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Investigations on warm dense plasma with PHELIX facility

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Application of high-resolution x-ray spectroscopy and radiography for investigations of plasma created by PHELIX laser.

- X-ray diagnostics of temperature, density, ionization state of **high-temperature** plasma created under interaction of high intense PHELIX laser pulse with **structured and homogeneous** targets.

- Observations of the **fast ions** generated in the PHELIX laser-produced plasma by X-Ray spectroscopy methods.

- X-ray spectroscopy and radiography of **warm dense matter**.

- Diagnostics of **MG-magnetic fields** generated in the laser-produced plasma by observations of X-Ray plasma satellites and Zeeman splitting of X-Ray spectral lines.

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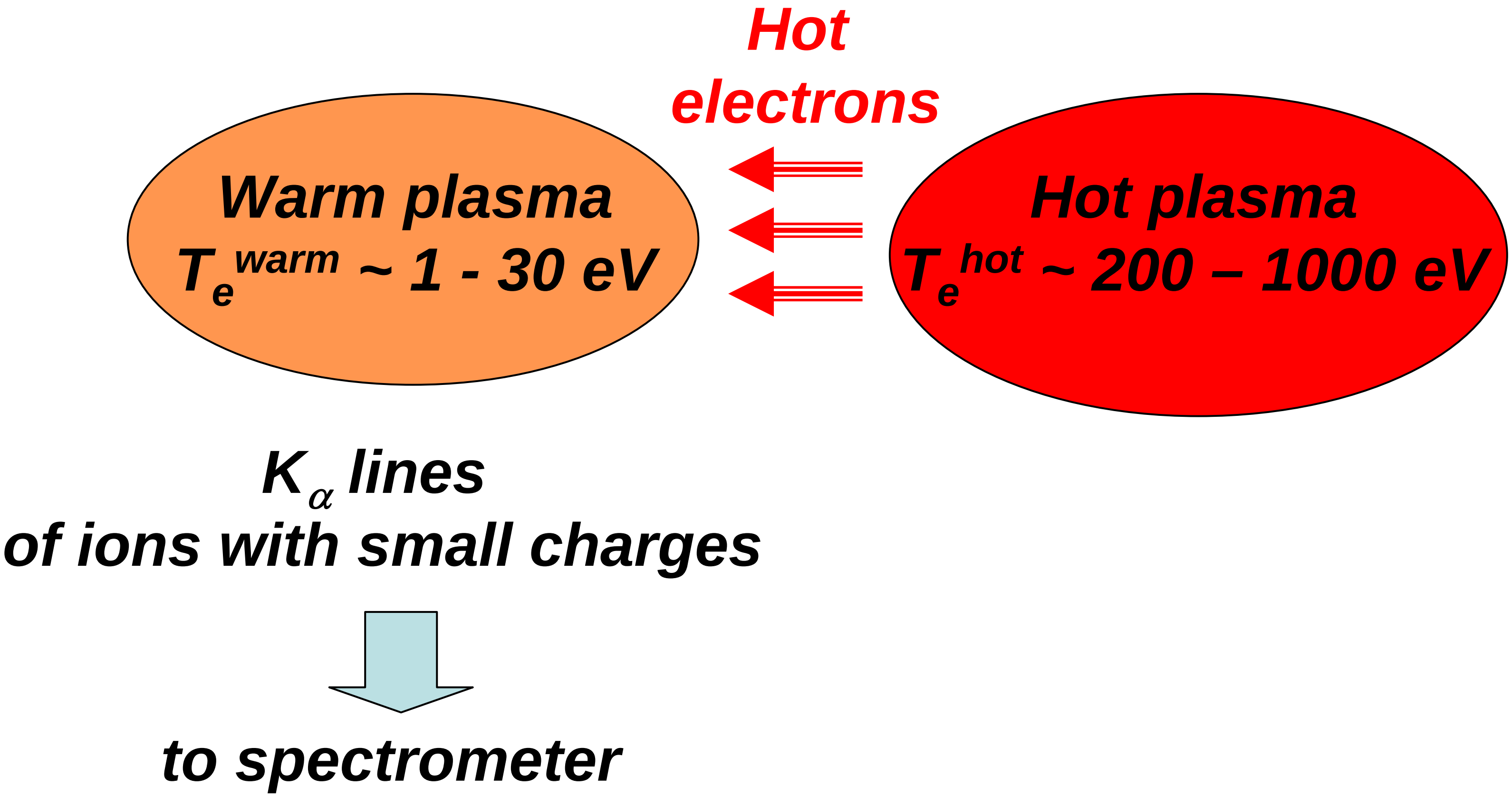
High resolution X-ray spectroscopy for WDM

