2nd International Conference on
Frontiers in Diagnostic Technologies
Frascati (Italy) 28-30 november 2011

Consiglio Nazionale
delle Ricerche

INO-CNR
Istituto
Nazionale di
Ottica

Istituto Nazionale di
Fisica Nucleare

A novel single-shot, spectrally resolved X-ray imaging technique of ICF relevant plasmas

Luca Labate
and C.A. Cecchetti, P. Koester, T. Levato, L.A. Gizzi

Intense Laser Irradiation Laboratory
Istituto Nazionale di Ottica
Consiglio Nazionale delle Ricerche
Pisa, Italy

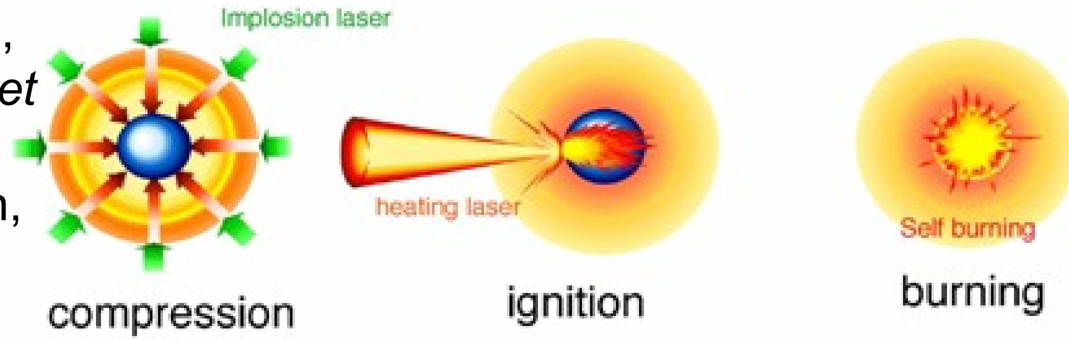
Also at
Istituto Nazionale di Fisica Nucleare
(Sezione di Pisa and Laboratori Nazionali di Frascati)

Contents

Contents

Scenario: the *fast ignition* approach to ICF

- The *fast ignition* approach to the Inertial Confinement Fusion, proposed in 1994 by M. Tabak *et al.*, aims at a) relaxing most of the requirements for the ignition, in terms of irradiation symmetry/uniformity, total energy required and b) allowing a higher gain to be obtained

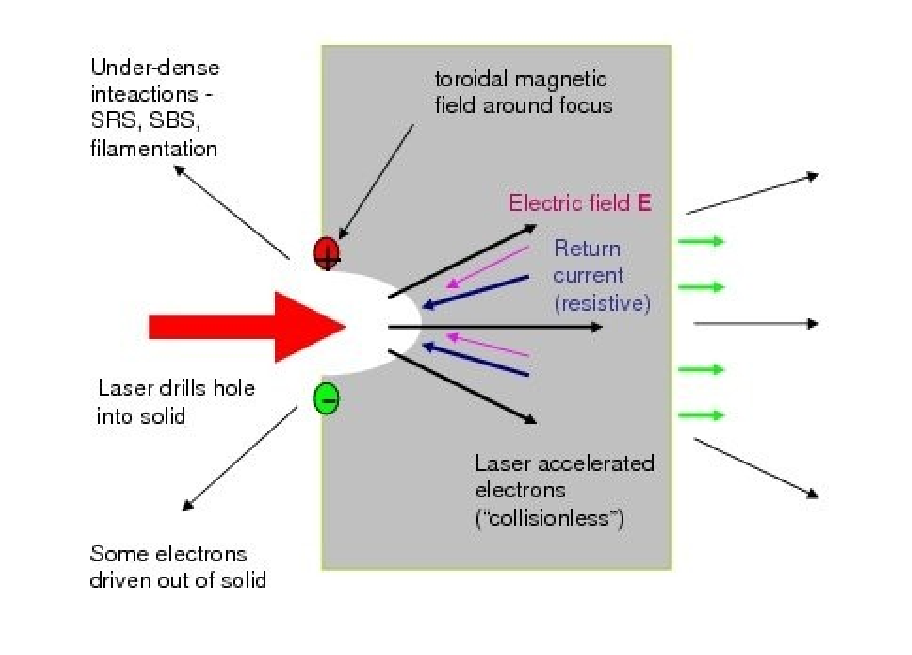


- The EU project for the infrastructure HiPER (High Power laser Energy Research), currently at the end of its preparatory phase, is expected to demonstrate high gain fusion reactors through advanced (*fast* or *shock ignition*) schemes

M. Tabak *et al.*, Phys. Plasmas **1**, 1626 (1994)

Scenario: fast electron beams

- Typical figures for the fast electron beam (for a compressed target density ~300 g/cm^3): beam total energy ~10kJ, deposited over a region ~10μm in a time ~10ps
- In terms of laser params, these requirements demand for the ignition laser to deliver a PW pulse with pulse duration ~10ps



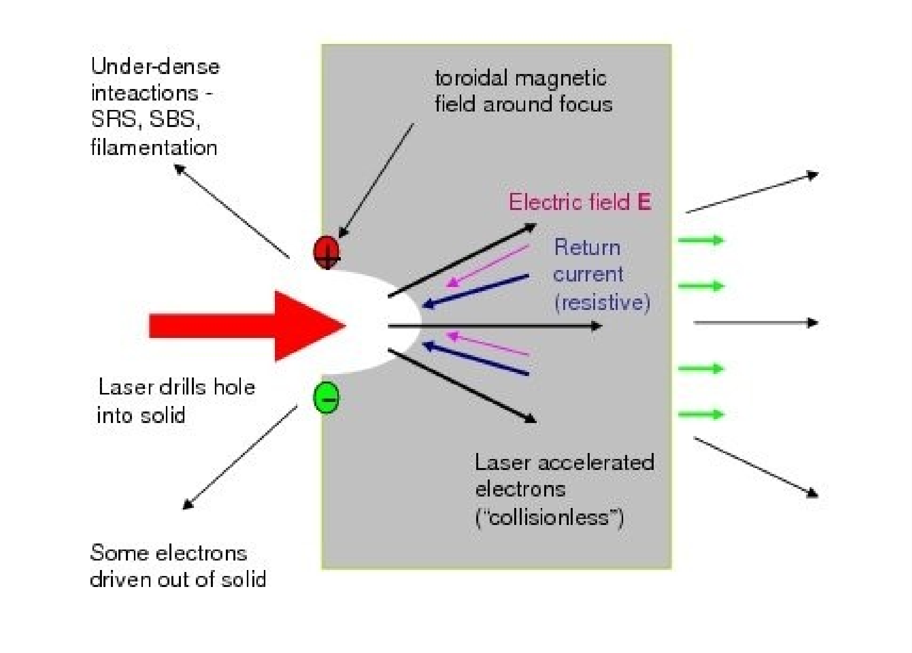
- Open issues:

- laser-to-electron energy conversion efficiency
- scaling laws for the electron kinetic energy versus laser intensity
- fast electron beam divergence
- fast electron transport in the compressed target material

