Istituto di Fisica Atomica e Molecolare
Area della Ricerca del CNR - Ghezzano - Pisa Italy

NEW CONCEPT X-RAY SOURCES AT IFAM

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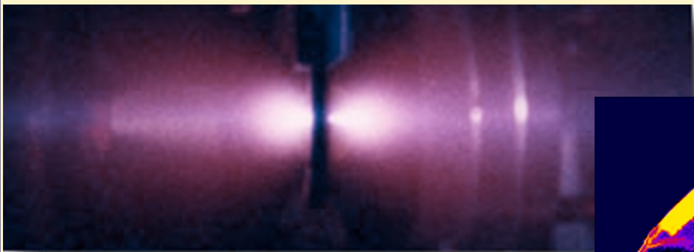
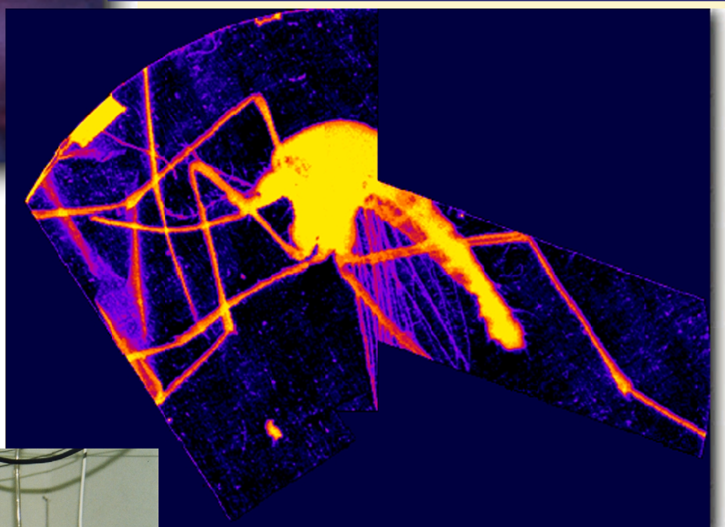
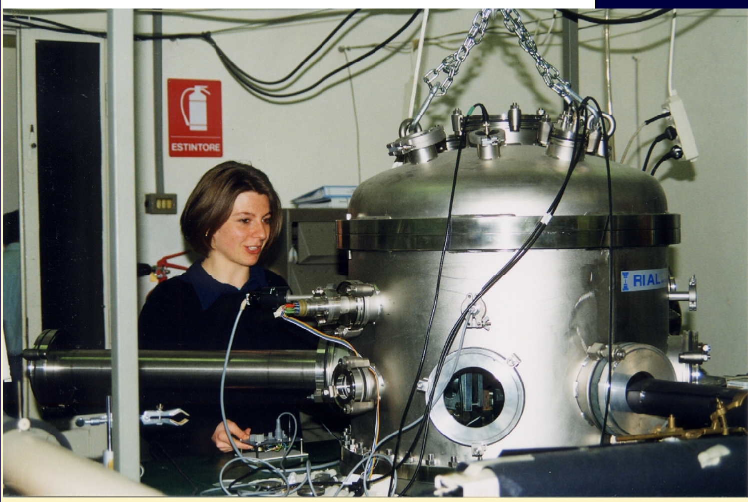




Rapporto Interno IFAM
N.4/2000 del 1/12/2000



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Introduction

The dramatic development of high-power lasers has given new impulse to the applications of X-ray sources based on laser produced plasmas. The high repetition rate of CPA pulses is pushing the average power of laser-plasma sources to levels competitive with small synchrotron sources and is becoming of interest for industrial applications.

On the other hand, 'traditional' laser-plasma sources, based on low repetition-rate, high power nanosecond lasers, can now be characterised in great detail with respect to spectral, spatial and temporal properties so that sophisticated experiments can be performed in a variety of research fields including material sciences, chemistry, biology and medicine.
The work presented in this report is a compendium of the experimental activity performed during the last two years by the laser-plasma interaction Group in the field of generation and applications of laser-plasma X-rays.

A laser-plasma X-ray source has been set up at IFAM using a Single longitudinal mode, nanosecond Neodymium laser. The source has been studied using a wide range of techniques in order to characterise its spatial, spectral and temporal properties. The main results are summarised in the first section of this report.

The second section of this report is devoted to a description of some preliminary applications of the X-ray source to micro-radiography and bio-medical experiments. Examples of projection micro-radiography are shown which were obtained exploiting the small spatial extent of our laser-driven source.

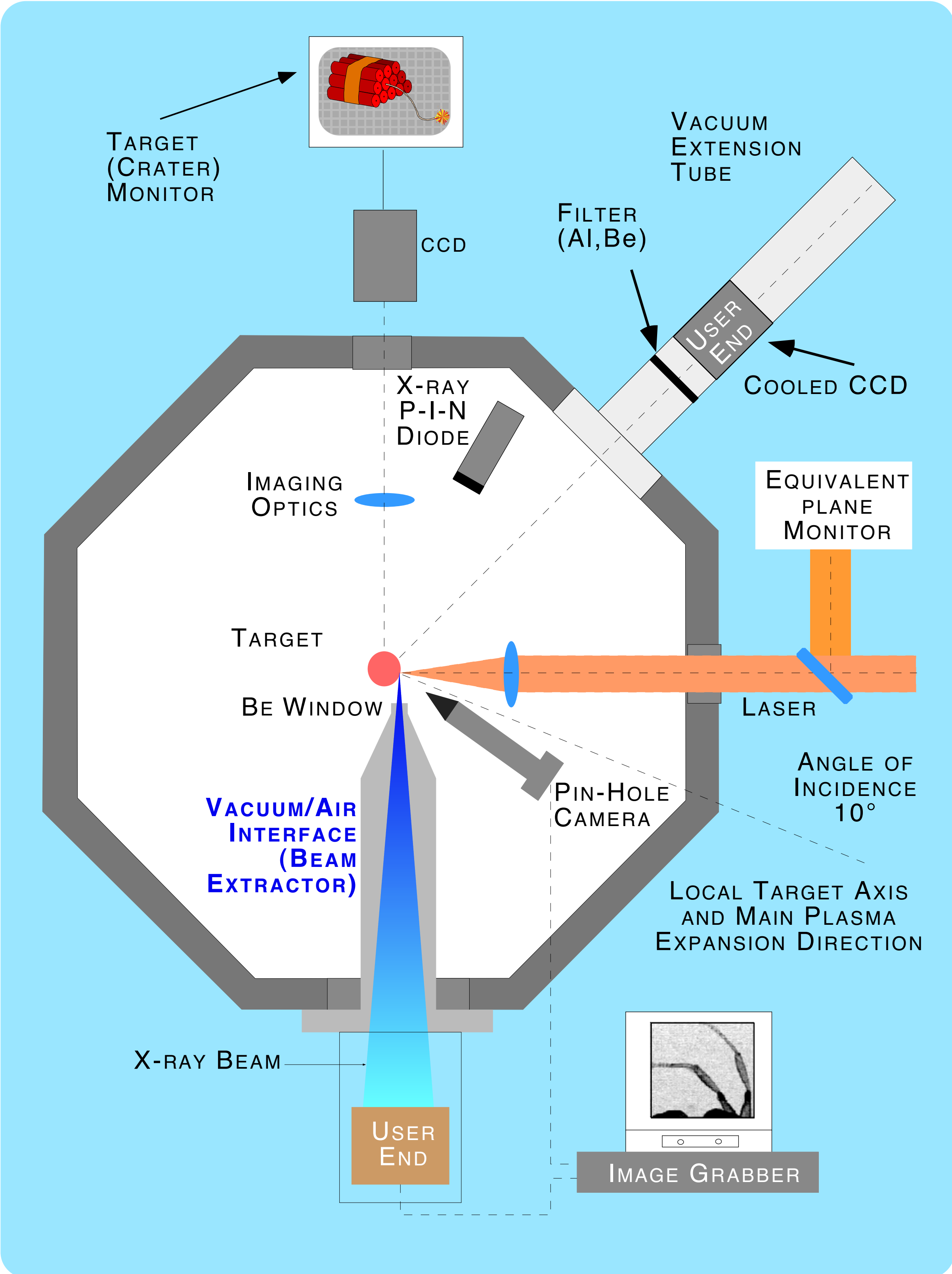
The third section introduces the experiments performed using the latest generation of Chirped Pulse Amplification (CPA), high intensity femtosecond lasers to generate short-lived highly transient plasmas. These plasmas are bright sources of hard X-ray radiation from the 10keV region up to the MeV region. New experimental techniques have been implemented to investigate this novel and unexplored regime of plasma formation and X-ray generation. In particular, low-noise, cooled CCD detectors have been developed to perform single-photon X-ray spectroscopy over a wide range of photon energies. This powerful spectroscopic technique has also been extended to the gamma-ray region using NaI(Tl) detectors.

Soft X-rays from Nanosecond-Laser Plasmas

Overview of the IFAM Source

Following a many-year experience in X-ray diagnostics of laser plasmas, the Laser-Plasma interaction Group at IFAM has established a laser-plasma X-ray source for development and applications. (See Pag.5 for a schematic view of the source with its main components for generation, monitoring and applications of X-rays)
The driving power of the source is a Single Longitudinal and Transverse Mode (SLTM) Neodymium laser operating at its fundamental wavelength of 1.064μm and capable of delivering 1J/ns in a 3 to 20 ns pulse on target. The use of a SLTM system has the major advantage of providing a good reproducibility of pulse shape and energy which result in a stable X-ray conversion efficiency from shot to shot within ten percent.

The IFAM Laser-Plasma X-ray Source



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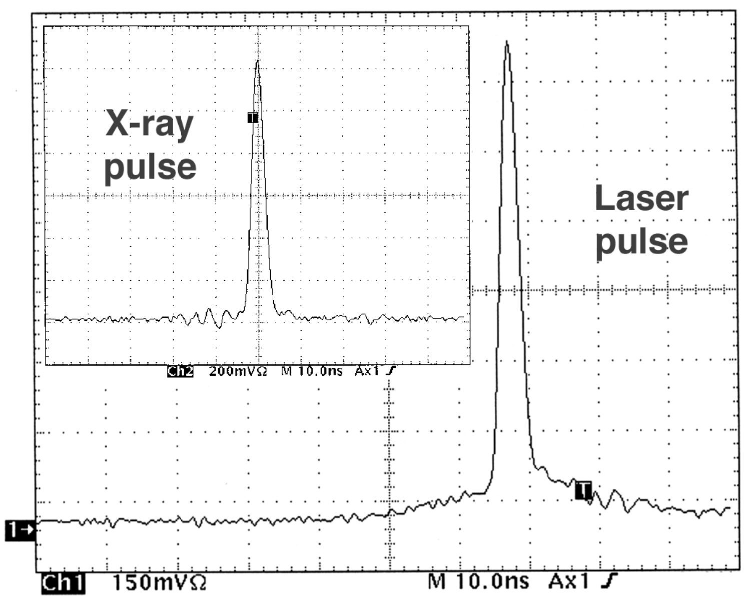
Overview of the IFAM Source (cont'd)

The pulse is focused with an f/4 optics on the surface of a helically moving cylindrical target at an intensity up to a few times 10^{13} W/cm^2. The helical motion of the target enables a fresh surface of the target to be exposed on each laser pulse with a simple mechanism. A set of basic optical and X-ray diagnostics monitor the focusing conditions in order to ensure a high degree of reproducibility of the interaction conditions from pulse to pulse.

