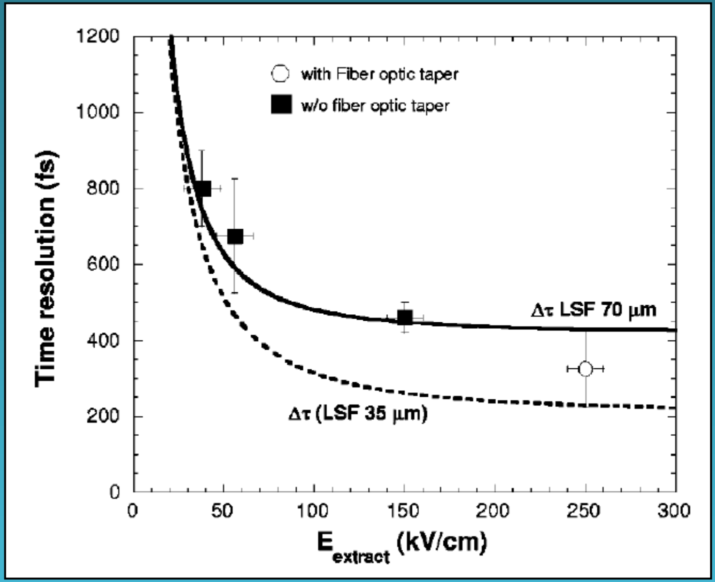


TIME RESOLUTION LIMITING FACTORS

- **TRANSIT TIME DISPERSION**

In the case of a potassium iodide photocathode the FWHM of the energy dispersion $\Delta\kappa T$ =0.61 eV

$$E_{extract} \approx \frac{2.3 \times 10^{7}}{t_{ph}(fs)} \ (\mathrm{V}/cm)$$



P. Gallant et al., Rev. Sci Instr. **71**, 3627 (2000)

In order to keep transit time dispersion at the 100 fs level, fields up to 2E5 V/cm are required. Such fields can be applied in the pulsed regime.

TIME RESOLUTION LIMITING FACTORS

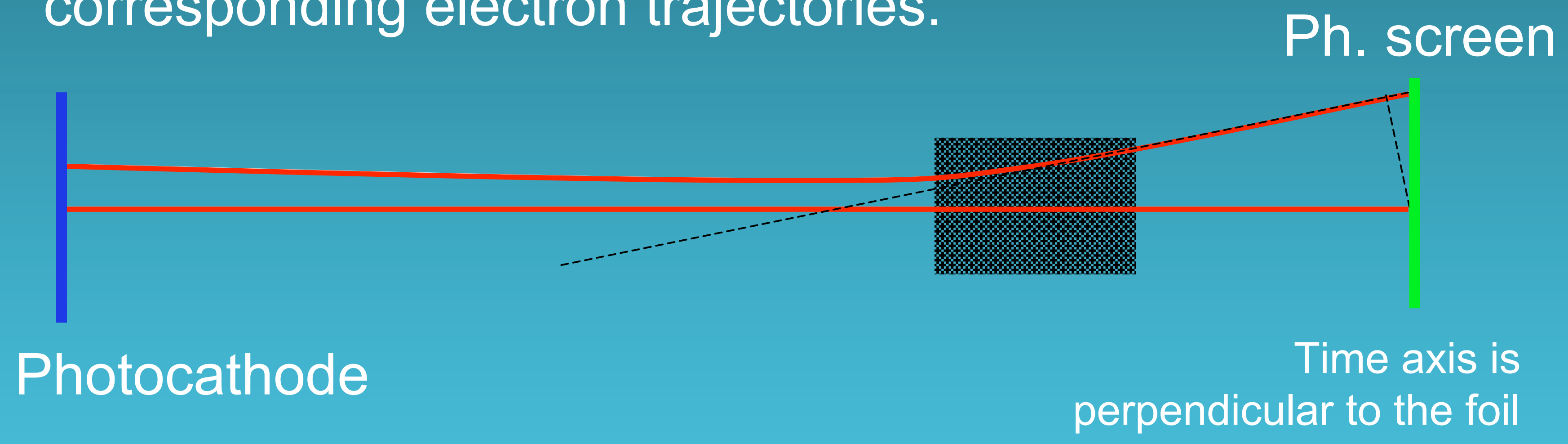
- **SPACE-CHARGE**: affects the time resolution where (along the propagation trajectory of electrons in the streak-camera) higher charge density occurs for a significant time. This contribution can be controlled by appropriate electron optics geometry and by operating the camera at a very low incident flux …

In general, the time resolution of a streak-camera is given by a Gaussian convolution of the three factors:

$$\Delta\tau = \sqrt{t_s^2 + t_{ph}^2 + t_{sc}^2}$$

IMAGE FORMATION PROPERTIES

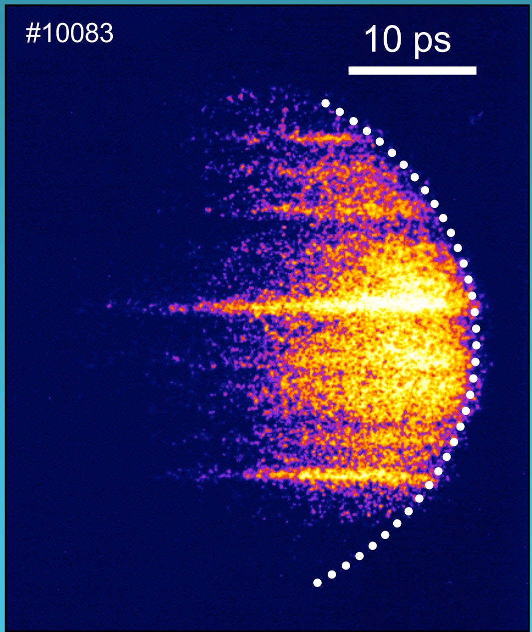
The final image on the phosphor screen suffers from severe aberrations off the optical axis, due to the geometrical properties of the SC tube and the corresponding electron trajectories.



Off axis trajectories reach the phosphor screen later in time

IMAGE FORMATION PROPERTIES

Time resolved spectrum of soft X-ray emission from a picosecond laser produced carbon plasma. The spectrum was obtained using a flat-field grazing incidence grating (2400 l/mm) and a Kentech fast camera equipped with a KBr photocathode



Carbon Ly-α
(33.74 Å)

A fit of the curve is needed to perform image processing and remove curvature.

Fit parameters can be used to estimate the streak rate

See also D.Riley et al., PRL **69**, 3739 (1992)

Accumulation mode measurements

In many applications, low instantaneous X-ray flux and low dynamic range of streak cameras are a strong limitation

↓

In these circumstances it is necessary to proceed with accumulation of data over a large number of shots

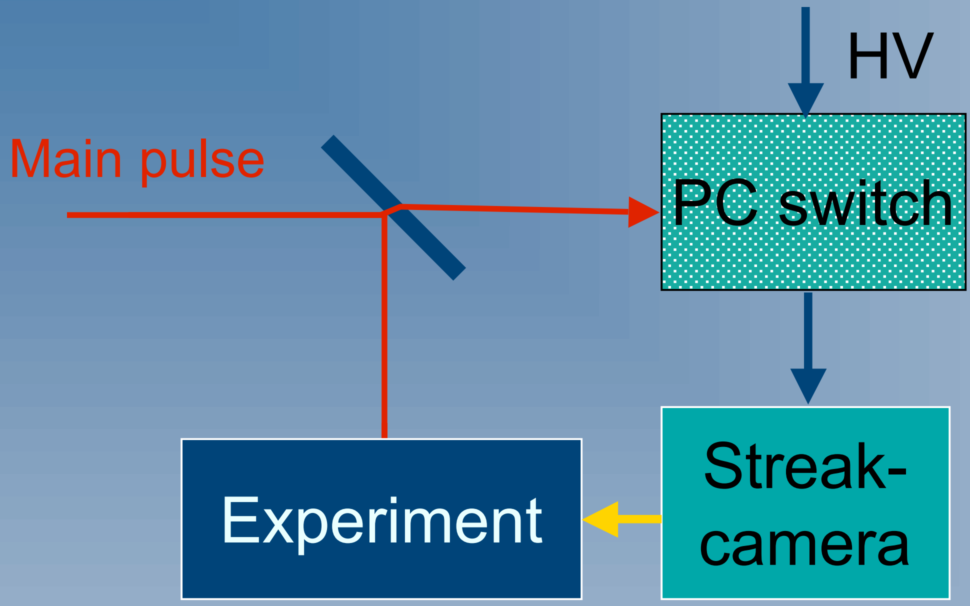
↓

In order for accumulation to be meaningful in time-resolved measurements, the temporal shot-to-shot fluctuations (jitter) must be much smaller that the time-resolution aimed for.

