Научный совет РАН по комплексной проблеме
"Физика низкотемпературной плазмы"

Заседание 11 ноября 2019 г.
Президиум РАН, г. Москва

Диагностика сверхплотной нагретой плазмы создаваемой лазерными импульсами петаваттной мощности

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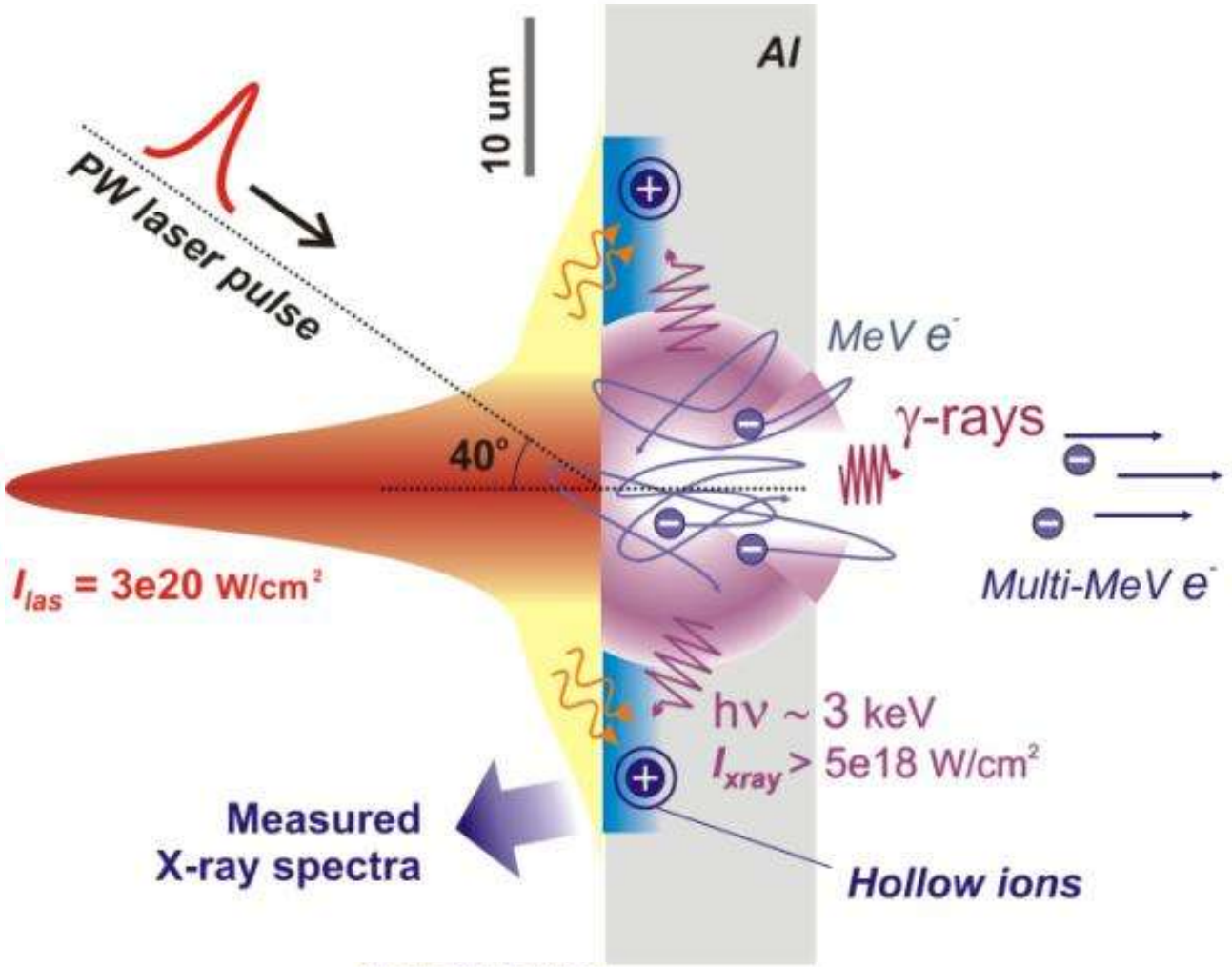
Объединенный институт высоких температур РАН
Национальный исследовательский ядерный университет «МИФИ»

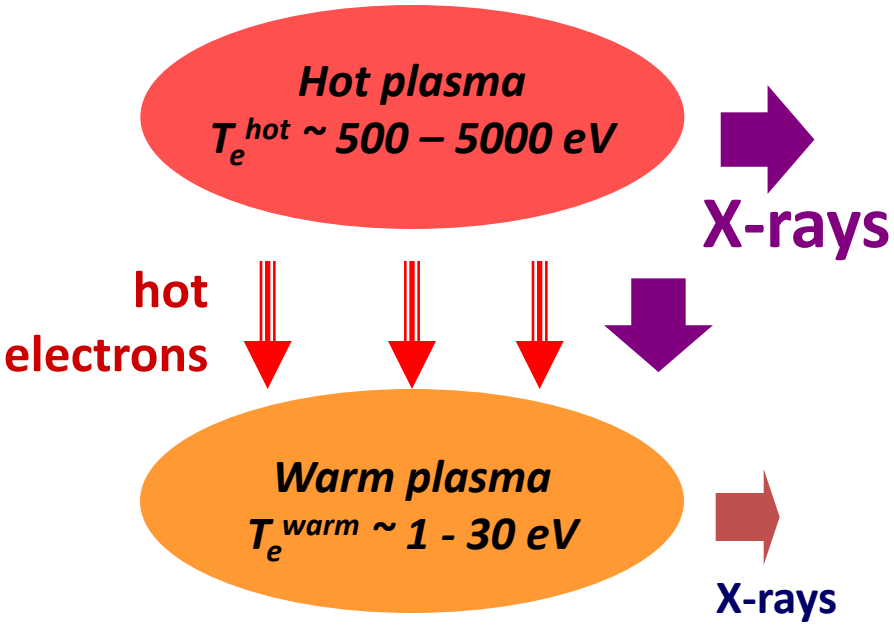
Physics behind PW laser pulse interacting with solids

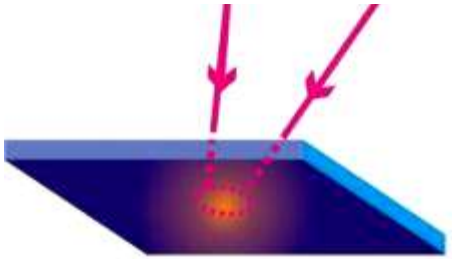


WDM studies using optical lasers – principle and setup

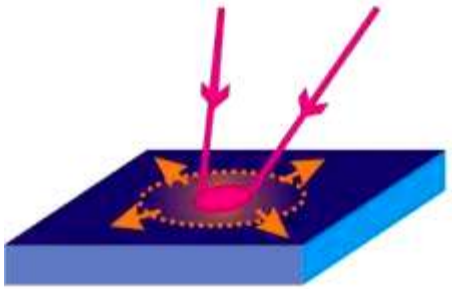
Hot plasma (T_e ~ 1 keV), commonly in laser focus

WDM – (T_e ~ 10-100 eV, N_e~10^{23} cm^{-3})

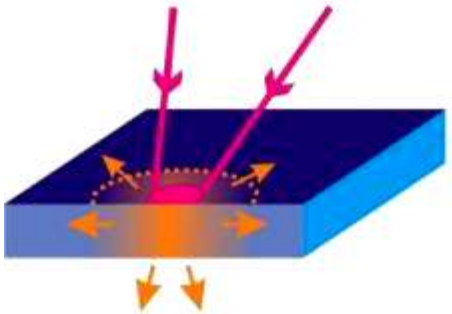




rear side of thin foil



vicinity of hot plasma
at front side



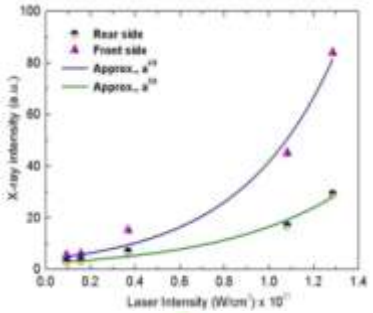
along electron trajectory
deep into the target

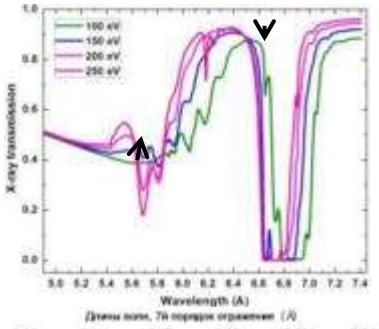
By means of X-ray spectroscopy
T_e^{warm} can be determined when over 10 eV.

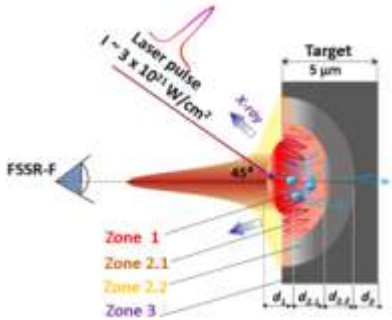
Spatial resolution is of crucial importance.

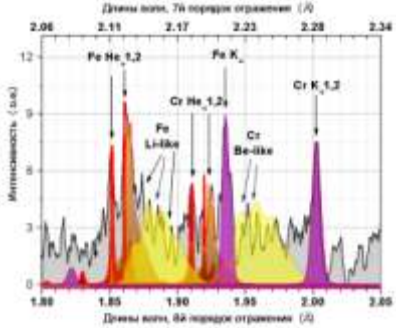
X-ray imaging and spectra diagnostics capabilities

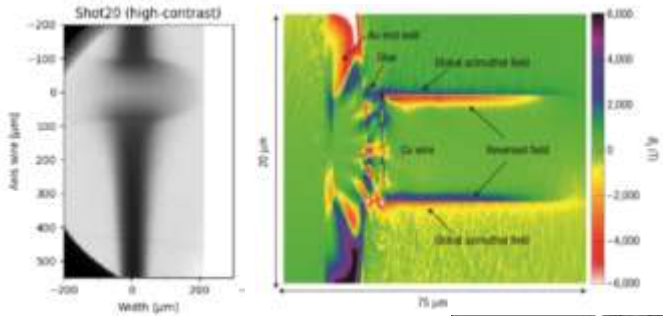
- X-ray emissivity and
  X-ray transport properties
- Hot and warm plasma
  temperatures
- Plasma density -
  shocks and electron currents
- Atomic states and
  density effects (hollow ions, IPD)

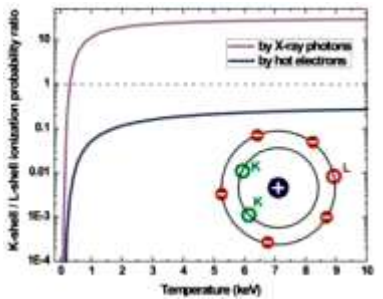


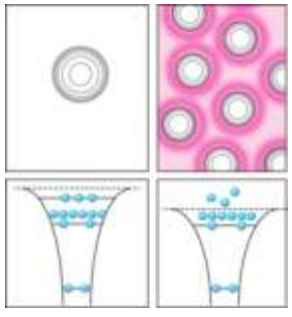




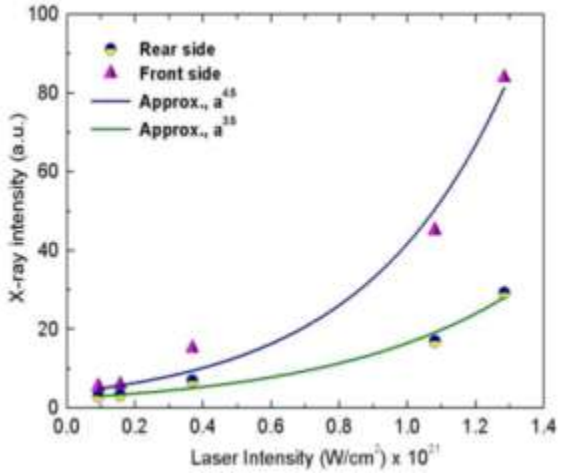


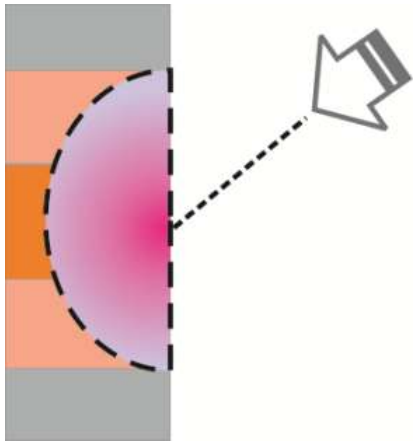


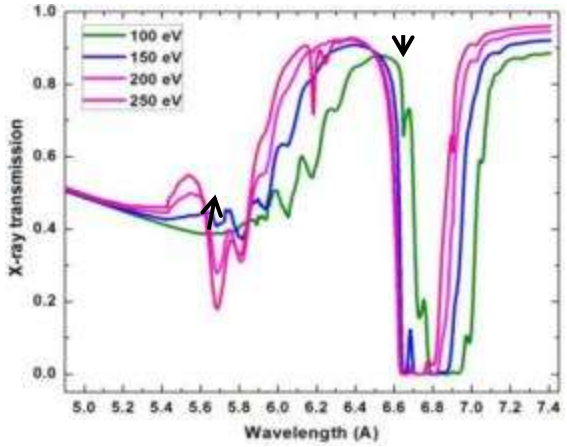




X-ray emissivity and X-ray transport properties







Experiments with J-KAREN-P Laser facility

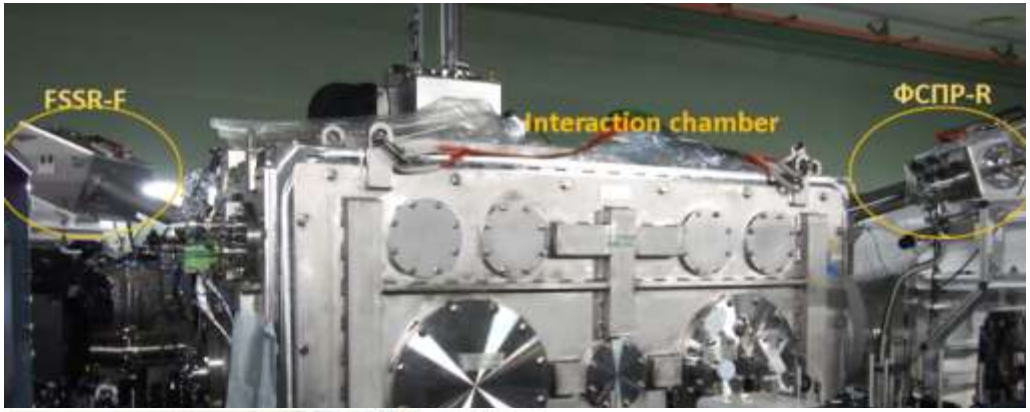
Experiments at J-KAREN-P (since march 2016)
Kansai Photon Science Institute, Kyoto, Japan

J-KAREN-P laser facility:

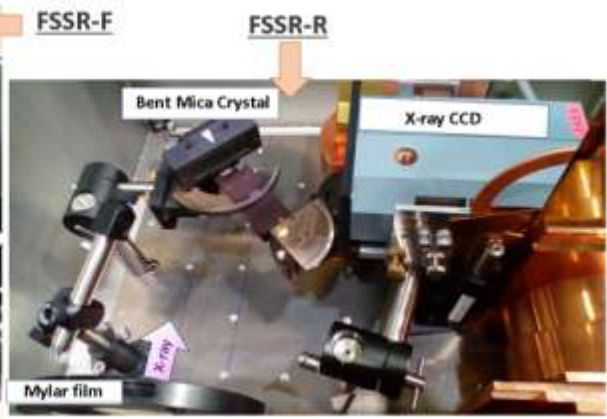
- Ti:Sapphire, OPCPA
- Wavelength λ= 800 nm
- Laser power P_{laser}= 0.35 PW
- Laser contrast up to $C_{laser} \sim 10^{12}$
- Pulse duration $\tau \sim$ 40 fs
- Energy on target up to E~ 14 J



High resolution X-ray spectrometers coupled with CCDs, 2 channels

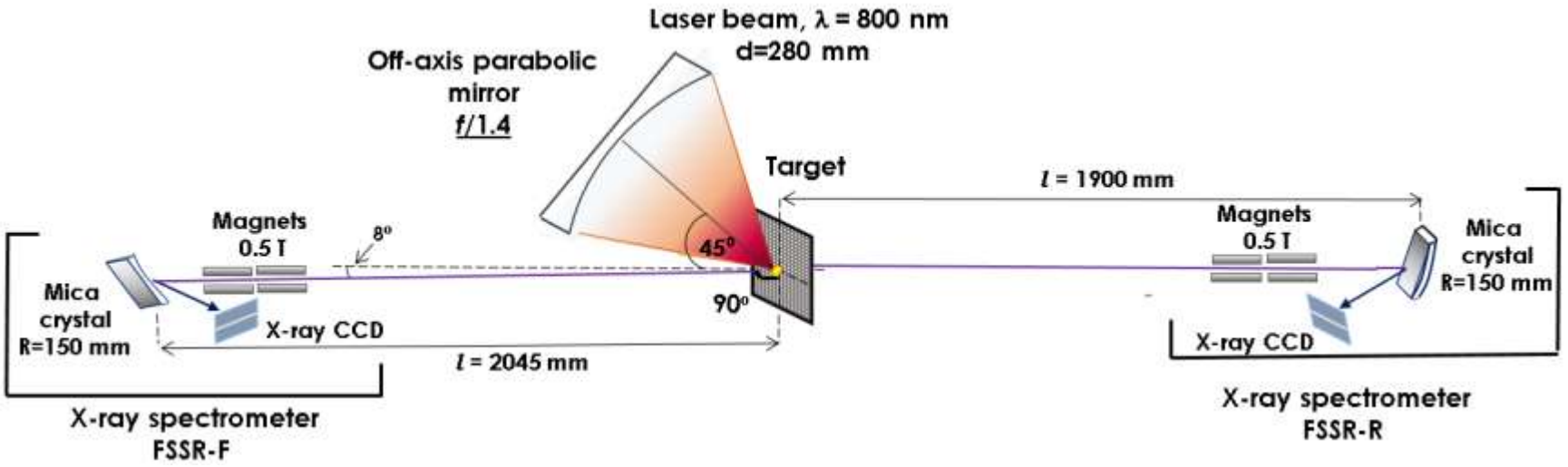




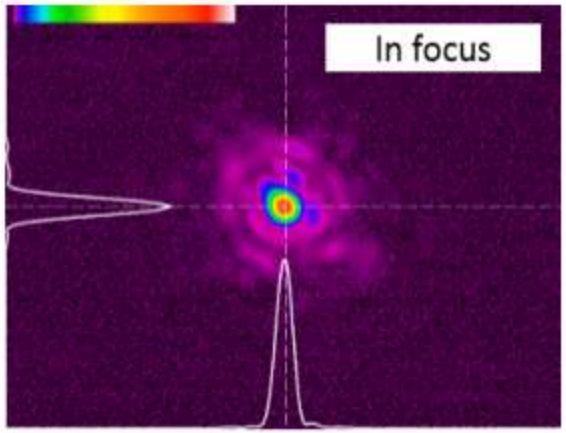


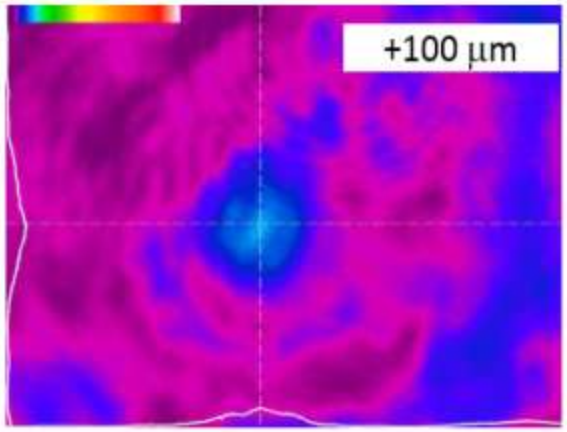
FSSR in vacuum chamber

Experimental Setup J-KAREN-P laser facility

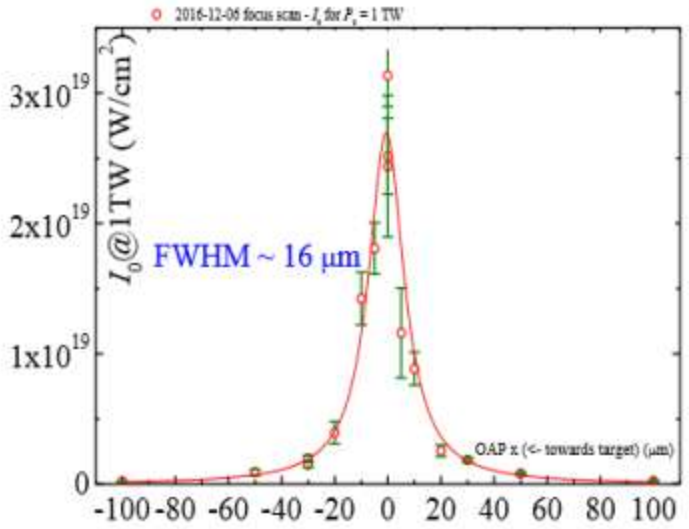


Sharp laser focusing with f/1.4 parabola. Focal spot diameter ~1,5 μm



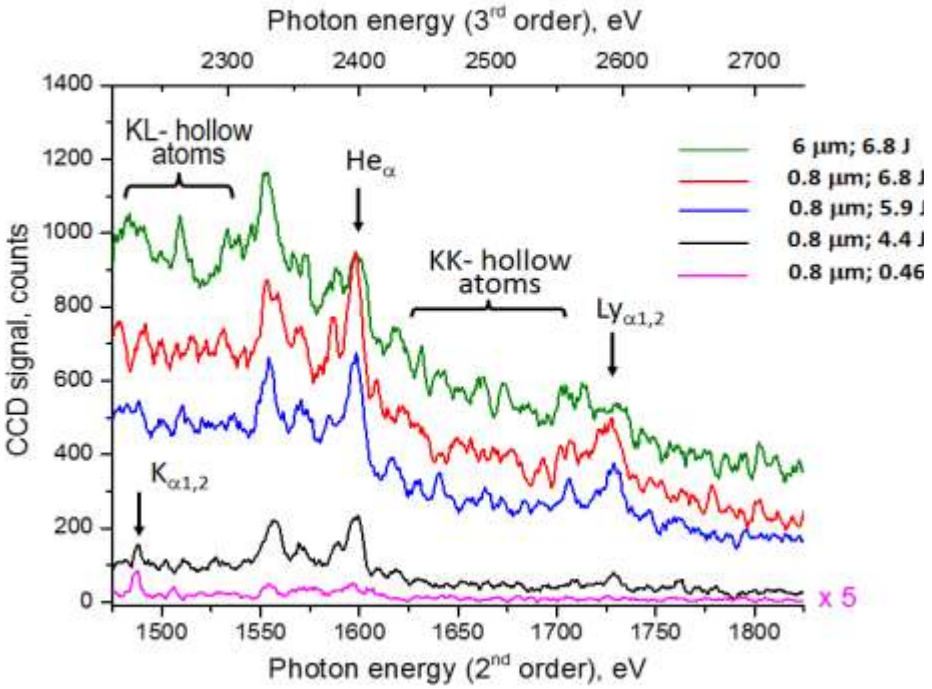


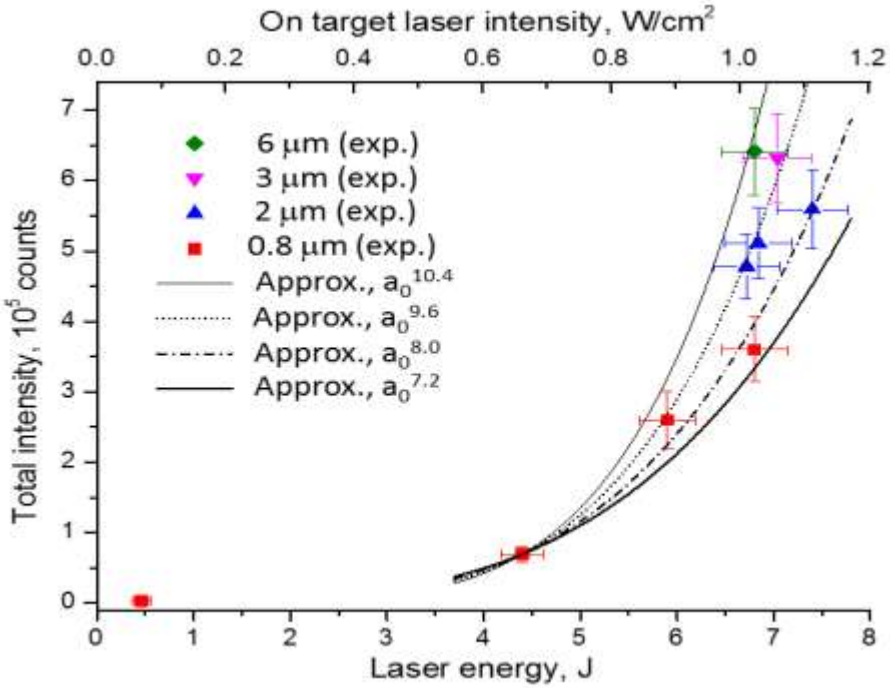
Focal spot snaps



Laser intensity on target vs target shift

Al x-ray spectra measurements @ J-KAREN





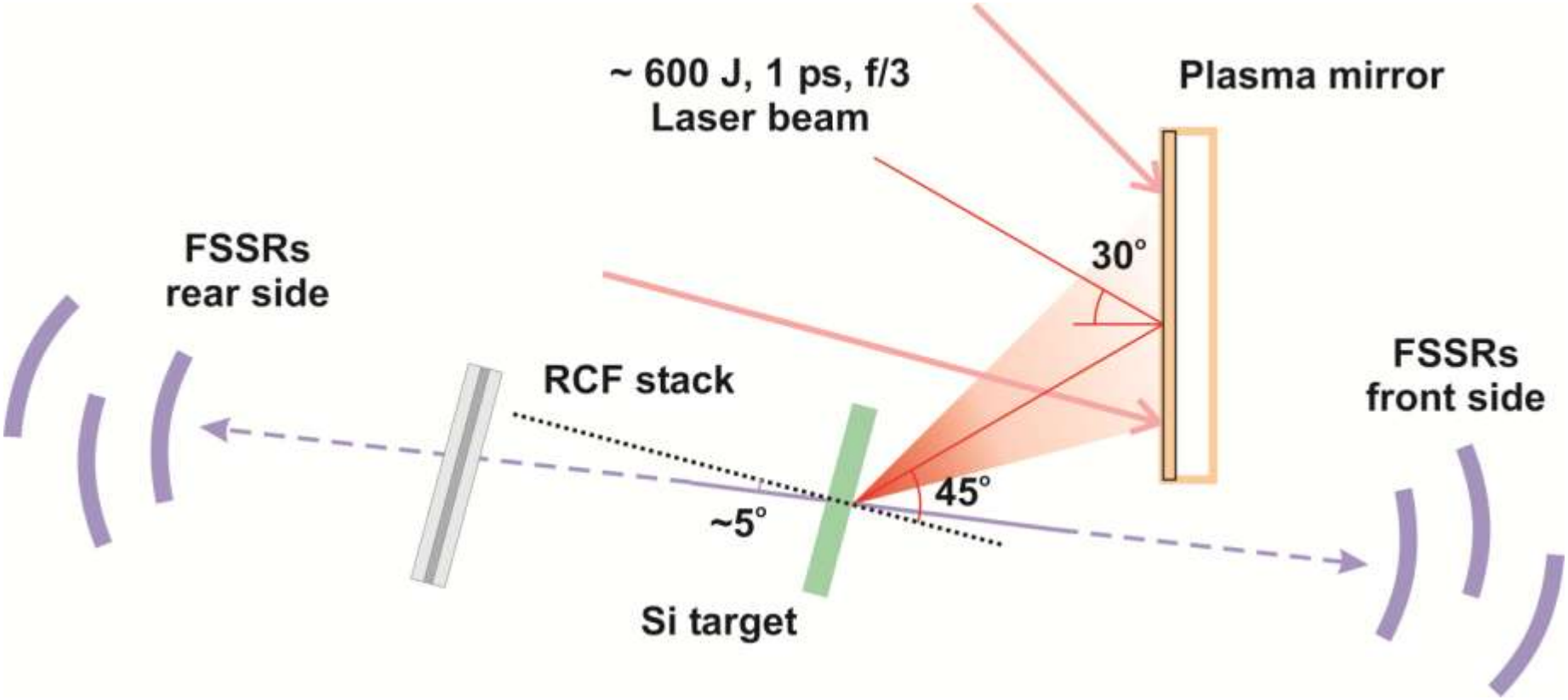
Nonlinear growth of X-ray intensity in 1.5-2 keV band is observed for laser intensity I_{las} ranged from 2e20 W/cm² to 1.1e21 W/cm²

$$I_{X\text{-}ray} \sim a_0^{\,8}, \text{ or } I_{X\text{-}ray} \sim E_{las}^{\,4}$$

$$normalized\ laser\ field\ -a_0 = eE_{Las}/mc\omega$$

// A.Ya. Faenov et al., Scientific Reports. 5, (2015)

X-ray spectroscopy studies of solid-density PW plasma



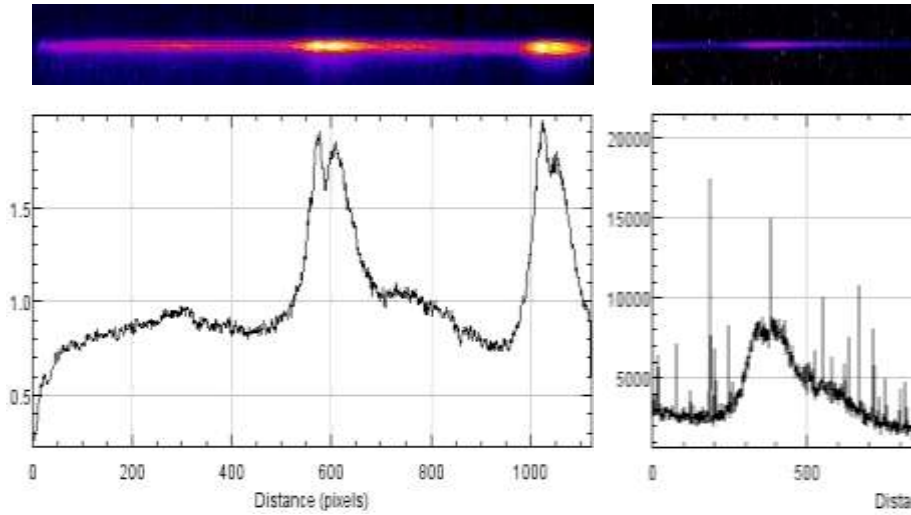
Experiment @ Vulcan PW: 5e20 W/cm2, 600J @1ps,
OPCPA + plasma mirror to ensure ultra high pulse contrast

Combination of 3 FSSRs at each side aligned at merged bands in order to cross-calibrate and combine the spectra.

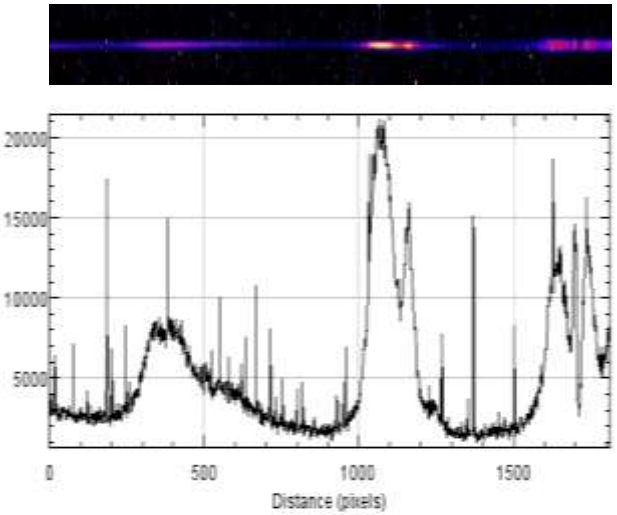
Shot23

Target: CH 3um + Si 2um + CH 3um	Energy: 550.1 J	Focal spot diameter: 7 um	Pulse length : 1.9 ps

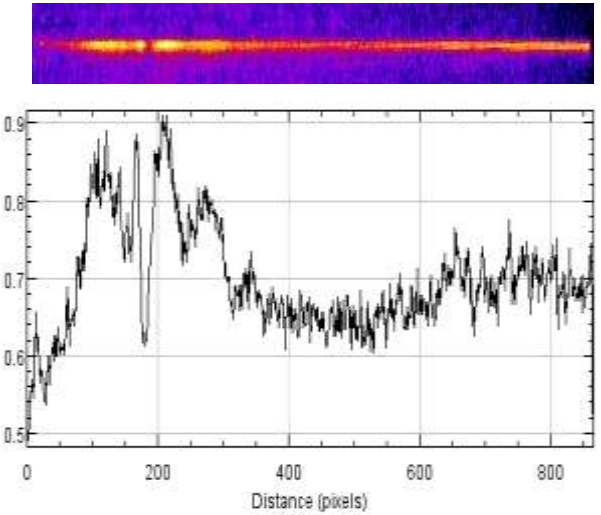
FShort



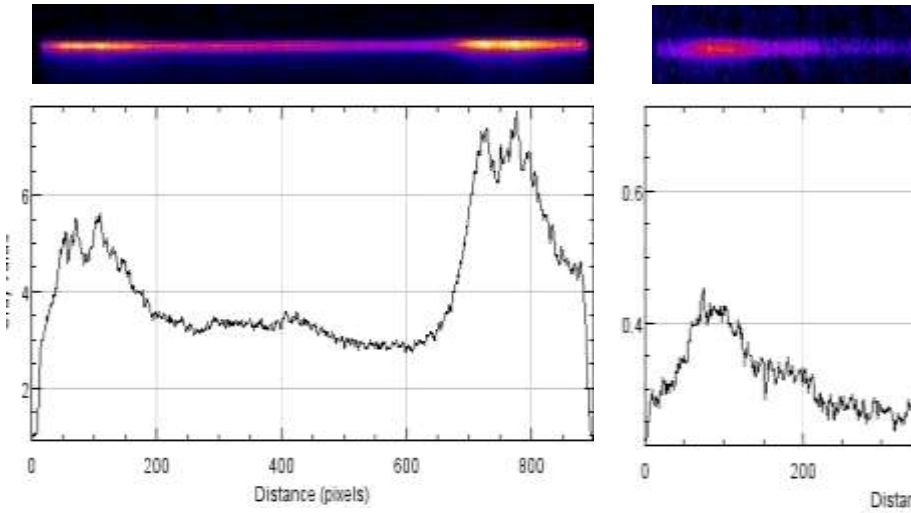
FMiddle (CCD)



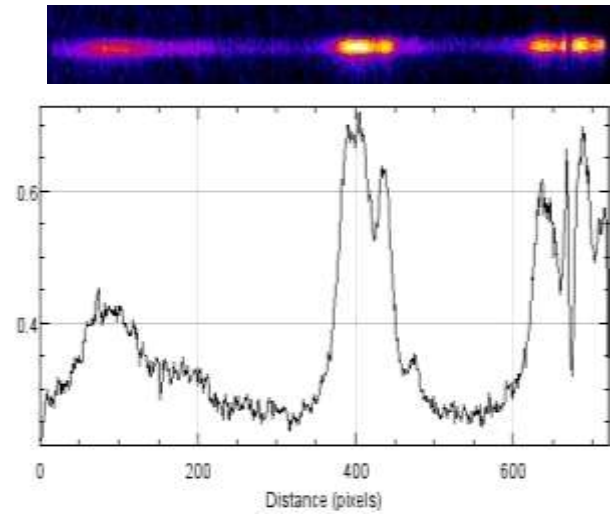
FLong



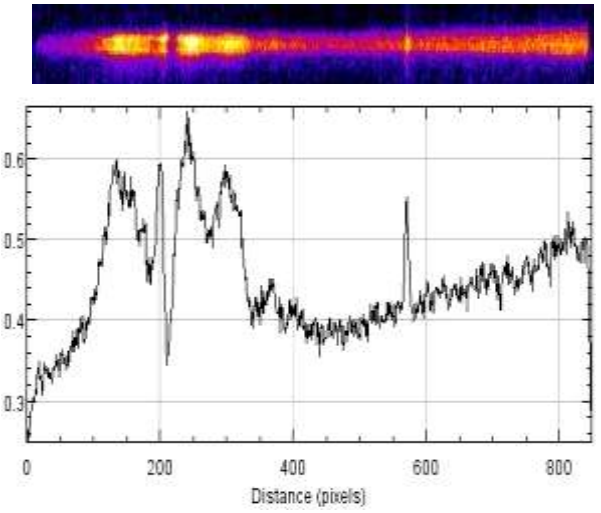
RShort



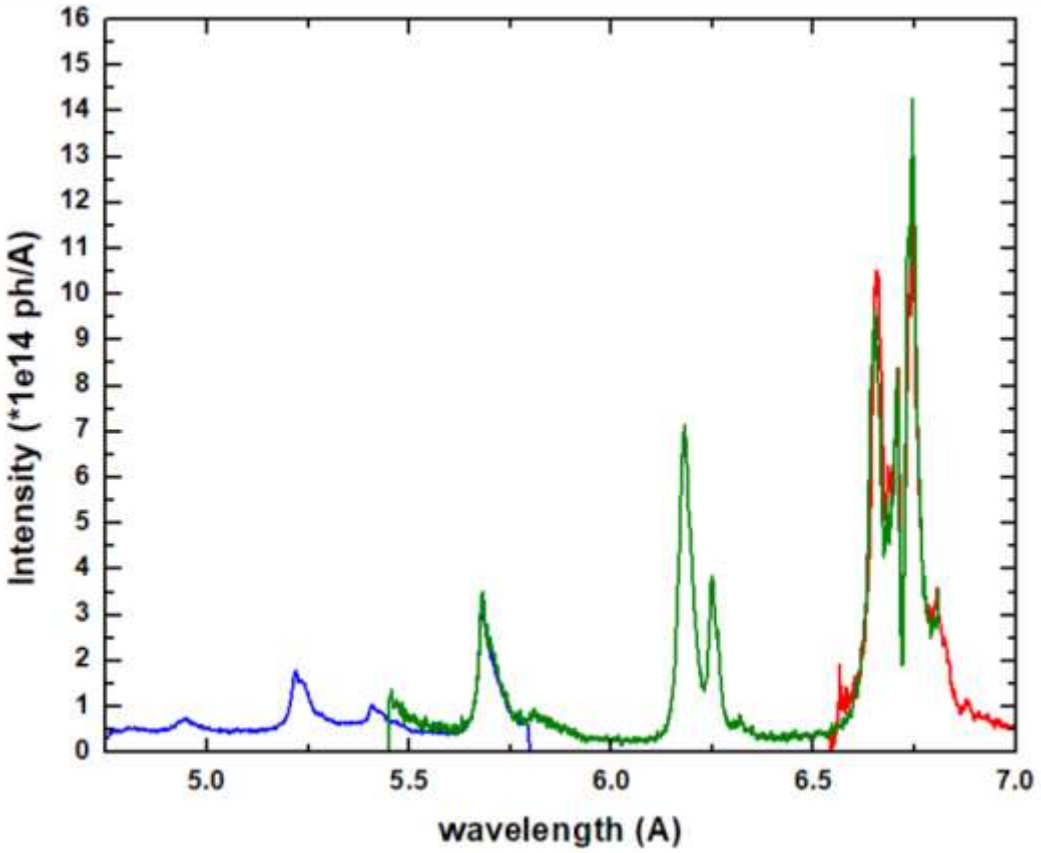
RMiddle

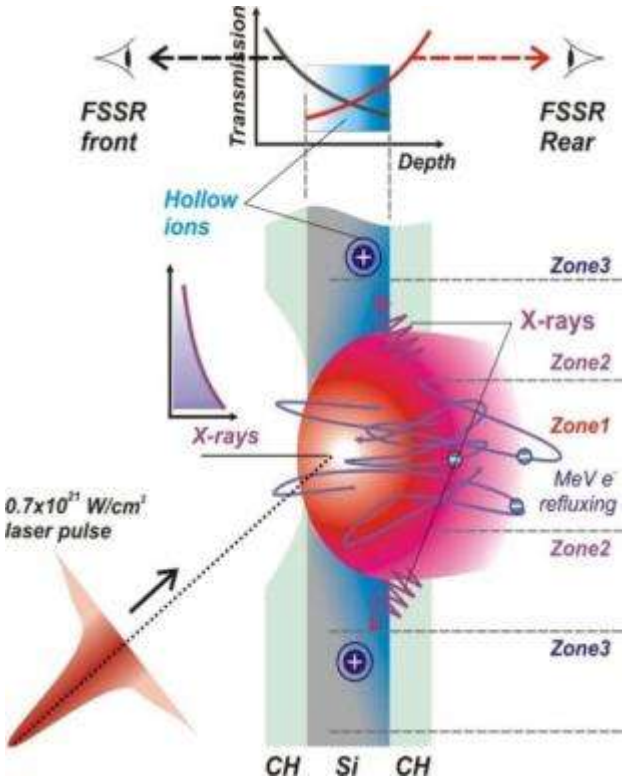


RLong



Revealing absolute intensity of X-ray source





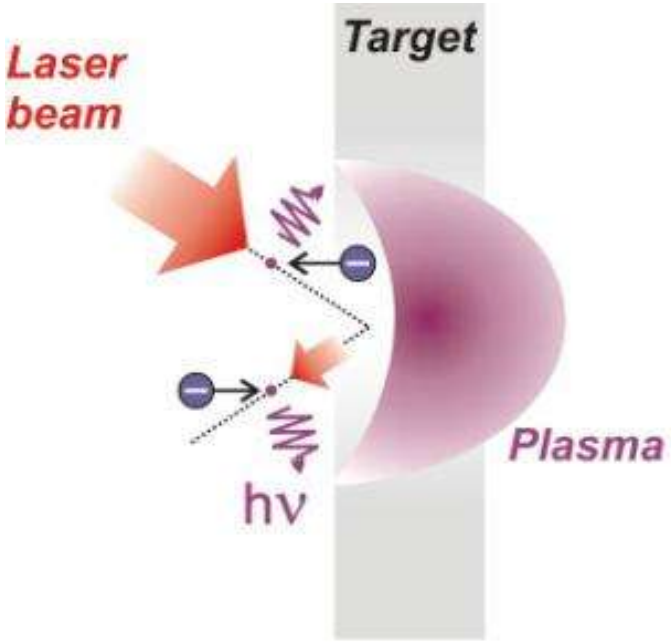
2e14 ph/A/2p corresponds to $E_{X\text{-}rays}$ = 0.5 J (in 2-3 keV photon energy range)

Assuming X-ray emission time ~ 1 ps laser pulse duration:

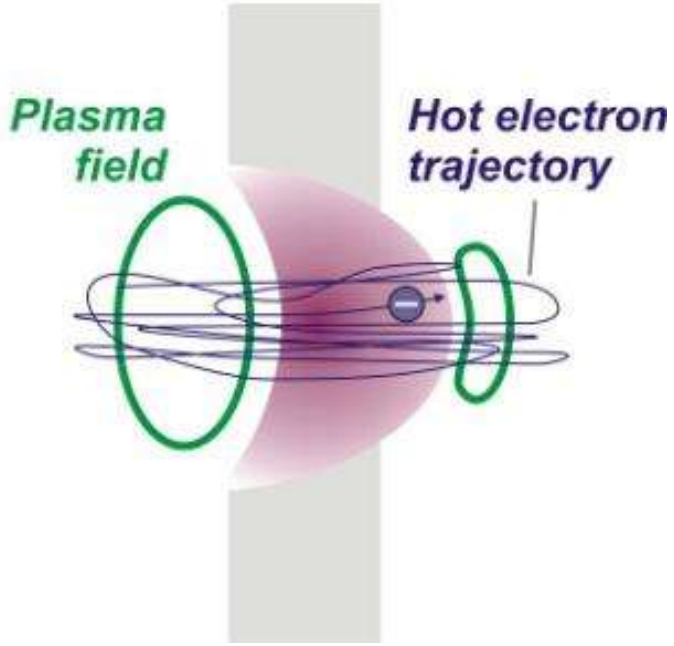
I_{Xrays} ~ 0.2e18 W/cm^2 - <u>as observed</u> in the direction close to the target normal

X-ray generation in PW plasma

E_{laser}, i.e. Thomson scattering at incident laser radiation



$E_{plasma\text{-}transv}$, i.e. Bremsstrahlung in a plasma during refluxing



$$f_R \approx \frac{2e^4}{3m^2c^5}\gamma^2\vec{v}\left\{\left(\vec{E}+\vec{v}\times\vec{B}/c\right)^2-\left(\vec{v}\cdot\vec{E}/c\right)^2\right\}$$

$$P \sim T_h^2 E^2 \exp\left(-\varepsilon(\theta/T_h)\right)$$

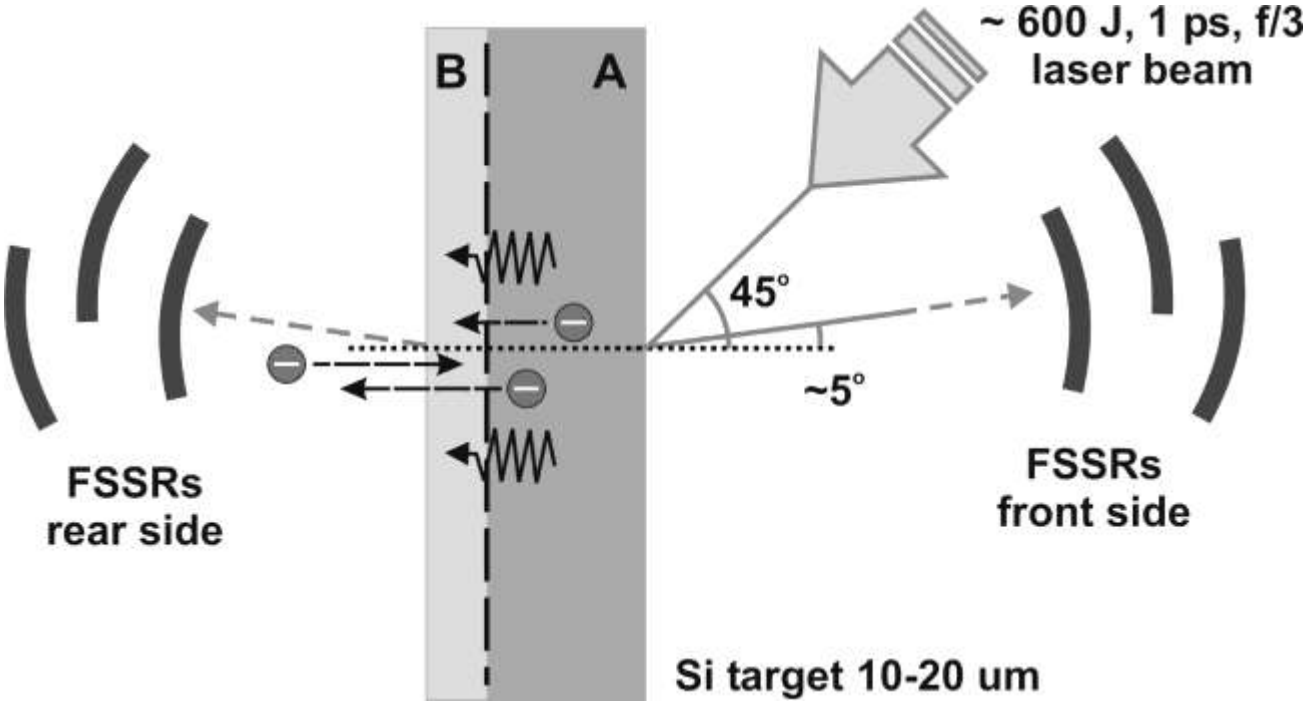
With I_{Las} = 3e20 W/cm^2

I_{Xray} ~ 5e18 W/cm^2

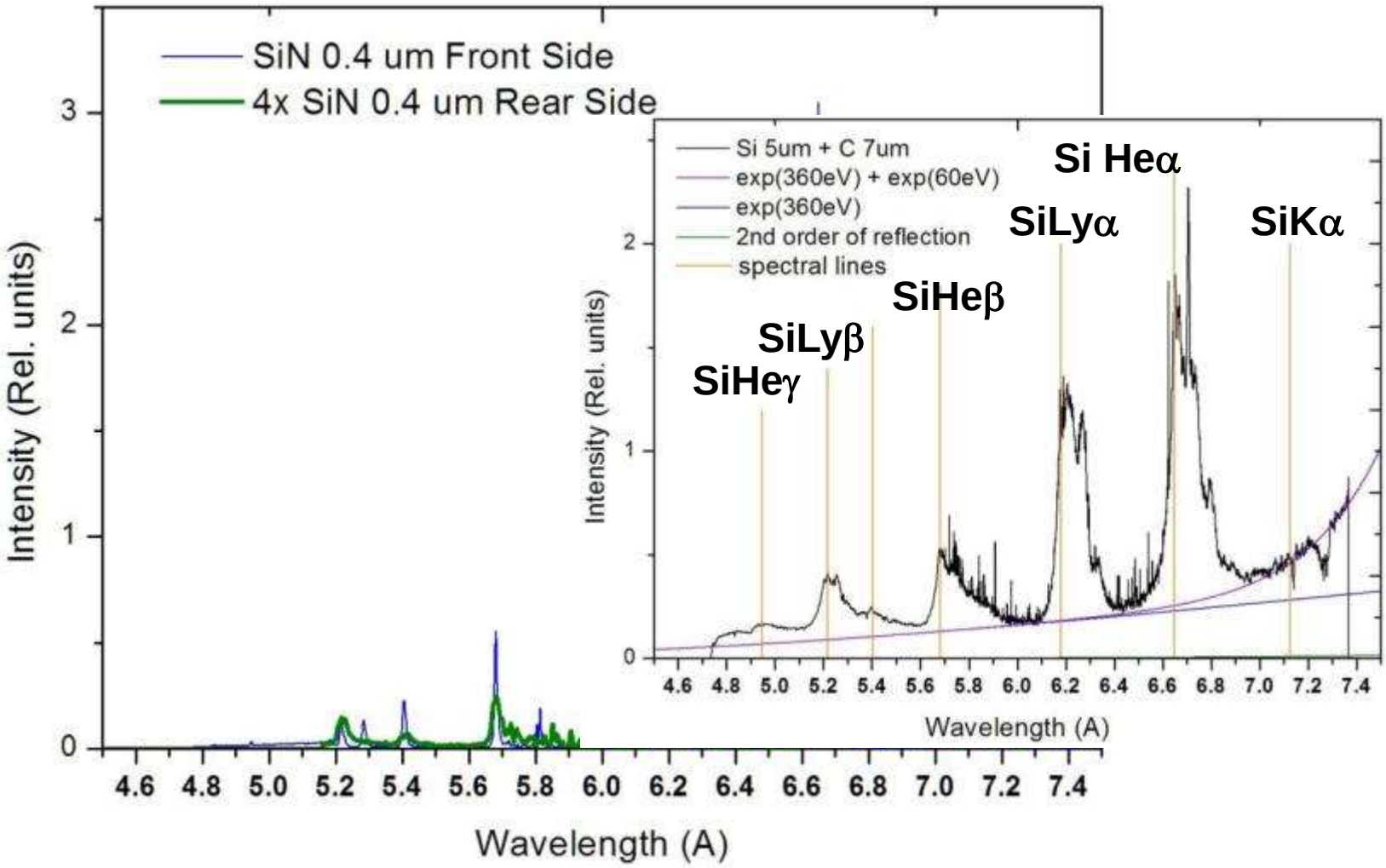
to be estimated

Refluxing is very important to increase the electron flux *inside* the plasma.
Thin (~ μm) targets is more effective due to higher electron oscillation frequency.

X-ray transport properties of laser-initiated WDM



Absorption spectroscopy



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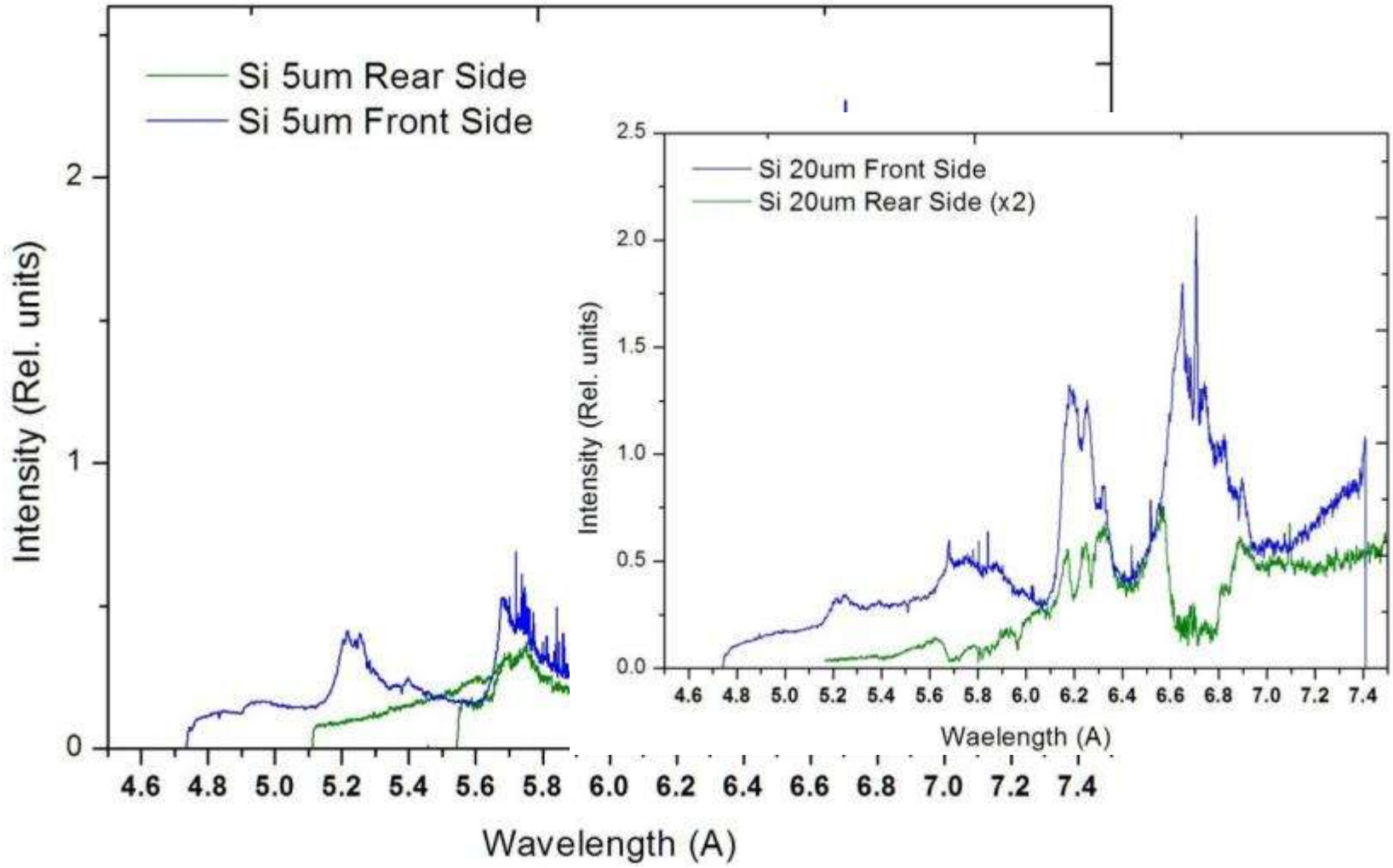
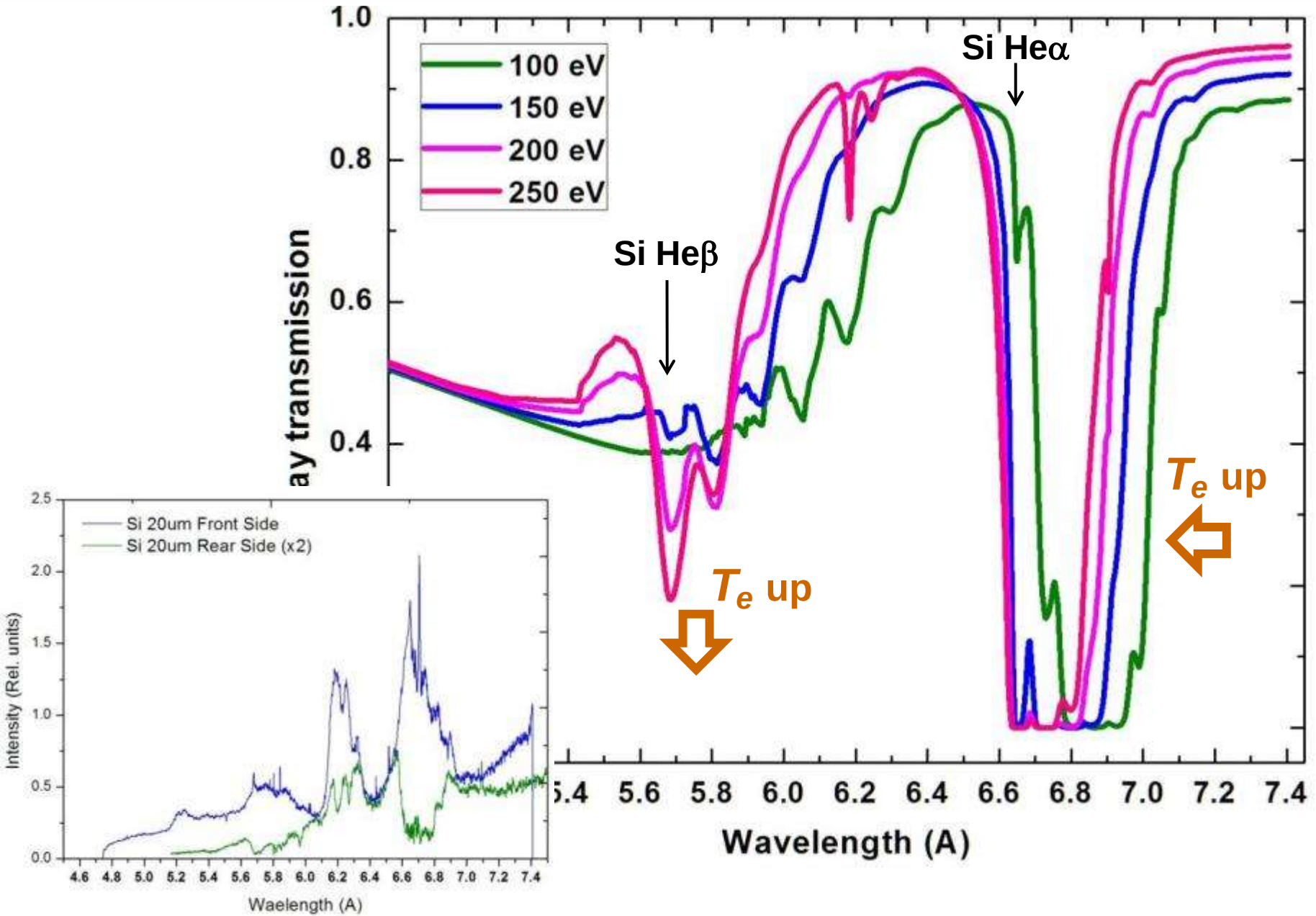
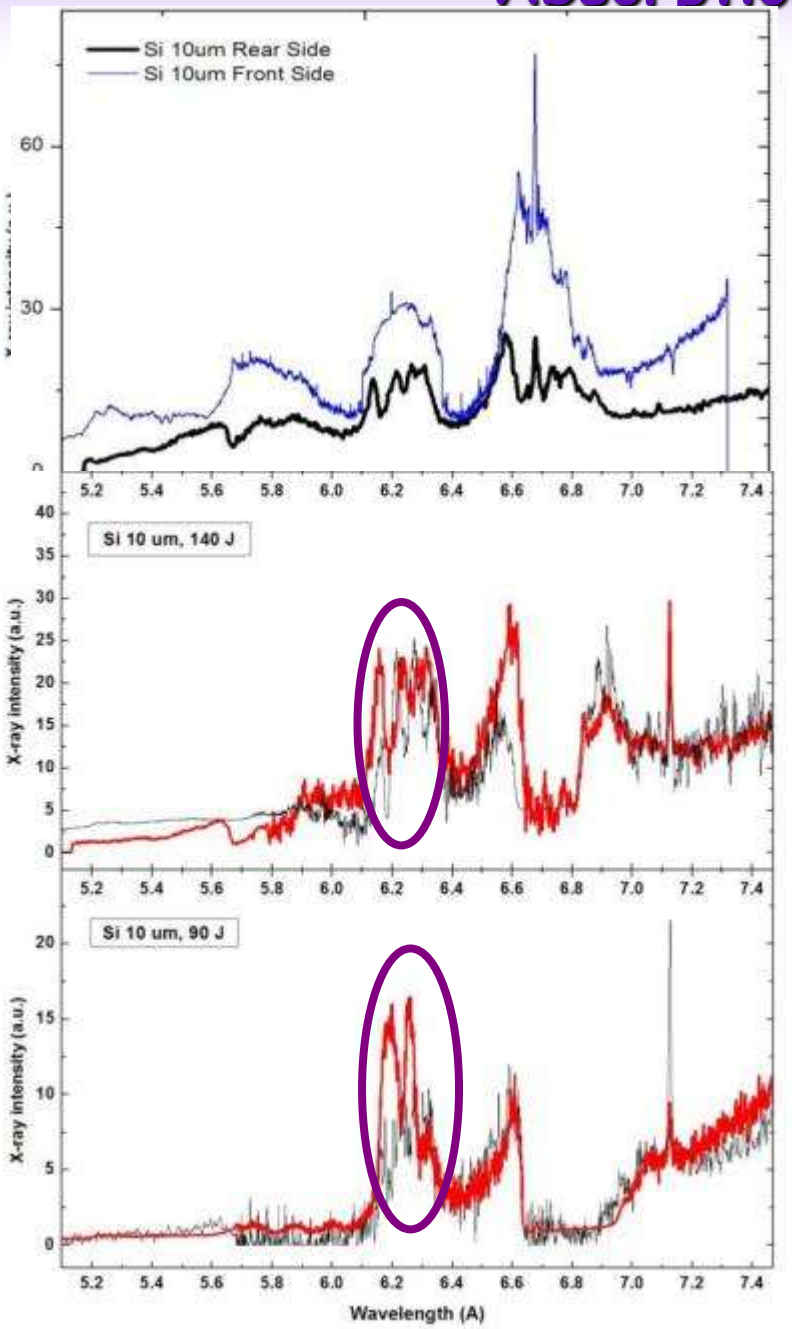


Absorption spectroscopy



Absorption spectroscopy



The spectra from the rear are simulated with use of PrismSPEC absorption mode, when the initial front side spectra is taken for the source

T_e = 320 eV (20 um, 550 J pulse)

d_b = 5 um

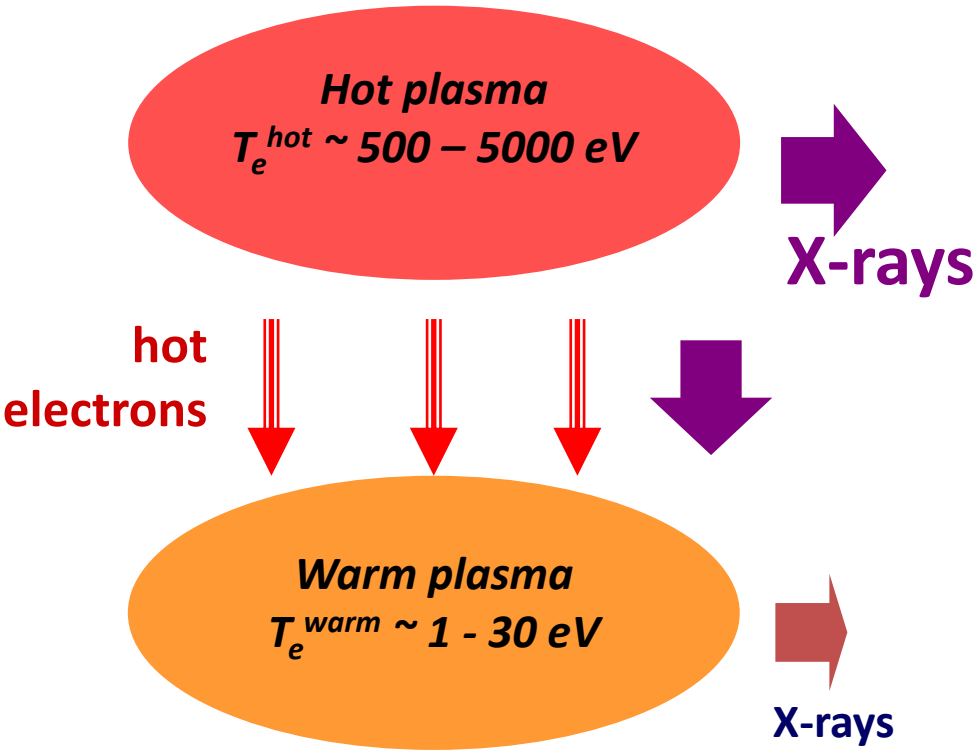
T_e = 300 eV (10 um, 140 J pulse)

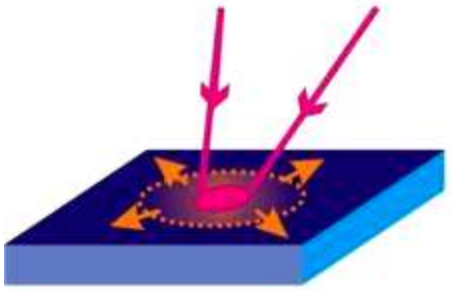
d_b = 5 um

T_e = 140 eV (10 um, 90 J pulse)

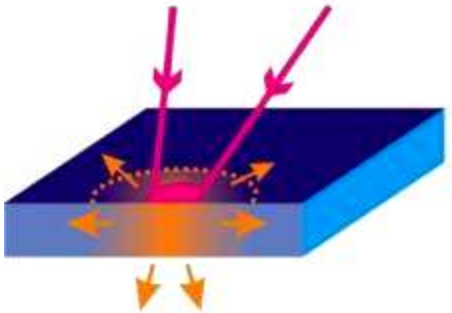
Often, the spectra could not be described in-full by a single Te – as H-like and He-like lines are absorbed differently, i.e. by different plasma zones.

WDM Temperature measurements



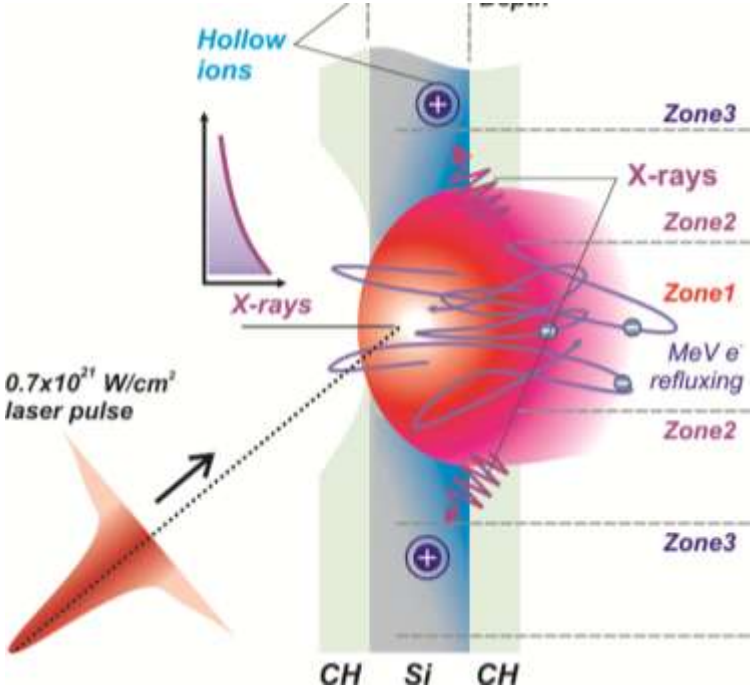


vicinity of hot plasma
at front side

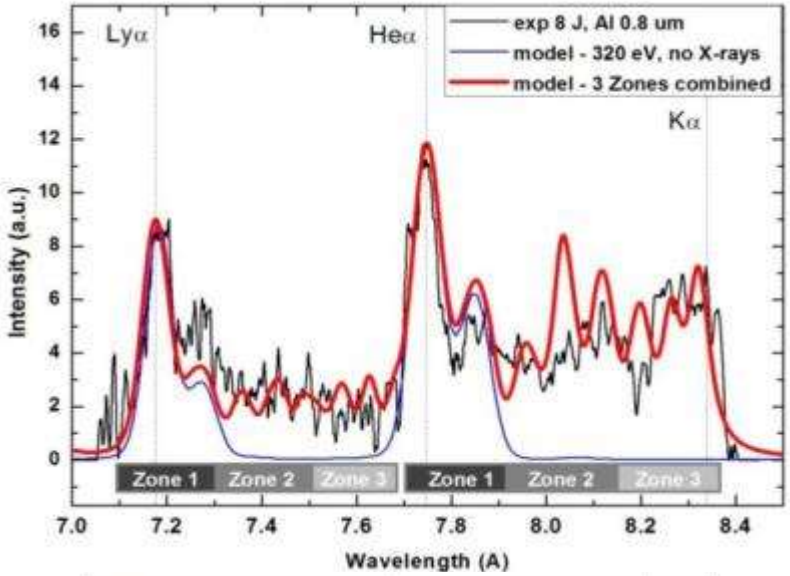


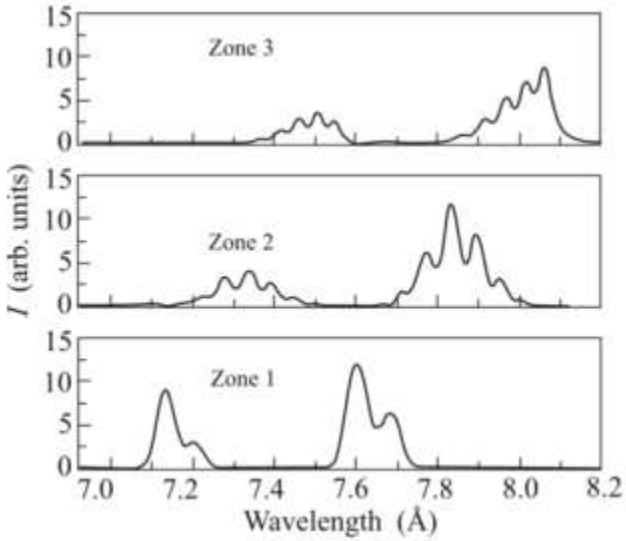
along electron trajectory
deep into the target

Experiment at PEARL facility

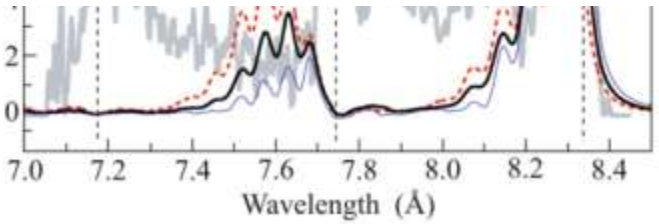


E = 10 J, τ = 60 fs, d_{foc} = 6 um, I = 4e20 W/cm2



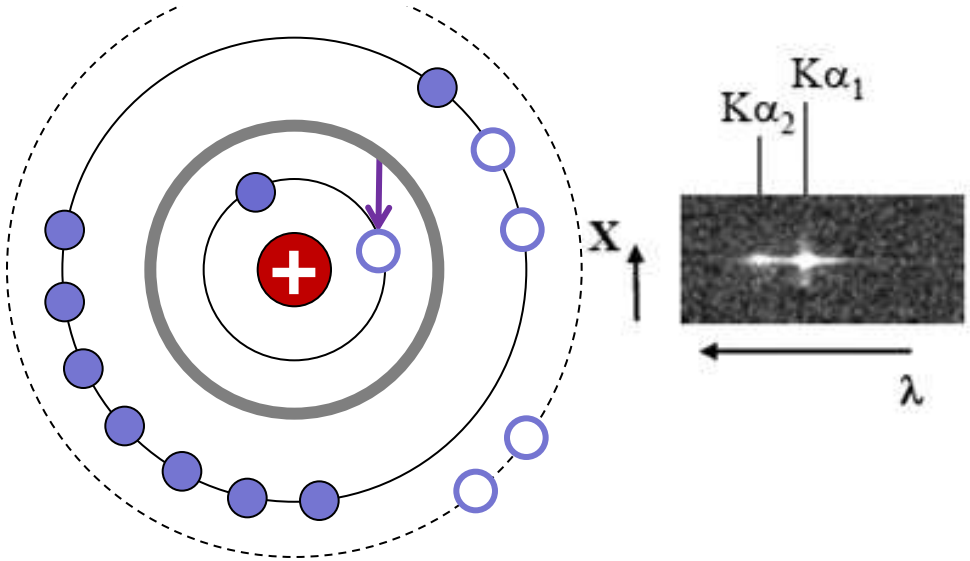


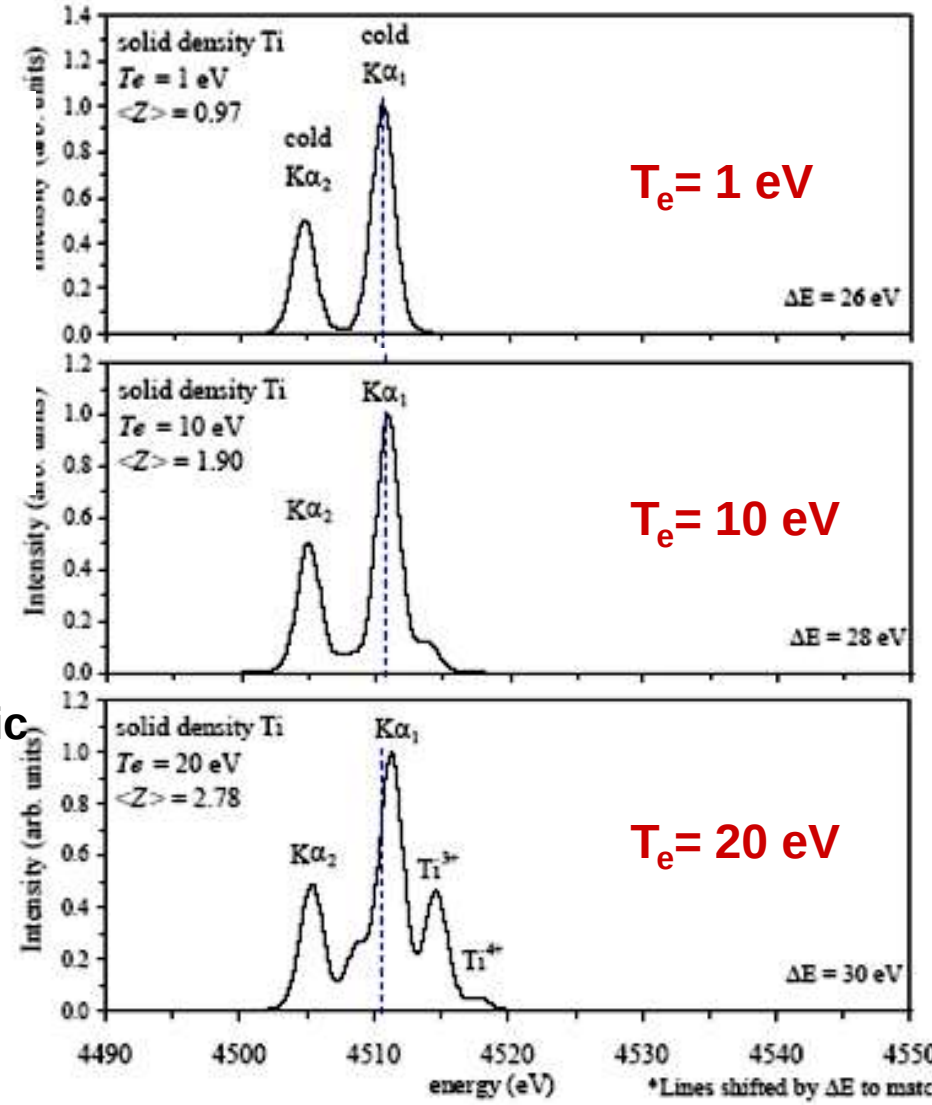
Zone	1	2	3
N_e, cm^{-3}	1.7×10^{22}	3×10^{23}	3×10^{23}
T_e, eV	315	60	5
T_r, keV	–	1.5	1.2



X-ray specs diagnostic capabilities

Satellites to "cold" Kα-line:





As the temperature of the solid increases, M/N-shells of atoms ionize and characteristic K-shell lines shift to higher energies.

For Ti - removing 4s electrons produces a shift of only ~ 1 eV, while removing M-shell 3l electrons produces a ~4 eV shift.

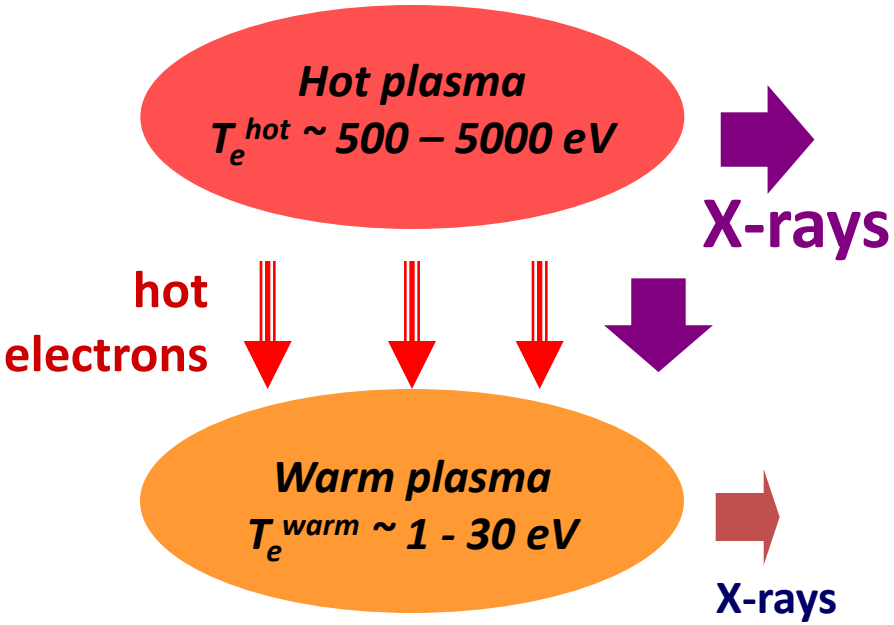
Spectral resolution of $\delta\lambda/\lambda \sim 3000 \div 5000$ is in demand.

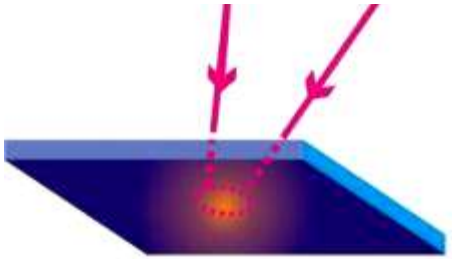
To create K-shell vacancy is not an issue for high intensity laser plasma due to a high yield of fast electrons

WDM studies using optical lasers – principle and setup

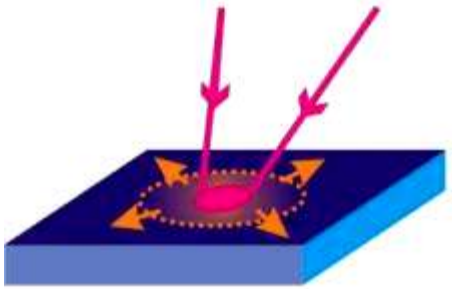
Hot plasma (T_e ~ 1 keV), commonly in laser focus

WDM – (T_e ~ 10-100 eV, N_e~10^{23} cm^{-3})

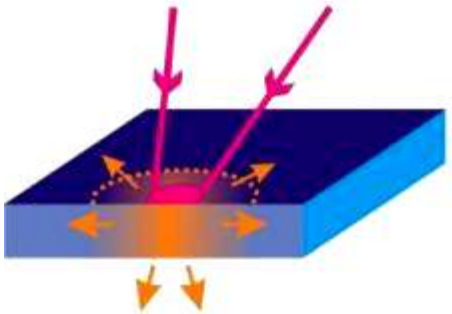




rear side of thin foil



vicinity of hot plasma
at front side

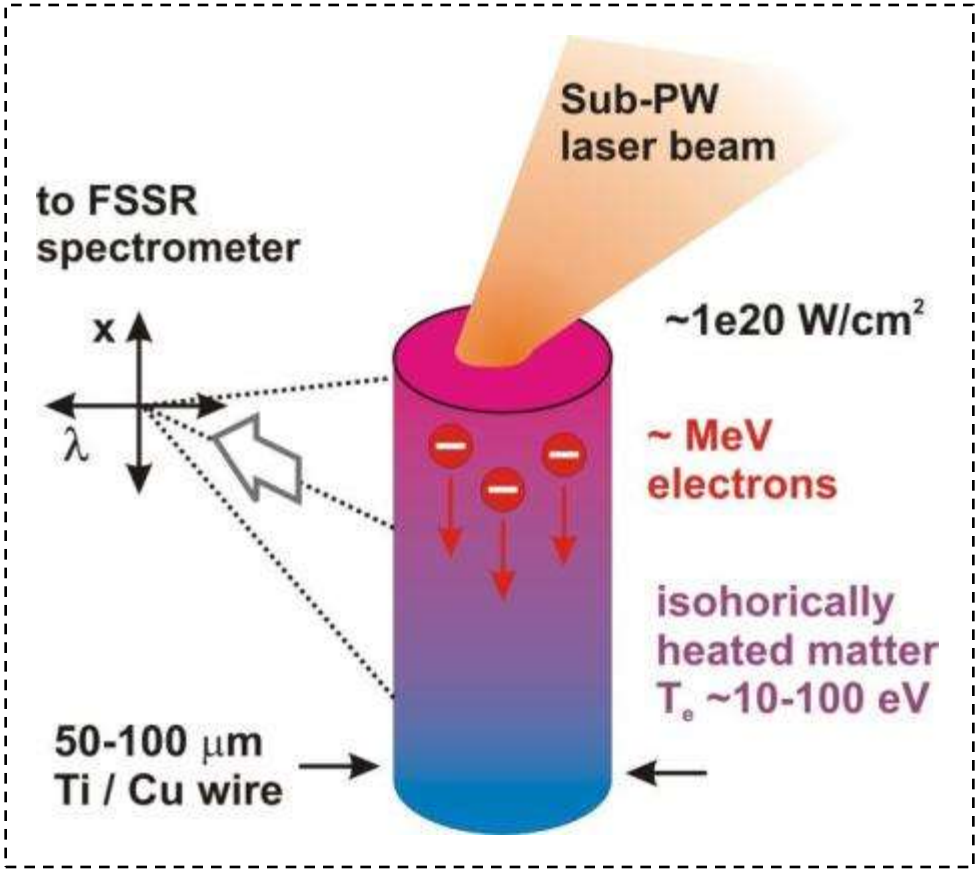


along electron trajectory
deep into the target

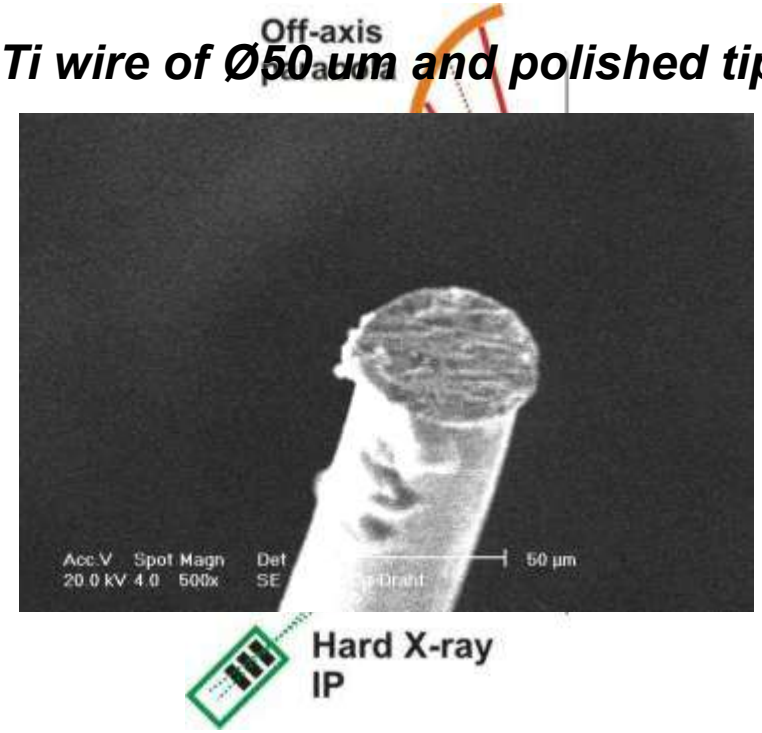
By means of X-ray spectroscopy
T_e^{warm} can be determined when over 10 eV.

Spatial resolution is of crucial importance.