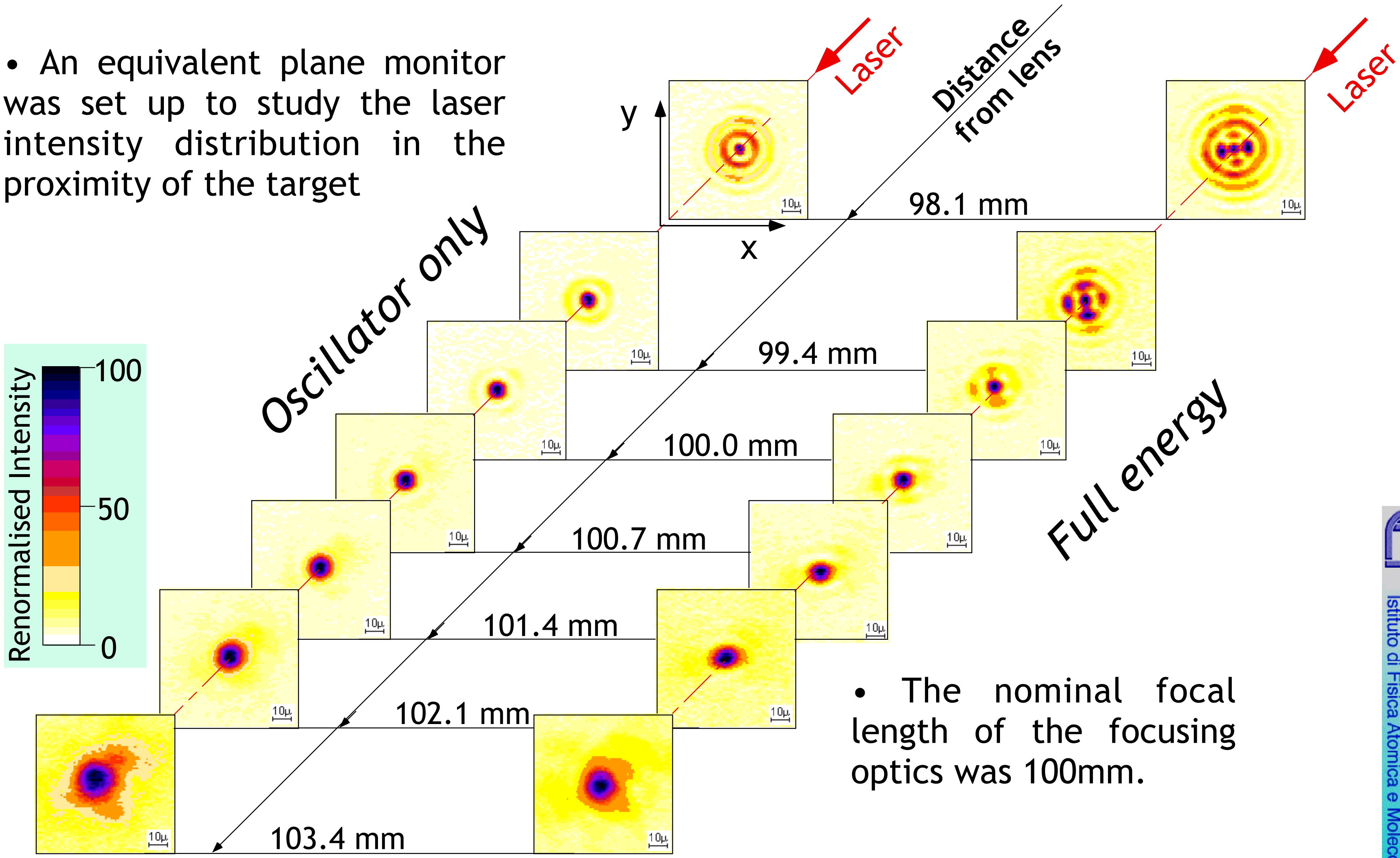
Laser characterisation

Particular attention has been devoted to the characterisation of the laser performance and in particular to the pulse shape and to the intensity profile in the focal spot. The laser energy is controlled by varying the charging voltage of the amplifiers and is constantly monitored by a calibrated photodiode. The pulse-shape of both the laser pulse and the X-ray pulseis monitored using a photodiode and a PIN diode respectively with a rise time of ≈1ns. The shape of a typical 3ns pulse and the corresponding X-ray pulse is shown opposite. An equivalent plane monitor (EPM) has also been set up and the results of this study are reported in the figures on page 7 and 8. Several images of the focal spot have been taken across the focal region and the best focus was found to be close to the diffraction limit.



Laser Characterisation: Equivalent Plane Monitor

- An equivalent plane monitor was set up to study the laser intensity distribution in the proximity of the target



- The nominal focal length of the focusing optics was 100mm.

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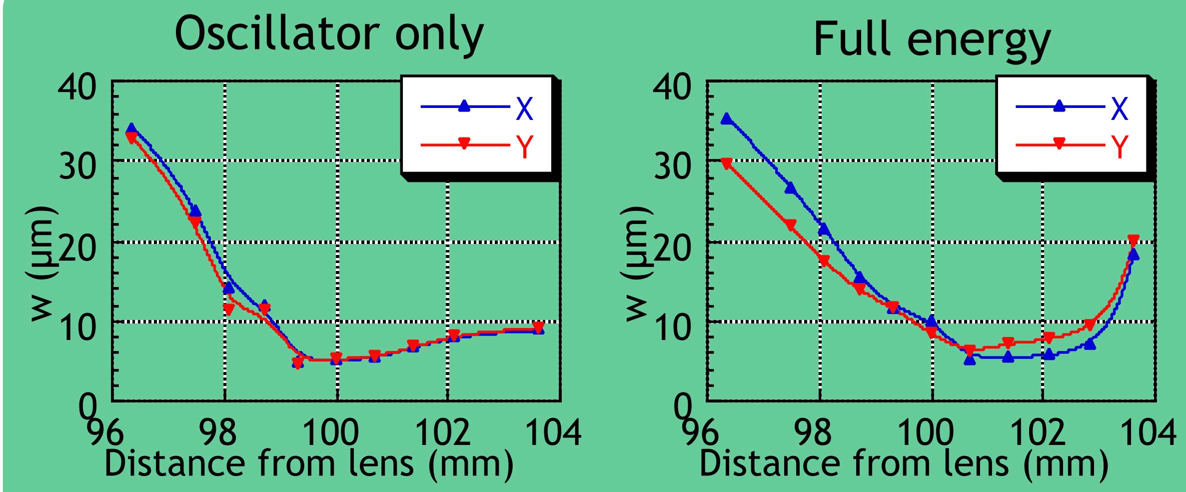
Width of the focal spot on target

Measurements of the laser intensity profile as a function of the distance from the focusing optics yields the transverse size of the beam along two mutally perpendicular axes.



Minimum transverse size of the beam

Oscillator only	Full energy
$w_x = 4.8 \pm 2.0\ \mu m$	$w_x = 5.2 \pm 2.0\ \mu m$
$w_y = 4.6 \pm 2.0\ \mu m$	$w_y = 6.0 \pm 2.0\ \mu m$

- The highest intensity in the focal spot is $10^{15}\ W/cm^2$
- The focal spot size at full energy is close to the diffraction limit

X-ray spectroscopy and imaging using CCDs

The spatial and spectral properties of the X-ray source are studied and monitored by using pin-hole cameras with micrometer resolution and X-ray crystal spectrometers coupled to CCD detectors.

The X-ray image/spectrum can be detected by a standard (8-bit) windowless CCD camera when qualitative information and shot-by-shot monitoring is required. An example of the information that can be obtained using such a simple device is shown on p.10 where a set of three images obtained from irradiation of a Cu target at three different laser intensities. The images consist of a central bright spot, slightly elongated in the vertical direction and a weaker tail-like structure.

From images like these one can obtain the plasma expansion velocity and, with a simple calculation, an estimate of the temperature of the plasma plume. For a longitudinal plasma extent of approximately 100μm and a timescale to reach the steady-state expansion regime of 1 ns we obtain a sound speed of 1×10^7 cm/s. For a Cu target and assuming an ionisation degree of ≈15 we obtain an electron temperature of ≈265eV.

When more detailed information is required, low-noise, high dynamic range (15-bit) cooled CCD detector is used instead. These latest generation CCD detectors can be profitably used in place of X-ray films traditionally used in this research field. In fact, as described in detail below (see p.11) their performance is comparable to or better than that of the best X-ray film with the invaluable great advantages related to its ease of use.

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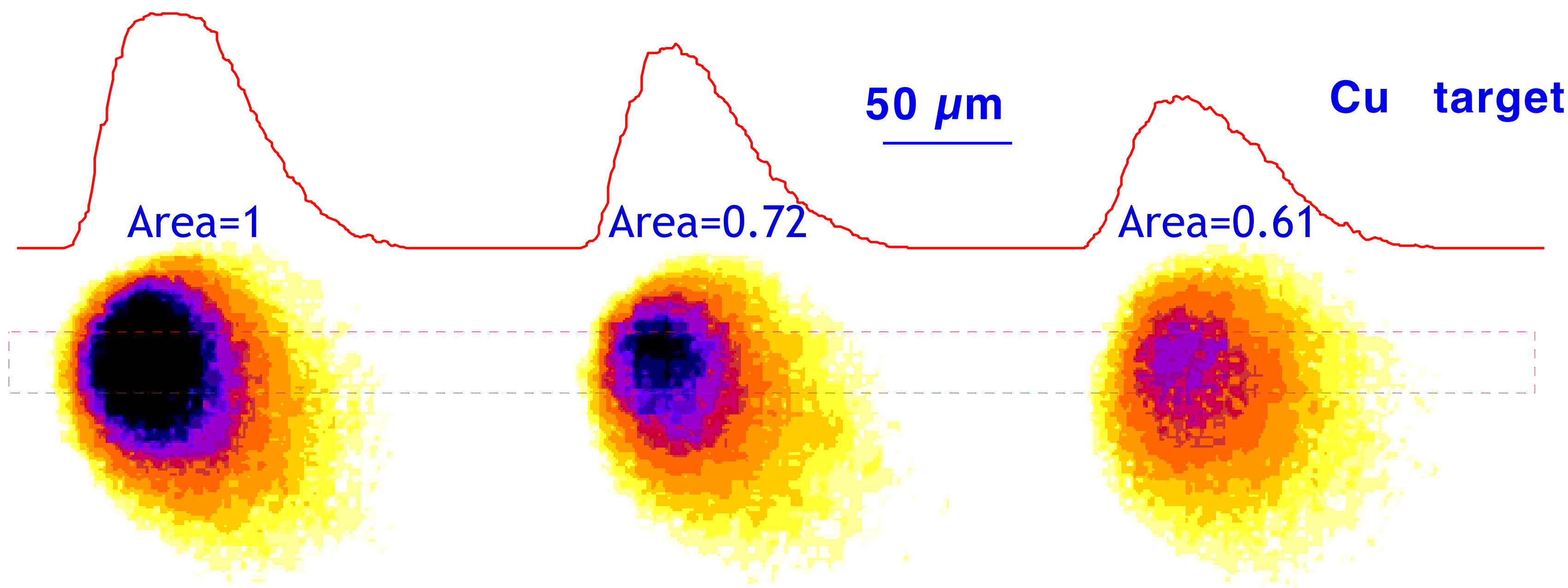
X-RAY IMAGE WITH STANDARD CCD