↓

In pump and probe experiments with kilohertz Ti:Sapphire lasers (possibly combined with synchrotron sources), the laser pulse is used to pump the sample and to trigger a photoconductive switch

Jitter control using photoconductive switches



The streak-camera deflection plates are driven by high ramping voltage pulses generated through a single photoconductive switch. The resistance of the switch is inversely proportional to the absorbed laser energy [1]:

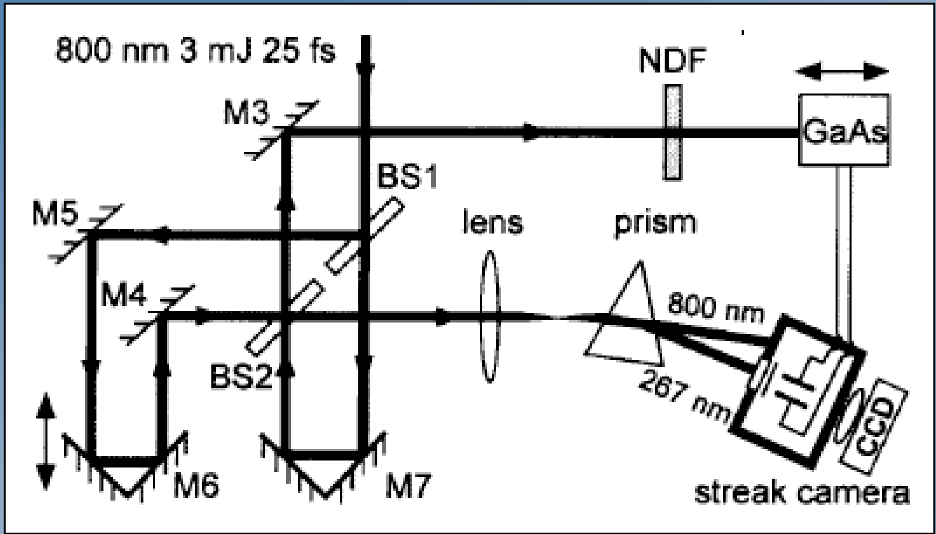
$$R_{sw} = h\nu\, l V_0 / 2 v_s e E_a = \alpha / E_L$$

The timing jitter of the photoconductive switch arises from laser-pulse energy fluctuations.

$$\tau_j = t_{ramp} \left(\Delta E_L / E_L \right) \left(\alpha / \left(\alpha + R + E_L \right) \right)$$

[1] G. Mourou and W. Knox, Appl. Phys. Lett. 35, 492 (1979)

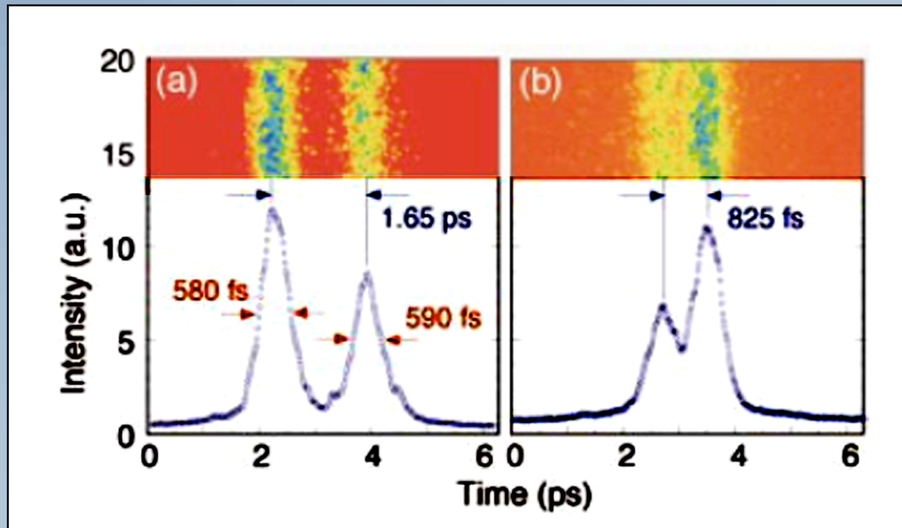
Synchronising Laser and Streak-camera



J.Liu et al., Appl. Phys. Lett., **82**, 3553 (2003)

The streak-camera deflection plates are driven by high ramping voltage pulses generated through a single photoconductive switch.

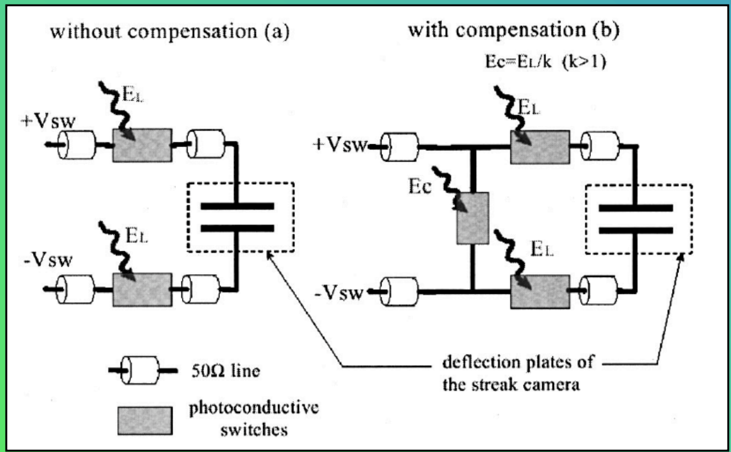
Streaked images and corresponding average lineouts of two 30 fs UV (4th H of TiSa) separated by 1650 fs (a) and 825 fs (b), accumulated over 6000 shots and a 1.2% rms energy fluctuations.



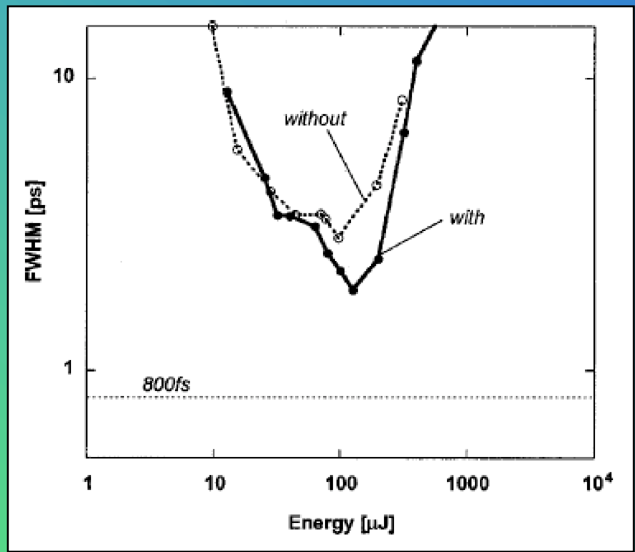
J. Liu et al., APL **82**, 3553 (2003)

Jitter free set-up

Laser systems characterised by a large energy fluctuation require a more complex set-up [✜]



Additional jitter arises from shot-to-shot fluctuations of the pulse contrast (prepulse and/or ASE)



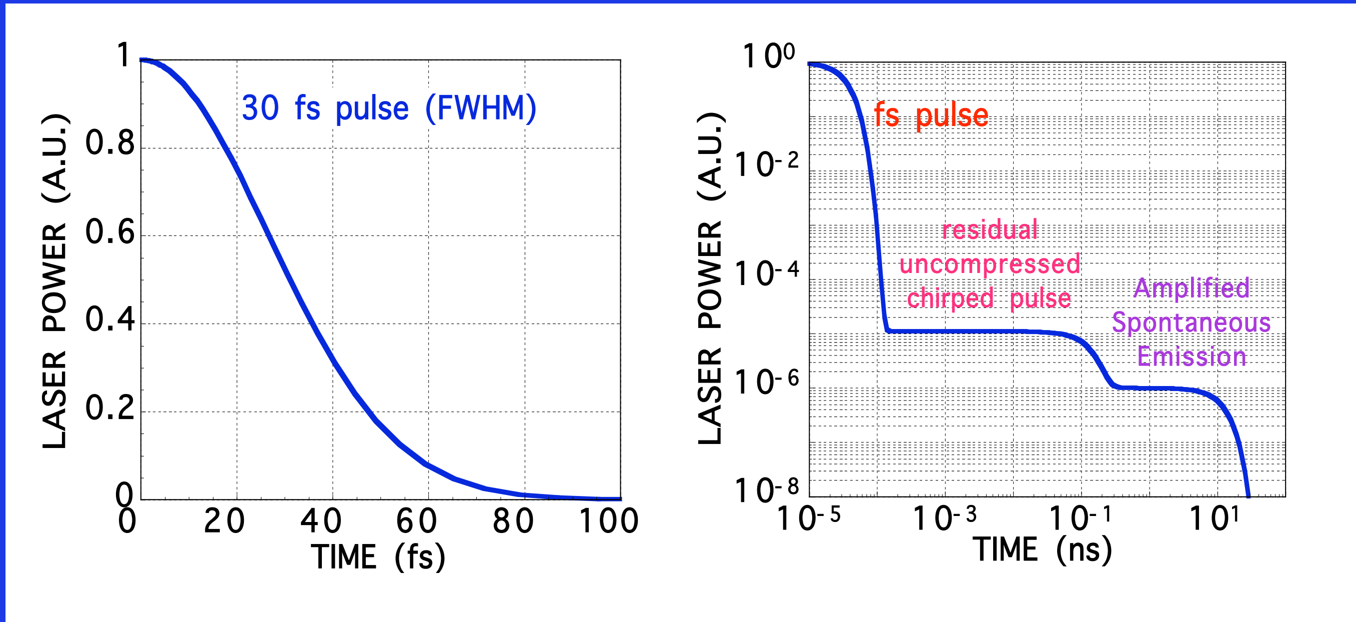
The use of additional PC switch in parallel enables a jitter free configuration to be achieved

Dynamics of laser pulse (prepulse) must be controlled …

[✜] C. Belzile et al., Rev. Sci. Instr. **73**, 1617 (2002)

TYPICAL CPA LASER PULSE DYNAMICS

The type of interaction of femtosecond pulses with solida depends critically upon the laser-pulse intensity on a large dynamic range