The way to produce and investigate WDM



Hot electrons

Warm plasma

$T_e^{warm} \sim 1 - 30$ eV

Hot plasma

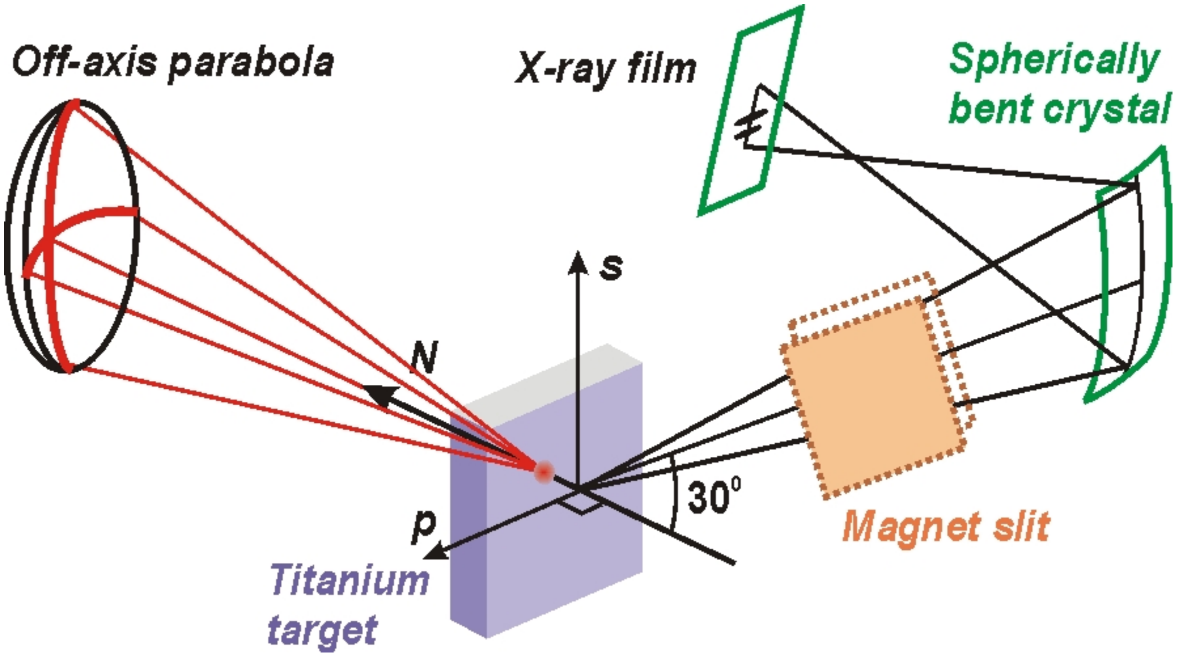
$T_e^{hot} \sim 200 – 1000$ eV

K_α lines
of ions with small charges

to spectrometer

Directly measured value– plasma ionization state;
T_e^{warm} can be determined

X-ray spectrometers and experimental setup

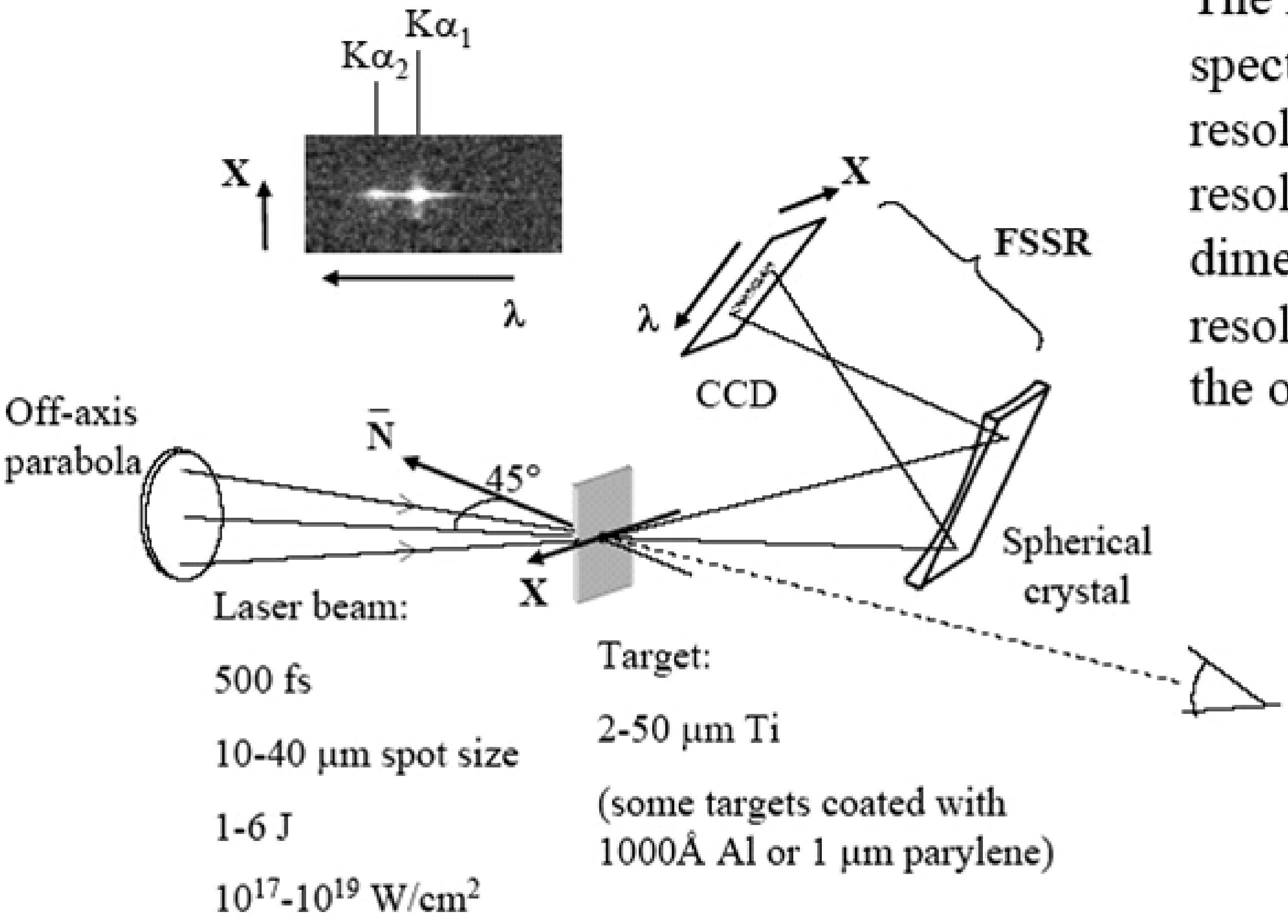


Hot plasma (T_e ~ 1 keV) on the front side of foil target

WDM – on the rare side of the foil target (T_e ~ 10 eV, N_e~10^{23} cm^{-3}

FSSR spectrometers provide high spectral and spatial resolution, simultaneously

Experiments on COMET LLNL facility



Laser beam:

500 fs

10-40 μm spot size

1-6 J

10^{17}-10^{19} W/cm^2

Target:

2-50 μm Ti

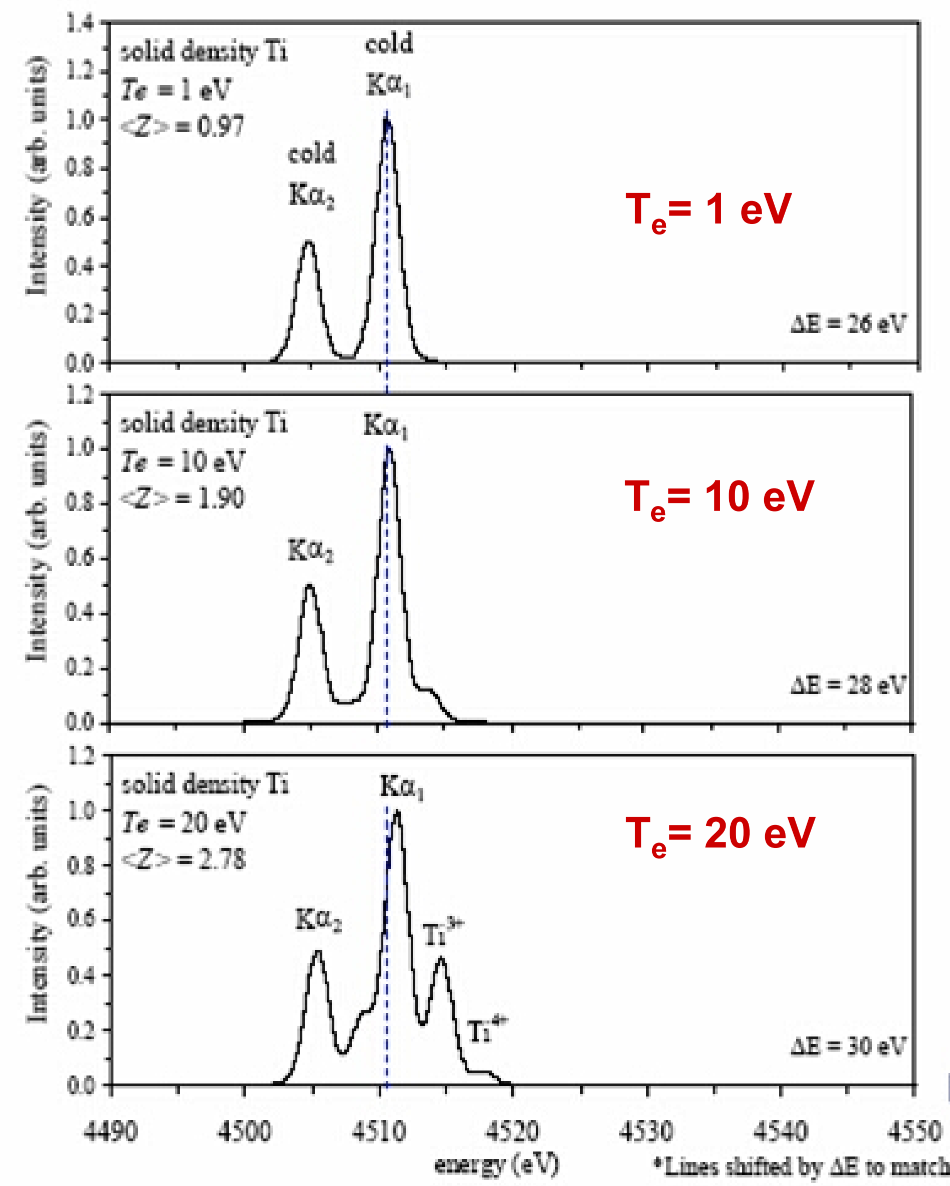
(some targets coated with 1000Å Al or 1 μm parylene)

The FSSR-2D (focusing spectrometer with spatial resolution) has spatial resolution of 48 μm in one dimension and spectral resolution $\lambda/\delta\lambda \sim 3800$ in the other.

Electron and photon counting detectors ($\lambda/\delta\lambda = 42$) also view the back side of the targets.

// T. Ditmire group, UT Austin and LLNL

Inner-shell Kα of solid Ti, T_e = 1 – 20 eV

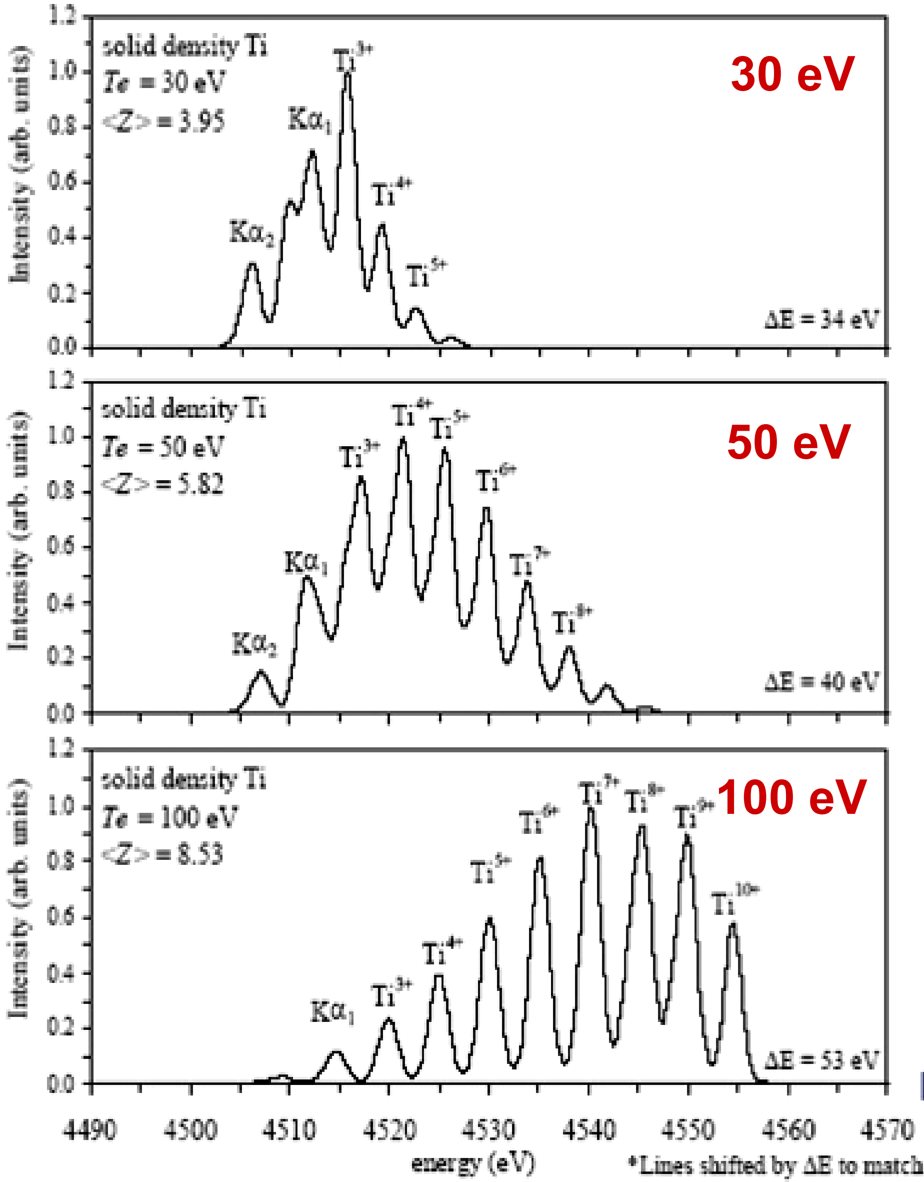


*Lines shifted by ΔE to match CXRO value for cold $K\alpha_1$

As the temperature of the solid increases, ionizing the Ti atoms, the characteristic K-shell lines shift to higher energies. Removing the 4s electrons (Ti^{1+} and Ti^{2+}) produces a shift of only ~ 1 eV, while removing M-shell (3*l*) electrons (Ti^{3+} - Ti^{10+}) produces a ~4 eV shift for each charge state.