Particular realization – free standing wire target



Ti wire of Ø50 um and polished tip

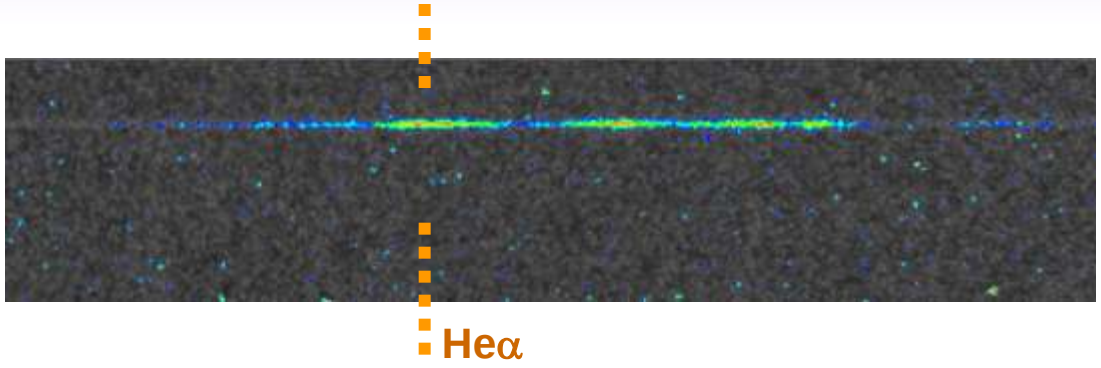


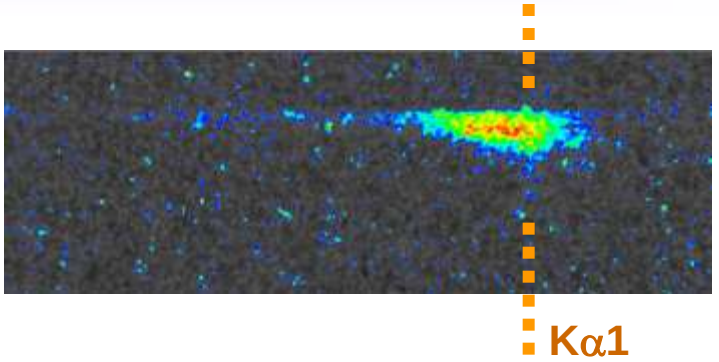


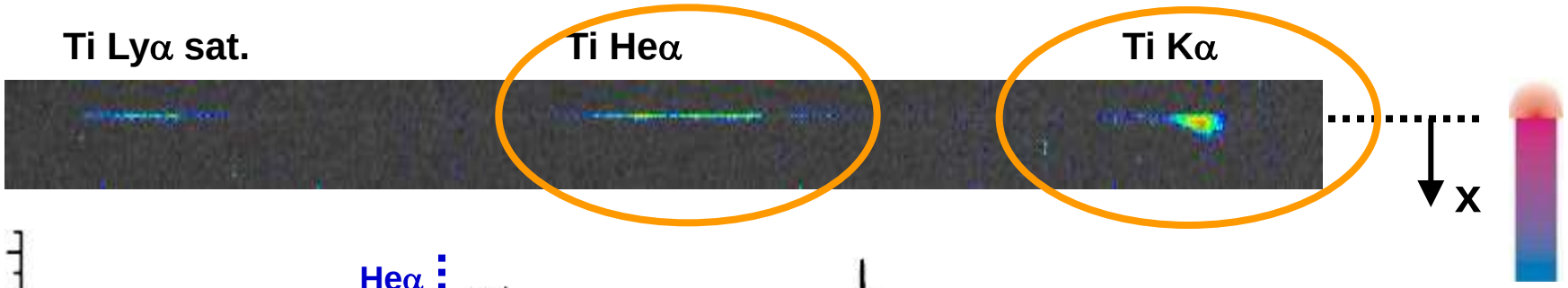
PHELIX laser beam used:

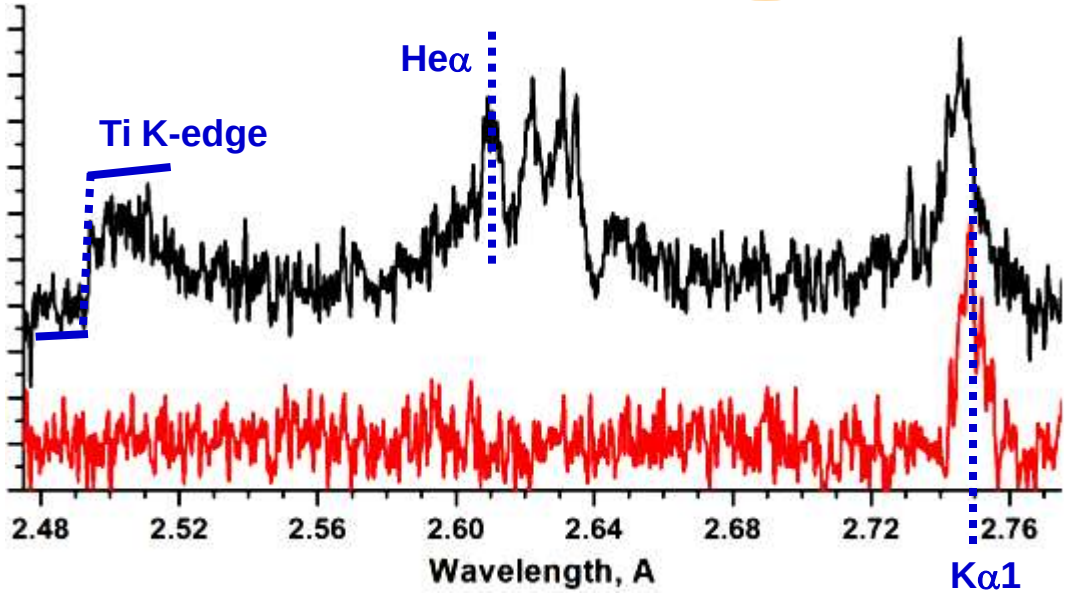
- **200 J** on target, **1 ps** pulse duration
- focused by off-axis parabola to **~5 um** spot Ø
- on polished tip of the wire
- high pulse contrast of 1e6-**1e10** on demand

Experimental results - references



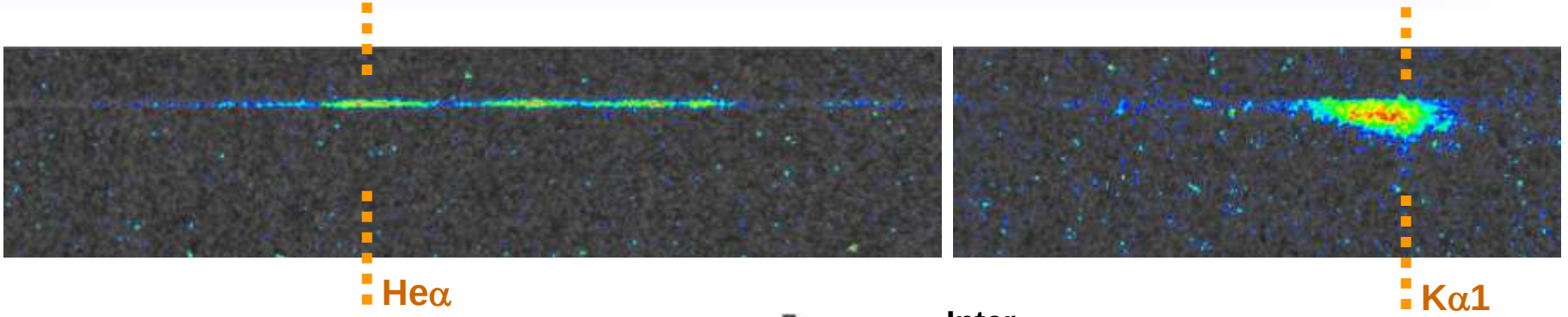


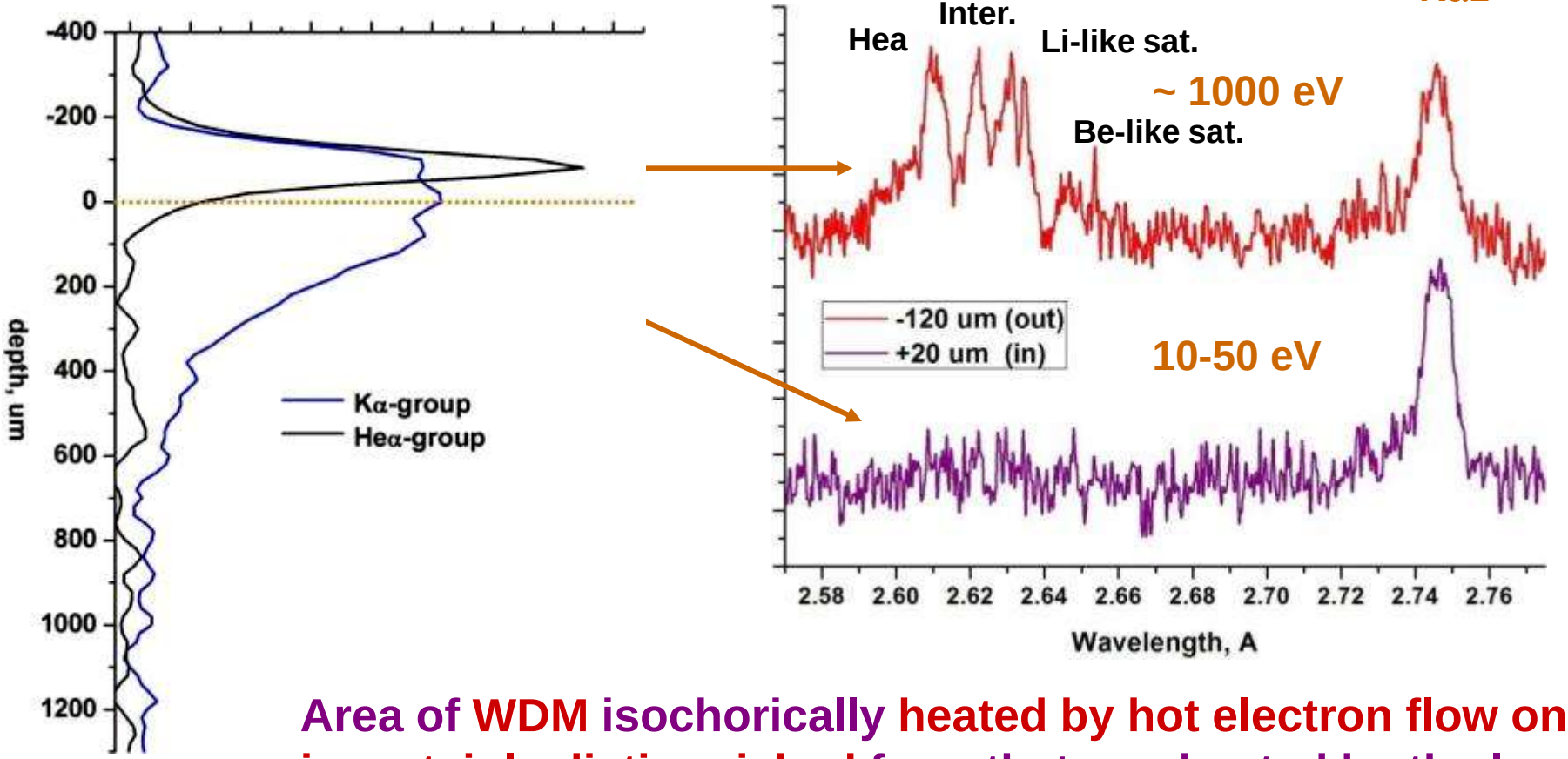




Reliable and precise references for spectral dispersion: K-edge of absorption, neutral Kα1. Positions of Kα-satellites can be measured with 1 mÅ precision

Experimental results - references



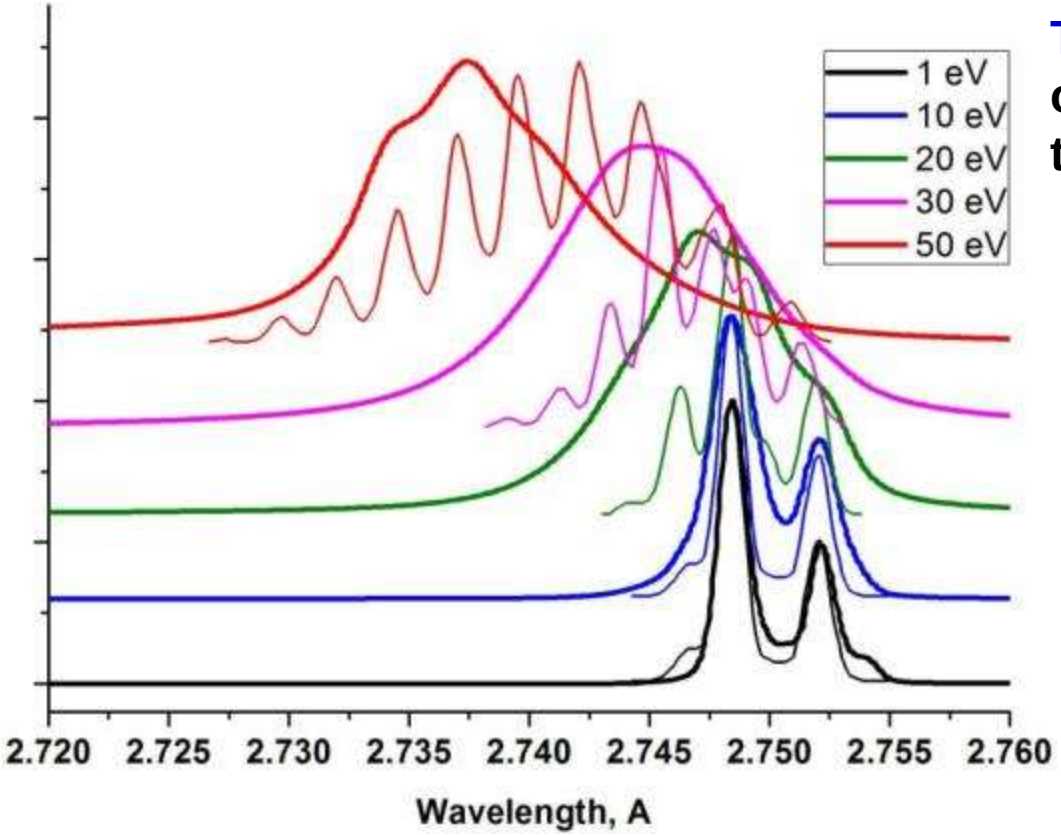


Area of WDM isochorically heated by hot electron flow only is certainly distinguished from that one heated by the laser

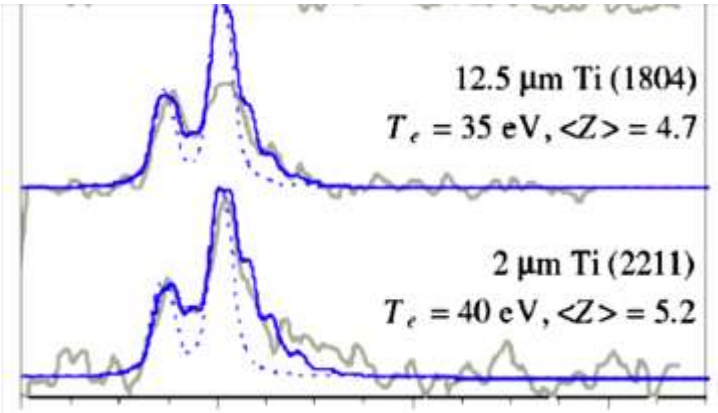
Spectra simulation issues

First spectra simulations for WDM radiation applied configuration-averaged MUZE model // S.B. Hansen et al., *PRE* 72, 036408 (2005)

Several synthetic DL/CA approaches are developed, particularly with a combination of NLTE FLYCHK and FLYSPEC codes // M. Murillo et al. PRE 87, 063113 (2013)

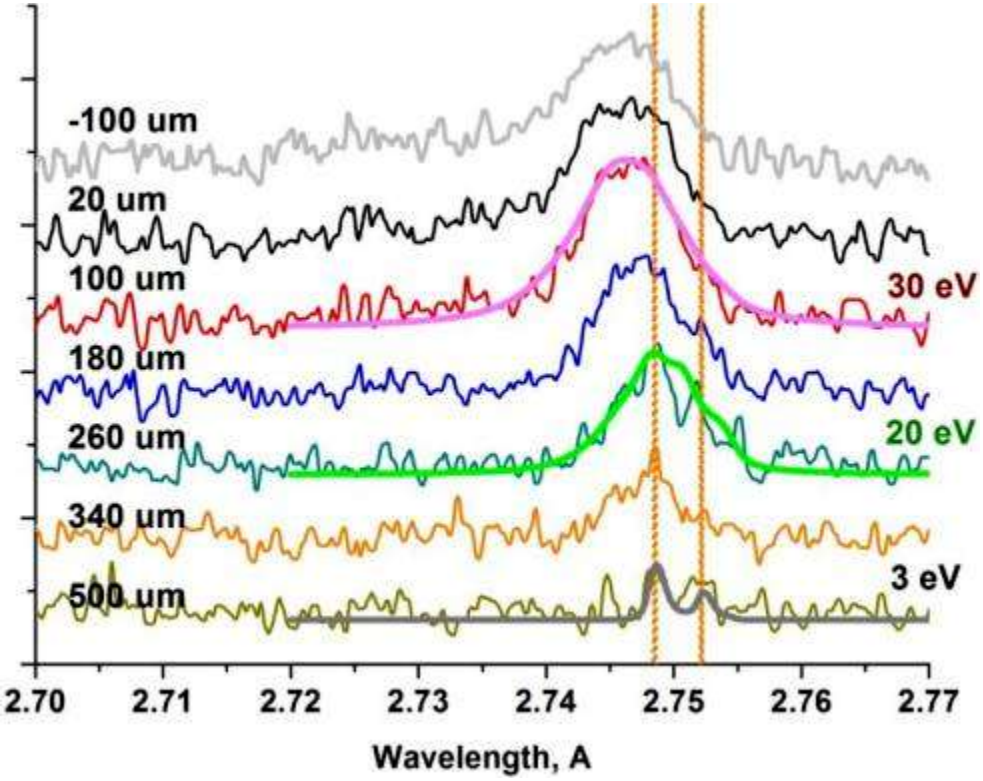


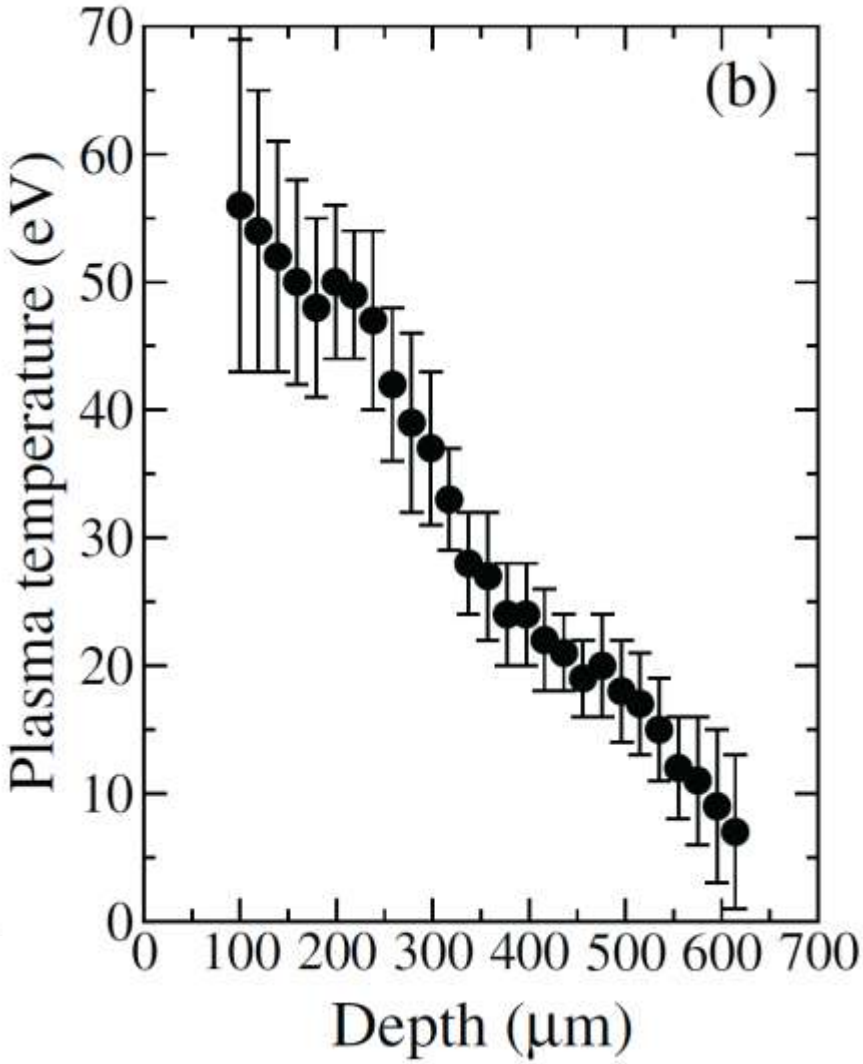
T_e values obtained ago with use of simplified models overestimate the actual heating of WDM ~ 1.5-2 times.



Experimental results – T_e measured

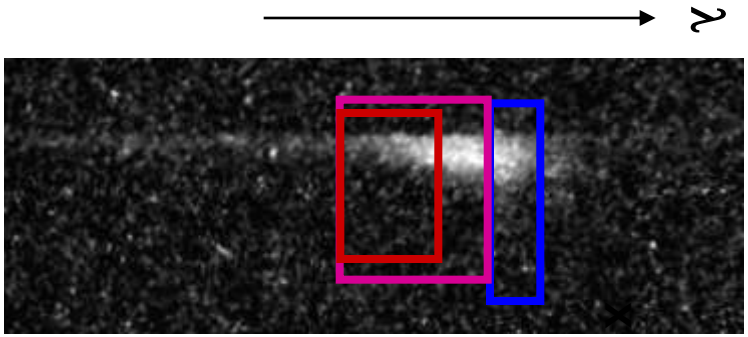
0.5 ps, 200 J, 6 um focusØ
I ~ 5e20 W/cm^2

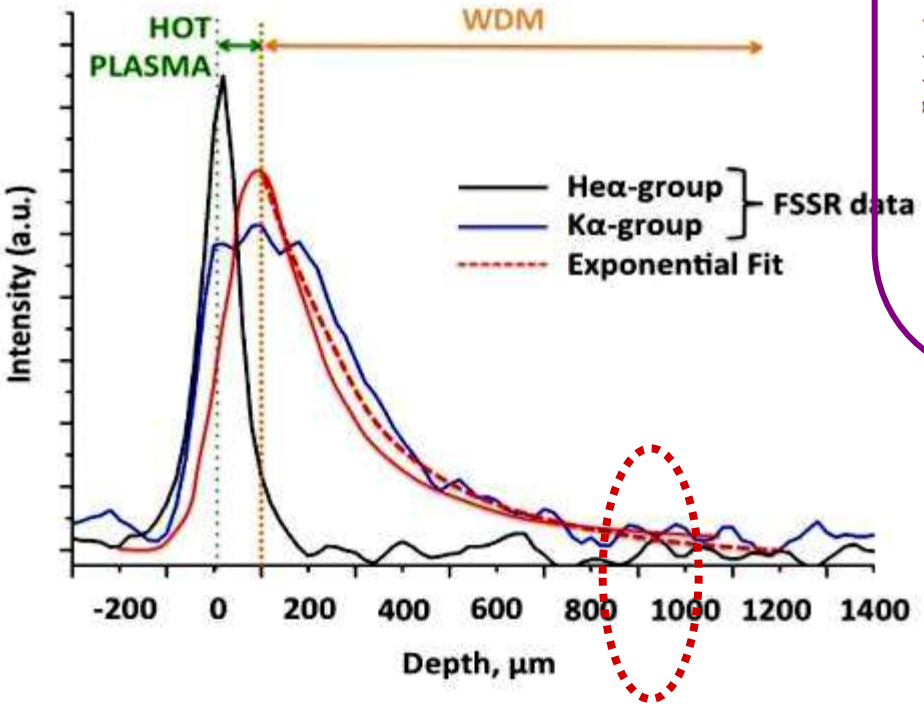




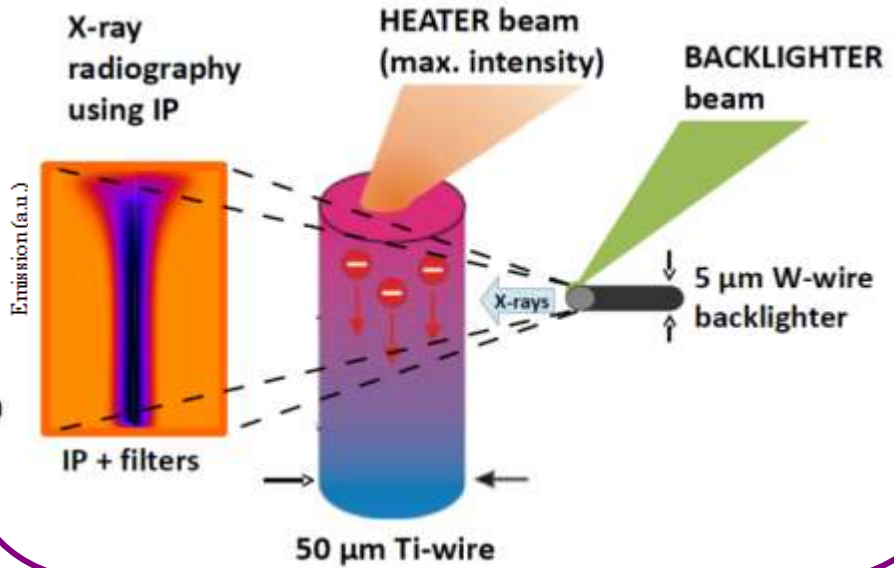
In both cases highest T_e achieved by isochoric heating is of ~50 eV, which is in general below expectations

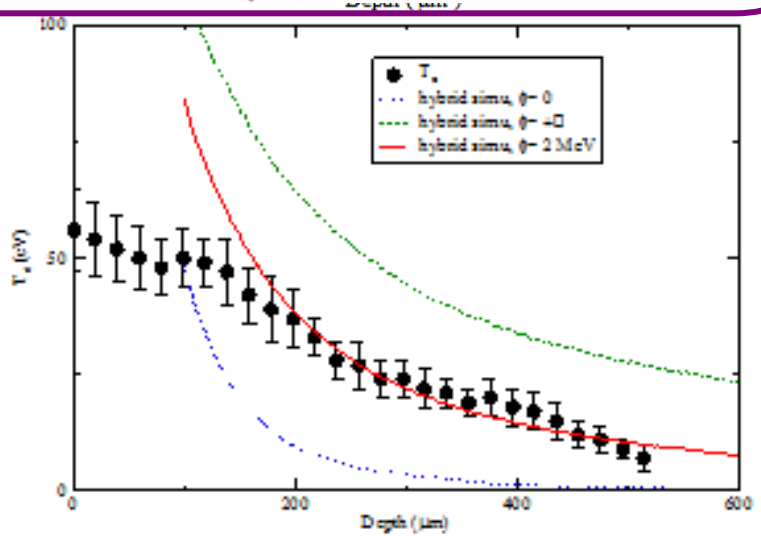
X-ray emission spatial range and hybrid simulations





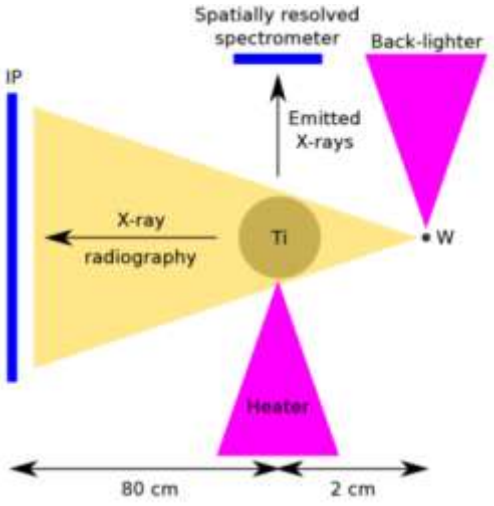
To reveal the correct potential barrier on the wire edges we have to spot the expanding wire shape in experiment

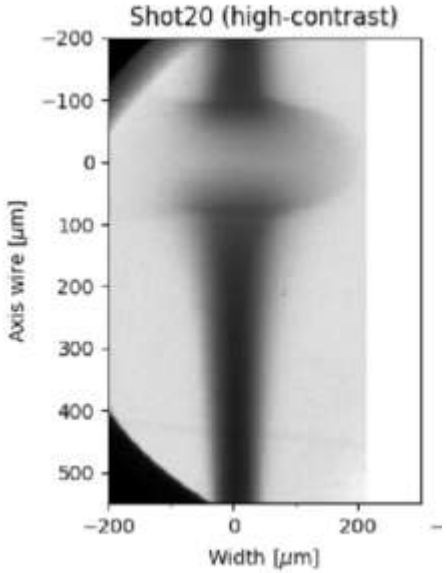


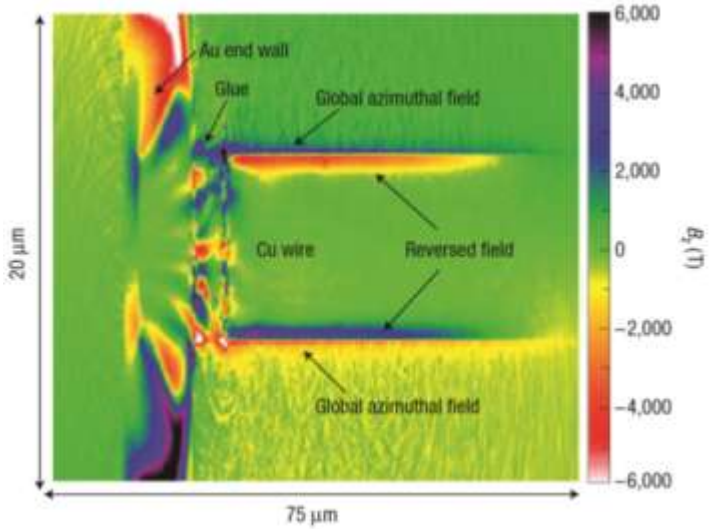


Kα is emitted not far then ~1 mm deep: 3D simulation of fast electron currents in mass-limited targets is needed

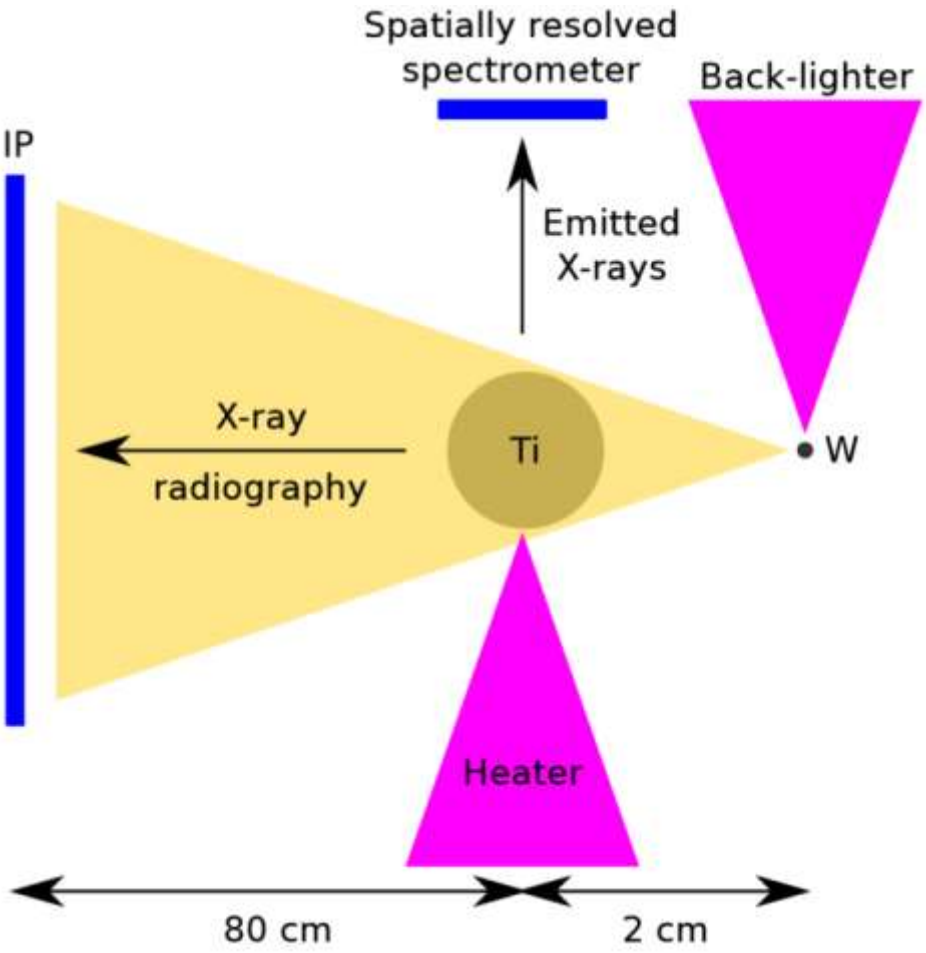
X-ray radiography to measure plasma density and hydrodynamics of WDM

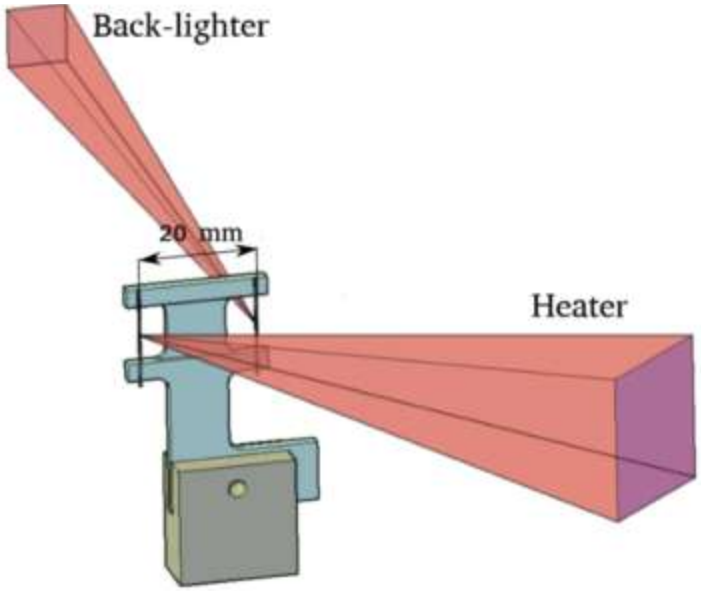






X-ray radiography approach





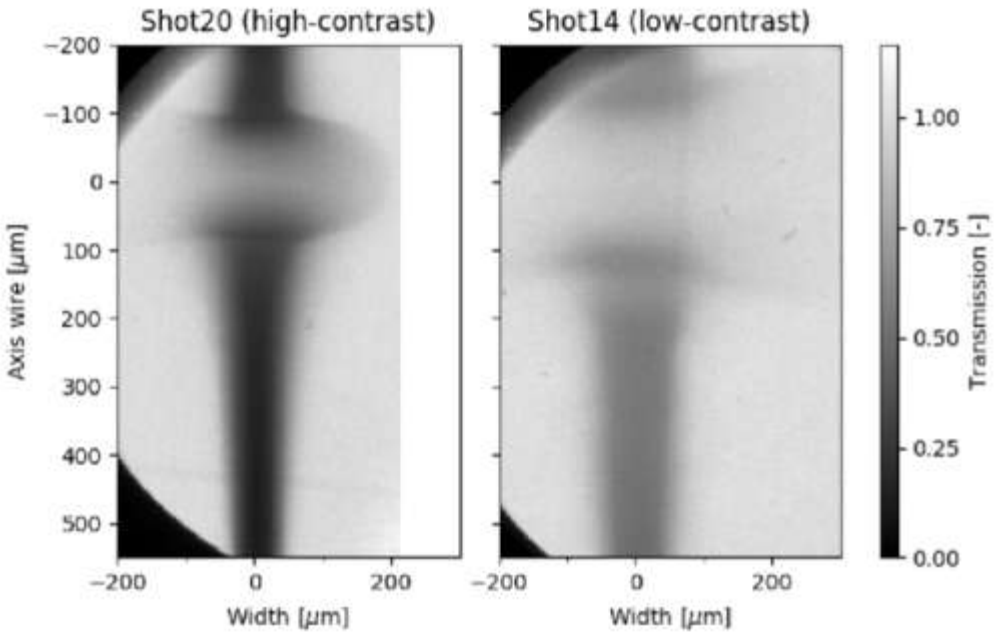
PHELiX @ GSI:

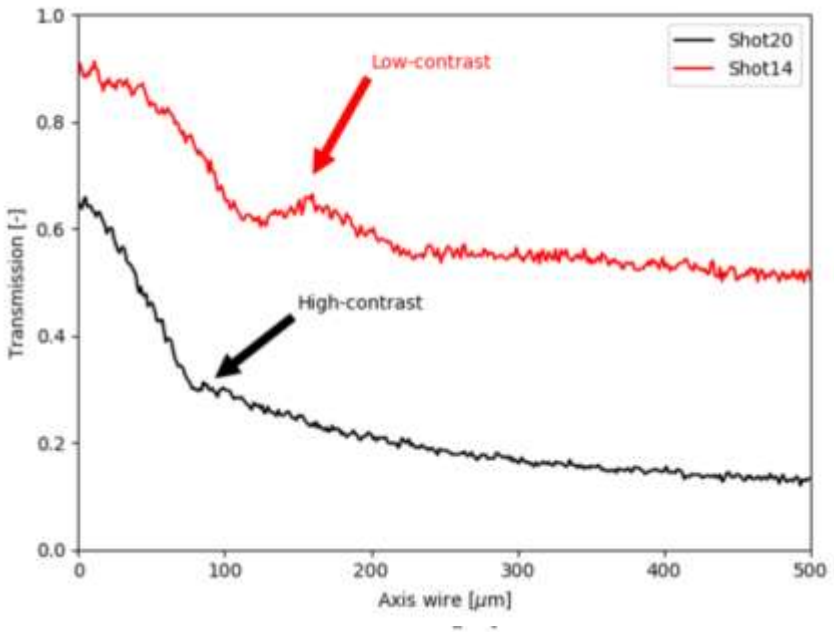
Beams parameters	Heater	Back-lighter
λ [nm]	1064	1064
Δt [ps]	0.5	0.5
Pulse energy [J]	50	50
Intensity [W/cm^2]	$\sim 10^{20}$	$\sim 10^{20}$

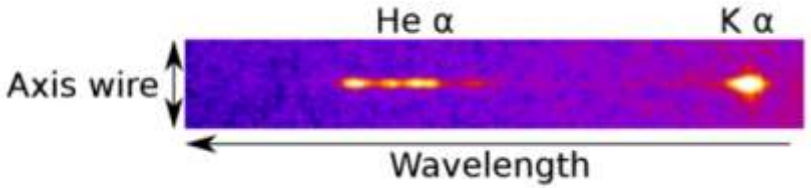
Targets:

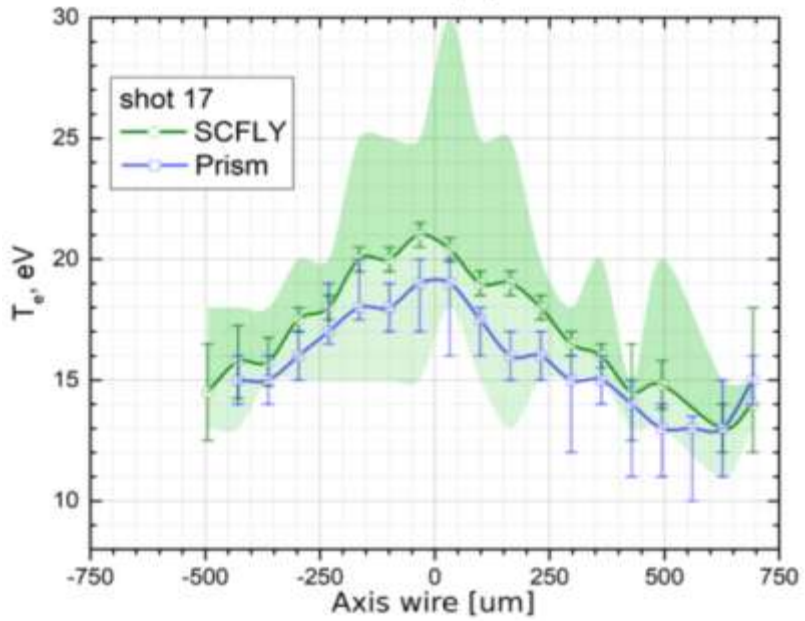
Parameters	Heater	Back-lighter
Type	wire	wire
Diameter [μm]	50	5
Compound	Ti	W

X-ray radiography data for wire target

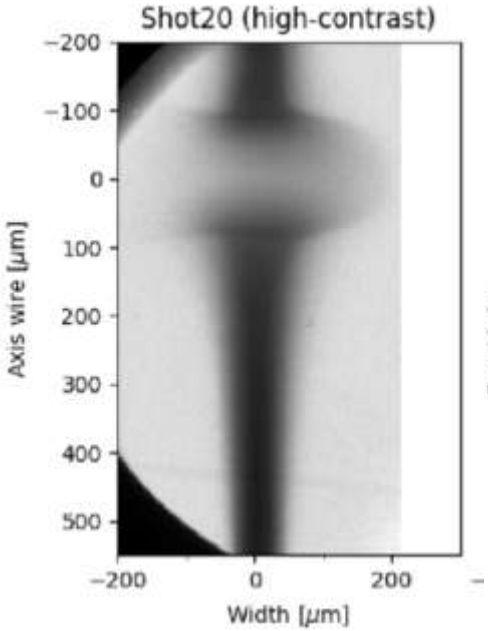


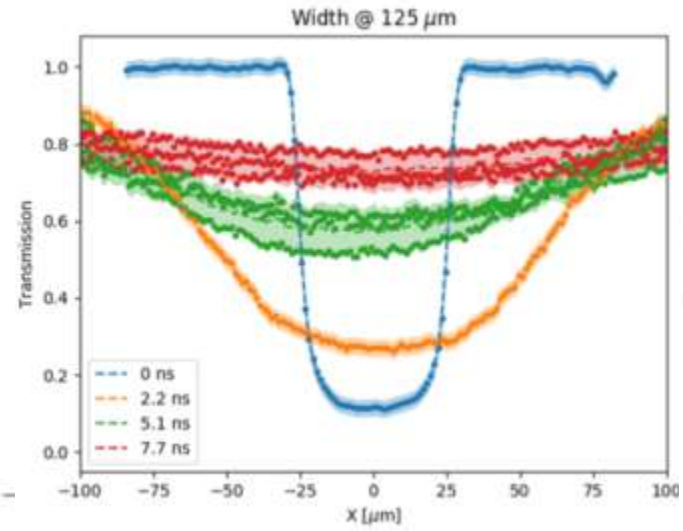


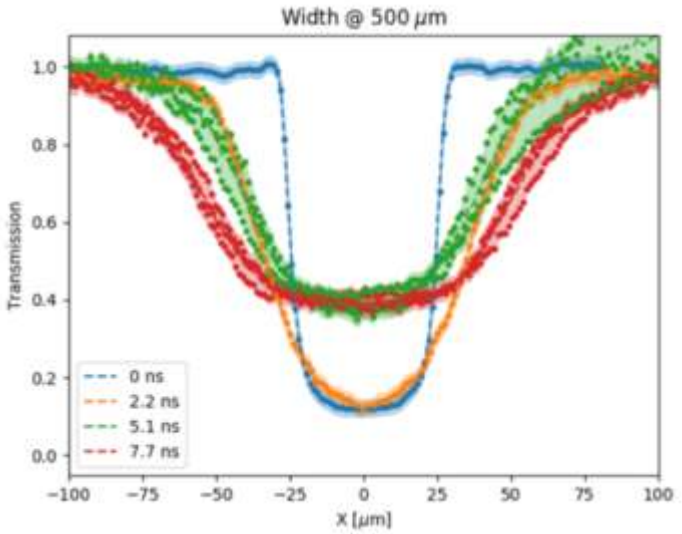




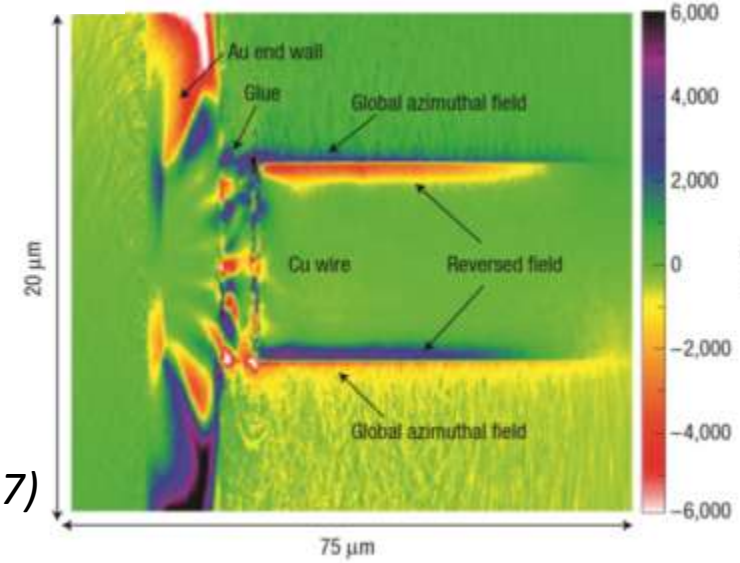
Early expansion, inhomogeneous heating / e-currents

