Workshop on High Energy Density Physics with Laser and Ion Beams
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Investigation of fast ions generated in a laser-produced plasma heated by PHELIX and their interaction with solids and airgel targets

Experimental background

Facilities

ZNIIMASH, Moscow reg., Russia

Max Born Institute, Berlin, Germany,

Hebrew University, Jerusalem, Israel

Saclay Laboratory, CEA, France

CELIA, Bordeaux University, France

LULI, Ecole Polytechnique, France

CNR-INFM, Politecnico, Milan, Italy

IPCF/CNR, Pisa, Italy

APRC, JAERI, Japan

Los Alamos National Laboratory, USA

Livermore National Laboratory, USA

University of Maryland, USA

Laser parameters

Laser pulse:

λ = 0.53 – 1 μm

E = 1 – 6000 мJ

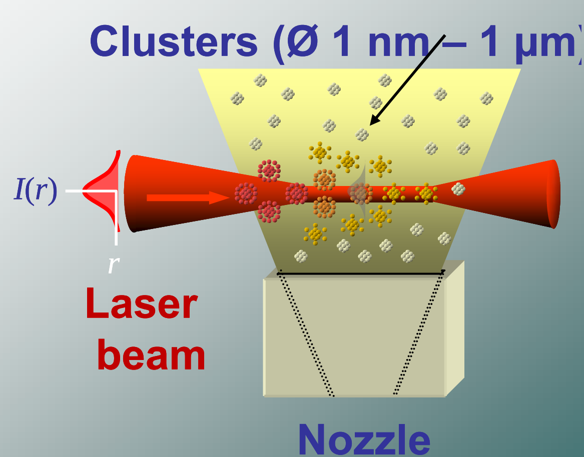
τ = 20 – 1000 fs

Q = 10^{15} – 2×10^{19} W/cm^2

Single shot, f = 1 – 20 Hz

Novel targets

Clusters



Application of high-resolution x-ray emission spectromicroscopy for investigations of plasma produced by PHELIX laser

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

- X-ray diagnostics of **warm dense matter**.

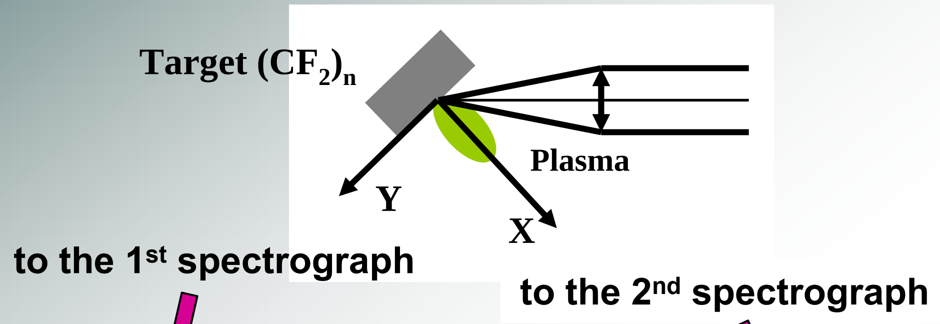
- Observation of the **fast ions** generated in the PHELIX laser-produced plasma by X-Ray spectromicroscopy methods.

- 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.

IHED
JIHT RAS

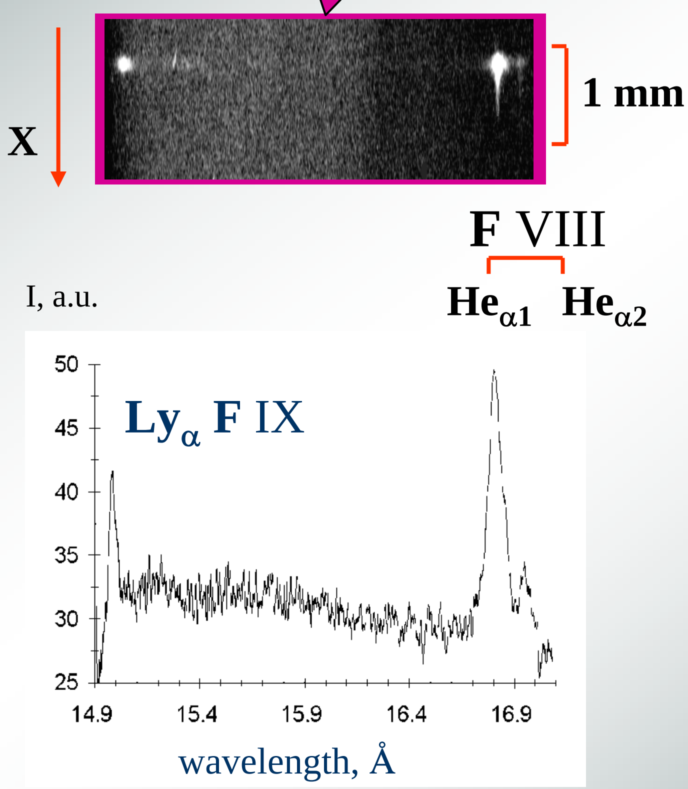
PHELIX
Petawatt High-Energy Laser for Heavy Ion Experiments

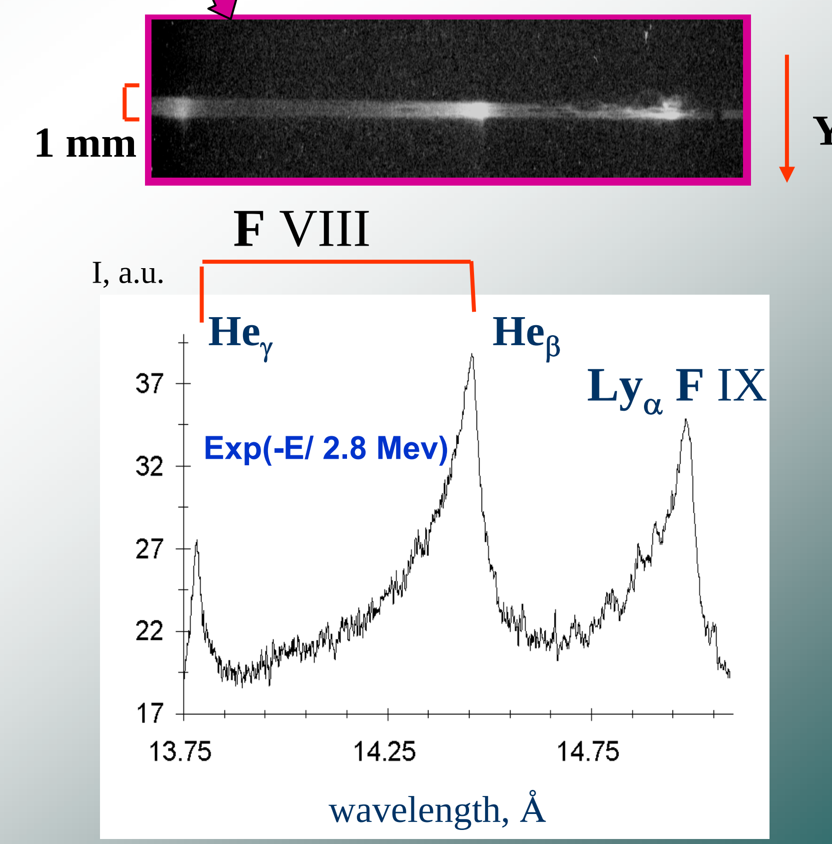
Observations of the **fast ions.** Solid target.