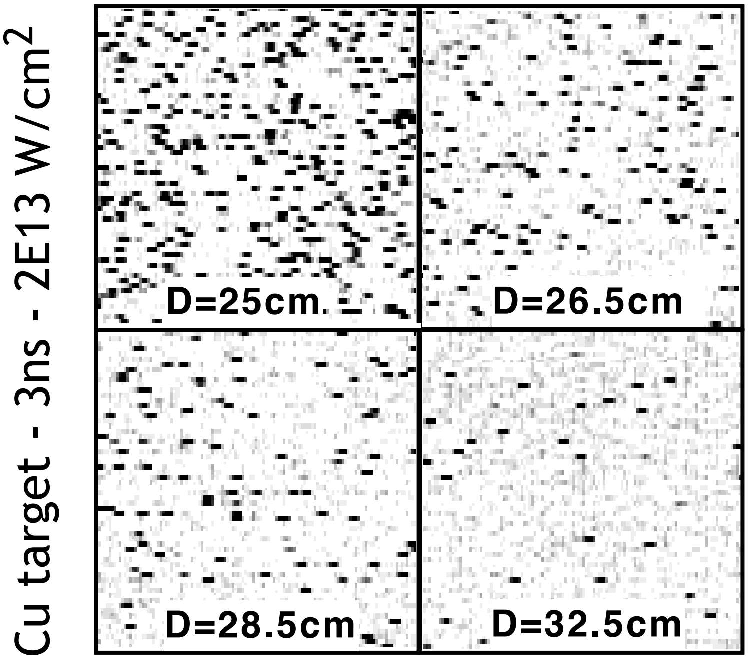
- X-ray images of the source are taken using a pin-hole camera equipped with a 10μm pin-hole and a standard CCD camera (without protective glass).



I_L=2 x10^{13} W/cm^2 I_L=1.5 x10^{13} W/cm^2 I_L=1x10^{13} W/cm^2

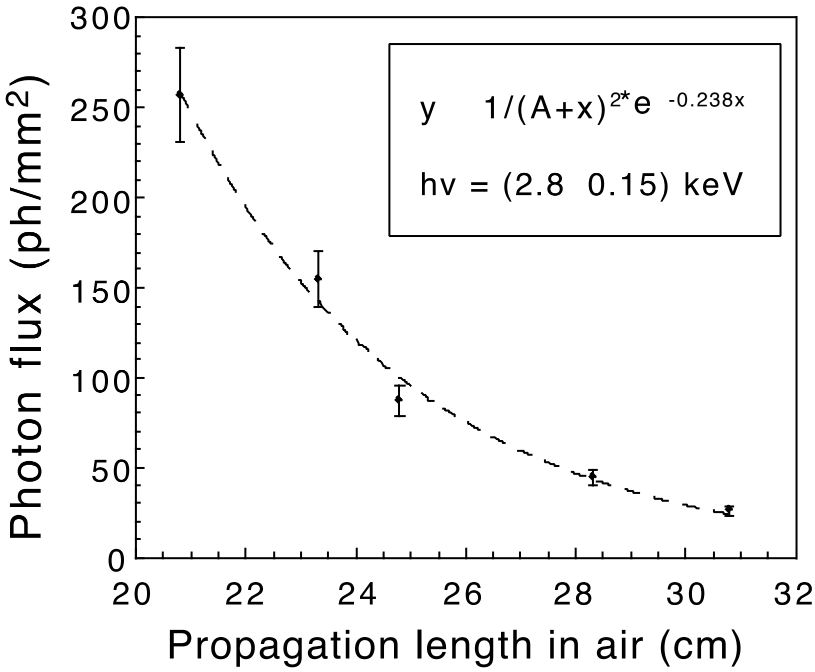
- Standard CCD detectors enable an easy shot-by-shot monitoring of the main source parameters including size, brightness and pointing with μm accuracy.

Photon Counting with Standard CCD



Standard CCD detectors can be used to perform X-ray photon counting. In this case, the photons propagating through a 30μm Be window outside the vacuum chamber are strongly attenuated by absorption in air.

- In the case of a Cu target, the typical photon energy after propagation in air is 3keV. The photon flux extrapolated at the minimum accessible distance in air (≈10cm) is approximately 3×10^6 ph/cm^2.



Cooled CCD Detectors in X-Ray Spectroscopy and Imaging of Laser-Plasmas

Technical specifications

- Back illuminated Peltier cooled CCD
- Dynamic range: 15 bit (10^4)
- Low termal noise (working temperature -40 °C)
- Spatial resolution: 1100x330 pixels of 15 μm

Signal to thermal noise ratio: up to 20000 (acq. time 10 ms)

Other sources of noise in the spectrometer

- Laser light scattered from the plasma
- X-rays scattered from the chamber

Total Signal to Noise ratio: > 1000

CCDs	Photographic Films
* Linearity	* High spatial resolution
* High signal to noise ratio	! Low dynamic range
* IR to X-ray sensitivity	! Low energy cut-off
* High dynamic range	! Require development
* High sensitivity	! Require calibration
* Direct digital acquisition	! Require digital conversion
* High repetition rate	! Single acquisition cycle
! Low spatial resolution	

X-RAY SPECTRAL PROPERTIES OF LASER-PLASMAS

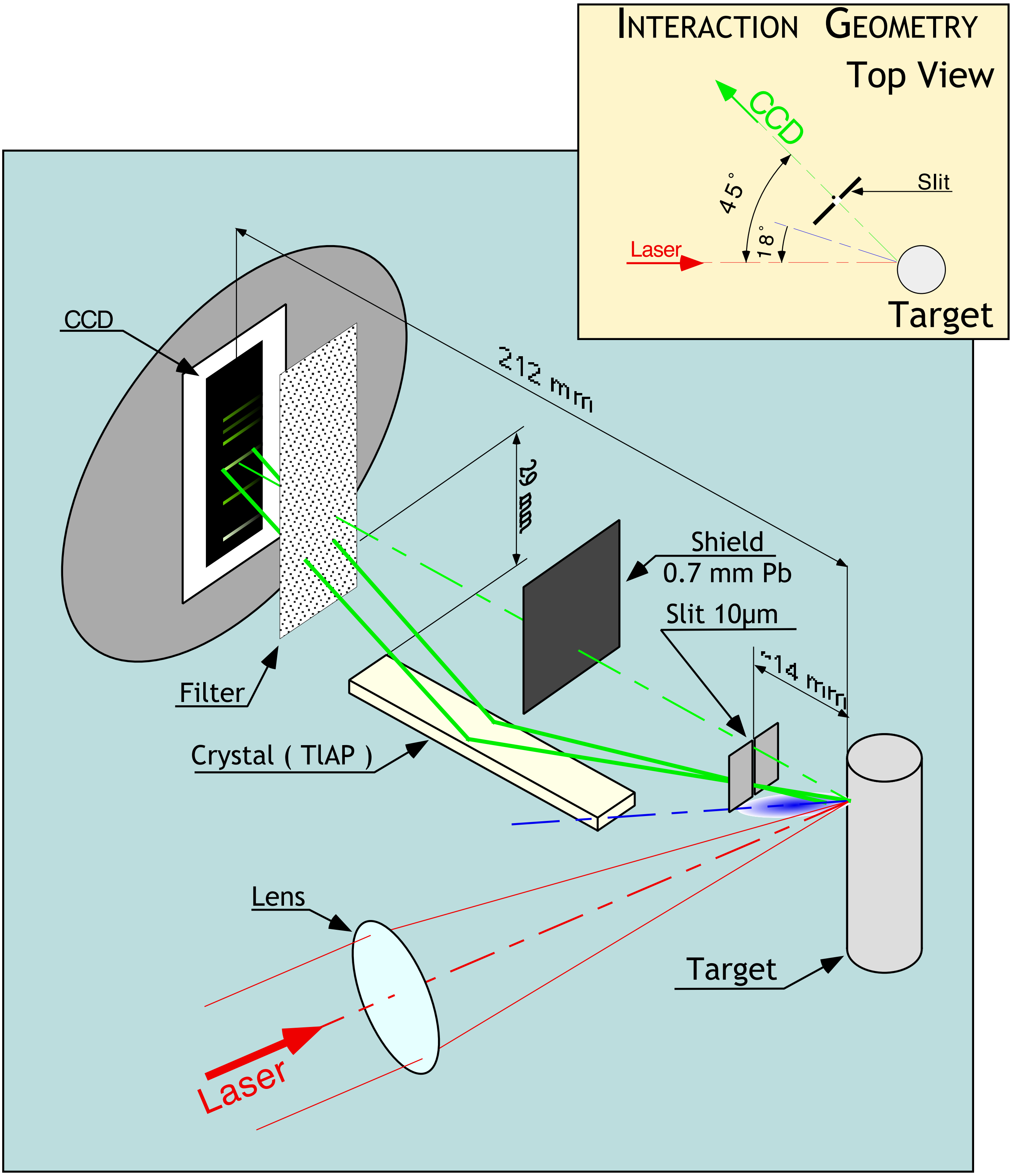
Three main processes contribute to the X-ray emission from plasmas, namely bound-bound (lines), free-bound (recombination) and free-free (bremsstrahlung) transitions.

In the case of low Z materials almost full ionisation of the atoms is achieved with most of the X-ray emission originating from bremsstrahlung emission.

In the case of medium Z materials (e.g. aluminium), laser plasmas are characterised by highly ionised atoms with predominance of H-like, He-like configurations (one or two electrons left in the inner K-shell). Collisional excitation and radiative de-excitation of these species lead to intense line emission which can be energetically comparable to recombination and bremsstrahlung emission. In this case the typical emission wavelengths are those of the so-called resonance lines originating from radiative transitions between levels with principal quantum numbers n=2 and n=1 of the H-like and He-like ions. In the case on Al these wavelengths are 7.17 Å (1729 eV) and 7.75 Å (1600 eV) respectively (see page 14). A first analysis of such spectra shows that:

- The X-ray source size is substantially greater than the laser spot size. Plasma hydrodynamics dominates.
- The source size does not change considerably over 5-6 Rayleigh lengths. Focusing is not critical.
- The region of Al He-α emission is greater than that of Al-Ly-α emission. Finite thermal conductivity effects.
- The intensity of lines peaks near the focal position and changes slowly around it. Line emissivity is stable.
- No appreciable change of line-widths is observed within that region. Small changes of the effective source size.