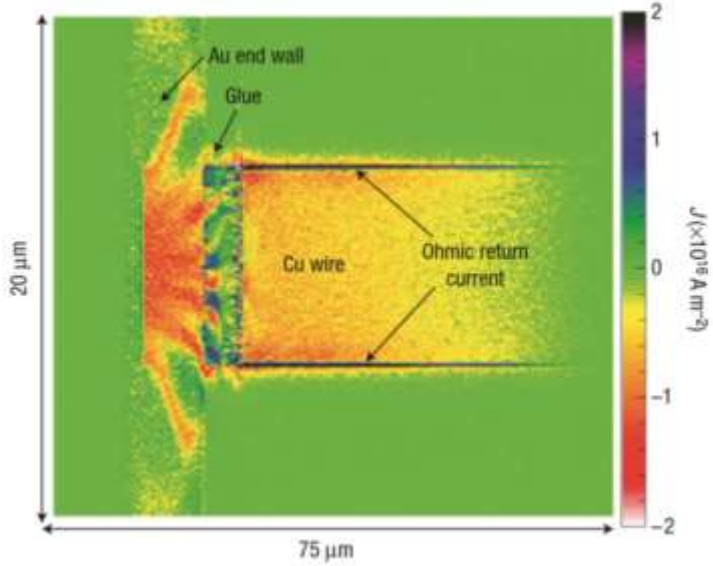






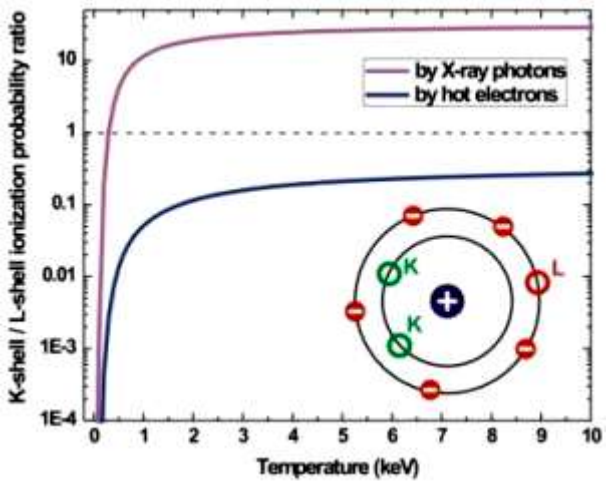
2.2 ns delay

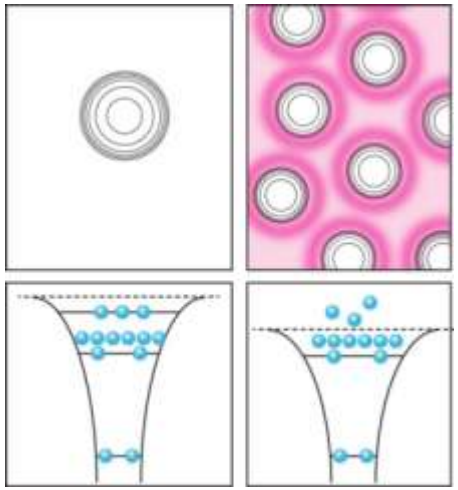




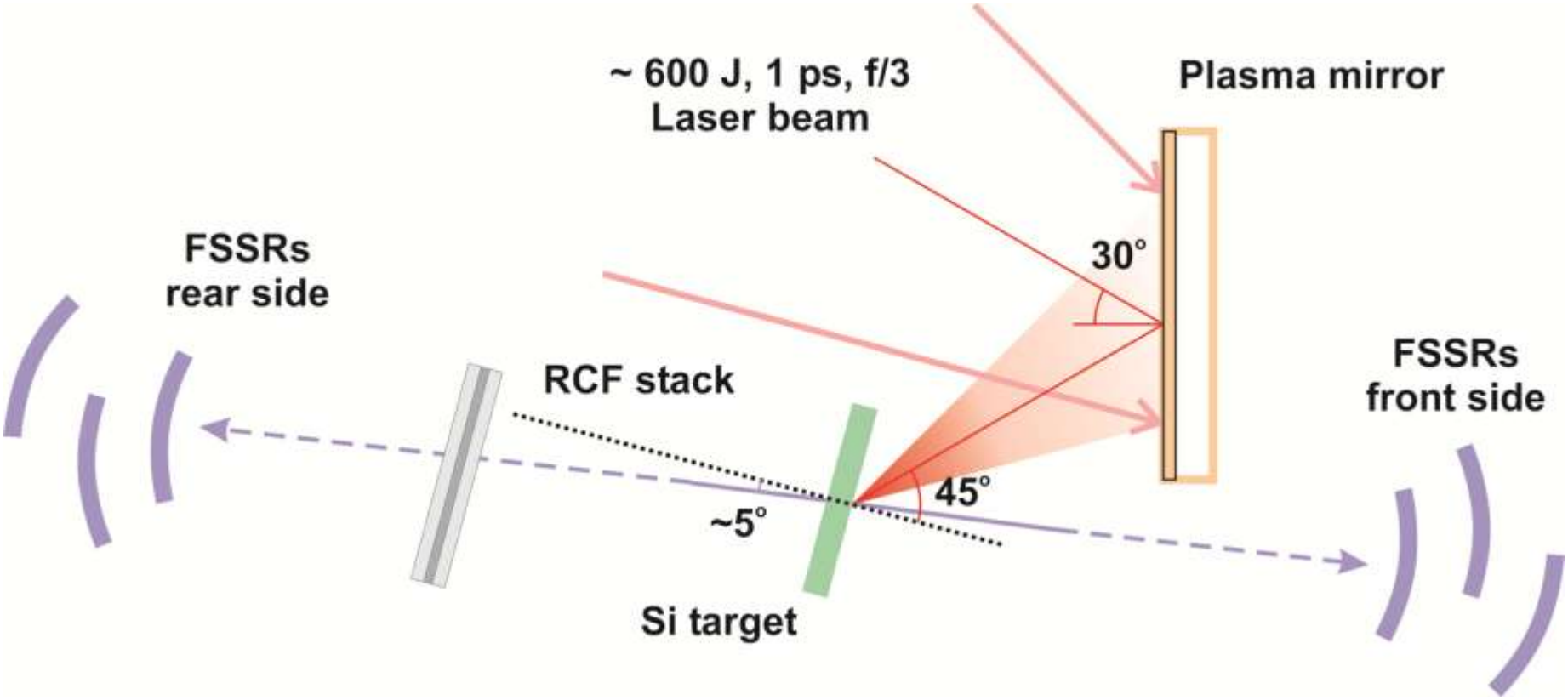
// J. Green et al. Nature Phys 3 (2007)

Exotic atomic states and solid density effects





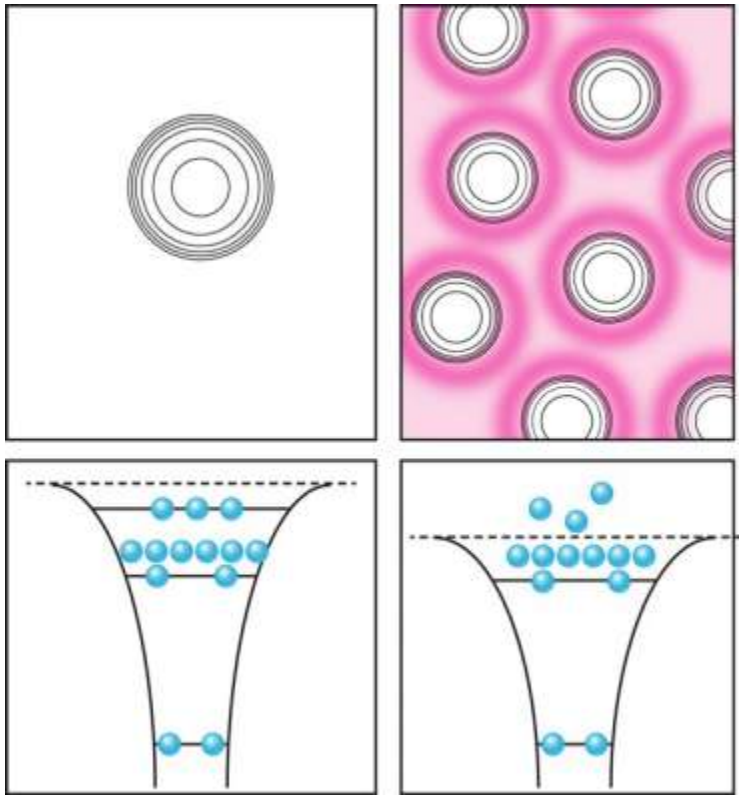
X-ray spectroscopy studies of solid-density PW plasma



Experiment @ Vulcan PW: 5e20 W/cm2, 600J @1ps,
OPCPA + plasma mirror to ensure ultra high pulse contrast

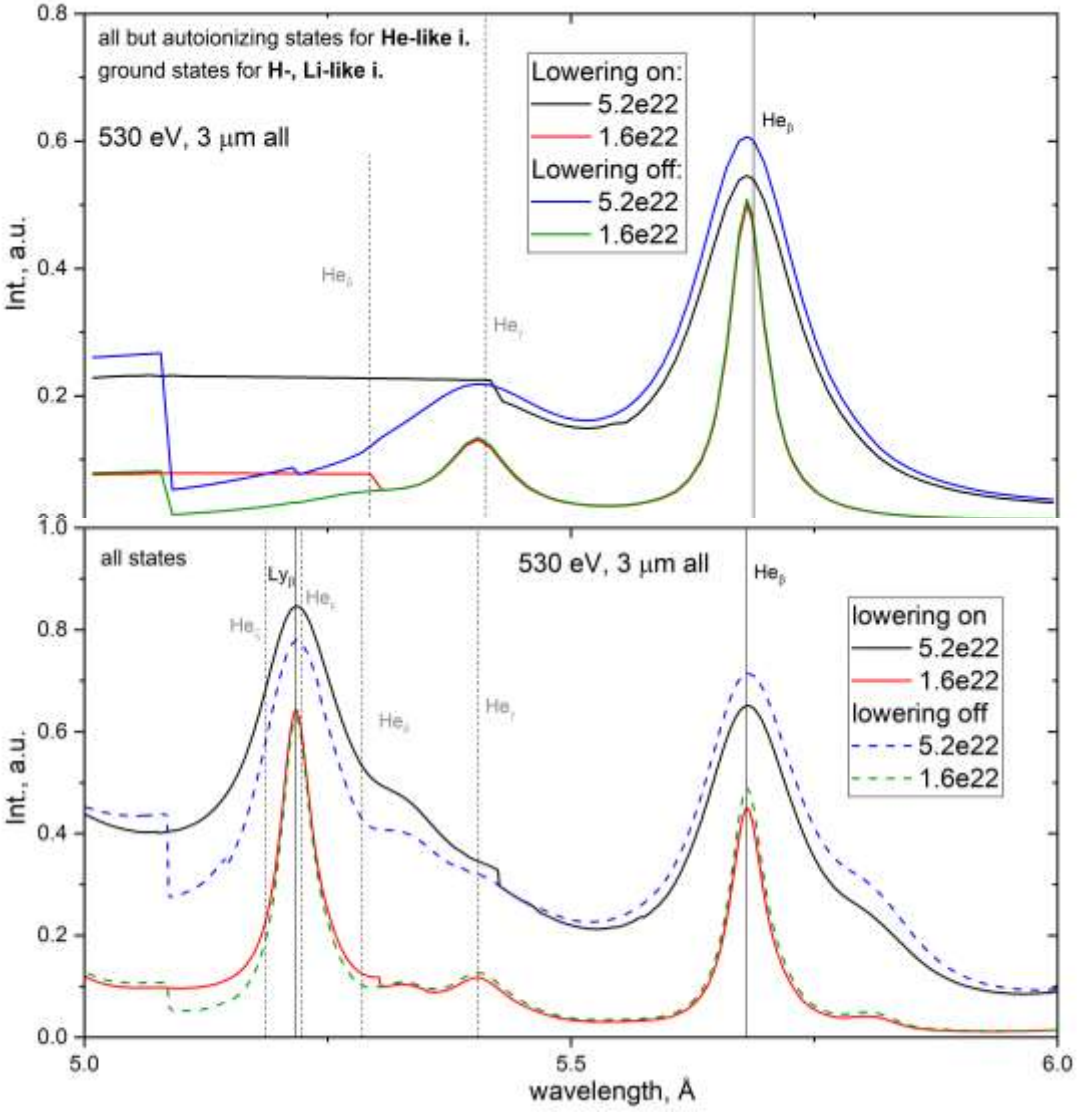
Combination of 3 FSSRs at each side aligned at merged bands in order to cross-calibrate and combine the spectra.

Effect of ionization potential depression

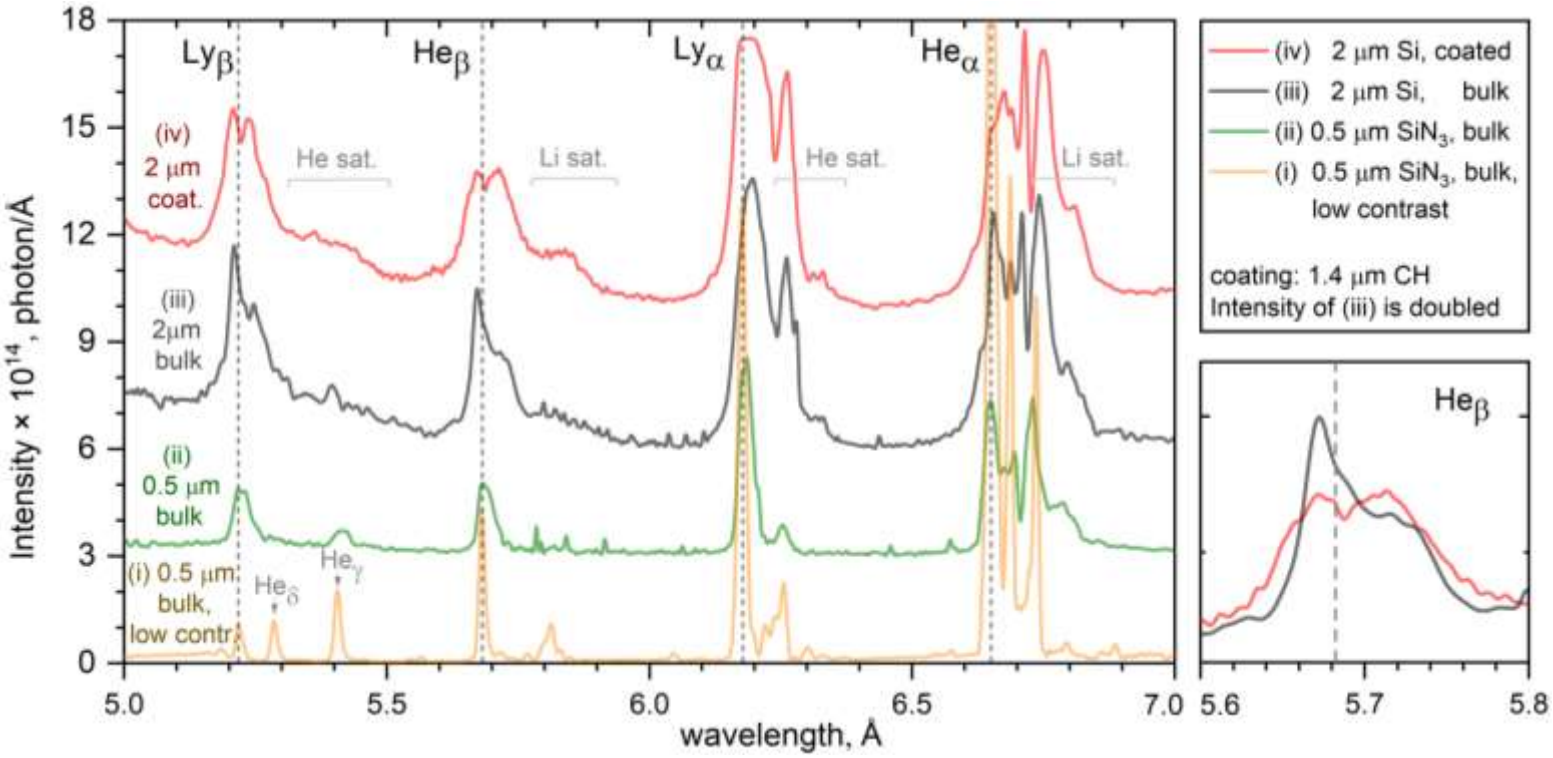


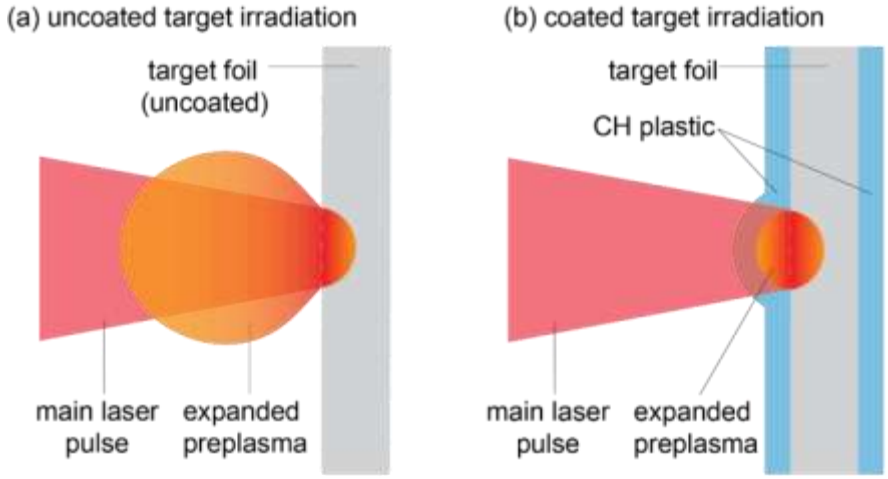
Hummer and Mihalas model for occupation probabilities // Astrophys J., 331 (1988)

Spectra modeled by PrismSPECT code – considering and excluding IPD effect

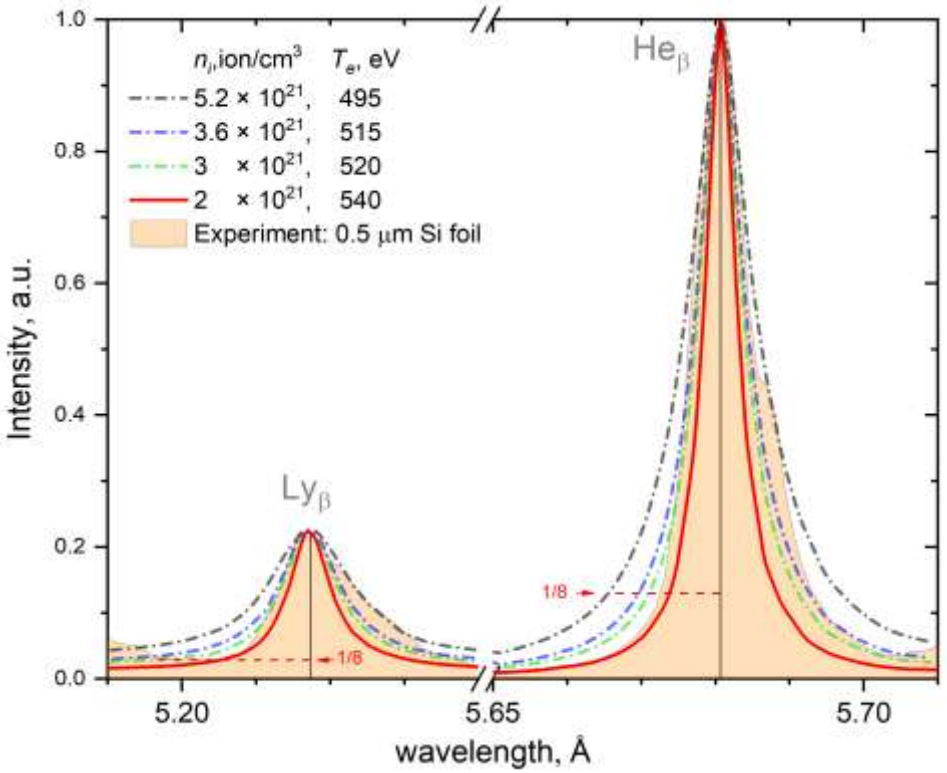


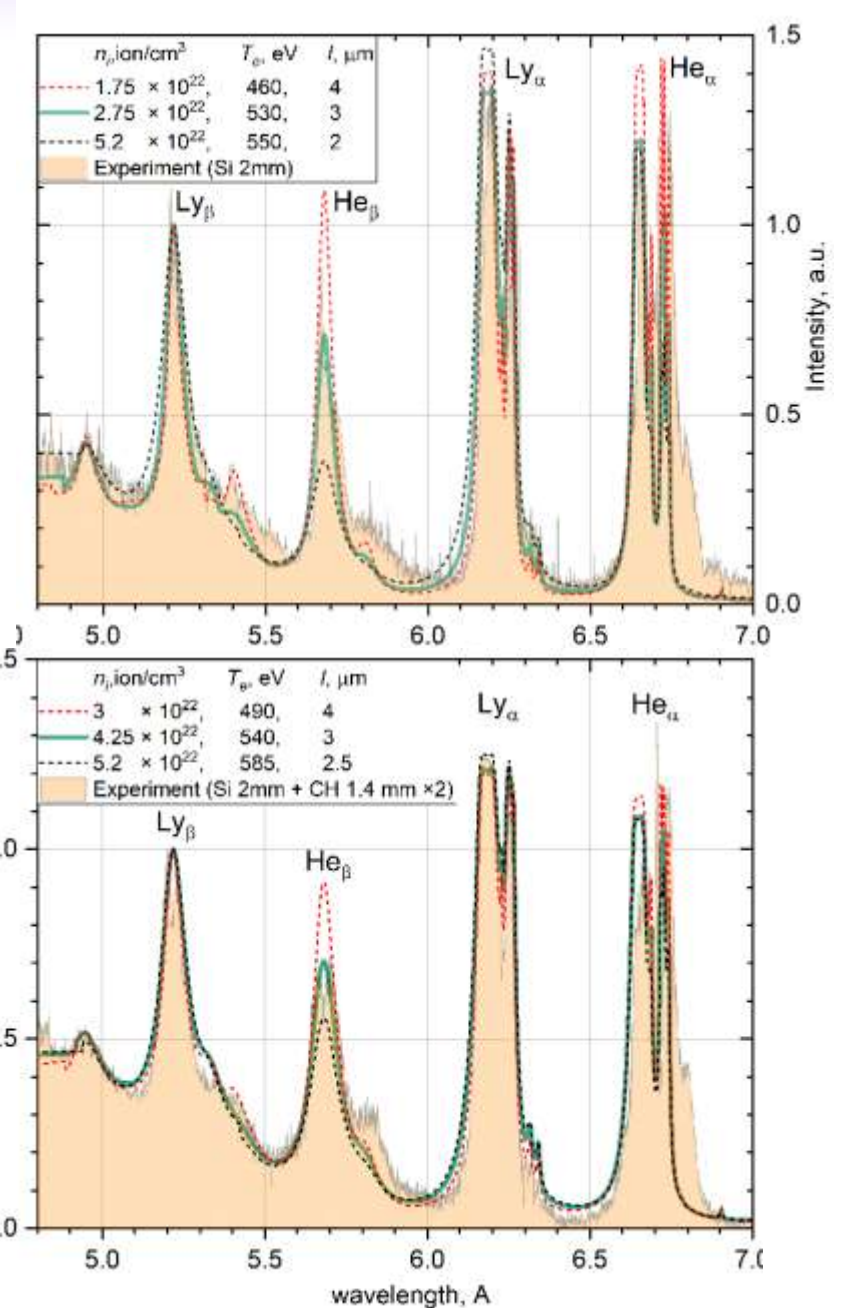
Spectral features depending on type of the target





Stark broadening consideration





SiN3 0.5 um foil, uncoated

Ni = 2(±0.5)E21 ion/cm^3

dE/dv ~ 1.5-2.5 × 10^6 J/cm^3

Si 2 um, uncoated

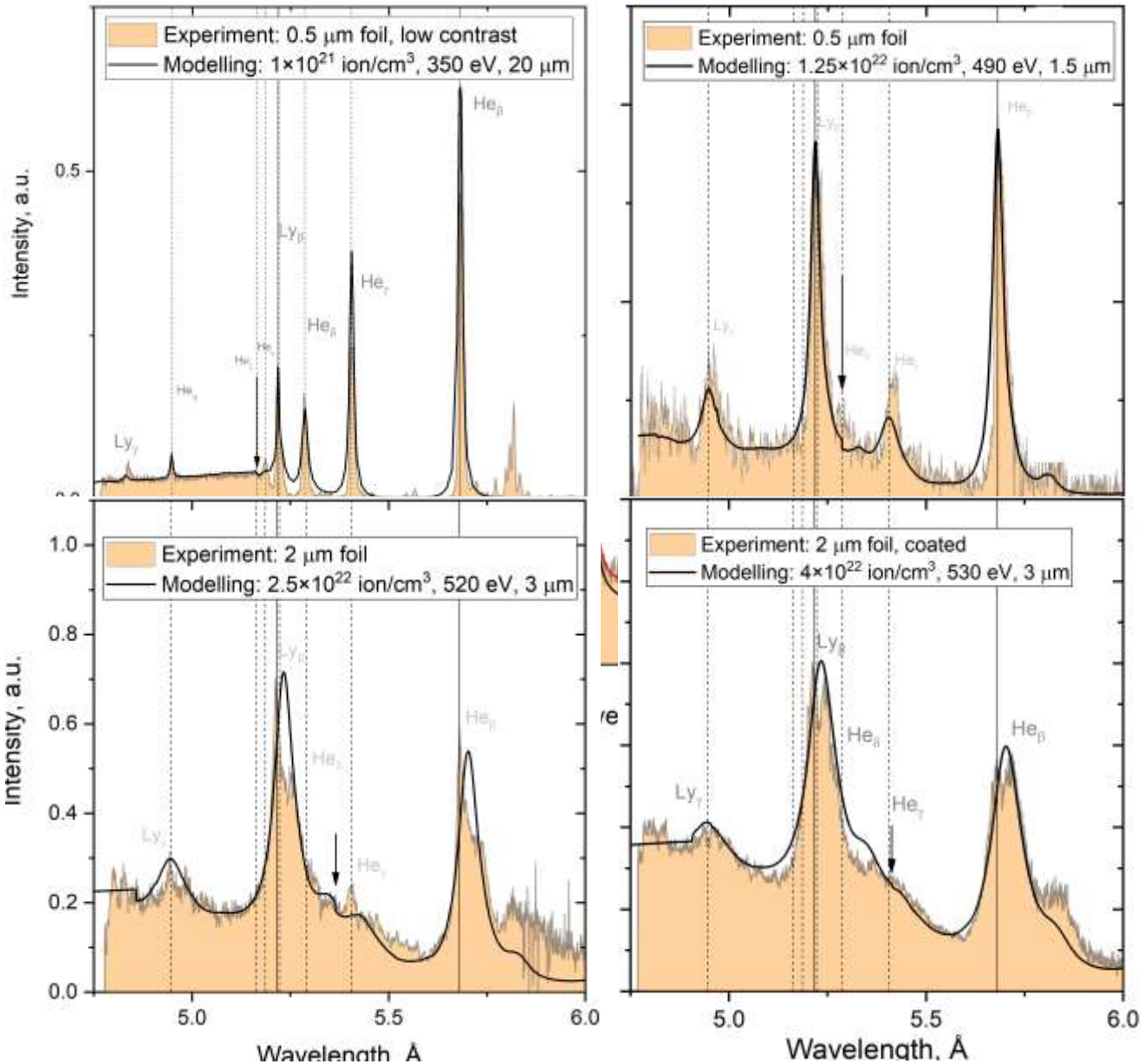
Ni = 2.8(±0.4)E22 ion/cm^3

Si 2 um coated with 1.4 um CH

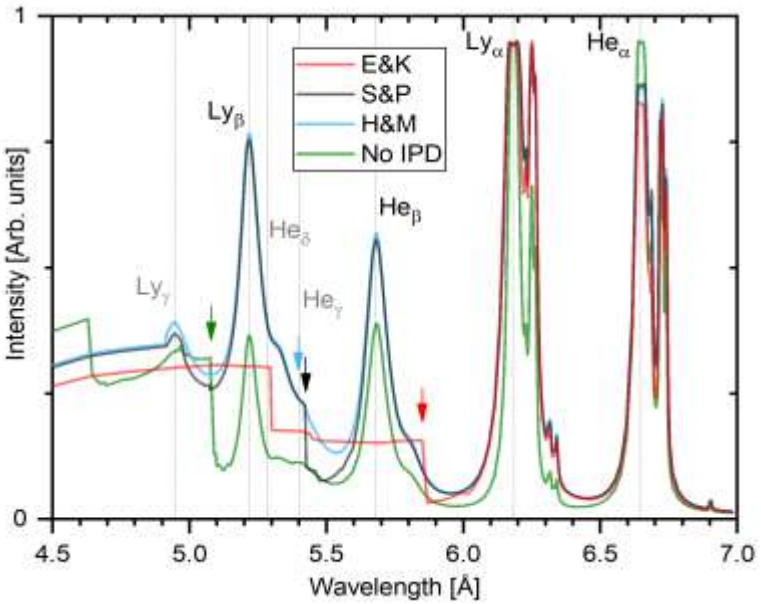
Ni = 4.2(±0.4)E22 ion/cm^3

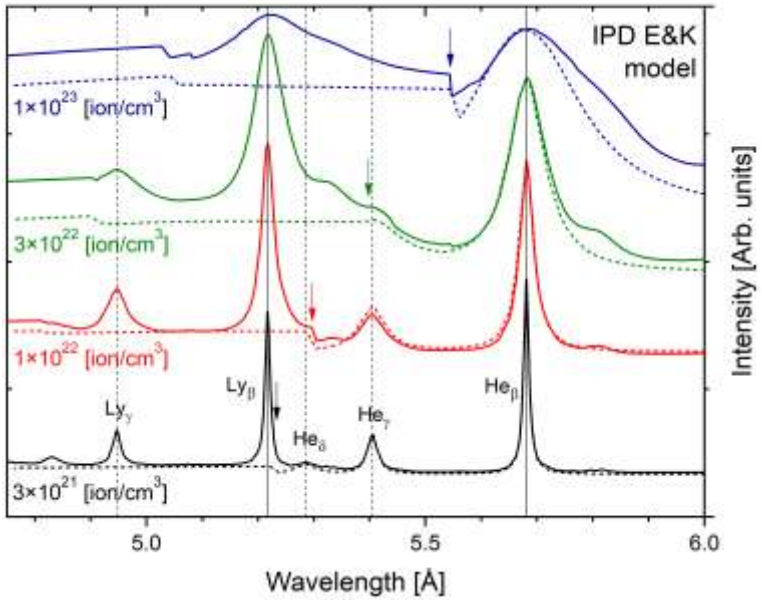
dE/dv ~ 5 × 10^7 J/cm^3

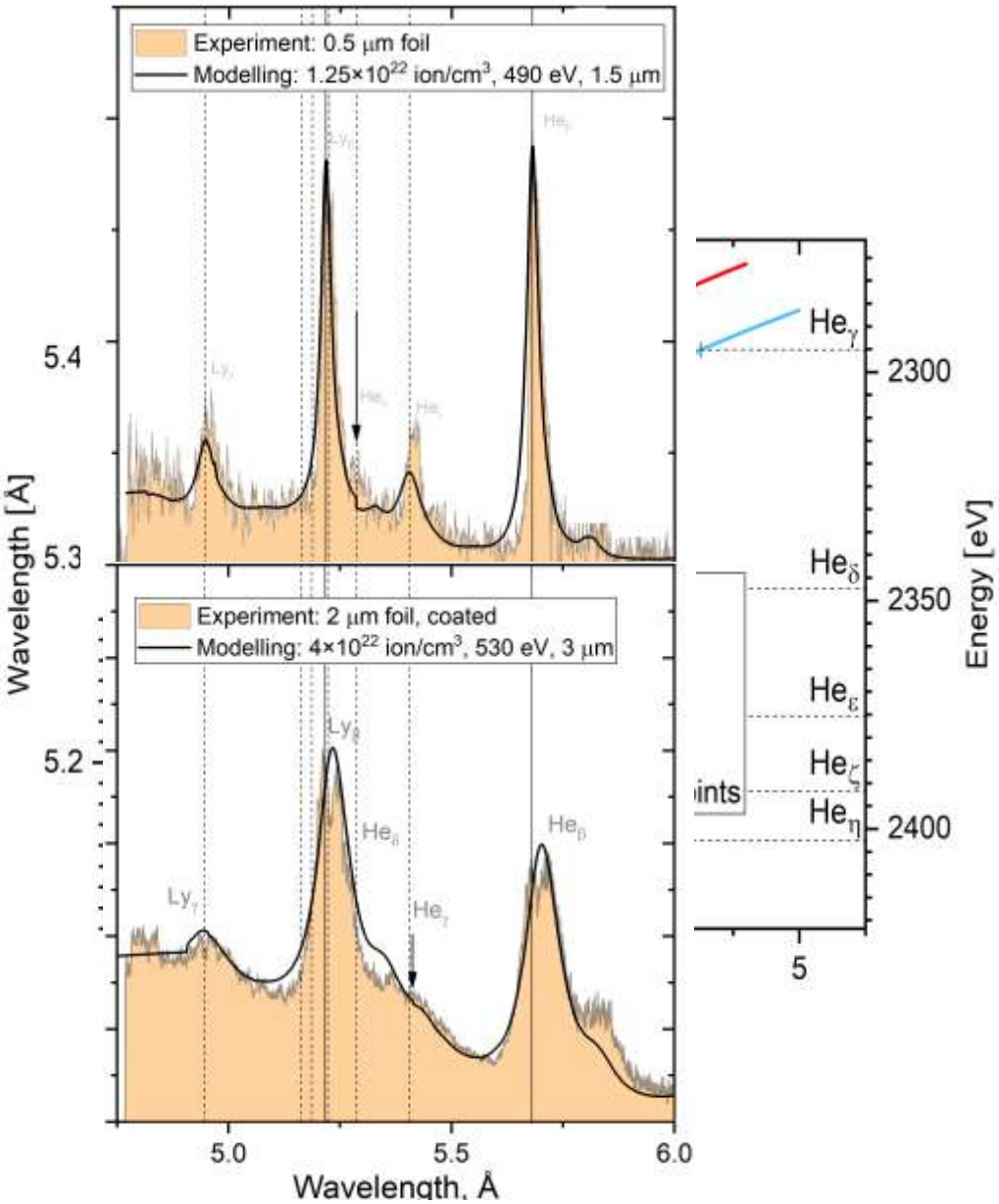
X-ray spectra depending on plasma density



Verifying ionization potential depression model







Radiation dominated matter

Radiation Dominated Regime of matter -
when plasma radiation dominates particle dynamics

// C.P. Ridgers *et al*. PRL **108**, 165006 (2012). L.L. Ji et al. PRL **112**, 145003 (2014), ….many

+ up to 30% of optical laser radiation could be transformed to *γ* -ray flash)

To reach RDR – the laser field should reach 1e23-1e24 W/cm^2 intensity ☹

Radiation Dominated Kinetic Regime -
when plasma radiation processes dominate atomic kinetics

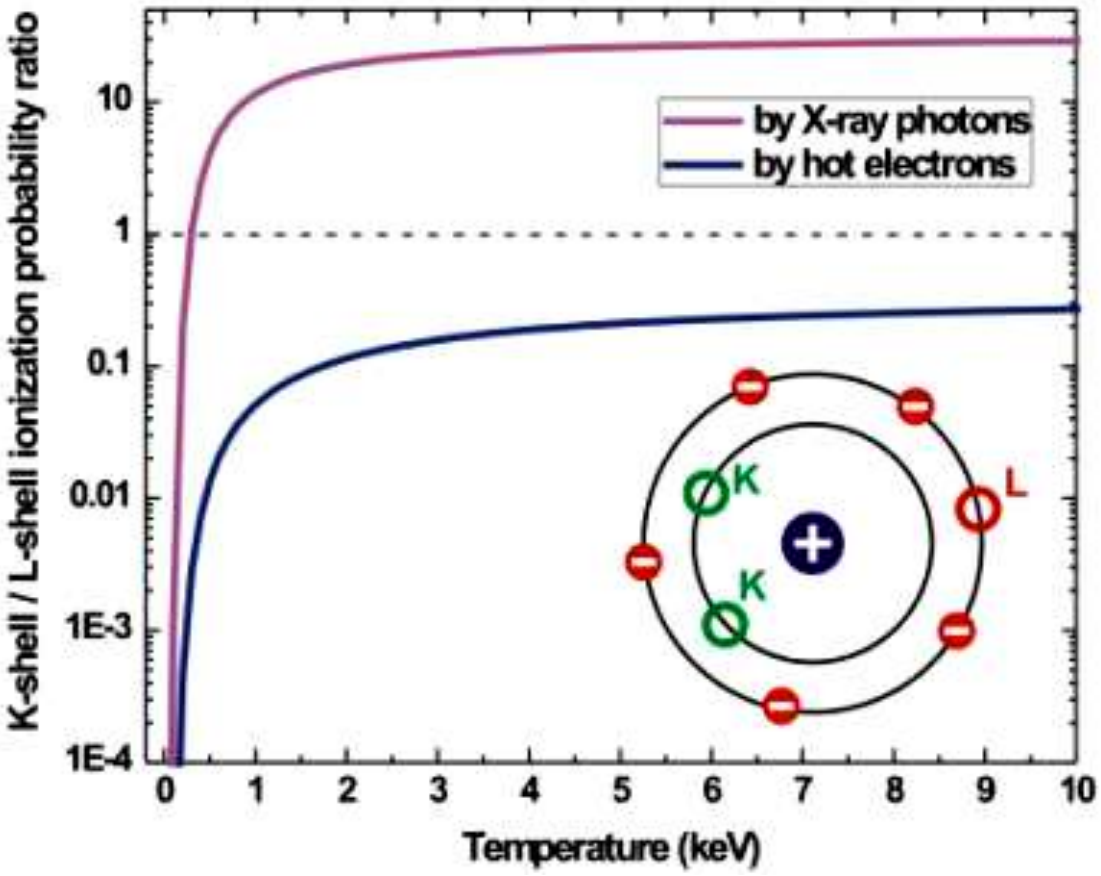
// J. Colgan *et al.*, PRL **110**, 125001 (2013)

To reach RDKR – the laser field of ~ 1e21 W/cm^2 should be enough ☺

Plasma produced by intense XFEL beam is a good example of RDKR.

