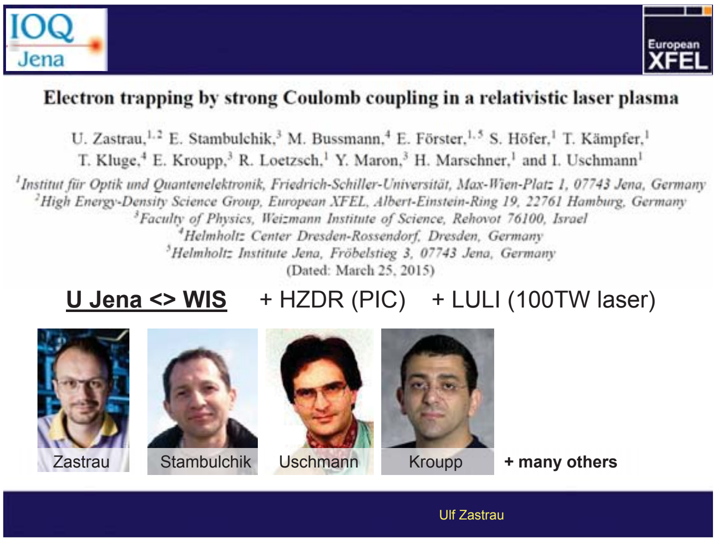
March 26, 2015

Workshop on Modern Methods of Plasma Spectroscopy

Electron trapping by strong Coulomb coupling in a relativistic laser plasma

Ulf Zastrau[1,2]

[1] X-ray Optics Group, Institute for Optics and Quantum Electronics
Friedrich-Schiller-University of Jena, Germany
[2] High Energy-Density (HED) Science Group,
European XFEL, Hamburg, Germany



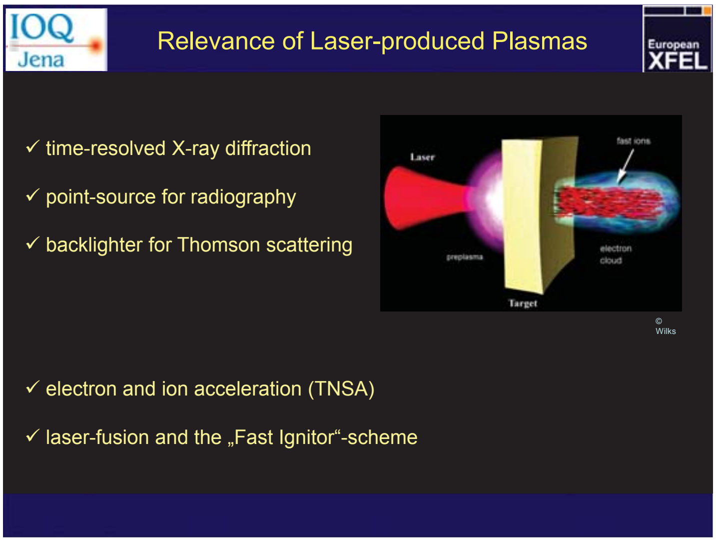
Electron trapping by strong Coulomb coupling in a relativistic laser plasma

U. Zastrau,[1,2] E. Stambulchik,[3] M. Bussmann,[4] E. Förster,[1,5] S. Höfer,[1] T. Kämpfer,[1]
T. Kluge,[4] E. Kroupp,[3] R. Loetzsch,[1] Y. Maron,[3] H. Marschner,[1] and I. Uschmann[1]

[1] Institut für Optik und Quantenelektronik, Friedrich-Schiller-Universität, Max-Wien-Platz 1, 07743 Jena, Germany
[2] High Energy-Density Science Group, European XFEL, Albert-Einstein-Ring 19, 22761 Hamburg, Germany
[3] Faculty of Physics, Weizmann Institute of Science, Rehovot 76100, Israel
[4] Helmholtz Center Dresden-Rossendorf, Dresden, Germany
[5] Helmholtz Institute Jena, Fröbelstieg 3, 07743 Jena, Germany
(Dated: March 25, 2015)