Experimental Set-up for X-ray Spectroscopy

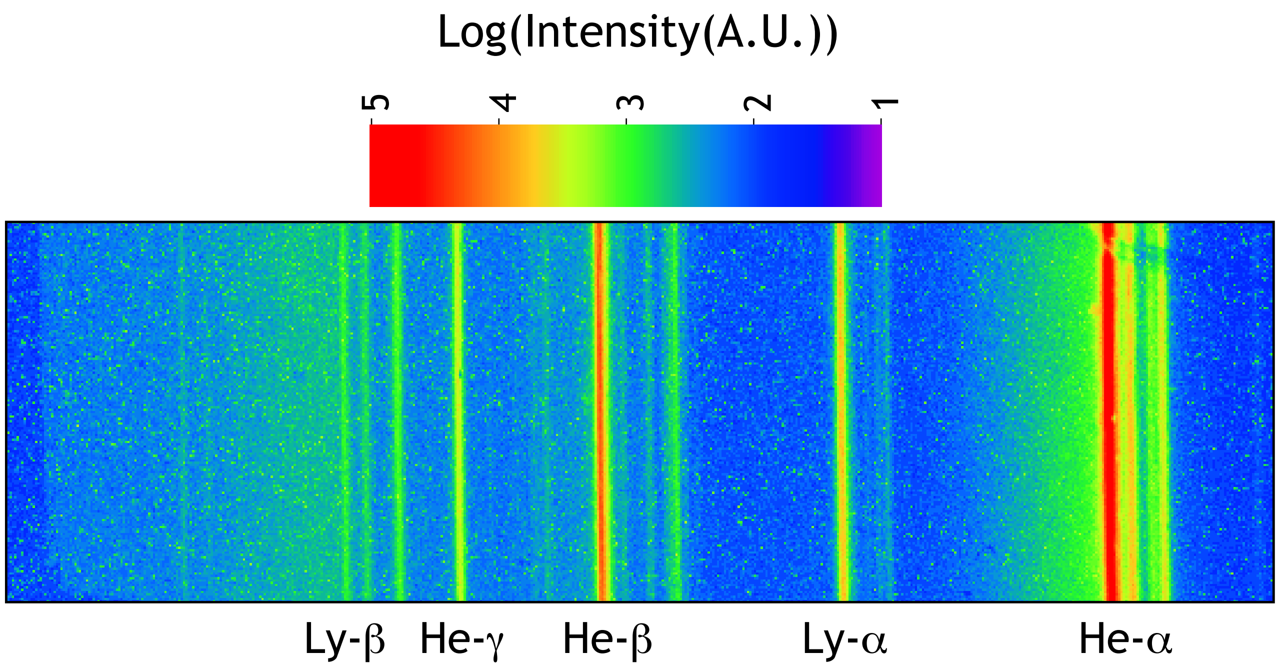


High Dynamic Range Spectrum of Al Plasma

Spectrum of the X-ray line emission from a laser-produced Al plasma generated by a 3ns Nd laser pulse focused on target at an intensity of 9×10^{12} W/cm^2. The dominant species in the plasma was Al^{11+} with the He-α line ($1s^2$-1s2p) giving a dominant contribution to the X-ray emission.

Raw CCD Image: Spectrum of Al plasma

- Acquisition time 10 msec
- Background removed

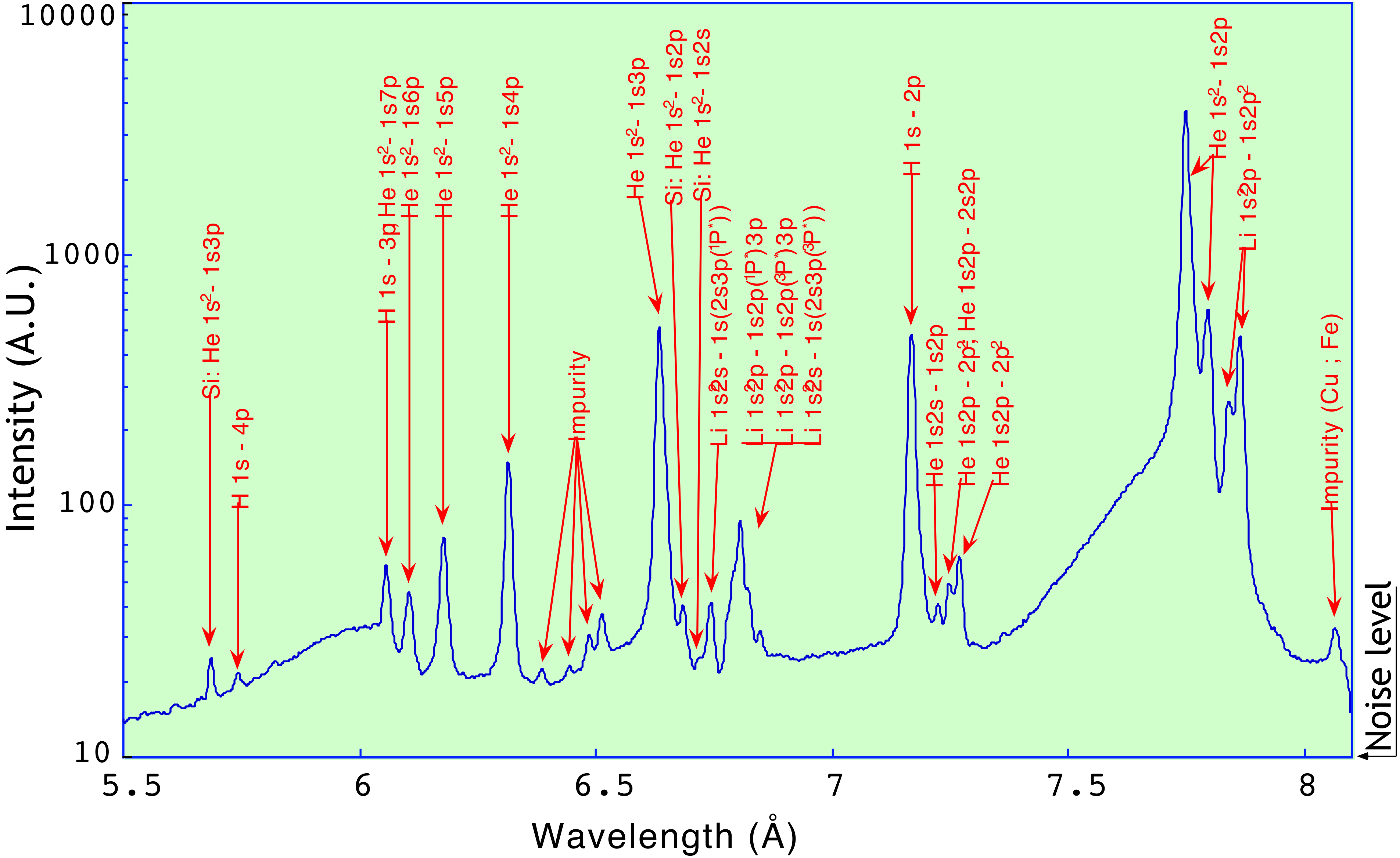


Data analysis

- Removal of single photon background (diffused X-rays)
- Integration along curved paths of same wavelength
- Correction for CCD sensitivity and filter transmittivity

FINAL SPECTRUM FROM ALUMINIUM(*) TARGET

(*) Anticorodal: Al with addition of Si 1.4%; Fe 0.5%; Mg 0.6 %; Mn 0.3%; Cr ~0.1%; Zn 0.1%; Ti,Cu <0.1%



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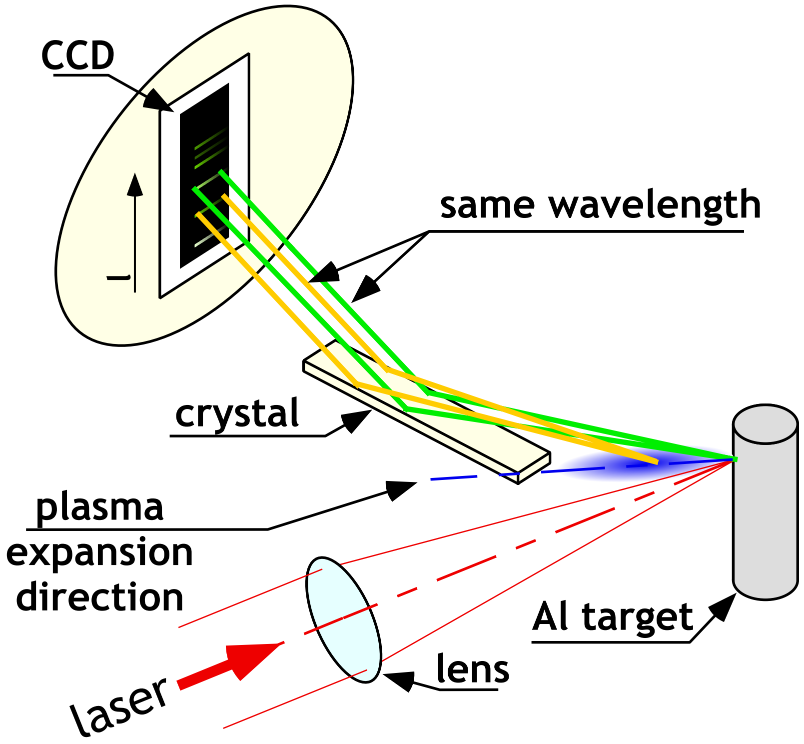
SOURCE SIZE FROM LINE WIDTH

The widths of the lines resolved by a crystal spectrometer are ultimately determined by the spatial distribution of emitting ions. The geometry of the source-spectrometer-CCD system can be fully resolved by taking into account the position and the curvature of the main spectroscopic lines in the CCD plane. Knowing the spectrometer geometry it is possible to obtain the effective source size from the line width. Different sizes are obtained from different lines:

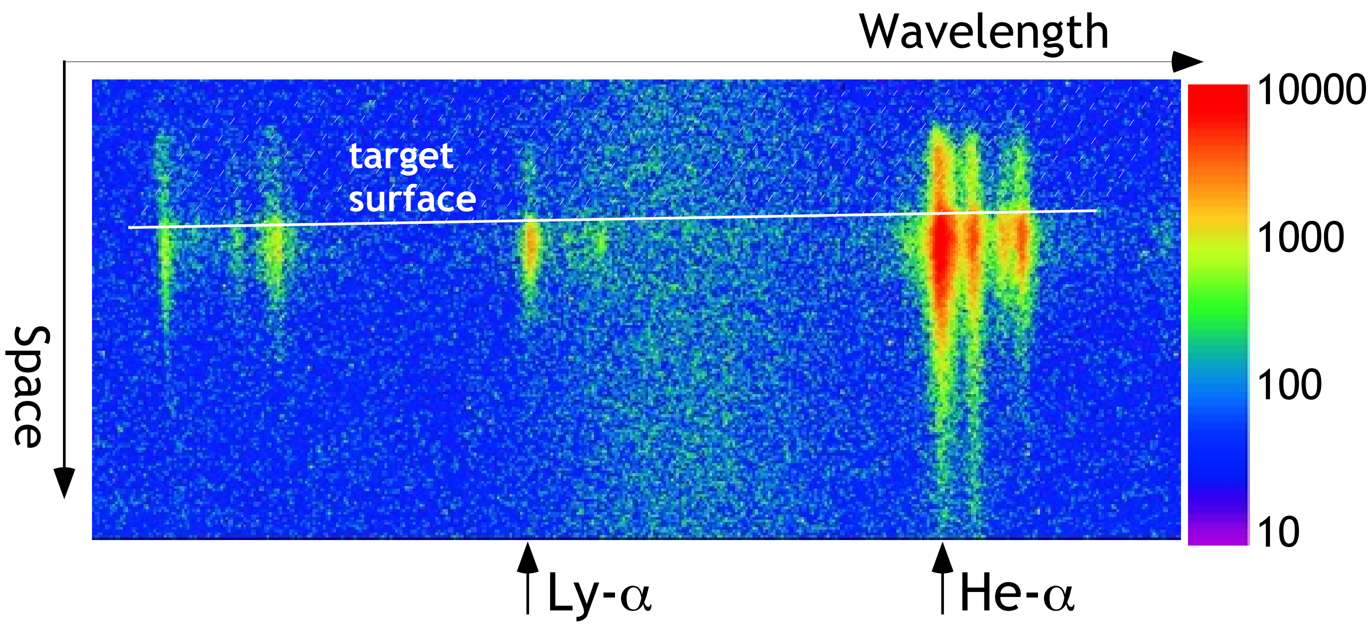


width of	He α	79±5 μm
"	He β	70±5 μm
"	Ly α	54±3 μm

Line emission from Hydrogen-like Al ions originates from a narrower region of plasma than that giving rise to Helium-like Al emission.