Ti:Sa laser (Saclay)

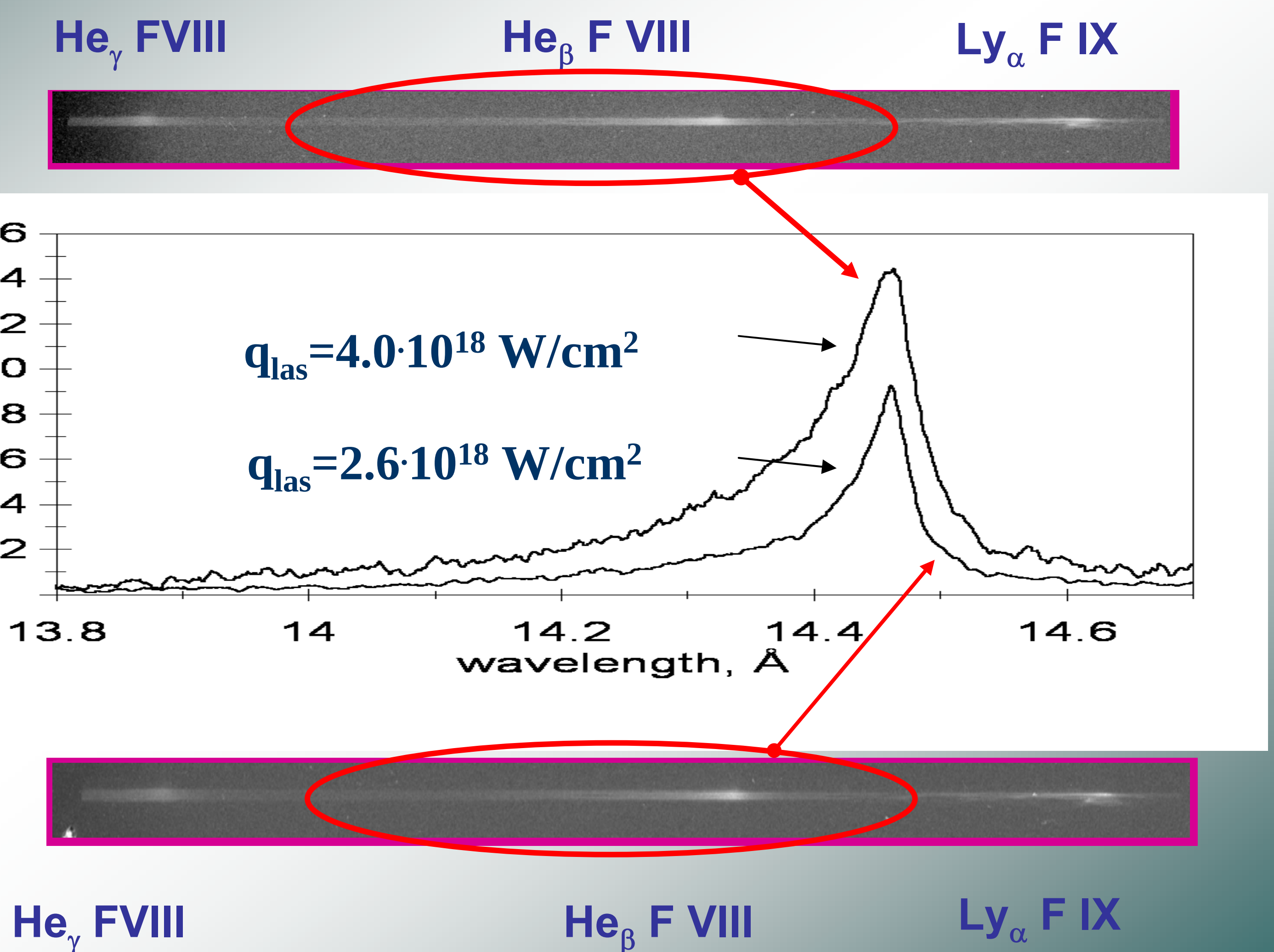
τ_{las}=60 fs, q_{las}=4x10^{18} W/cm^2





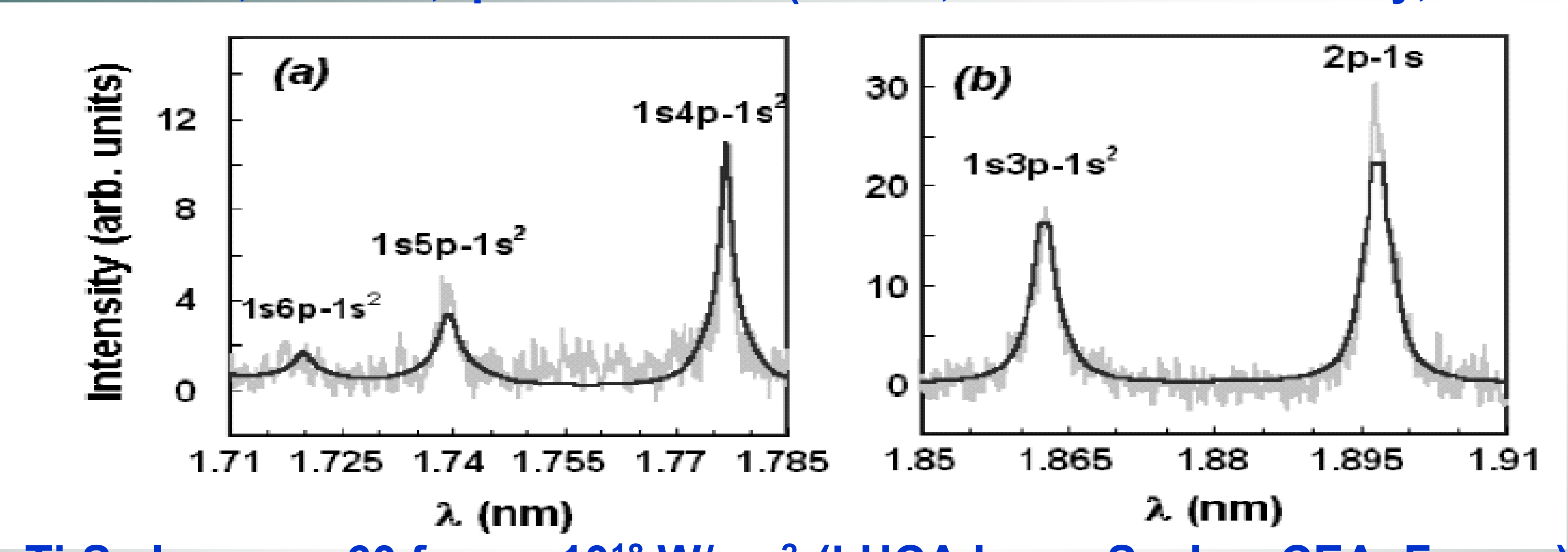
Observations of the fast ions. Solid target.