U Jena <> WIS + HZDR (PIC) + LULI (100TW laser)

Zastrau Stambulchik Uschmann Kroupp **+ many others**



Relevance of Laser-produced Plasmas

- ✓ time-resolved X-ray diffraction
- ✓ point-source for radiography
- ✓ backlighter for Thomson scattering
- ✓ electron and ion acceleration (TNSA)
- ✓ laser-fusion and the „Fast Ignitor"-scheme

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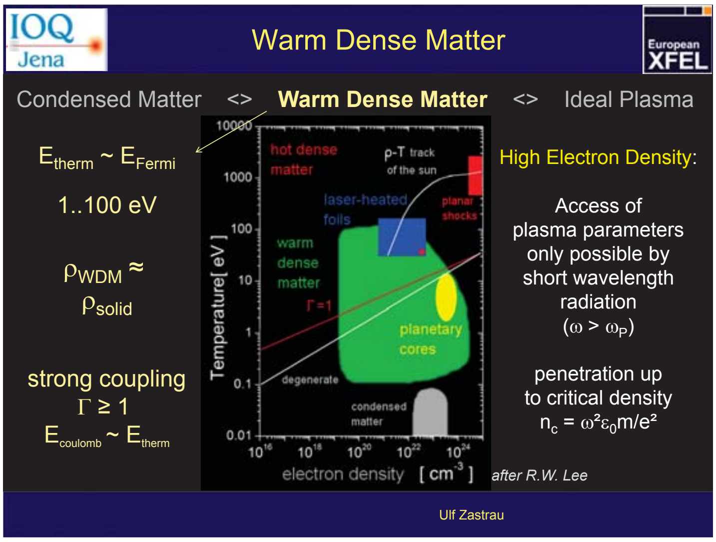


Warm Dense Matter

Condensed Matter <> **Warm Dense Matter** <> Ideal Plasma

$E_{therm} \sim E_{Fermi}$

1..100 eV

$\rho_{WDM} \approx \rho_{solid}$

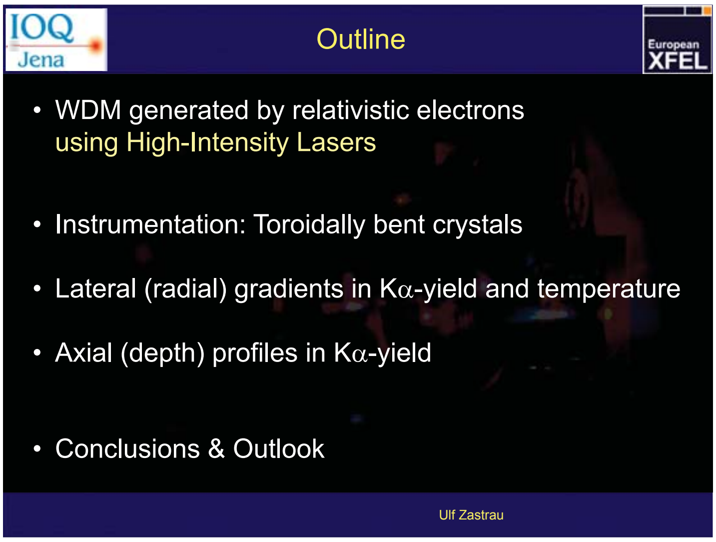
strong coupling
$\Gamma \geq 1$
$E_{coulomb} \sim E_{therm}$

High Electron Density:

Access of plasma parameters only possible by short wavelength radiation
($\omega > \omega_P$)