Space Resolved Spectra

Space-resolved spectra are obtained placing a 10μm slit at the entrance of the crystal spectrometer to give a 15X magnified 1-D image of the plasma on the CCD. The resulting spectrum gives additional information on the spatial distribution of each line along a given axis.



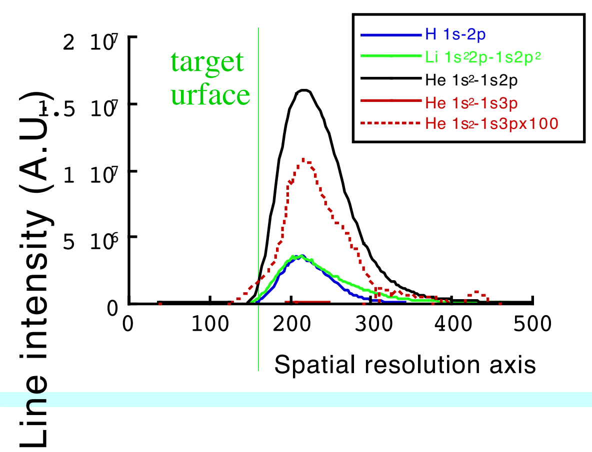
Data analysis requires:

- Removal of single photon noise
- Correction for CCD sensitivity and filters transmittivity
- Removal of distorsion due to the reflection off the crystal
- Correction of the residual tilt of the slit.

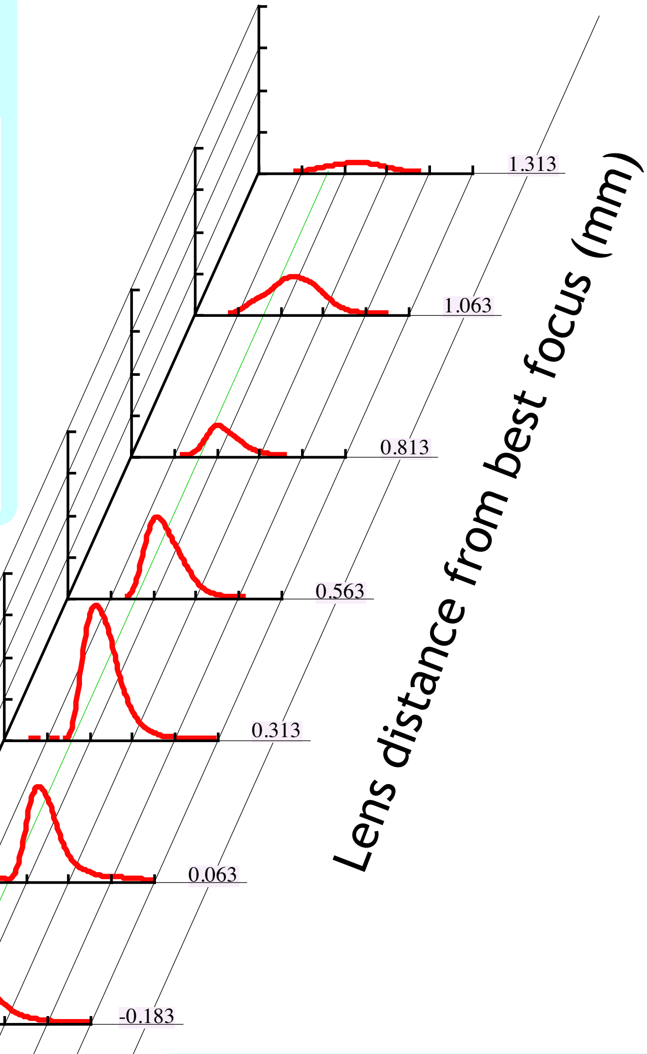
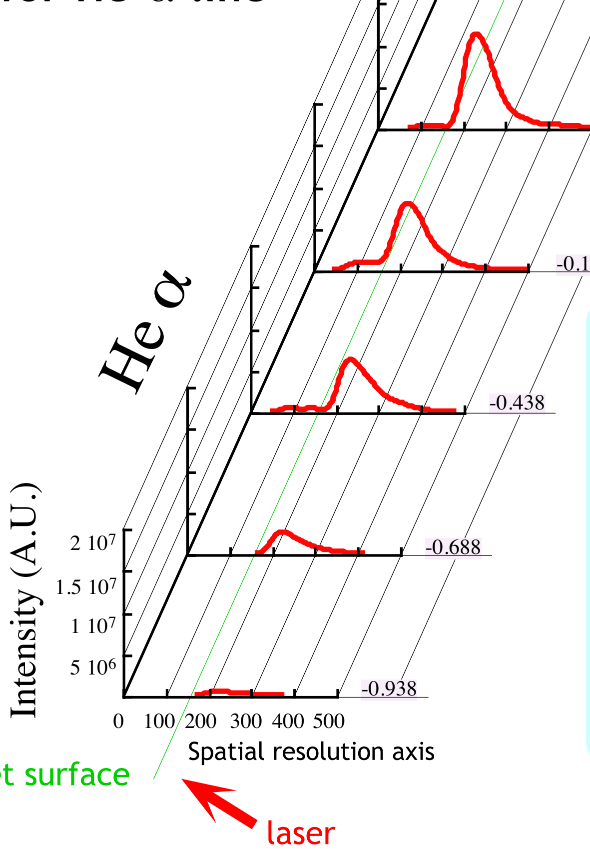
Line Intensity Distribution

- Line intensity along the spatial resolution axis is measured for each position of the focusing optics around the best focus.

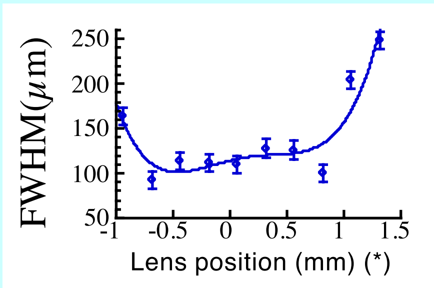
Intensity of main lines for a lens-target distance 0.313mm greater than the best focus distance



Intensity profiles relative to different lens-target distances for He-α line

Width of the region of He-α emission around the best focus position



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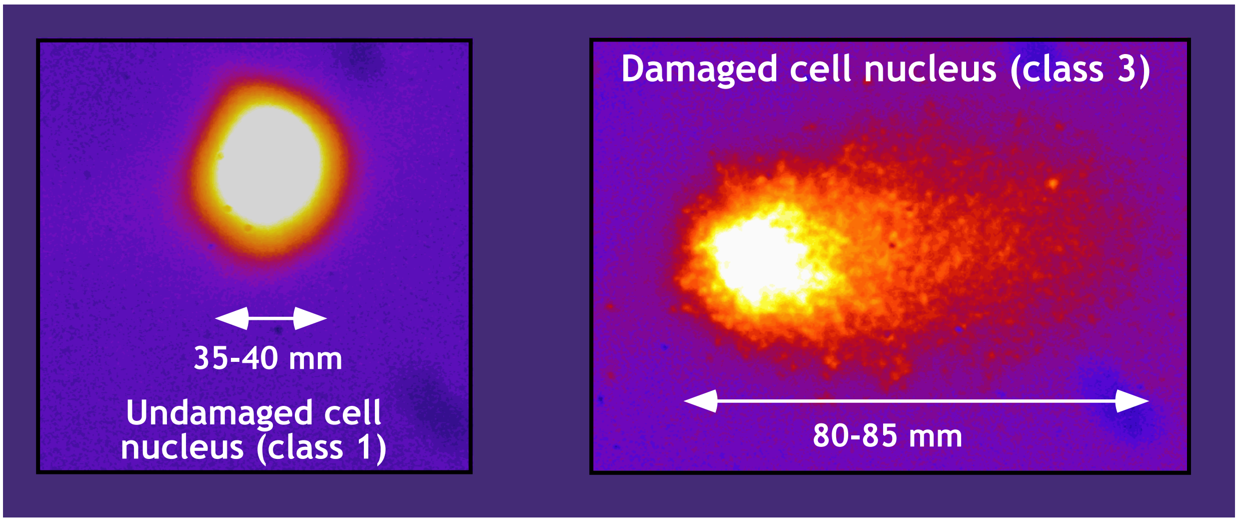
EXAMPLES OF APPLICATIONS OF LPP X-RAYS

X-ray microscopy and X-ray induced damage in biological samples are important examples of applications of X-rays. In principle, X-ray microscopy is capable of high spatial resolution imaging comparable to that of electron microscopes, with the great advantage of a much more penetrating power strongly dependent on the sample atomic number. The final resolution is ultimately determined by the source size which, in the case of LPP X-rays is very small, typically of the order of the laser focal spot diameter. This is a very interesting property which can be readily exploited to obtain, with no need of additional devices, radiography of small, biological samples with a resolution of a few microns and a temporal resolution as high as a few nanoseconds.
The X-ray doses available on a single laser shot exposure of our source fully meet the conditions required for an important class of biological experiments based on X-ray induced DNA damage providing an ideal alternative to the long time exposures needed with X-ray tubes. The vacuum chamber is equipped with a 25μm thick Be window which acts as a vacuum-air interface for direct access to the X-rays at atmospheric pressure, a necessary condition for soft X-ray irradiation of *in vivo* biological samples.
In our configuration the sample is placed close to the Be window where the photon flux can be estimated to be approximately 3×10^6 ph/cm^2 which corresponds to an X-ray energy flux of 1.5 nJ/cm^2.