High-temperature plasma under external intense X-rays

X-Ray photons preferentially ionize inner shells rather than outer shells

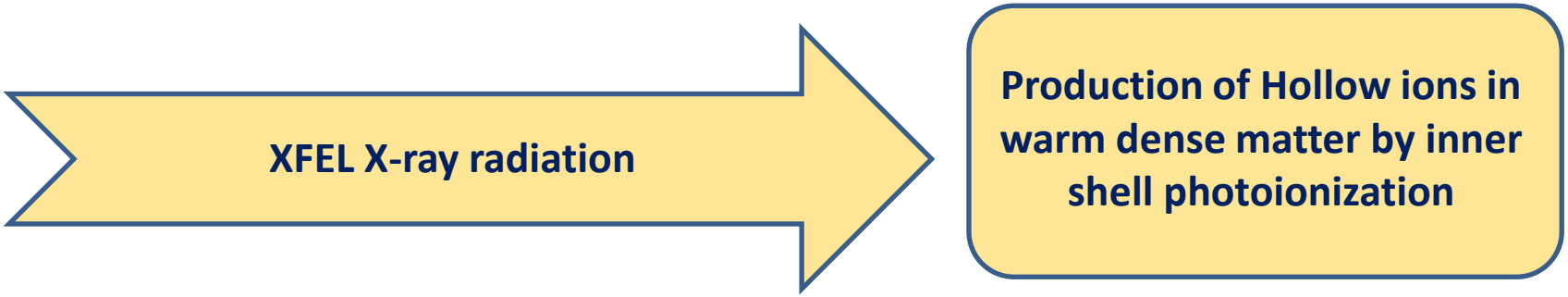


Exotic hollow atom states – the states with a number of K and/or L shell vacancies, but still populated outer shells

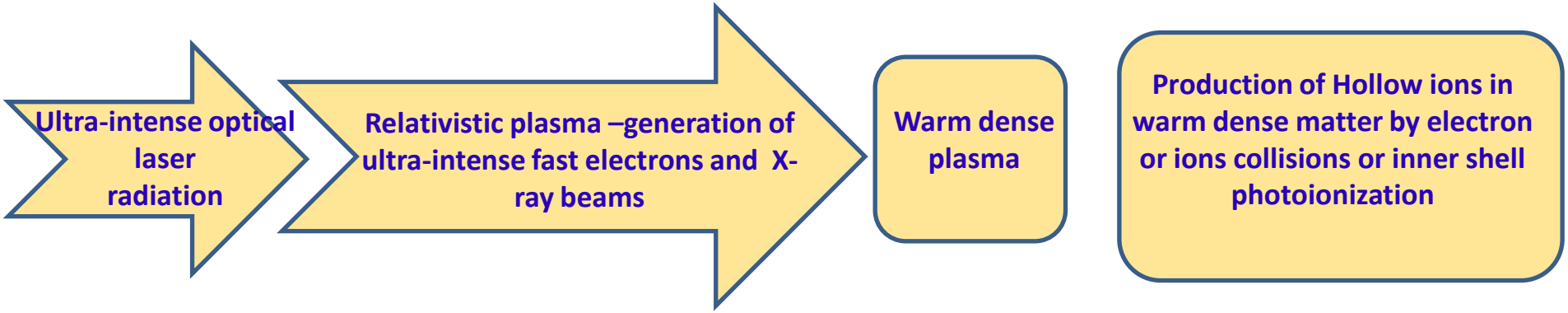
KK Hollow ion spectra can be dominant in the plasma emission if there is an ultra-bright X-ray source

WDM with exotic atomic states due to intense X-rays

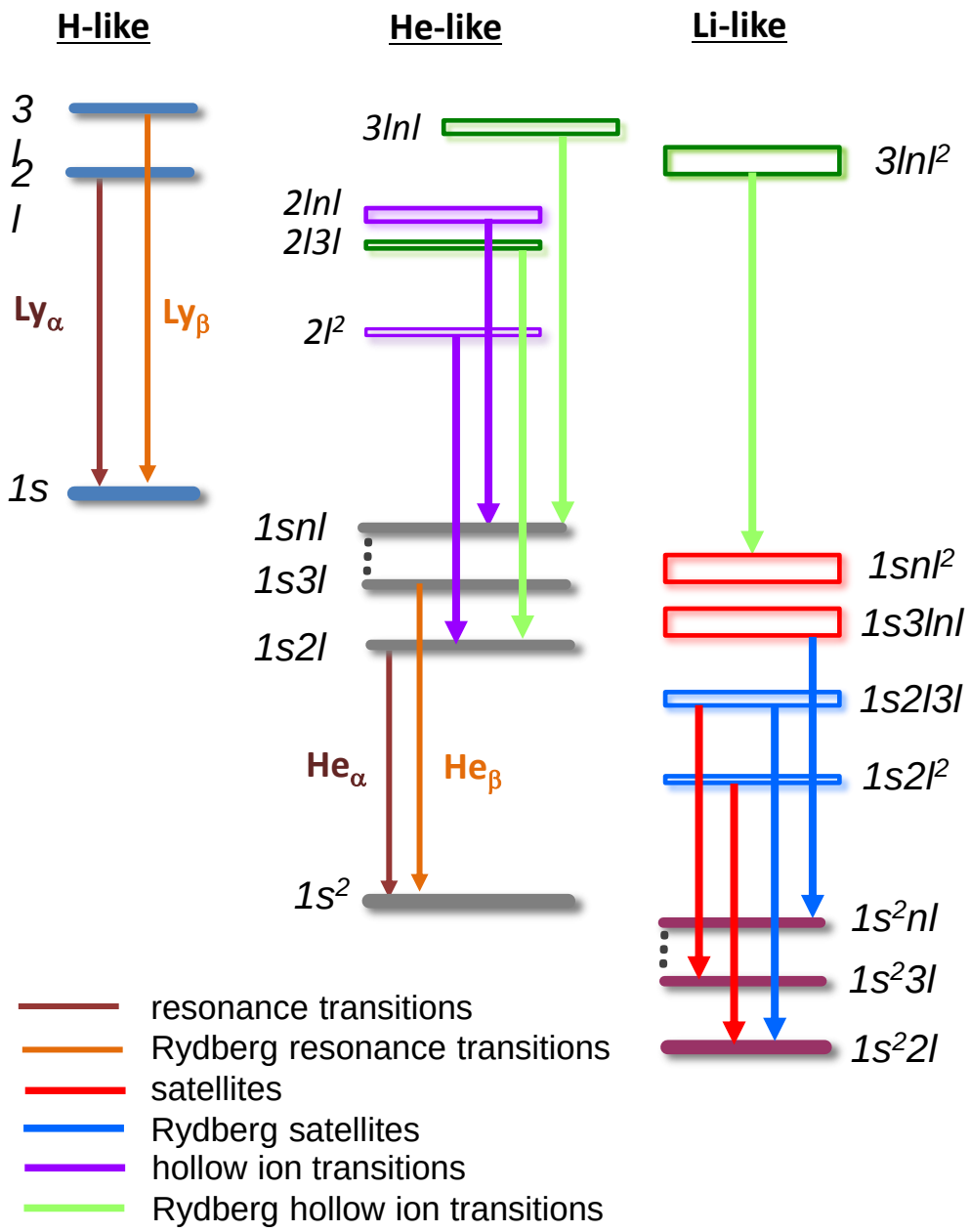
1. Direct excitation by ultra-intense X-ray laser or XFEL pulses

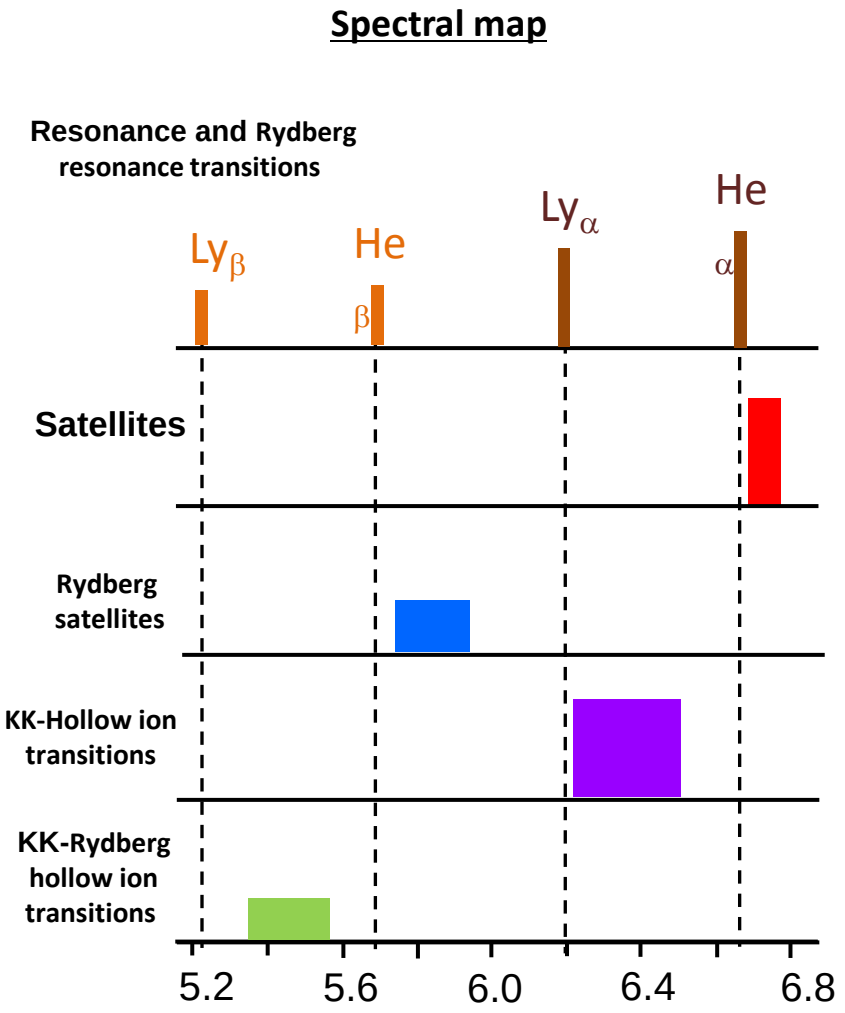


2. Indirect excitation by visible ultra-intense laser pulses

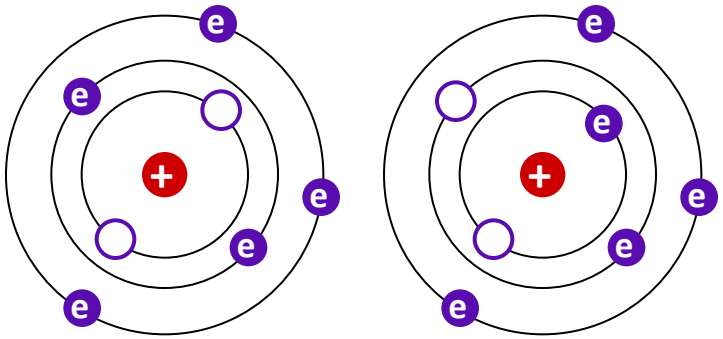


High-n hollow atom states and radiation transitions





Hollow atom spectroscopy, principles



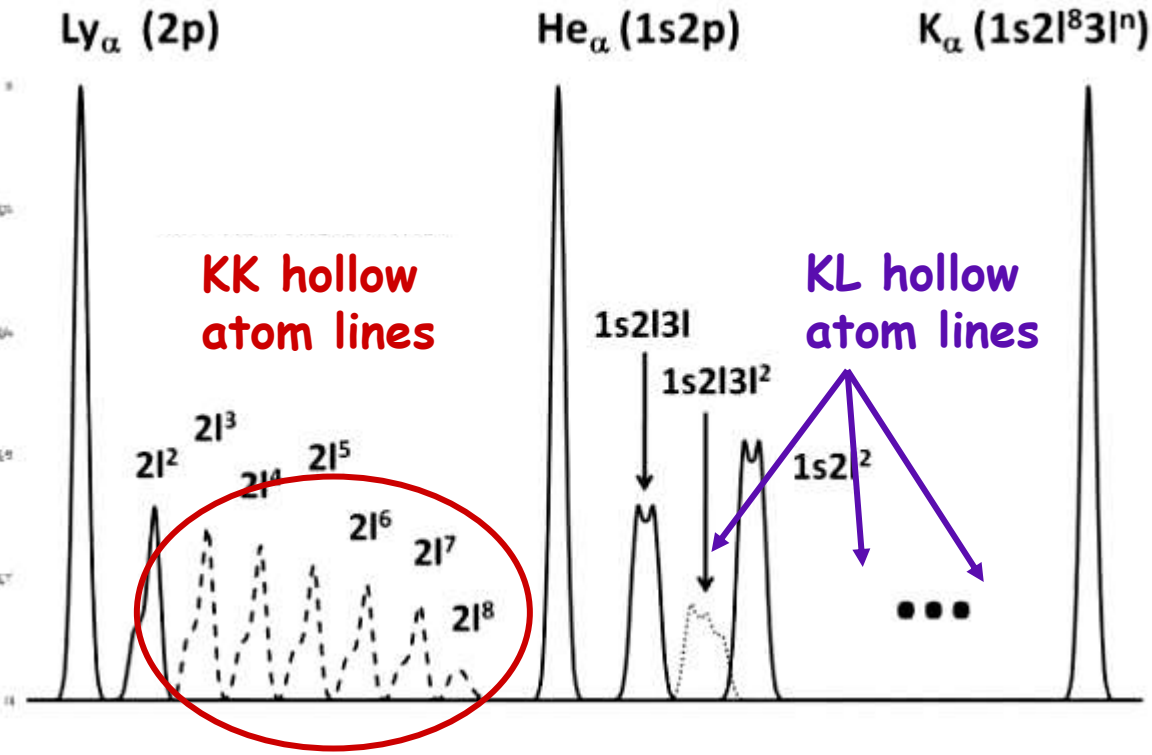
Exotic hollow atom states may be created by hot electron flow or X-ray radiation (external beam or plasma itself of)

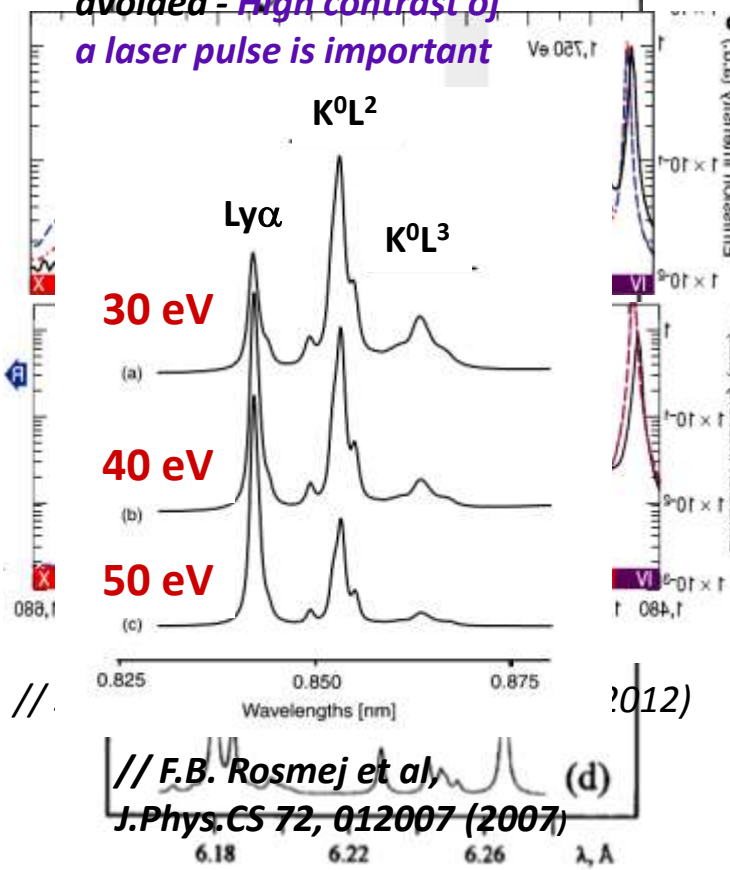
First observation in laser plasma

~ 1997, LANL, 1e19 W/cm2

Target heating prior inner shell excitation should be avoided - High contrast of a laser pulse is important

Hollow atom spectral lines induced by intense quasi-monocromatic X-ray radiation of LCLS

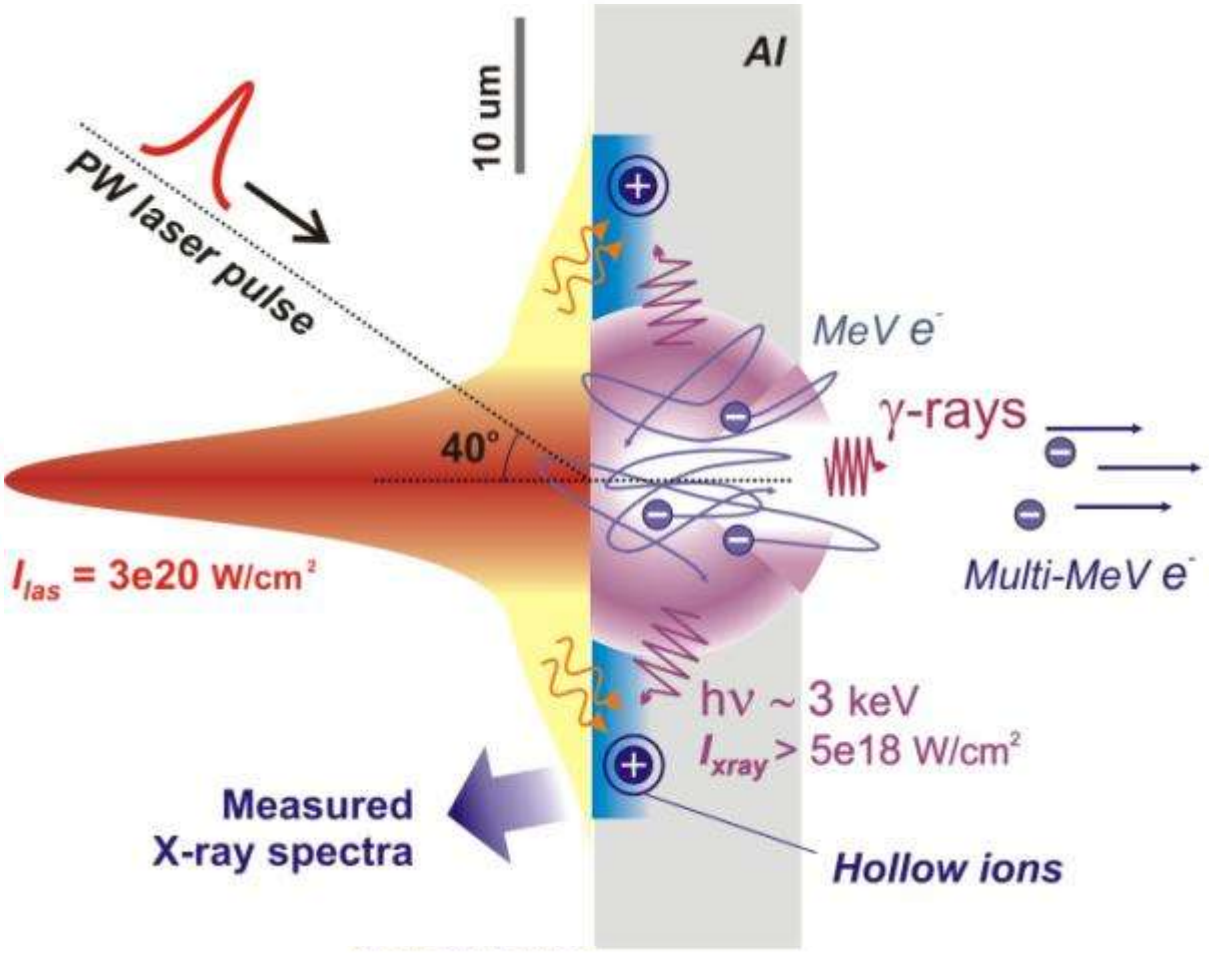




// F.B. Rosmej et al, J.Phys.CS 72, 012007 (2007)

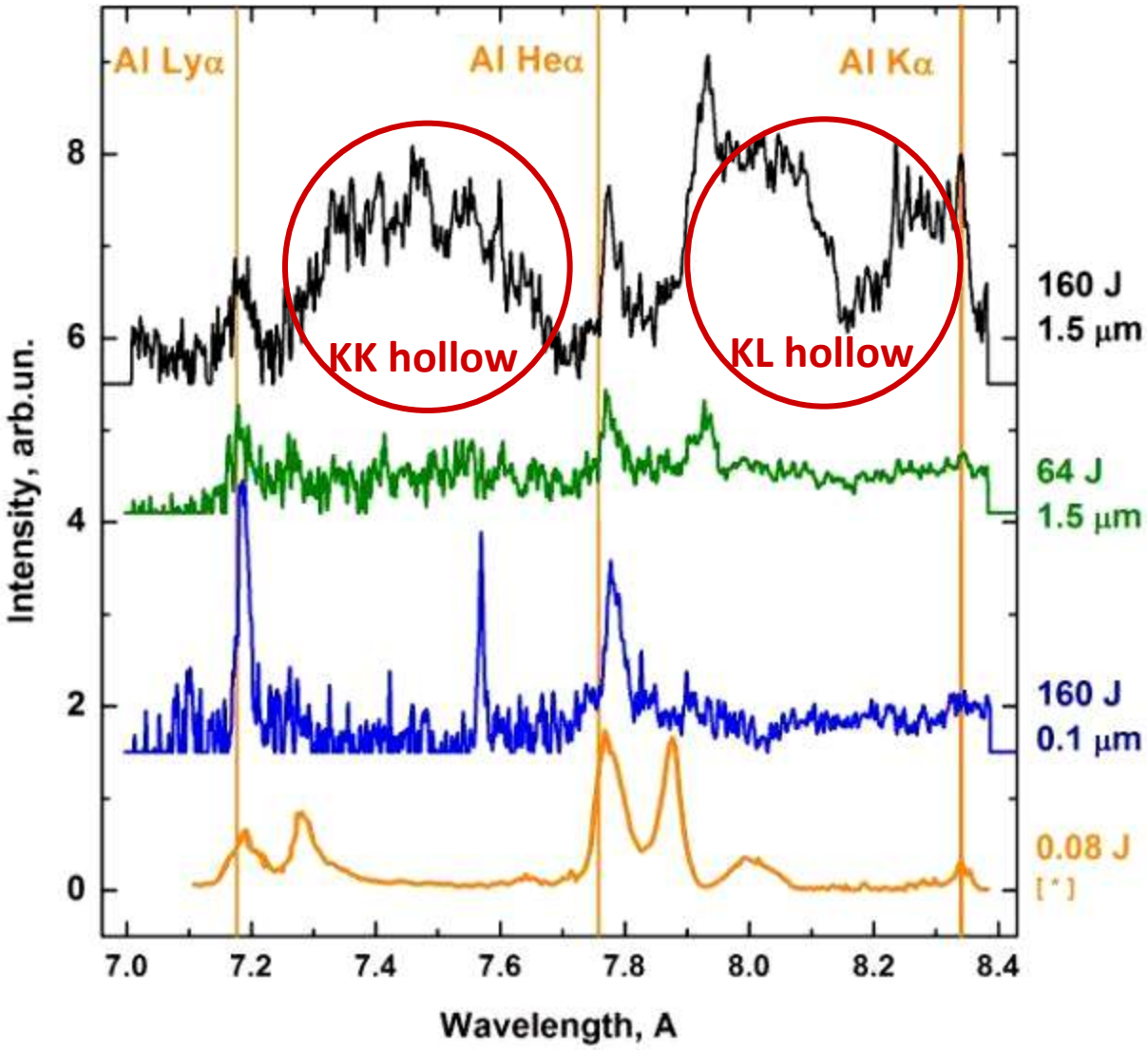
Becomes very significant for high intensity lasers

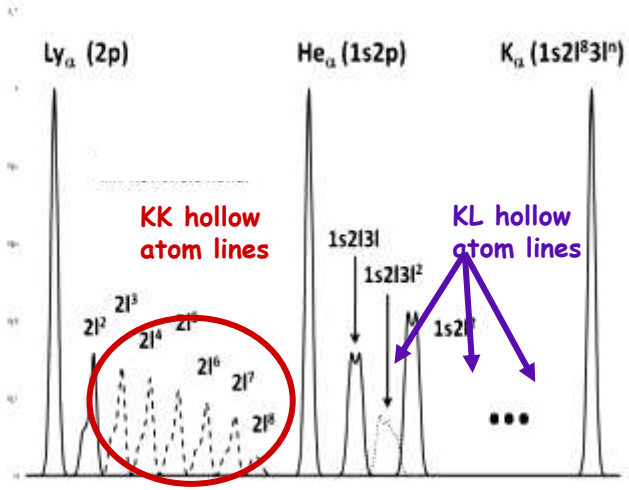
Hollow atom generation in PW plasma



Refluxing is very important to increase the electron flux *inside* the plasma.
Thin (~ μm) targets is more effective due to higher electron oscillation frequency.

Hollow atom spectra observation





$I_{max} = 3\times10^{20}$ W/cm^2

Laser energy – 160 J on target

Pulse duration – 0.7 - 1.2 ps

1ω = 1054 nm

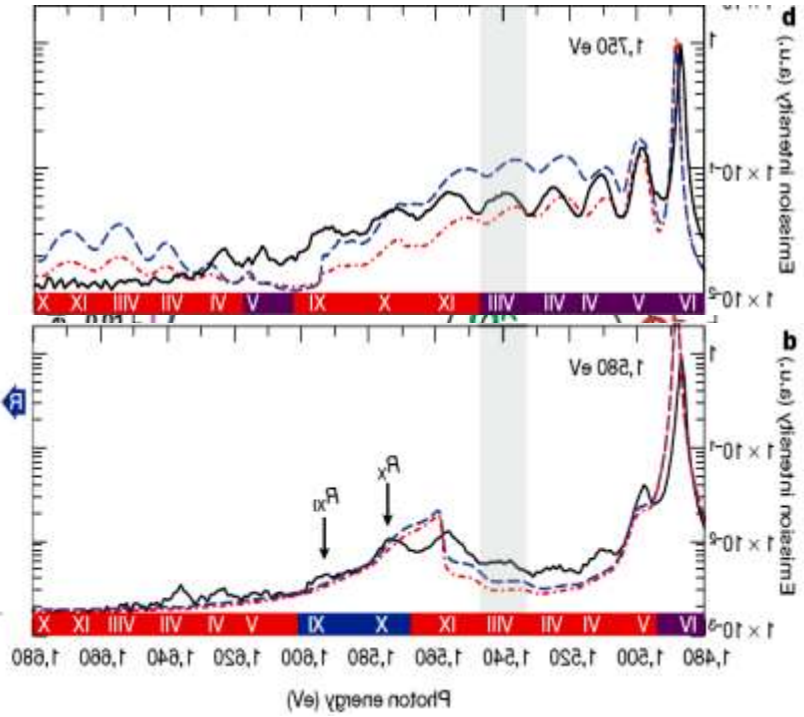
High contrast of OPCPA

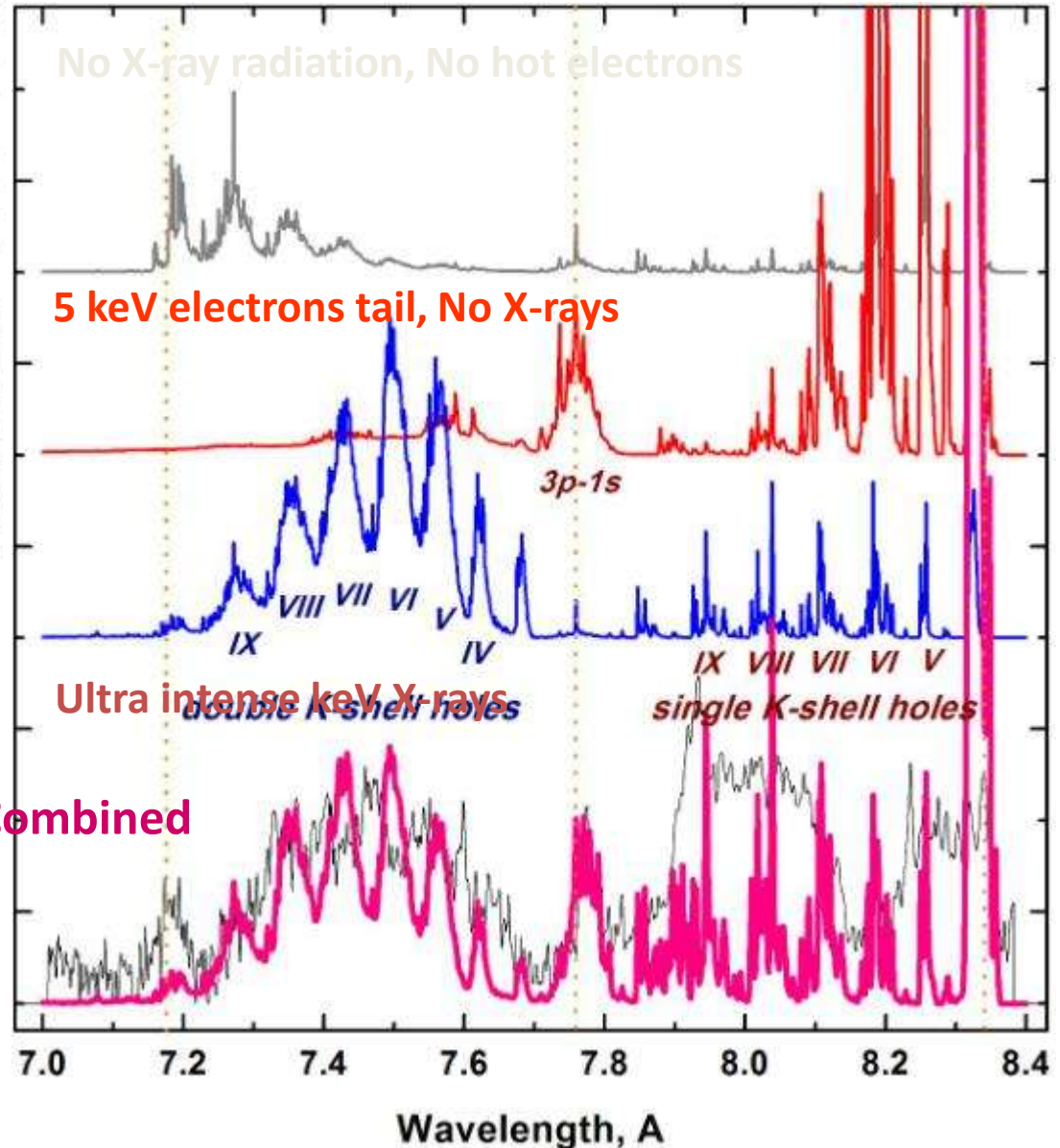
Vulcan PW laser

[*] U. Andiel et al., Appl. Phys. Lett. 80, 198 (2002)

NLTE ATOMIC spectra simulations

// J. Colgan *et al*. *High Energy Density Physics* 7, 77 (2011)





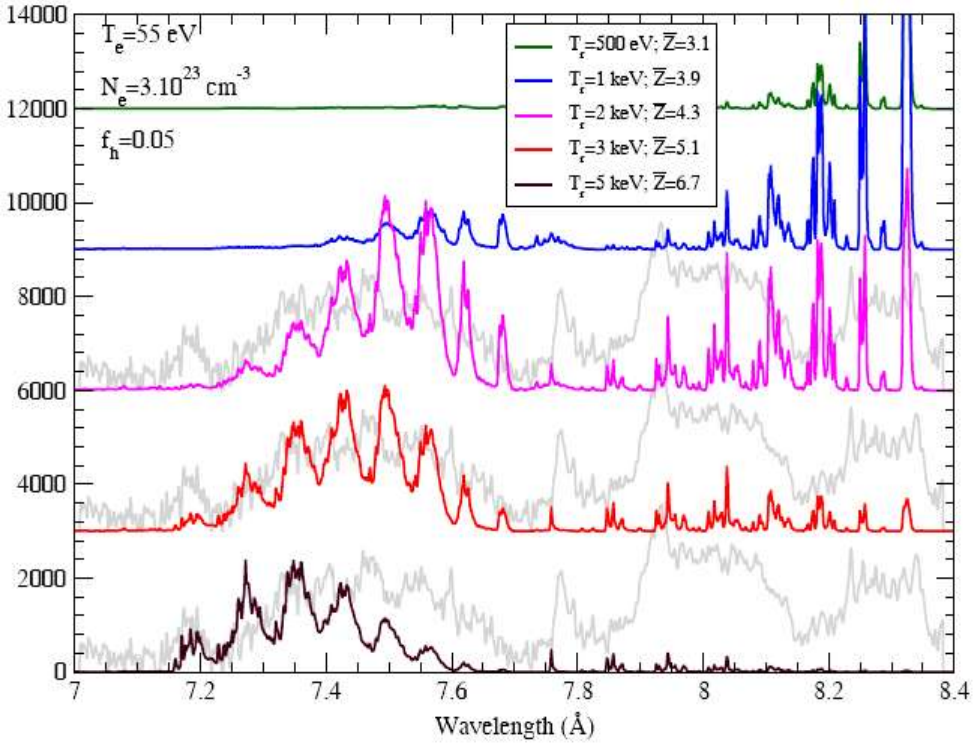
bulk T_e = 55 eV

N_e = 3x10^{23} cm^{-3}

5% of 5 keV electrons

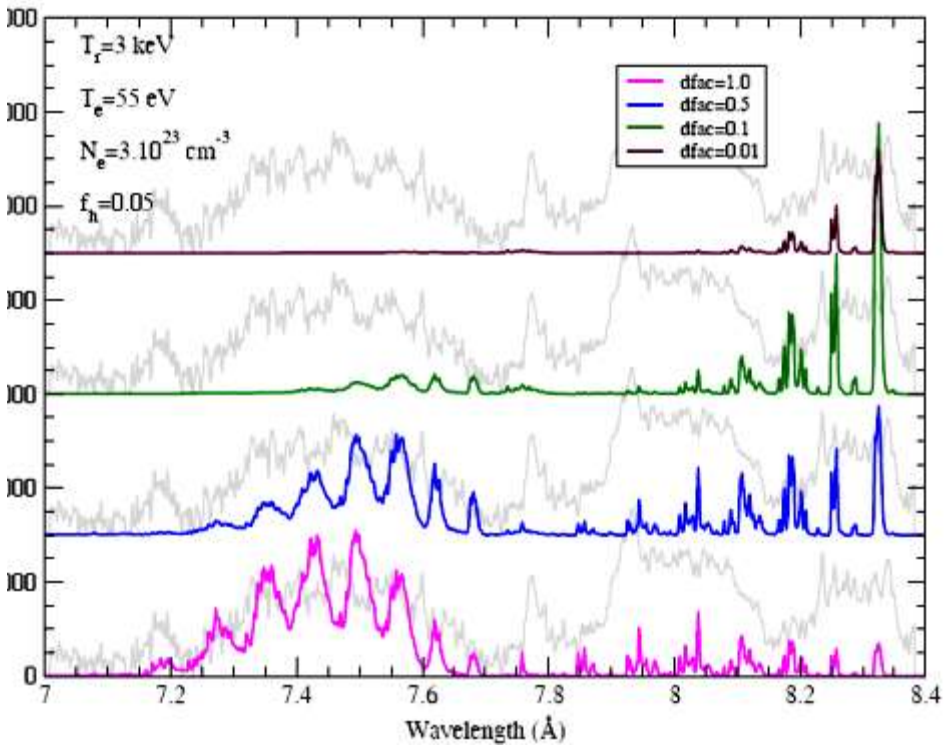
Parameters of X-ray source via hollow atom spectra

Radiation temperature



Varying Trad in 0.5 – 5 keV range

Source brightness



Testing Dilution factor in 0.01 – 1 range

Confirms the source of I_{xray} > 1E18 W/cm^2 intensity

and T_{rad} ~ 3 kev existing

Collaboration

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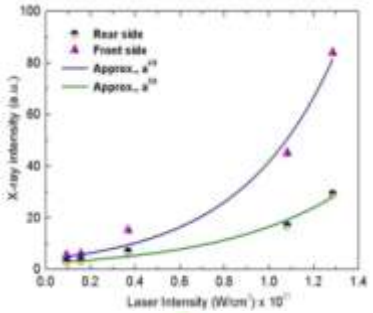
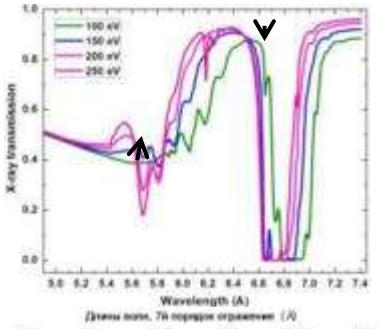
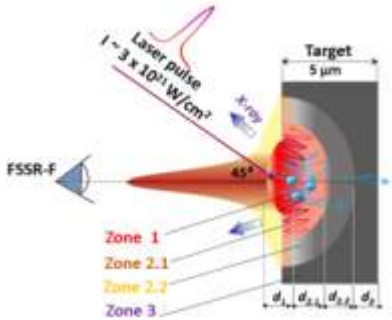
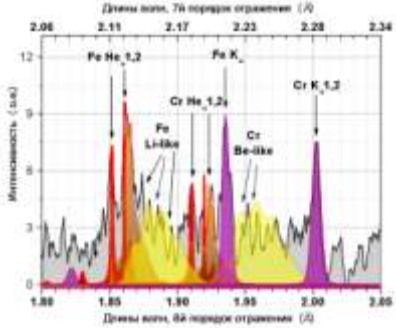
X-ray imaging and spectra diagnostics capabilities

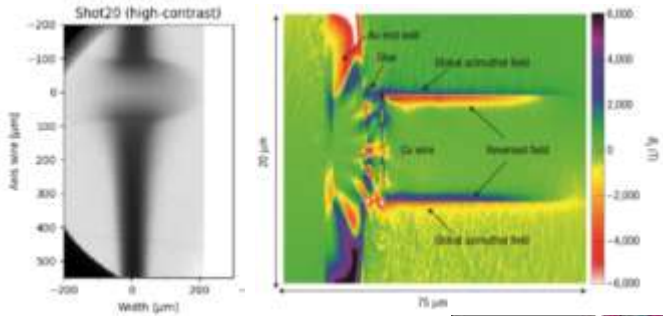
- X-ray emissivity and
  X-ray transport properties
- Hot and warm plasma
  temperatures
- Plasma density -
  shocks and electron currents
- Atomic states and
  density effects (hollow ions, IPD)

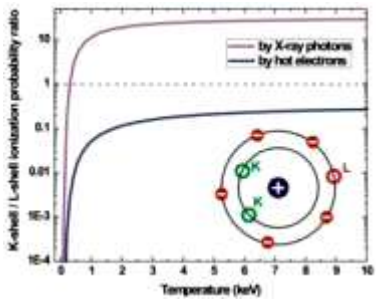


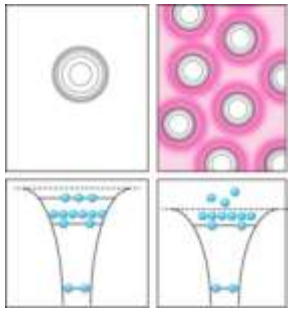






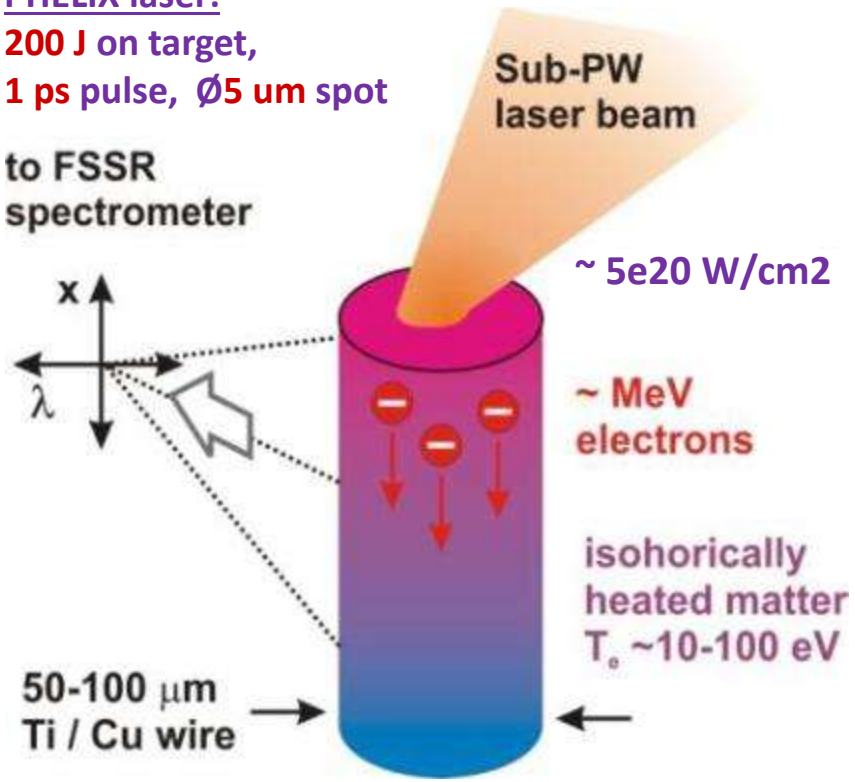


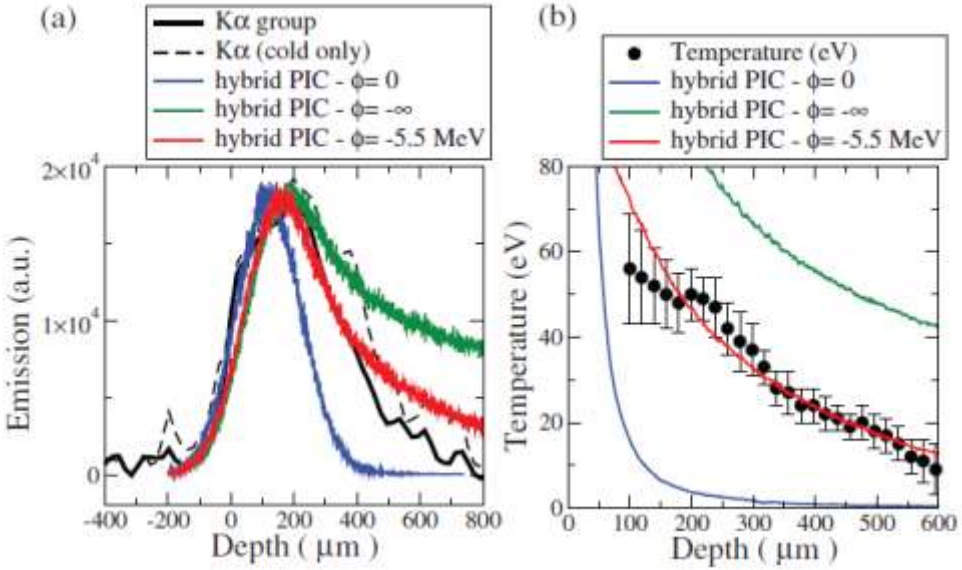




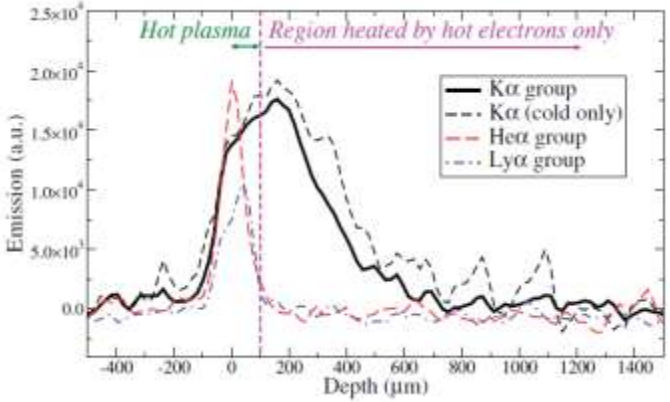
Изохорический нагрев плотного вещества (WDM) потоком лазерно-индуцированных релятивистских электронов в проволочных мишенях

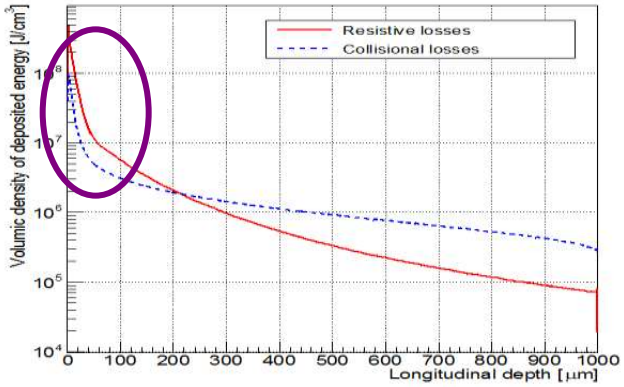
PHELIX laser:
200 J on target,
1 ps pulse, Ø5 um spot





- ✓ **Зарегистрирован прогрев вещества электронами до температур 10-50 эВ на глубине 0.2 ÷ 1.5 мм**
- ✓ **Средняя энергия ускоренных электронов ~2.6 МэВ**
- ✓ **Определено отношение резистивных и столкновительных потерь энергии электронами**