Between 10 and 20 eV, satellites are evident on the blue sides of the cold Kα lines.

Inner-shell Kα of solid Ti, T_e = 30 – 100 eV

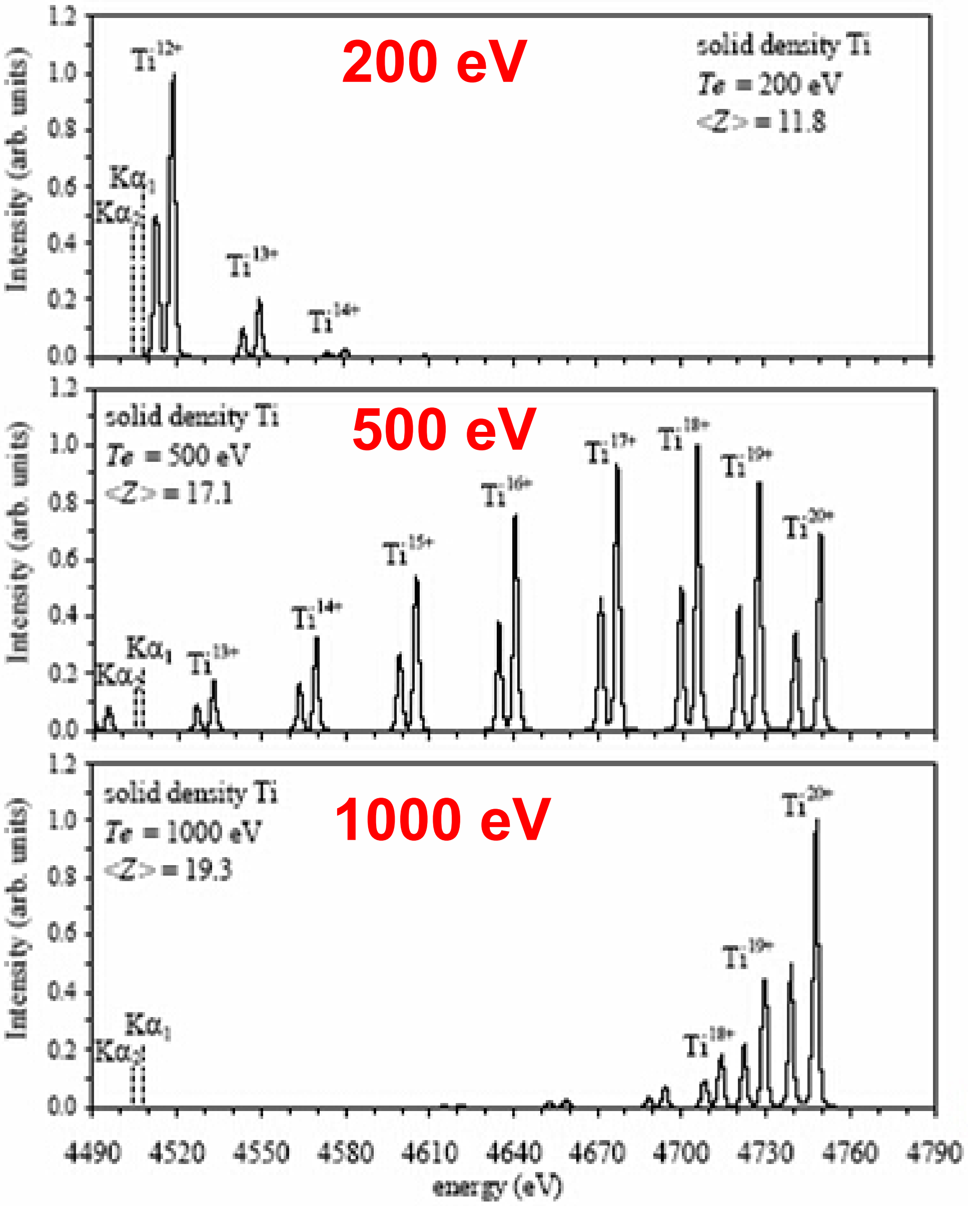


*Lines shifted by ΔE to match CXRO value for cold $K\alpha_1$

With further increases of temperature, Ti burns through the M-shell ions, producing Kα emission shifted by about 4 eV for each charge state. This shift is very near the energy difference between the $K\alpha_1$ ($2p_{3/2}$- $1s_{1/2}$) and $K\alpha_2$ ($2p_{1/2}$- $1s_{1/2}$) lines.

Between 30 and 100 eV, the mean energy of the Kα emission feature shifts by 30 – 50 eV.

Inner-shell Kα of solid Ti, T_e = 200 – 1000 eV



*No line shifts

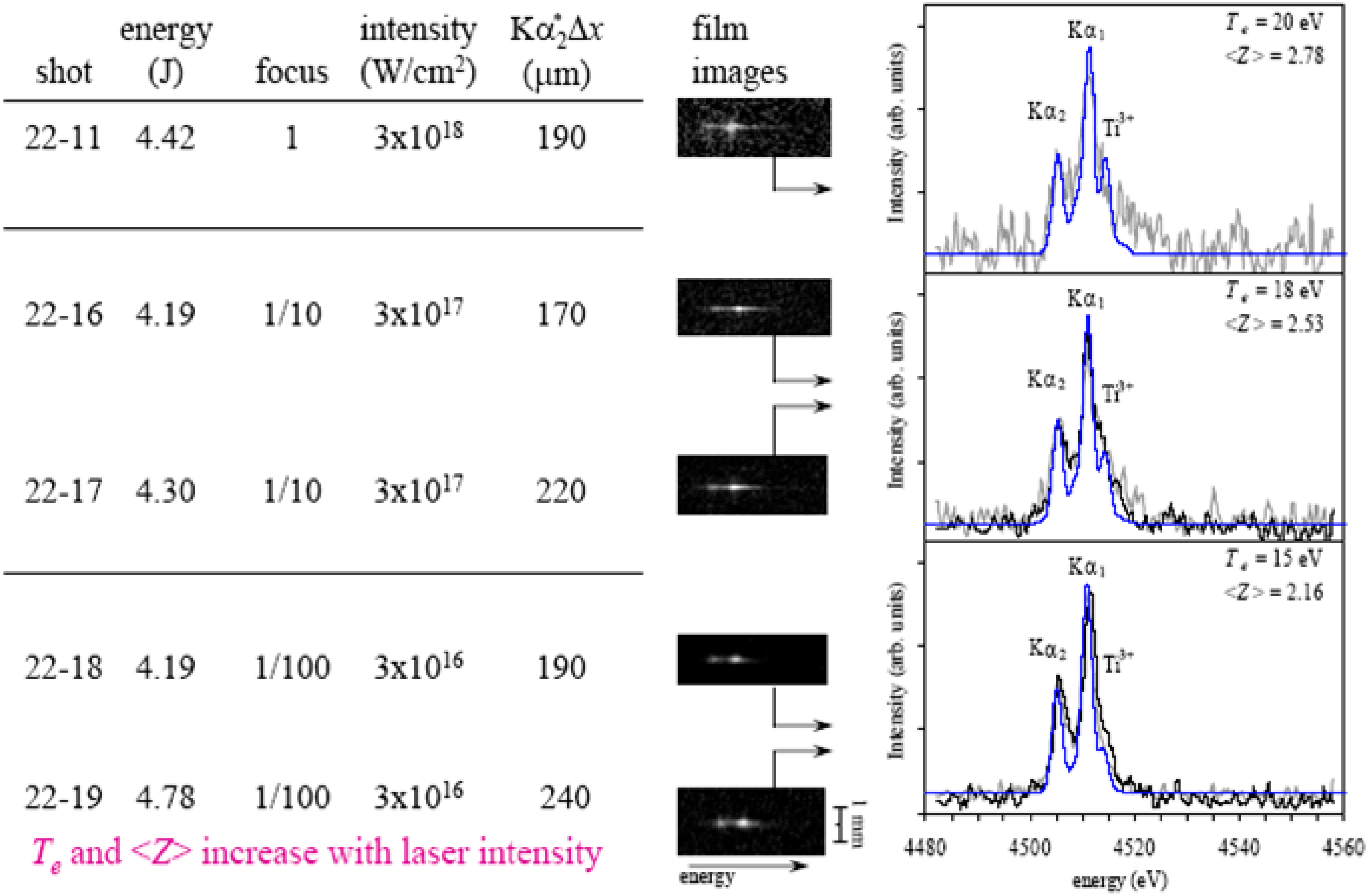
As Ti burns through the L-shell ions, the inner-shell Kα emission is shifted by about 30 eV for each charge state; each such shift is comparable to the total shift in mean energy from neutral Ti to Ti^{10+}.