UHI-10 Ti:Sa laser, Saclay :
λ_{las}=0.8 μm, τ_{las}=60 fs

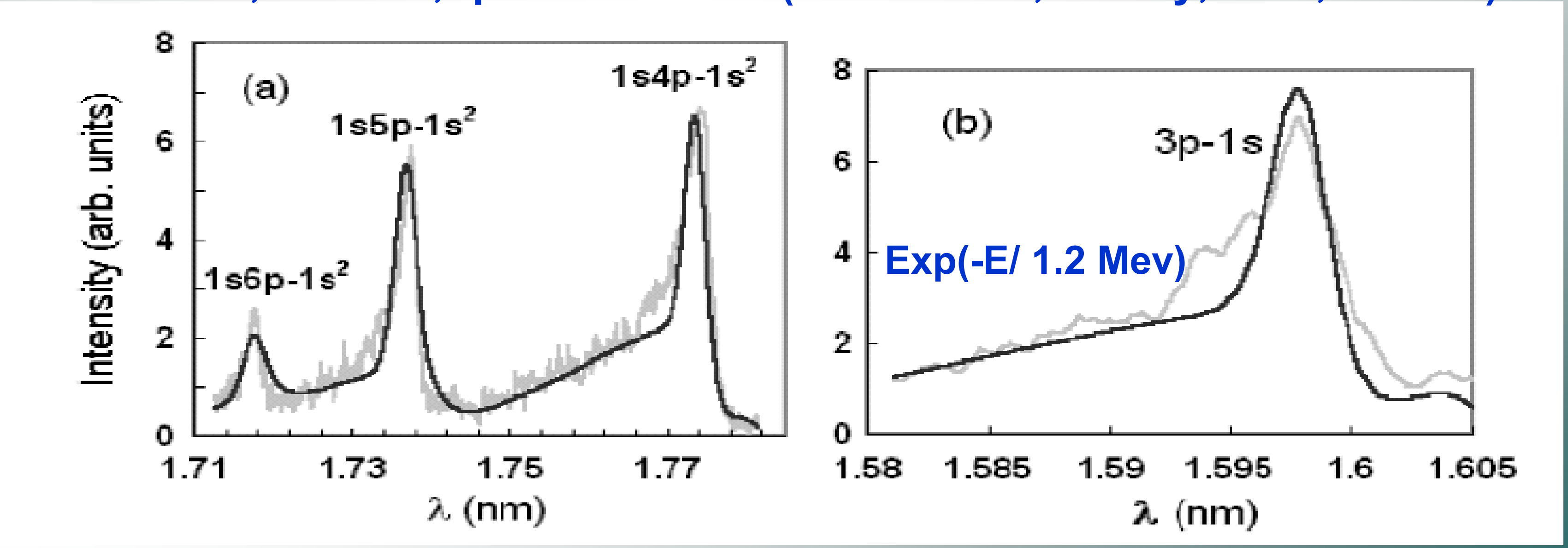


Observations of the fast ions. Cluster target.

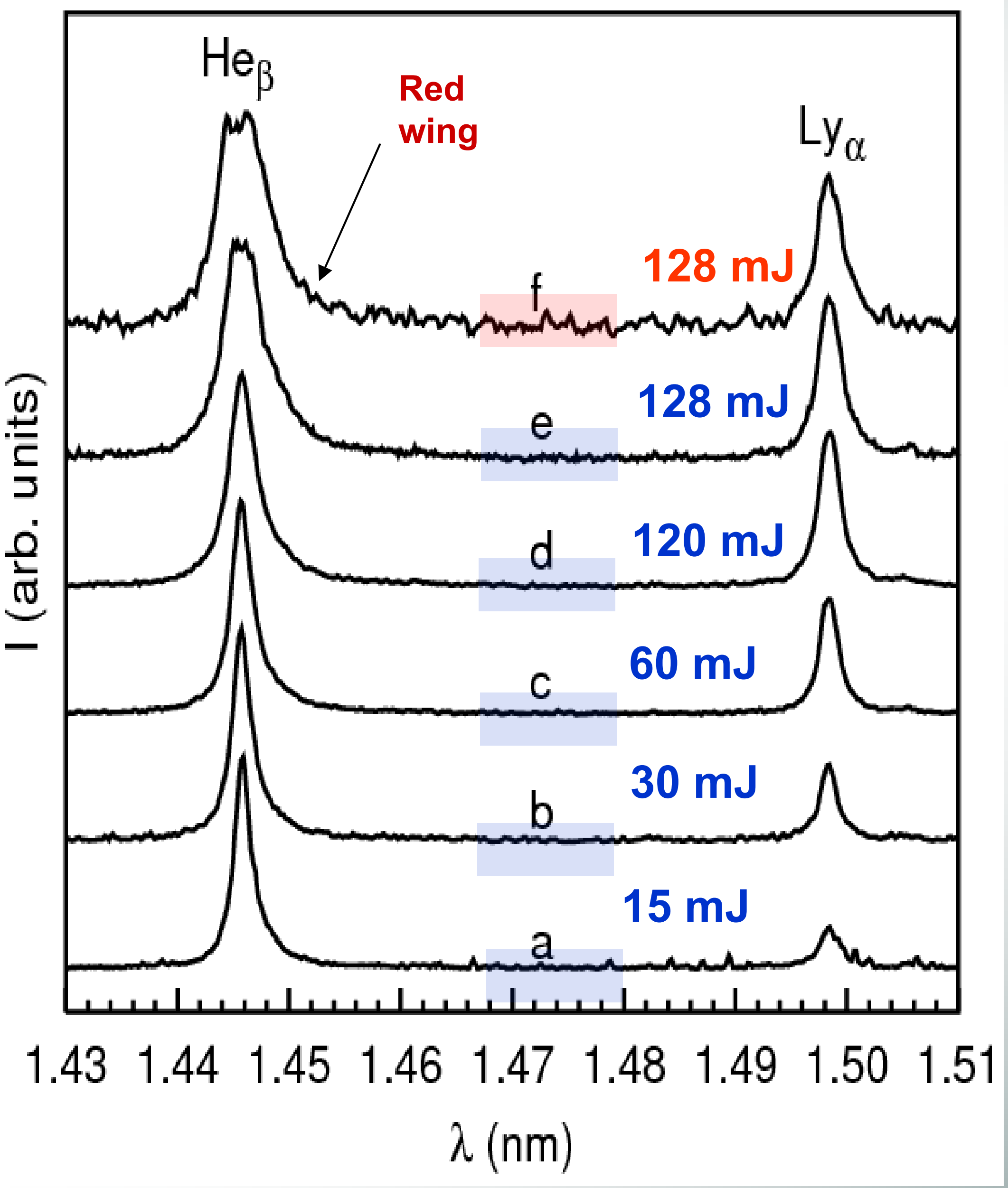
Ti:Sa laser, τ~ 35 fs, q ~ 10^{17} W/cm^2 (CELIA, Bordeaux University, France)