S. Atzeni *et al.*, Phys. Plasmas **15**, 056311 (2008)

Motivations: studying fast electron transport

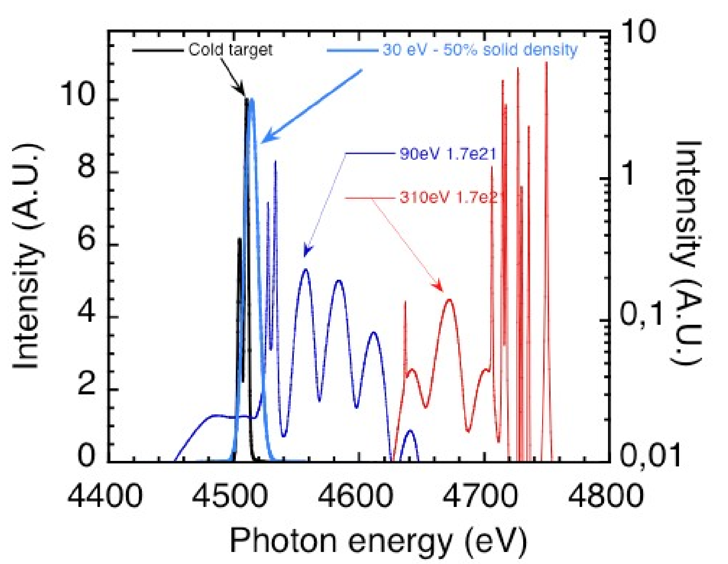
- The expected fast electron currents are of the order of MA, which requires the (resistive) propagation of a “return current” to be established
- Transient electric/magnetic fields are also expected to be established
- Electron current instabilities are also expected to build up
- Return current will give rise to resistive thermal heating that acts to modify the spectral features of the X-ray emission
- X-ray spectroscopy is a powerful tool to study this fast electrons transport



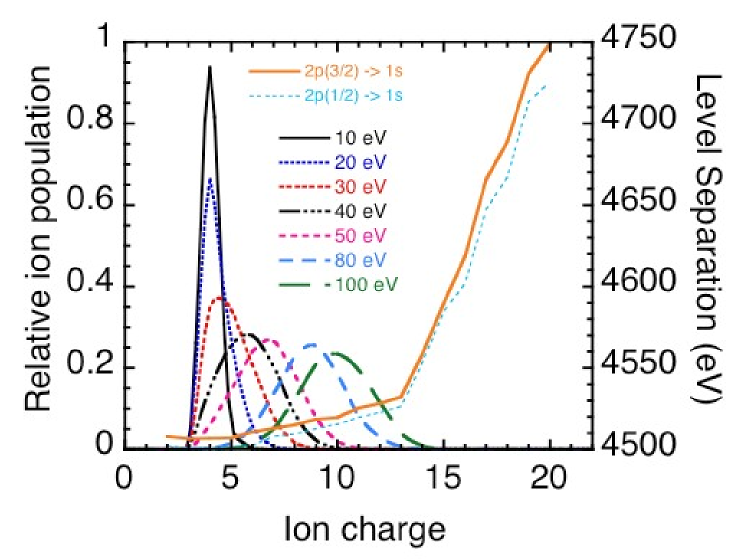
- Foil targets can be used to investigate f.e. transport in solids and plasmas through detection of Kα emission

Motivations: studying fast electron transport [2]

- Fast electron energy deposition gives rise to local heating in the target substrate. Heating will generate weakly ionised (warm) dense matter.

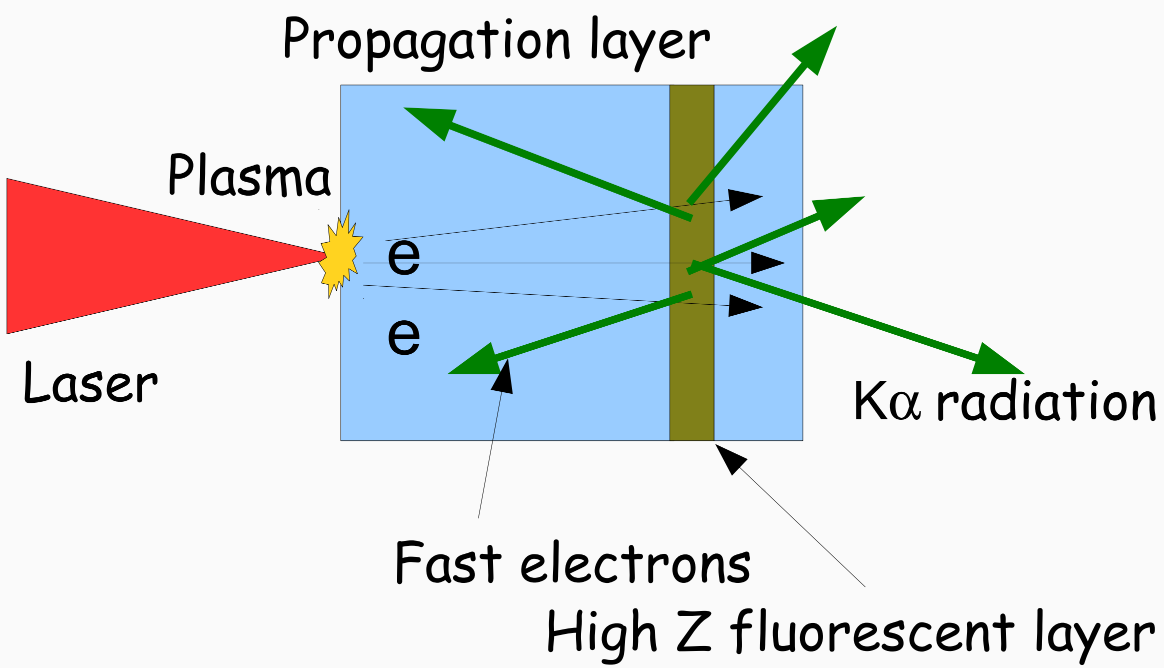


Spectra calculated using the kinetic code FLYCHK for a cold/warm target and for a hot, critical density plasma. K-shell emission components fall in the 4.5 - 4.8 keV range



- X-ray spectroscopy of shifted Kα components can be used to infer the electron temperature of the bulk target and to speculate on the role of refluxing of the fast electron beam at the target rear side