Above about 1 keV, K-shell ionization stages are reached:

He-like (Ti^{20+}): 4750 eV

H-like (Ti^{21+}): 4970 eV

Effect of laser intensity



shot	energy (J)	focus	intensity (W/cm²)	$K\alpha_2^*\Delta x$ (μm)
22-11	4.42	1	3×10^{18}	190
22-16	4.19	1/10	3×10^{17}	170
22-17	4.30	1/10	3×10^{17}	220
22-18	4.19	1/100	3×10^{16}	190
22-19	4.78	1/100	3×10^{16}	240

T_e and <Z> increase with laser intensity

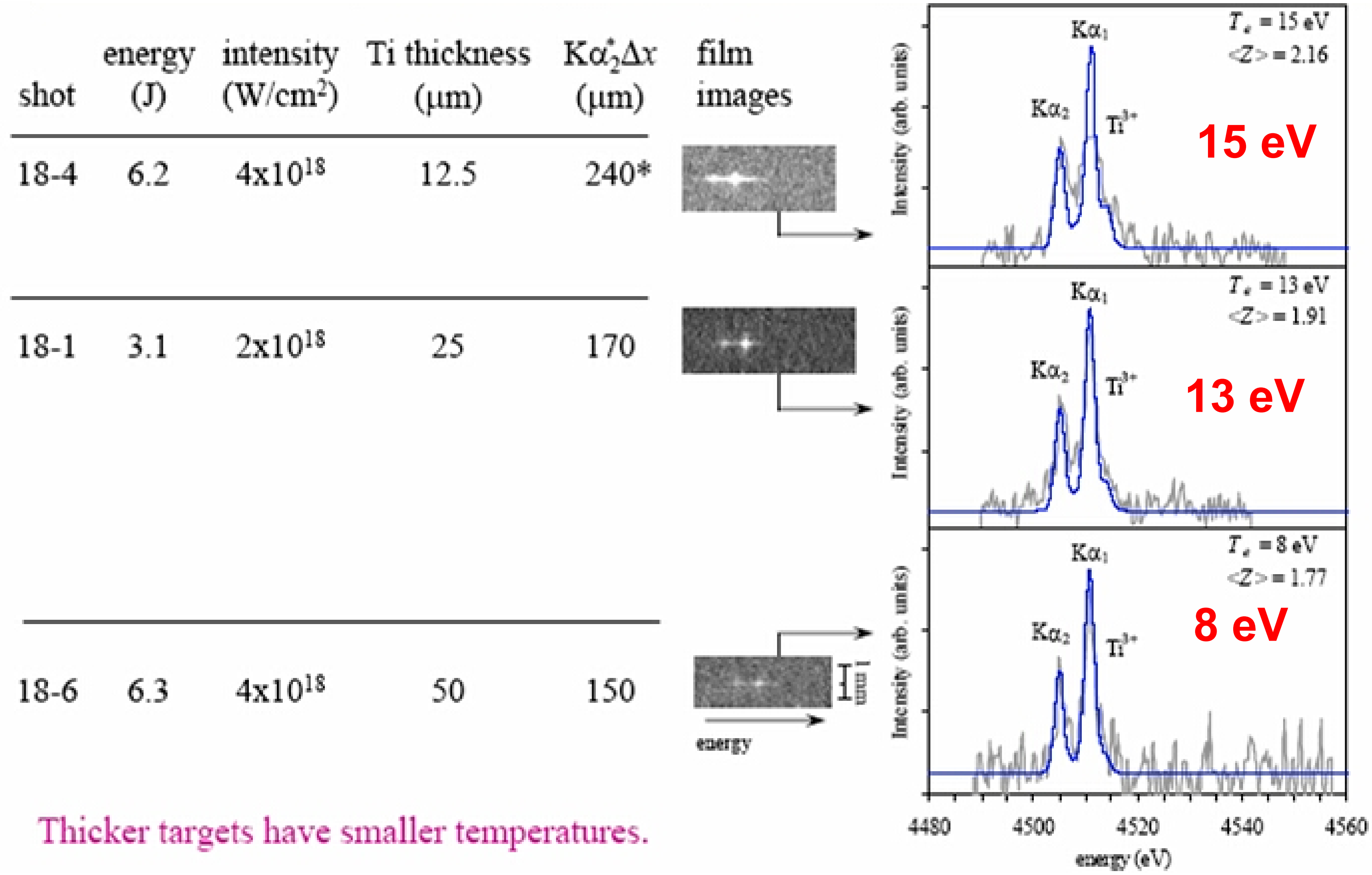
T_e=20 eV

T_e=18 eV

T_e=15 eV

// T. Ditmire group, UT Austin and LLNL

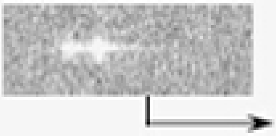
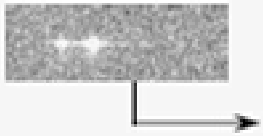
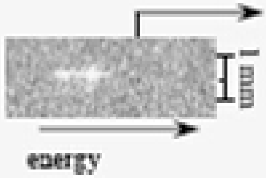
Effect of Ti foil thickness (Ti +0.1 um Al)

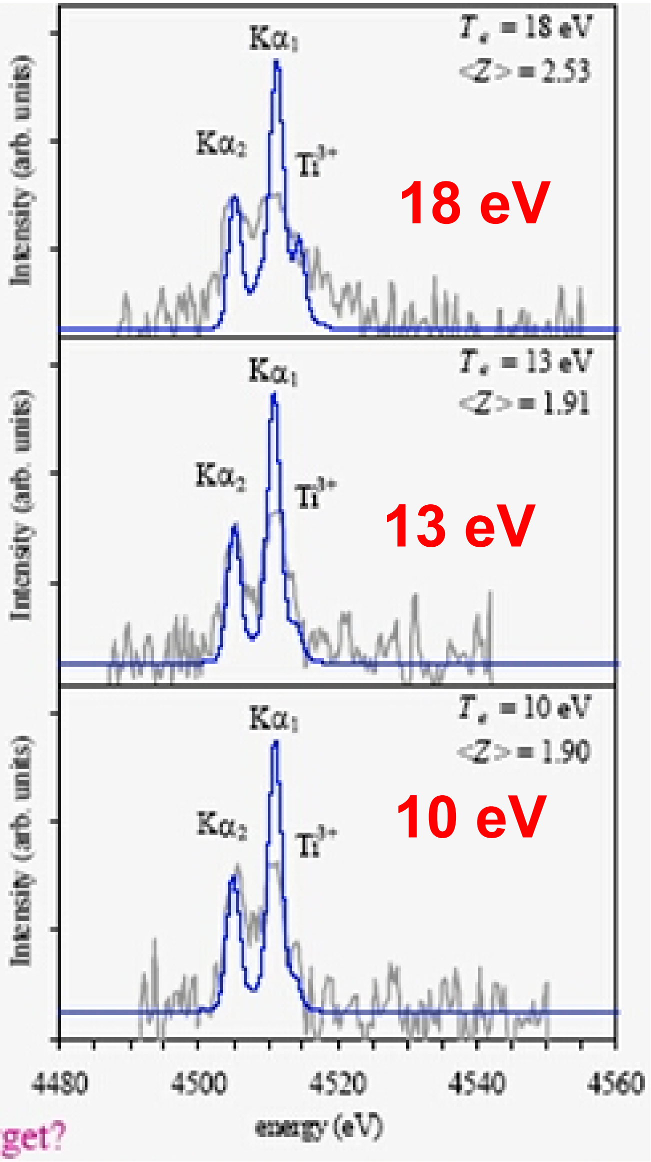


shot	energy (J)	intensity (W/cm^2)	Ti thickness (μm)	$K\alpha_2^*\Delta x$ (μm)	film images
18-4	6.2	4x10^{18}	12.5	240*	
18-1	3.1	2x10^{18}	25	170	
18-6	6.3	4x10^{18}	50	150	

Thicker targets have smaller temperatures.