Ti:Sa laser, τ~ 60 fs, q ~ 10^{18} W/cm^2 (LUCA laser, Saclay, CEA, France)



Measured x-ray spectra in the region of He_β and Ly_α lines of fluorine ions



Politecnico di Milano, Italy

Laser:
Pulse duration = 1 ps
Pulse energy = (15 ÷ 128) mJ
Laser contrast = 10^{-2} – 10^{-4}

Targets:
1 - Teflon slab (traces *a* –*e*)
2 – Teflon 80-μm foil (trace *f*)

Note :

The curves are normalized to the peak intensity of the Heb line

Modeling and diagnostics

The x-ray spectroscopy **diagnostics of fast ions** in plasma is based on a fact that

the spectral line shape is sensitive to the ion velocity distribution function

due to the Doppler effect

Theoretical modeling of the experimentally **observed He_β and Ly_α line shapes**

and **their relative intensities** allows an estimation of the plasma parameters:

the electron temperature T_e

the electron density N_e

the ion energy distribution function E_{ion}

The analysis of experimental data shows: the distribution function of ions strongly differs from the single-temperature Maxwellian distribution

$$f_j(v) = a_{\mathrm{c},j} f_{\mathrm{M}}(\bar{v}_{\mathrm{c},j}, v) + a_{\mathrm{w},j} f_{\mathrm{M}}(\bar{v}_{\mathrm{w},j}, v) + a_{\mathrm{f},j} f_{\mathrm{M}}(\bar{v}_{\mathrm{f},j}, v)$$

$$a_{\mathrm{c},j} + a_{\mathrm{w},j} + a_{\mathrm{f},j} = 1 \qquad (3)$$

where $$f_{\mathrm{M}}(\bar{v}, v) = 1/(\sqrt{\pi}\bar{v}) \exp(-v^2/\bar{v}^2)$$

is the Maxwell distribution function defined by the effective ion temperature

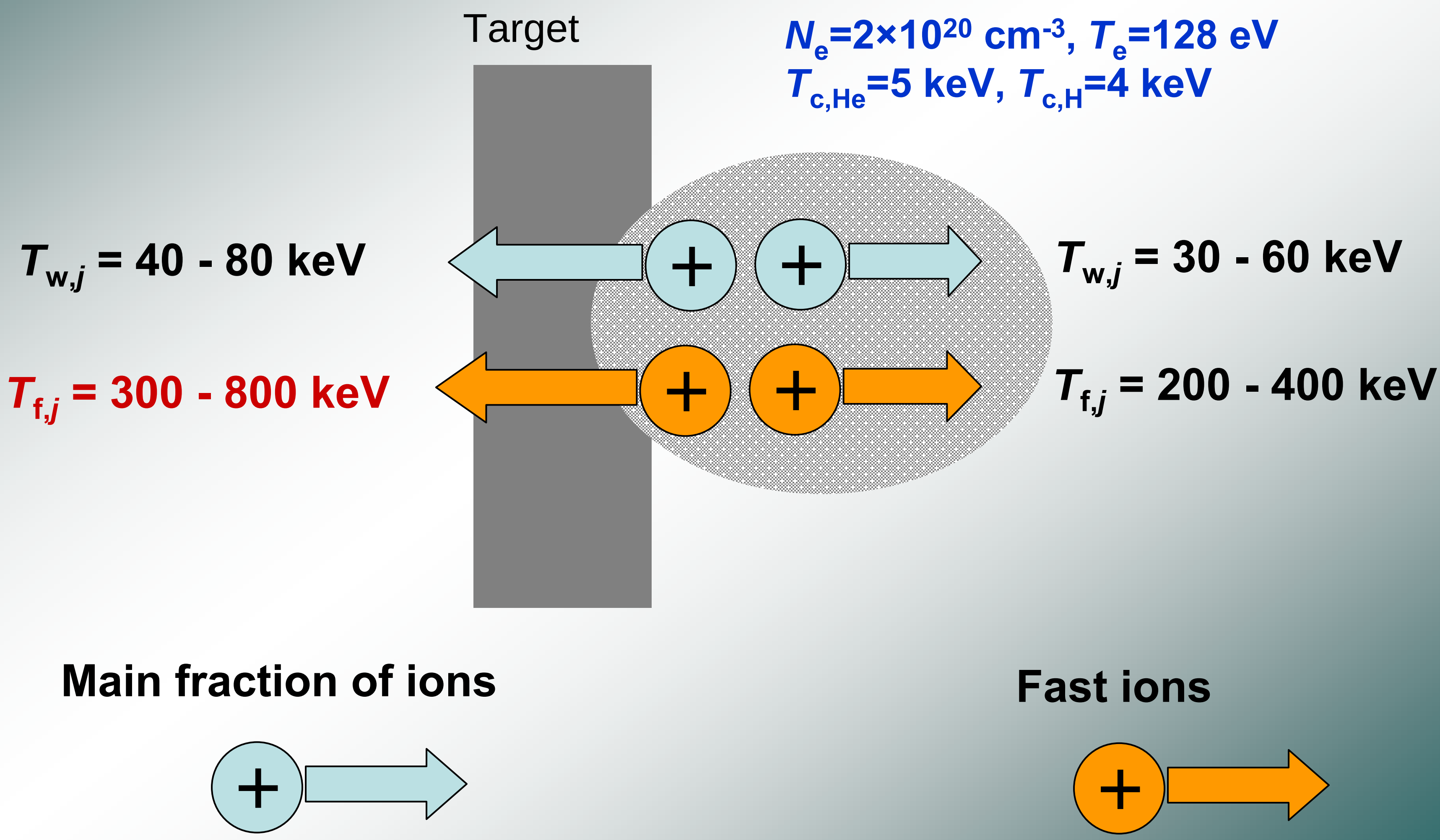
$T = M\bar{v}^2/2$, *M* is the ion mass.