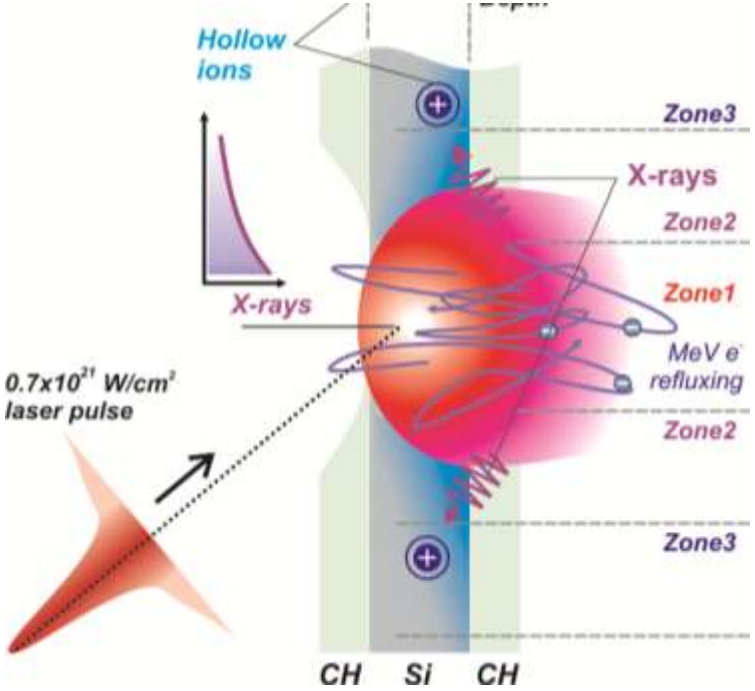




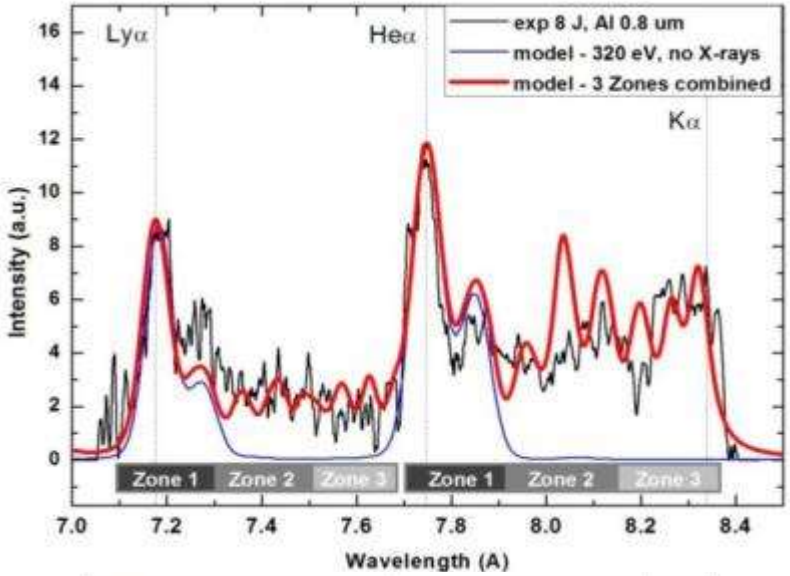
- ✓ **Определена роль возвратных электронных токов и самофокусировки электронного потока в плазменном поле**

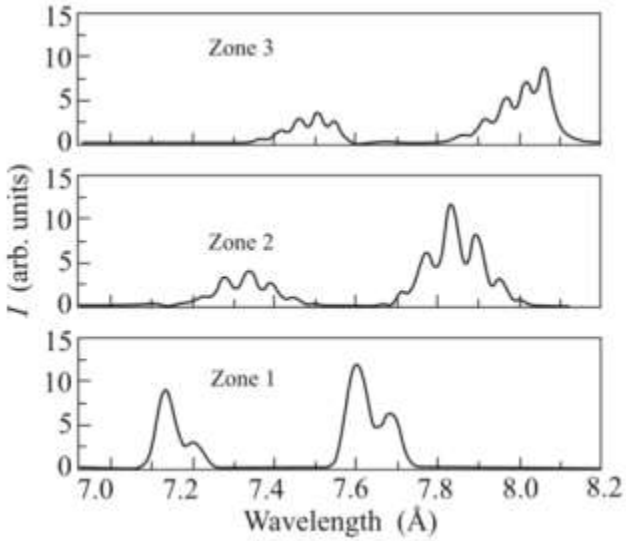
Опубликовано в *Europ.Phys.Lett. 114,* 45002 (2016)

Experiment at PEARL facility

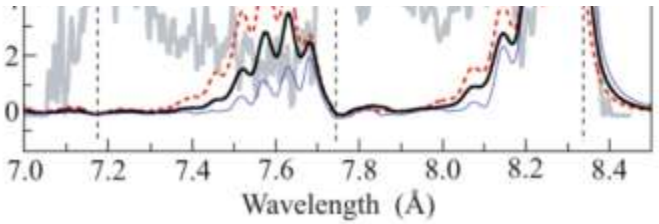


E = 10 J, τ = 60 fs, d_{foc} = 6 um, I = 4e20 W/cm2





Zone	1	2	3
N_e, cm^{-3}	1.7×10^{22}	3×10^{23}	3×10^{23}
T_e, eV	315	60	5
T_r, keV	–	1.5	1.2



Experiments with J-KAREN-P Laser facility

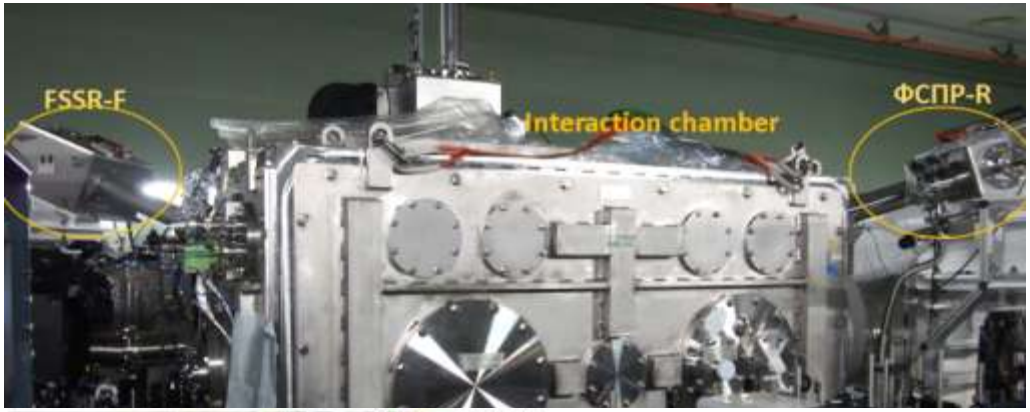
Experiments at J-KAREN-P (since march 2016)
Kansai Photon Science Institute, Kyoto, Japan

J-KAREN-P laser facility:

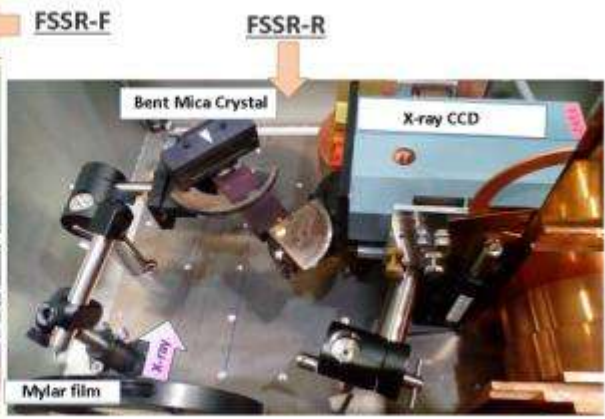
- Ti:Sapphire, OPCPA
- Wavelength λ= 800 nm
- Laser power P_{laser}= 0.35 PW
- Laser contrast up to C_{laser} ~ 10^{12}
- Pulse duration τ ~ 40 fs
- Energy on target up to E~ 14 J



High resolution X-ray spectrometers coupled with CCDs, 2 channels

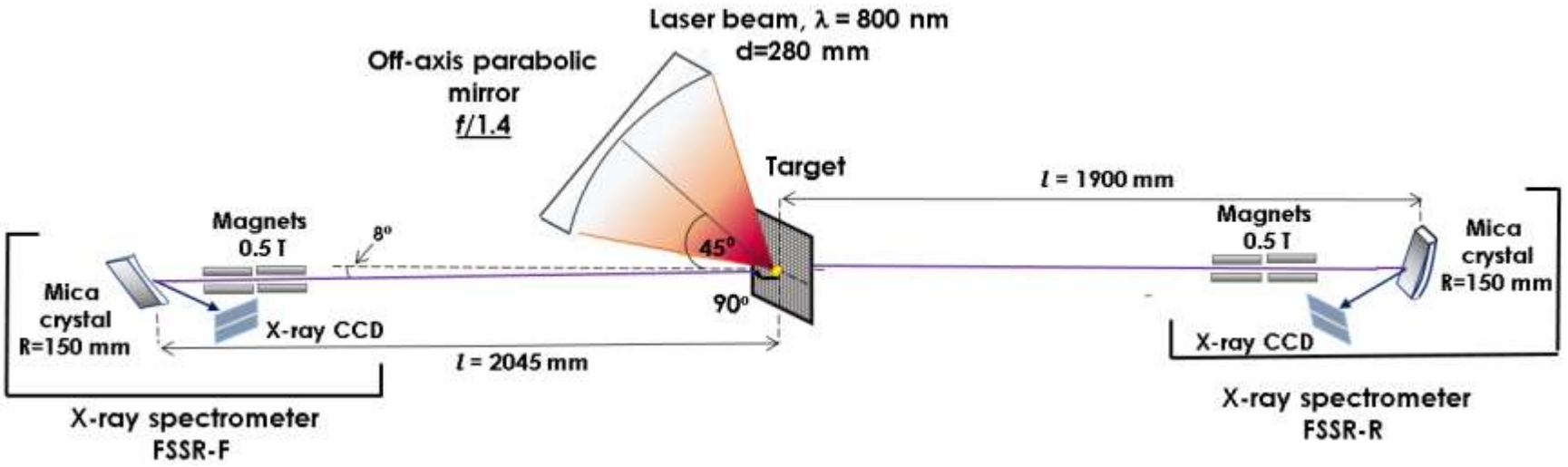




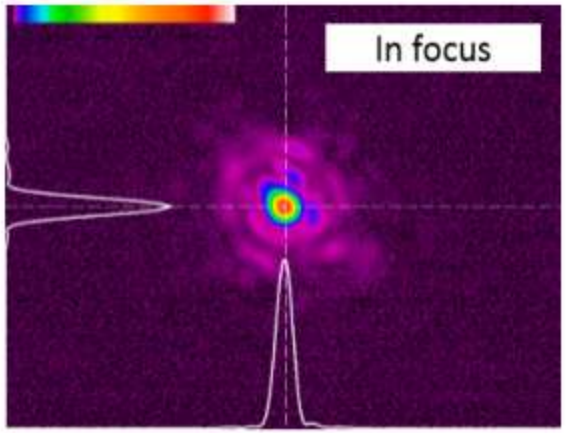


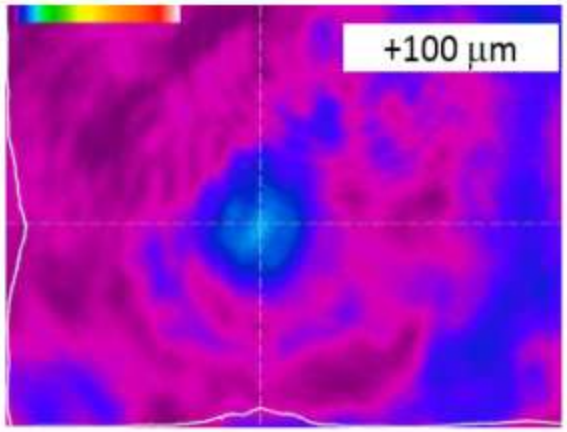
FSSR in vacuum chamber

Experimental Setup J-KAREN-P laser facility

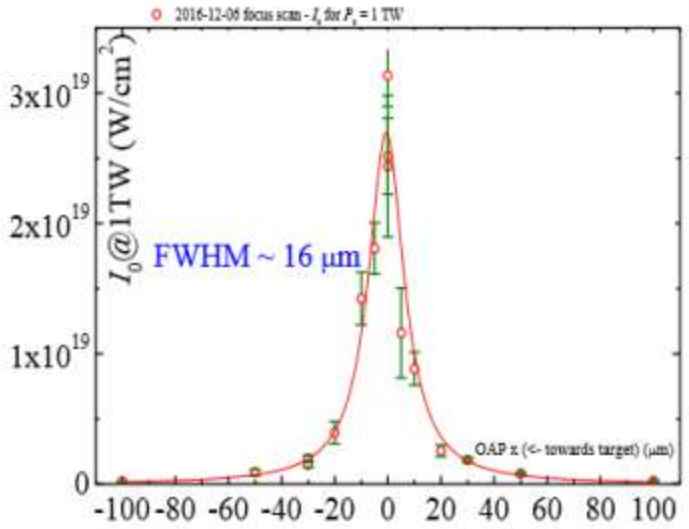


Sharp laser focusing with f/1.4 parabola. Focal spot diameter ~1,5 μm



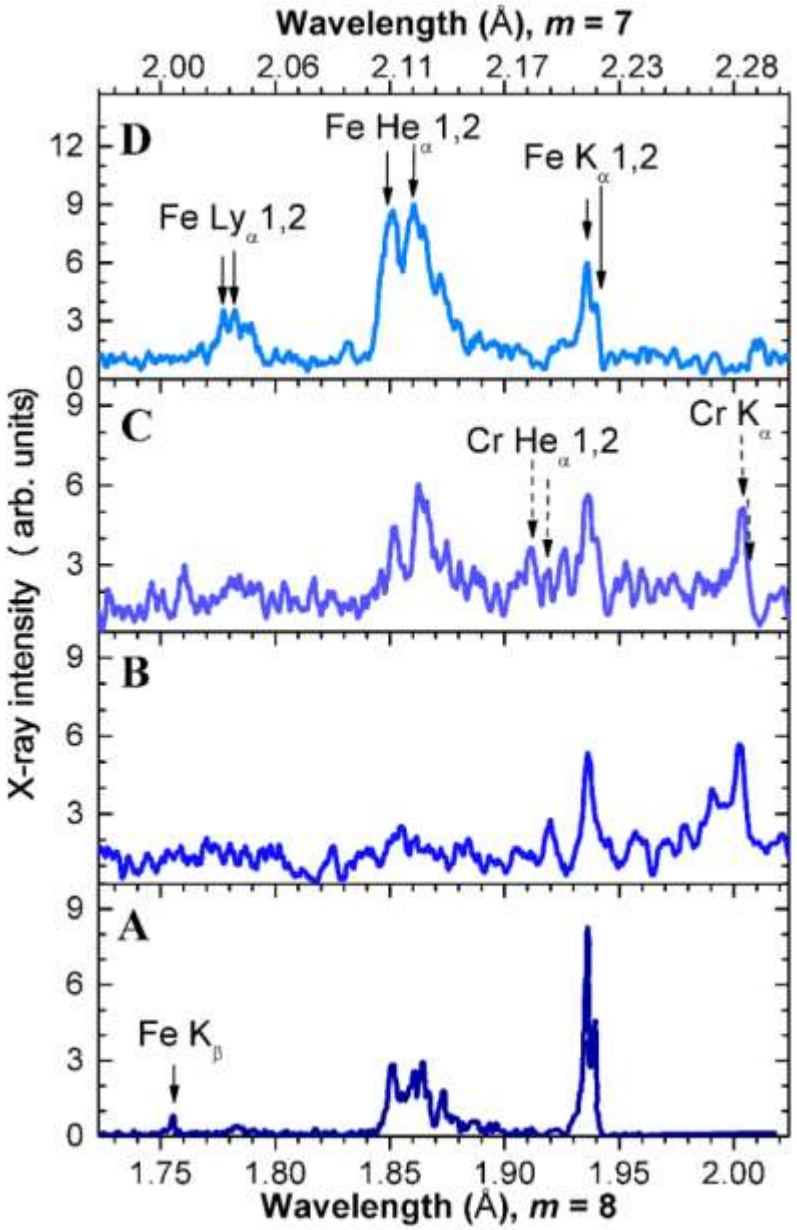


Focal spot snaps



Laser intensity on target vs target shift

X-ray spectra depend on laser contrast



X-ray spectra of steel plasma allowed to observe laser contrast improvement, which results in appearance of transitions in multi-charged Fe and Cr ions and growth of its relative intensities.

Laser contrast ~10^{12}

I_{las} = 9e21 W/cm²

Laser contrast ~10^{12}

I_{las} = 3e21 W/cm²

Laser contrast ~10^{6}

I_{las} = 3e21 W/cm²

Laser contrast >10^{10}

I_{las} = 1e21 W/cm²

Electron impact ionization

$$C_i N_e \tau_{plasma} > 1$$

Here C_i is collisional ionization rate, which is strongly dependent on T_e

$$\tau_{plasma} \sim L_{plasma}/v_T$$

where L_{plasma} is plasma dimension and v_T is plasma expansion speed

T_e must exceeds $E_i/4$ → **high I_{las} is essential, though not so high as for OFI**

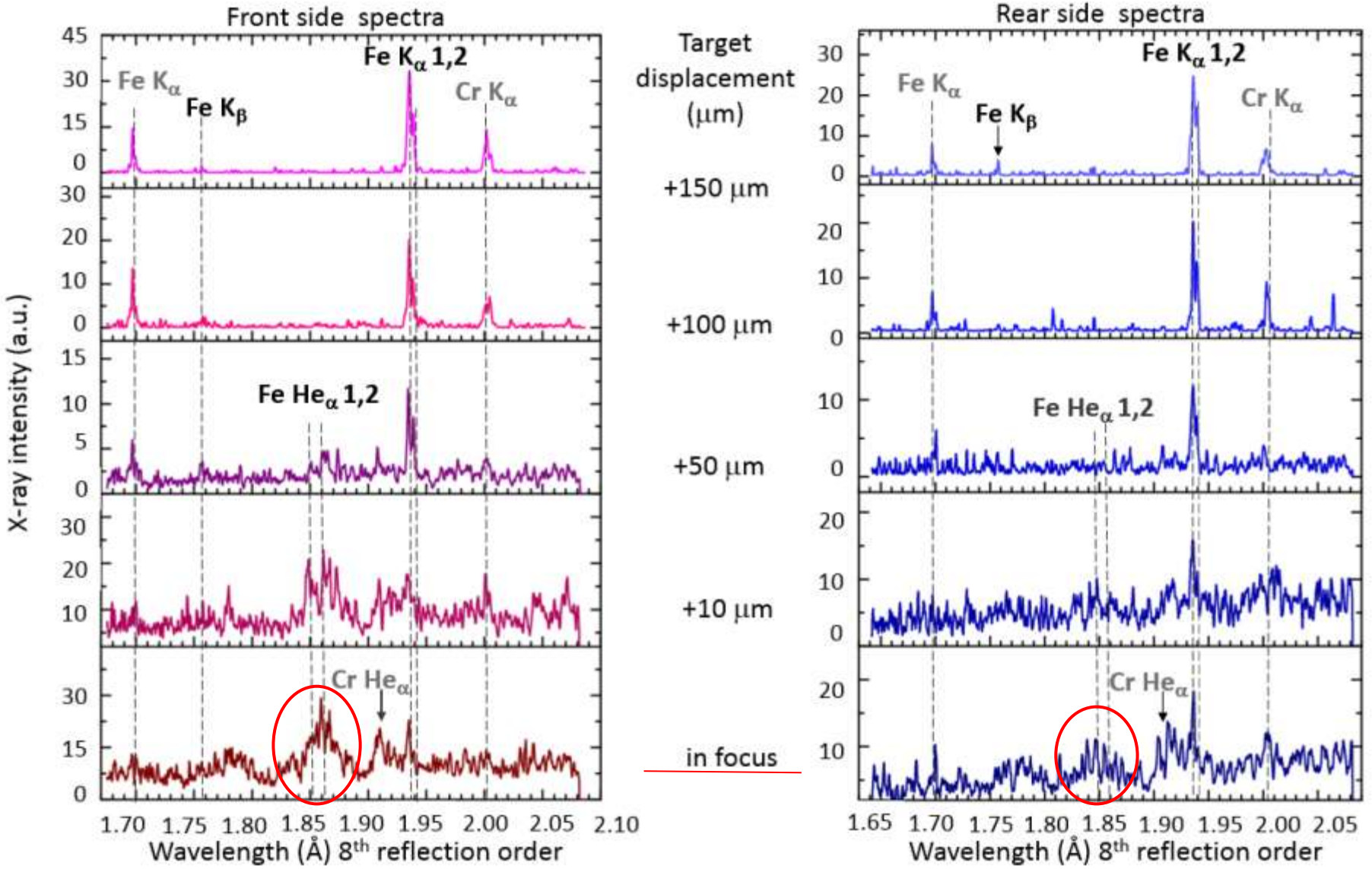
To obtain high I_{las} :

1) increase E_{las} → expensive
2) decrease $R_{focal\ spot}$ → decreasing of L_{plasma} and τ_{plasma}

The best solution is to use maximal possible value N_e (solid state value)

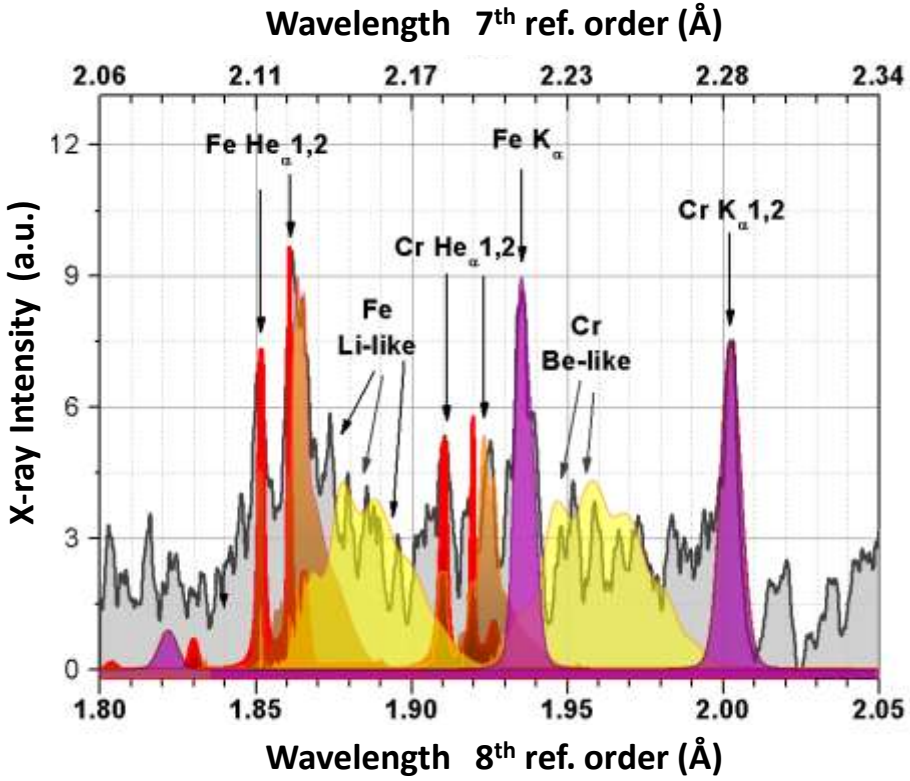
Very high laser contrast $I_{pulse}/I_{prepulse} > 10^{11}$ is necessary

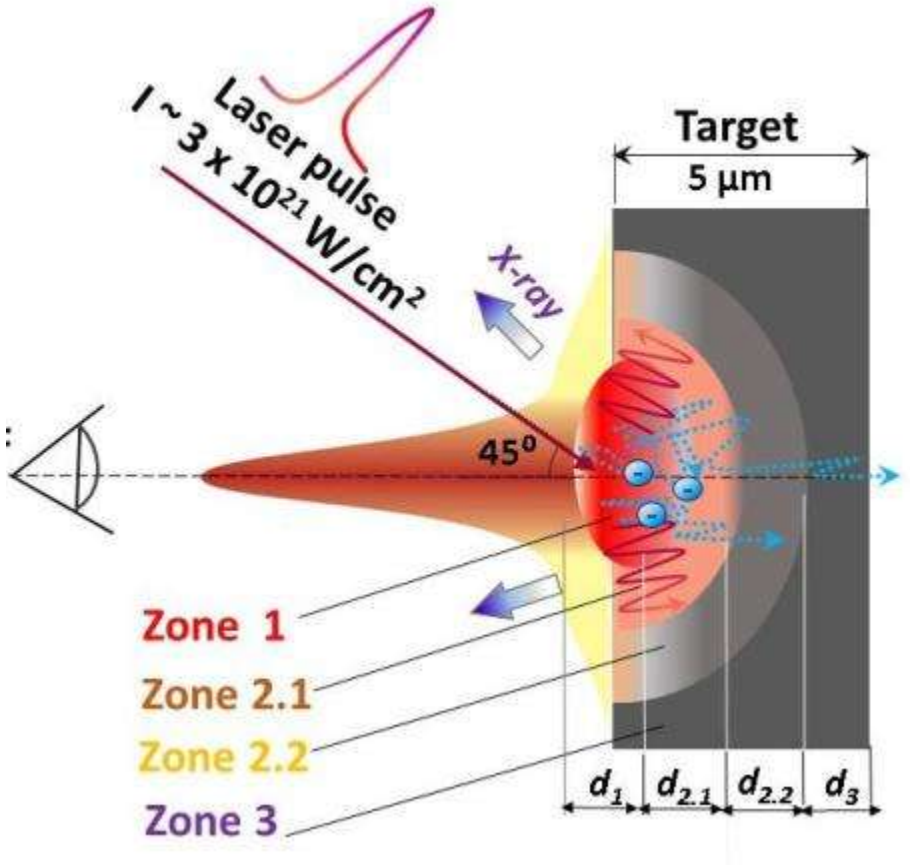
X-ray Fe spectra measurements @ J-KAREN-P



X-ray spectra emitted from front/rear sides of 5 μm thickness stainless steel (SUS) foils

Plasma with strong gradients – multiple zones approach





Zone 1 (T_e ~ 2-3 keV)

High temperature plasma created by laser pulse on the focal spot area. Generation of MeV electrons oscillated though the target and bright x-ray photons

$$T_{e1} > T_{e2.1} > T_{e2.2} > T_{e3}$$

Zone 2 (T_e ~ 0.1-1 keV)

Plasma with Ne close to solid and Te below than plasma in 1 Zone.

$$N_{e1} < N_{e2}$$

$$N_{e2.1} = N_{e2.2} \approx N_{solid}(Fe) \sim 2.4 \times 10^{24} cm^{-3}$$

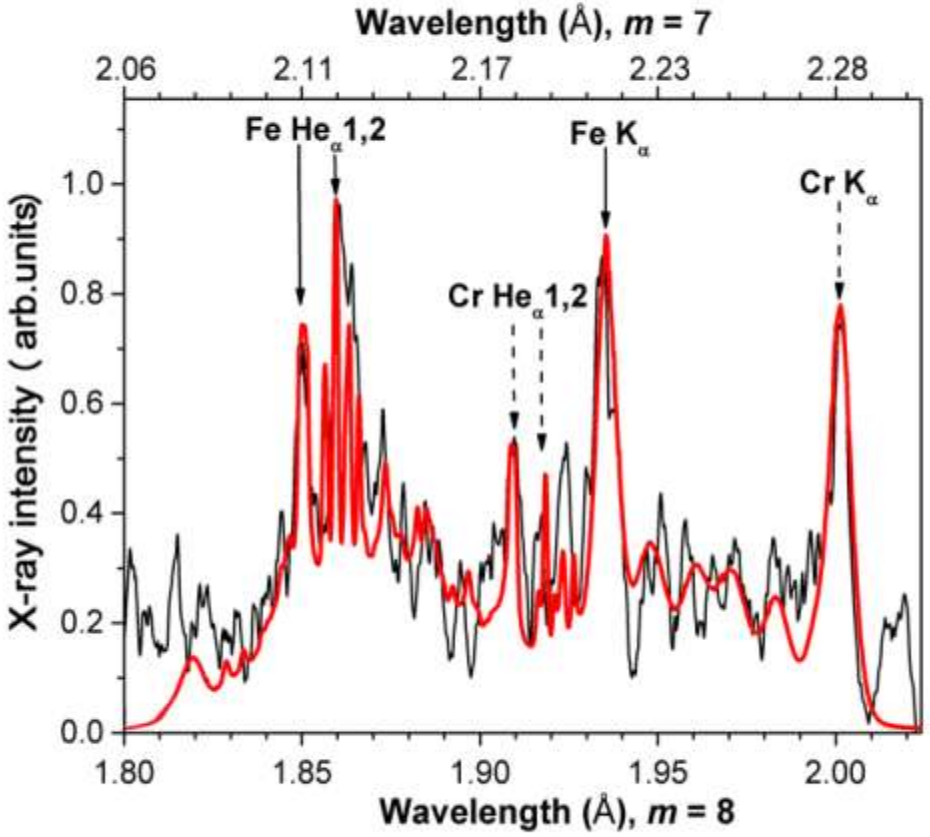
$$N_{e3} < N_{e2}$$

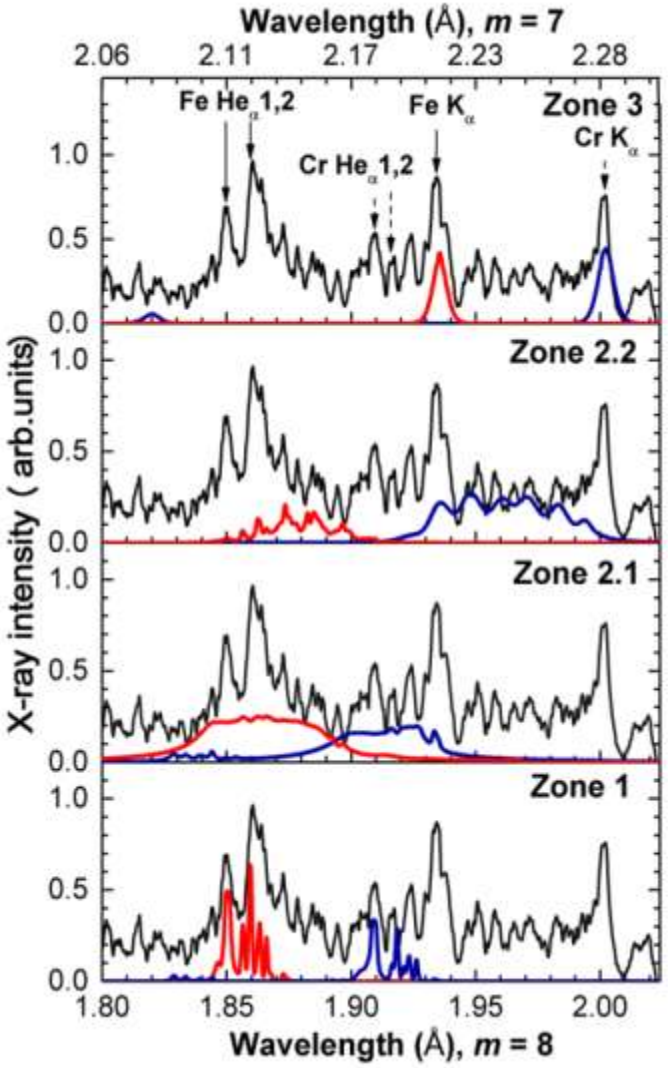
Zone 3 (T_e ~ 10-30 eV)

Target regions heated mostly be hot electrons from zone 1. Plasma with lowest Te.

Integrated spectra and revealed plasma parameters

I_{las} = 3e21 W/cm²





Zone	1	2.1	2.2	3
N_i (cm^{-3})	2×10^{21}	8×10^{22}	8×10^{22}	8×10^{22}
N_e (cm^{-3})	5×10^{22}	5×10^{23}	5×10^{23}	2.3×10^{23}
T_e (eV)	2200 (±120)	1100(±100)	300(±50)	20 (±5)
T_{hot} (keV)	0.1%, 10 keV	0.1%, 10 keV	0.11%, 10 keV	0.1%, 10 keV
Electron energy density (J/cm^3)	1.04 ×10^7	1.6 ×10^8	5×10^7	9.3×10^5

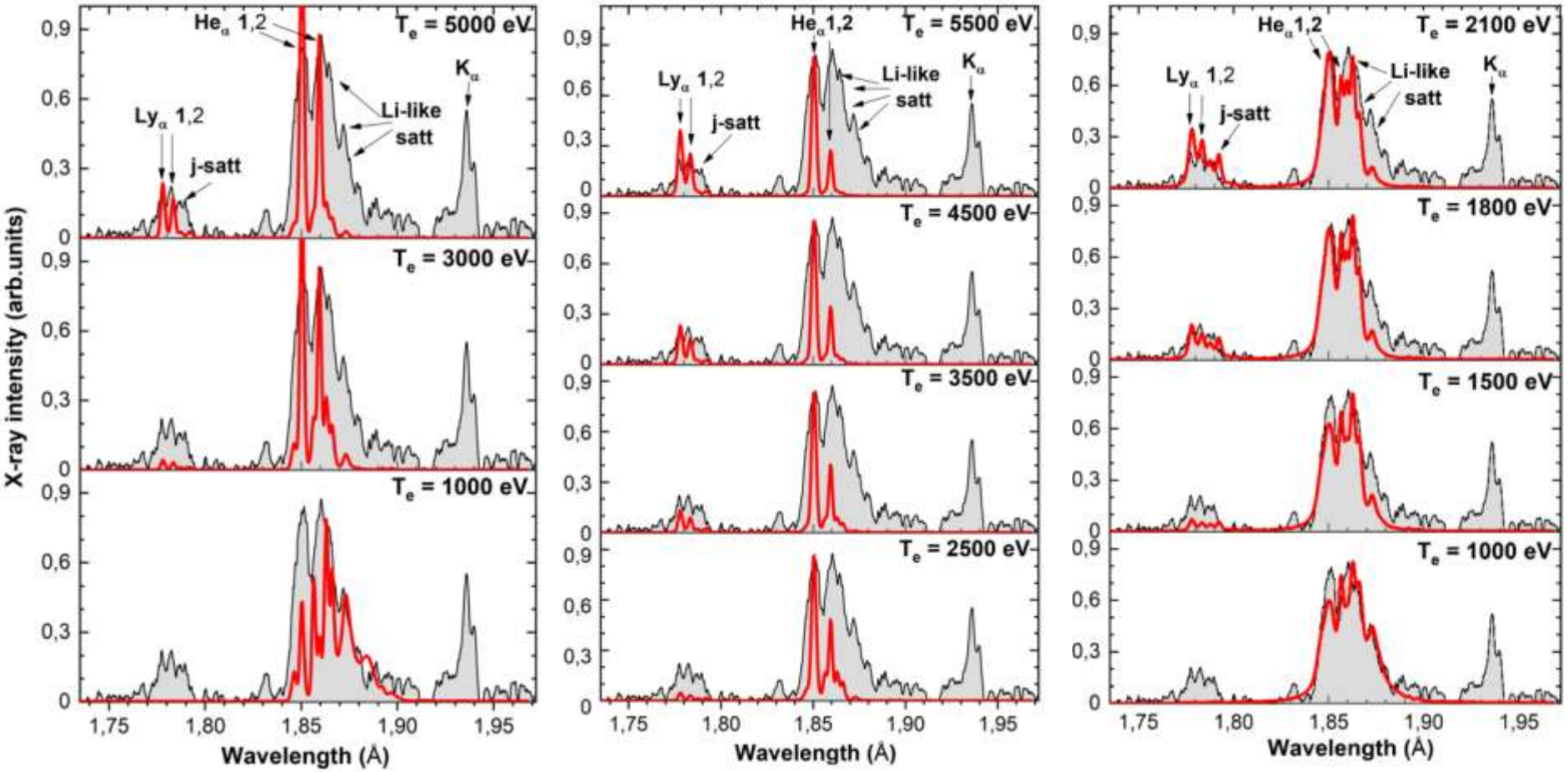
Measured spectra - revealing plasma parameters

I_{las} = 9e21 W/cm^2 – *Fe 5 um target*

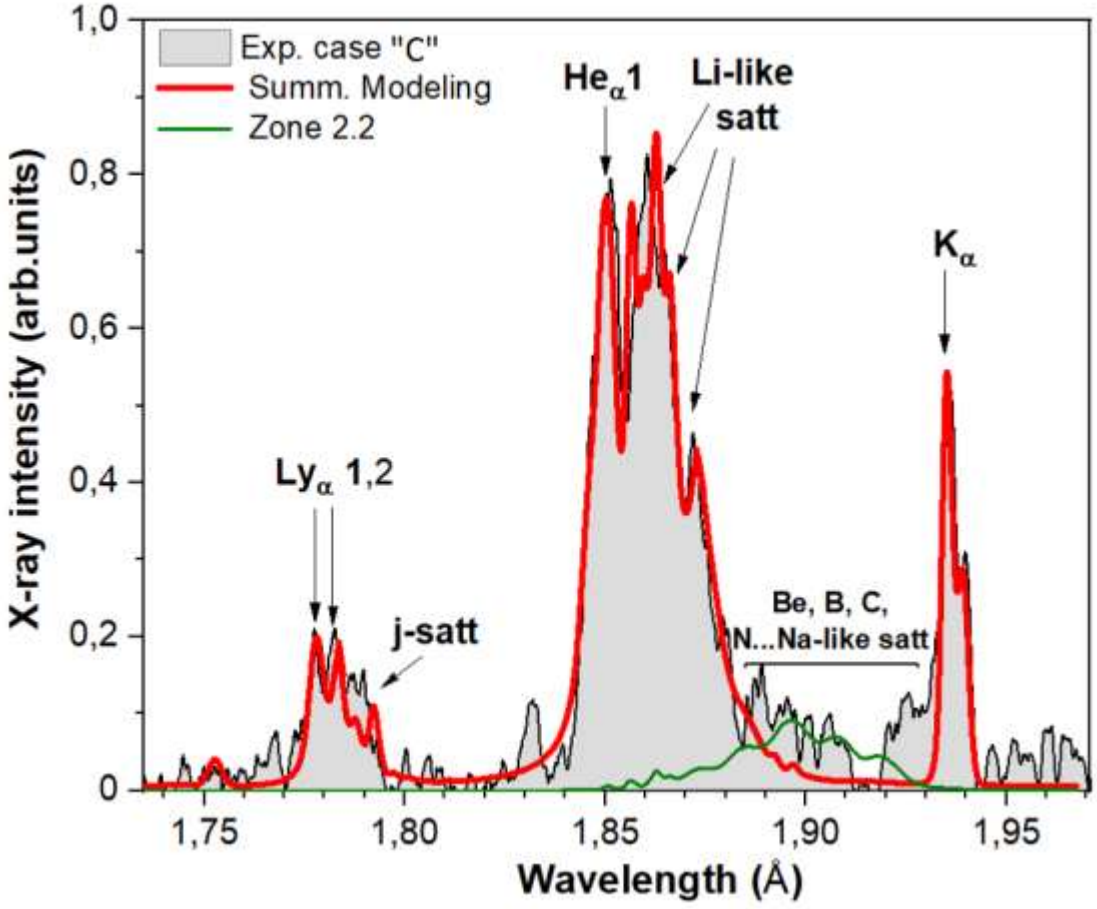
Critical density
No optical thickness

Relativistic critical density
Optical depth 2 um

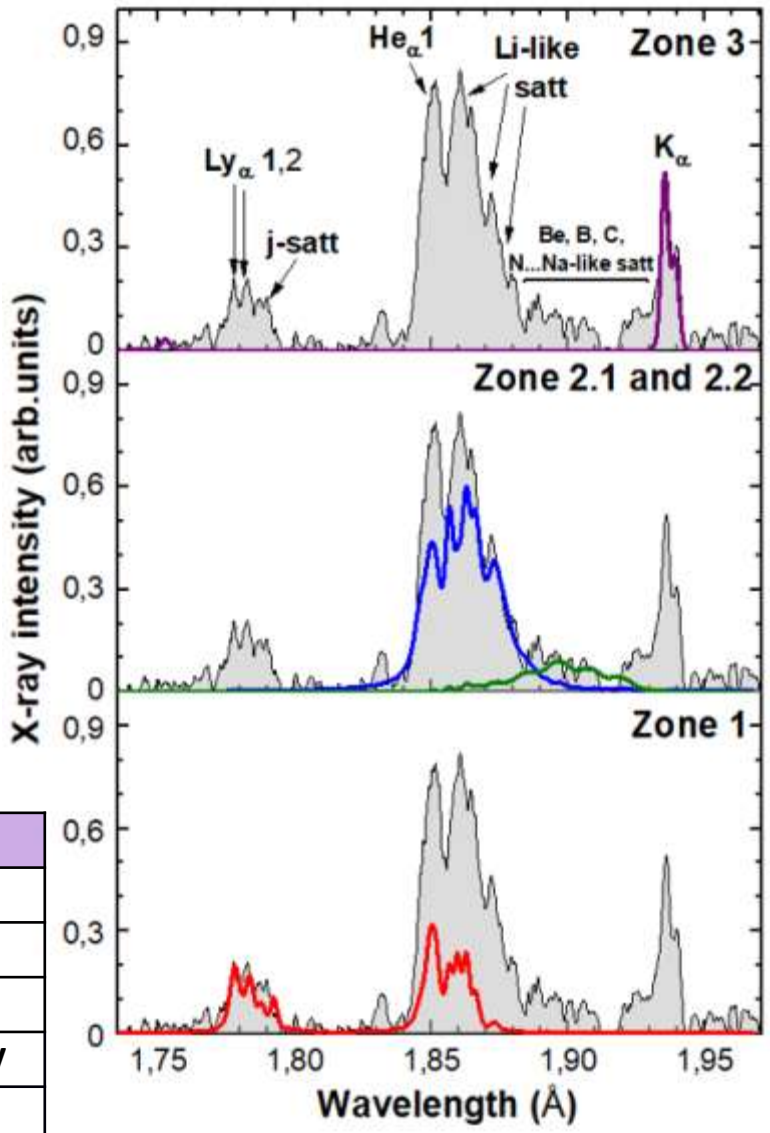
Solid density
Optical depth 0.5 um



Integrated spectra and revealed plasma parameters

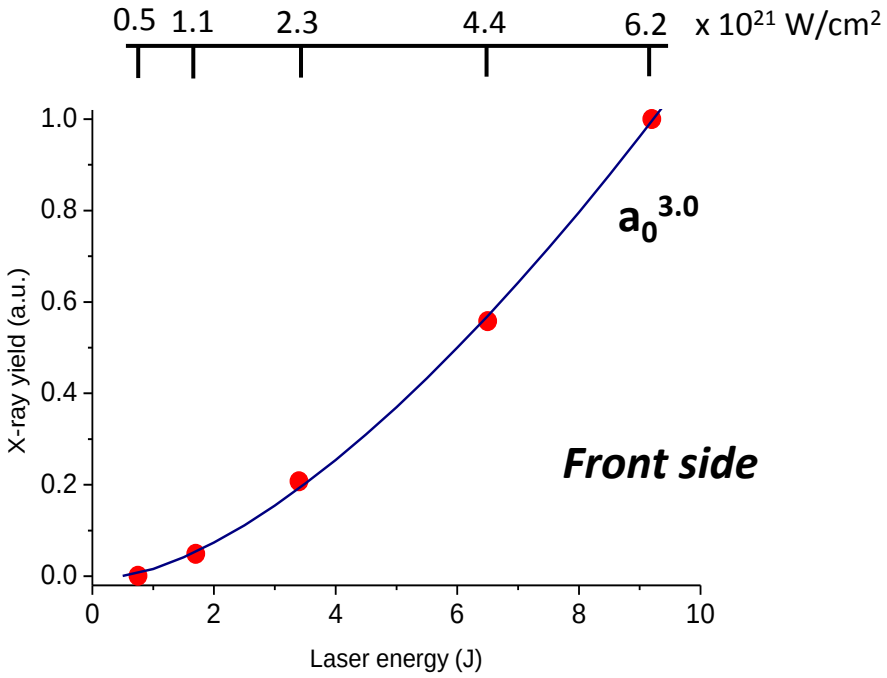


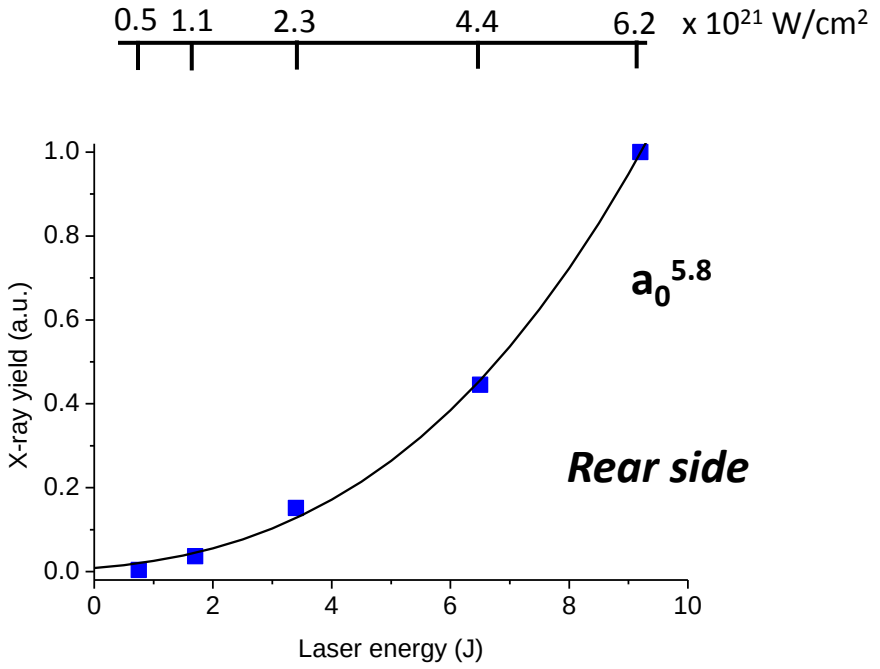
I_{las} = 9e21 W/cm^2 – Fe 5 um target

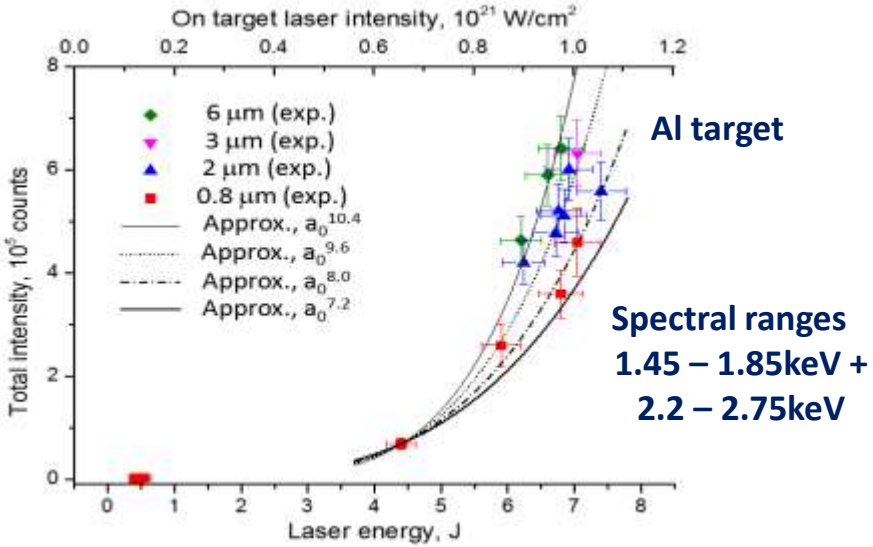


Zone	1	2	3
Ni (cm^{-3})	8e22	8e22	8e22
N_e (cm^{-3})	1.9e24	1.8e24	5.5e23
T_e (eV)	2500(±200)	900(±100)	80(±20)
T_{hot} (keV)	0.1%, 10 keV	0.1%, 10 keV	0.1%, 10 keV
Energy density (J/cm^3)	7.8× 10^8	2.6 ×10^8	7 ×10^6