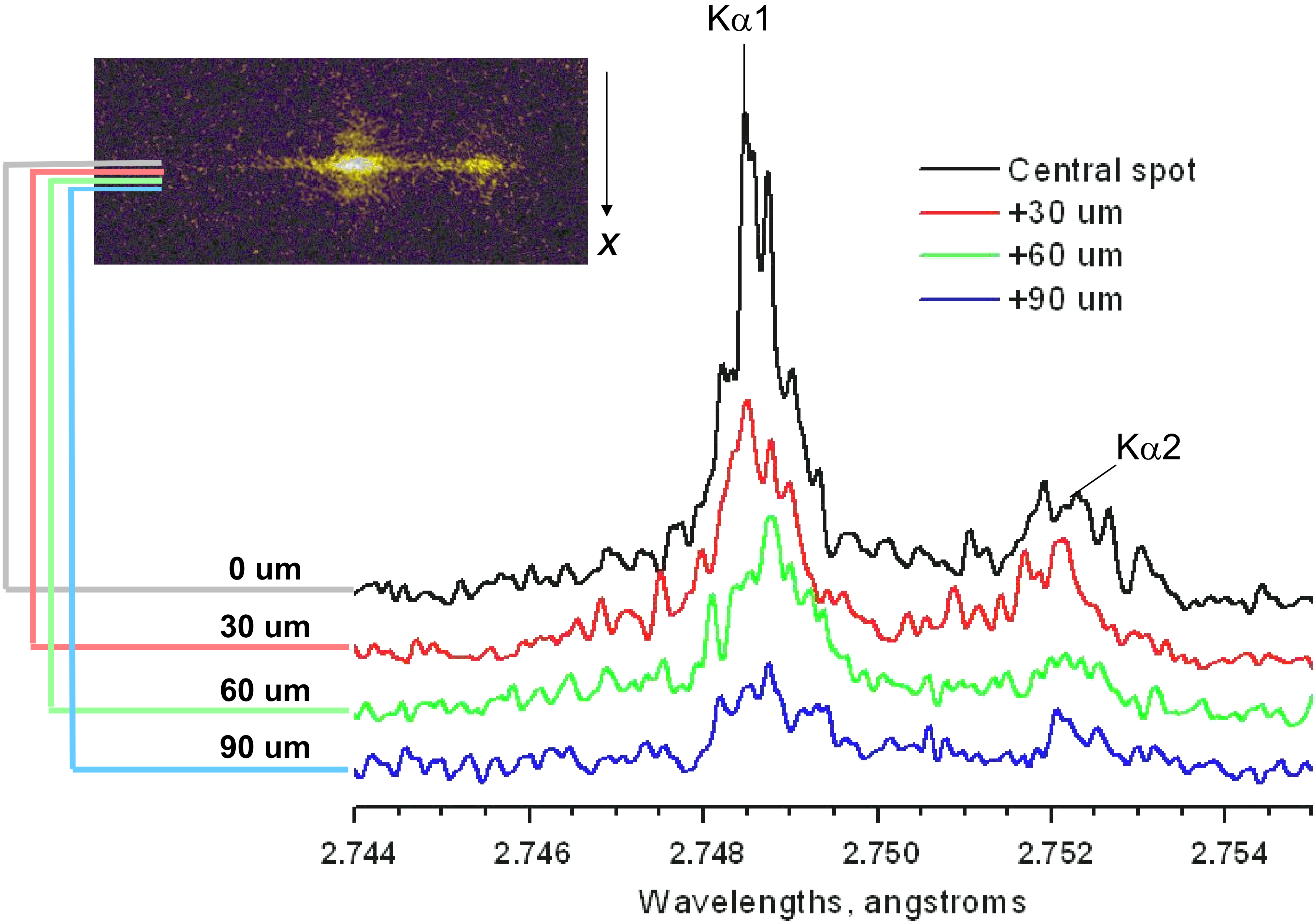
Effect of coating on 25 um Ti foil

shot	energy (J)	intensity (W/cm^2)	Coating	$K\alpha_2^*\Delta x$ (μm)	film images
29-16	5.41	3x10^{18}	none	430*	
29-15	5.34	3x10^{18}	1000 Å Al	190	
29-23	4.72	3x10^{18}	1 μm parylene (both sides)	220	

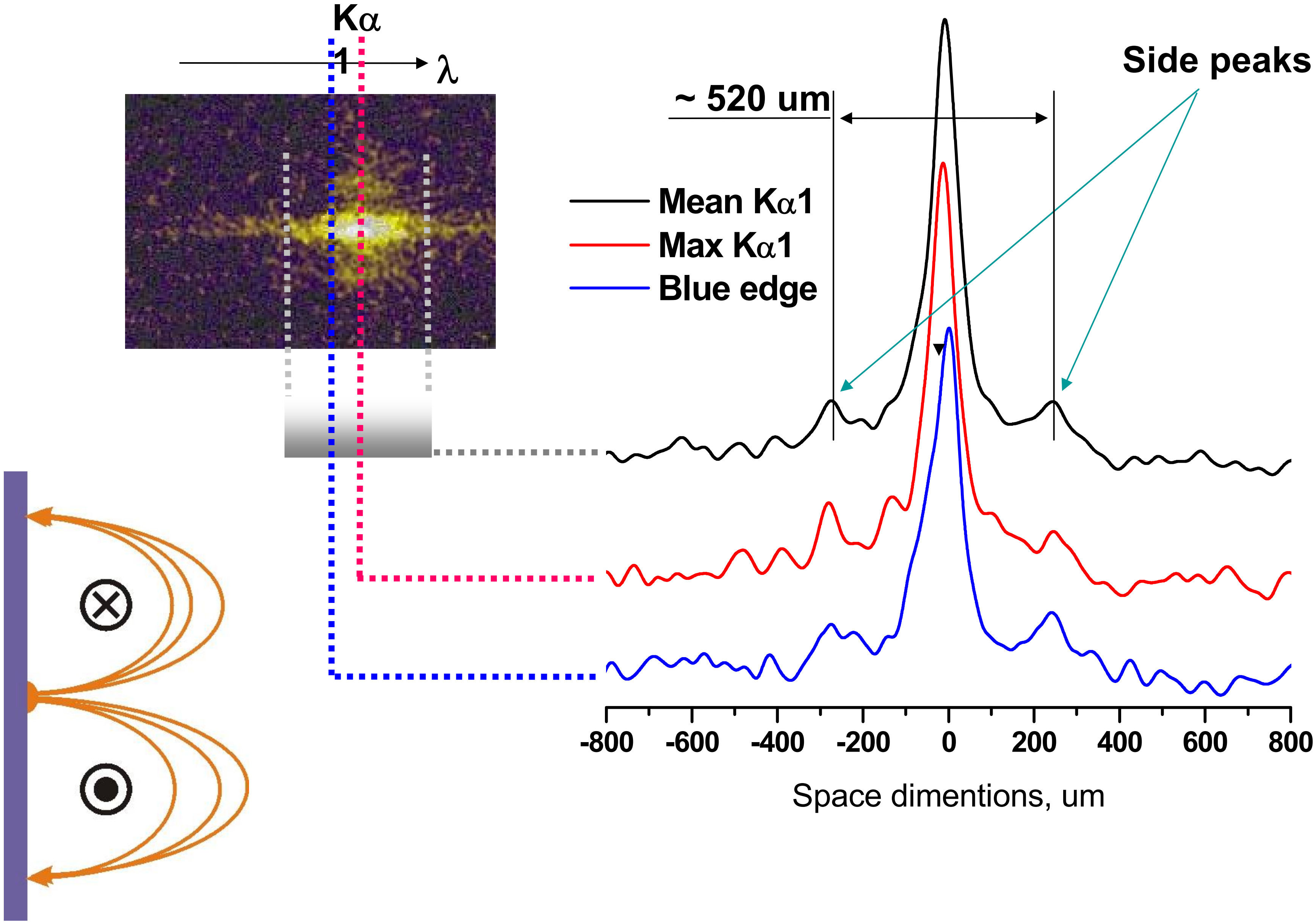


Coatings decrease observed <Z>:
less Ti in a hot front-side plasma? Or less efficient heating of the whole target?

Spatial resolution along target plane

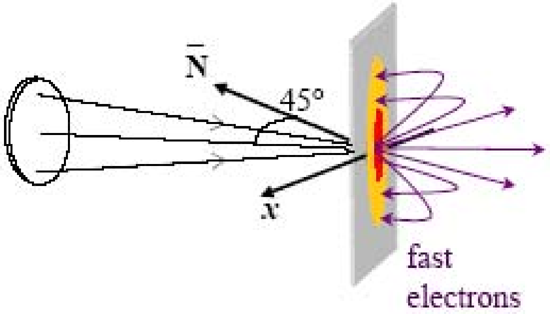


Spatial resolution and “fountain effect”

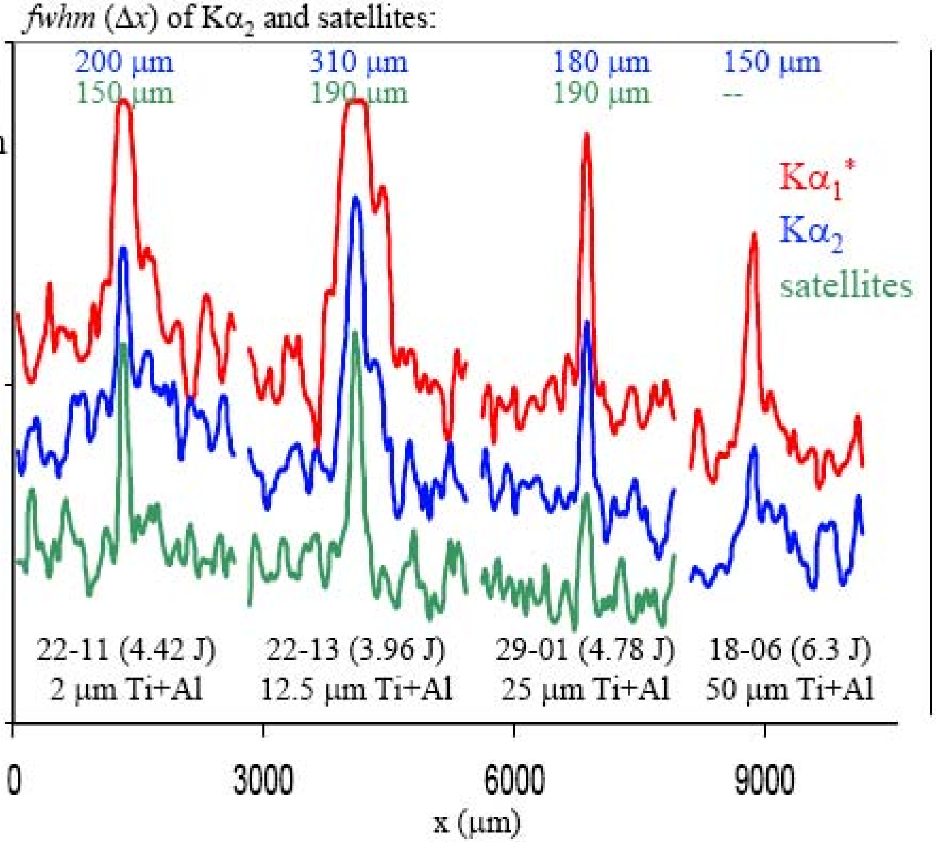


Line widths change with energy and target

Satellite emission (4515-4520 eV) is narrower than Kα emission in thin targets: evidence for a “fountain effect?”