In this equation:

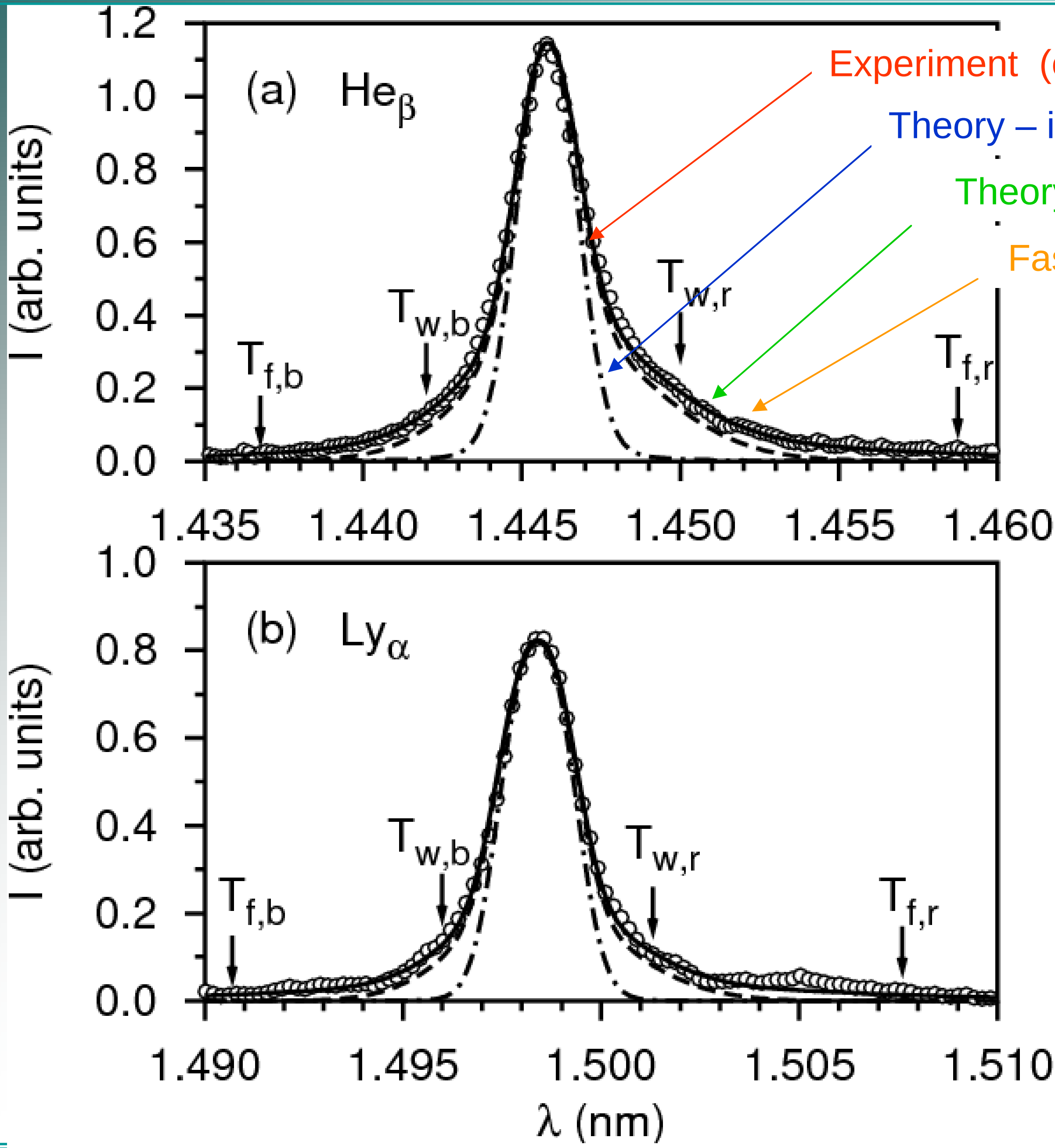
- the first term is defined by the effective temperature $T_{\mathrm{c},j}$ contributes to the central part of a line;
- the second term contributing to the nearby line wings is defined by the effective temperature $T_{\mathrm{w},j}$;
- the third term characterizes the far wings by is the temperature of fast ions $T_{\mathrm{f},j}$.

In order to reproduce the observed line asymmetry different values of *temperature and normalizing parameter* were used for the blue and red line wings .

The differences of corresponding values characterize anisotropy of the ions velocity distribution functions.



Spectral line shapes of He_β and Ly_α lines of fluorine ions in Teflon plasma



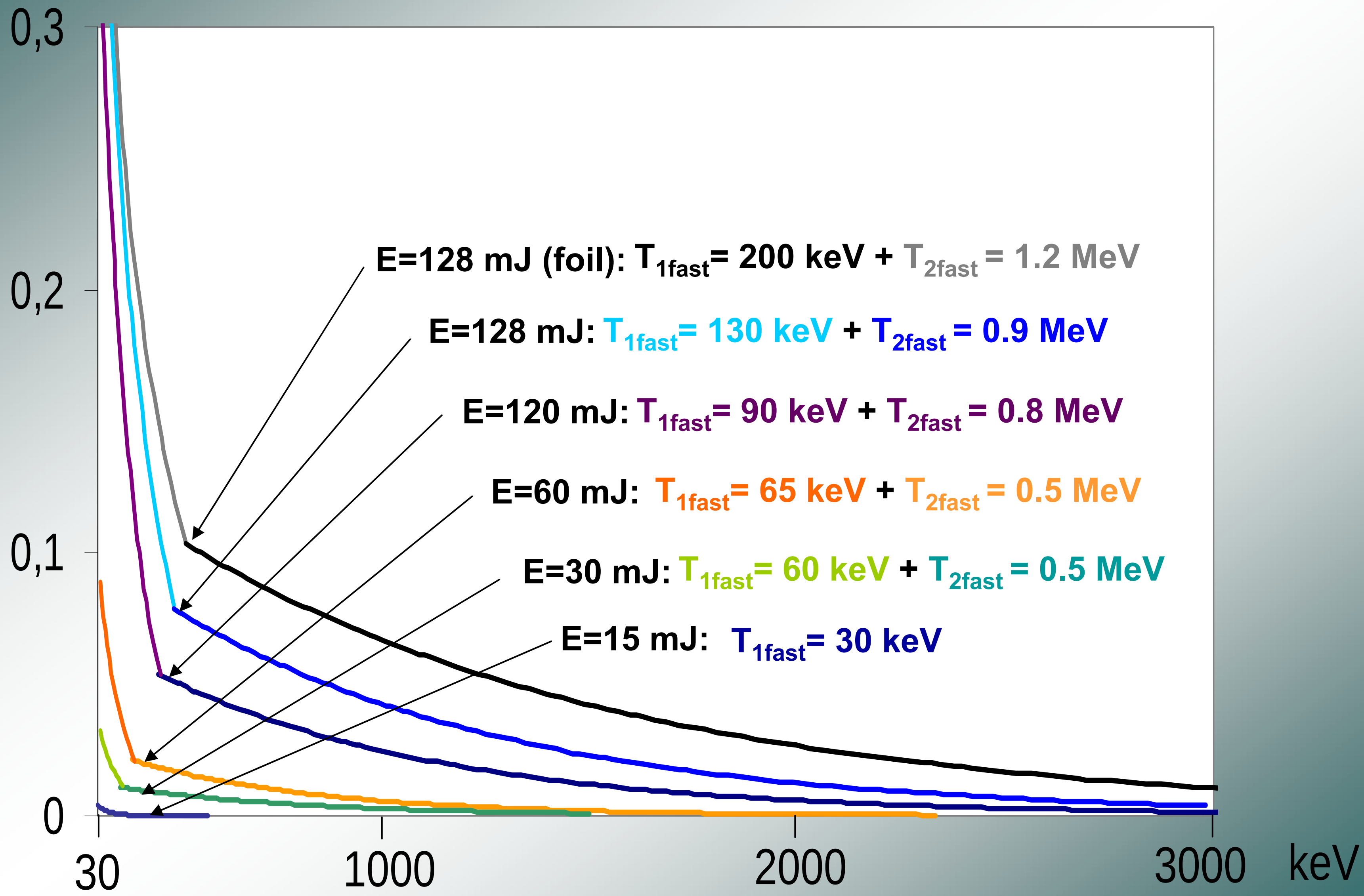
N_e=2×10^{20} cm^{-3}, T_e=128 eV
$T_{c,He}$=5 keV, $T_{c,H}$=4 keV