X-ray yield on energy of laser pulse (spectral range 6.05 – 7 keV)







Faenov et al. Sci. Rep. 5, 13436 (2015)

Low Z (Al); 1.5-2.0 keV range:

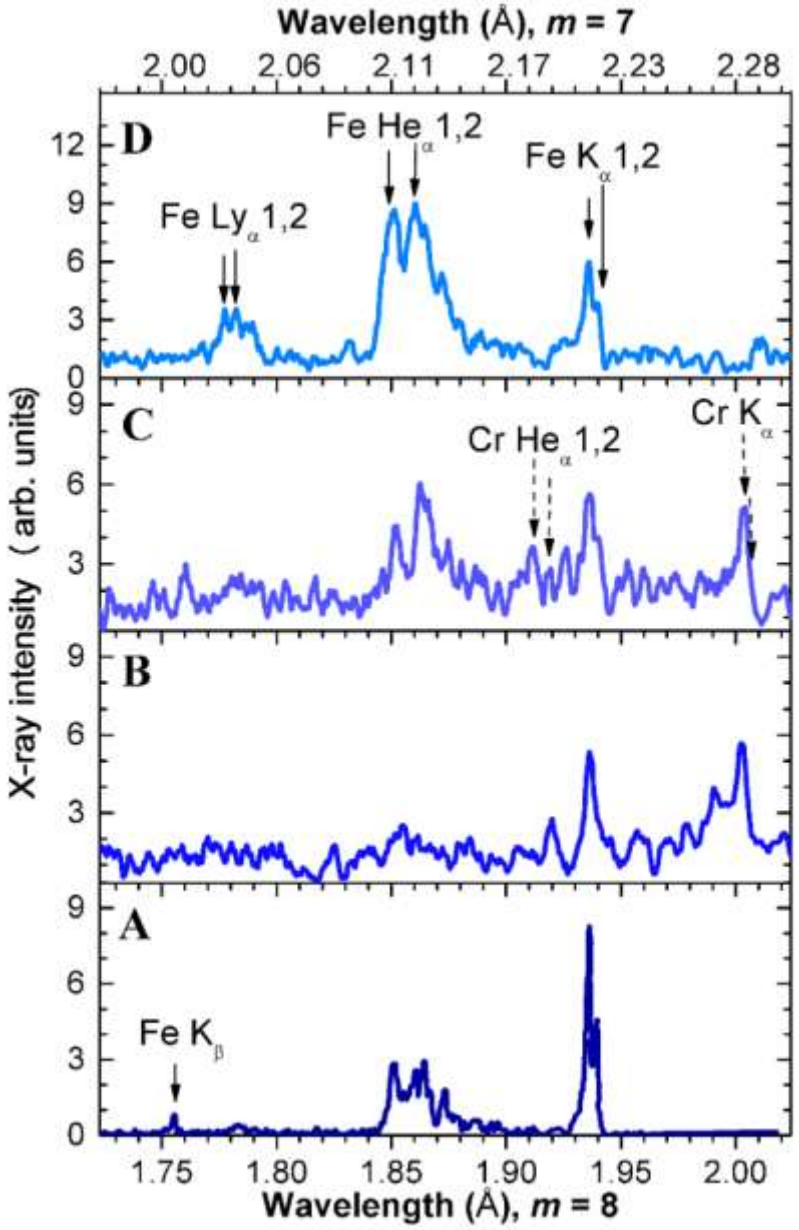
$I_{X\text{-}ray} \sim a_0^{8}$

High Z (Fe); 6 – 7 keV range:

$I_{X\text{-}ray} \sim a_0^{3\text{-}5}$

Solid-density effects in X-ray spectra of ultra-relativistic laser plasma

X-ray spectra depend on laser contrast



X-ray spectra of steel plasma allowed to observe laser contrast improvement, which results in appearance of transitions in multi-charged Fe and Cr ions and growth of its relative intensities.

Laser contrast ~10^{12}

I_{las} = 9e21 W/cm²

Laser contrast ~10^{12}

I_{las} = 3e21 W/cm²

Laser contrast ~10^{6}

I_{las} = 3e21 W/cm²

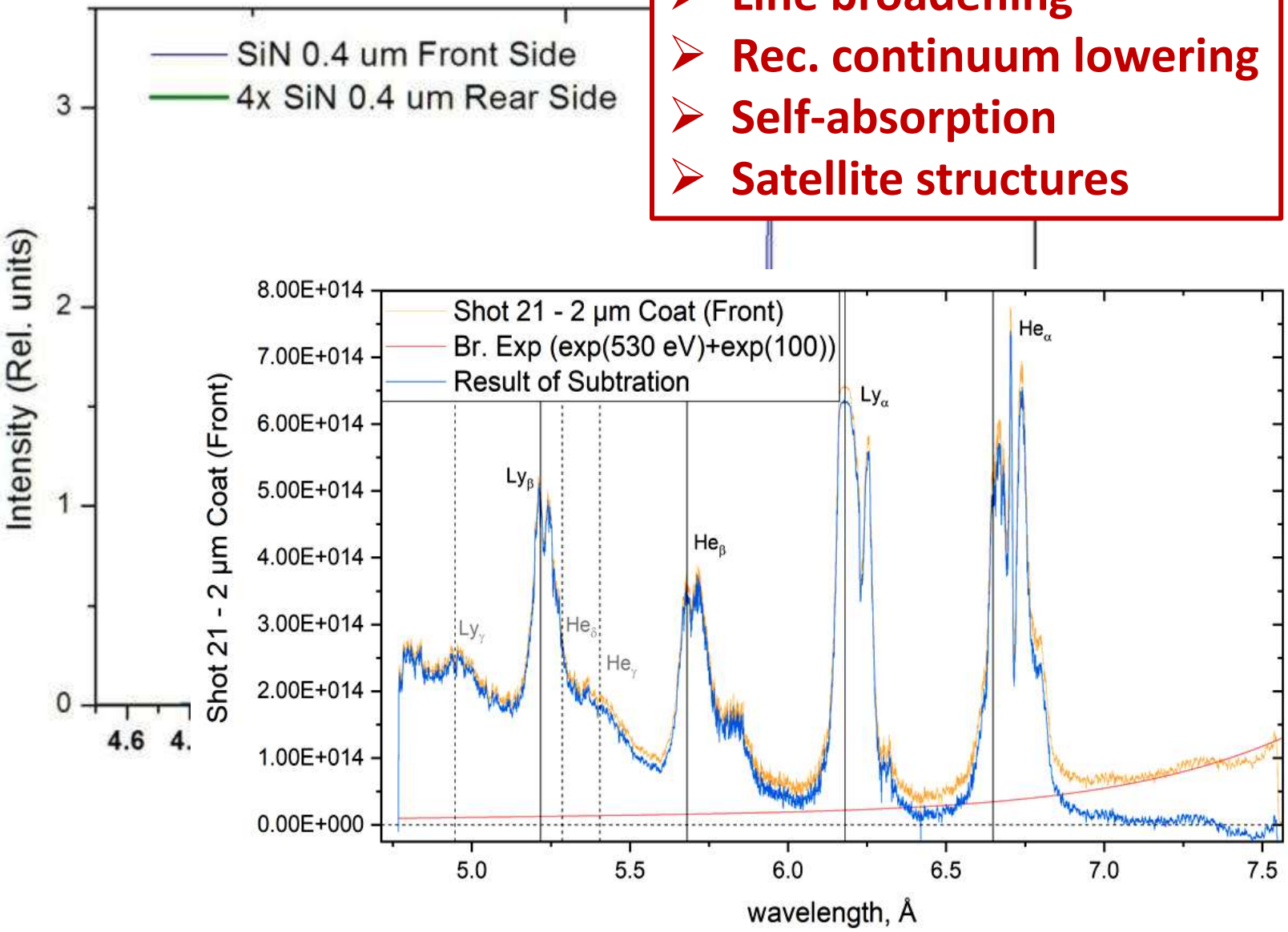
Laser contrast >10^{10}

I_{las} = 1e21 W/cm²

// talk of Maria Alkhimova

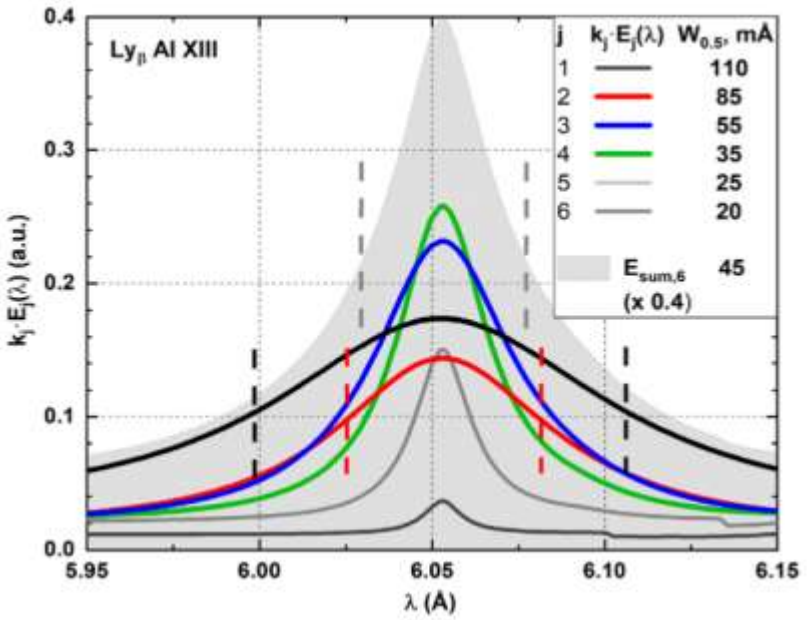
Solid-density plasma emission spectra

- Line broadening
- Rec. continuum lowering
- Self-absorption
- Satellite structures

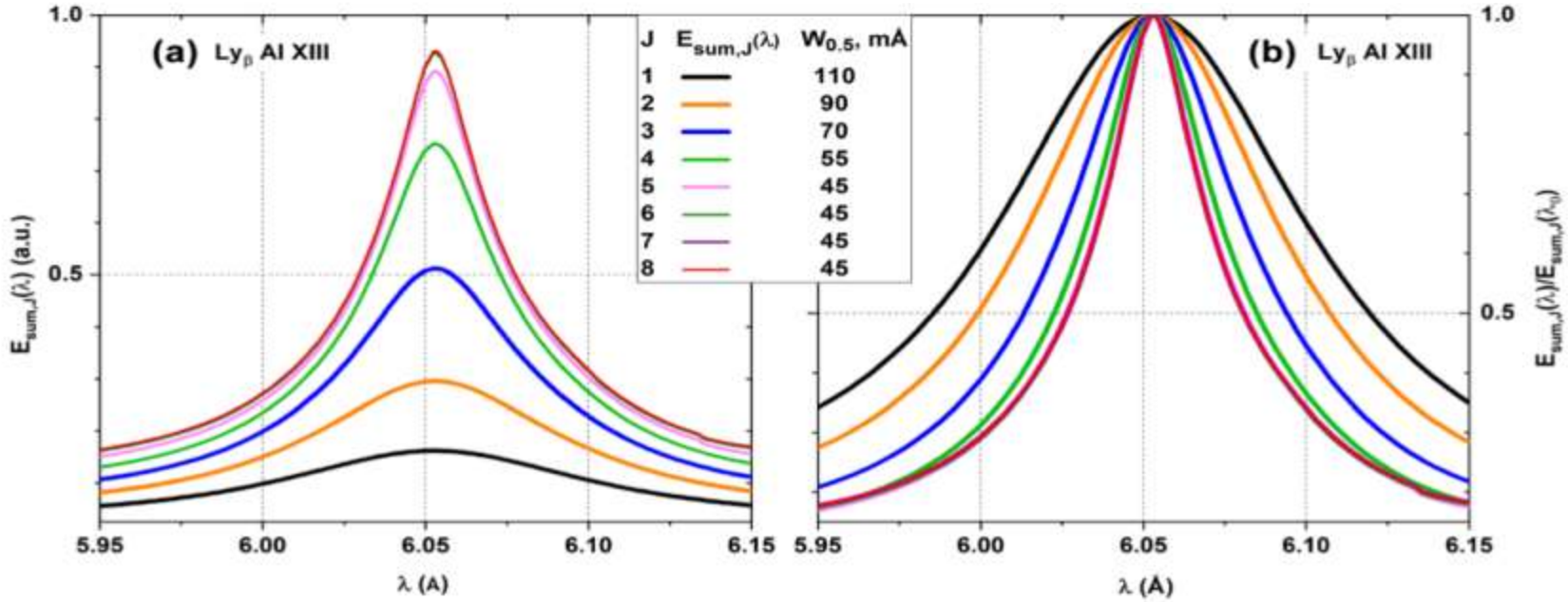


Revealing the initial density from time-integrated data

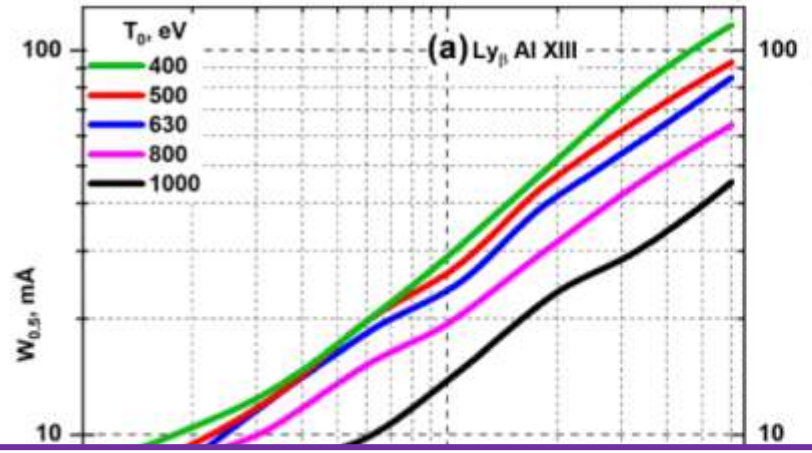
Considering the plasma freely expands from the target surface and cools down adiabatically (γ =1.4)

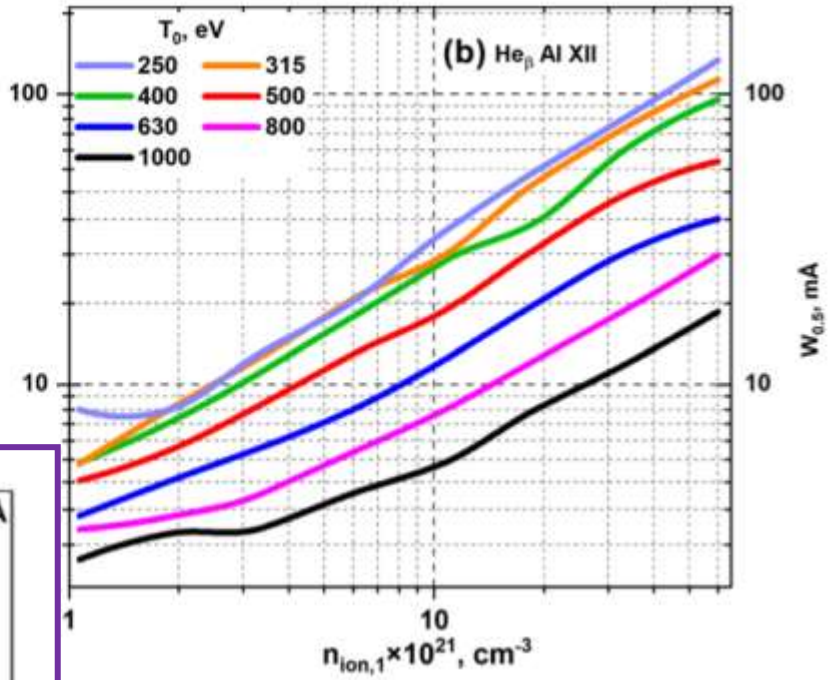


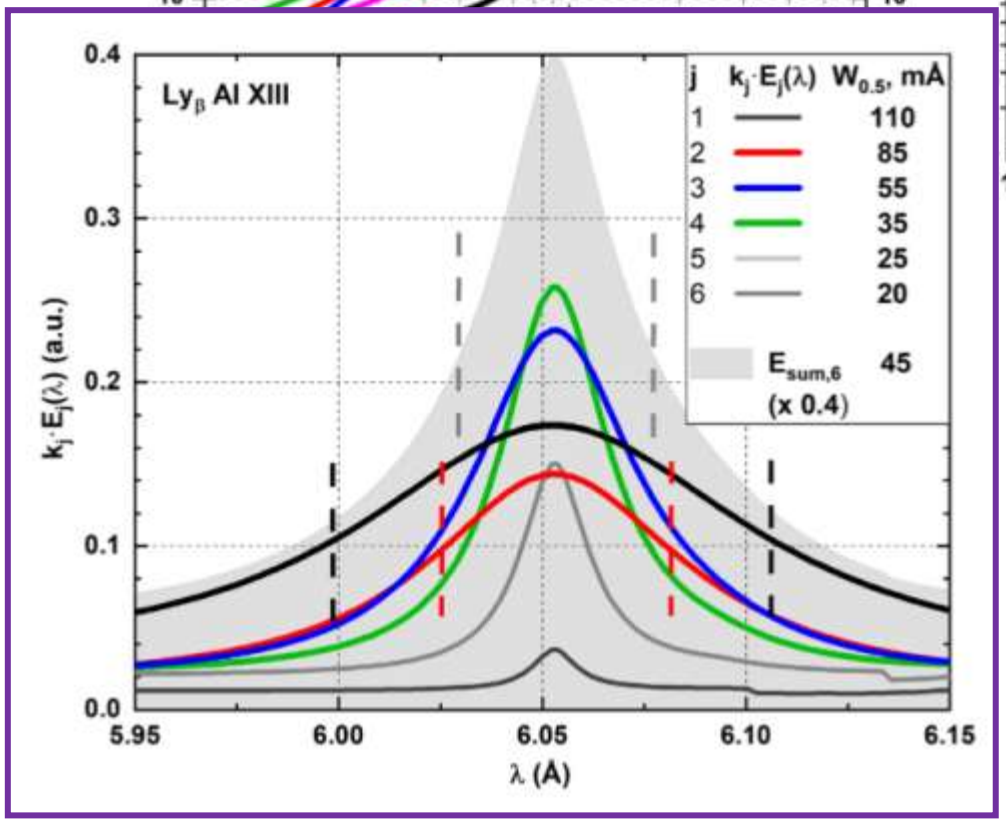
Al Lyβ spectral line profiles calculated for different stages of plasma expansion



Revealing the initial density from time-integrated data

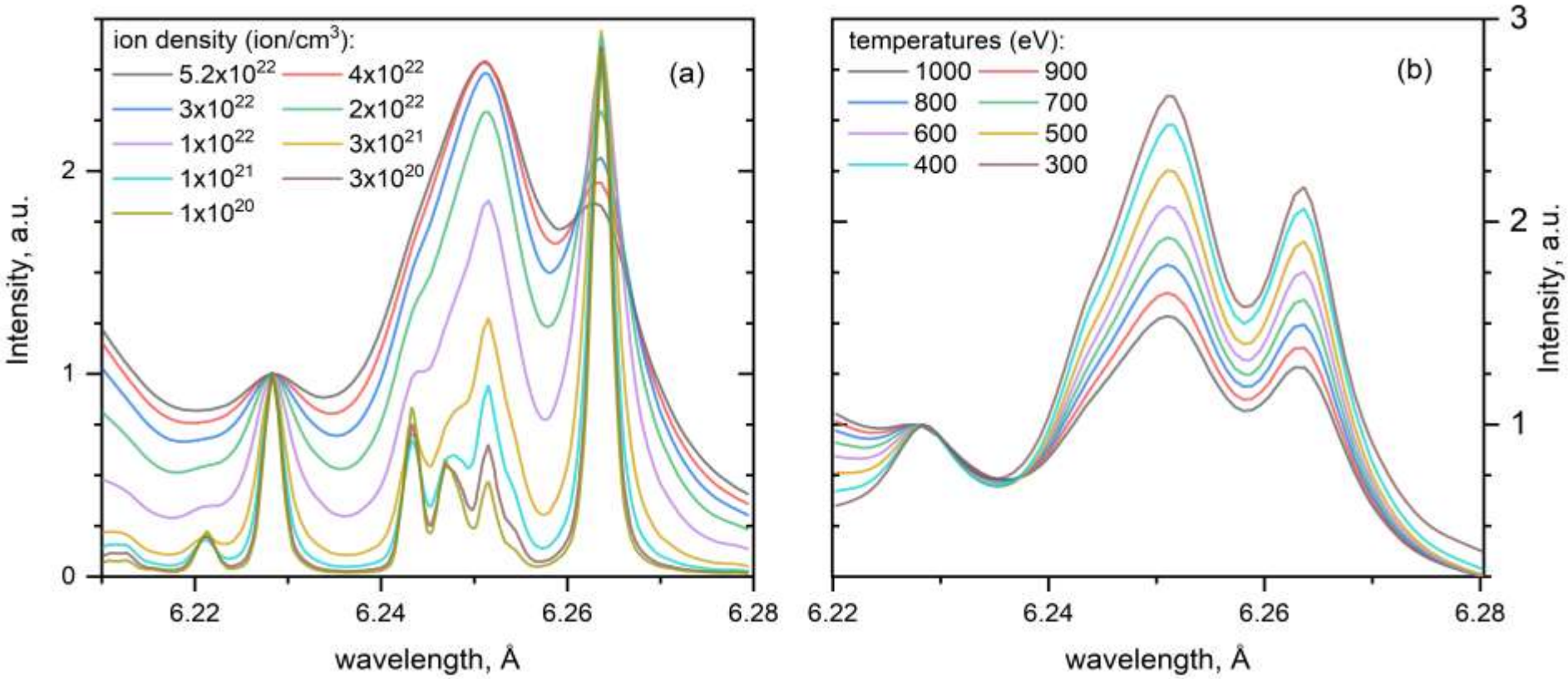






Using adiabatic plasma expansion approach the correction factors are calculated allowing to interpret the width of Lyb or Heb spectral lines measured in time-integrated spectra and to reveal the initial density of the most hot stage of plasma after the impact of the main pulse

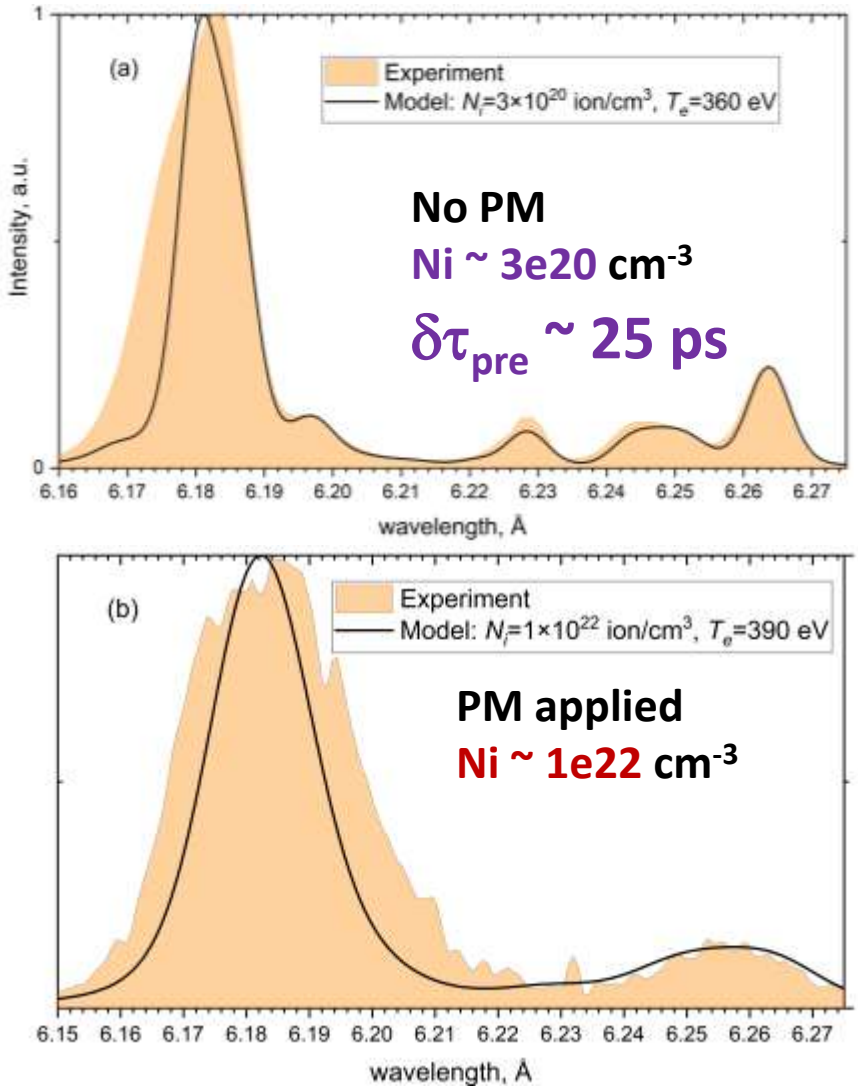
Dielectronic satellites analysis



The dielectronic satellite structure is highly sensitive to plasma density, while weakly depending on Te

For optically-thin plasma the ratio between satellite structure and resonance line intensities determines by Te and weakly depending on Ne

Capability to control laser pulse contrast



No PM

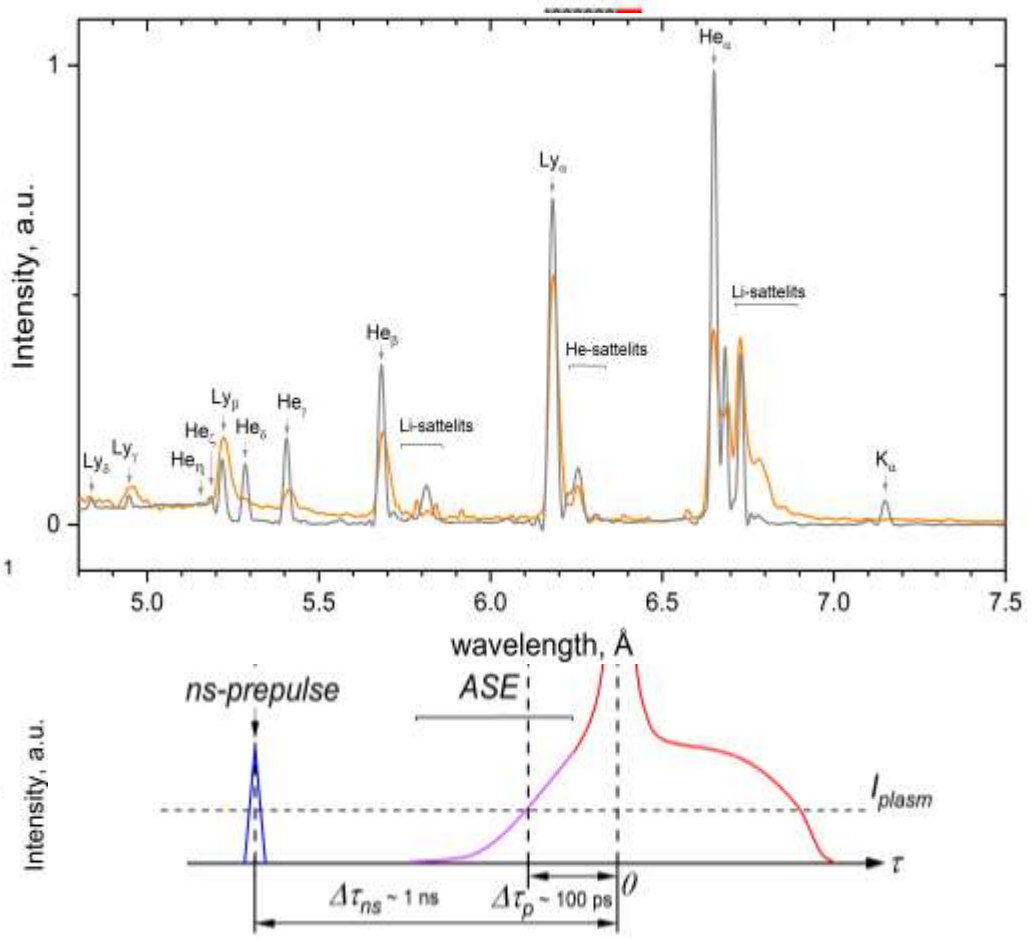
Ni ~ 3e20 cm^{-3}

$\delta\tau_{pre}$ ~ 25 ps

PM applied

Ni ~ 1e22 cm^{-3}

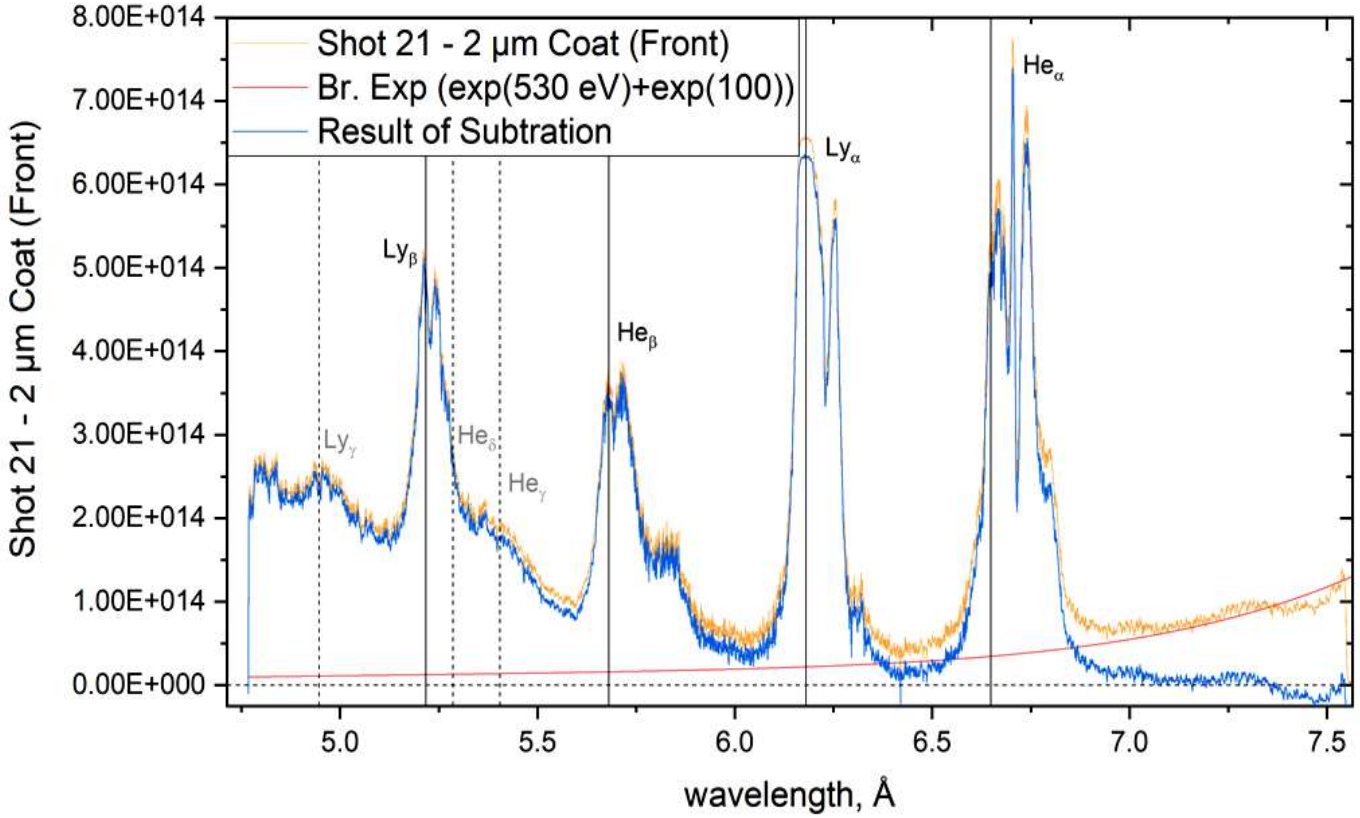
"$\delta\tau_{pre}$ ~1 ps" ~ τ_{main}



Assuming HD of plasma expansion (v ~5e7 cm/s) the plasma density observed in X-rays allows to estimate the time when the preplulse reaches ionization threshold

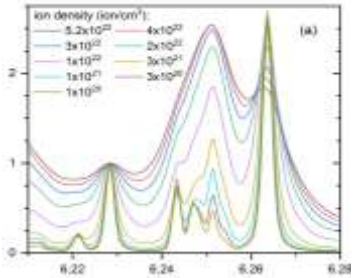
Recombination continuum

- Line broadening
- Satellite structures
- **Rec. continuum lowering**
- **Self-absorption**

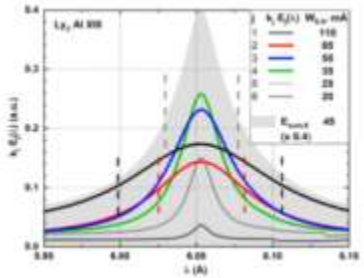


Summary

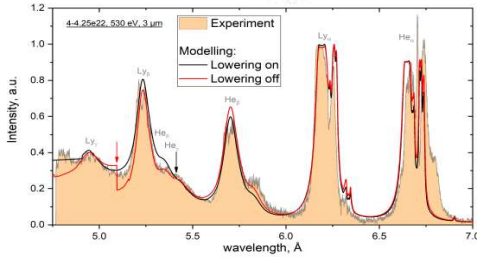
- **Several solid-density effects are observed** in X-ray spectra emitted by Si targets irradiated by high-contrast PW laser pulses.



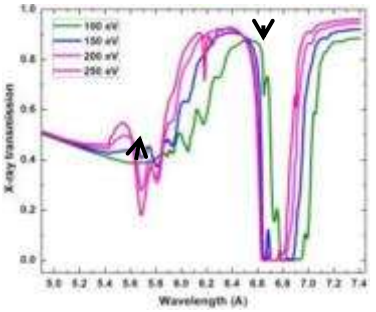
- **Plasma density is measured** by means of X-ray spectroscopy analysis **showing the effects** of different **target configuration and** further enhancement of the **laser pulse contrast**



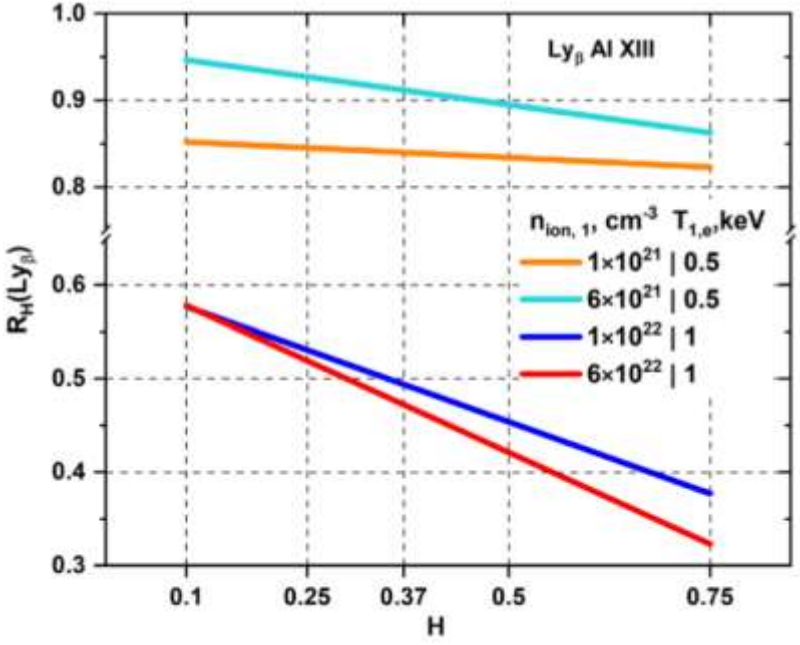
- **Diagnostic** approach helping to **estimate the density of plasma in the moment** of the main laser pulse impact is developed considering **time-integrated** spectral data

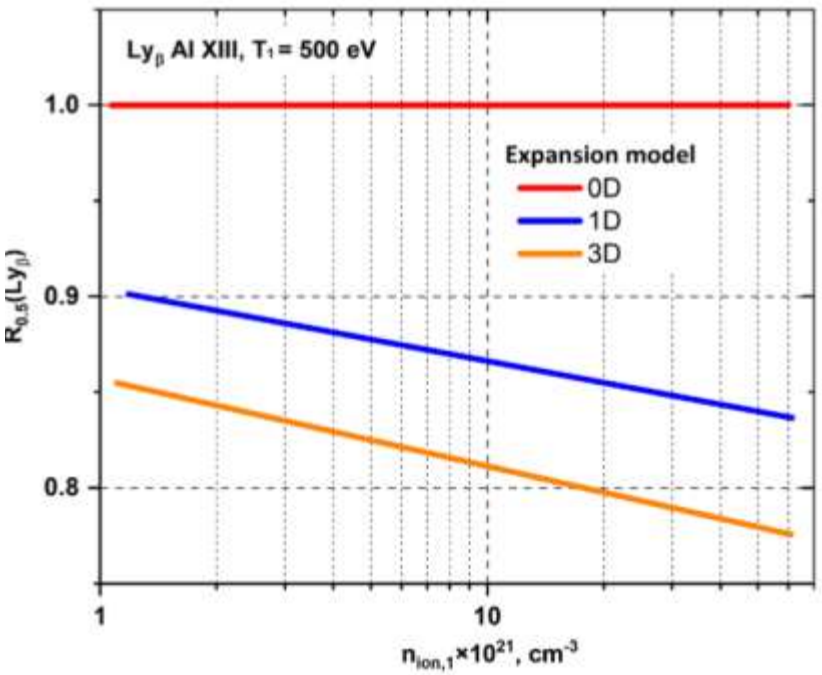


- **The effect of ionization potential depression /** recombination continuum lowering is observed in the emission of solid-density Si plasma. The shift of recombination continuum edge is **compared with H&M IPD model**

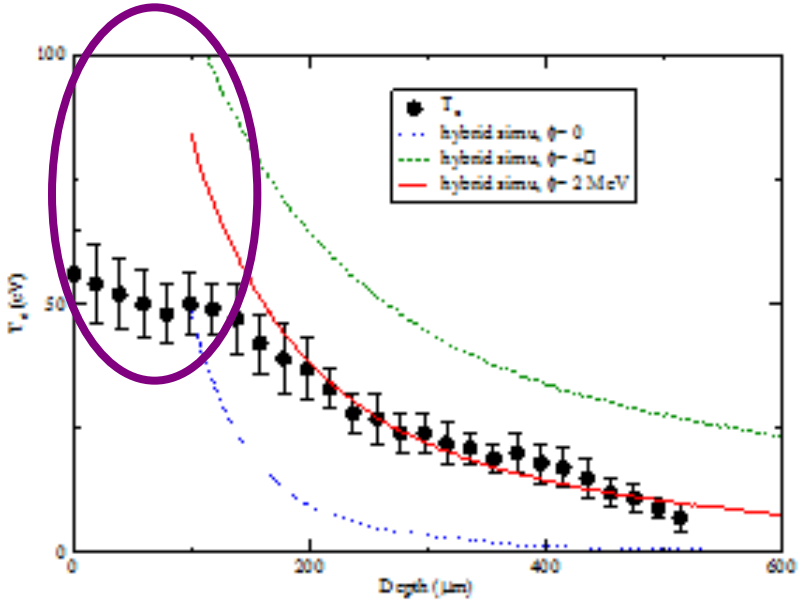


- **Method of absorption X-ray spectroscopy** is developed to study the heating of a matter irradiated by the emission of relativistic laser plasma. Either the temperature of low-emissive WDM can be determined or WDM opacity models can be verified.