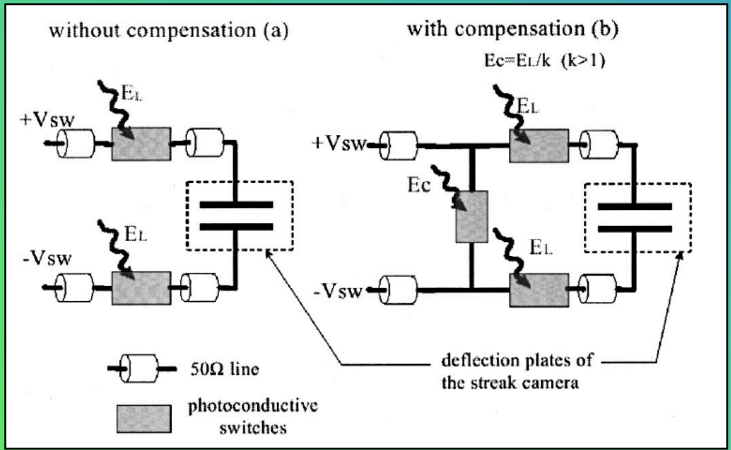


Contrast ratio (CPA power/ASE power) for TiSa lasers tipically smaller than to 10^7

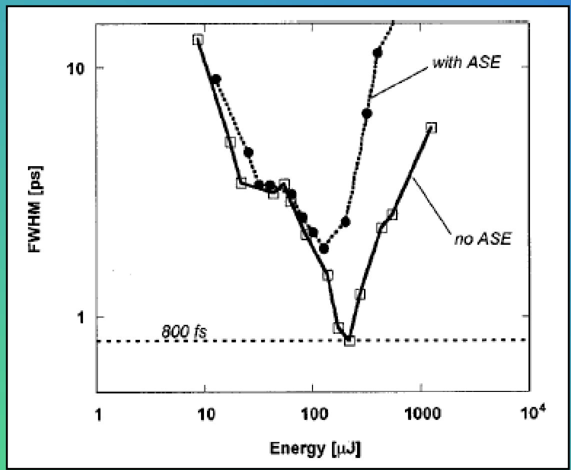
Contrast ratio can be improved in many ways: frequency doubling, plasma mirror, saturable absorbers …

Jitter free set-up

Laser systems characterised by a large energy fluctuation require a more complex set-up [✜]



Additional jitter arises from shot-to-shot fluctuations of the pulse contrast (prepulse and/or ASE)



Reduction of ASE with saturable amplifiers gives jitter-free performance

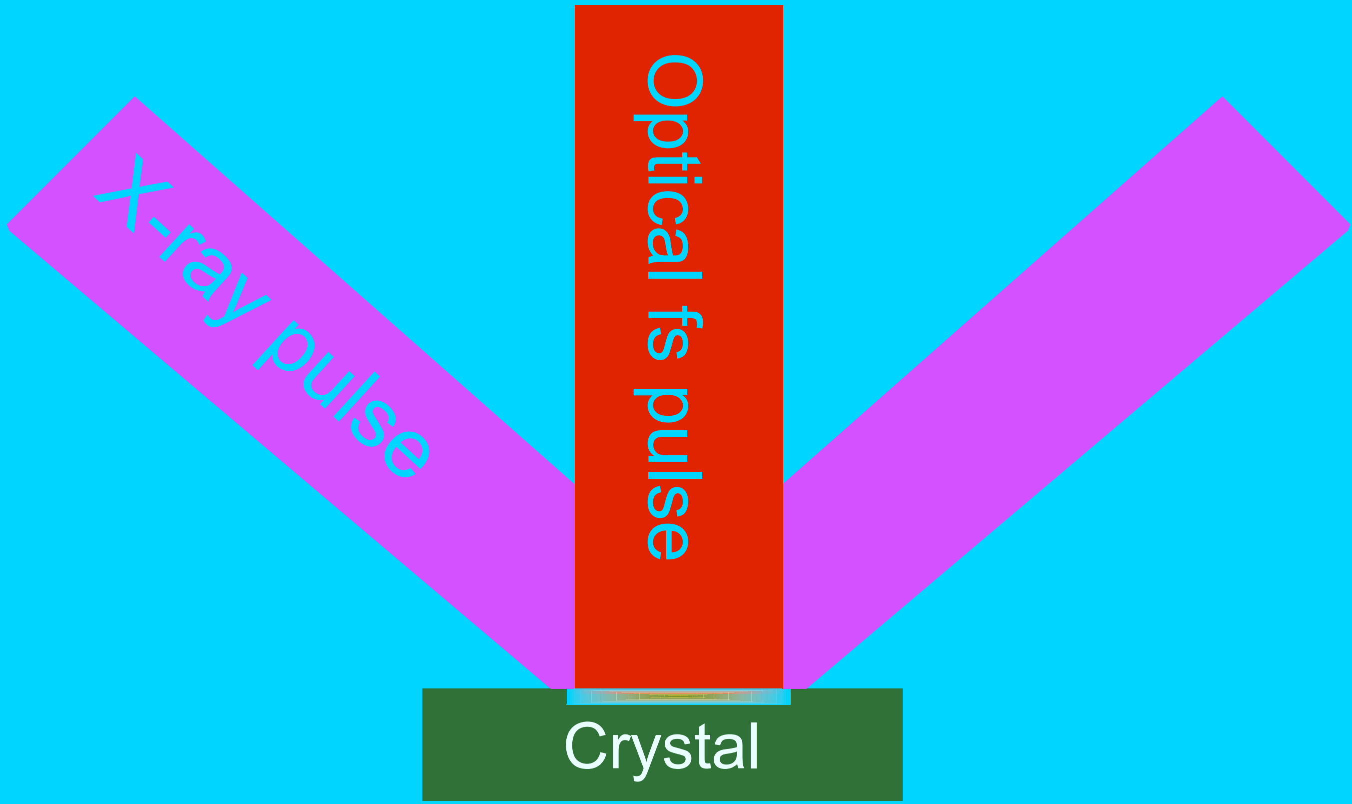
[✜] C. Belzile et al., Rev. Sci. Instr. **73**, 1617 (2002)

Indirect techniques

Cross correlation

Cross-correlation measurement

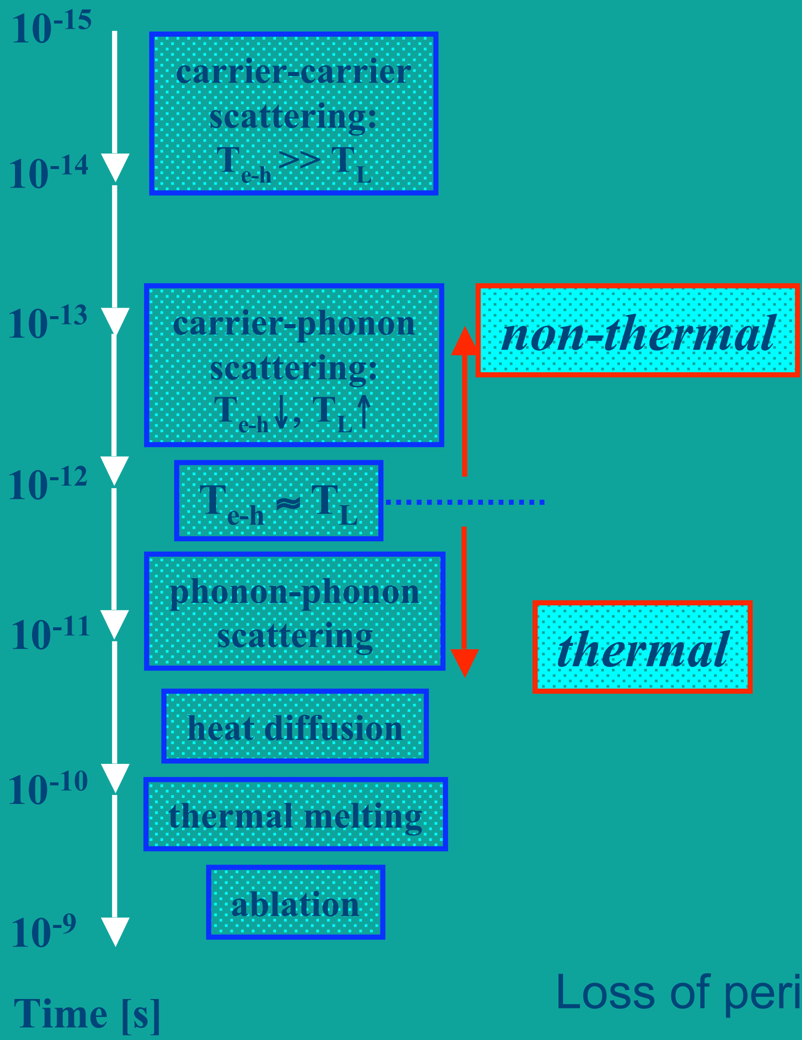
The pulse duration of a femtosecond X-ray pulse can be investigated performing a cross-correlation measurement based upon a laser-triggered ultrafast structural changes in crystals

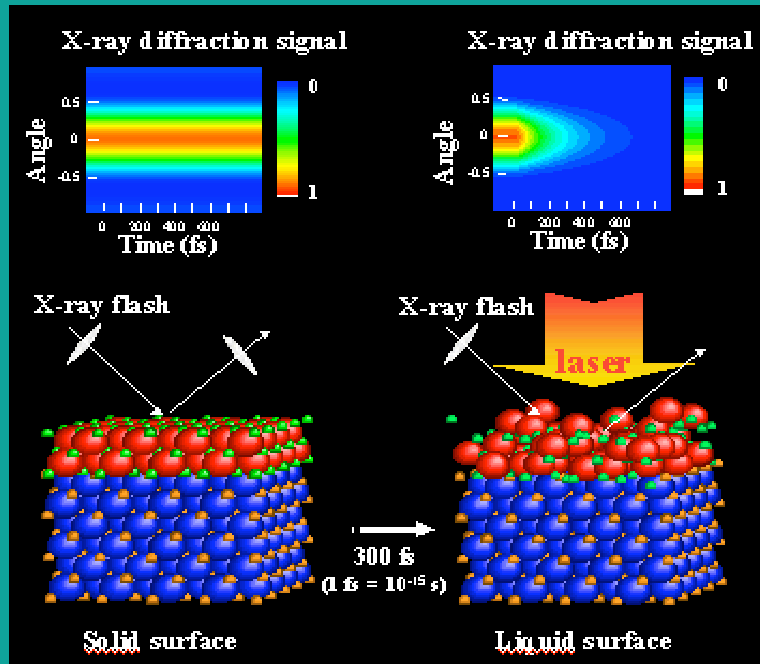


Provided structural changes are occur on a time-scale faster than the X-ray pulse width, information on the pulse evolution can be derived by the cross correlation curve.