Or simply an indication of front-side plasma gradients?



* Pixel bleeding can occur in *x* where lines are saturated

WDM investigations – suggestions

We suggest in the frame of the EMMI project:

Using ultrahigh laser fluxes ~ 10^{19}-10^{20} W/cm^2 to increase spectral brightness and find which of excited levels can exist in strongly coupled plasma by mean of registration K_α, K_β, K_γ,… spectral lines

To provide higher energy of hot electrons on front target surface, so the investigations of WDM for large Z materials will be available.

X-ray and ion radiography of WDM

Laser generated plasma as a source of probe radiation

Intense laser pulse is unique and useful tool to generate a flux of X-ray photons as well as energetic charge particles, simultaneously

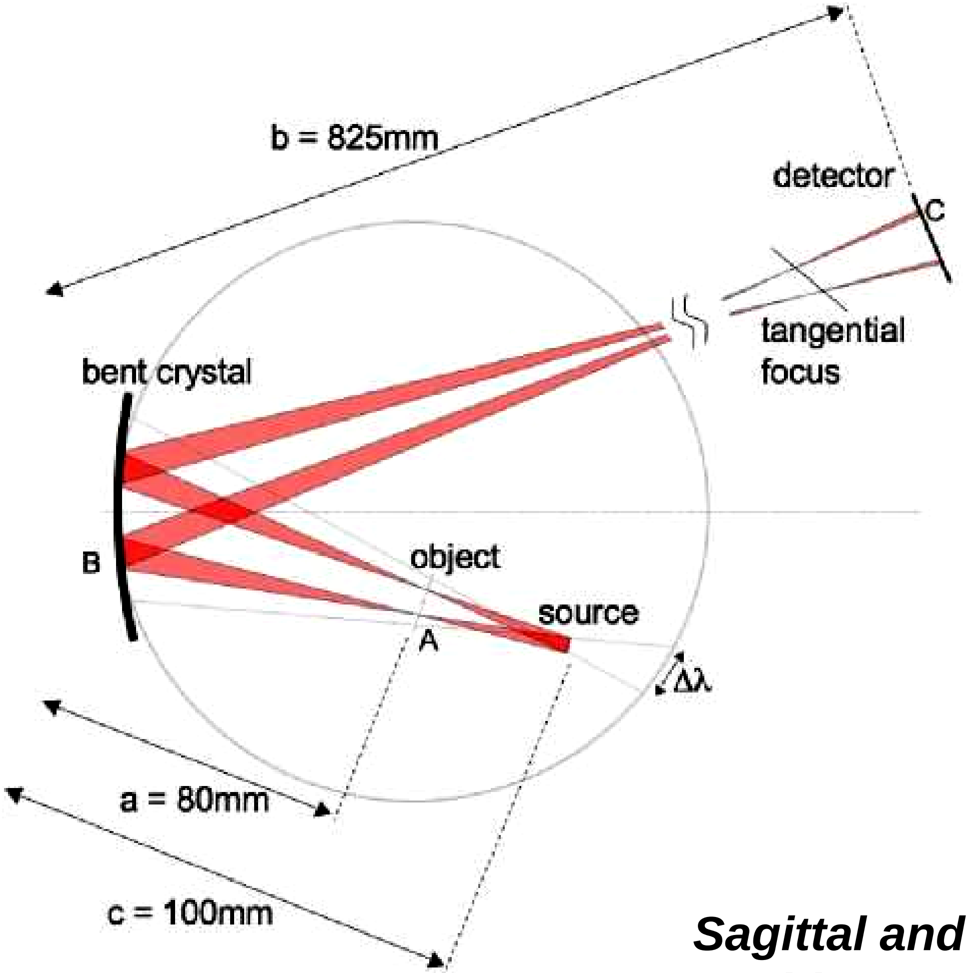
- ○ Both fluxes can be used for shadowgraphy imaging and absorption measurements of different objects and processes including low contrast structures in plasma
- ○ Following diagnostic opportunities can be realized
  - ○ Ion and proton radiography
  - ○ X-ray absorption imaging and spectroscopy
  - ○ X-ray phase contrast imaging

Source size is important to provide spatial and spectral resolution, spatial coherency

Energy of probing particles and monochromatization are important to provide the sensitivity on density and chemical staff of an object

Source brightness and scheme luminosity are important to provide wider dynamic range, precise measurements and image quality

X-ray monochromatic backlighting scheme



Features:

- Backlighter and object are inside Rowland circle

= High luminosity

= Higher spatial resolution

- Angle of radiation incidence is far from normal one

= Wide spectral range

= Spatial resolution tunable

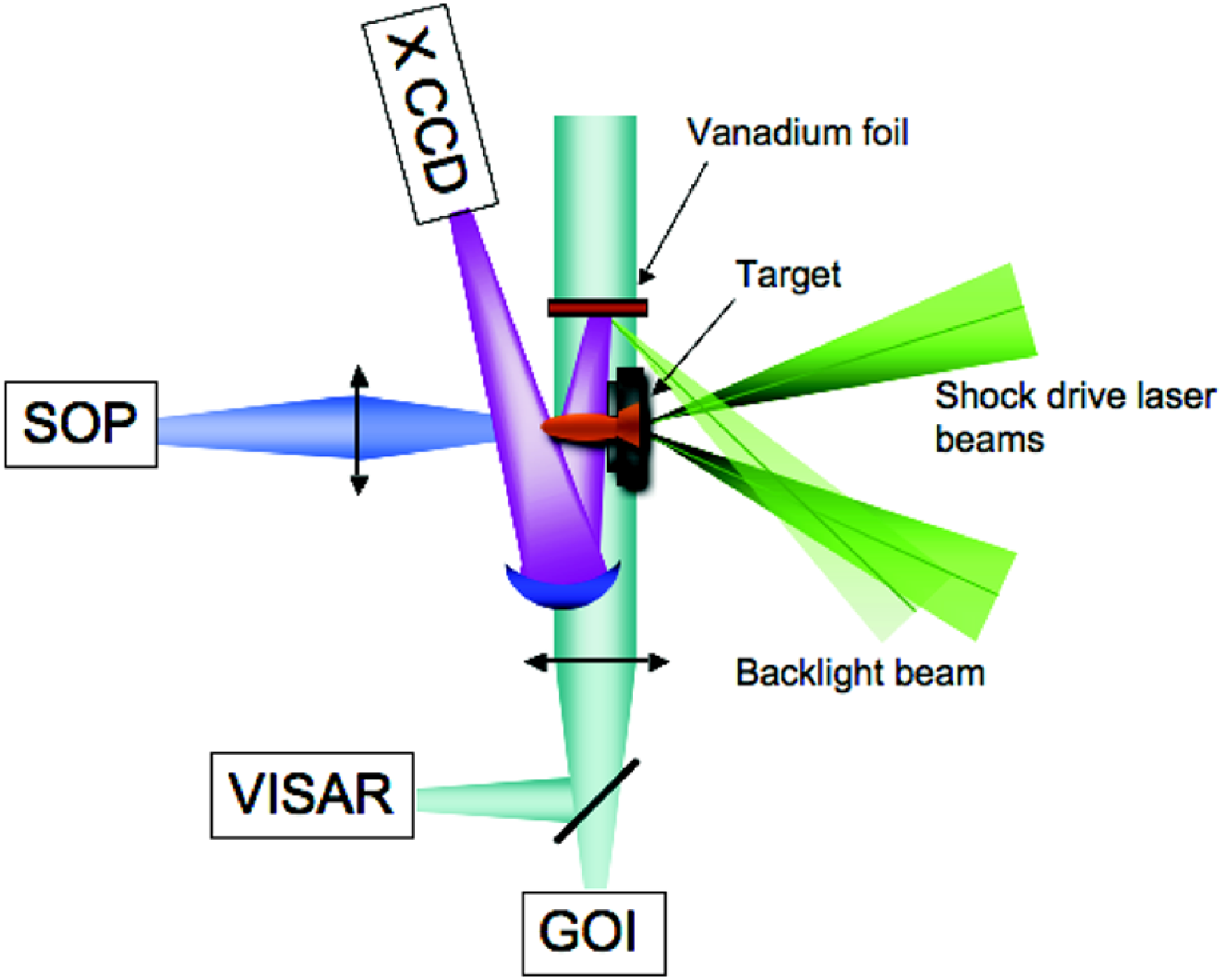
$$f_t = \frac{aR\sin\theta}{2a - R\sin\theta}, M_t = \frac{c}{c-a}\left[\left(\frac{2}{R\sin\theta} - \frac{1}{c}\right)b - 1\right],$$

$$f_s = \frac{aR}{2a\sin\theta - R}, M_s = \frac{c}{c-a}\left[\left(\frac{2\sin\theta}{R} - \frac{1}{c}\right)b - 1\right].$$

Sagittal and tangential focuses are not on the same position. By choosing detector position the spatial resolution along each direction can be tuned up.