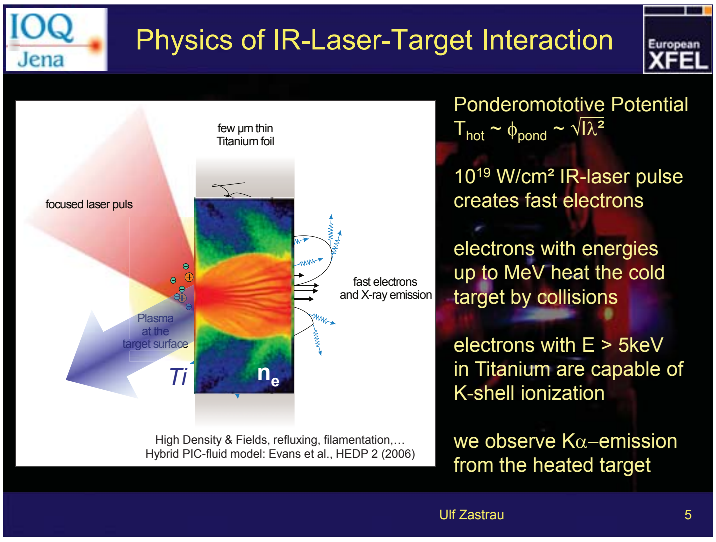
penetration up to critical density
$n_c = \omega^2 \varepsilon_0 m/e^2$

after R.W. Lee



Outline

- WDM generated by relativistic electrons using High-Intensity Lasers
- Instrumentation: Toroidally bent crystals
- Lateral (radial) gradients in Kα-yield and temperature
- Axial (depth) profiles in Kα-yield
- Conclusions & Outlook



Physics of IR-Laser-Target Interaction

High Density & Fields, refluxing, filamentation,…
Hybrid PIC-fluid model: Evans et al., HEDP 2 (2006)

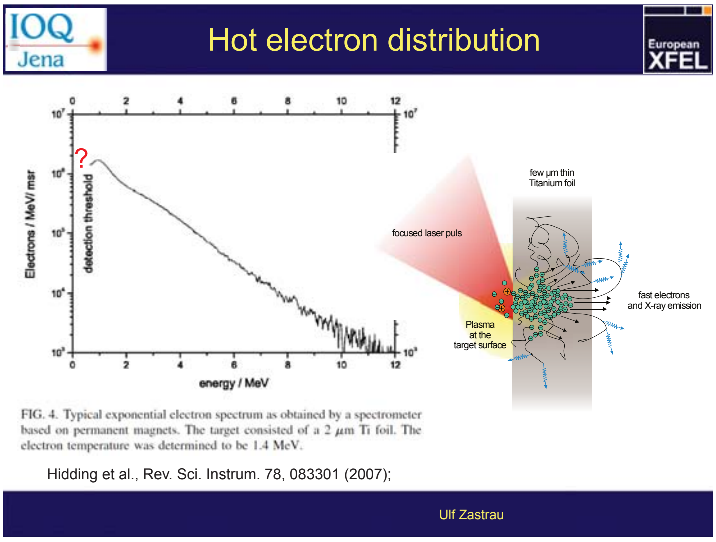
Ponderomototive Potential
$T_{hot} \sim \phi_{pond} \sim \sqrt{I\lambda^2}$

10^{19} W/cm² IR-laser pulse creates fast electrons

electrons with energies up to MeV heat the cold target by collisions

electrons with E > 5keV in Titanium are capable of K-shell ionization

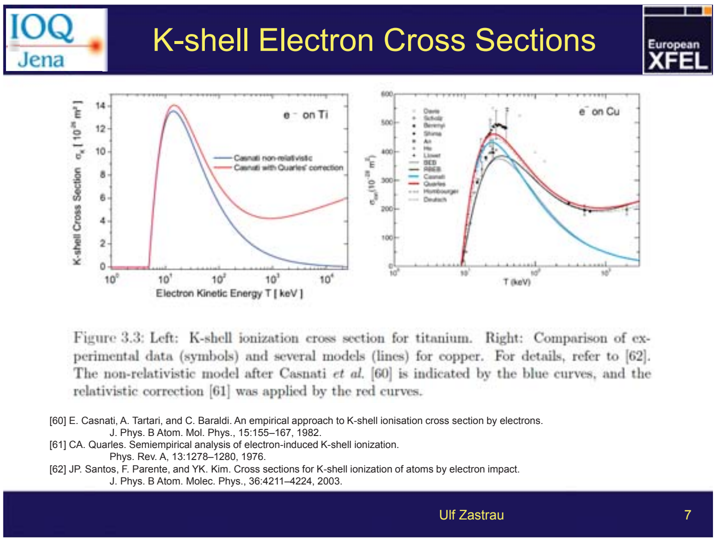
we observe Kα–emission from the heated target