Blue wings:
$T_{w,He}$=50 keV, $T_{w,H}$=25 keV
Red wings:
$T_{w,He}$=80 keV, $T_{w,H}$=35 keV

Blue wings:
$T_{f,He}$=0.35 MeV, $T_{f,H}$=0.25 MeV
Red wings:
$T_{f,He}$=0.7 MeV, $T_{f,H}$=0.35 MeV

Laser: 1 ps; 120 mJ

Fraction and Energy of Fast Ions vs. Laser Energy



The fast ion fraction with energy above *E*, estiamted from experiments

$$P_j(E) = b_j \int_{\sqrt{2E/M}}^{\infty} f_{\mathrm{m}}(v_{\mathrm{f},j}, v)\,dv = b_j\left[1 - \mathrm{erf}\left(\sqrt{E/T_{\mathrm{f},j}}\right)\right]$$

At $F = 4\times10^{16}$ W cm^{-2}mm^2 (P_{las} = 128 mJ, τ_{las} = 1 ps)

$P_j^{\,He}$ ~ 3% for ions with energies around 1 MeV !

Fast ions generation reasons: Creation of the non-uniform plasma under strong laser pulse with low contrast

Laser intensity : 5×10^{16} W cm^{-2}
Prepulse intensity : 5×10^{12} - 5×10^{14} W cm^{-2}

The scale of plasma density gradient: $L_n \approx c_s t_p \approx$ **100 μm**

where $c_s=(ZT_{e,p}/M)^{1/2}$ - the speed of ionic sound

t_p - the characteristic prepulse duration

$T_{e,p}$ - the electron temperature of preplasma

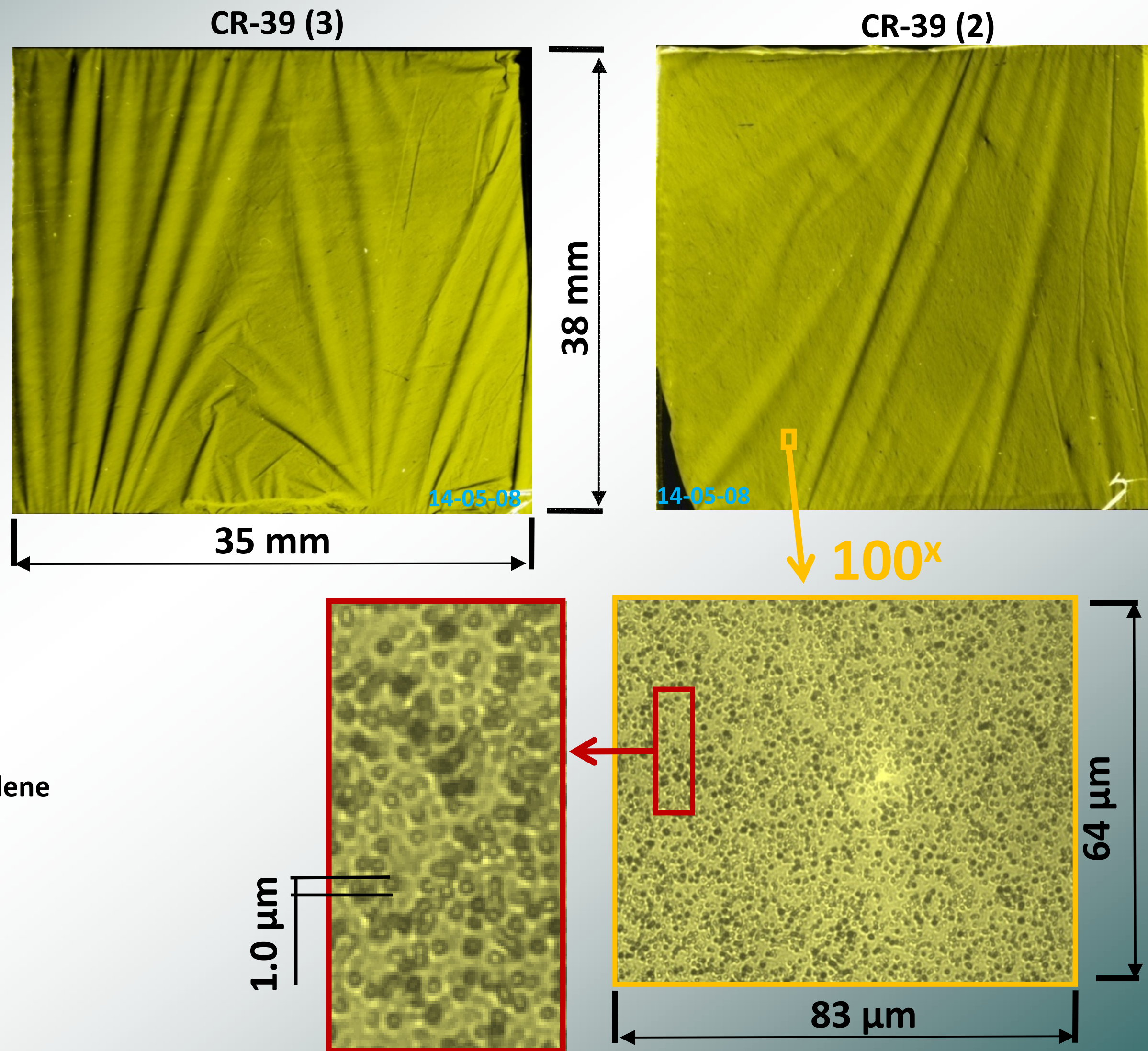
Z - the ion charge

Validation of spectroscopy results

Energy of transmitted ions:

Polypropylene , t = 1 μm	
^{4}He	100 keV
^{1}H (proton)	85 keV
^{16}O	320 keV
^{12}C	270 keV

Images of the 1 micron thickness polypropylene foil, obtained with the low energy ions:



<u>Experimental conditions (14-05-08):</u>

Laser: 36 fs, 4.7 TW, 4x10^{17} W/cm^{2}

Target : 90%He + 10% CO_2 (P_{gas} = 60 bar)

N_{shots} = 2800

Samples: CR-39 plates, covered by polypropylene

Distance to the target:

CR-39(2) - 140 mm

CR-39(3) - 160 mm

Angle of irradiation (to the laser beam axis):