- Monochromatic scheme allows to measure object density or chemical staff in precise according to probe radiation absorption

Experimental setup



// M. Koenig group, LULI Ecole Polytechnique

Main laser:

1 ns, 2ω,
300 J, d = 400 um
I = 5*10^{13} W/cm^2

Backlighting laser:

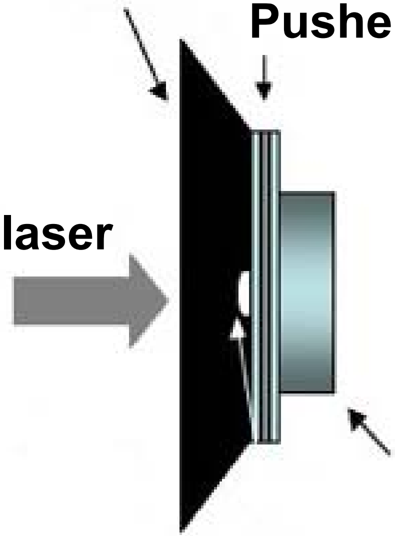
1 ns, 2ω,
250 J, d = 150 um,
I = 10^{15} W/cm^2

Spherical crystal:

Quartz, 2d = 4.912 A
II reflection order
Curvature 150 mm
Magnification 10

Target design

Shock wave generation in CH sliver



Holder

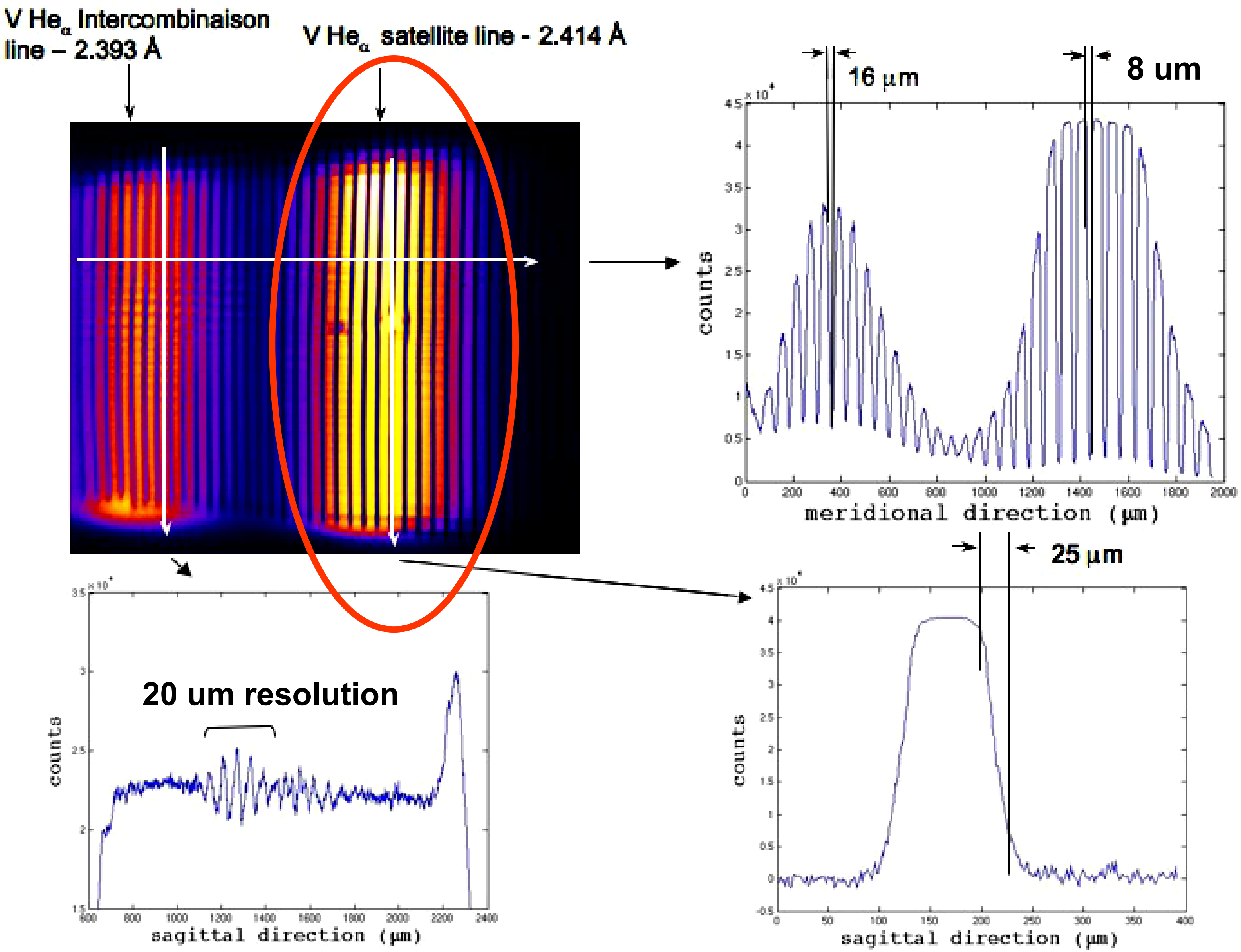
Pusher

ns laser

Composite pusher
CH 10 um + Al 10 um + CH 10 um

CH sliver

Calibration results



V He_{α} Intercombinaison line – 2.393 Å

V He_{α} satellite line - 2.414 Å

16 µm

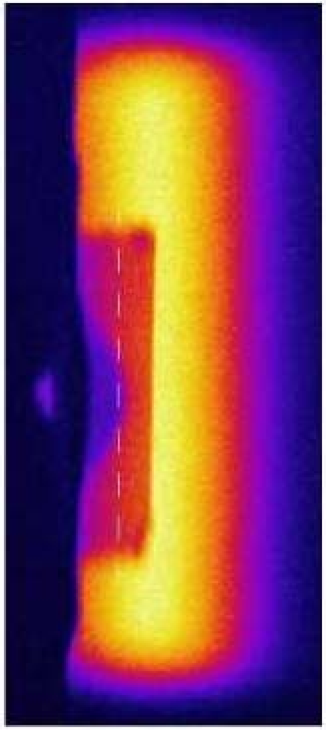
8 um

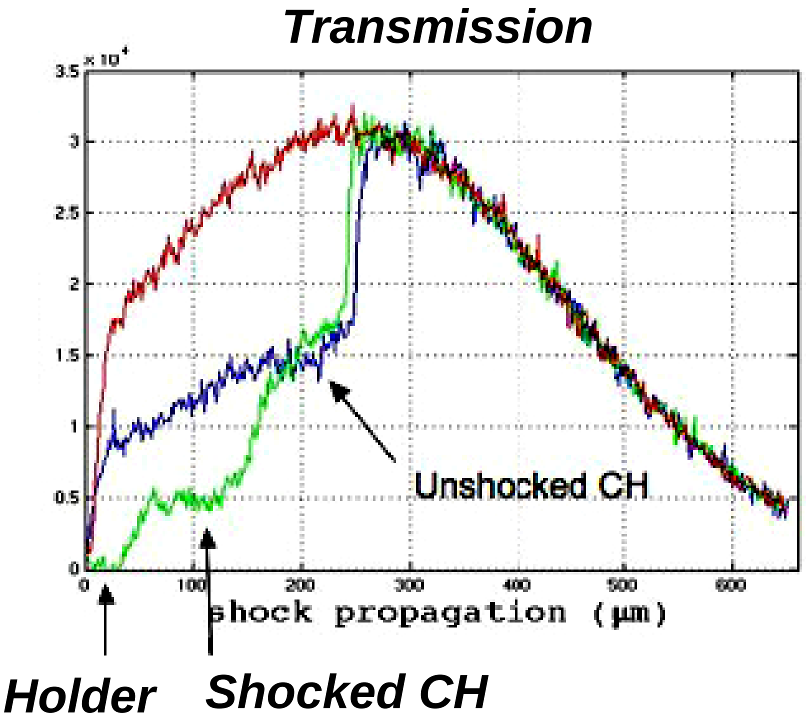
25 µm

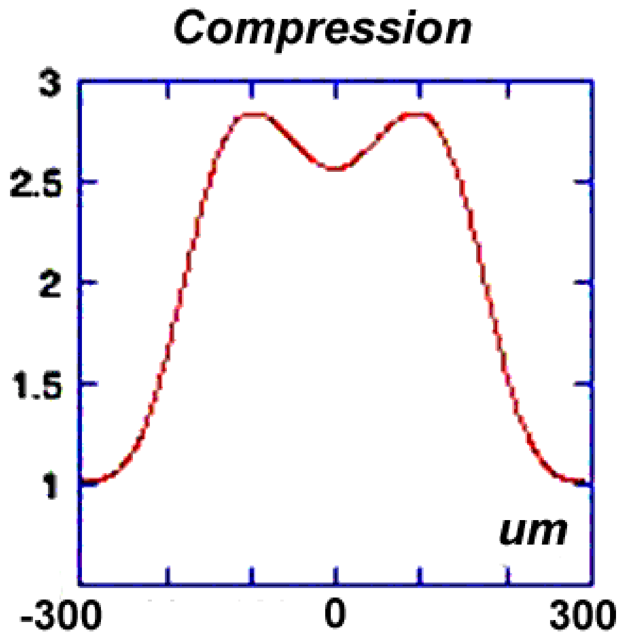
20 um resolution

Shock wave density measurements

X-ray backlighting image in V Heα spectral line



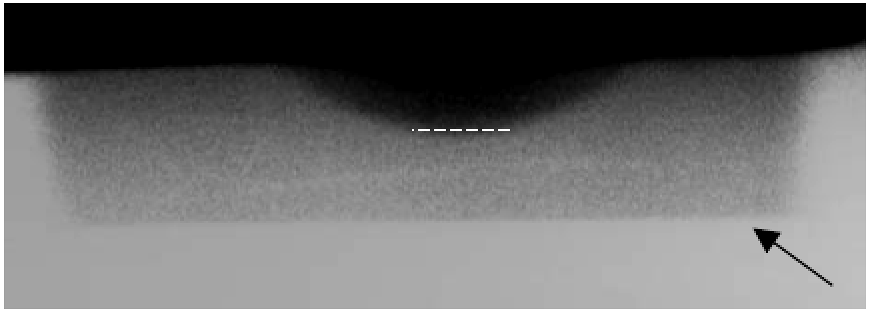




- **Due to spectral selectivity of backlighting image**
  the density profile of the object can be measured in precise.
  with spatial resolution along shock front.
  The maximum compression of 2.85 is obtained for shock wave in CH sliver