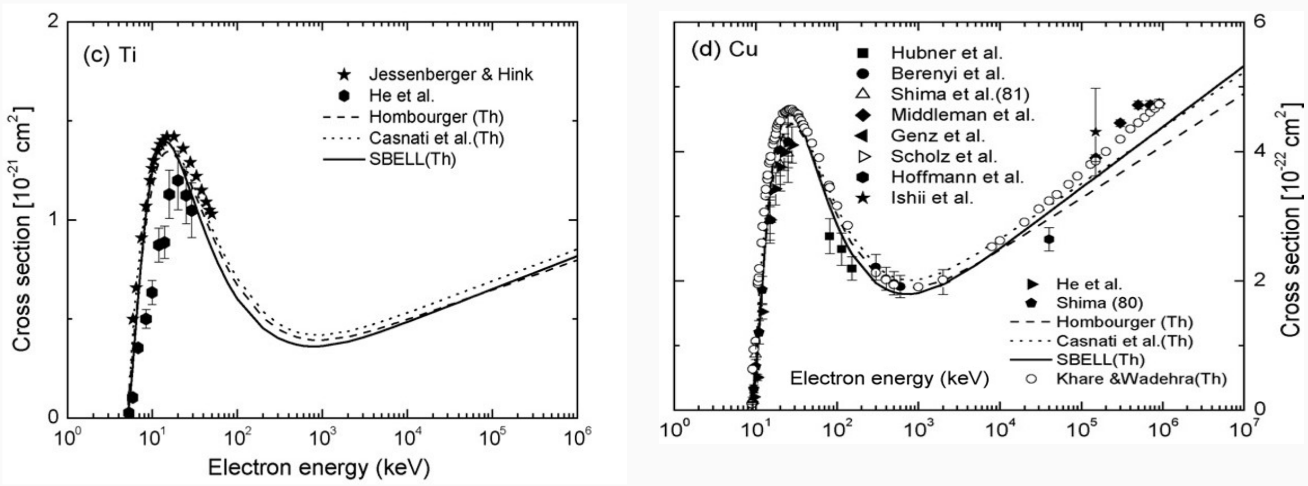
Experimental study of fast electron transport



- Space resolved imaging is needed to identify regions of X.ray emission characterised by different physical conditions
- Multi layer targets with multi-energy tracing elements would provide a detailed fast electrons propagation history

Bragg crystals as an experimental tool

- As an experimental tool, flat (seldom) or bent Bragg crystals are employed
- Bragg crystal suffer from two major drawbacks:
  - the collection efficiency is strongly dependent upon the target temperature, due to the shift of the observed emission lines. When used in an imaging configuration, this may also affect the observed shape of the object being imaged out
  - the efficiency of the available configurations is quite poor at high photon energies. On the other hand, the behaviour of the ionization cross section by fast electrons as a function of the Z atomic number would push for the use of high Z number tracer layers (see figures below)



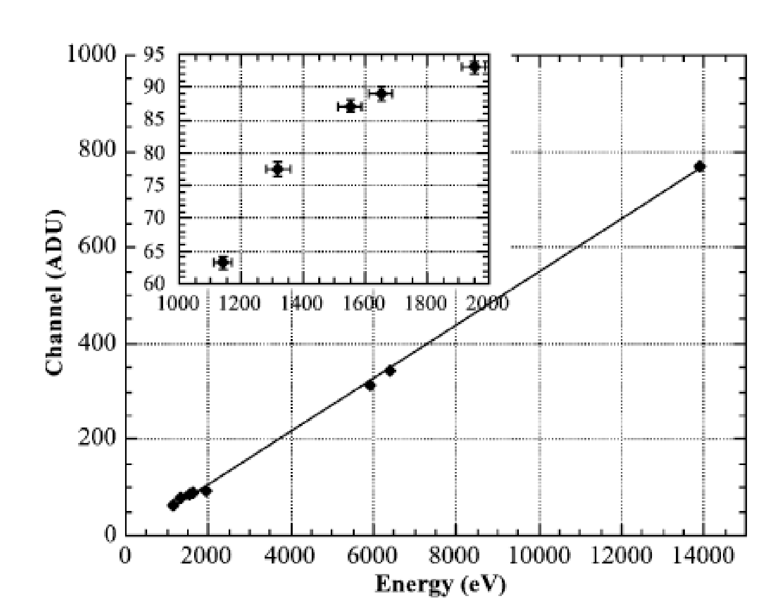
- Furthermore, bent Bragg crystals are difficult to be used at PW, “harsh” environments, where noise from high energy particles/photons is a major issue

Contents

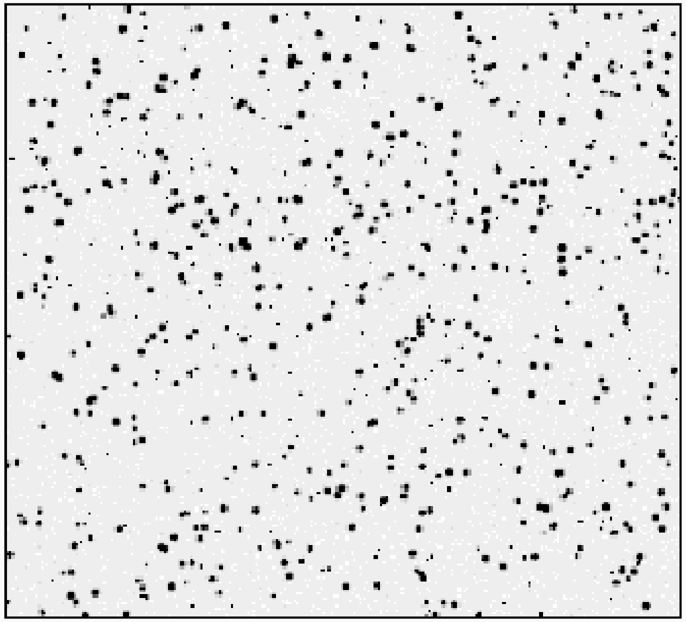
- Scenario and motivations. Overview of fast electron transport diagnostics
- Single-hit CCD spectroscopy
- The EEPHC (Energy-Encoded PinHole Camera) diagnostic
  - General principles
  - The single-shot EEPHC
  - A few examples of recent experimental results

Single-hit CCD spectroscopy

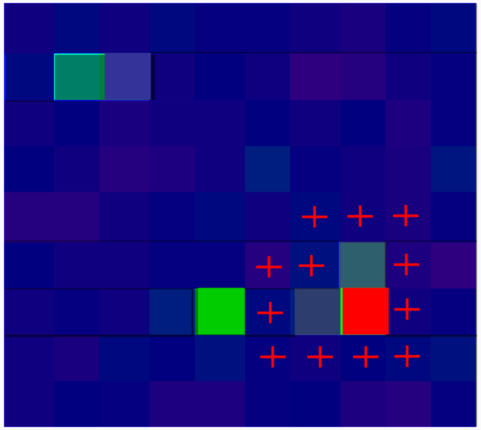
- CCD working in the so-called single-photon regime allows a direct, dispersive element free, spectroscopy in a large spectral range with spectral resolutions of the order of $\delta\lambda/\lambda \sim 10^{-1}$
- As it is well known, this detection technique basically relies on the linear relationship between the X-ray photon energy and the released electron charge, so that when only 1 photon (actually much less on average) hits each pixel the spectrum of the incoming radiation can be retrieved by simply taking an histogram
- Deviation from linearity of X-ray CCDs is found to occur only for photon energies lower than ~1keV



Single-hit spectroscopy data analysis



- Charge spreading across neighbouring pixels, dark current, dead layers and channel stops
  - Need of a careful (and tricky) analysis
    - Background subtraction
    - Event reconstruction
    - Local background subtraction
    - Event shape fit with a suitable 2D function
    - ...