Ly$_\beta$ Al XIII
$n_{ion,1}$, cm^{-3} $T_{1,e}$,keV
1×10^{21} | 0.5
6×10^{21} | 0.5
1×10^{22} | 1
6×10^{22} | 1
R_H(Ly$_\beta$)
H
1.0
0.9
0.8
0.6
0.5
0.4
0.3
0.1
0.25
0.37
0.5
0.75

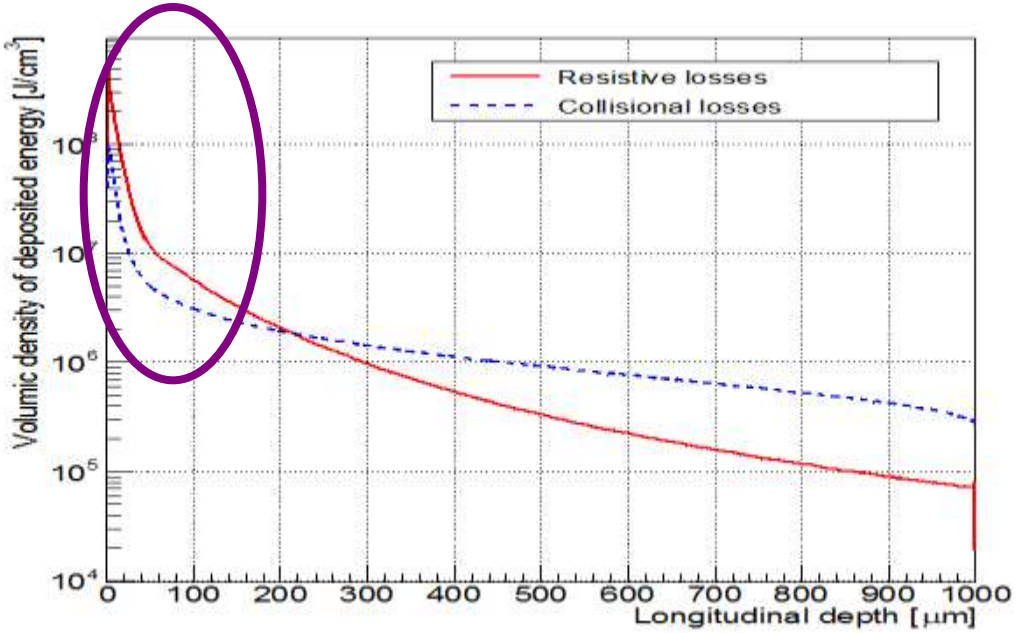

Ly$_\beta$ Al XIII, T_1 = 500 eV
Expansion model
0D
1D
3D
$R_{0.5}$(Ly$_\beta$)
$n_{ion,1}$×10^{21}, cm^{-3}
1.0
0.9
0.8
1
10

Hybrid simulation data, resistive vs collisional losses



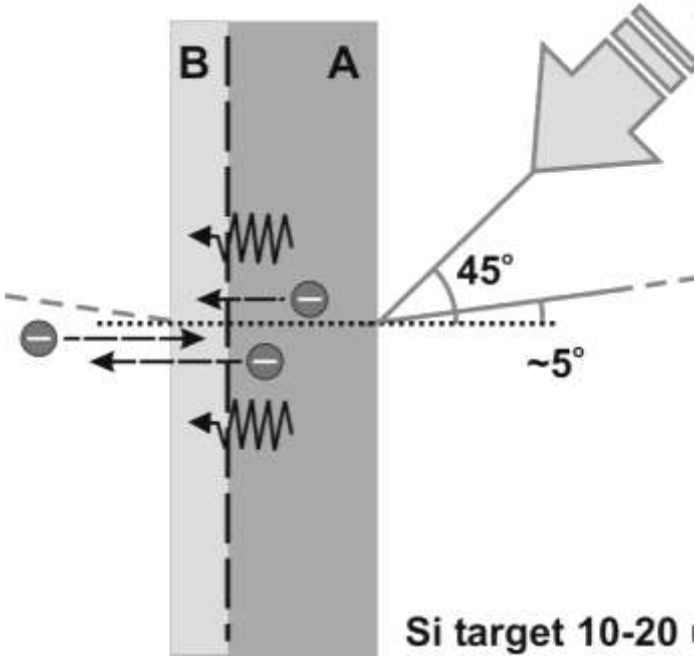
Allowing to estimate the effect of refluxing at wire boundaries, as well as the ratio between collisional and resistive losses

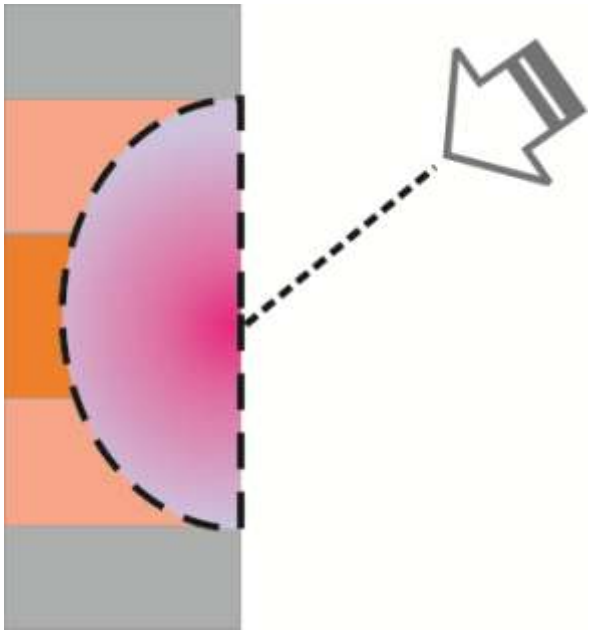
At first 150 um of the trajectory resistive losses may exceeds collisional ones by factor of 2.3



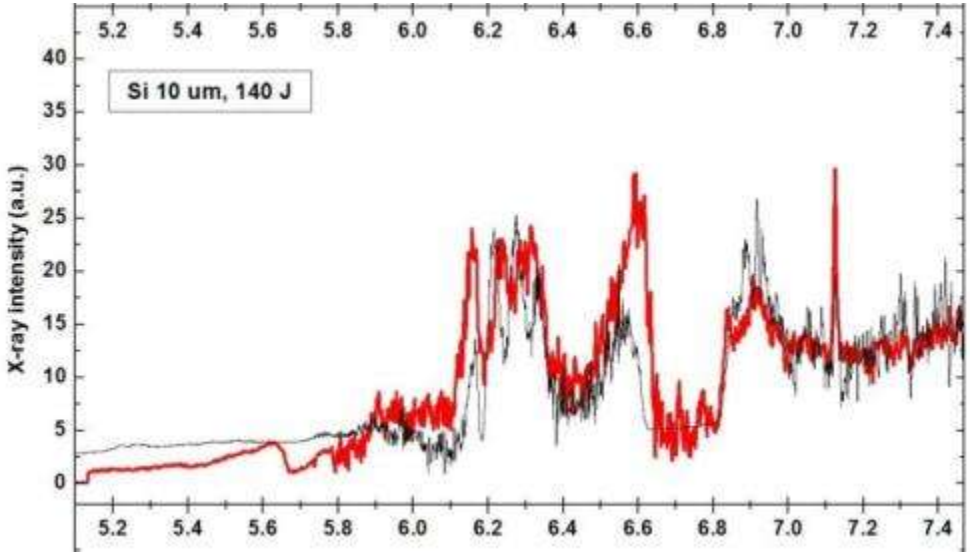
"Depression" of isohoric heating of matter at the beginning of MeV electrons stopping trajectory is still challenging question

Model is developing…

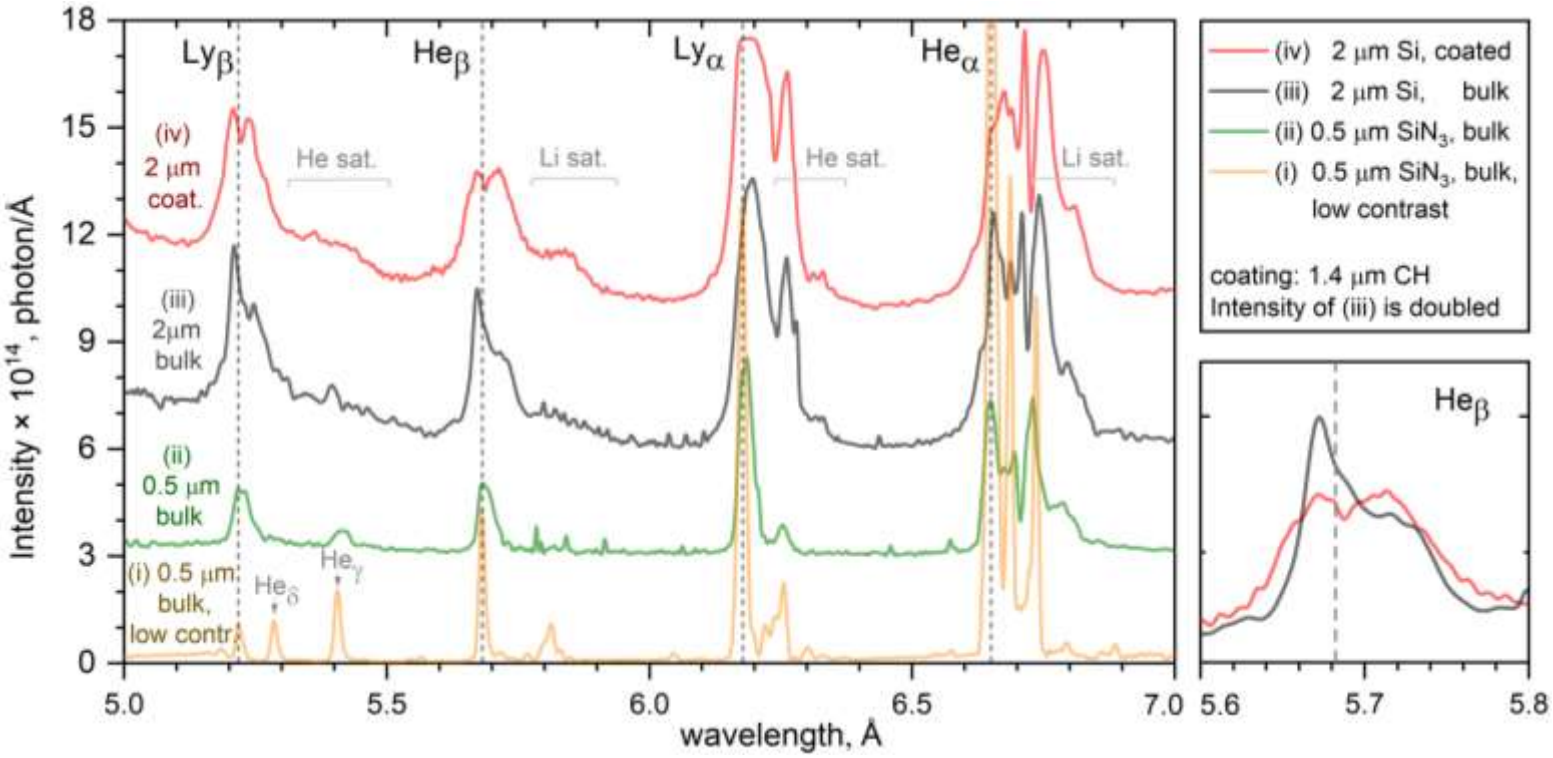


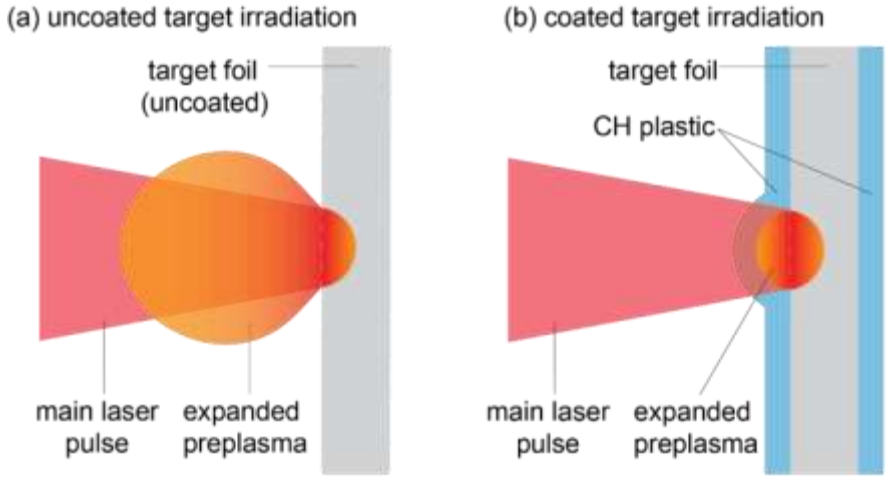


Si target 10-20



Spectral features depending on type of the target

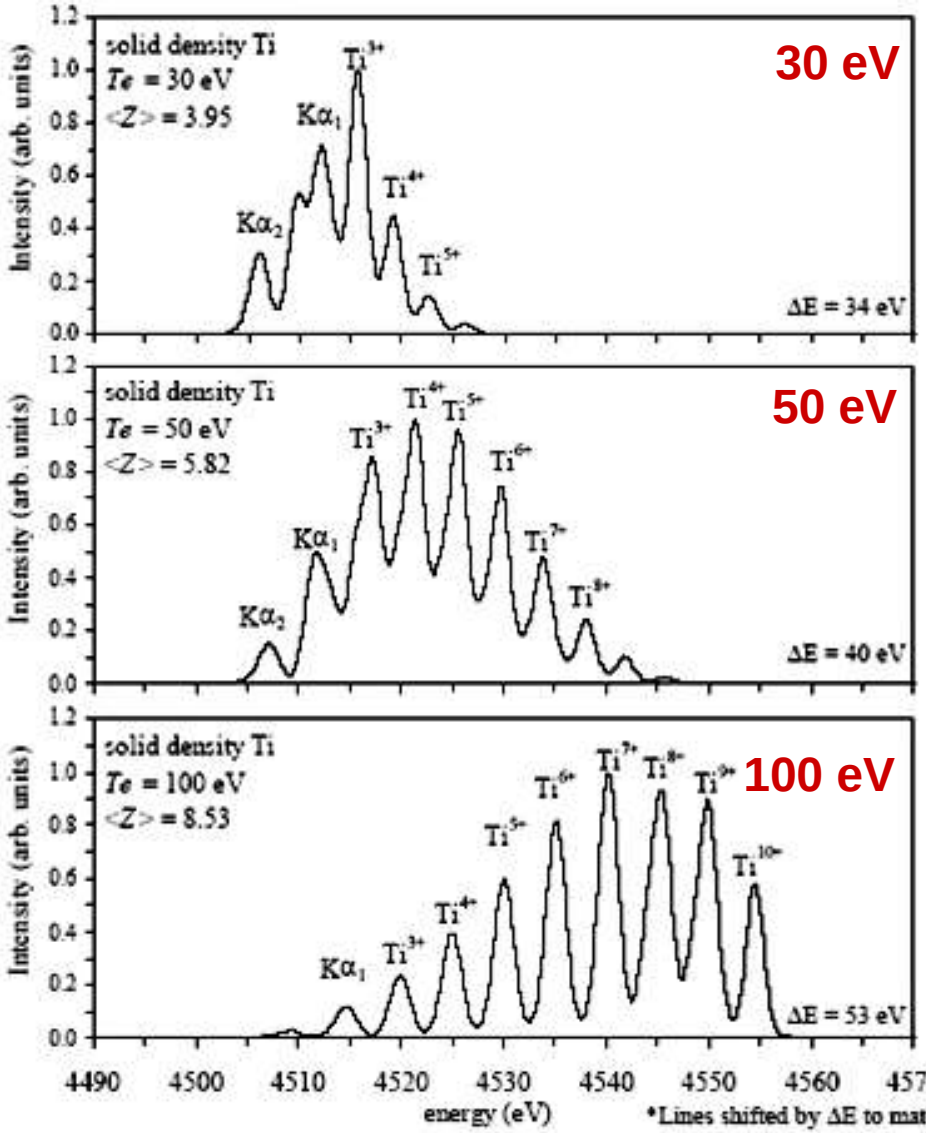




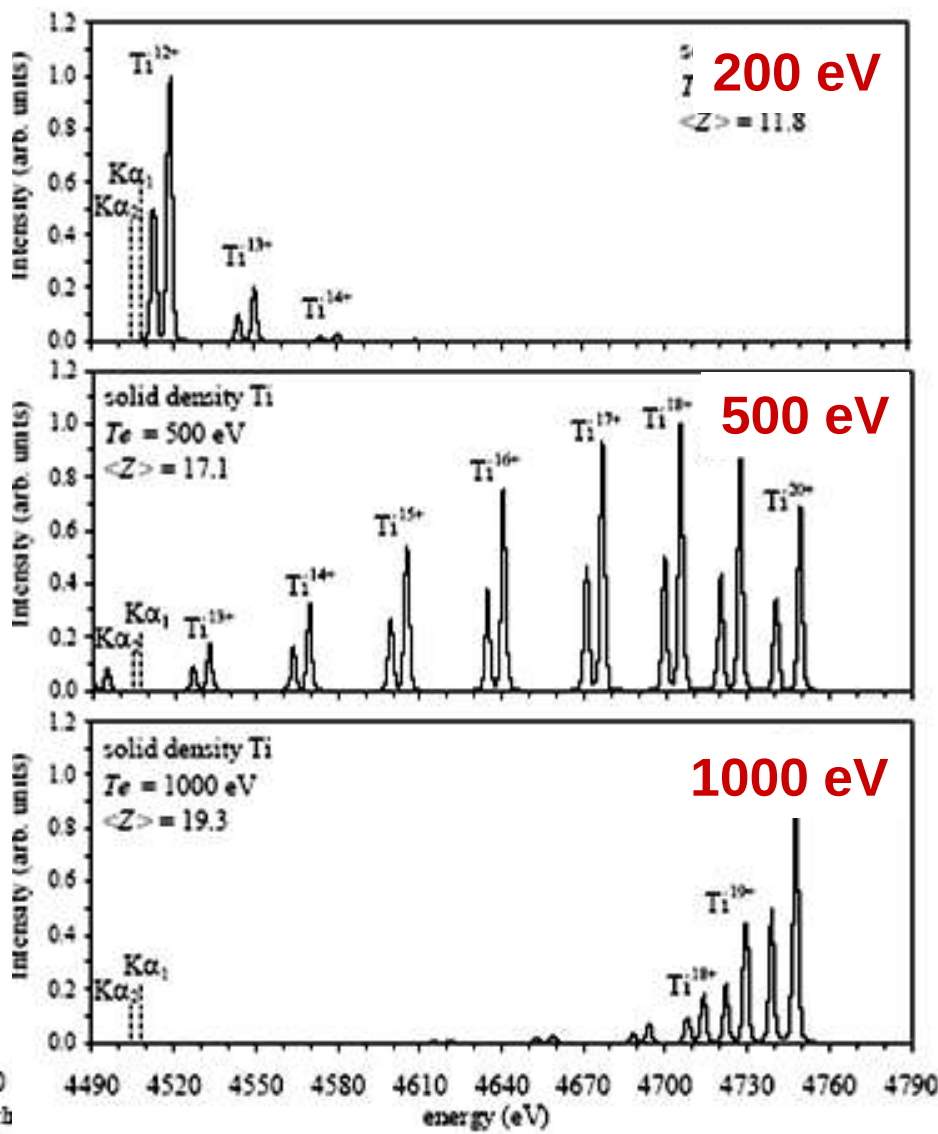
X-ray specs diagnostic capabilities, 30-1000 eV range

// S. Hansen et al, *MUZE* model, Voigt line shapes (2005)

Further M-shell ionization



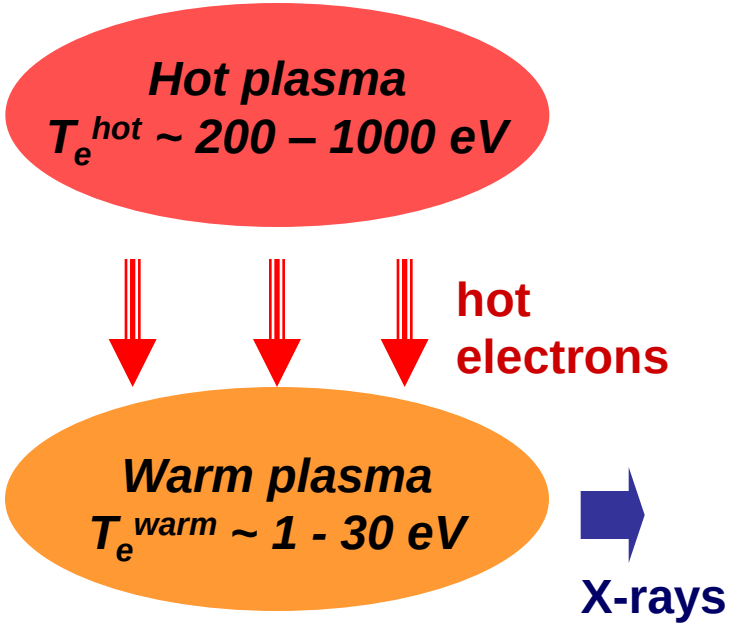
When L-shell ionization turns on

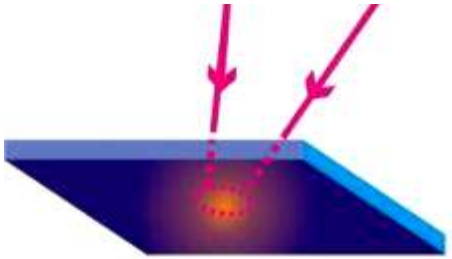


WDM studies using optical lasers – principle and setup

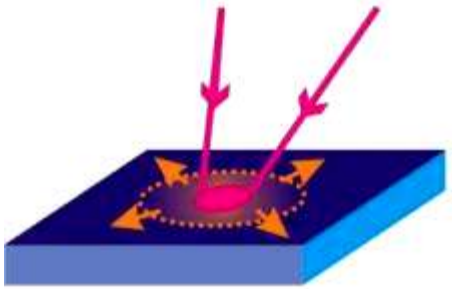
Hot plasma (T_e ~ 1 keV), commonly in laser focus

WDM – (T_e ~ 10-100 eV, N_e~10^{23} cm^{-3})

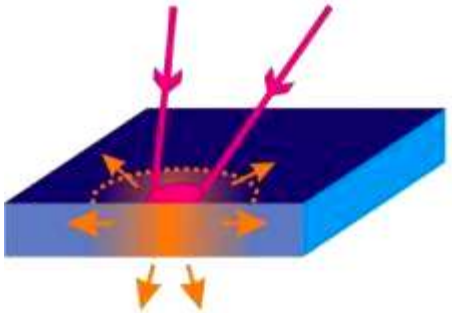




rear side of thin foil



vicinity of hot plasma at front side



along electron trajectory deep into the target

By means of X-ray spectroscopy T_e^{warm} can be determined when over 10 eV.

Spatial resolution is of crucial importance.

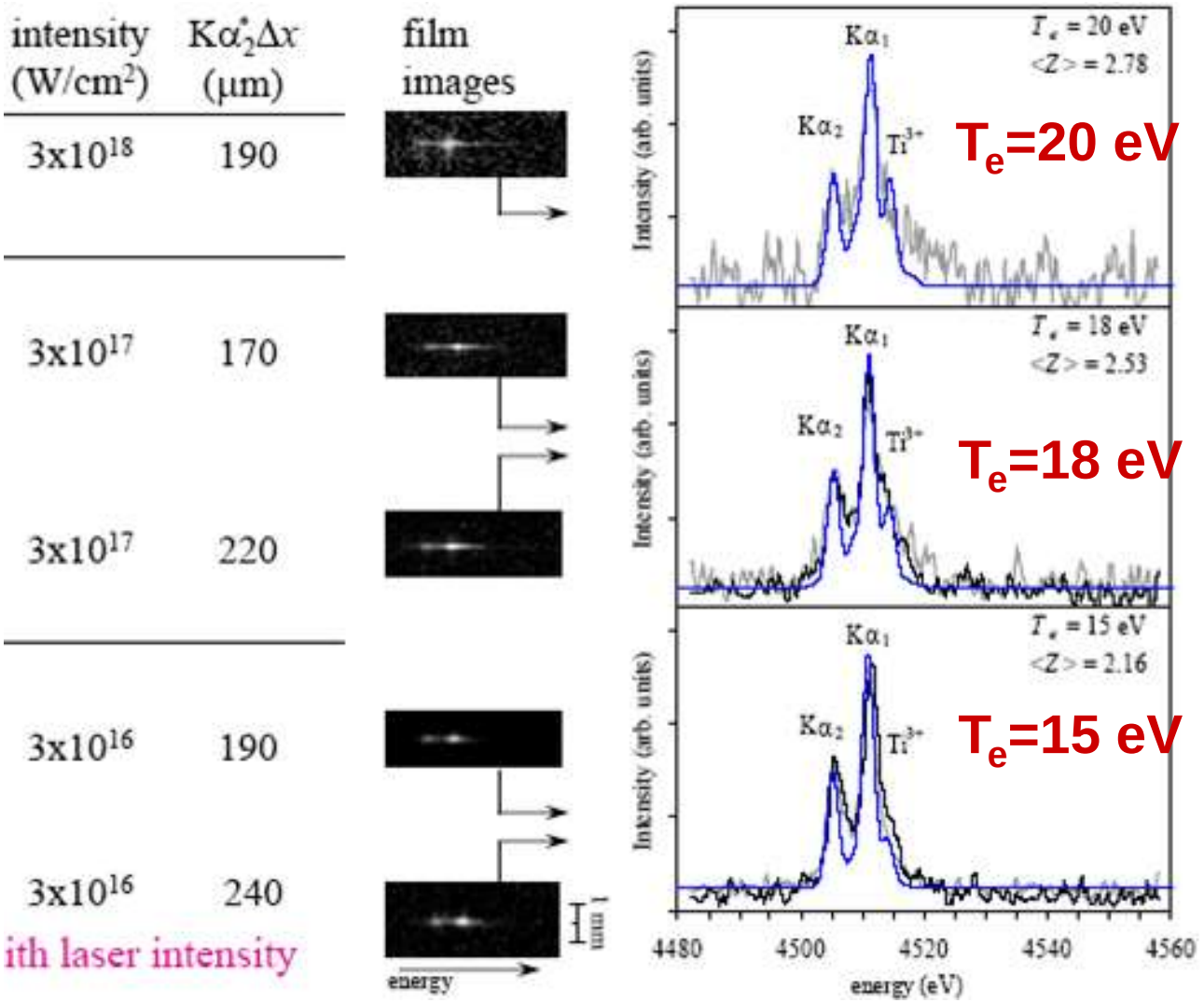
Previous observations

Rear-side spectra:

Laser energy – 1-6 J
Pulse duration – 0.5 ps
I_{max}= 1 x 10^{19} W/cm^2
Target – Ti foils 2-50 μm

T_e is described with few eV precision in the range of 15-25 eV

Though the laser intensity was varied in the range of 1e16 – 1e18 W/cm^2 the temperature increases just for a few eV.



T$_e$=20 eV
T$_e$=18 eV
T$_e$=15 eV

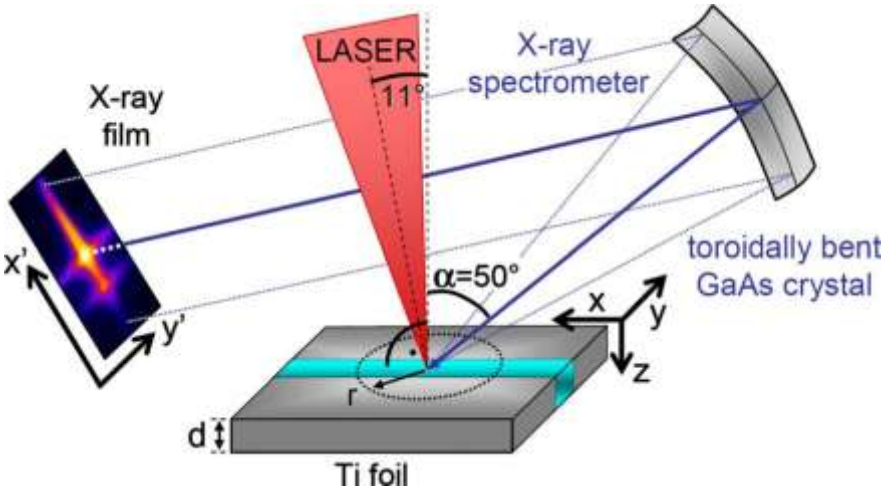
// S.B. Hansen et al, PRE **72, 036408 (2005)**

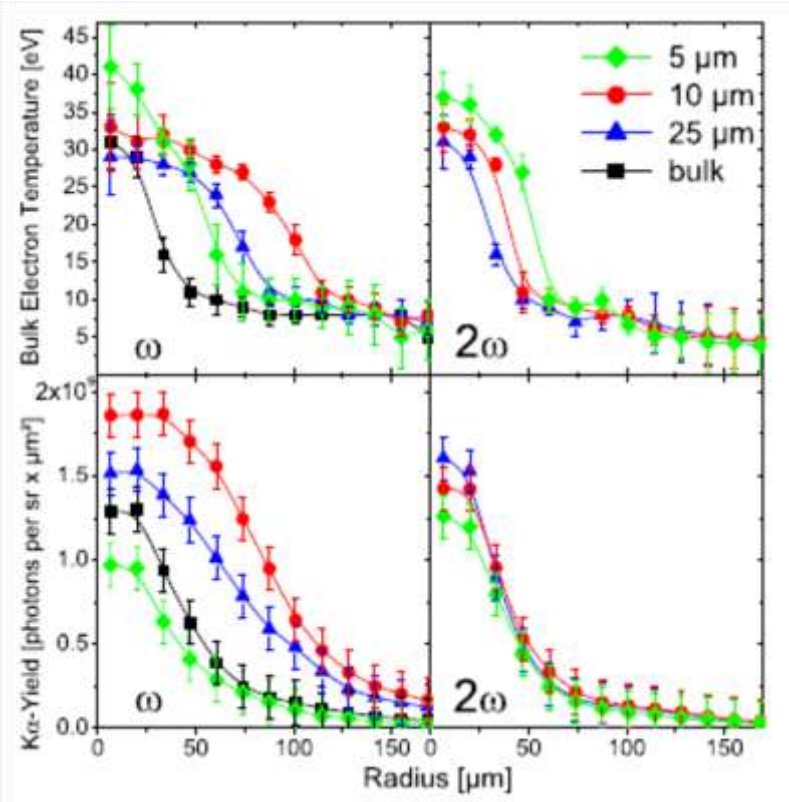
Previous observations

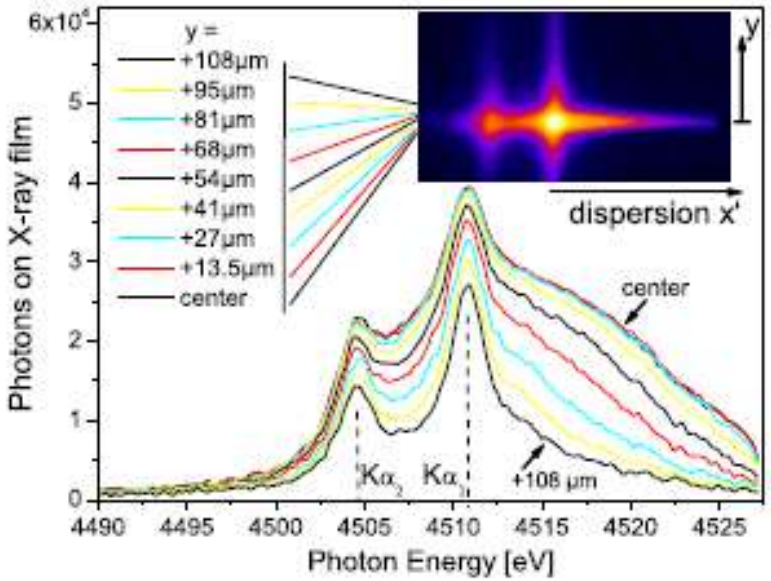
WDM at the front side of laser irradiated bulk solids, in the vicinity of focal spot

// U. Zasrau et al. PRE 81, 026406 (2010)

0.35 ps, 15 J, I ~ 5e19 W/cm^2







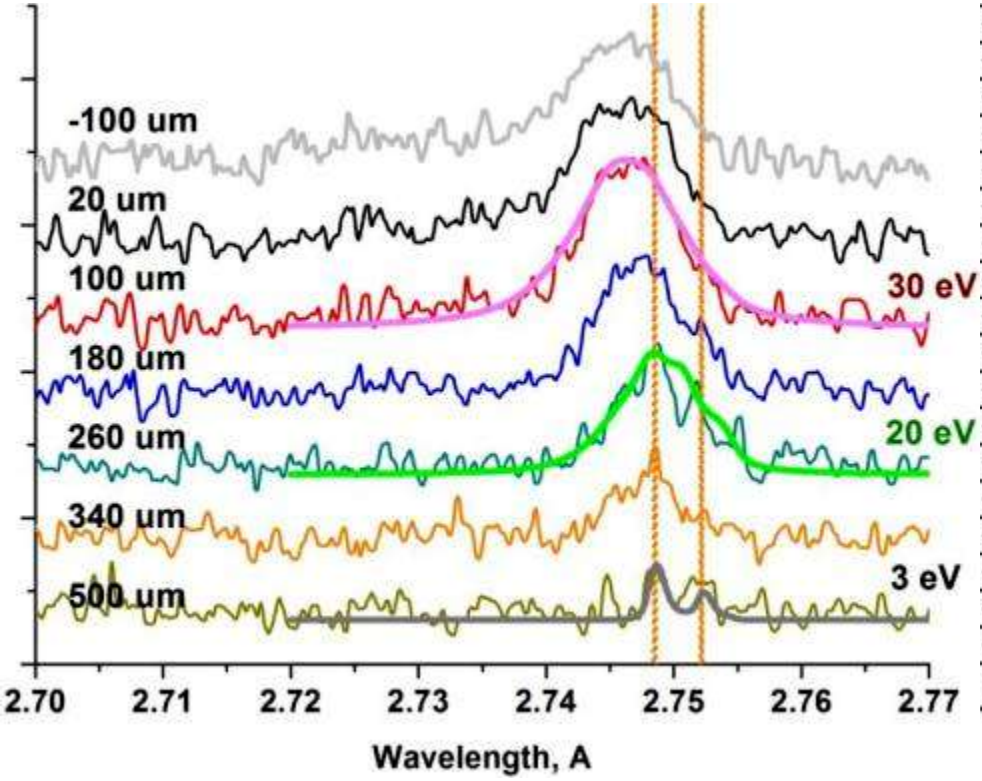
T_e ~40 eV - near the focal spot

T_e ~10 eV - at 100 um from the center

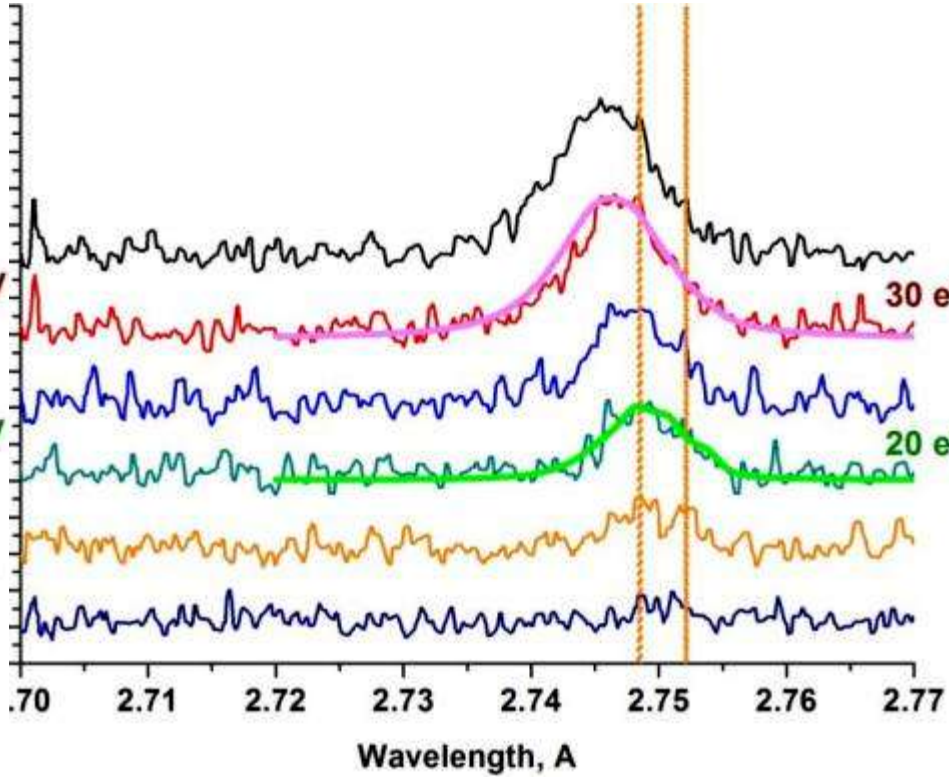
Exponential decrease of Ka-line intensity

Experimental results – T_e measured

0.5 ps, 200 J, 5 um focusØ
I ~ 5e20 W/cm^2



0.7 ps, 200 J, 15 um focusØ
I ~ 4e19 W/cm^2

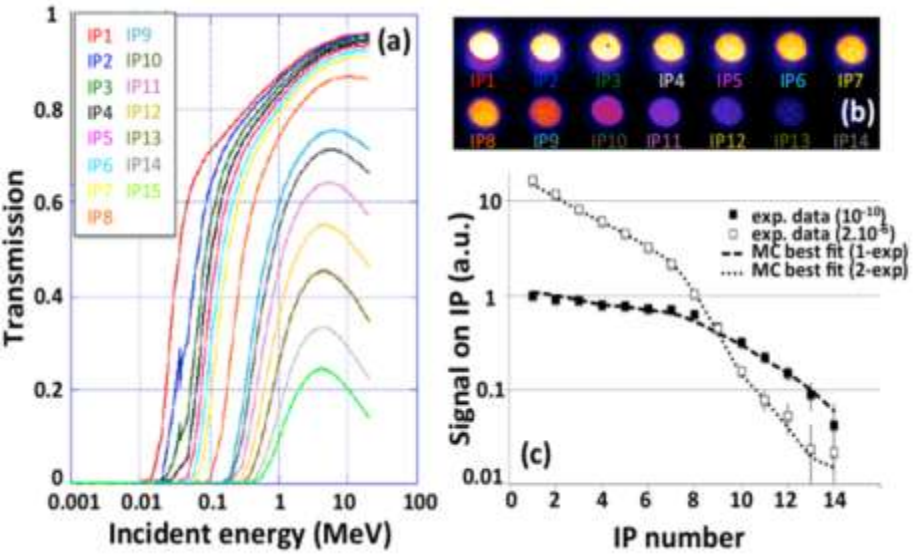


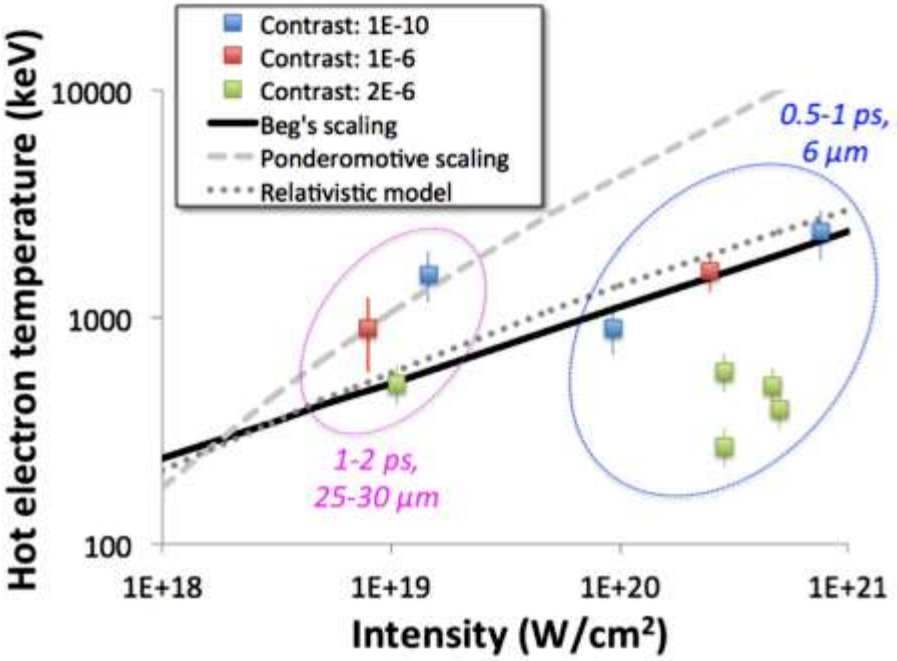
In both cases highest T_e achieved by isochoric heating is of ~ 50 eV

Laser power delivered to the target front surface is more important for the heating of the deep-lying matter, instead of the focusing intensity (at least in the case of mass-limited target)

Hard X-rays data

Estimations on hot electron energy spectra using bremstrahlung cannon data





Stopping power of cold Ti for 2 MeV e^- is of ~0.6 MeV/mm

The stopping range of 3 mm was expected due to collisional losses in cold Ti

T_{hot} measured with tight laser focusing follows Beg's scaling law

Hard X-ray data gives the temperature of hot electron tail of ~2 MeV (as expected)