CR-39(2) - 30°

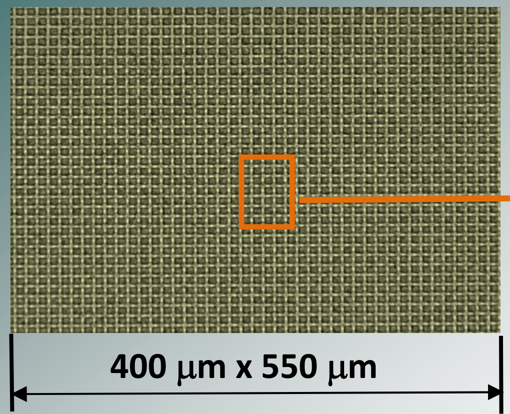
CR-39(3) - 90°

<u>Estimated number of ions:</u> > 10^{8} ions/shot

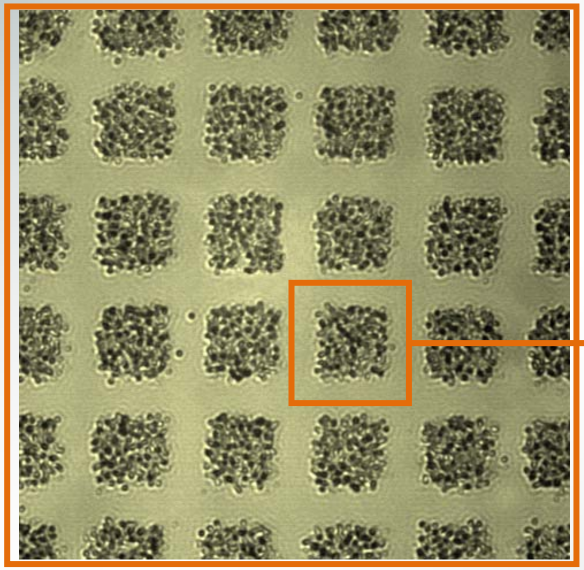
CR-39 low ions energy observations confirmed isotropic ion distribution from the cluster plasma

Application of FLP ion source: Images of 2000 lpi Cu grid

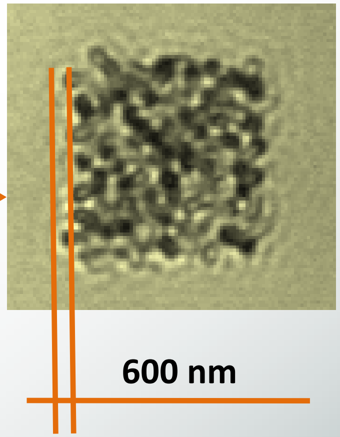
The 2000 lpi grid ion image



Fragment of the image

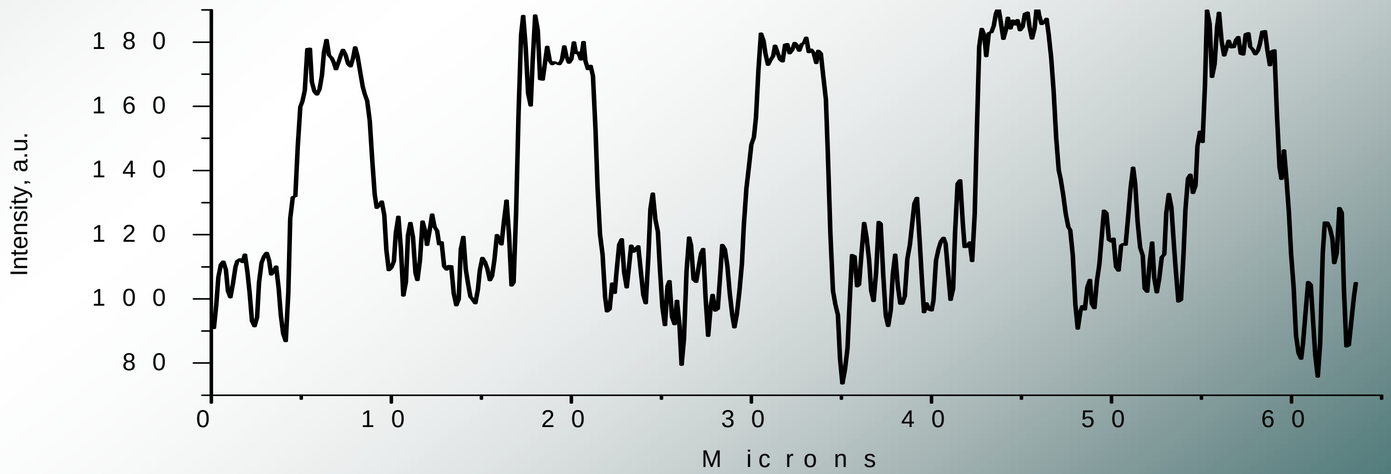


(observed under reflection mode of the confocal microscope, M = 100^x)