Non-thermal melting

Periodicity of the sample is disrupted on a very short time-scale



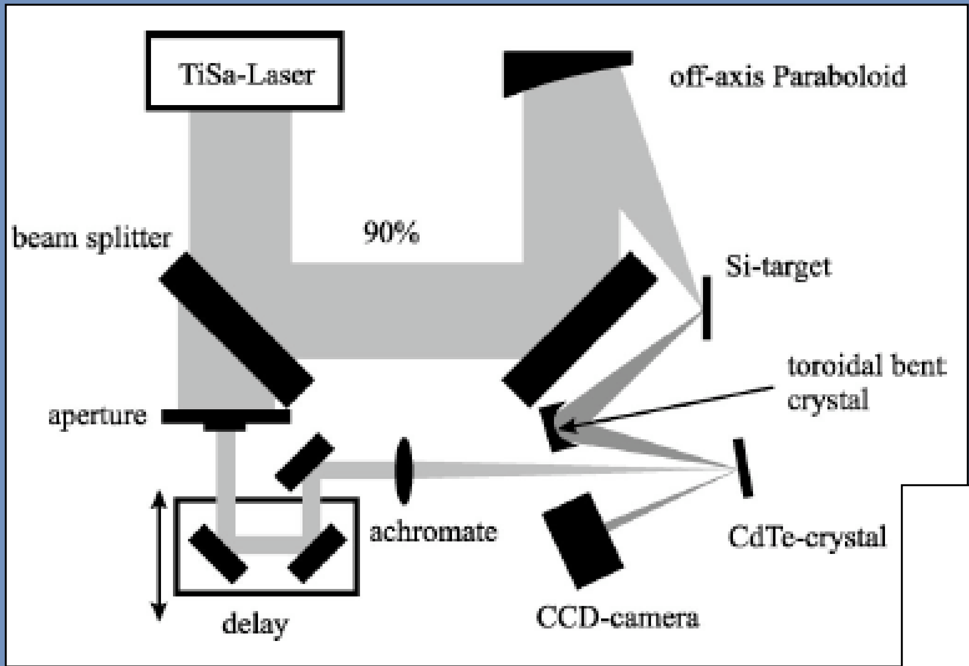


A. Rousse et al, Nature 410 (2001)

Loss of periodicity ➔ no more constructive interference

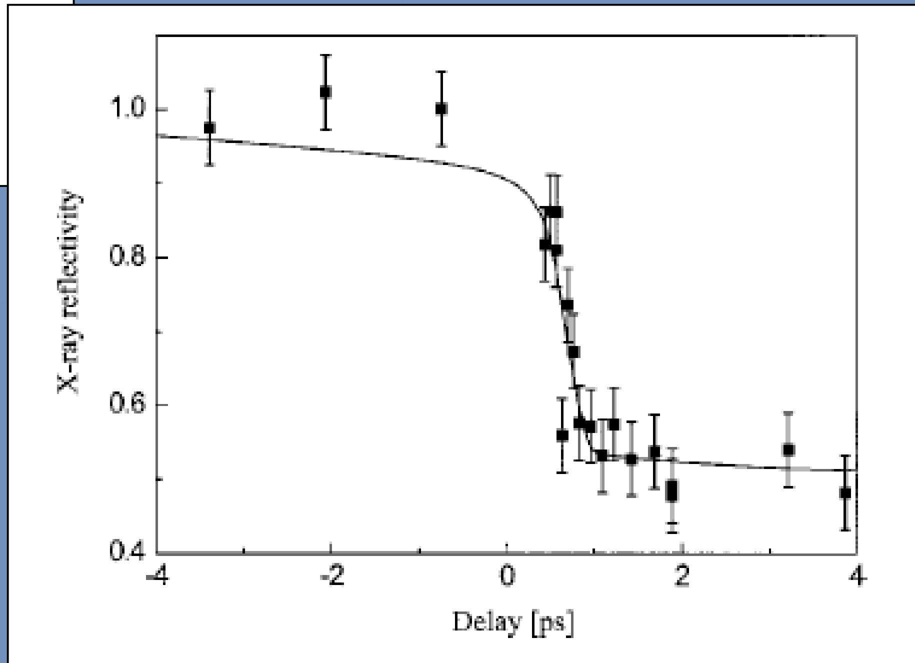
Sokolowski-Tinten et al., Phys. Rev. Lett. **87**, 225701 (2001)

Cross-correlation measurement



X-ray signal is Bragg reflected by a CdTe crystal in a pump and probe scheme

T.Feurer et al., Phys. Rev. E, **65**,016412 (2001)



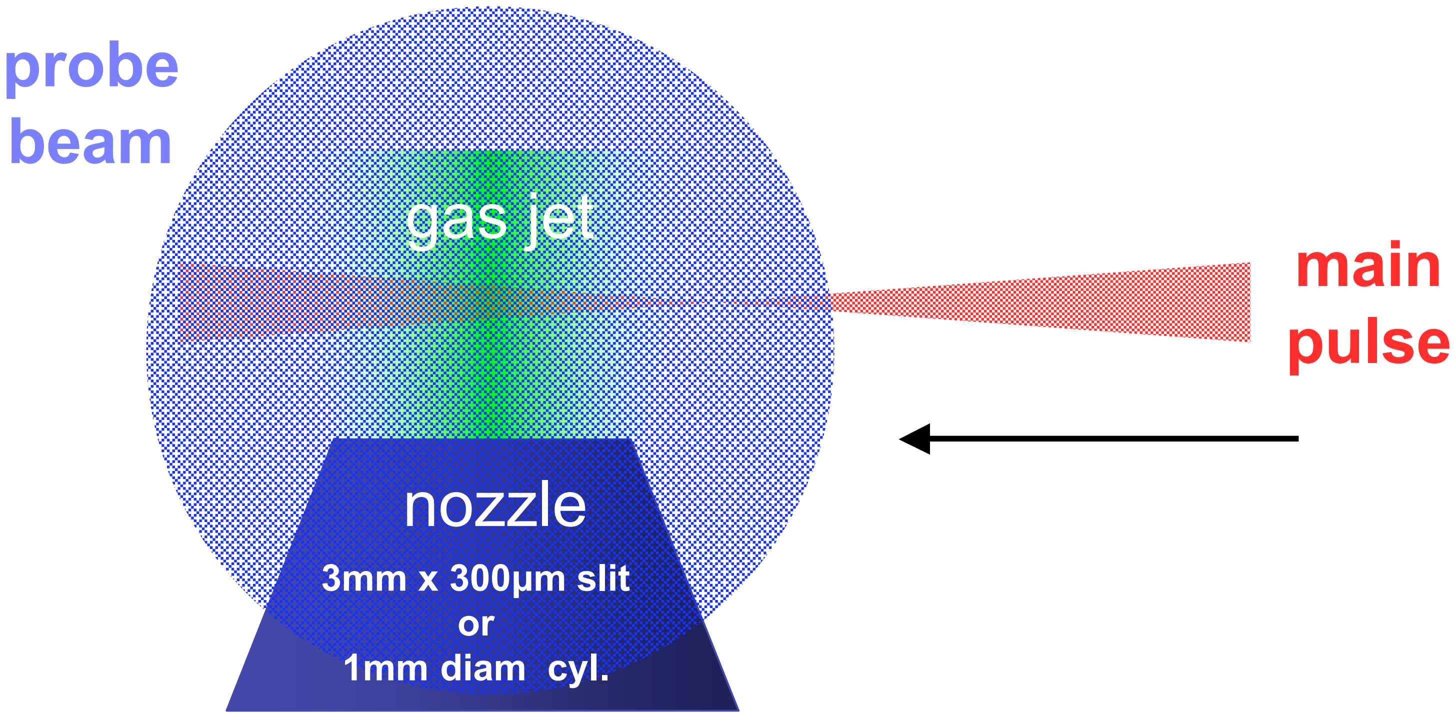
Bragg reflected signal drops in a fraction of a picosecond following disruption of CdTe lattice due to non-thermal melting

Indirect techniques

Pulse detection via plasma ionisation

Study of pulse propagation

The pulse propagates in a gas jet



Ionisation model

Ionisation potential

Rate of t.i.