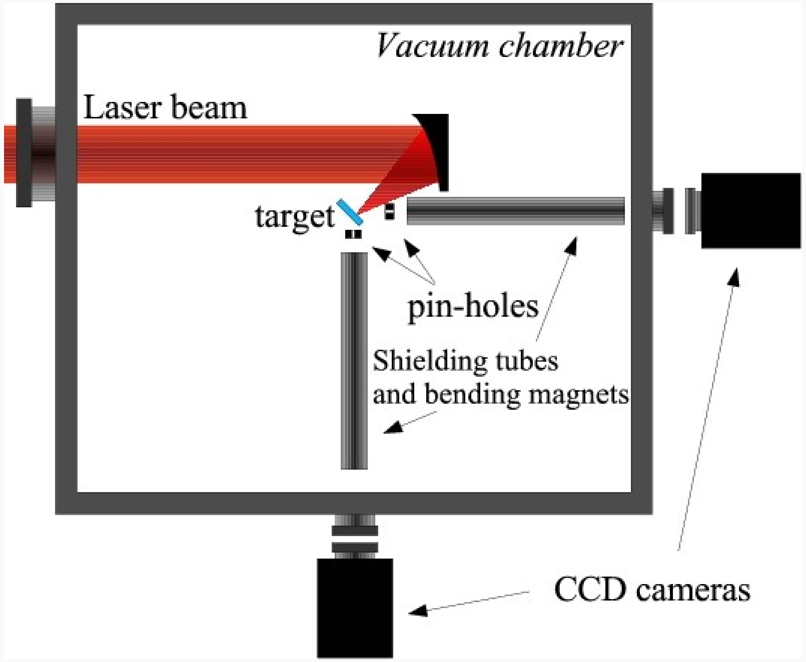
L. Labate *et al.*, Nucl. Instrum. Meth. Phys. Res. A **495**, 148 (2002)

Contents

- Scenario and motivations. Overview of fast electron transport diagnostics
- Single-hit CCD spectroscopy
- The EEPHC (Energy-Encoded PinHole Camera) diagnostic
    - General principles
    - The single-shot EEPHC
    - A few examples of recent experimental results

An Energy-Encoded PinHole Camera (EEPHC)

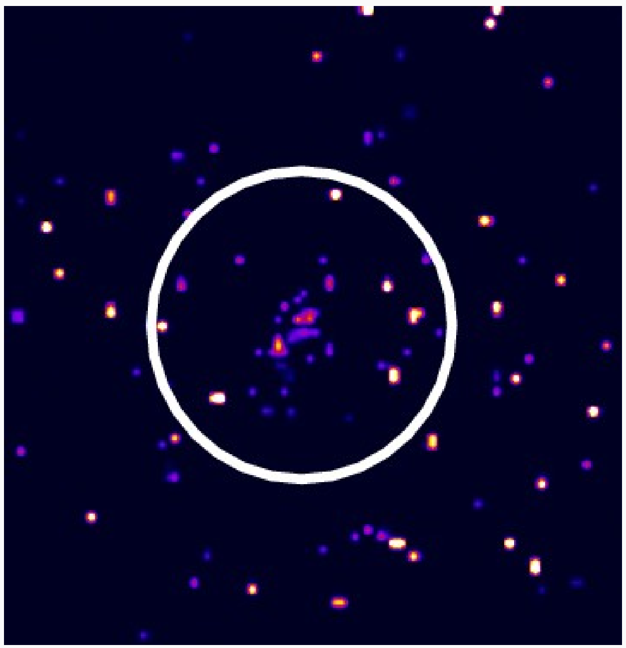
- Simple PH camera scheme with a CCD detector
- The CCD detector is forced to operate in the single-hit regime by using suitable X-ray attenuators (e.g., mylar foils in the simplest case or more complex combination of materials when a flat transmission is required over a broad energy range)



L. Labate *et al.*, Rev. Sci. Instrum. **78**, 103506 (2007)

An Energy-Encoded PinHole Camera (EEPHC) [2]

From each shot a "single-photon image" is obtained, that is a collection of single-photon events whose position on the detector plane is related to its origin in the object (plasma) plane



Data analysis:
- Single-photon event reconstruction
- Image reconstruction for the desired photon energy range from a large number of shots

If small target/PH/detector displacements can be suspected to occur from shot to shot, potentially affecting the spatial resolution, an "event center-of-mass" alignement procedure can be performed to each acquisition

L.A. Gizzi *et al*., Plasma Phys. Controll. Fusion **49**, B221 (2007)

Contents

A way toward a single-shot EEPHC

- Our EEPHC requires a few hundreds of “low flux images” to collect a sufficient number of photons per spectral band to build up a full image

- Experiments at high-energy laser facilities require single-shot measurements

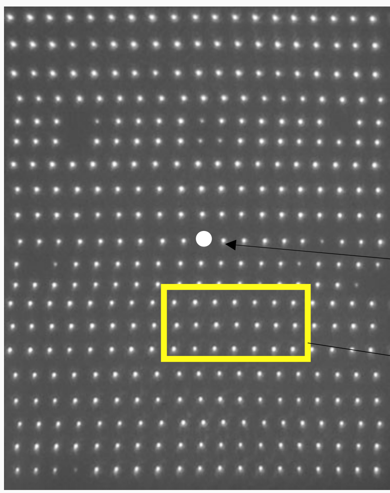
- One of the possible approaches to address this issue is to use an array of closely spaced pinholes to image out the source on a large area CCD (or CCD array) detector

- A custom array of pinholes is needed, due to the constraints on the pinhole diameters (<10mm), substrate thickness (~100mm) and material

- The distance between neighbouring pixels must be set according to
  - the expected source size (in order to avoid an overlap of different neighbour “single-photon images”)
  - the required magnification
  - the available CCD chip size!

Custom pinhole array fabrication at ILIL-CNR

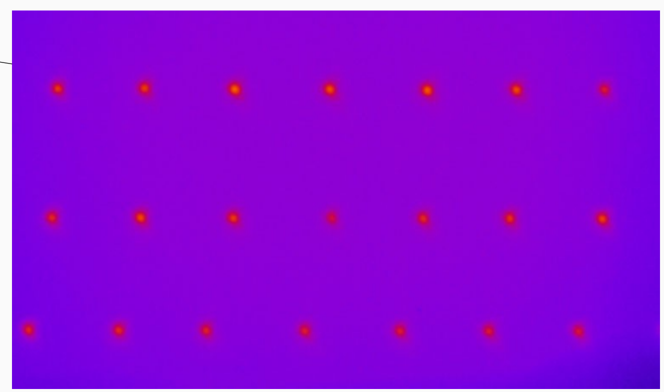
- Custom pinhole arrays have been produced at the ILIL laboratory of the CNR in Pisa by laser drilling of suitable substrates
- To this purpose, the frequency-doubled low-energy (~15mJ, 0.2TW) "probe" beam of a TiSa system has been tightly focused by means of a microscope objective onto the substrate surface



First 20X20 pin hole array sample made at ILIL on a 100µm thick W substrate.

