A new X-ray spectroscopy diagnostics of fast electron transport in high-density plasmas

L. Labate, C.A. Cecchetti, A. Giulietti, D. Giulietti, P. Kőster, T. Levato, L.A. Gizzi

Intense Laser Irradiation Laboratory – IPCF, Consiglio Nazionale delle Ricerche, Pisa and Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, Italy

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

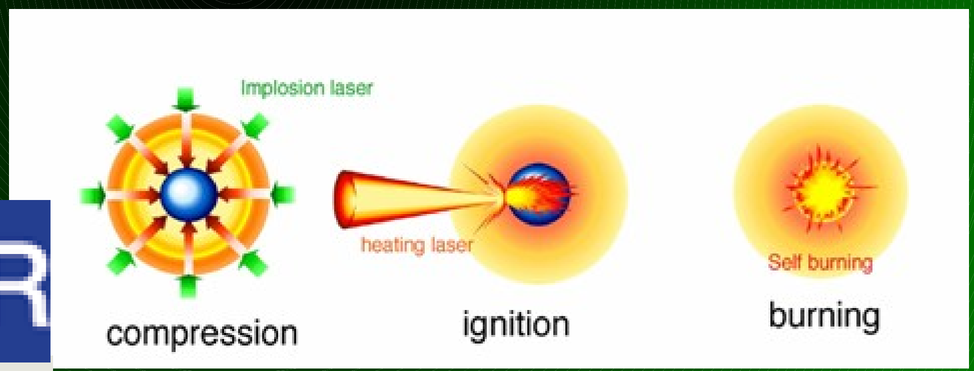
A. Antonicci, D. Batani

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

Support

Motivations for the study of fast electron transport

- Fast electrons, with kinetic energy from a few tens of keV up to some MeV, are efficiently produced in the interaction of short and ultrashort laser pulses with matter at an intensity $>10^{16}$ W/cm^2
- Understanding the processes of f.e. production and their transport in high-density matter is of a crucial importance in fields such as, e.g., the study of ultrashort and bright X-ray sources based on Kα radiation and the fast ignition approach to the ICF



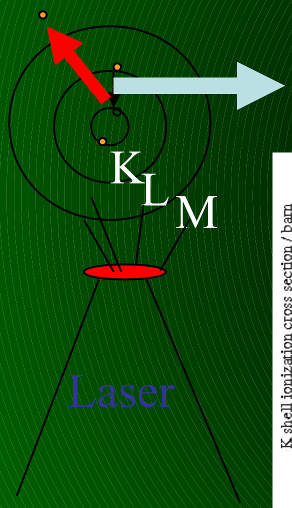
Required for the ignition of the pre-compressed fuel (300 g/cm^3):
- 10-100kJ energy
- Deposited in a region with ~20μm size
- In a time interval of ~10ps

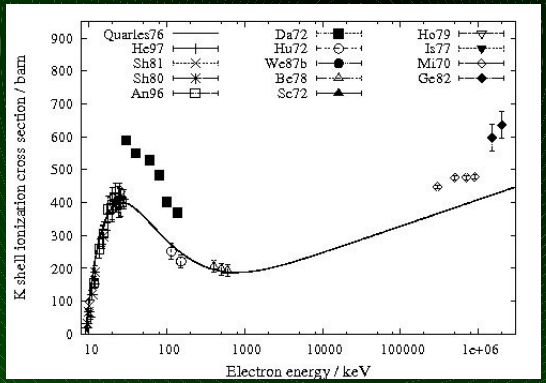
→ e- beam:
- K.E. ~ 1MeV
- Current ~ MA

→
- Alfven limit → return current
- e- beam instabilities
- Refluxing at density discontinuities

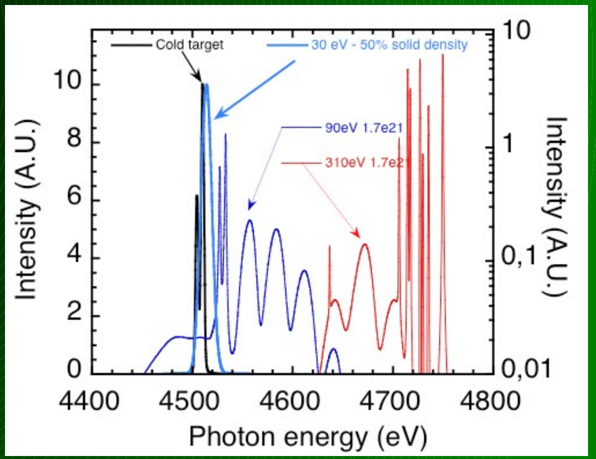
Diagnostics for fast electron transport

- The most adopted way of studying the f.e. transport in high-density matter is currently the observation of the Kα emission