$$\Gamma_{qs}(t) = A_{n^*,l^*} \; B_{l,|m|} \; I_p \left(\frac{2(2I_p)^{3/2}}{E \; f(t) \; |\cos\phi(t)|} \right)^{2n^*-|m|-1} \times \exp\left(-\frac{2(2I_p)^{3/2}}{3E\, f(t) \; |\cos\phi(t)|} \right)$$

Field Amplitude

Instantaneous phase

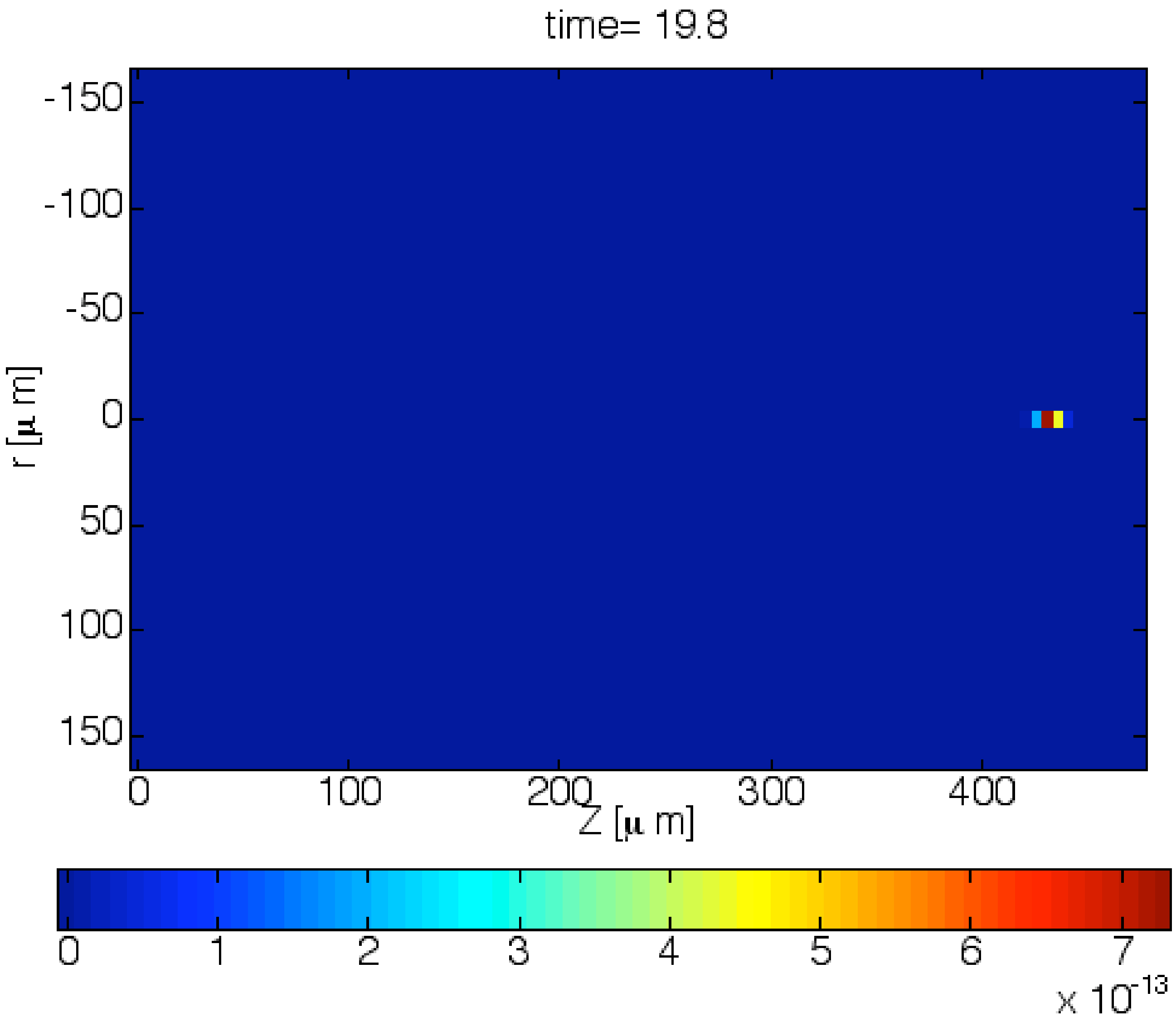
$$A_{n^*,l^*} = 2^{2n^*} \big/ (n^*\Gamma(n^*+l^*+1)\Gamma(n^*-l^*))$$

$$B_{l,|m|} = (2l+1)(l+|m|)! \big/ (2^{|m|}\,|m|!\;(l-|m|)!)$$

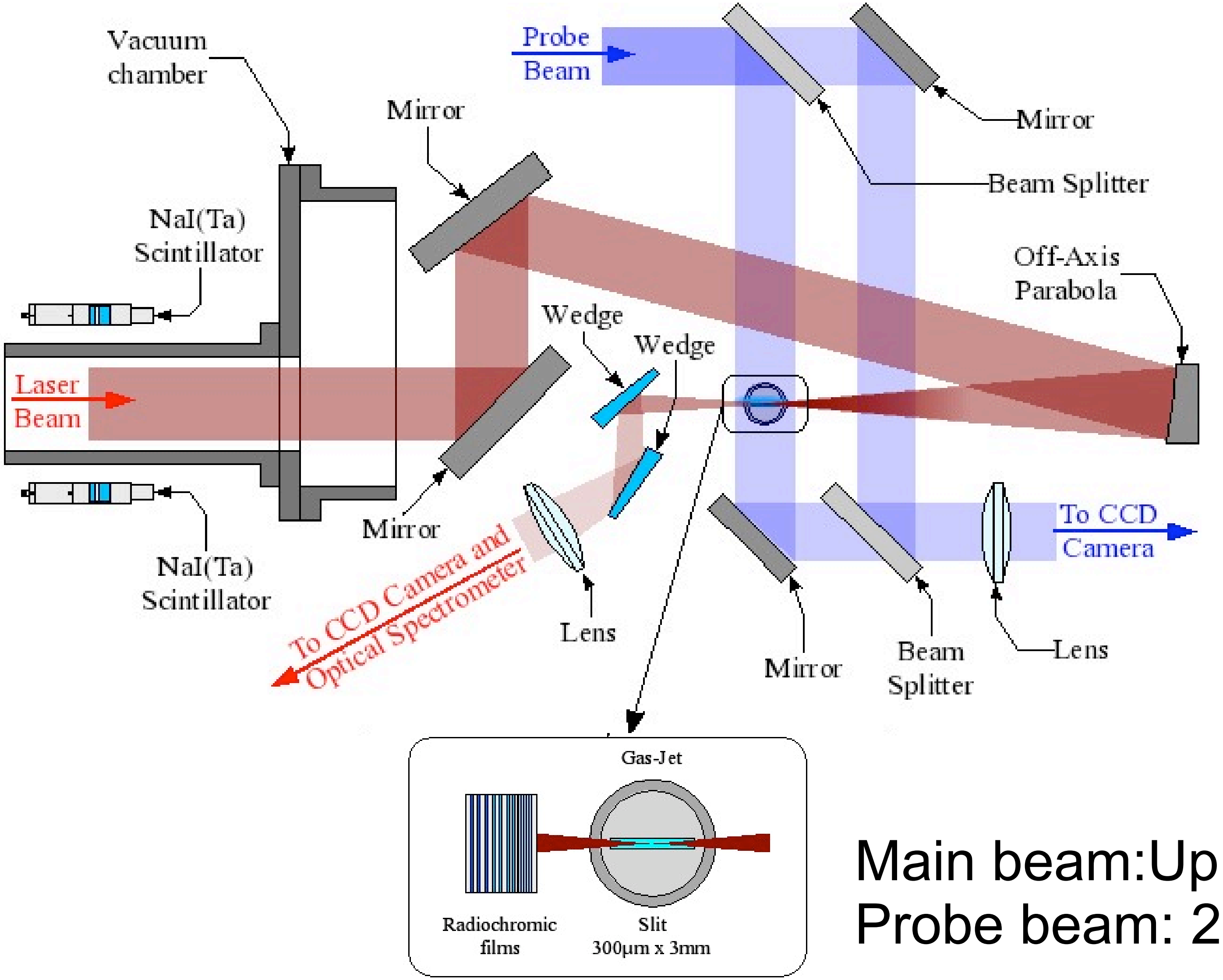
$$\gamma \text{ - } 1,\; \gamma^2 = I_p \big/ 2U_p,\; U_p = E^2 \big/ 4\omega_L^2\,(a.u.)$$

G.L.Yudin and M.Y. Ivanov, PRA, 64013409 (2001)

Calculated density map (N_2)



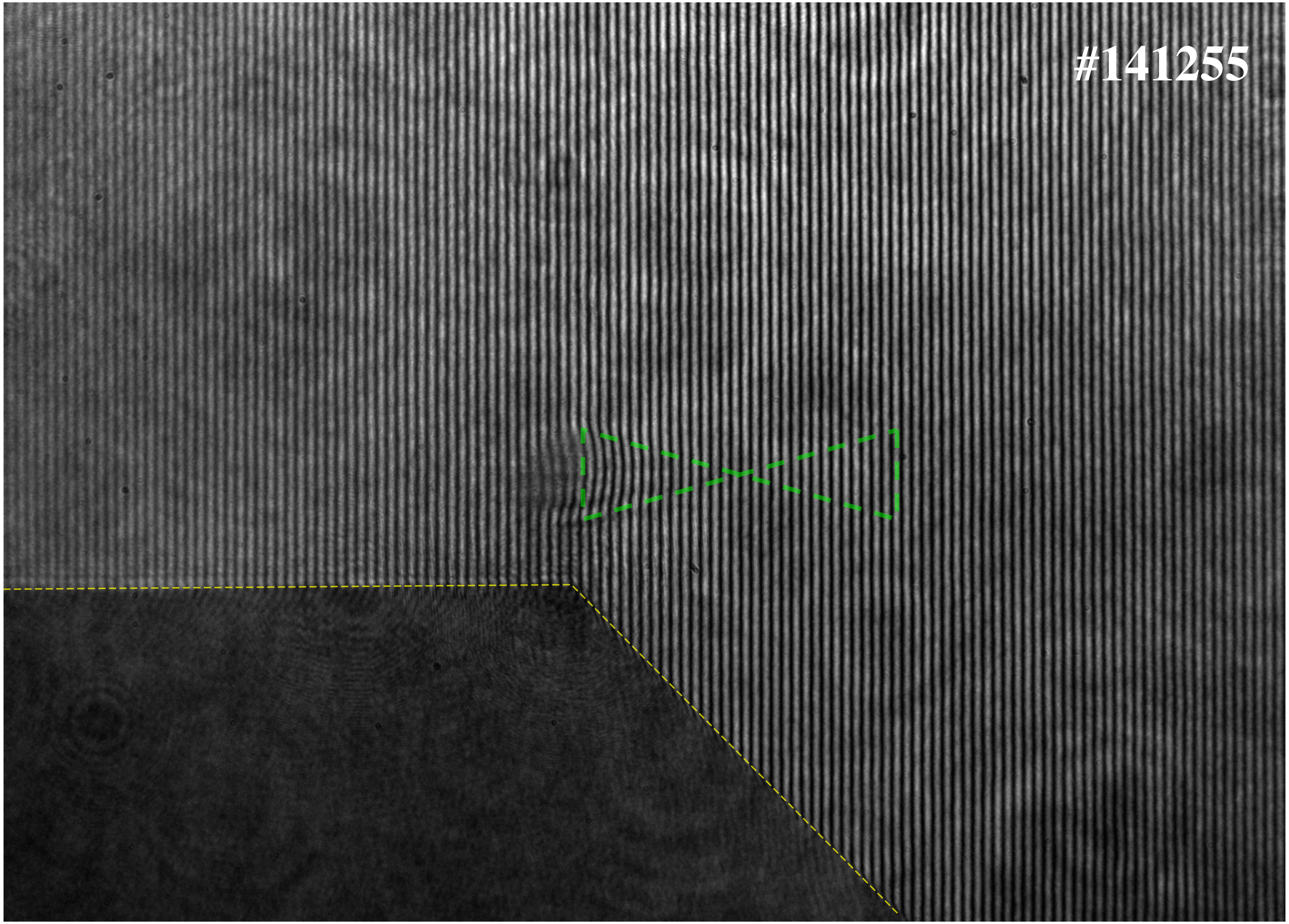
An overview of the experiment



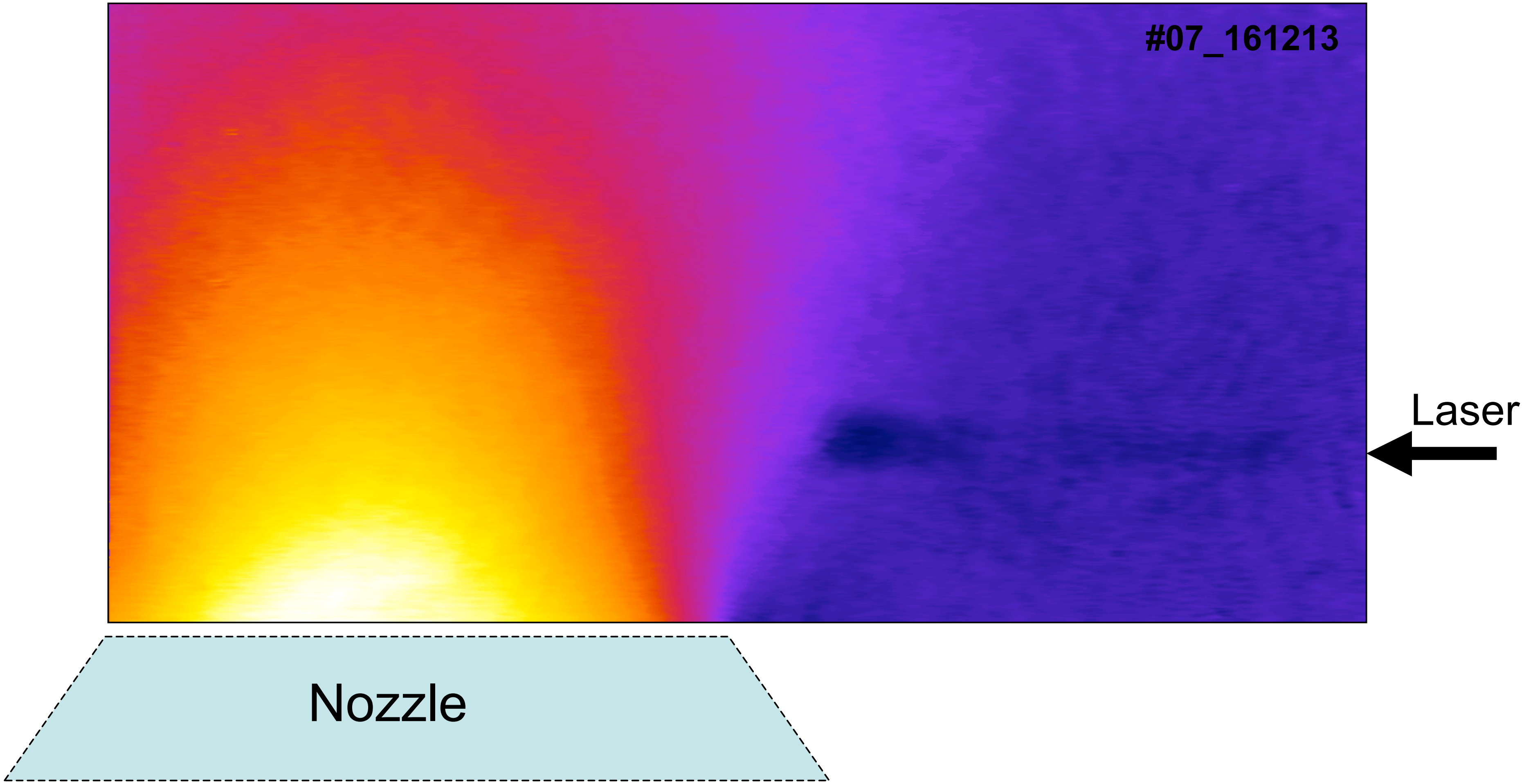
MAIN DIAGNOSTICS
- **Interferometer**
- **5,5μm/px and 1,64 μm/px**
- **Probe pulse duration (70-80 fs)**
- **Transmitted beam measurements (image and spectrum**
- **γ-ray detectors (NaI+PM)**
- **Radiochromic film detector (SHEEBA)**

Main beam:Up to 0.7 J, 65 fs
Probe beam: 2ω

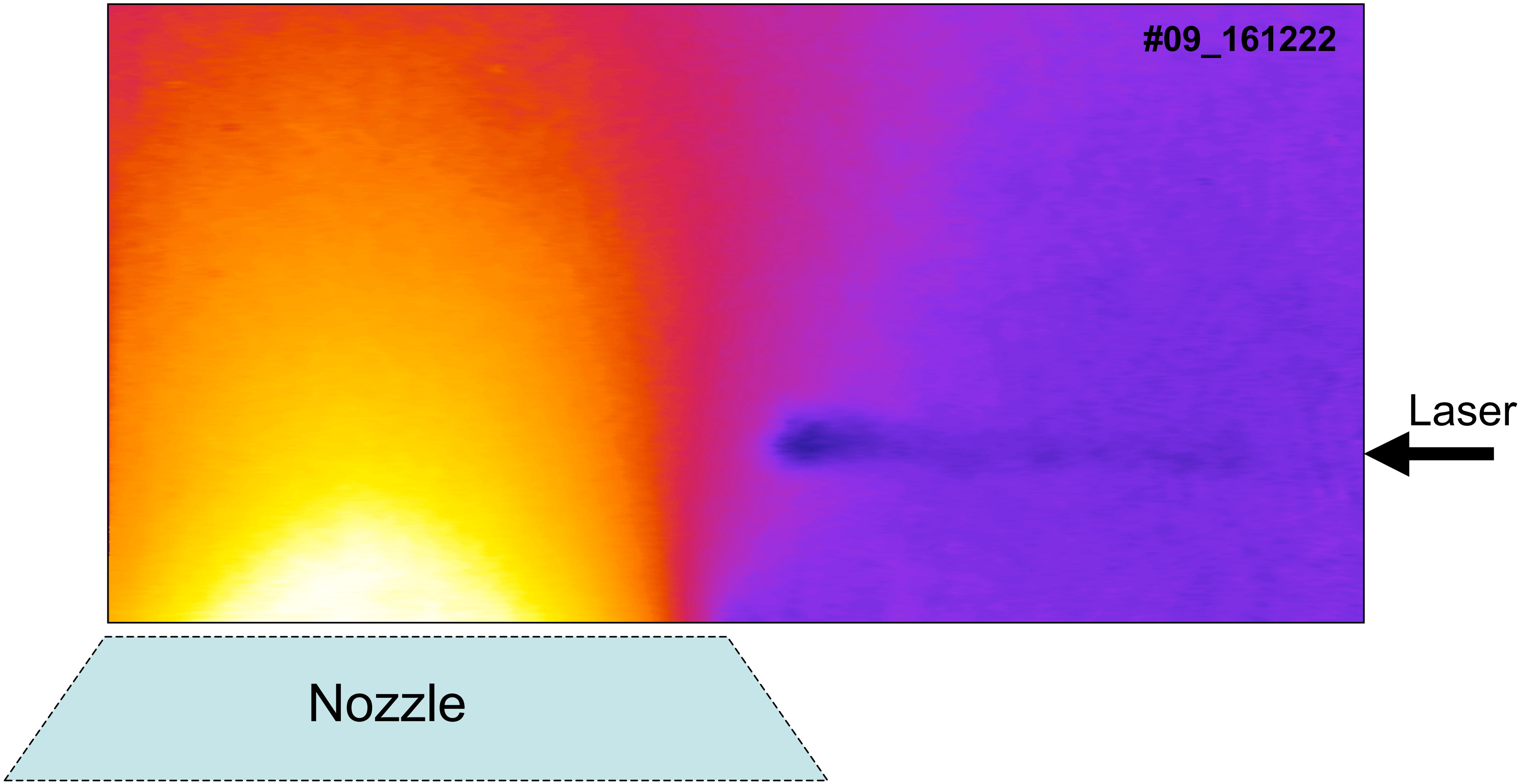
Interferometry with a fs probe pulse



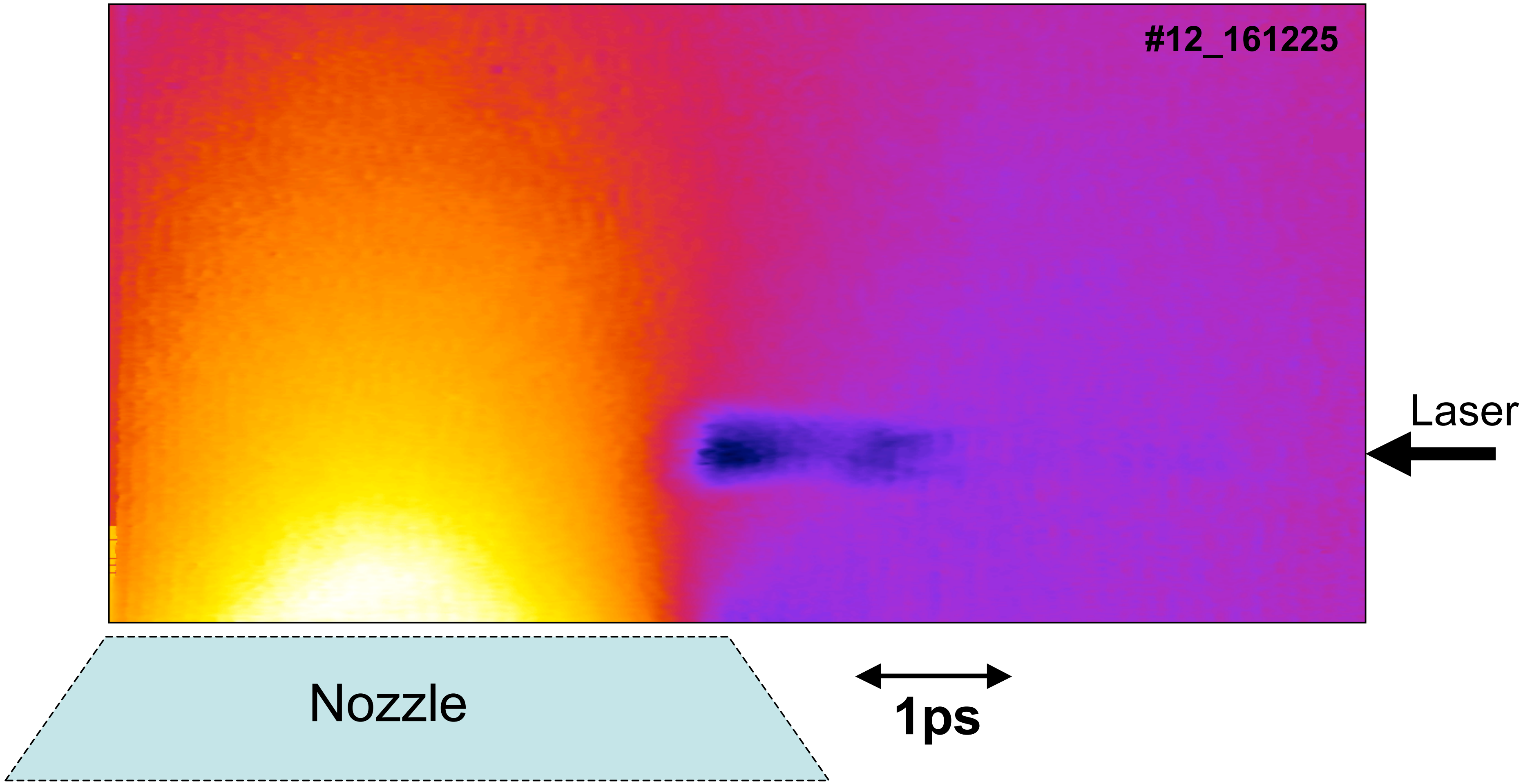
Map of phase shift (N_2)



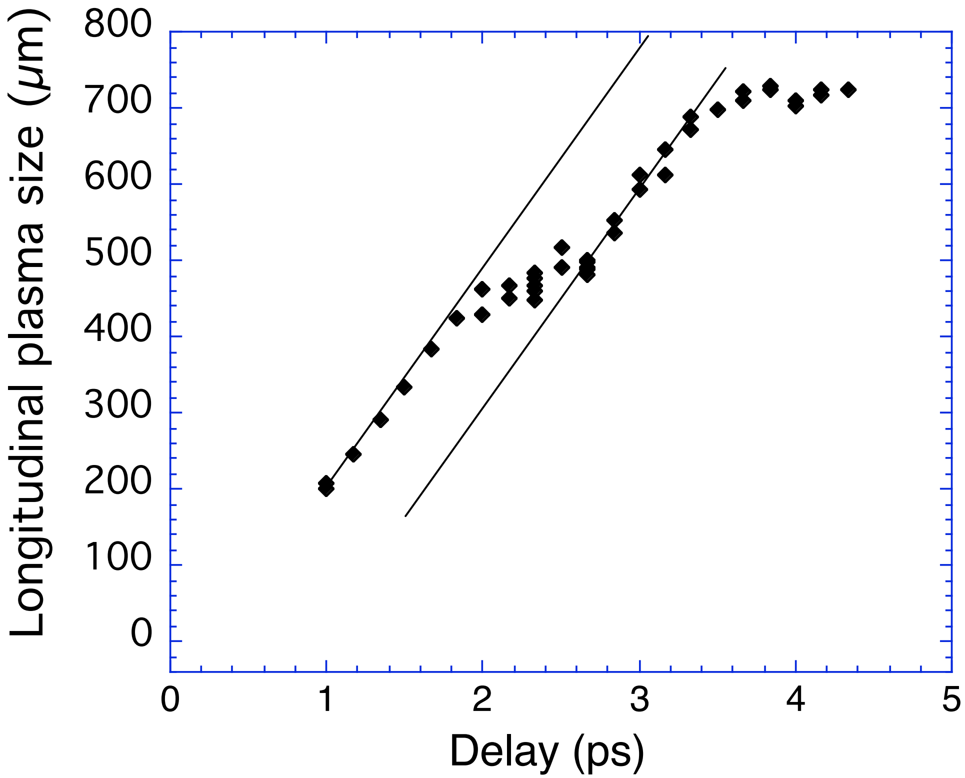
Map of phase shift (N_2)

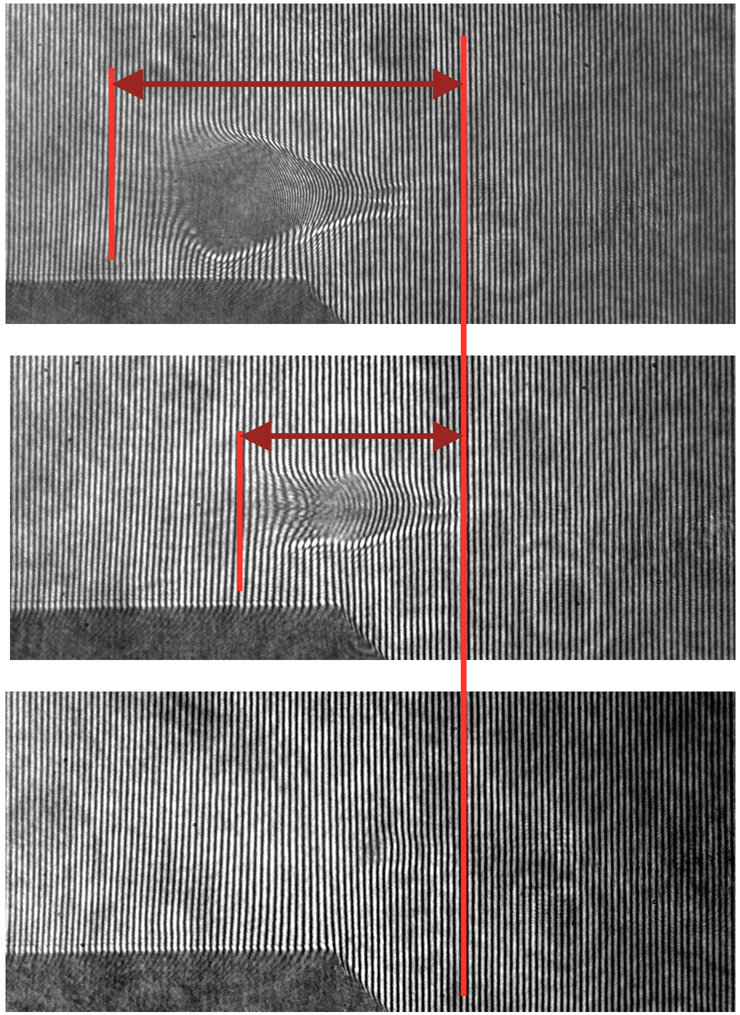


Map of phase shift (N_2)

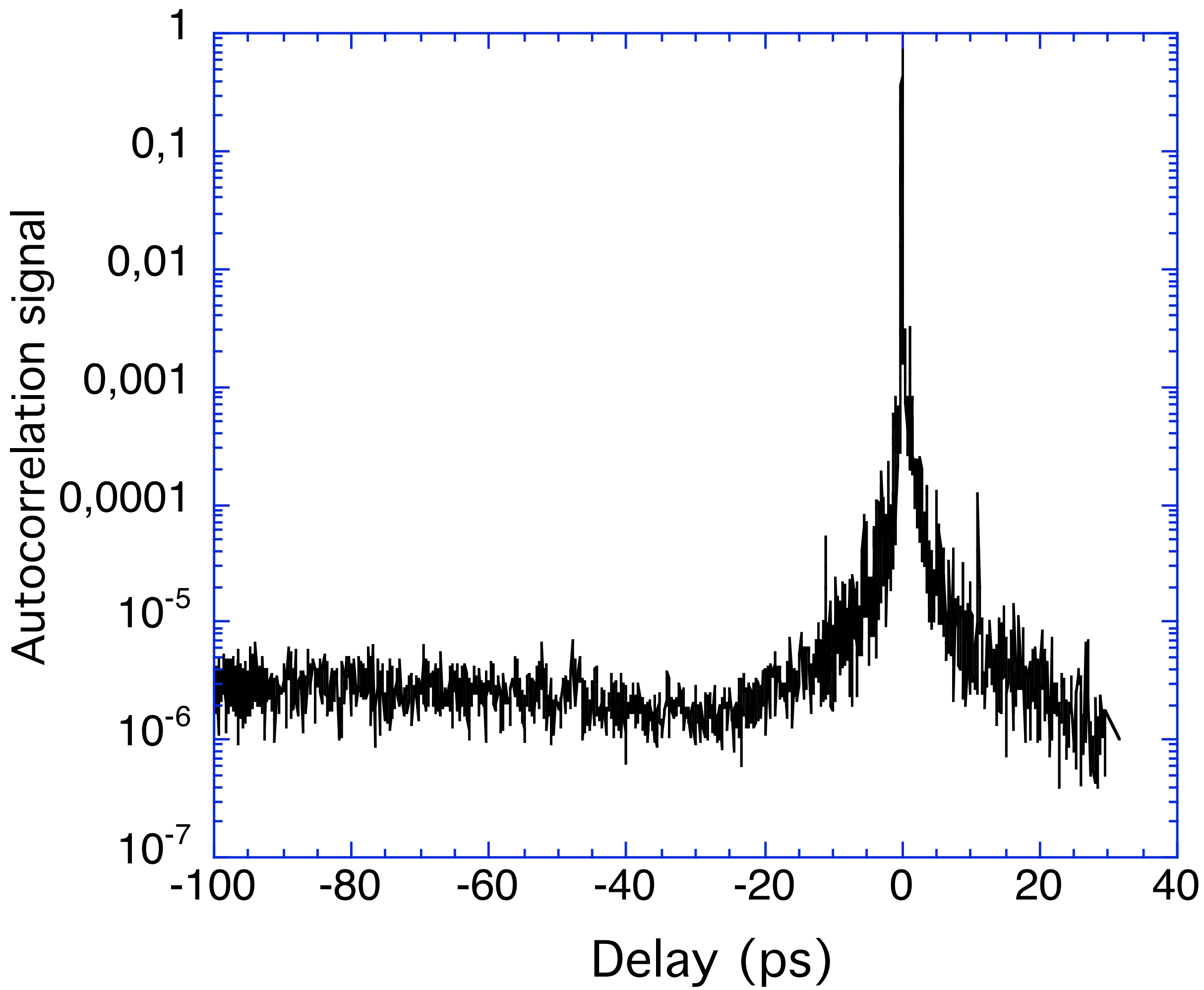


History - Longitudinal extent (N$_2$)

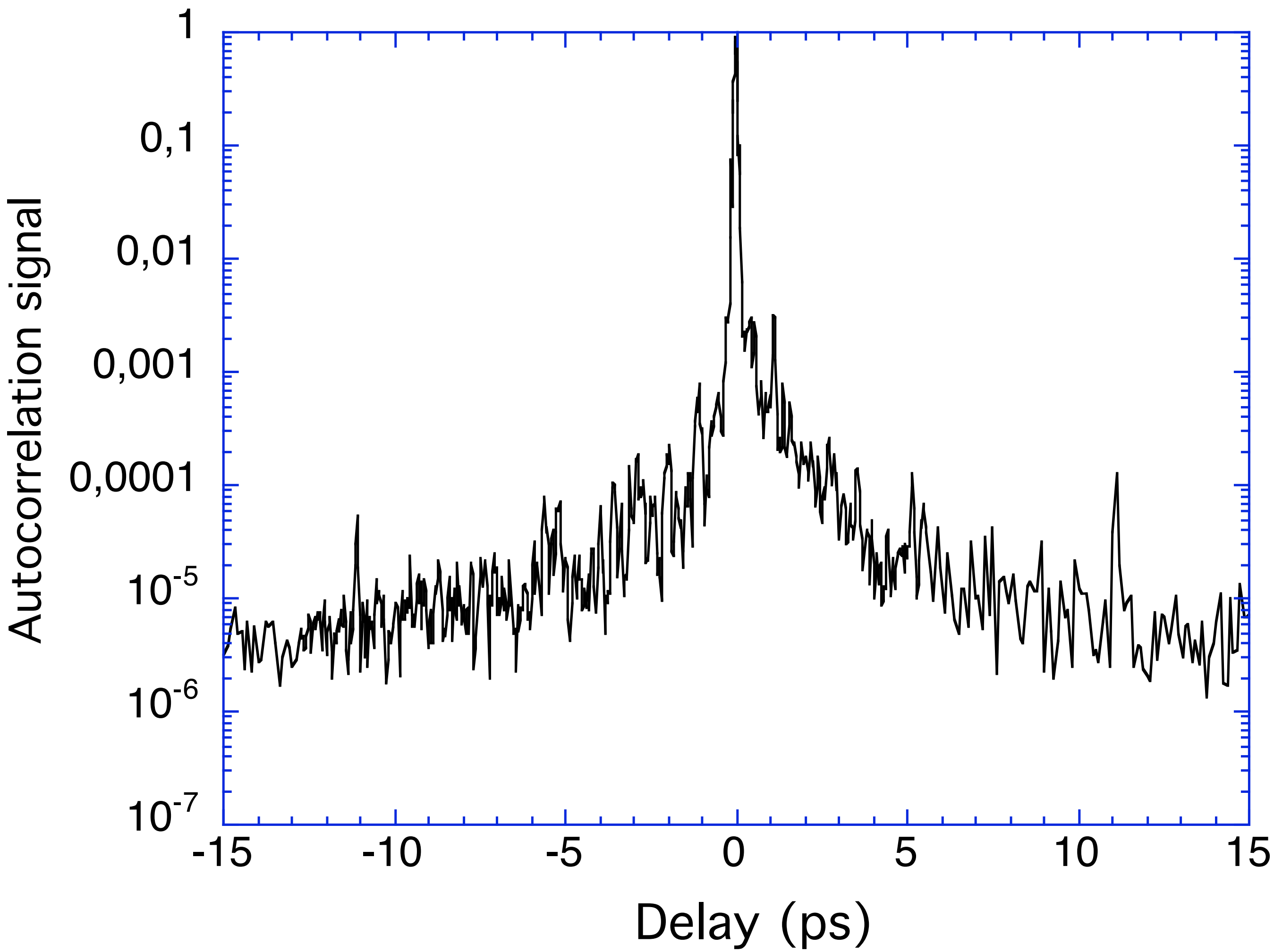




Third order autocorrelation of the SLIC laser pulse



Picosecond scale features



PROPOSALS OF FUTURE ACTIVITIES WITHIN SPARX

- STREAK-CAMERA DEVELOPMENT
  - Photocathode characterization: new materials with low secondary electron dispersion;
  - Electron optics design: reduce transit time dispersion;
  - Implementation of photoconductive switch triggering system (already proposed within SPARC).
- CROSS-CORRELATION TECHNIQUES
  - Implement with existing intense laser systems (already proposed within SPARX)
  - Investigate possible extension to soft X-rays and EUV
- IONISATION IN GASES
  - Promote a case study for ultra-high temporal resolution temporal investigation of optical/EUV pulses