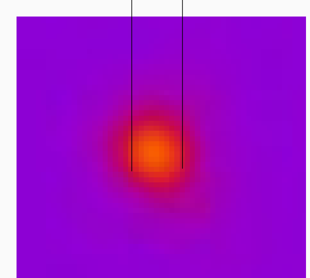
Alignment pin-hole

1mm



65µm

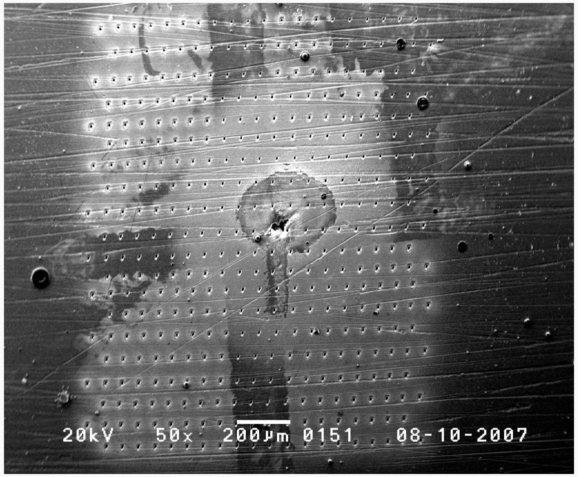
7µm FWHM

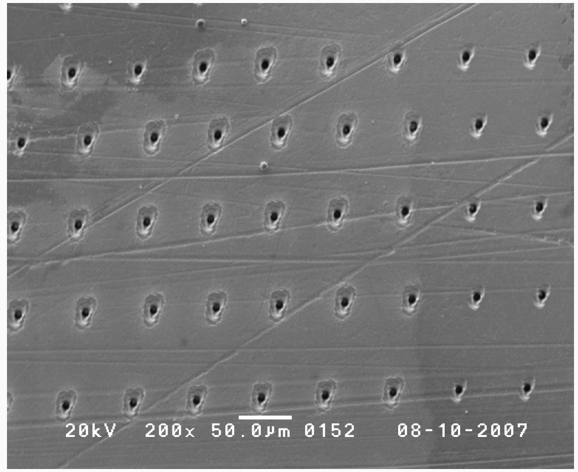


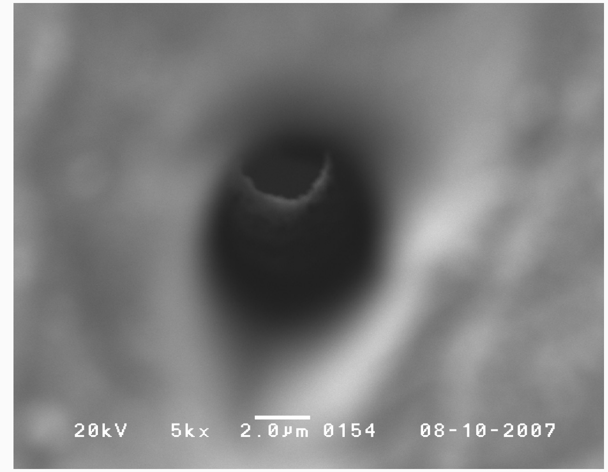
Optical microscopy images

T. Levato *et al.*, Nucl. Instrum. Meth. Phys. Res. A **623**, 842 (2010)

Custom pinhole array fabrication: SEM images

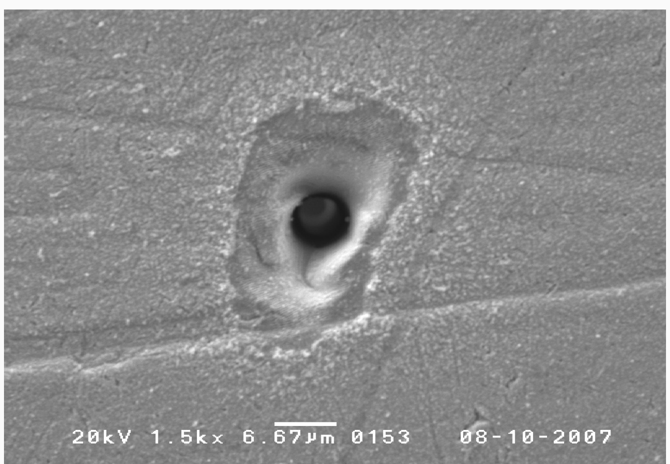


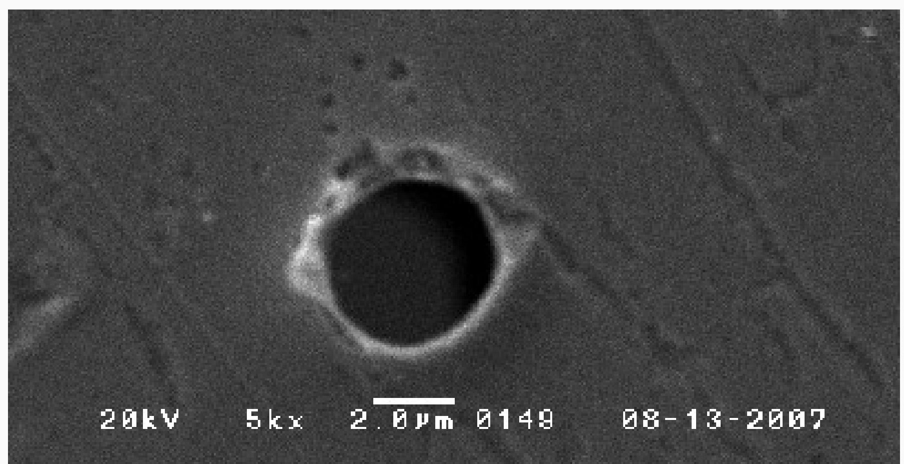




Front side

Rear side

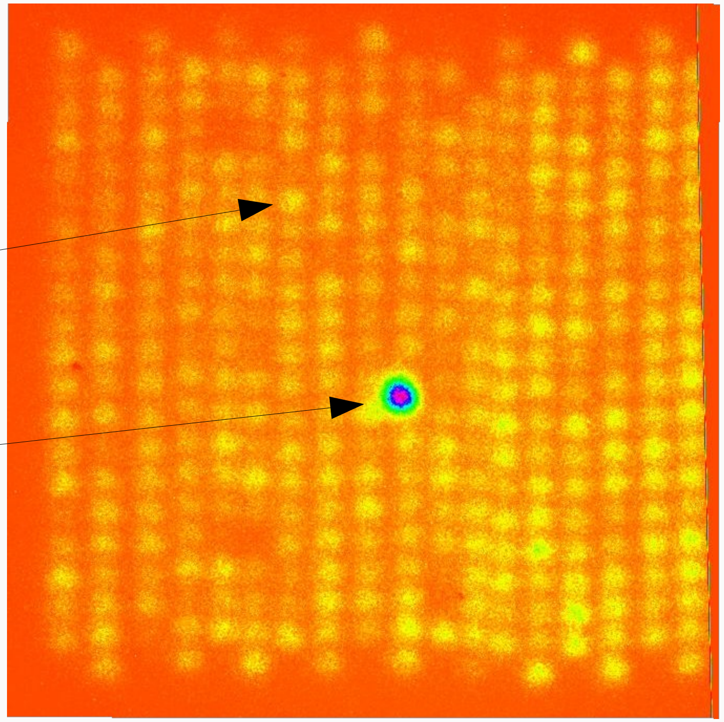


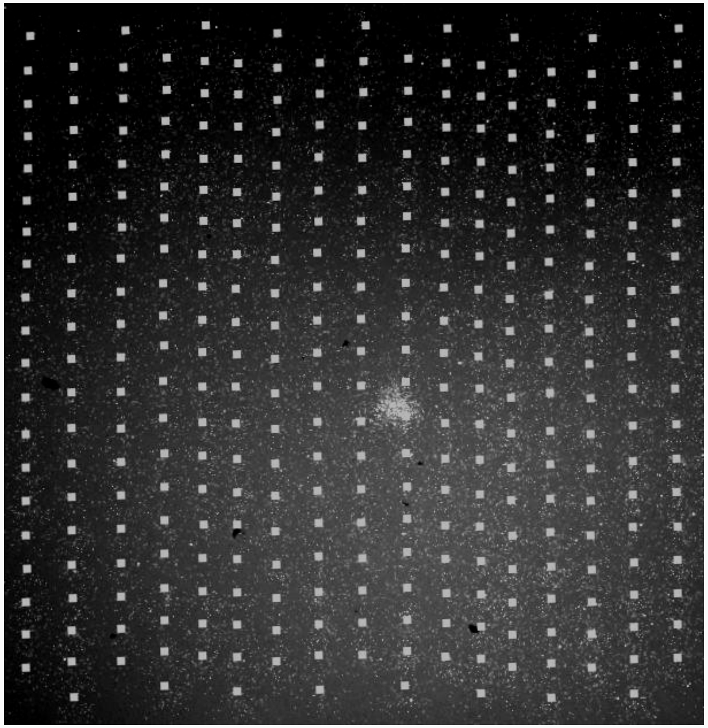


Single-shot EEPHC: examples

Images through pinholes

Larger pinhole for alignement





- The individual "single-photon images" can finally be collapsed into a single one to get the final results

Issues related to the spectral and spatial resolution

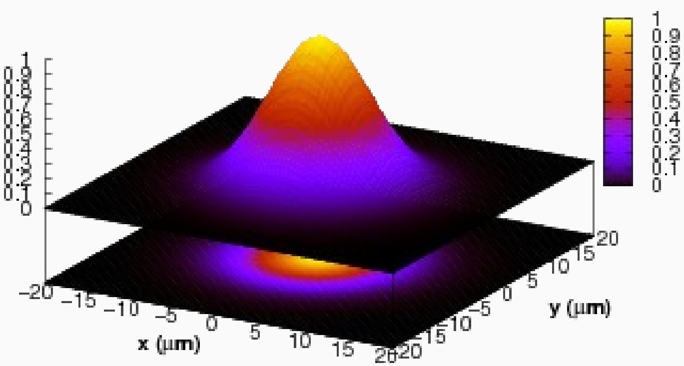
- The spectral resolution is of the order of a few % over a broad spectral range (up to a few tens of keV)
- The Point Spread Function takes the form