Hot electron distribution

FIG. 4. Typical exponential electron spectrum as obtained by a spectrometer based on permanent magnets. The target consisted of a 2 µm Ti foil. The electron temperature was determined to be 1.4 MeV.

Hidding et al., Rev. Sci. Instrum. 78, 083301 (2007);



K-shell Electron Cross Sections

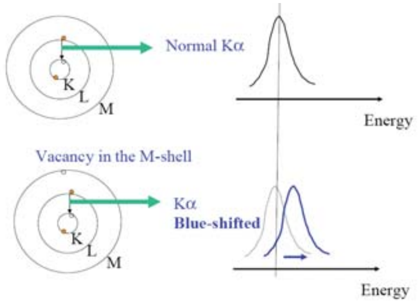
Figure 3.3: Left: K-shell ionization cross section for titanium. Right: Comparison of experimental data (symbols) and several models (lines) for copper. For details, refer to [62]. The non-relativistic model after Casnati *et al.* [60] is indicated by the blue curves, and the relativistic correction [61] was applied by the red curves.

[60] E. Casnati, A. Tartari, and C. Baraldi. An empirical approach to K-shell ionisation cross section by electrons. J. Phys. B Atom. Mol. Phys., 15:155–167, 1982.
[61] CA. Quarles. Semiempirical analysis of electron-induced K-shell ionization. Phys. Rev. A, 13:1278–1280, 1976.
[62] JP. Santos, F. Parente, and YK. Kim. Cross sections for K-shell ionization of atoms by electron impact. J. Phys. B Atom. Molec. Phys., 36:4211–4224, 2003.

Blueshift of Kα lines <> M-shell ionization

Start of **M-shell** ionization at temeratures	of a few eV
Start of **L-shell** ionization at temperatures	~100 eV
Start of **K-shell** ionization	> keV temperature

→ **K-shell NOT thermally ionized, can act as a probe**

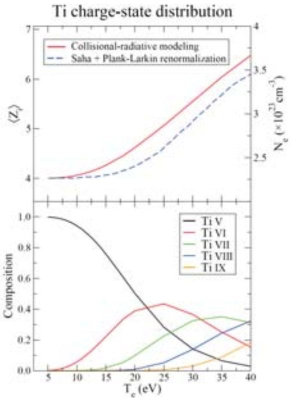


eV ion-temperature-sensitive!

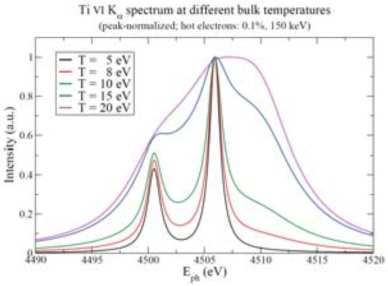
Acts on $K\alpha_1$ & $K\alpha_2$

Modeling of Ti Kα line emission

Evgeny Stambulchik *et al.*, J. Phys. A **42** (2009), 214061 1-5



In bulk titanium, delocalized quasi-free electrons have to be taken into account.
*→ A low-temperature-limit charge-state is **Ti V** (four-times ionised, Ti^{4+}).*

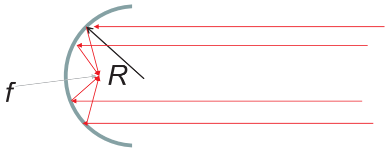


The Kα emission duration is ≤ 1ps ($T_i = T_e$ is assumed)