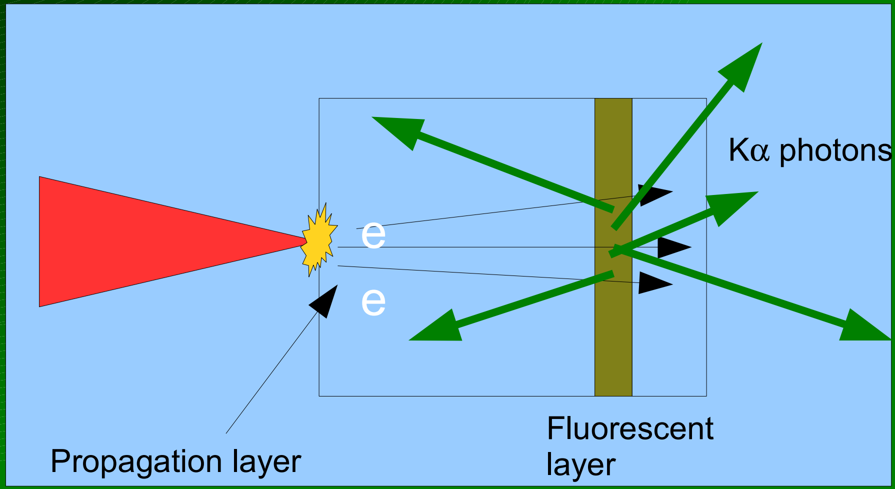




Kα emission from cold and ionized atoms: infos about local temperature

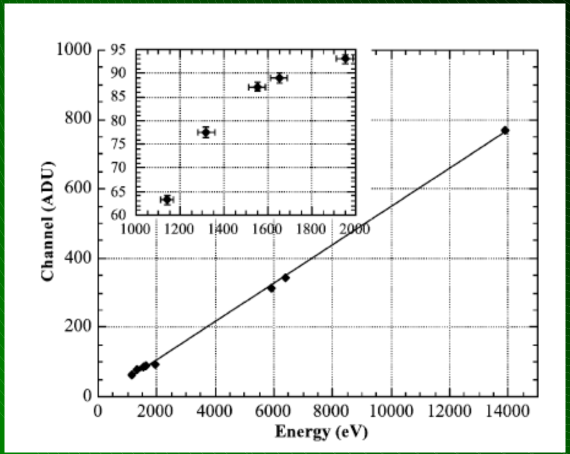


- Multi-layer targets with different, ad hoc, fluorescent layers at different depth are usually employed
- At least a 1D spatial resolution is needed to image out regions with different features
- This is usually accomplished by means of bent Bragg crystal, which allows 1D or 2D imaging at selected wavelengths



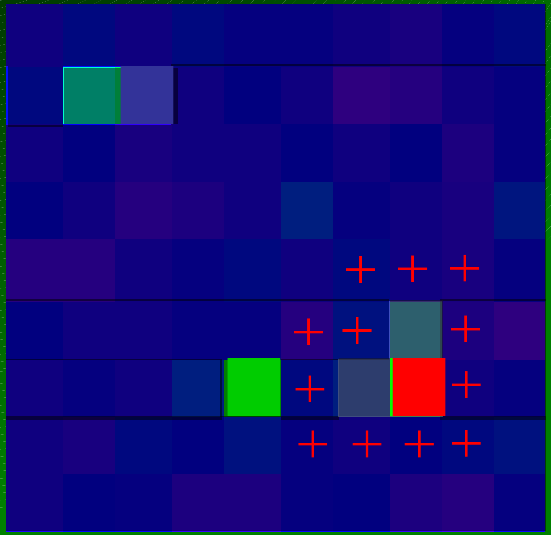
Single-photon (or single-hit) CCD X-ray spectroscopy

- 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 detction technique basically relies on the linea 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



- Charge spreading across neighbouring pixels, dark current, dead layers and channel stops

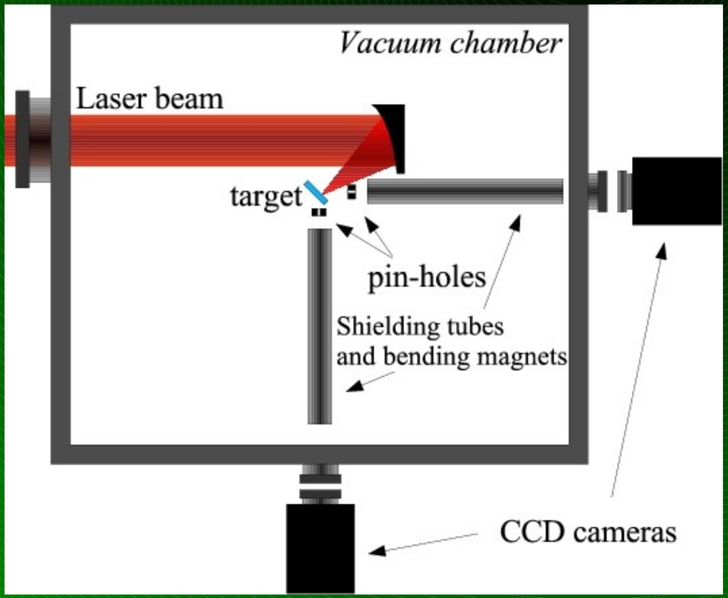
→ Need for a careful (and tricky) analysis



- Background subtraction
- Event reconstruction
- Local background subtraction
- Event shape fit with a suitable 2D function
- ...

X-ray energy-encoded pinhole camera (multi-shot)

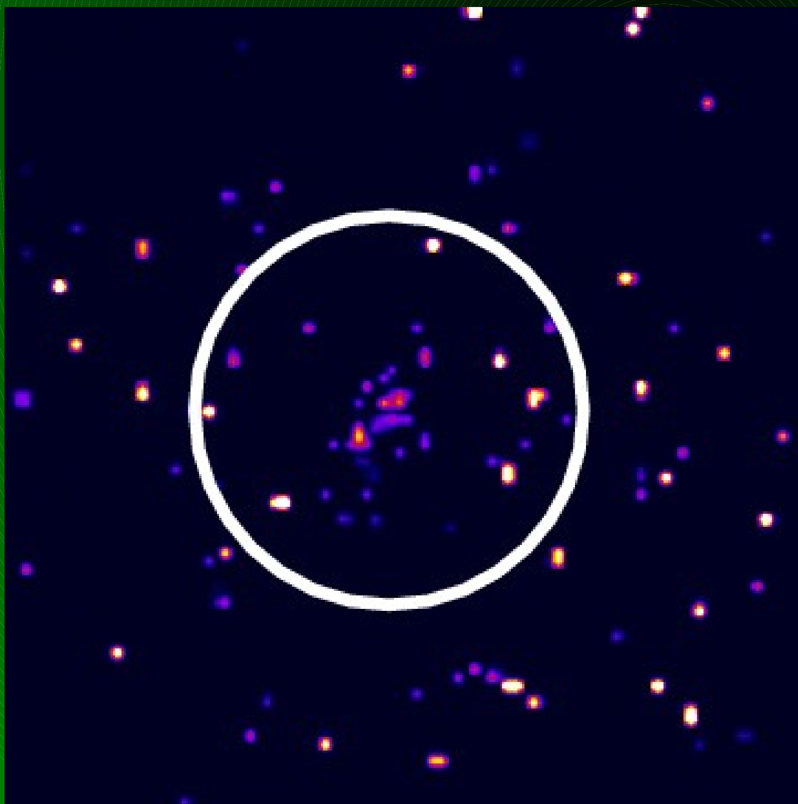
- PH camera equipped with a CCD detector
- The CCD is forced to operate in the single-photon regime (e.g. By using X-ray attenuators), so that the energy of each photon can be retrieved
- By summing up the contributions from a sufficient number of acquisitions (i.e., laser shots), images of the source at any selected energy range can be retrieved



- The first experiment employing such a diagnostic technique has been carried out at the IOQ-Jena facility, using the JeTi laser:
  •70fs duration pulses
  •~600 mJ after compression
  •10 Hz rep rate
  • Focused at an intensity up to ~10^{19} W/cm^2

EE PH camera (multi-shot): example of an "image" and data analysis

- 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

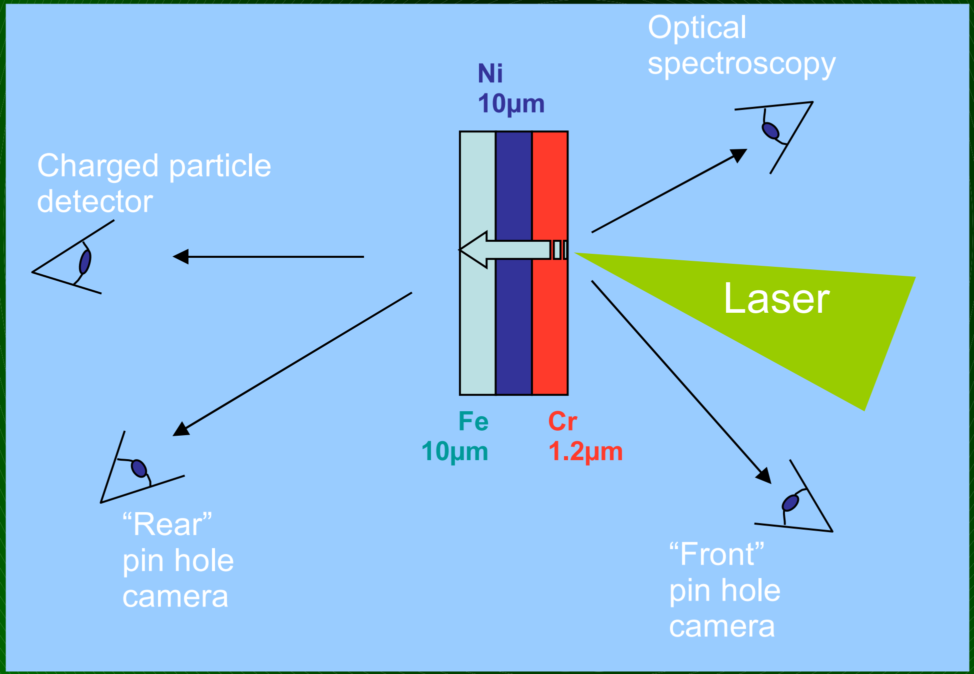


- Data analysis:
  •Single-photon event reconstruction
  •Image reconstruction from a large number (~350) shots

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

EE PH camera (multi-shot): f.e. transport study with multi-layer targets

- We have used multi-layer targets to study the f.e. Transport through dielectric and metallic layers



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

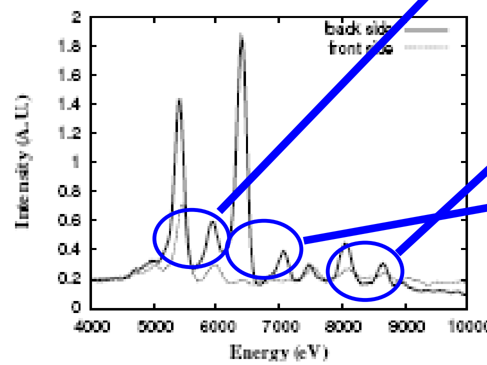


FIG. 5: X-ray spectrum obtained from 350 laser shots irradiation of a Cr-Ni-Fe target.

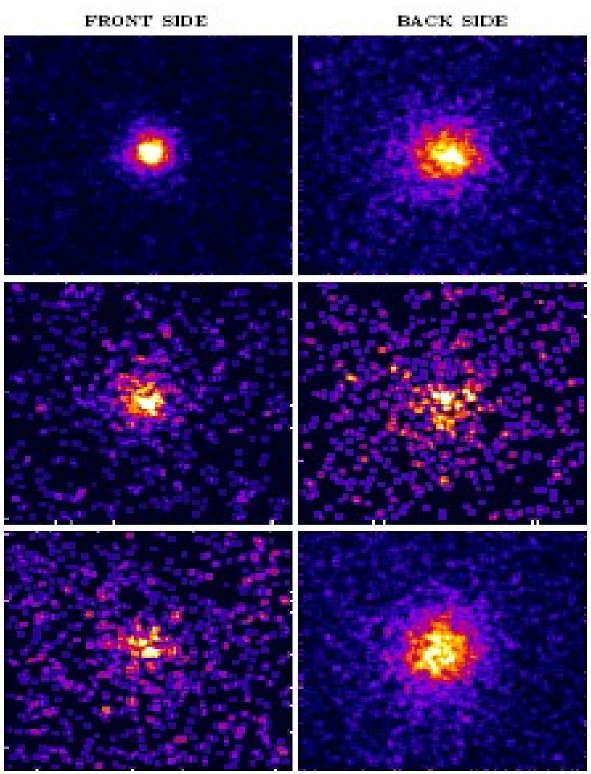
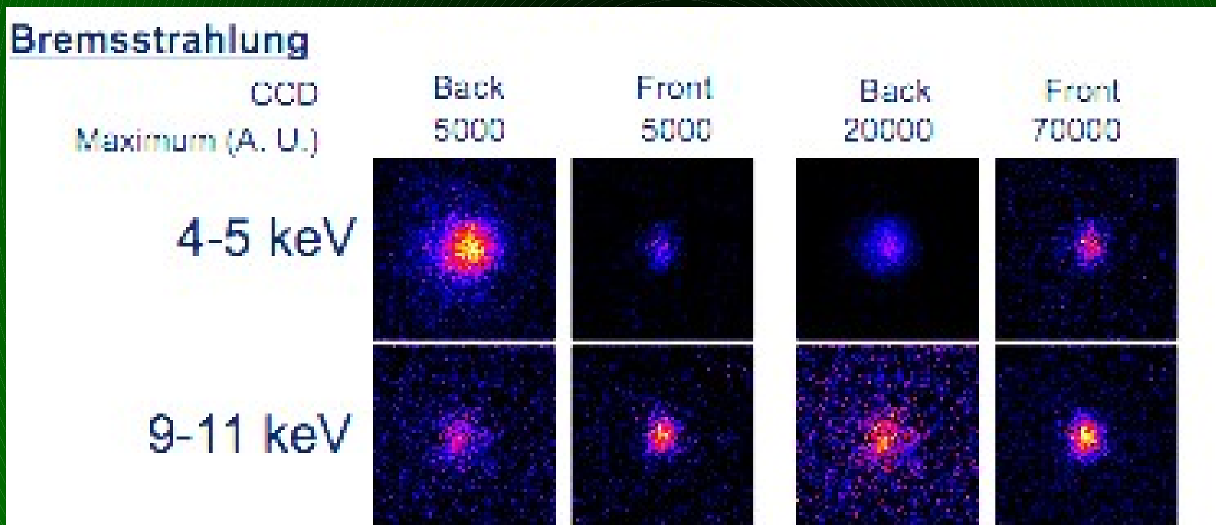


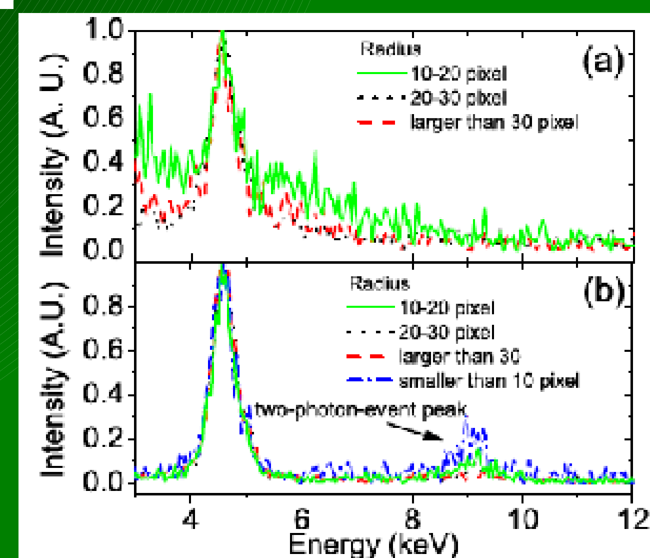
FIG. 6: X-ray images of the source at the Kα and Kβ energy (considered together) of the different target materials, obtained from 350 shots on a Cr-Ni-Fe target: *top:* Cr, *middle:* Ni, *bottom:* Fe. The image size is 156 µm in both the horizontal and vertical direction.

EE PH camera (multi-shot): f.e. transport study with multi-layer targets (2)

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



Evidence of non-isotropic emission, due to Bremsstrahlung

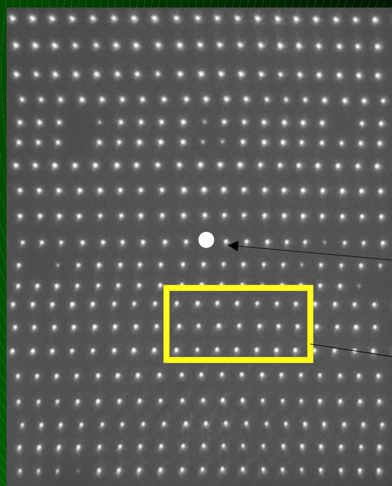


EE PH camera extension to single-shot measurements

- Our imaging technique 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 (RAL, OMEGA/EP, PALS, LULI) 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 detector
- Custom array of pinholes is needed, due to the constraints on the pinhole diameters (<10µm), substrate thickness (>>10µm) and material
- The distance between neighbouring pixels must be set according to
  - The expected source size
  - The required magnification
  - The available CCD chip size!

Custom pinhole array fabrication at ILIL

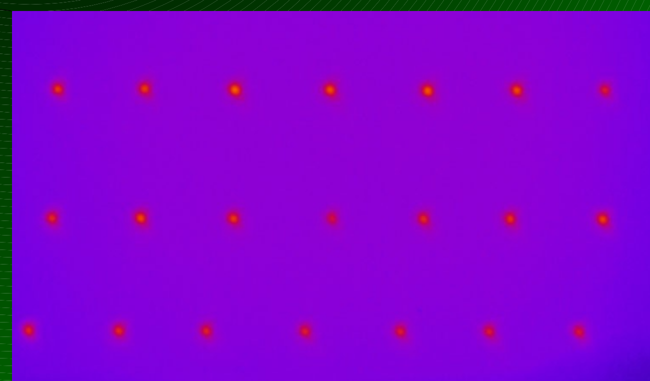
- Custom pinhole arrays have been produced at the CNR Intense Laser Irradiation Laboratory by laser drilling of suitable substrates



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

Alignment pin-hole

1mm

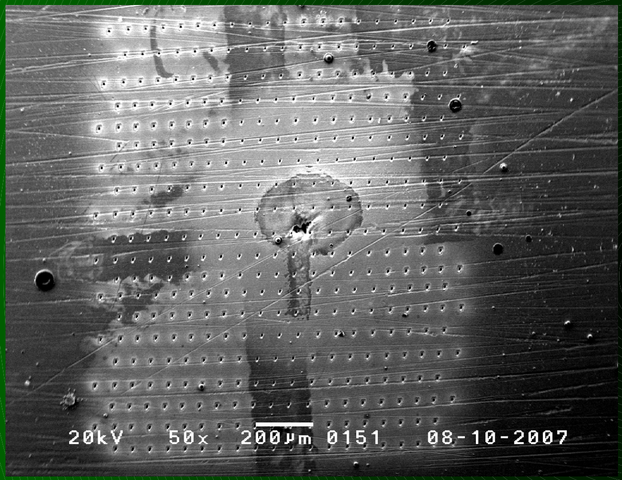


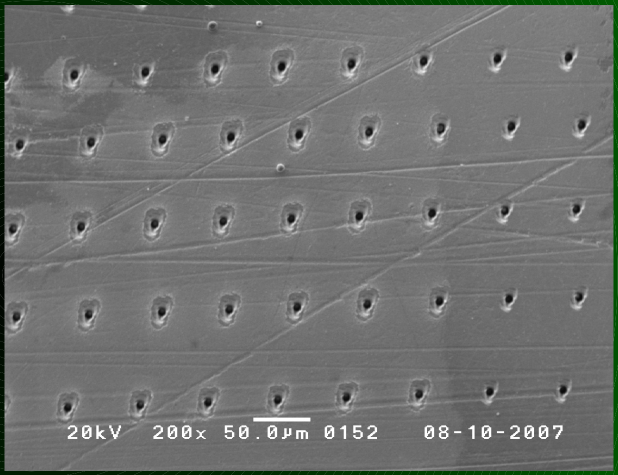
65μm

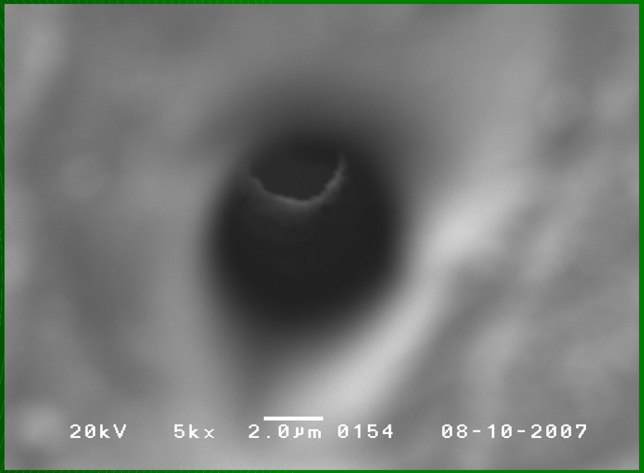
7μm FWHM

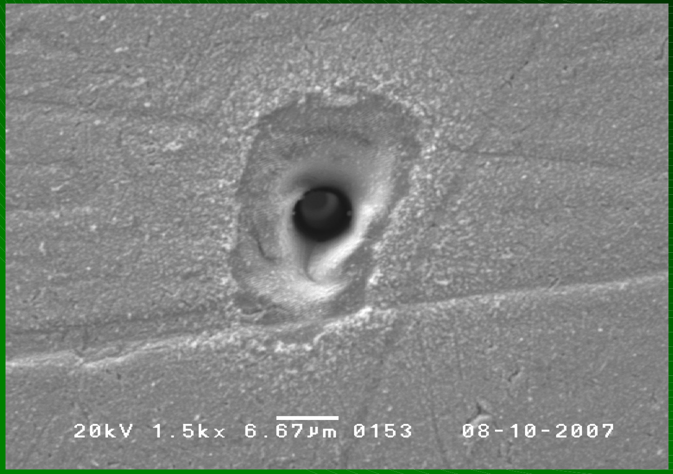
Optical microscopy images

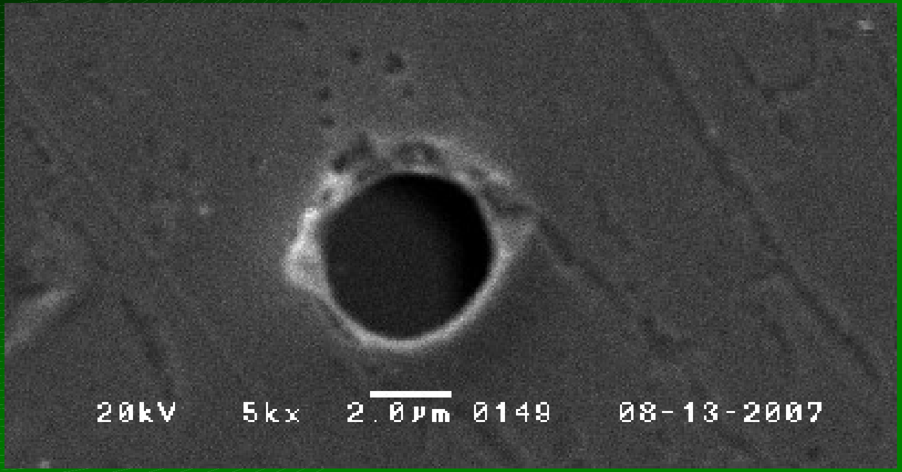
SEM characterization of the pinhole arrays











Single-shot EE PH camera: first experiment

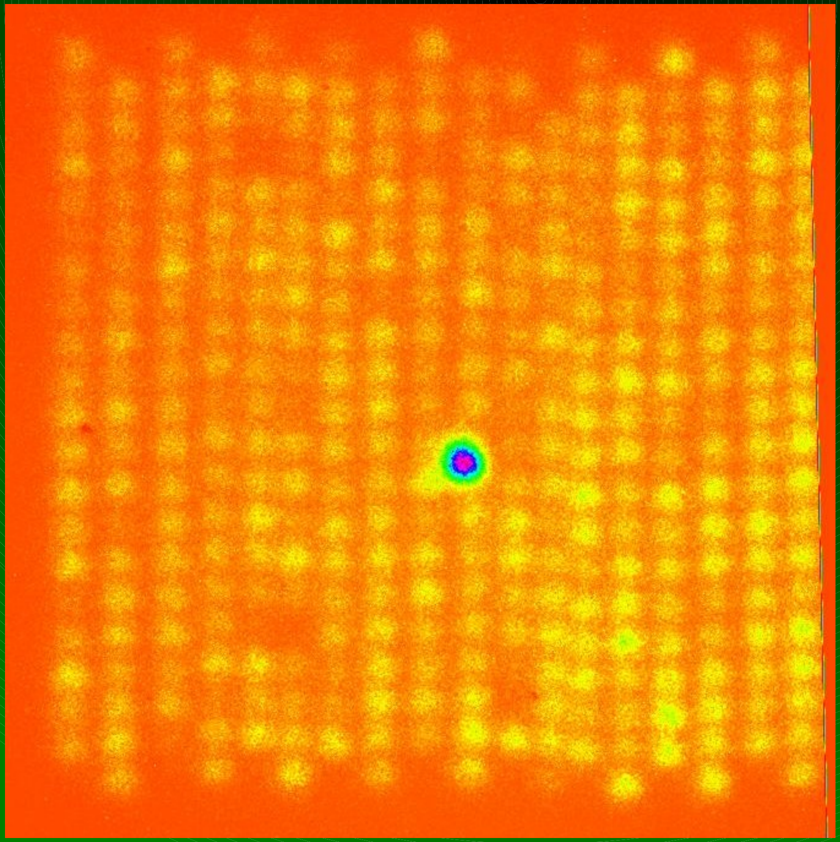
- The first experiment using the diagnostics in its single-shot version has been carried out at the PALS facility in Prague

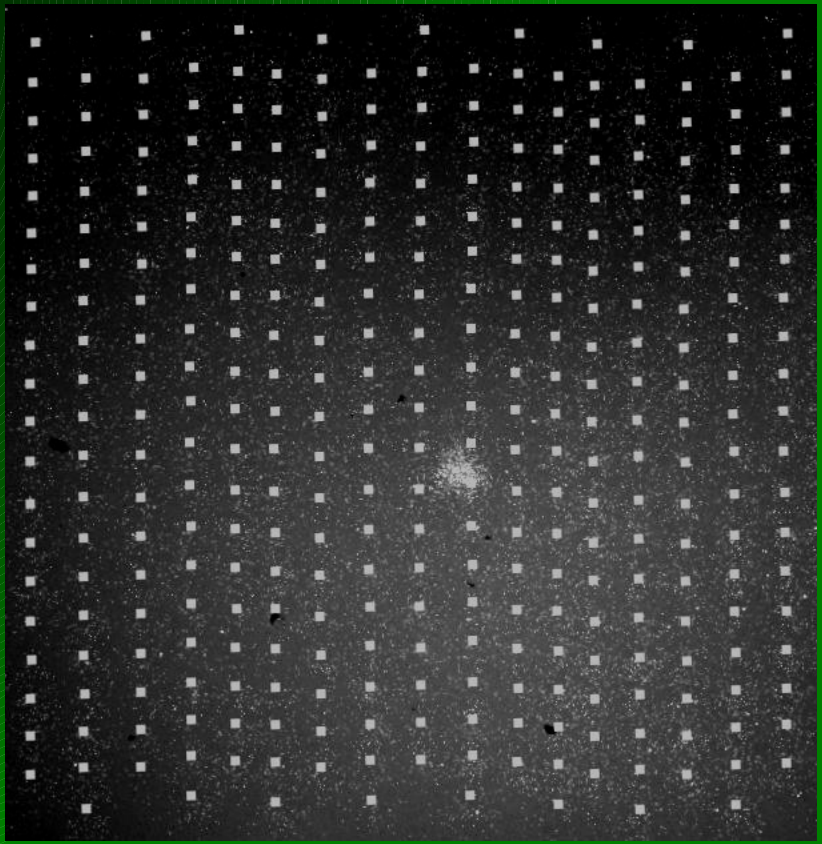
General	Fundamental wavelength	1.315 l'm
	Pulse duration	300 to 400 ps
	Pulse contrast (prepulses & ASE)	~10^{-7}
	Repetition shot rate	25 min
	Output energy stability (over 10 shots)	< ą1.5 %
Main beam	Pulse energy at 400 ps	1 000 J
	Pulse power at 400 ps	3 TW
	Diameter	290 mm
	Conversion efficiency to 3 ω	55 %

Target: thick Ti foil
Intensity:10^{15} W/cm^2
Wavelength: 3w (438nm)
Pulselength: 200ps
Energy 60J
Spot size.: 100 μm^2, Target-PHA distance:12cm PHA-CCD distance: 60cm;
CCD array size: 1024x1024 pxls
Pixel size:13.5x13.5 μm^2

Single-shot EE PH camera: first experiment

- X-ray images of the source through each pinhole have been obtained at different X-ray attenuation levels, down to the single-photon operation
- An image obtained at a high phton flux on the CCD is used in order to superimpose the pinhole array pattern to the actual signal pattern

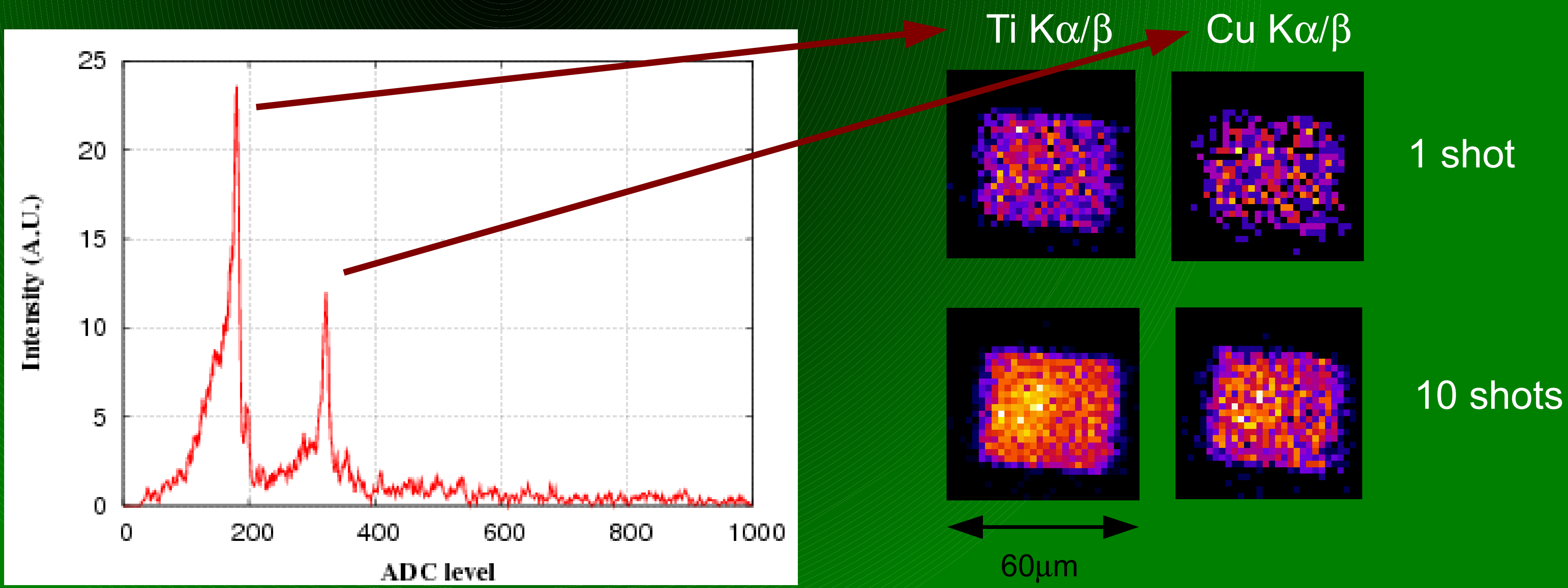




Single-shot EE PH camera: first results

- Individual images from each pinhole are finally superimposed taking into account the actual pinhole array position and geometry (angle, stretching factors, ...)

Example: Cu (0.5µm) – plastic (10µm) – Ti (0.5mm) target, shooting on the Cu side, EE PH camera looking from th rear side of the target



Conclusions

- A new diagnostic technique has been developed for the fast electron transport studies through Kα spectroscopy
- The diagnostics is based upon the use of a pinhole camera equipped with a CCD detector operating in the single-photon condition
- A 2D spatial resolution down to some microns can be obtained and a simultaneous spectral resolution of ~10% over a large spectral interval, roughly corresponding to the useful detection range of the CCD detector
- The technique has been successfully employed in experiments with high repetition rate laser systems on a multi-shot basis
- The diagnostics has been extended to the single-shot operation by using custom made pinhole arrays. Preliminary experiments have been carried out at PALS, RAL PW and IOQ-Jena, which showed the validity of this approach