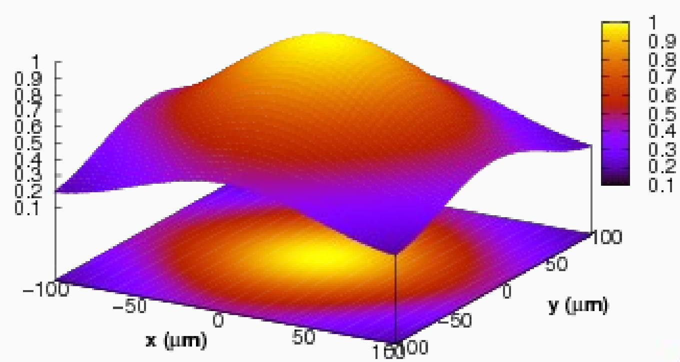
$$\mathrm{PSF}(x'_s, y'_s; x_d, y_d) = \sum_{i,j} \prod_{\alpha} \left[c_\alpha(E) + (1 - c_\alpha(E)) \sum_{k,l} \left[1 - H\left(\sqrt{\xi_\alpha^2 + \eta_\alpha^2} - R_{PH} \right) \right] \right]$$

with $\xi_\alpha = x'_s + \frac{z_p + \alpha\delta_s}{p+q}(x_d + x_{ij}^{(i)} - x'_s) - x_{kl}^{(p)}$ $\quad \eta_\alpha = y'_s + \frac{z_p + \alpha\delta_s}{p+q}(y_d + y_{ij}^{(i)} - y'_s) - y_{kl}^{(p)}$

where $x_{ij}^{(i)}$ is the position of the center of the image through the ij pinhole, $x_{kl}^{(p)}$ is the position on the PHA plane of the *kl* pinhole, … The sum is carried out over all the pinholes and the product over "thin" slices of the PHA, each having a transmission coefficient $c_a(E)$. R_{PH} is the radius of each pinhole.

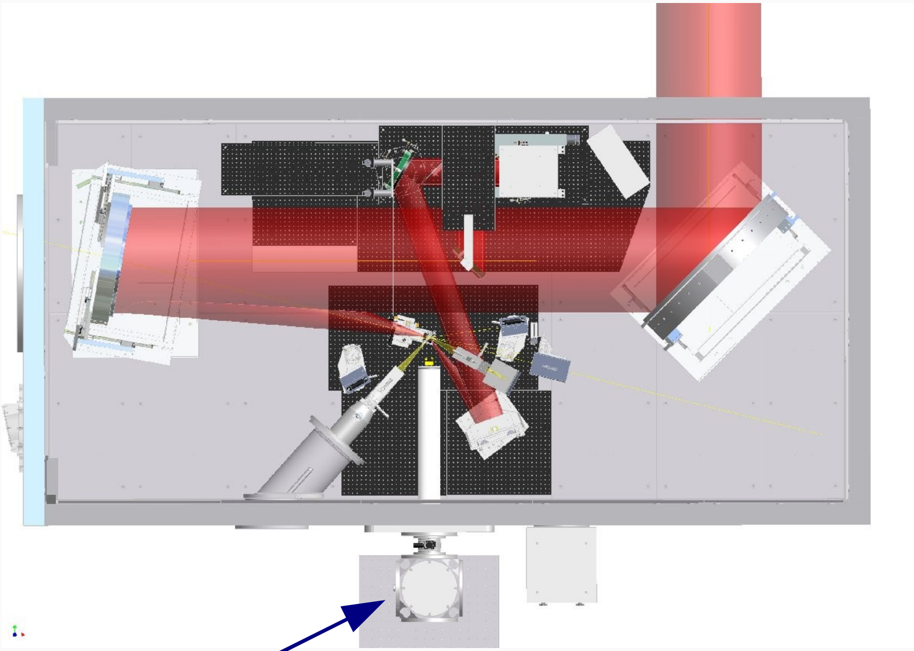
- As a general rule of thumb, the source size must be much smaller than the neighbour pinholes separation in order for the overlapping effects to be negligible



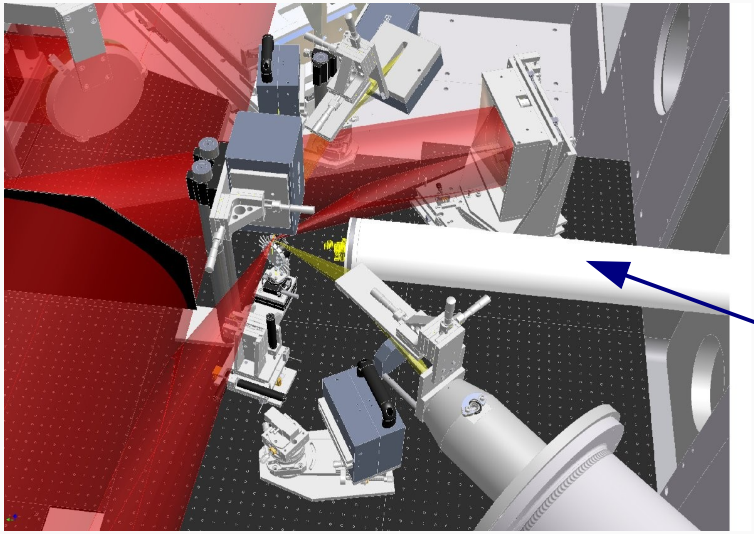


An example of the setup at RAL Target Area PW

- The single-shot EEPHC has been recently employed in a PW environment in an experiment in Vulcan Target Area Petawatt



CCD chamber

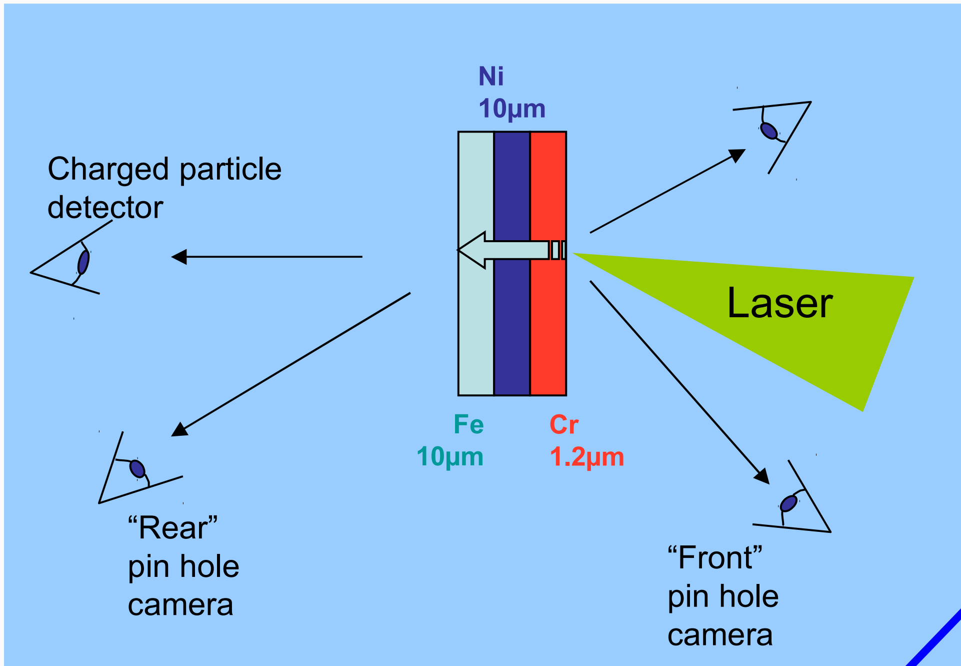


Shielding tube:
- plastic 10mm
- Al 13mm
- plastic 7mm

Contents

- Scenario and motivations. Overview of fast electron transport diagnostics
- Single-hit CCD spectroscopy
- The EEPHC (Energy-Encoded PinHole Camera) diagnostic
  - General principles
  - The single-shot EEPHC
  - A few examples of recent experimental results

EEPHC: some results [1]



Element	Kα (keV)	Kβ (keV)
Cr	5.41	5.95
Ni	7.48	8.26
Fe	6.40	7.06

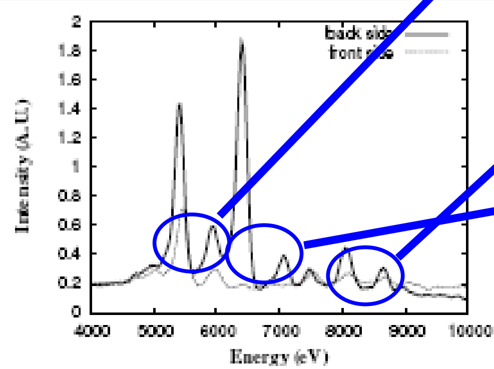


FIG. 5: X-ray spectrum obtained from 350 laser shots irradiation of a Cr-Ni-Fe target.

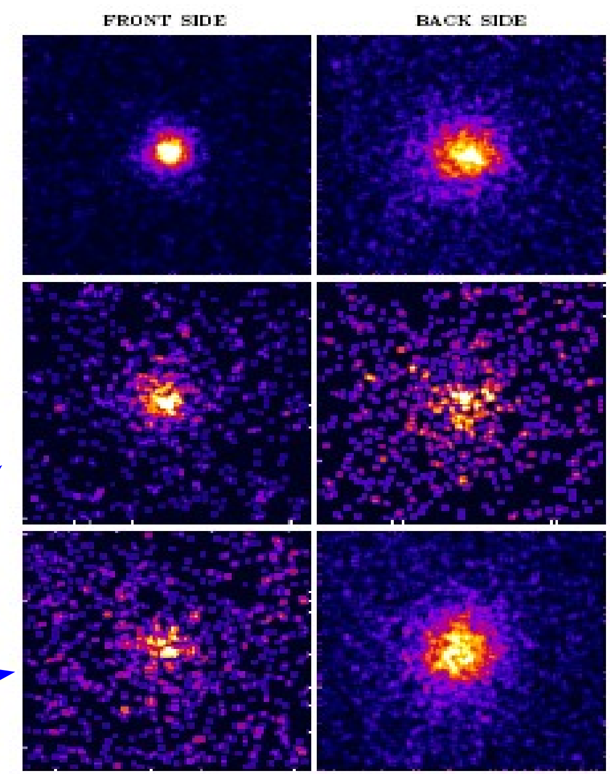


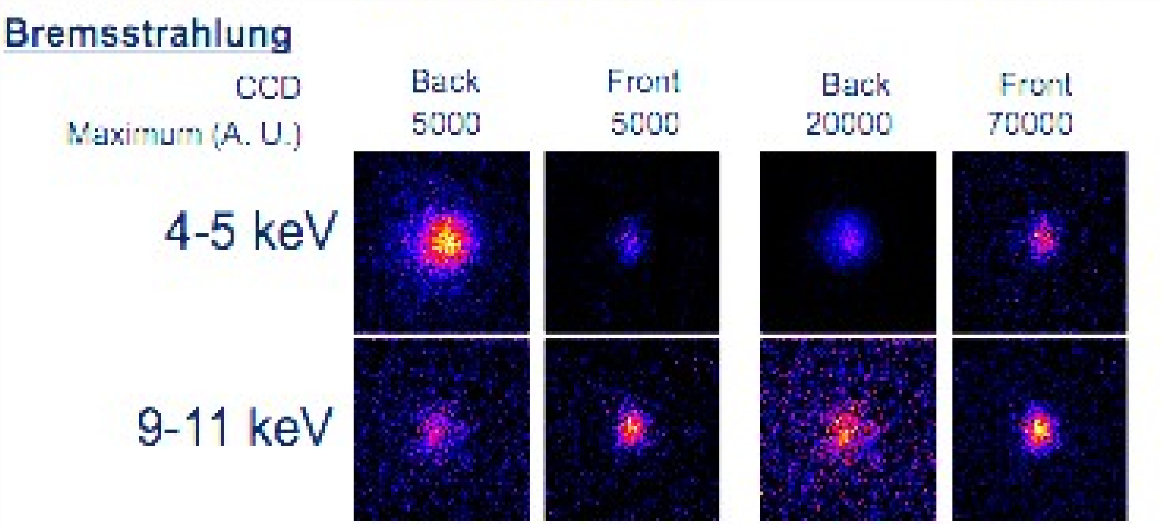
FIG. 6: X-ray images of the source at the Kα and Kβ energy (considered together) of the different target materials, obtained from 350 shots on a Cr-Ni-Fe target: *top:* Cr, *middle:* Ni, *bottom:* Fe. The image size is 156 μm in both the horizontal and vertical direction.

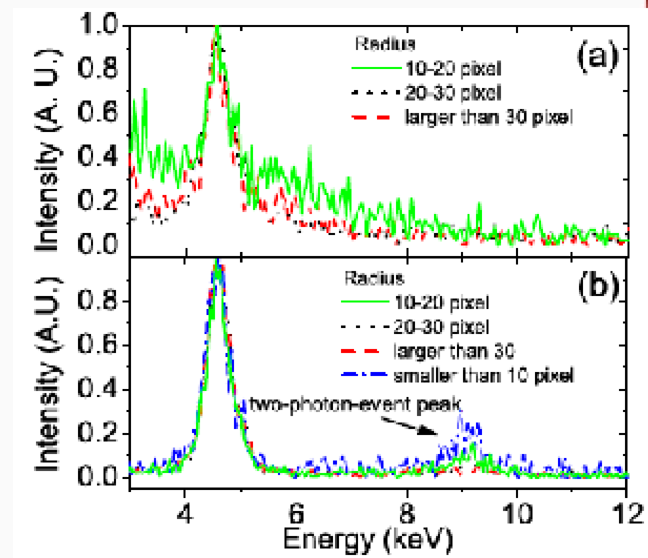
L. Labate *et al.*, Rev. Sci. Instrum. **78**, 103506 (2007)

INO-CNR Istituto Nazionale di Ottica

EEPHC: some results [2]

- Provided a sufficient number of photons has been collected, the source can of course imaged out at energy ranges where no spectral lines are supposed to be present and only continuum (low energy Bremsstrahlung) emission is expected to contribute to the X-ray spectrum



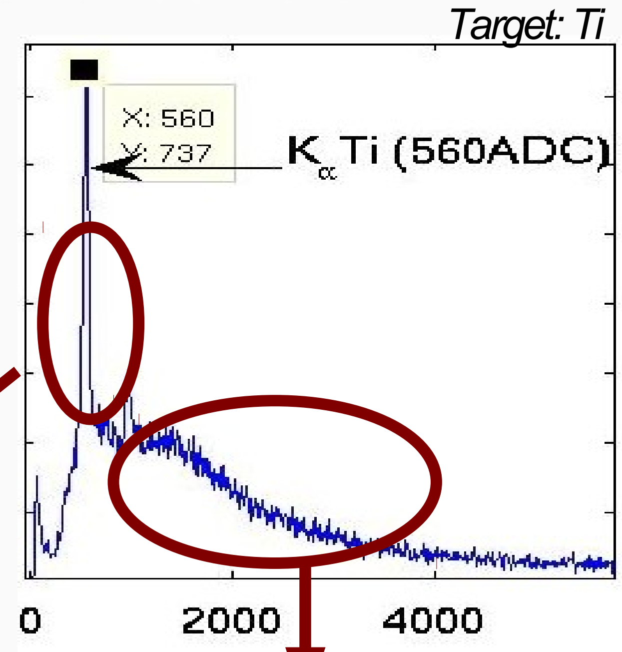


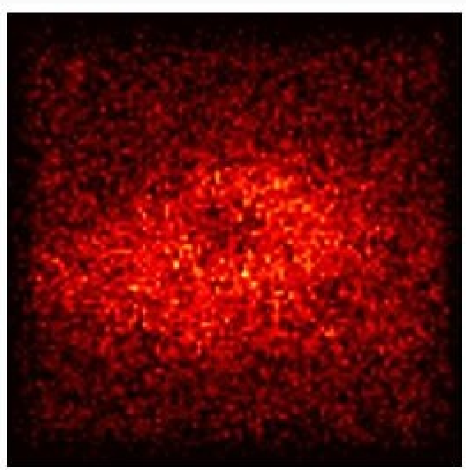
Evidence of non-isotropic emission, due to Bremsstrahlung

F. Zamponi *et al.*, Phys. Rev. Lett. **105**, 085001 (2010)

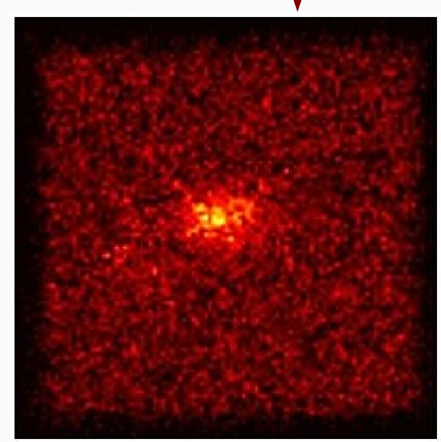
EEPHC: some results [3]

- Results from a recent experiment at RAL PW show that a high-energy X-ray emission comes from a small spot while the Ka emission region exhibits a minimum





~80μm



INO-CNR Istituto Nazionale di Ottica

Summary and conclusions

- In the past few years, a new concept X-ray spectroscopic tool has been being developed, based upon the use of single-hit CCD detectors

- This new diagnostic allows 2D X-ray images with simultaneous spectral resolution of ICF plasmas to be obtained, with spatial resolution of the order of a few µm and spectral resolution of a few %, over a large spectral range (up to a few tens of keV)

- Although the spectral resolution is rather poor when compared to the one attainable by using Bragg crystals, this new tool is particularly suited for the study of fast electrons transport in high-energy-density plasmas, such as those encountered in the fast ignition approach to ICF

- This new diagnostic tool has been successfully employed in recent experimental campaigns carried out at multi-TW- and PW-scale laser facilities

Collaborations

S. Hőfer, T. Kämpfer, R. Lőtzsch, A. Lübcke, I. Uschmann, F. Zamponi, E. Főrster

Institut für Optik und Quantenelektronik, Friedrich-Schiller-Universität, Jena, Germany

M. Kozlova, T. Mocek, J. Polan, B. Rus

Department of X-ray laser, PALS Centre – Institute of Physics, Czech Academy of Sciences, Prague, Czech Republic

D. Batani

Dipartimento di Fisica, Università di Milano Bicocca, Milano, Italy

N. Booth, G. Gregori, B. Li, M. Makita, J. Mithen, C. Murphy, M. Notley, R. Pattathil, D. Riley, N. Woolsey

University of York and Rutherford Appleton Laboratory, UK

EEPHC (multi-shot): some results (2)