2D imaging with toroidal crystals

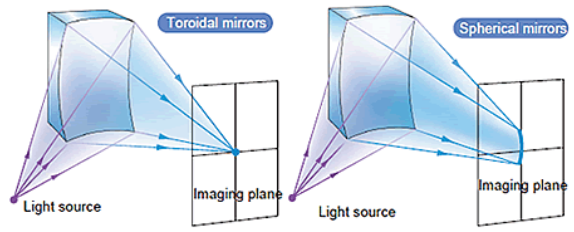
Focusing with concave sphere at ~ 90°

focal length is determined by $f = R/2$, where R is the radius of the sphere



Problems: Only close to 90°. X-ray source is in the reflected pathway. Also, the incidence angle varies. For x-rays, deviations larger than the rocking curve will stop reflecting.

From Sphere to Torus



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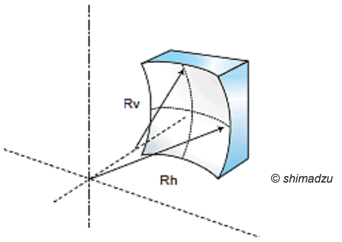
Sperical reflectors at Θ<90° cause astigmatism.

Shape of a toroidal mirror



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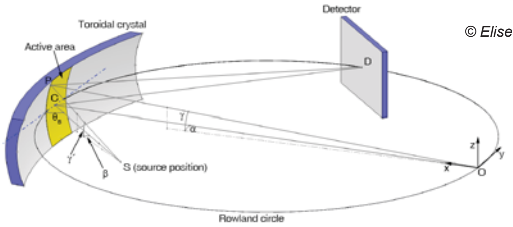
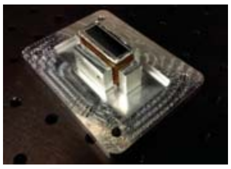
Toroidal form has two independent focal lengths:

$$f_v = \frac{R_v}{2}(\sin\Theta_B)^{-1} \qquad \text{and} \qquad f_h = \frac{R_h}{2}\sin\Theta_B$$

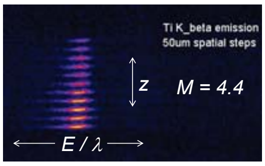
Imaging optics for mid-Z K-shell emission based on toroidally bent perfect crystals



© Eliseo Gamboa



Example:
GaAs 111
50 μm thin
bent to
R_v =100 mm
R_h = 1060 mm



Relativistic Ti plasmas:

Radial gradients in

Kα-yield ***J(r)*** and

temperature $T_e^{bulk}(r)$

École Polytechnique
200 ans d'enseignement et de recherche

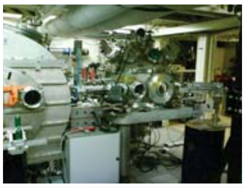
Experiment at 100TW Laser, LULI

LULI 100TW Laser

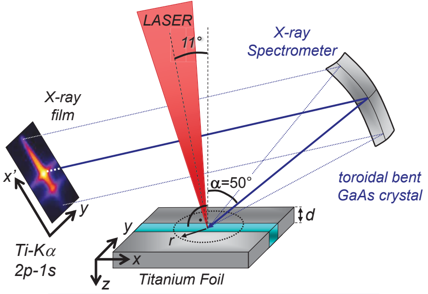
Ti:Sa + Nd:Glas

1057 nm central wavelength
330 fs pulse duration
max. 13 J energy in focus
8 µm focal diameter

→ Intensity ~ $5 \cdot 10^{19}$ W/cm²



standard operation (ω) and frequency doubling (2ω) to obtain higher prepulse contrast