Shock wave evolution and velocity

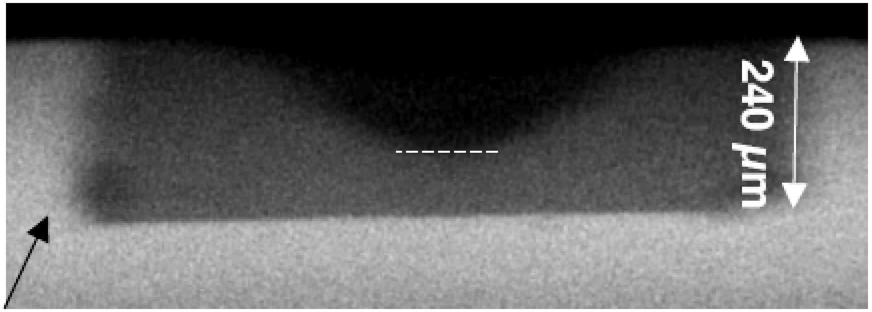
In order to resolve the evolution of imaging object the delay between main and backlighter laser pulses can be aligned



Shock position ~ 100 μm
at t = 5 ns

t = 5 ns

CH
sliver



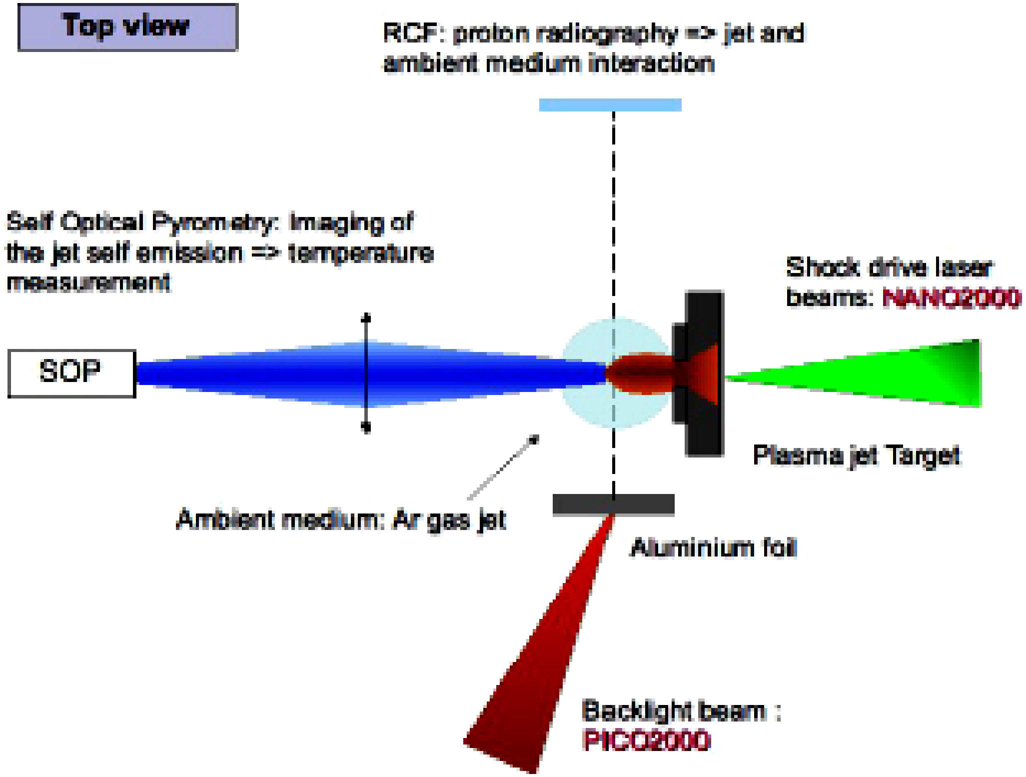
Shock position ~ 175 μm
at t = 9ns

t = 9 ns

Shock front velocity is measured to be equal 19 km/s

During the propagation the cylindrical symmetry of shock front is stable

Diagnostic



Obstacle

Brightness of x-ray source preferably depends on laser energy not by pulse intensity

On upgraded LULI facility 50 J in 1 ps is available now instead of 500 J in 1 ns before. X-ray source has brightness not enough for monochromatic shadowgraphy imaging.

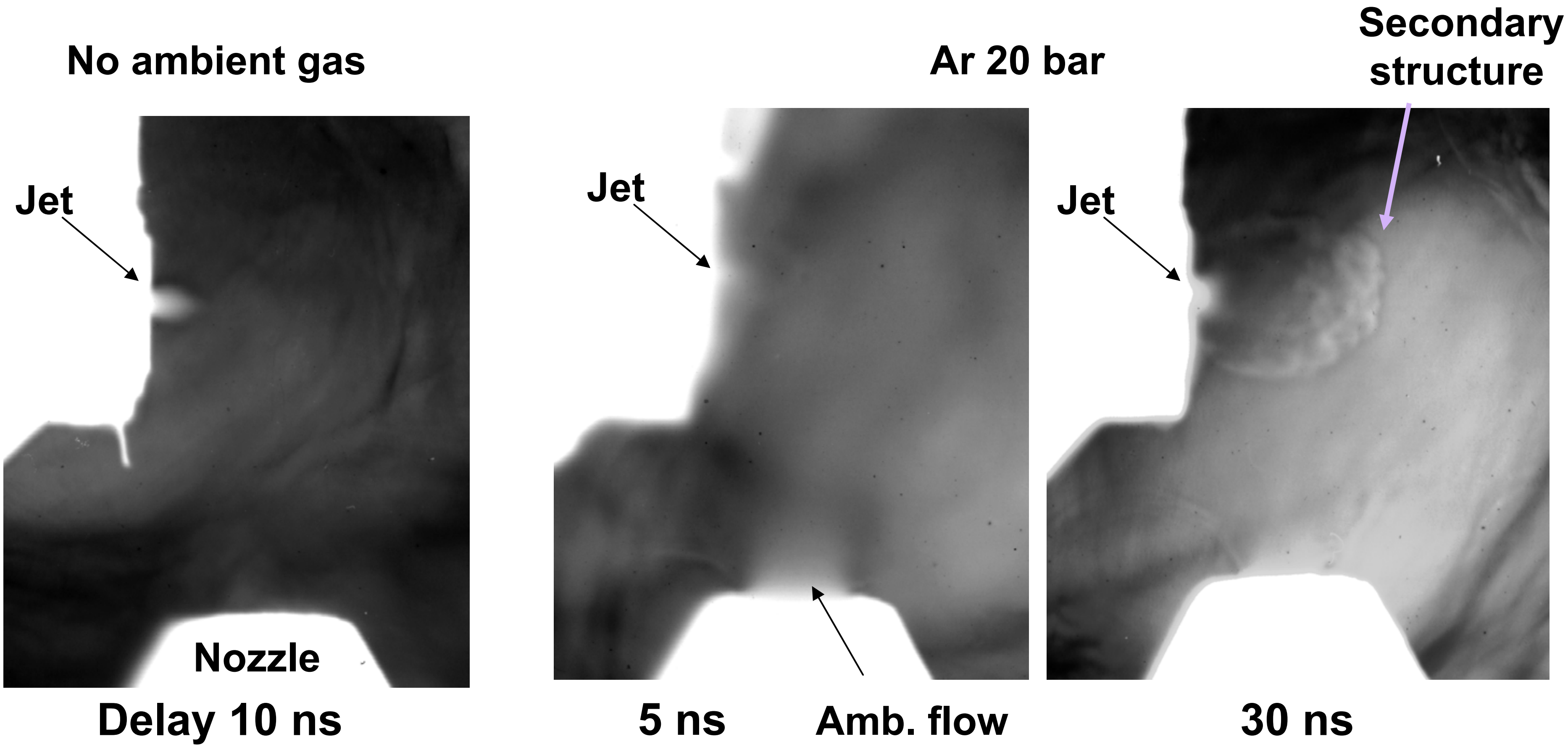
Temporary solution:

Change to proton radiography diagnostics in quite the same experimental setup. RCF film instead of X-ray crystal

Solution:

Special design for backlighting target. Increase of detector sensitivity

Proton radiography imaging results



Probe proton energy ~ 5 MeV

- **Proton radiography is perfect to image the evolution of plasma structures but not for quantitative measurements on their densities.
Further development of soft X-ray diagnostics is on demand.**

WDM investigations – suggestions 2, 3

We suggest in the frame of the EMMI project:

To study shock compression in WDM for higher Z materials, metals, by means of x-ray monochromatic shadowgraphy and ion radiography.

To develop hard X-ray backlighting imaging using fs PHELIX beam to produce bright source of probe radiation.

Conclusion

Available devices and methods

High resolution spectrometers
Spherically bent crystals
Modeling of spectra
Backlighting schemes
Absorption and phase contrast

Forthcoming tasks

Create and study of
  Super dense plasma
  Hot dense plasma
  Warm dense plasma
Effective sources for
ion- and proton-radiography
Images of nanoscale foils and
biological samples
Measurement of MG magnetic fields
Monocromatic imaging of
shock waves and plasma jets
Modeling of astrophysical
phenomena in laboratory
Investigation of new spectroscopy
phenomena

EMMI

PHELIX
Petawatt High-Energy Laser for Heavy Ion Experiments