Observing Comets with a Microscope

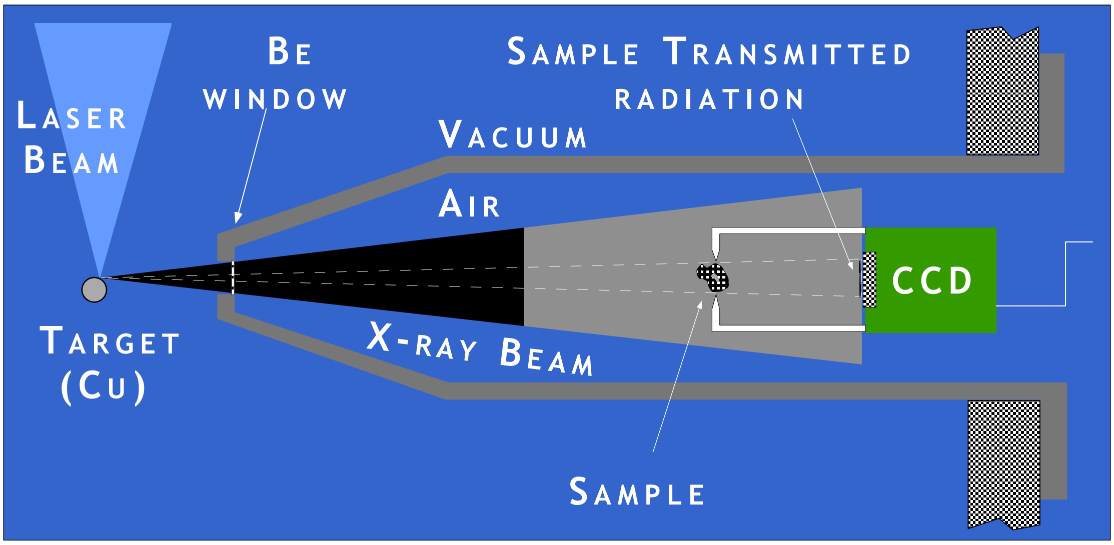
Two samples consisting of a 500μm thick layer of agarosio gel containing DNA of human leukocytes was exposed to LPP soft X-ray radiation (3keV) of doses of 0.5 and 1mGray respectively. After exposure, the samples were analysed using a technique based on single-cell gel electrophoresis (SCGE), also known as the *comet* essay. Fluorescence microscope images of the cells are taken before and after the damage.



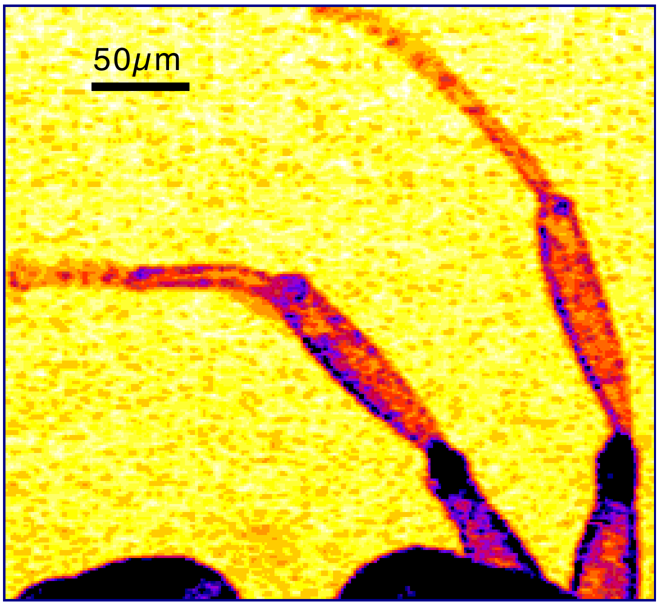
The evaluation of the radiation damage induced on the cell's DNA is carried out via measurement of some `comet parameters', namely the inertia and moment of the *tail* formed by the DNA fragments when the cell is placed in an external electric field.

Single Shot Micro-Radiography using Standard CCD

Set up for direct exposure in air
using a standard CCD detector



Sample image of an ant's leg:
single laser shot, 3ns, 1J on Cu target



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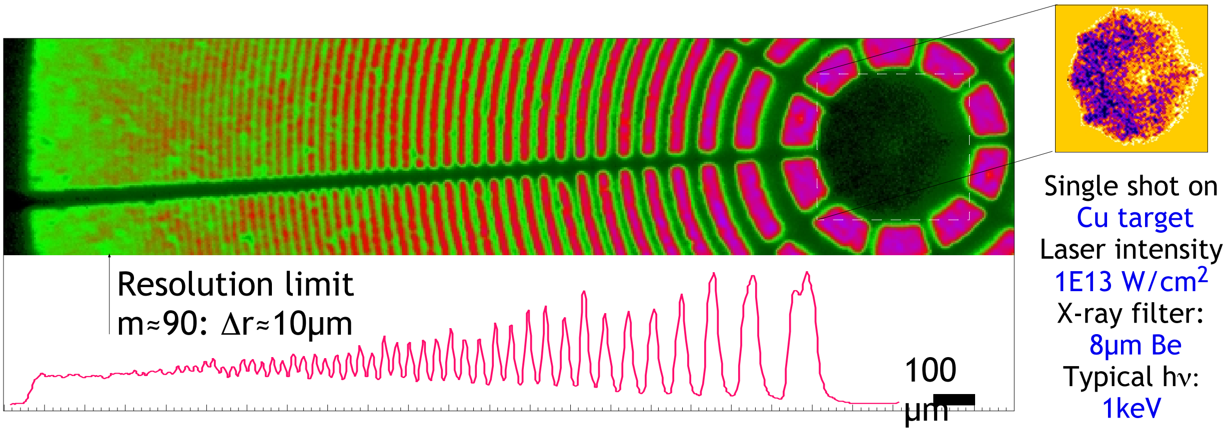
Resolution Test of MicroRadiography using a Zone Plate

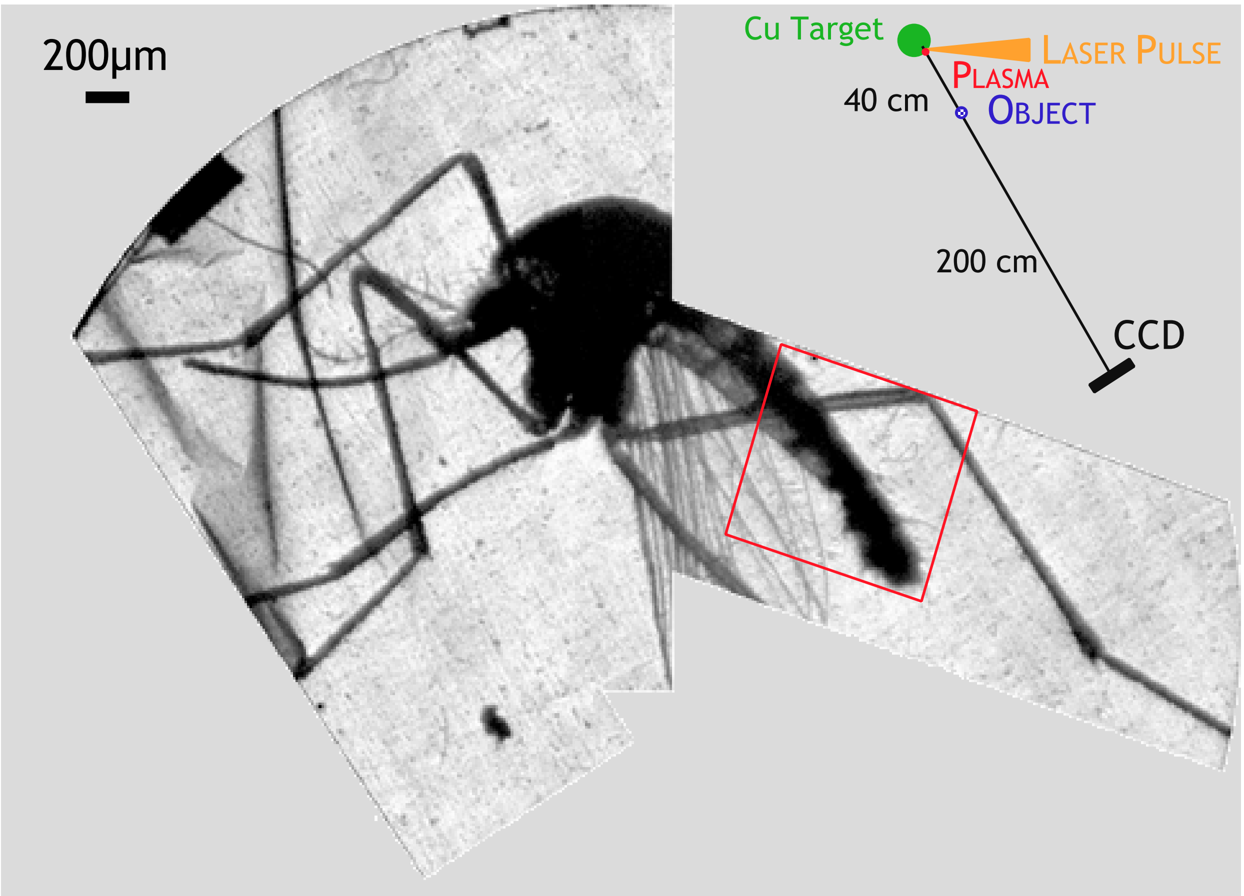
- A zone plate ($r_m \approx$ 195 µm $m^{1/2}$) is used to test the overall spatial resolution of the imaging system. The plate-detector distance is L=2.5m while the source-plate distance is 50 cm.



- The lower limit to the spatial resolution is set by diffraction effects. In fact the diffraction angle of $\lambda/d \approx$10Å/10µm=1E-4 at L=2.5m gives a Δx=2.5mm which is of the order of the Δr on the detector plane.
- In our geometry the working wavelength of the plate is of the order of 100Å. Only a small fraction of such a radiation is transmitted by the Be filter and is focused by the plate in the weak central spot which is visible on axis.

MICRO-RADIOGRAPHY WITH COOLED CCD DETECTOR

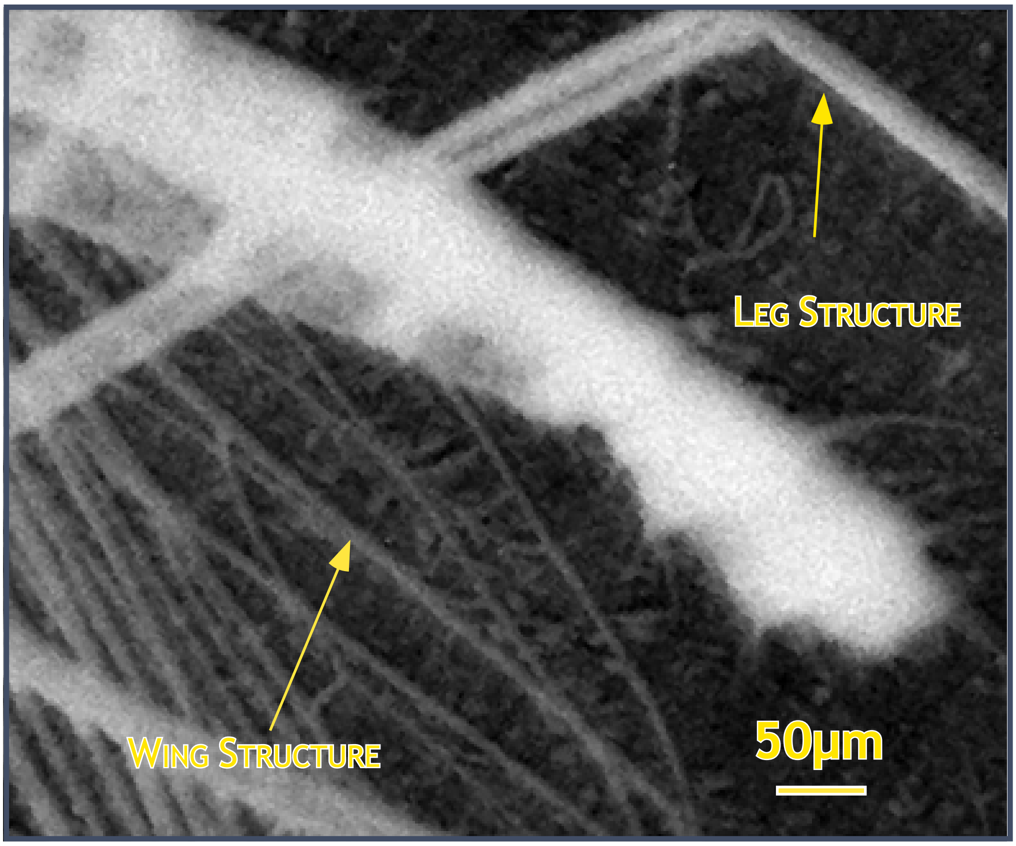
Collage of four images obtained from single exposure to laser-produced plasma X-ray pulse.



The *source* plasma was produced by laser irradiation of a Cu cylindrical target with a 3ns Nd:YAG laser pulse focused in a 10μm diameter spot. The intensity on target was 5×10^{13} W/cm^2. The source-object and the object-detector distances were 40cm and 200cm respectively.

Micro-Radiography with Cooled CCD detector

Detail of the previous image showing micron-sized details of the object

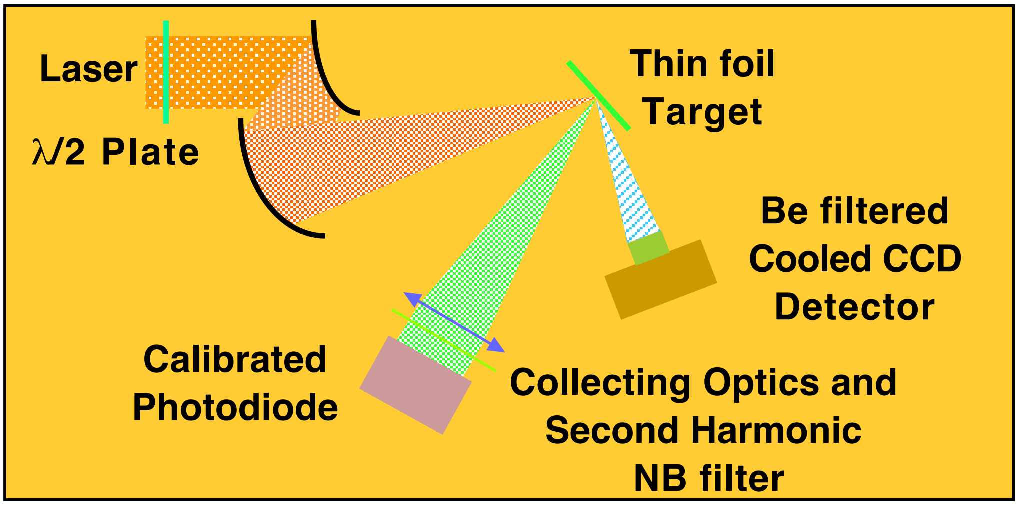


Main features and polarisation effects

The interaction of high power femtosecond laser light with matter is now recognized as a promising way of generating short intense x-ray pulses with photon enegies extending beyond.
Unique conditions of high plasma density and temperature can be achieved provided that pre-pulse free interaction occurs and plasma production actually occurs on the femtosecond time-scale. The effect of the nanosecond time-scale amplified spontaneous emission(ASE) typically present in these systems must be minimised.
In these circumstances, collisional absorption processes become inactive and polarisation of the laser light plays a crucial role. Its effect on energy coupling processes can be investigated analysing X-ray or Second Harmonic (SH) emission. In the case of p-polarized probe, SH clearly showed the effect of resonant enhancement of the electric field at the critical density typical of resonance absorption.
Recent experiments have also established the link between polarization of laser light and X-ray emission. These experiments provide striking evidence of enhanced coupling of *P* polarized light with the plasma, showing that collisionless absorption processes occur. The observed behaviour of SH and X-ray emission is a convincing evidence of the key role played by the classical resonance absorption in femtosecond interaction processes where short (sub-micron) scale-length plasmas can be created.

X-RAYS FROM FEMTOSECOND LASER-SOLID INTERACTIONS

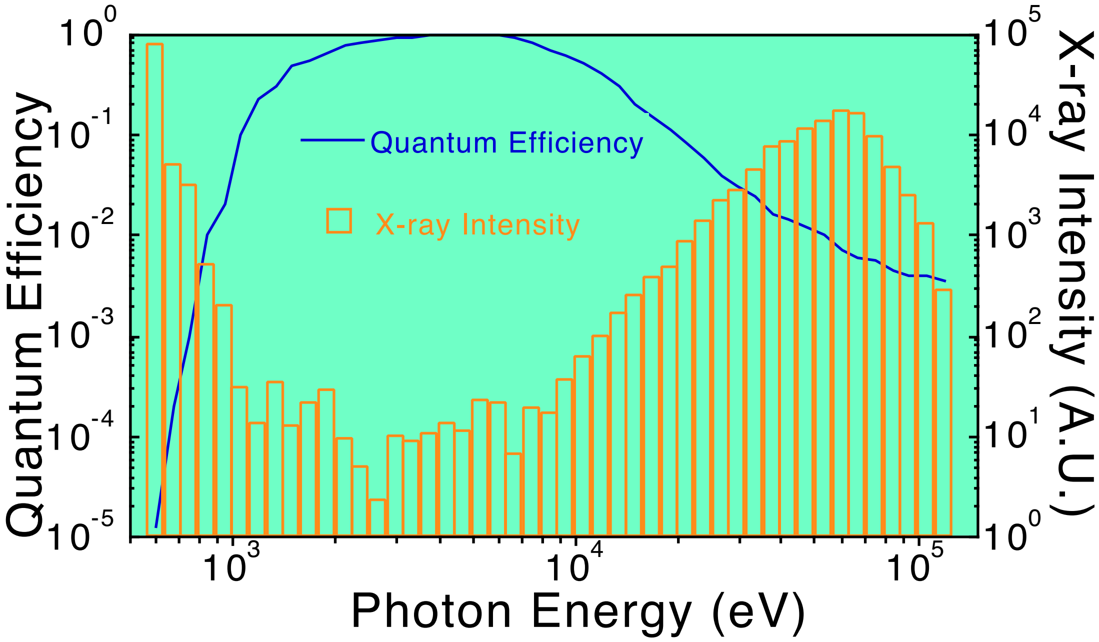
Energy coupling in high intensity femtosecond laser-target interactions has been investigated by studying the correlation between X-ray and second harmonic emission. By changing the polarisation of the laser light it is possible to discriminate between different absorption processes. Generation of specular second harmonic emission is a clear indication of the onset of resonance absorption.



A 30mJ - 150fs laser pulse is focused on a 800Å thick plastic target at an intensity of 5×10^{17} W/cm^2. The polarisation of the laser beam is varied from *s* to *p* by rotating a λ/2 wave plate.

X-RAYS FROM FEMTOSECOND INTERACTIONS
FINAL X-RAY SPECTRUM

A broad band X-ray spectrum over a wide range of photon energies has been obtained on-line for each laser-target interaction event.

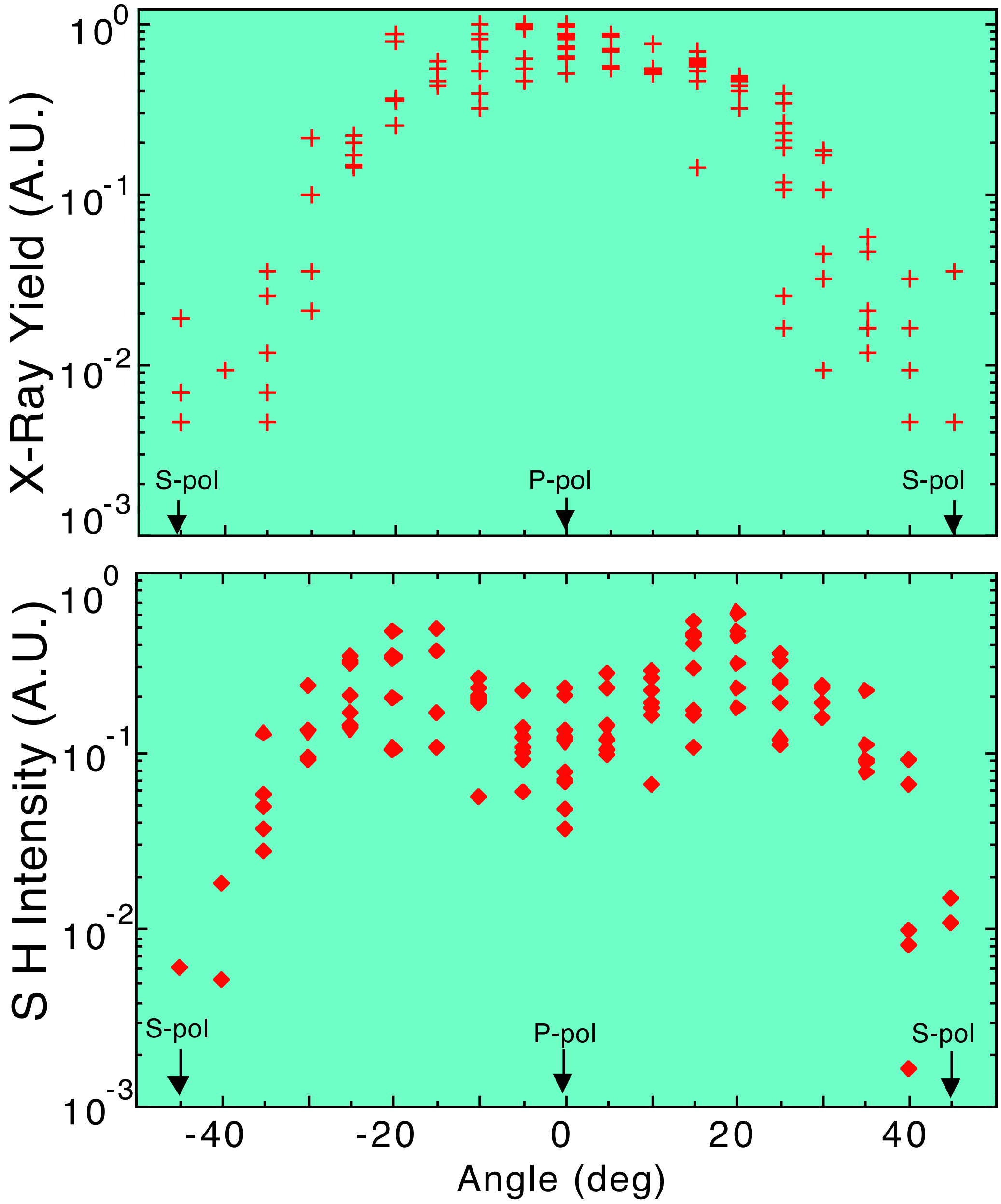


Spectrum recorded during the interaction of a 30mJ, 150fs laser pulse with a thin plastic target, at an intensity of 5×10^{17} W/cm^2 showing a strong component of hard X-rays.

A detailed analysis of the properties of X-rays gives valuable information on the physics of the interaction process and, in particular, on the dynamics of energy coupling processes.

Polarisation effects on X-ray emission

The intensity of X-ray and specular second harmonic emission are measured as a function of the polarisation of the incident laser radiation



Maximum X-ray emission occurs in conditions of p-polarization when stronger laser-target energy coupling occurs. The X-ray spectrum shows high energy photons up to several tens of keV.

Hard X-rays from Ultra-Short Laser Pulses

High energy electrons and photons

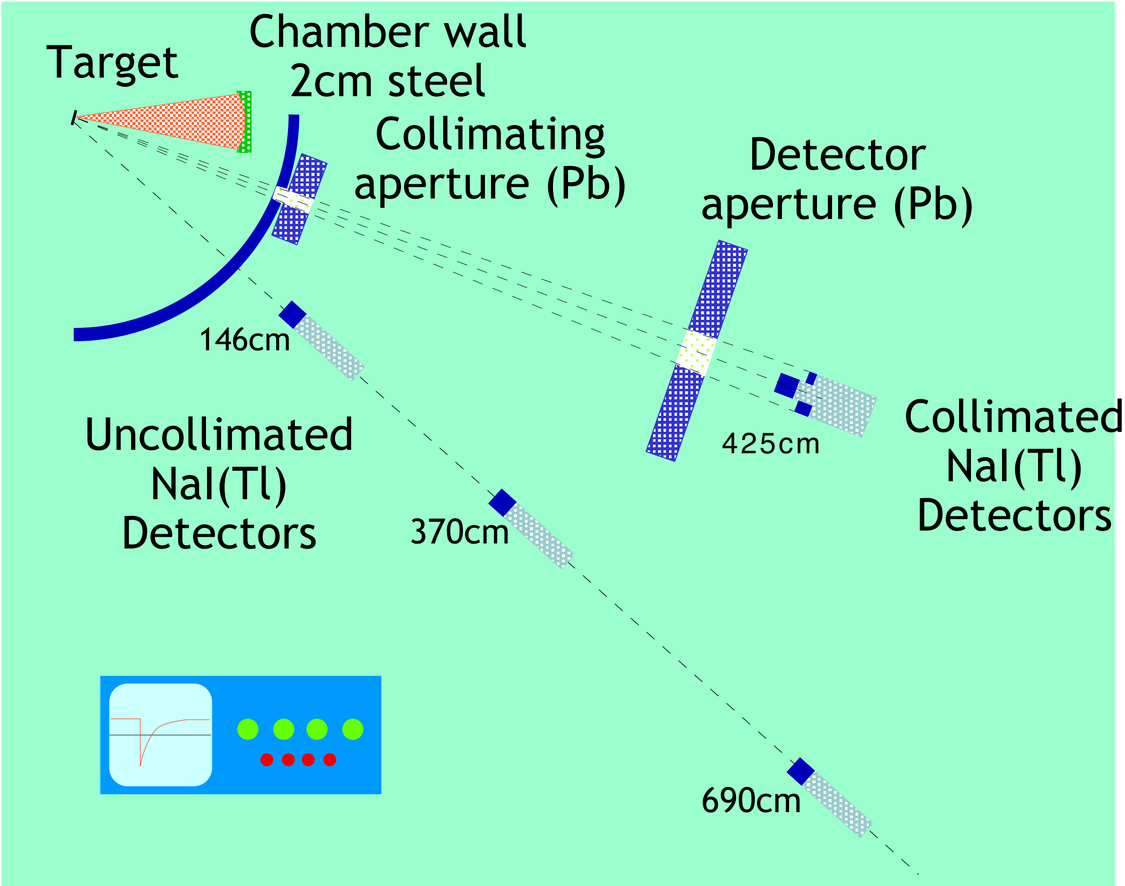
The interaction of very intense, ultrashort laser pulses with matter can accelerate electrons to very high energies. The interaction of these electrons with the target substrate or with the structures surrounding the target gives rise, via bremsstrahlung emission, to hard X-ray emission. This emission has been investigated in recent experiments in which intense, 30fs laser pulses were focused on thin (0.1 or 1 μm thick) plastic targets at an intensity as high as $5\times10^{18}W/cm^2$. A set of 6 NaI(Tl) scintillator detectors were used as shown in Fig.1

When dealing with large fluxes of pulsed X-ray radiation, the standard hard X-ray spectroscopic techniques typically used in high energy physics and astrophysics cannot be applied directly. In some circmstances, when high repetition rates are available, the average number of photons on the detector can be reduced to <<1 and single photon spectra can be obtained integrating over many (thousands) laser shots. Additionally, some information on the hard X-ray spectrum can be obtained by using several detectors whose sentitivities are optimised for different photon energies.

Experiments show that most of the X-ray photons emitted directly by the target have an energy greater than 100keV. Also there is evidence of a large photon background around 350-400 keV. This photons are probably generated by the interaction of very fast electrons generated by the laser-foil interaction with the matter surrounding the target and, in particular, by the target chamber.

Hard X-rays from Femtosecond Interactions

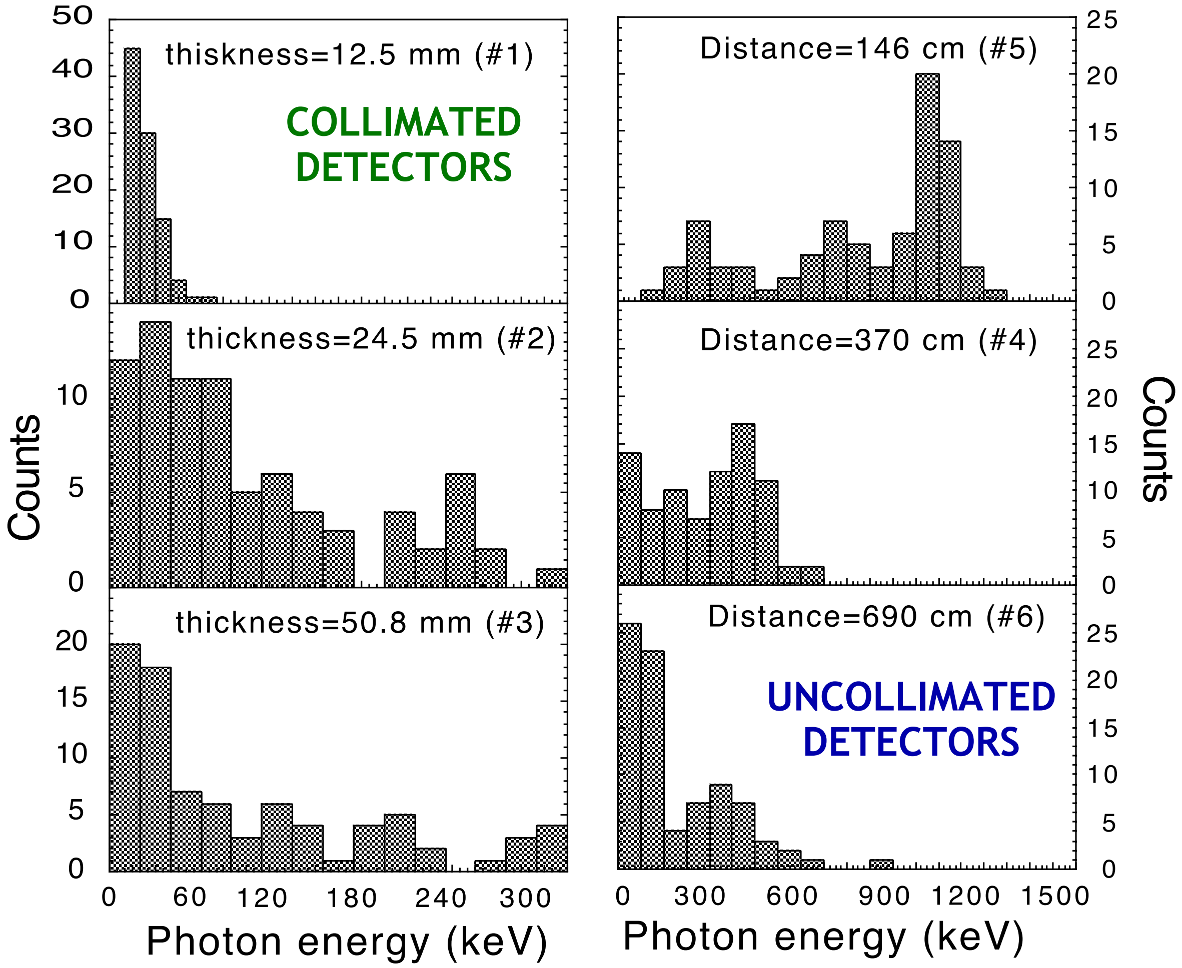
Experimental Set-Up



The hard X-ray radiation generated during the interaction of ultraintense laser pulses with matter is investigated by means of NaI(Tl) detectors. Collimated detectors measure the radiation coming directly from the target while uncollimated detectors measure the diffused radiation background.

HARD X-RAYS FROM FEMTOSECOND INTERACTIONS

For sufficiently large distances from the plasma NaI detectors see a single photon for each interaction event.



A large number of energetic photons (>50keV) are not absorbed by the thinner crystal. The typical energy of photons emitted directly by the target has an energy greater than 100keV.

Uncollimated detectors show a large photon background around 350-400 keV. This photons are generated by the interaction of very fast electrons with the target surroundings.

Main Results and Perspectives

- Detailed characterisation of a 'traditional' laser-plasma X-ray source was carried out using the latest generation of low-noise CCD based detectors.
- High dynamic range, space resolved spectroscopy was extensively used and can be easily implemented to provide on-line monitoring of fine spectral and spatial properties of laser-plasma X-ray sources.
- A single-shot, easy-to-use micron-resolution radiography equipment has been set-up and tested.
- High performance CCD detectors have also been used in the characterisation of the new generation of laser-plasma sources based on high intensity, ultra-short pulse CPA lasers.
- Plasmas generated by high intensity, prepulse-free femtosecond CPA pulses are bright sources of fast electrons and hard X-ray emission.

Laser-Plasma Interaction Group at IFAM-CNR Recent publications and Theses on X-rays from LPP and related topics

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- D.Giulietti and L.A.Gizzi, *X-ray emission from laser-produced plasmas*, La rivista del Nuovo Cimento, 21, 1 (1999).
- A.Giulietti, C.Beneduce, T.Ceccotti, D.Giulietti, L.A.Gizzi, R. Mildren, *A study of second harmonic emission for characterisation of laser plasma X-ray sources*, Laser and Part. Beams, **16**, 397 (1998).
- D. Teychenneé, A.Giulietti, D.Giulietti, L.A.Gizzi, *Magnetically induced optical transparency of overdense plasmas due to ultrafast ionisation*, Phys.Rev.E, Rapid Comm, **58**, R1245 (1998).
- L.A.Gizzi, A.Giulietti, O.Willi, *Time-resolved, multiframe X-ray imaging of laser-produced Plasmas*, J. X-ray Sci. Technol. **7,** 186 (1997).
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- Simona Marzi, *Laurea* degree Thesis, 1998
- Marco Galimberti, *Laurea* degree Thesis, 1998
- Luca Labate, *Laurea* degree Thesis, 2000