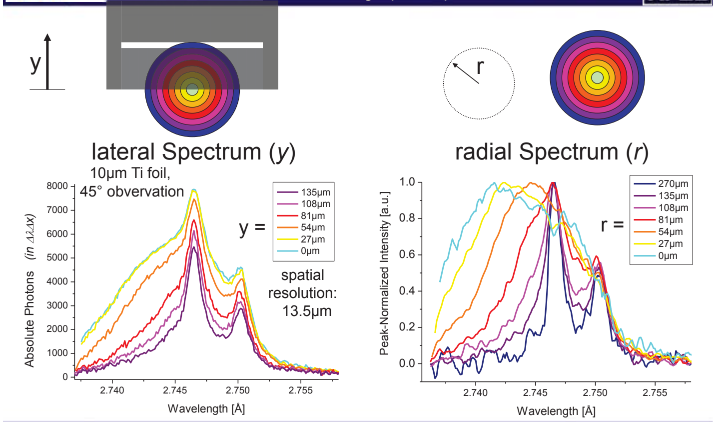


different titanium samples:
massive (bulk) and foils of 25, 10 und 5µm

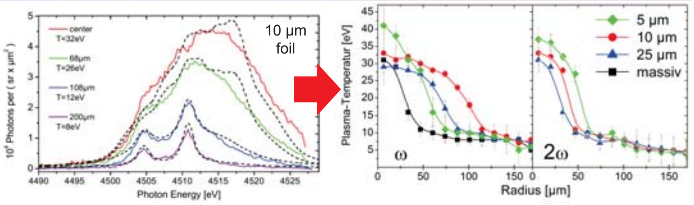
U. Zastrau et al., PRE **81** (2010), 026406 1-4

2D inverse Abel transformation

$5 \cdot 10^{19}$ W/cm² - single pulse spectra



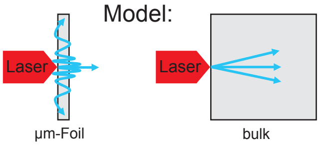
Radial Temperature Distribution



transition from cold to warm Titanium plasma:

blue-shift due to thermal M-shell ionization

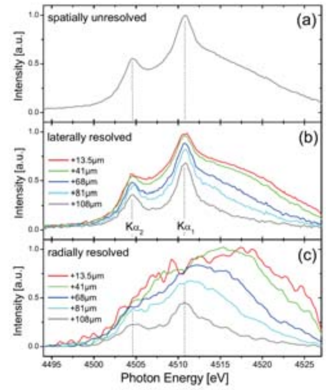
Model:

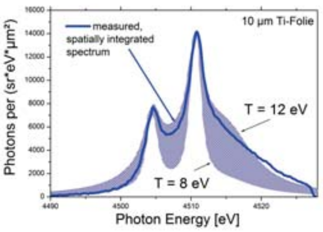


Theoretical line shape models:
Stambulchik,.., Zastrau, et al., J. Phys. A **42** (2009), 214061 1-5
Sengebusch,.., Zastrau, et al., J. Phys. A **42** (2009), 214056 1-10

U. Zastrau et al., PRE **81** (2010), 026406 1-4

Power of radial resolution method



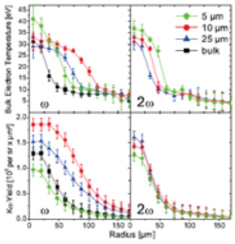


Spectrum of a simple, spatially integrating spectrograph yields 3 x lower temperature !

Zastrau *et al.*, HEDP **7** (2011) p. 47-53

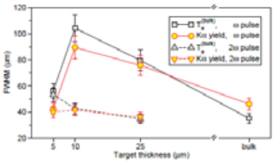
Radial Distributions: $T_e^{bulk}(r)$, J(r)

Courtesy E. Stambulchik



The maximum $T_e^{(bulk)}$ is constantly ~ 30 – 40 eV.
$T_e^{(bulk)}$ extends over ~ 50 µm ≫ laser focal spot.
2ω exposures: narrower distributions and more systematic dependencies on foil thickness.

Strong correlation between the spatial distributions of $T_e^{(bulk)}$ and $K\alpha$ yield is observed in each single-pulse measurement.