Distance source – CR-39 = 145 mm

Distance grid – CR-39 → in contact



Structures made of 100 nm Zr filter imaged on CR39

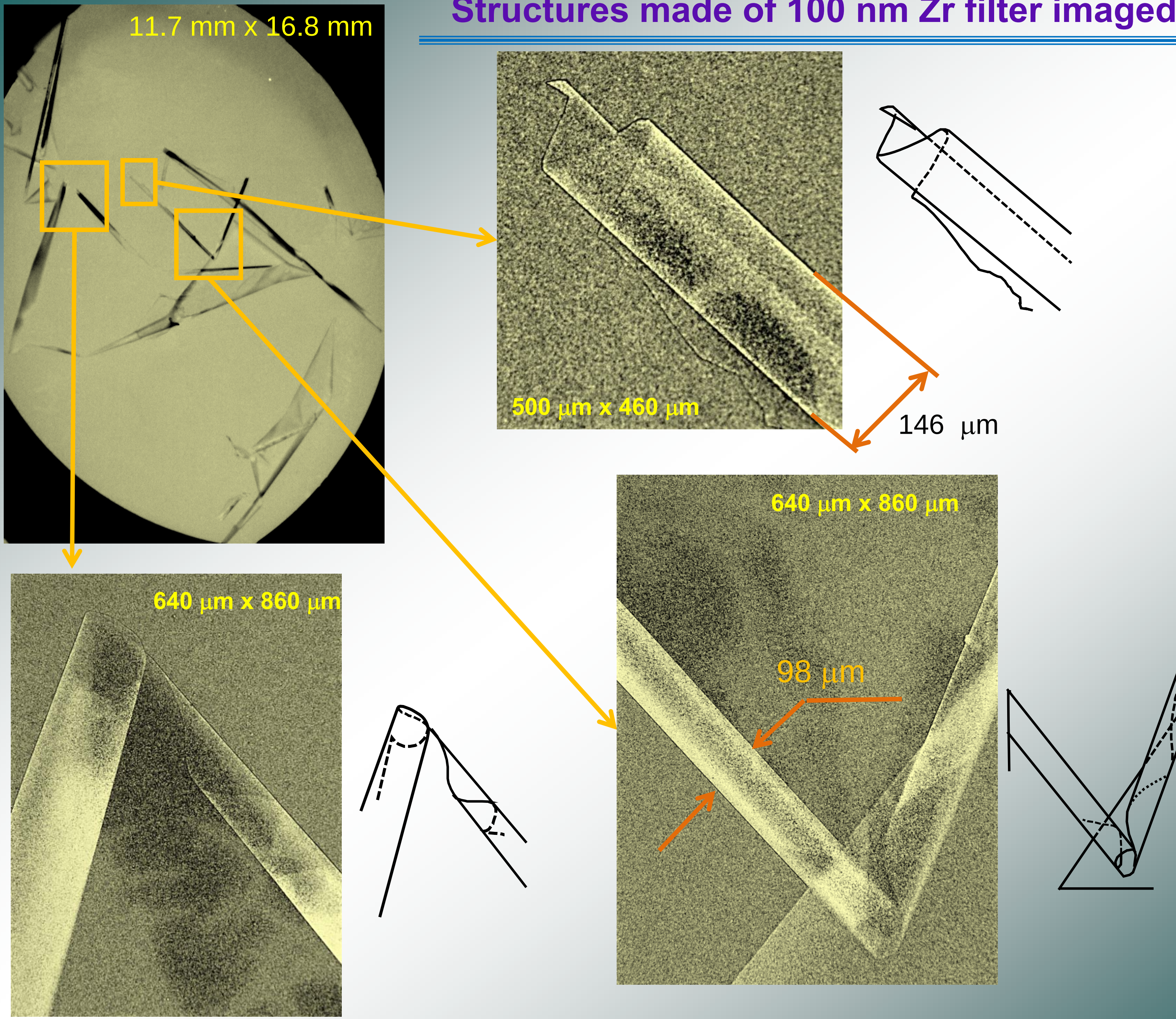
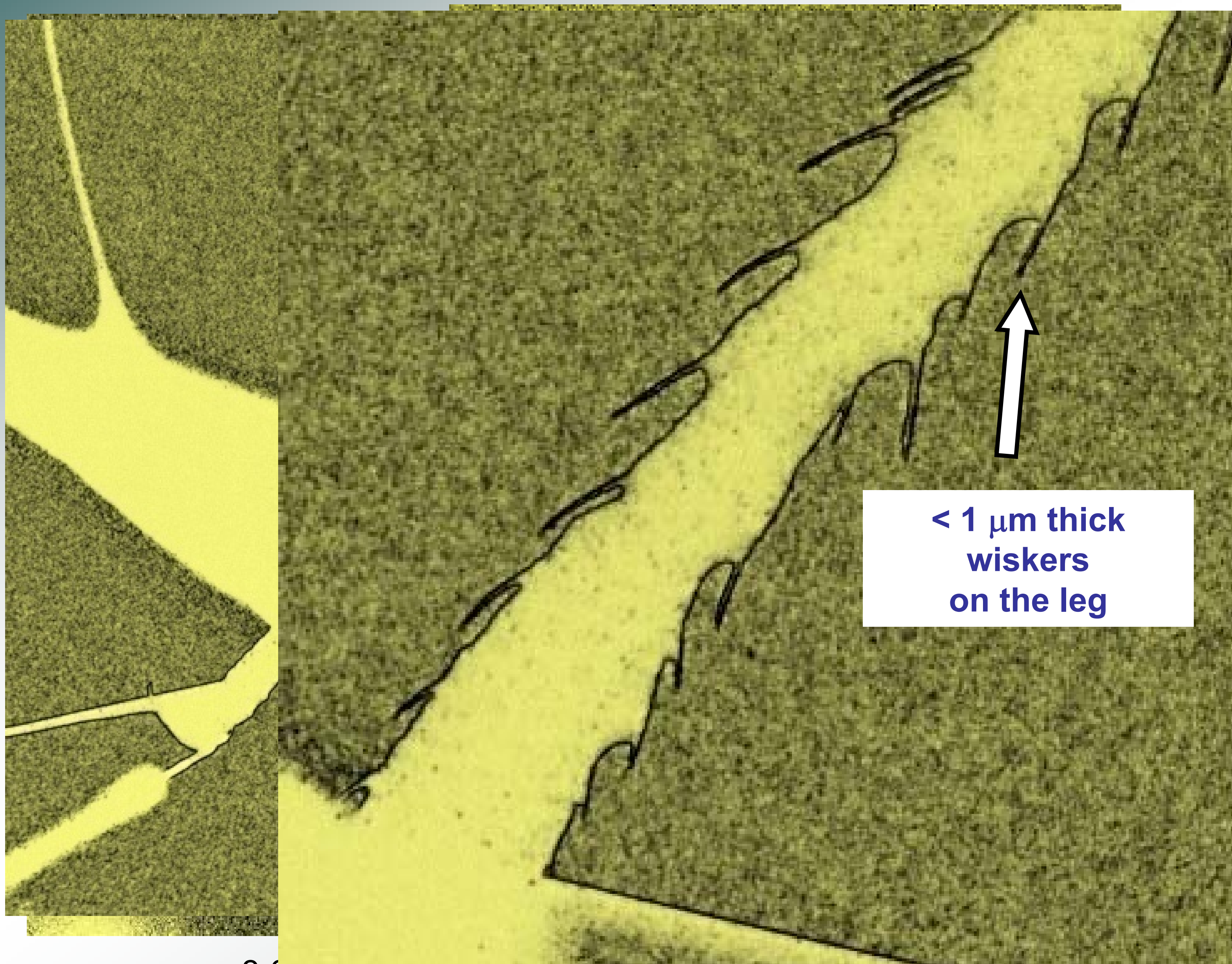


Image of Biological Samples on CR39 Detector



0.64 mm x 0.49 mm

0.55 mm x 0.40 mm

Distance sample – detector → in contact

Conclusions

Generation of fast ions from femtosecond laser plasma of different targets was studied using x-ray spectroscopy methods

Optimization of source parameters using x-ray spectroscopy allowed to achieve Ion flux (10^8 ions/shot) and energy (0.1 MeV/n) suitable for practical applications in ionography

We are moving forward and already observed generation of ions with energies up to 10 MeV/n. Additional research are necessary to increase ion flux $>10^{10}$ ions/shot in order to apply ultrafast laser plasma source as a table top fast ion source for investigation of interaction between ions and matter

Conclusions

We propose to use the X-Ray spectroscopy both for study generation of the fast ions in PHELIX-laser-produced plasma and for diagnostics of plasma created under interaction of fast ions with solids and airgel targets.

Maximum power output of the laser will be necessary to produce protons and multicharged ions with MeV energies. For production of such particles ultrathin Teflon and Al foils could be used as targets. Focusing spectrograph with spatial resolution together with vacuum-compatible, back-illuminated charge-coupled-device CCD camera will be necessary for the detection of X-ray spectra. Additional spectrograph can be installed to check parameters of the ions emitting from laser plasma.

Maximum energy, beam divergence and relative quantity of ions with different energies can be estimated from these measurements.

X-ray specrocopy will be used to study of the matter properties in the fast ion tracks in different materials including such practically important elements as silicon