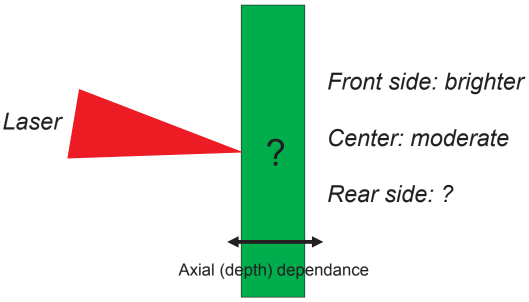


Relativistic Ti plasmas:

Axial Kα-yield ***J(z)***
via
X-ray emission tomography

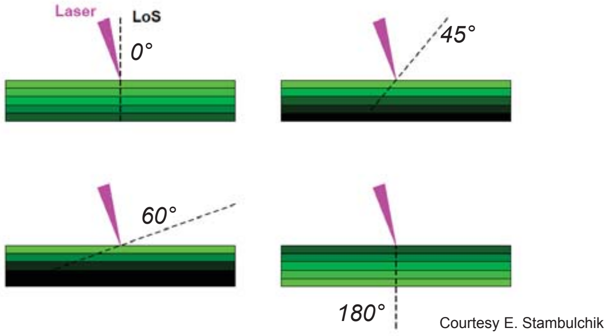
New task: depth yield

- Depth (axial) dependence



Kα emission tomography – use the plasma opacity

Observation from different incidence angles
→ effectively seeing radiation from difference depths.

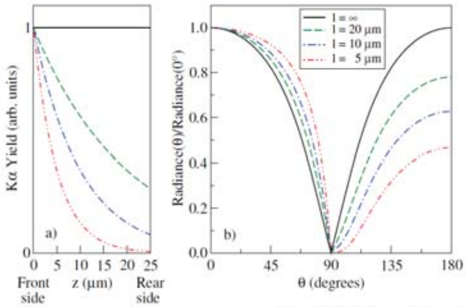


Courtesy E. Stambulchik

- Unpublished material has been removed

Models for exponential z-decay

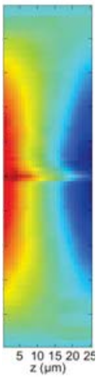
→ for each radius, we fit a decay length to model J(z)



E. Stambulchik, E. Kroupp, Y. Maron, U. Zastrau, I. Uschmann, and G. Paulus, Physics of Plasmas (1994-present) **21**, 033303 (2014).

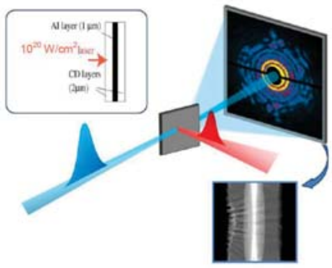
Conclusions I

- Toroidal crystals yield laterally resolved spectra of Ti Kα from relativistic laser plasma .
- Abel inversion → radial Kα yield and temperature
- Multiple angles → emission tomography (assuming constant opacity) yields axial depth dependence.
- By applying simple Gaussian and Exponential-decay models, we derived the 3D Kα-yield map of a relativistic laser plasma.



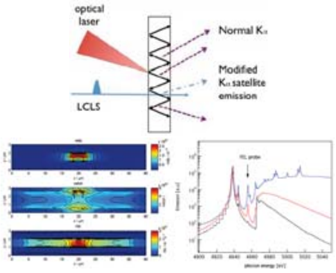
Outlook: Using a hard x-ray FELs to probe relativistic laser plasmas

Probing of Complex Ultra-Intense Laser-Plasma Interaction and buried layers with SAXS



LCLS proposal of A. Pelka, HZDR

Time and space-resolved measurement of hot electron transport in solid-density plasmas produced by an intense laser pulse



LCLS proposal of B.-I. Cho, GIST

Thank you for your attention.

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VolkswagenStiftung