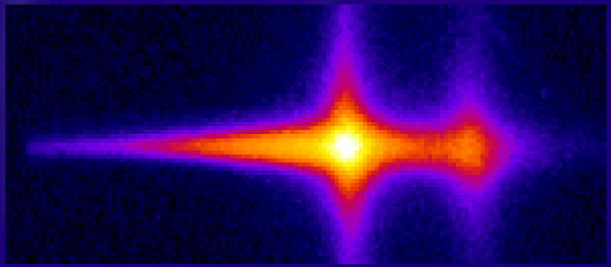
# X-ray Diagnostics of Extreme States of Matter



**Ulf Zastrau**, Ingo Uschmann, Ortrud Wehrhan, and Eckhart Förster

**X-ray Optics Group**, IOQ, University of Jena, Germany
**Helmholtz-Institute Jena**, Germany

# Outline of the Talk

- Extreme States of Matter &
  X-ray Spectroscopy using Bent Crystals

- Application of X-ray Plasma Diagnostics
  with Laser-Produced Plasmas

- Summary

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# Extreme States of Matter

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

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

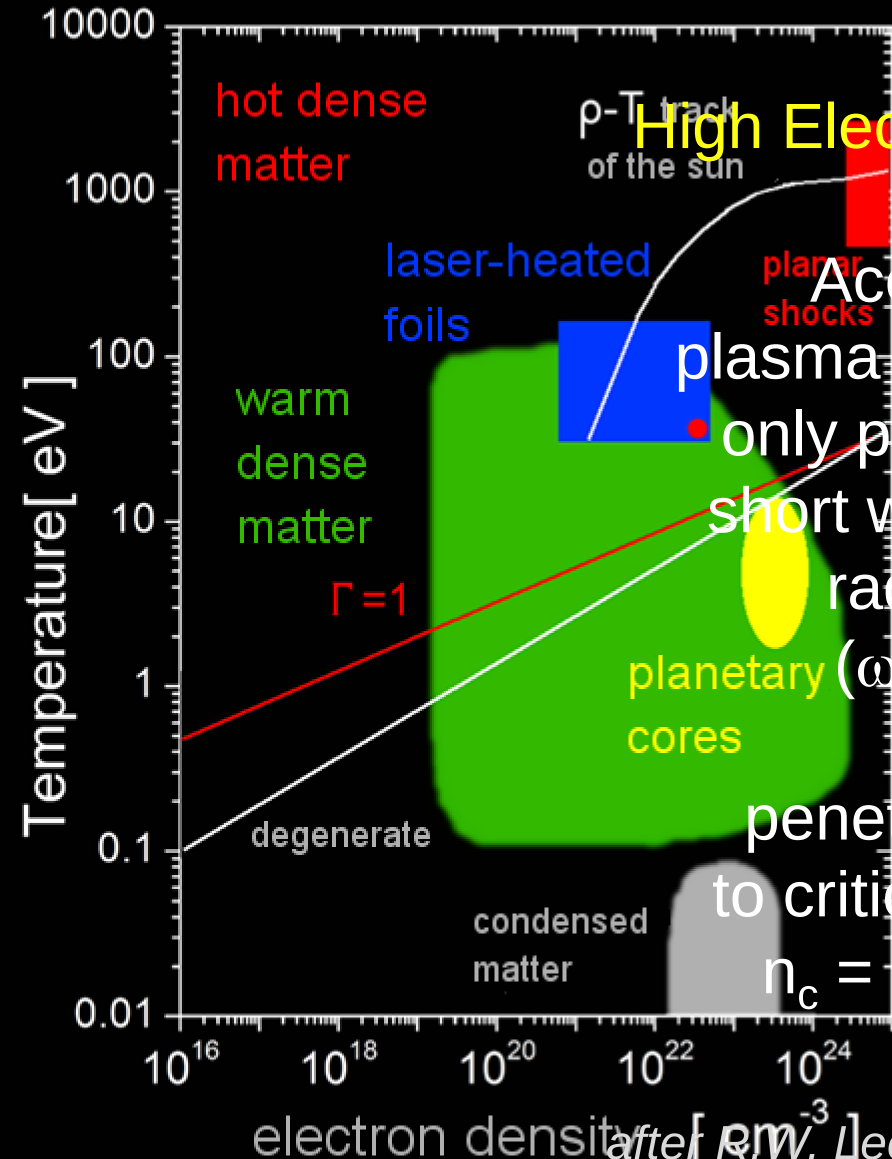
1..100 eV

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

strong coupling

$\Gamma \geq 1$

$E_{coulomb} \sim E_{therm}$



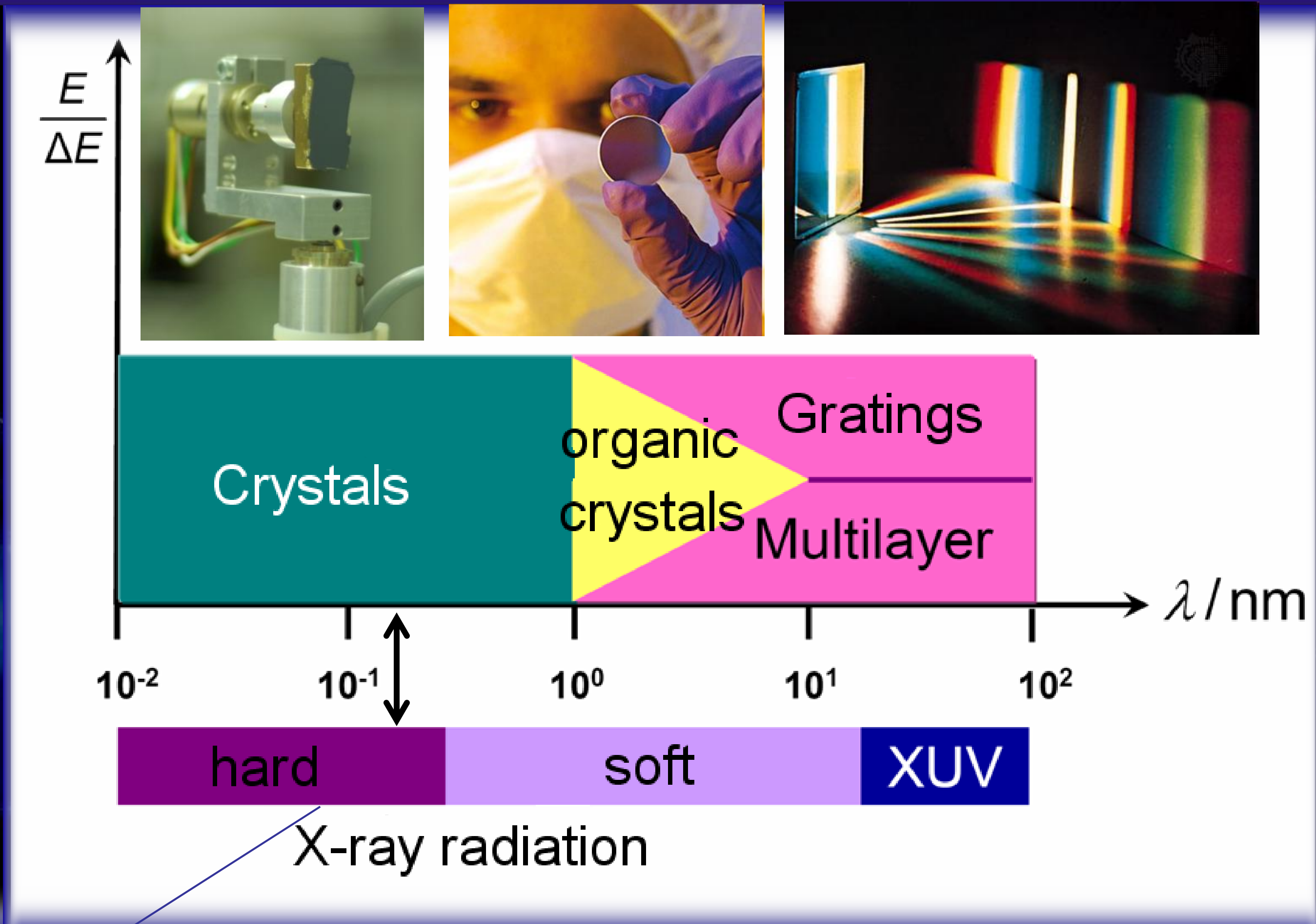

*after R.W. Lee*

**High Electron Density:**

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

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

# Spectroscopy of Solid Density Plasmas
## *by X-ray Photons*

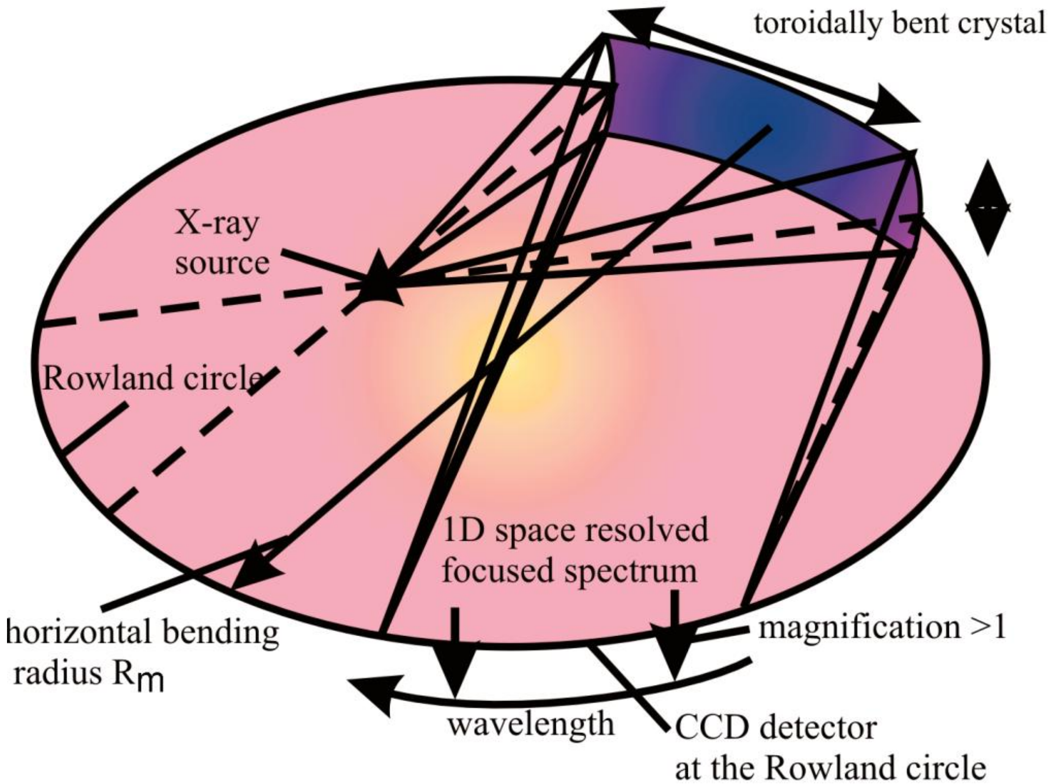



e.g., absorption length of λ=0.27 nm in Titanium (Z=22) : ~ 20 µm

in laboratory always transient micro-plasmas with strong gradients
→ spectroscopy with high spatial and temporal resolutions

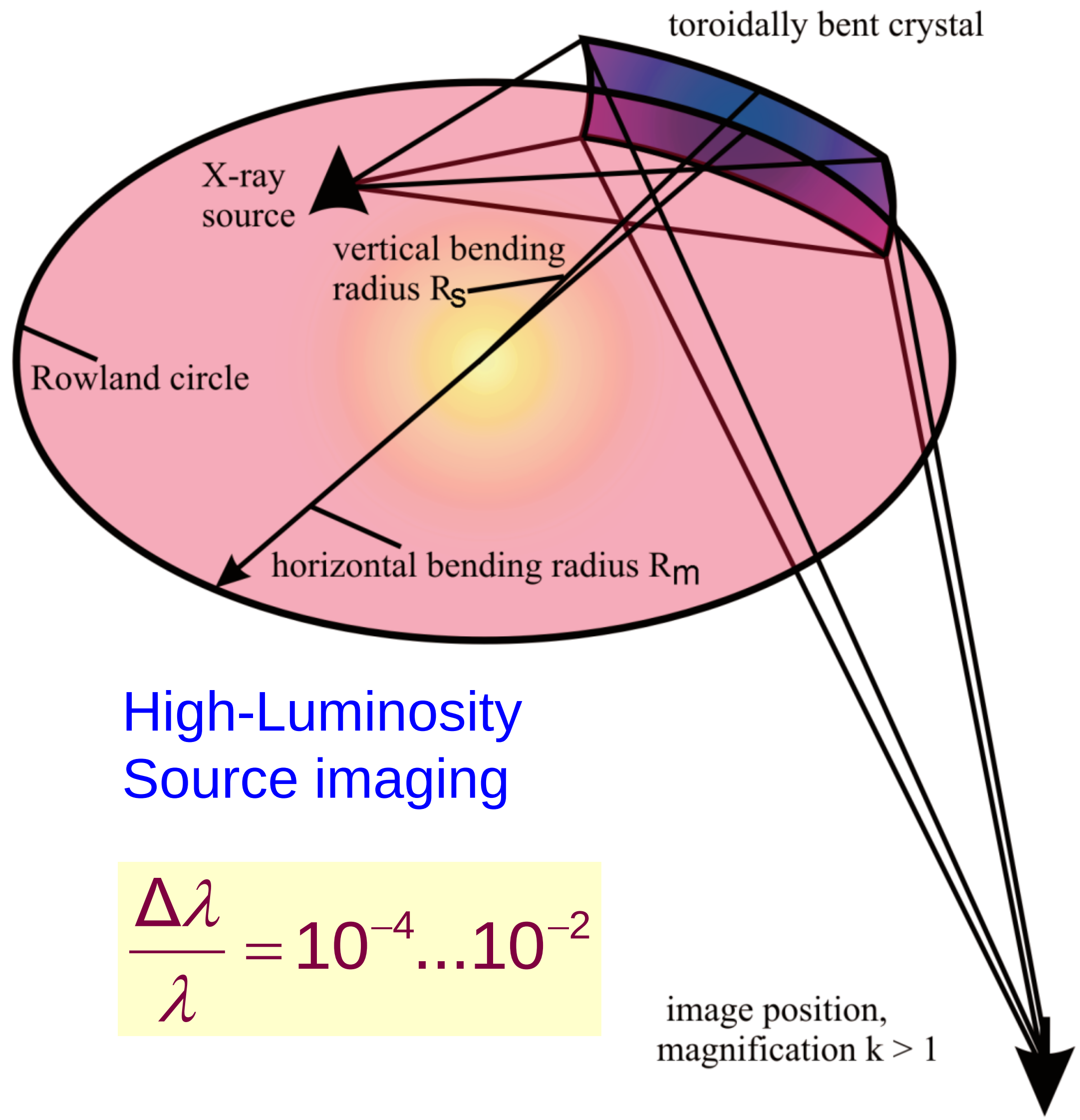
# Crystals as Dispersive Imaging Element for (0.1 – 2.5) nm

line focus at Rowland circle - $R_s/R_m < \sin^2 \Theta_B$




High-Luminosity Spectroscopy

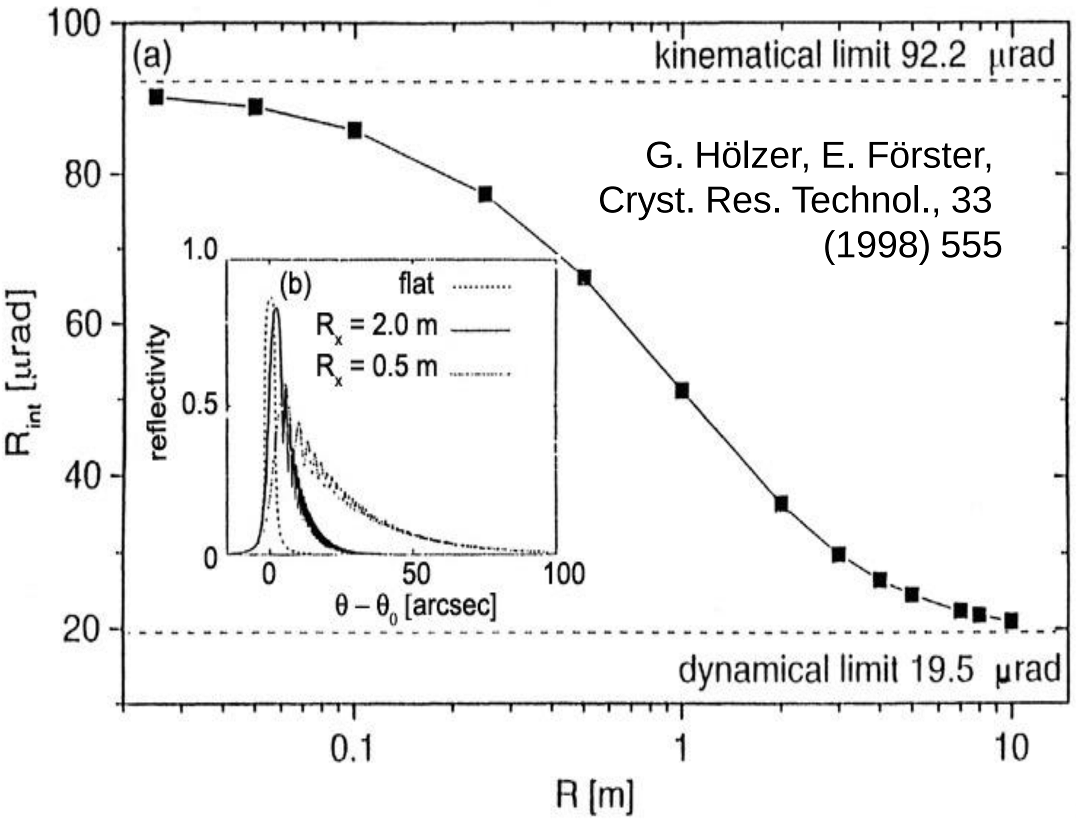
point to point focusing - $R_s/R_m = \sin^2 \Theta_B$

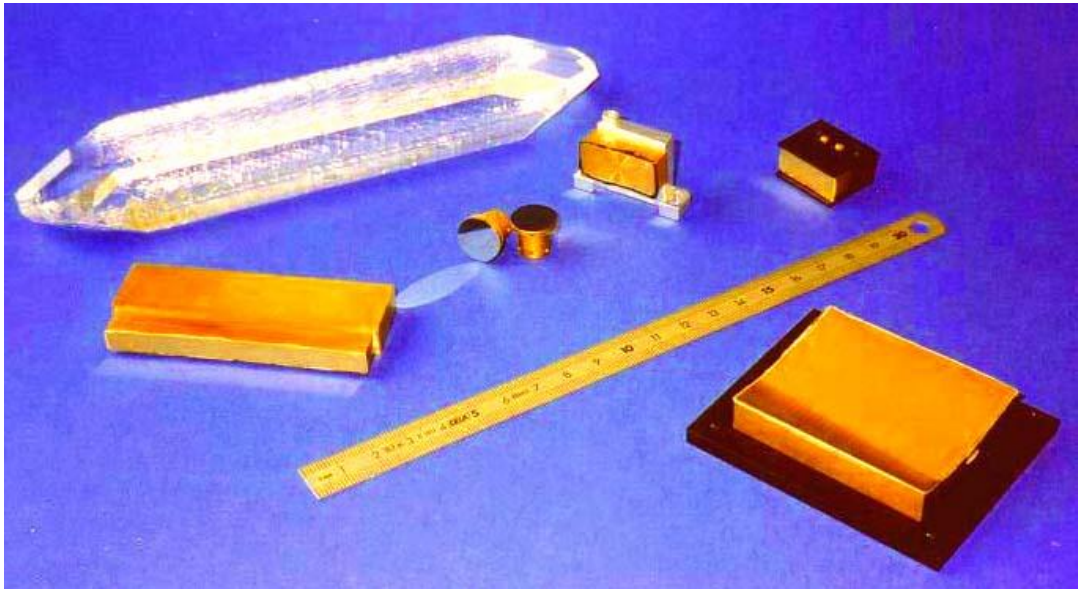


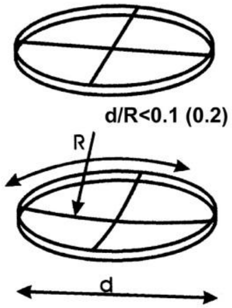

High-Luminosity Source imaging

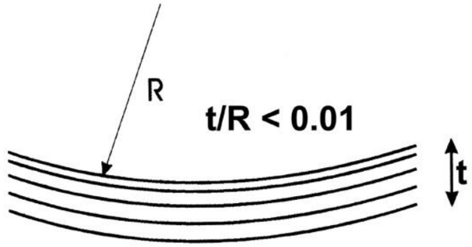
$$\frac{\Delta\lambda}{\lambda} = 10^{-4} \ldots 10^{-2}$$

# Reflectivity of Quartz 10.0 @ $CuK_{\alpha 1}$ vs. Curvature Radius






Integrated reflectivity (a) and typical reflection curves (b) as a function of the curvature radius $R_x$ of a cylindrically bent quartz crystal.

Crystal material: Silicon, Quartz, Germanium, Mica, TlAP, KAP

Formers: cylindrical, spherical, toroidal; Bending Radii: 100 mm ... 900 mm

Size: circular – 100 mm...25 mm, rectangular: up to 90 mm (one dimension)

Aperture: d / R < 0.1 (one dimension < 0.2); Crystal Thickness: t = (60 ... 80) μm

# Fabrication and Test of Toroidally Bent Crystals

**1.1** grinding and polishing of toroidal glass formers

**1.2** X-ray topography → ‚perfect' crystal block

**2.1** control of surface quality and bending radius $\Delta R / R < 0.001$

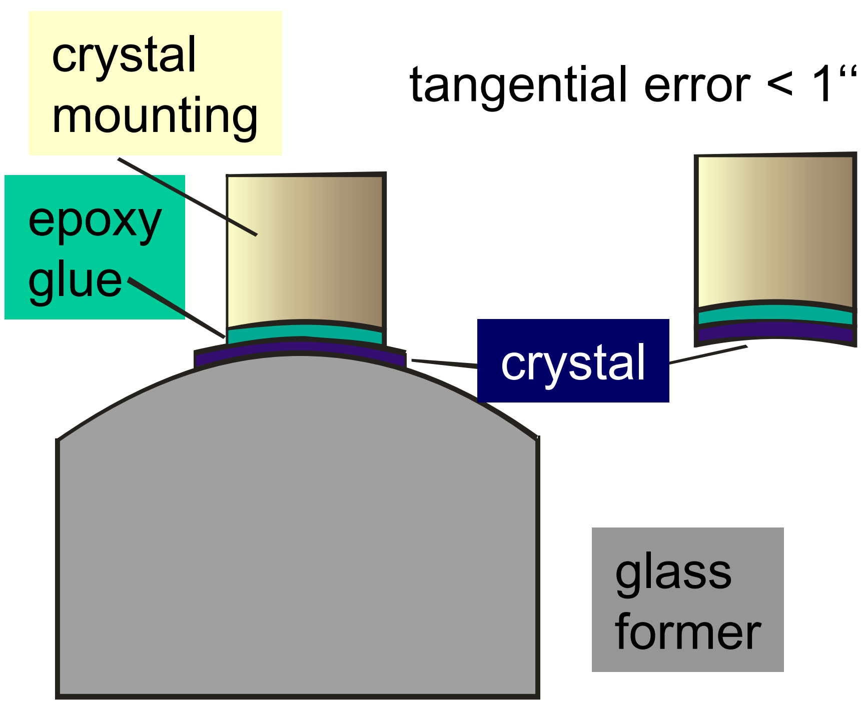
**2.2** oriented sawing (accuracy: 10' to 10''), grinding, polishing → 70 µm thick discs

**3.** optical contact with glass form sticking to crystal mounting with epoxy glue

**4.** optical and X-Ray imaging tests,

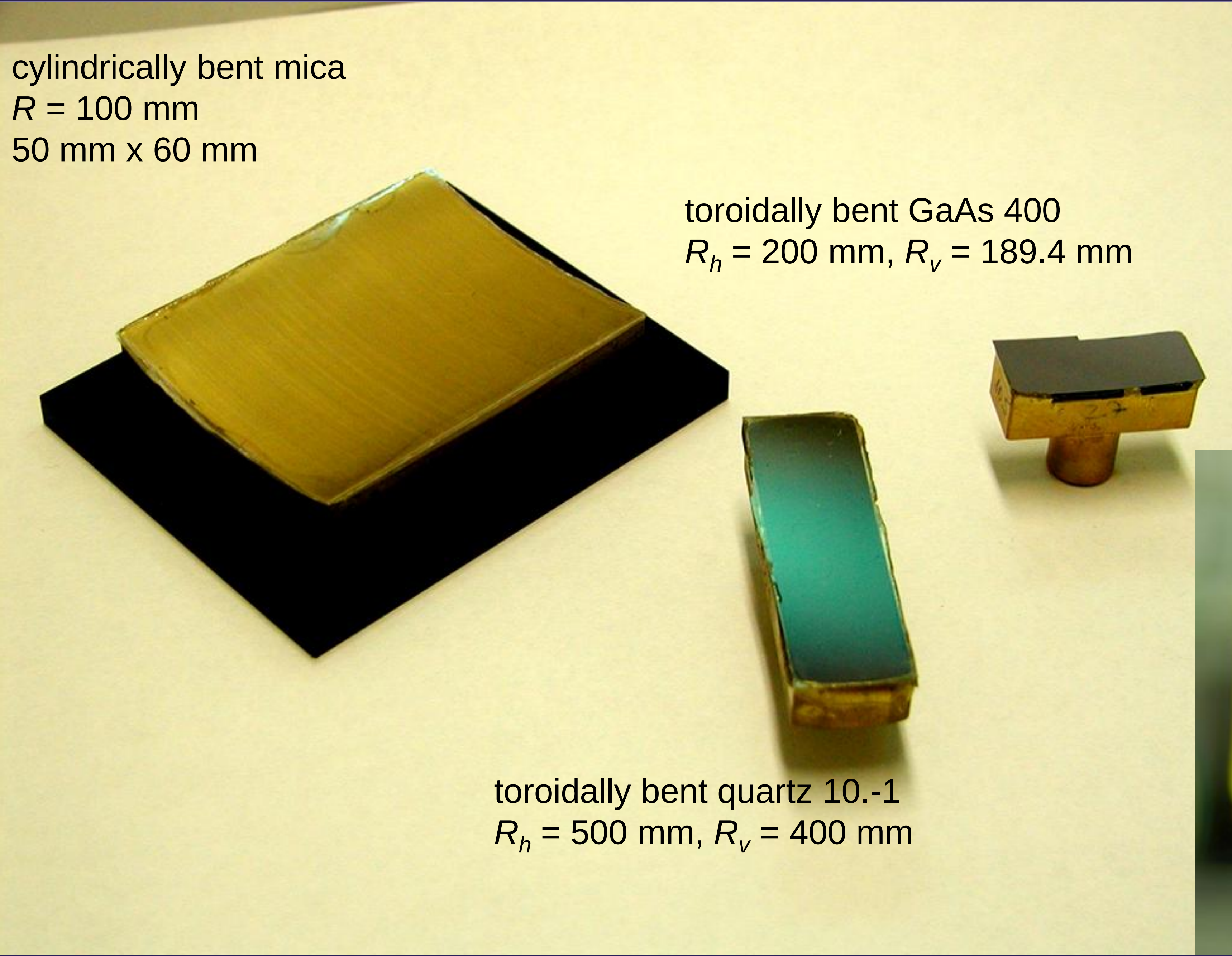
**5.** determination of the reflectivity (X-Ray tube or synchrotron),

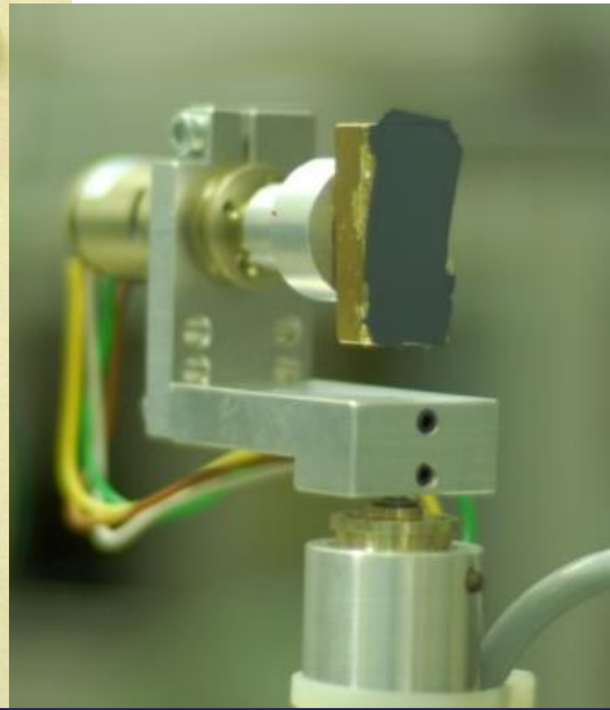
**6.** use in X-Ray spectroscopy, diffractometry and X-Ray imaging




Relation of the Curvature Radii: $R_v / R_h = \sin^2\theta$

# A few crystals



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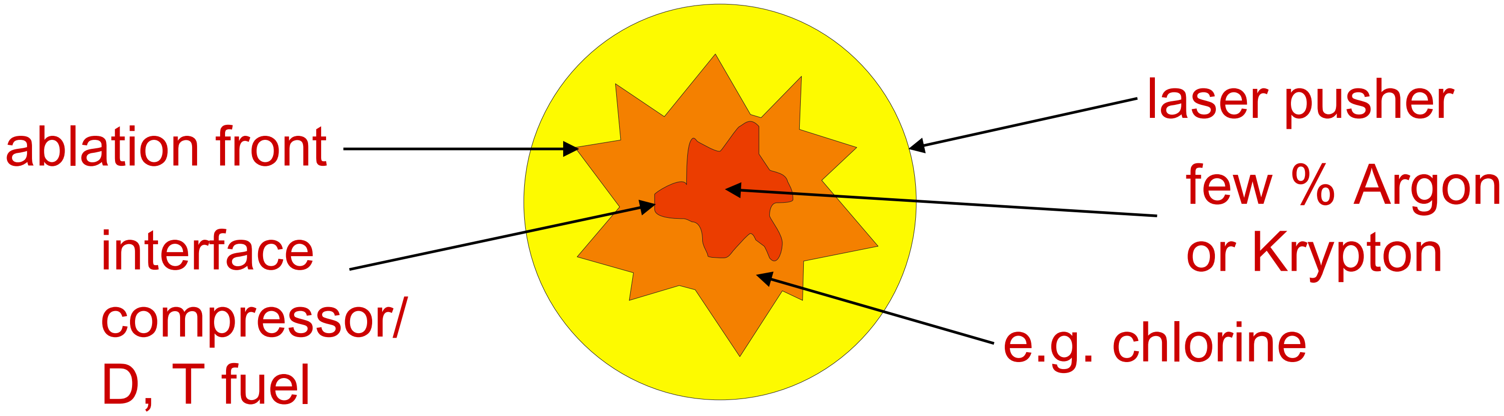
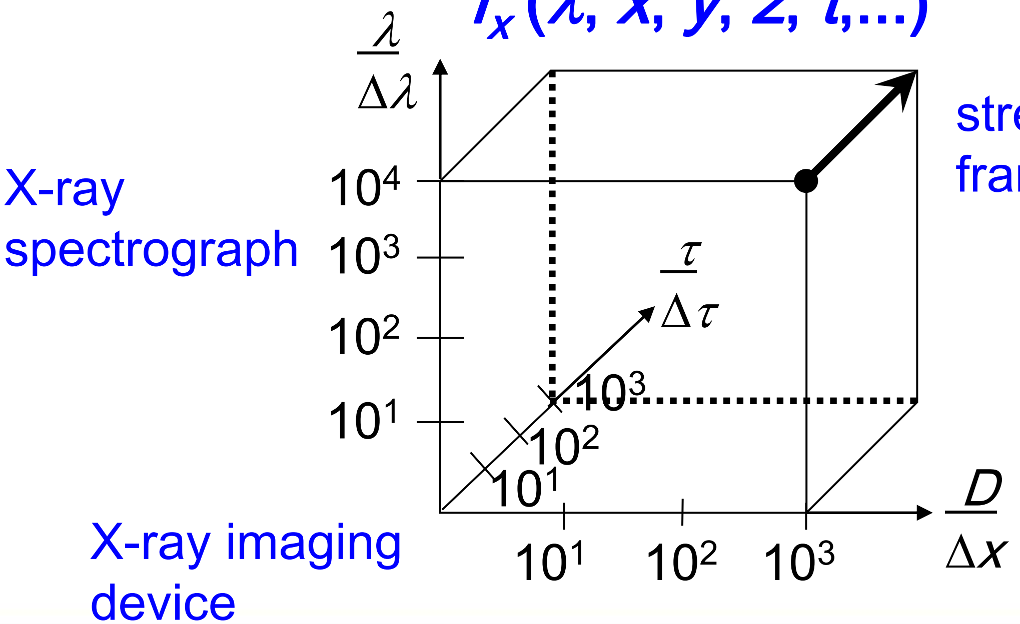
# X-Ray Diagnostics for Laser Fusion Experiments

High power laser: $E_L > 10^6$J, $\tau_L < 1$ns, $\lambda_L < 0.5\mu$m

main aim: supression of Rayleigh-Taylor instabilities




$I_x(\lambda, x, y, z, t, \ldots)$



# Laser System – GEKKO XII
# ILE Osaka, Japan (1990‘s)

# Laser Fusion Experiments in Direct-Drive Illumination Scheme

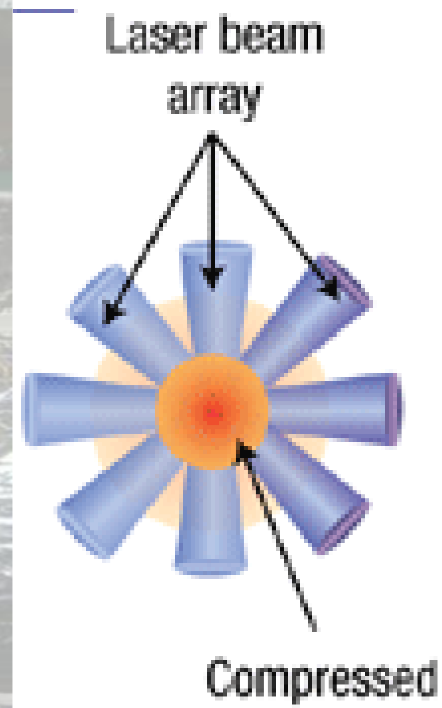
GEKKO XII in Osaka in the 90's:

- 12 laser beams, 2.55 kJ Nd glass laser at 526 nm

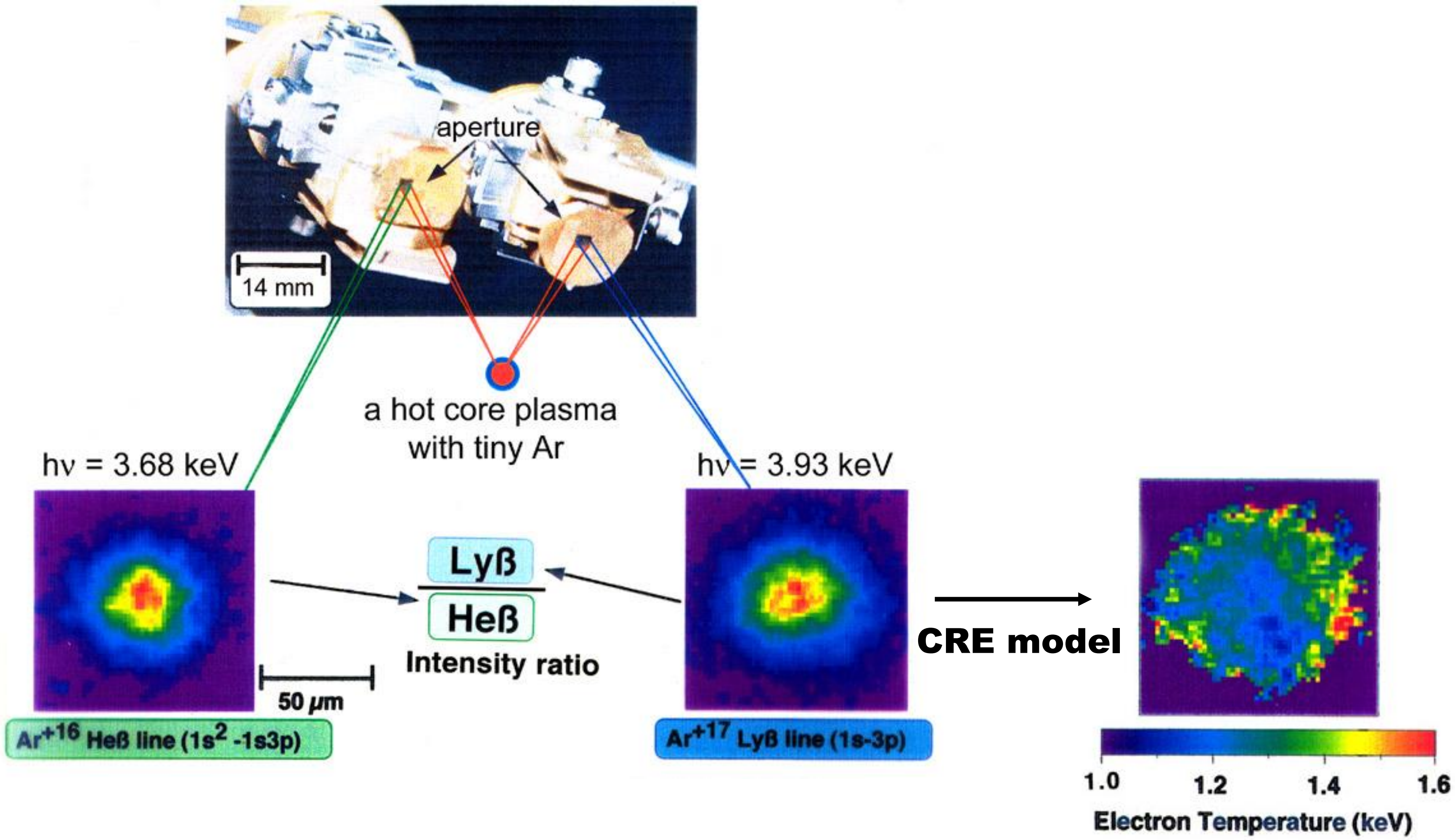
-Random phase plates smooth individual beams.

- Laser pulse: 0.2 ns prepulse, followed by a
- 1.6 ns square pulse with rise time of 0.05 ns.

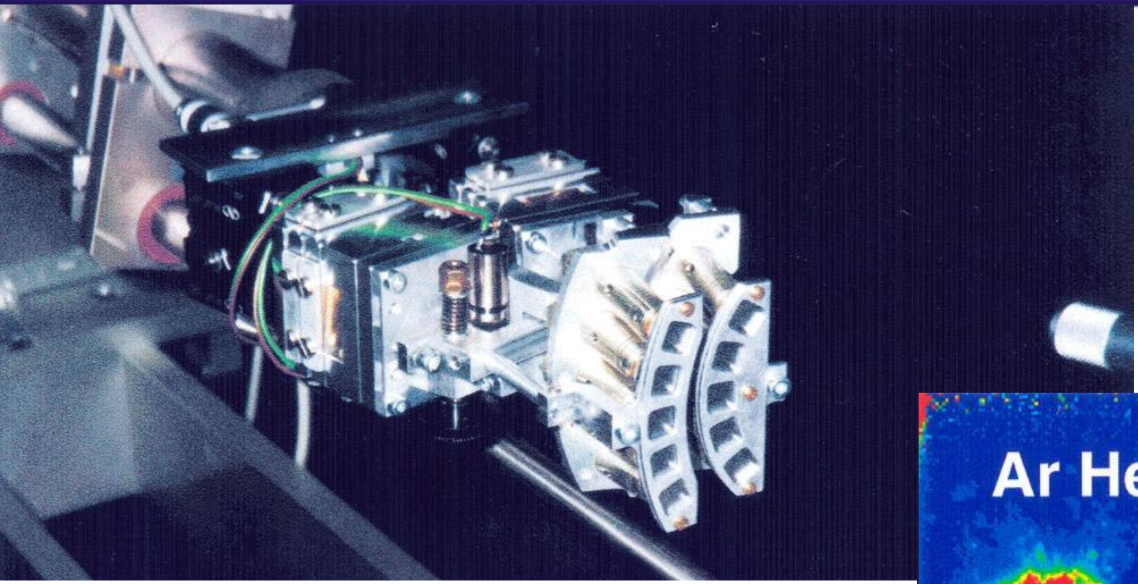
-Targets: CH plastic shells, 500 µm in diameter,
- with 8 mm CH wall thickness,
- filled with 30 atm of $D_2$ and
- doped with 0.075 atm of Ar (for diagnostic purposes).



# X-Ray Monochromatic Camera Using Two Toroidal Crystals

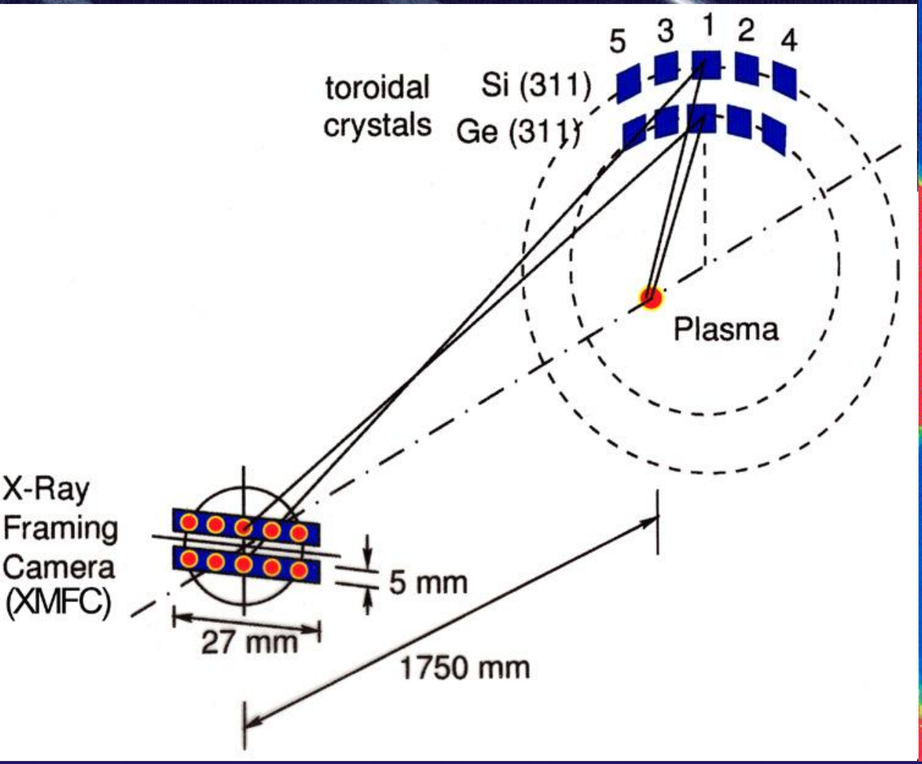


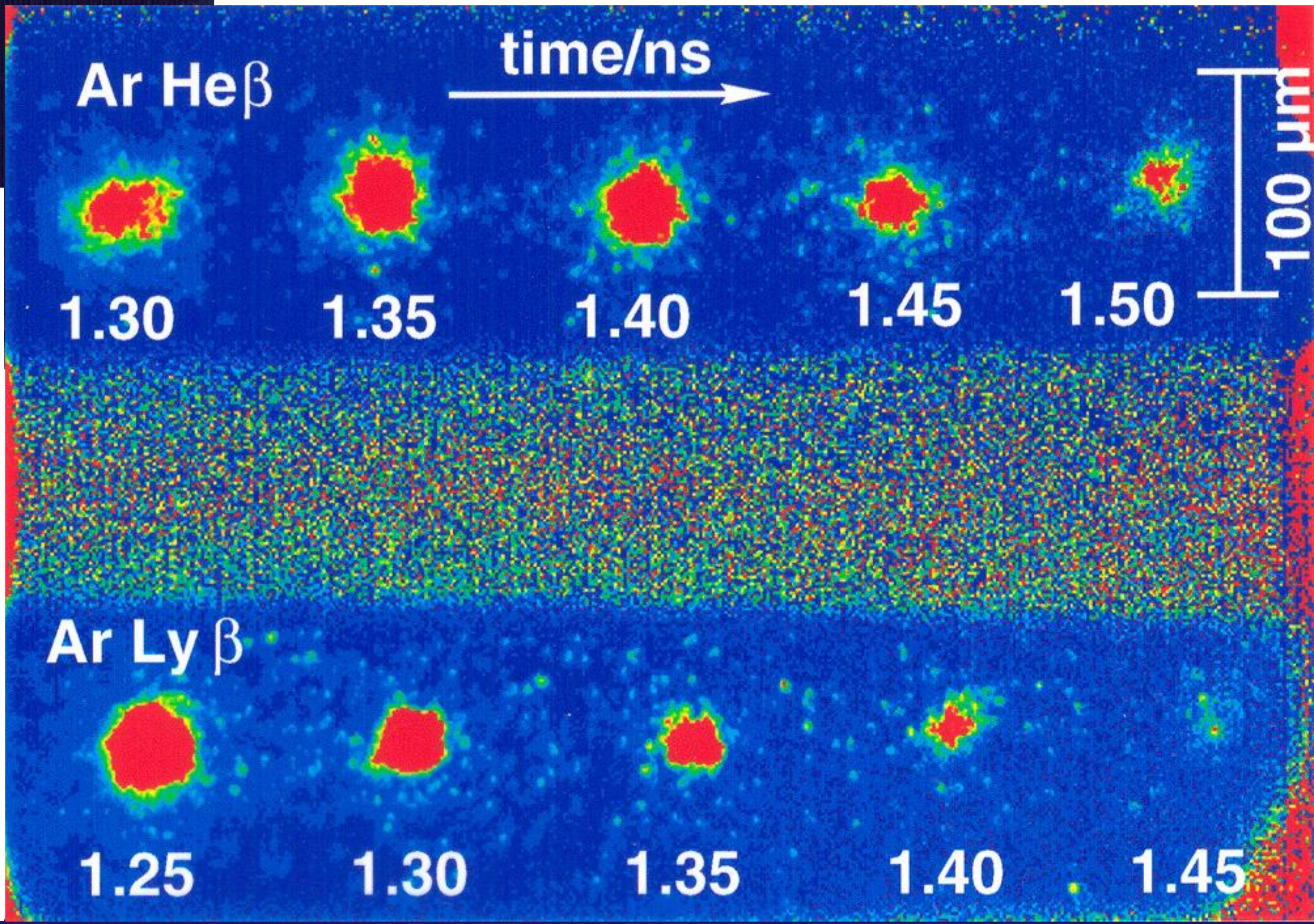
# 10 Channel X-ray Framing camera



Monochromatic X-ray Imaging of a fusion capsule implosion at GEKKO

**I. Uschmann et al., Rev. Sci. Instrum. 66, 734 (1995)**

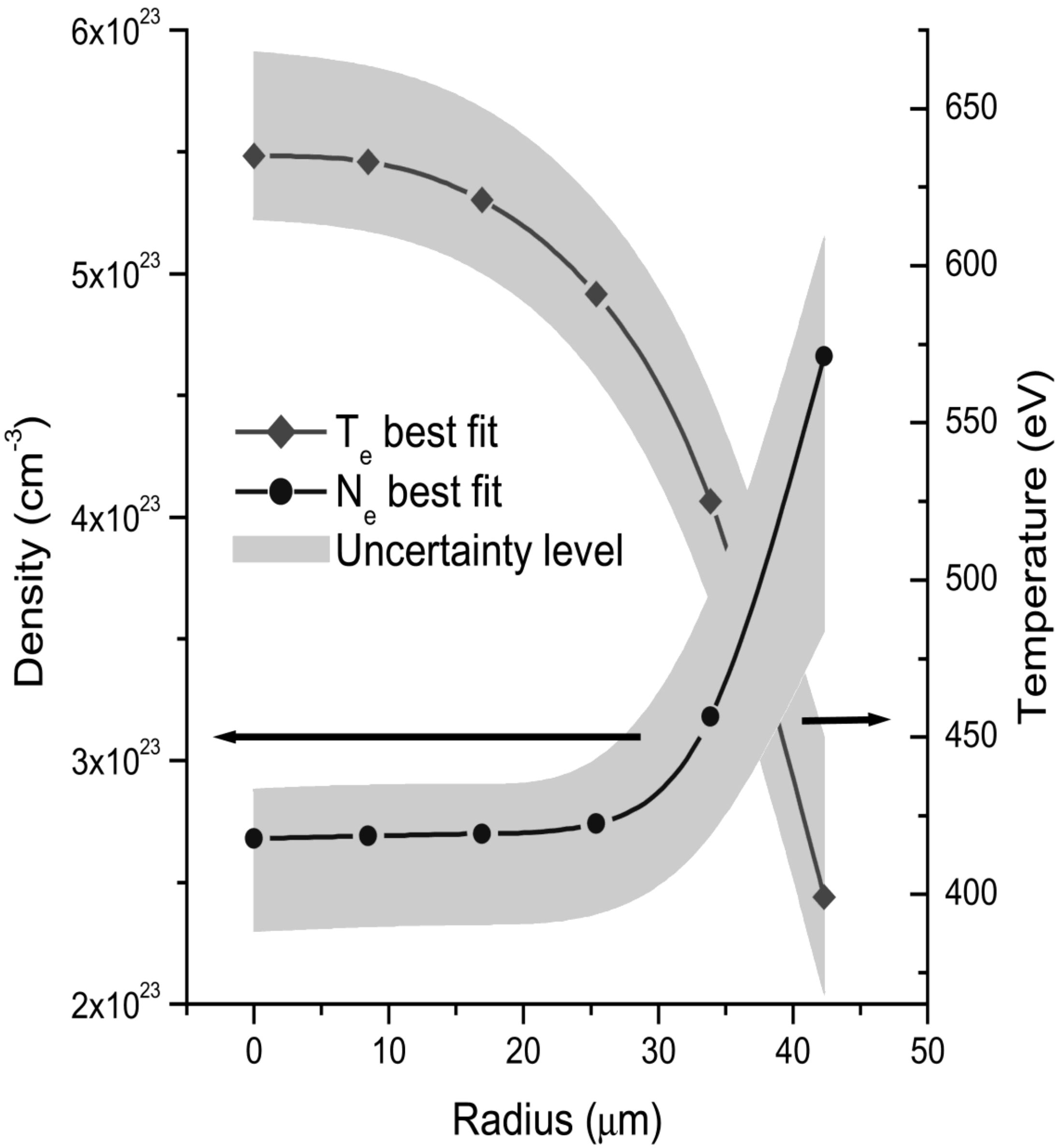


# Electron Temperature and Density Profiles

Self-consistent iterative procedure seeks $T_e(r,t)$ and $N_e(r,t)$ that yield the best fits to the monochromatic emissivity and the spectral line profile, consistent with data from uniform plasma model approximation.

(Two-criteria problem was handled with a nicked-Pareto optimality technique.)

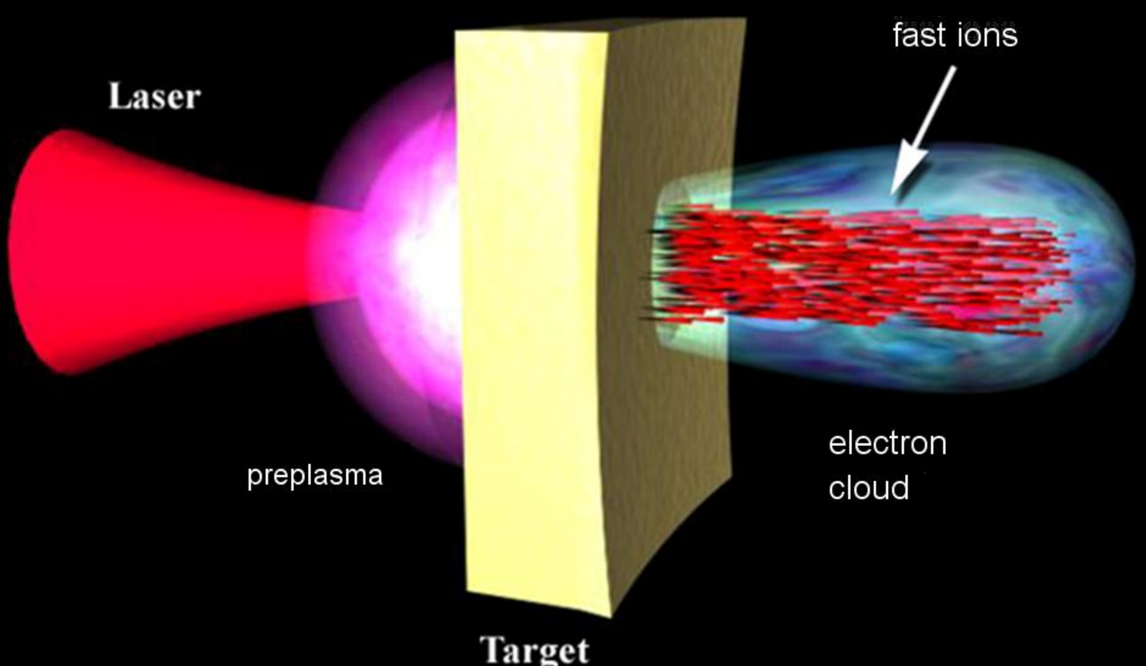



Ref.: I. Golovkin et al., PRL 88 (2002)

## Fundamental Parameter: Brightness

$$\frac{\text{number of X-ray photons}}{\text{time [s]} \quad \text{emitting size [mm}^2\text{]} \quad \text{divergence [mrad}^2\text{]} \quad \text{spectral bandwidth [\%]}}$$

- ✓ 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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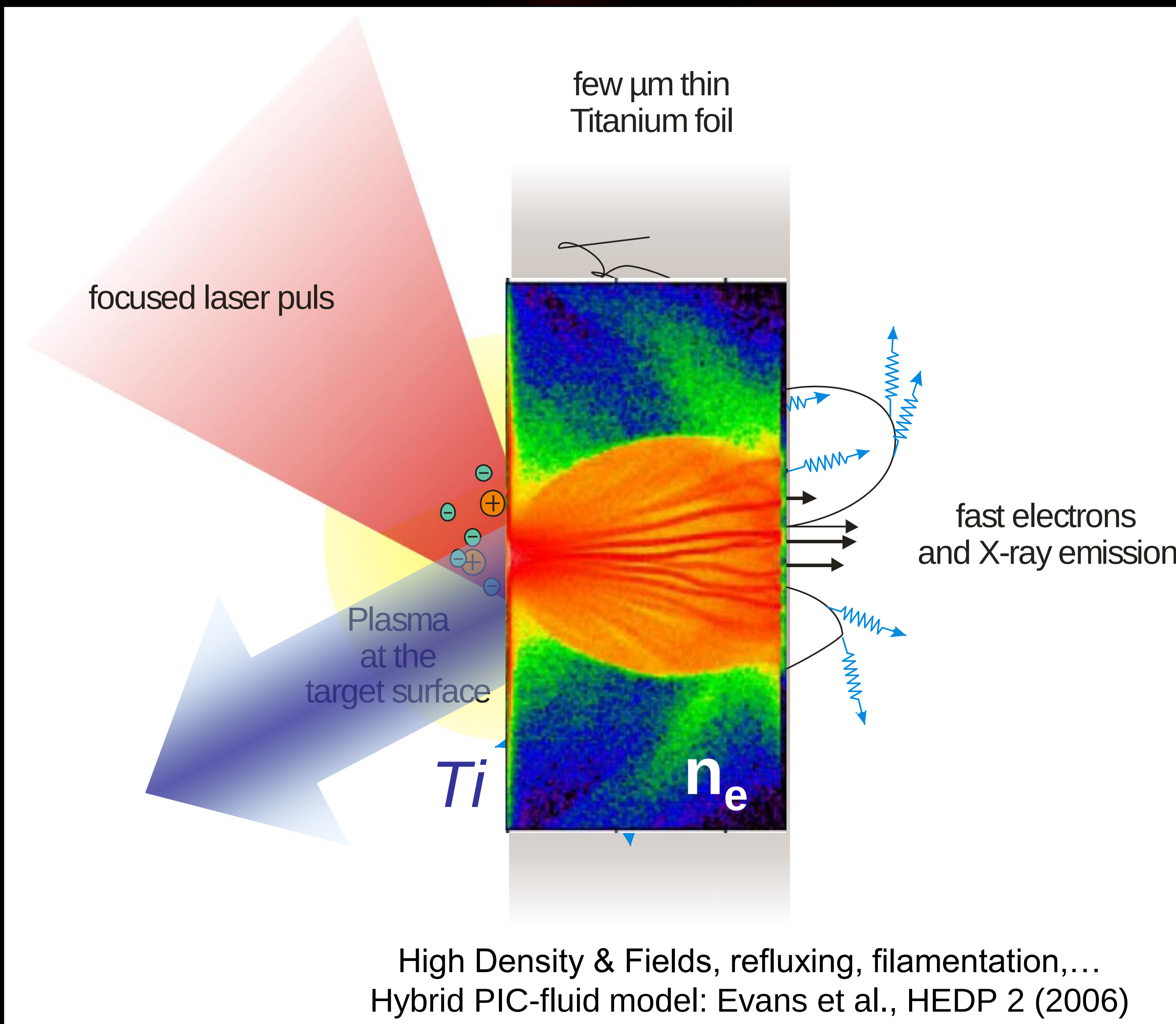
# Physics of IR-Laser-Target Interaction




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

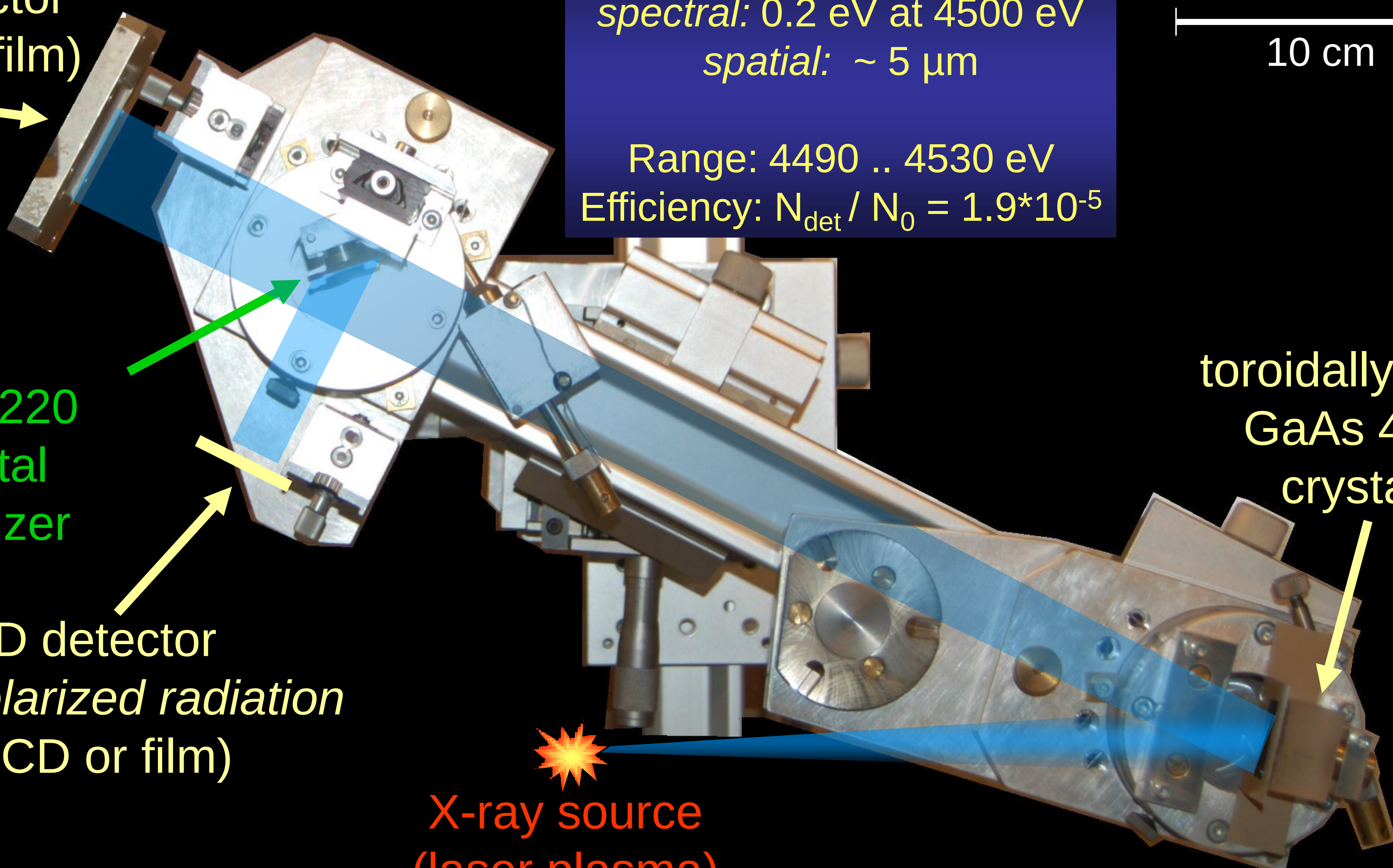
electrons with E > 5keV in Titanium are capable of K-shell ionization

we observe K$\alpha$–emission from the heated target

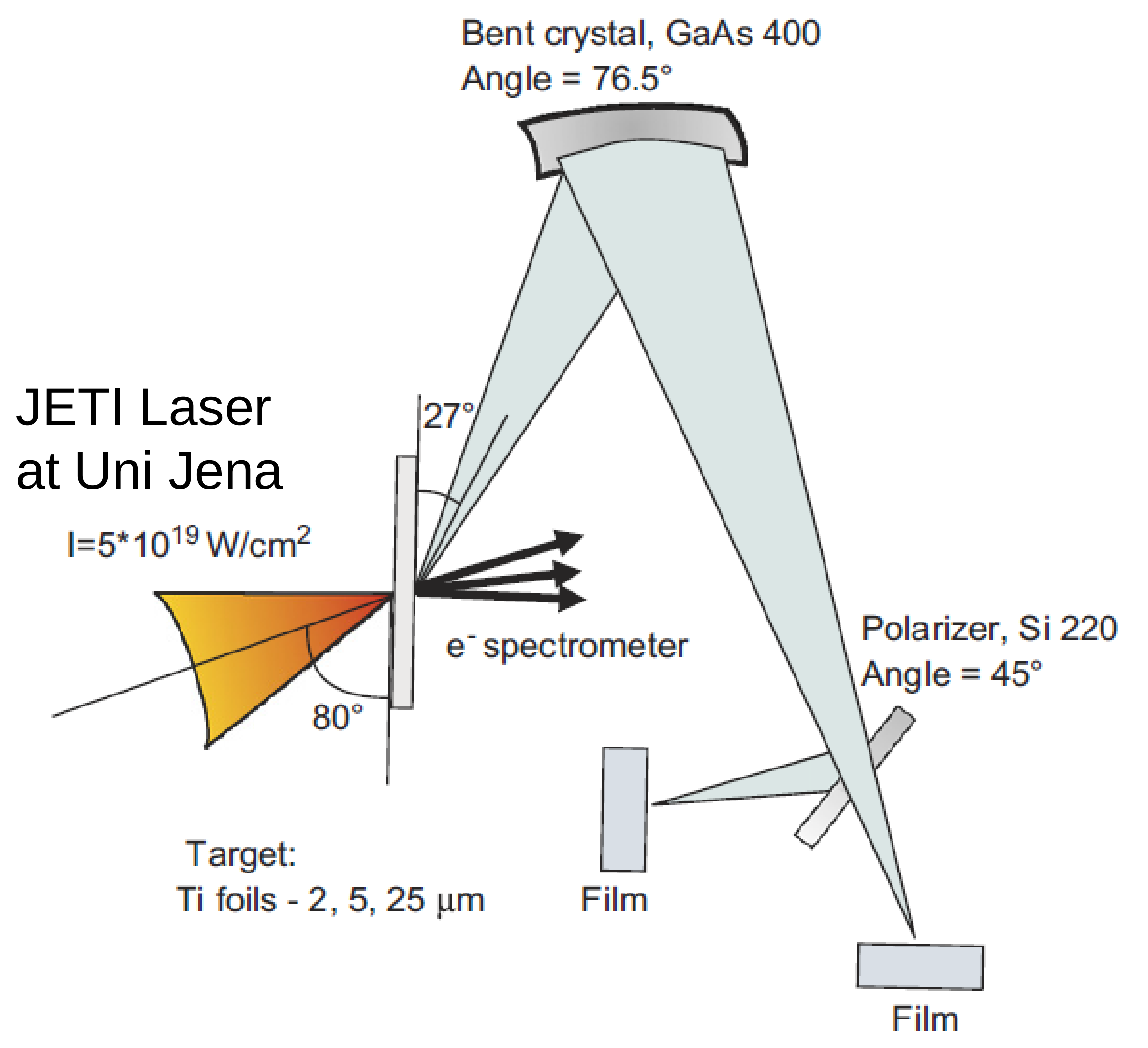
# GaAs 400 Crystal Spectro-Polarimeter

Resolution
*spectral:* 0.2 eV at 4500 eV
*spatial:* ~ 5 µm

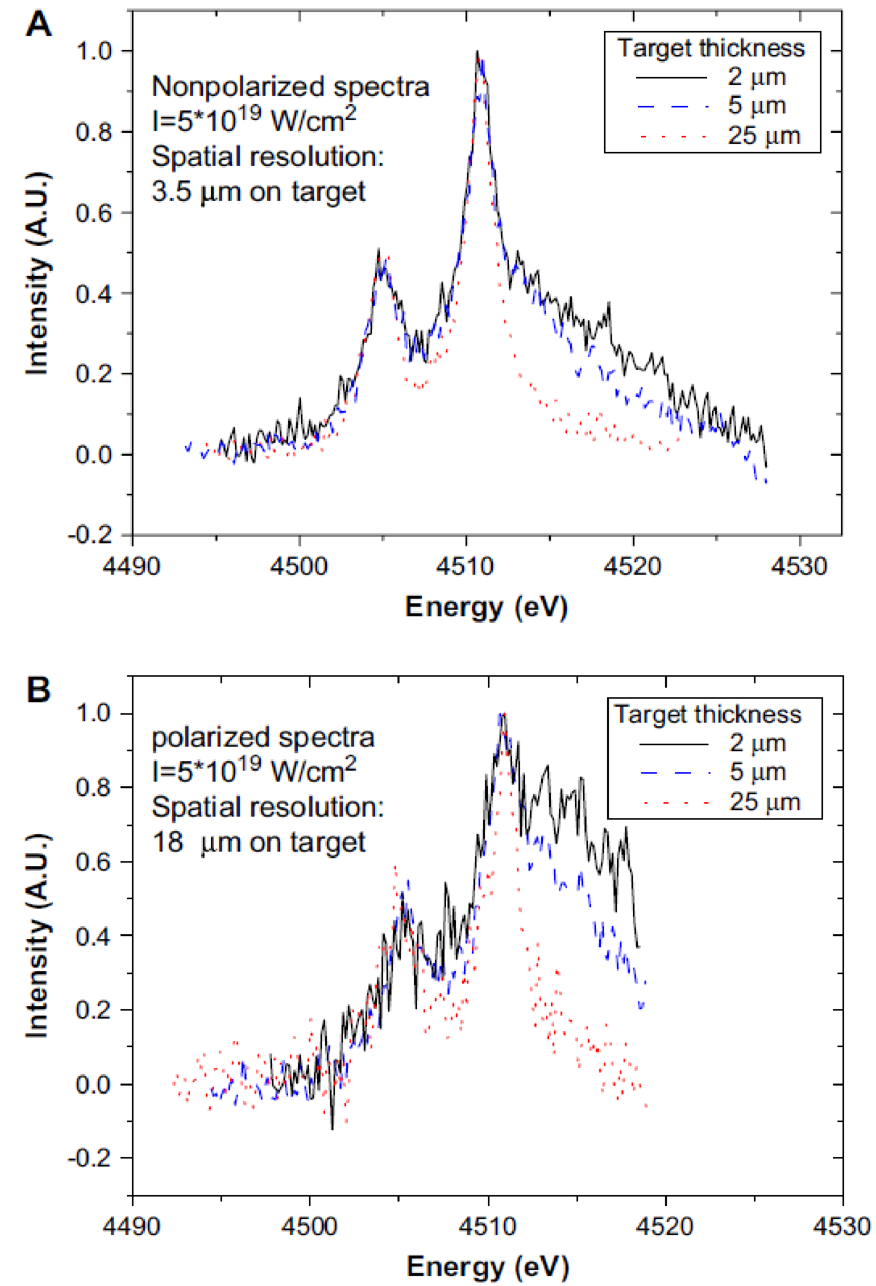
Range: 4490 .. 4530 eV
Efficiency: $N_{det} / N_0 = 1.9 \cdot 10^{-5}$



# Polarized Ti Kα blue satellites
## - anisotropy of relativistic electron beam ?




*F. Zamponi et al. / High Energy Density Physics 3 (2007) 297–301*



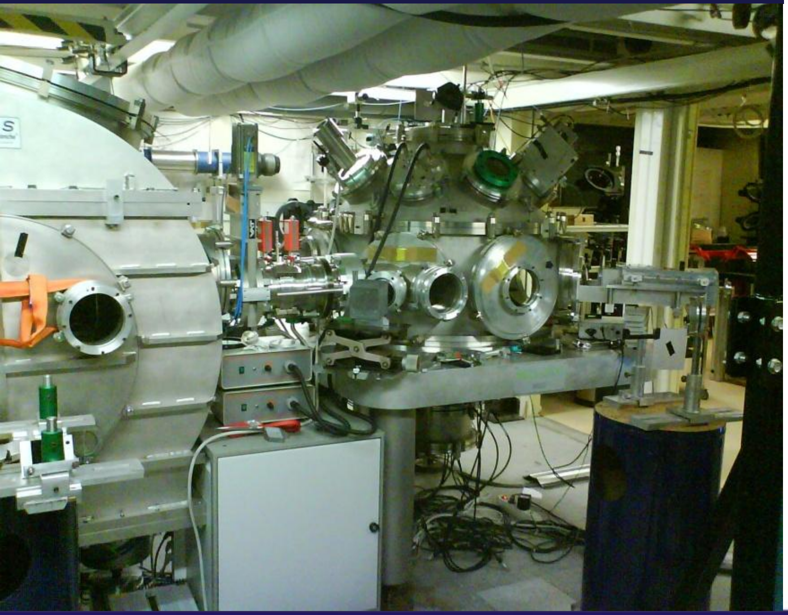
# Experiment at 100TW Laser, LULI

LULI 100TW Laser

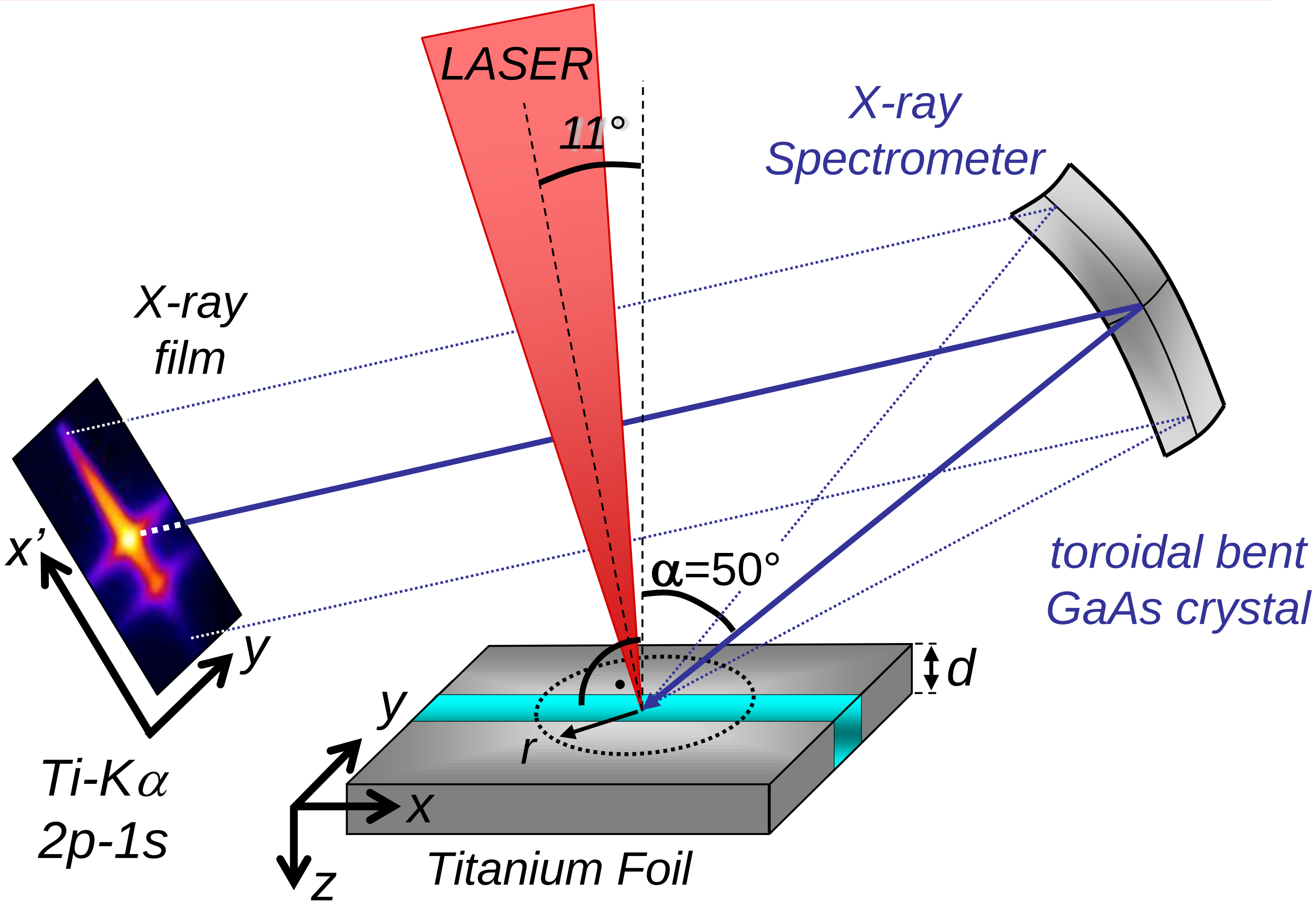
Ti:Sa + Nd:Glass

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

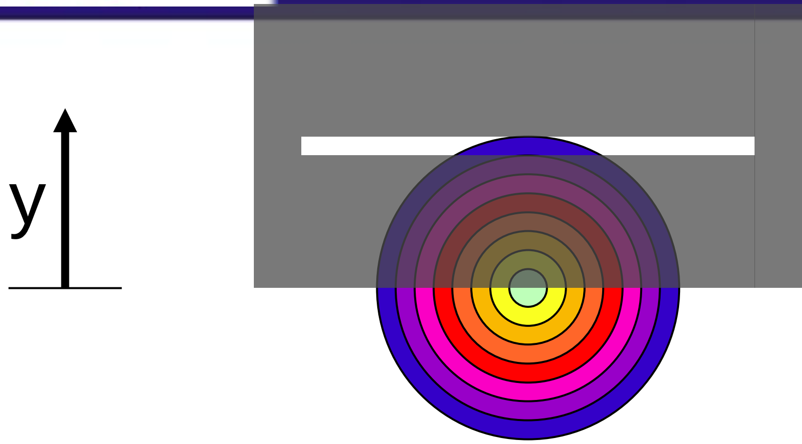


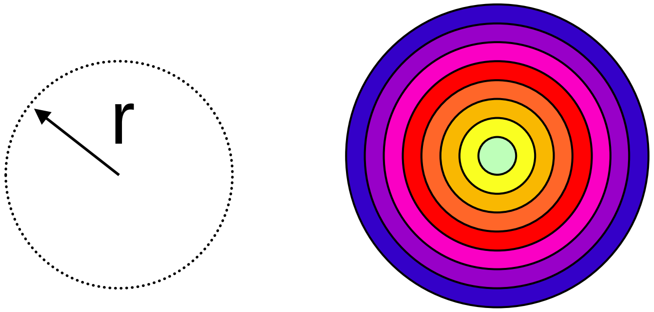

different titanium samples:
massive (bulk) and foils of 25, 10 und 5µm

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

# 2D inverse Abel transformation

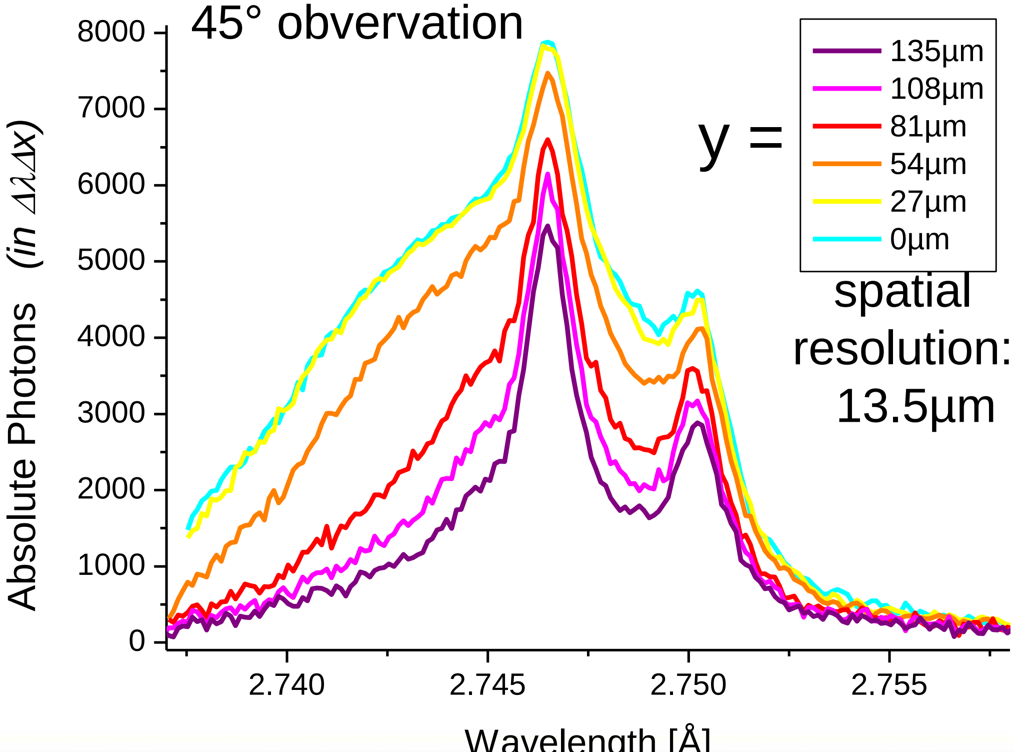
$5 \cdot 10^{19}$ W/cm² - single pulse spectra




## lateral Spectrum (*y*)

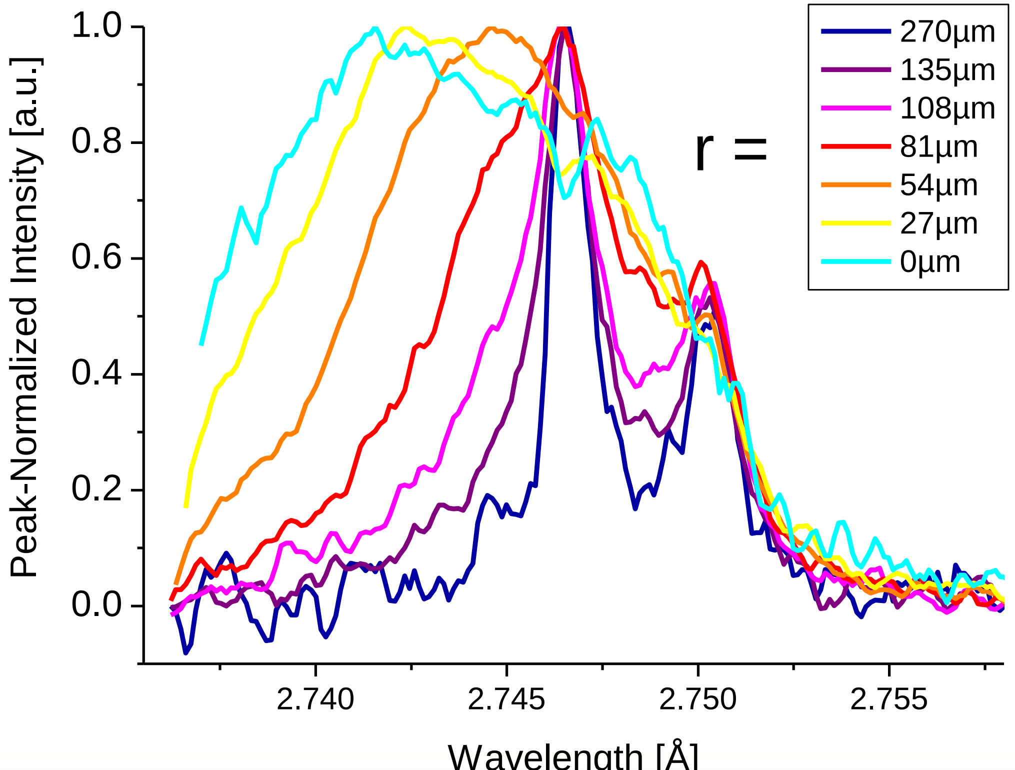
10µm Ti foil,
45° obvervation




y =

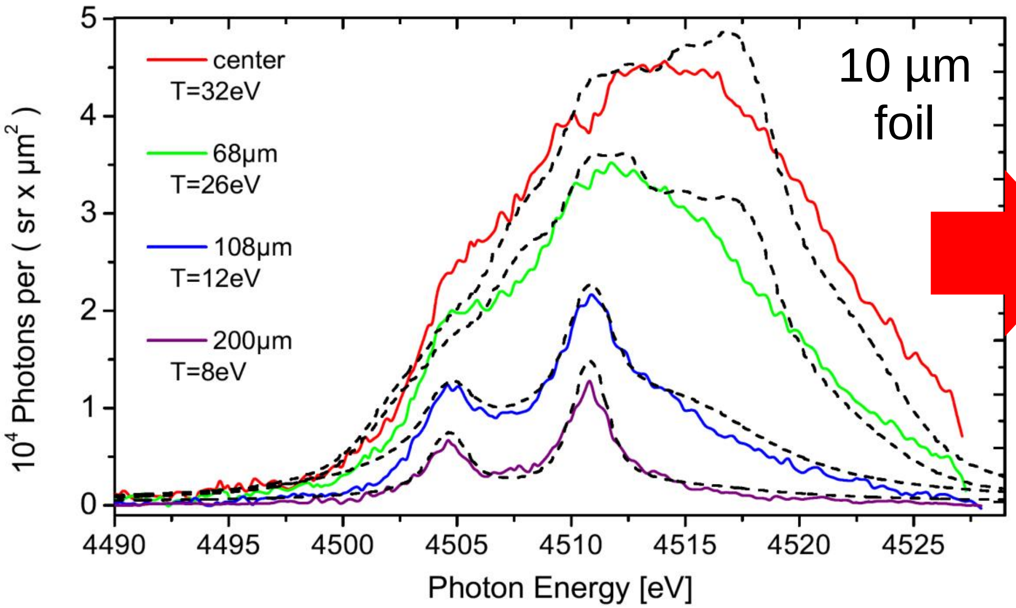
spatial resolution: 13.5µm

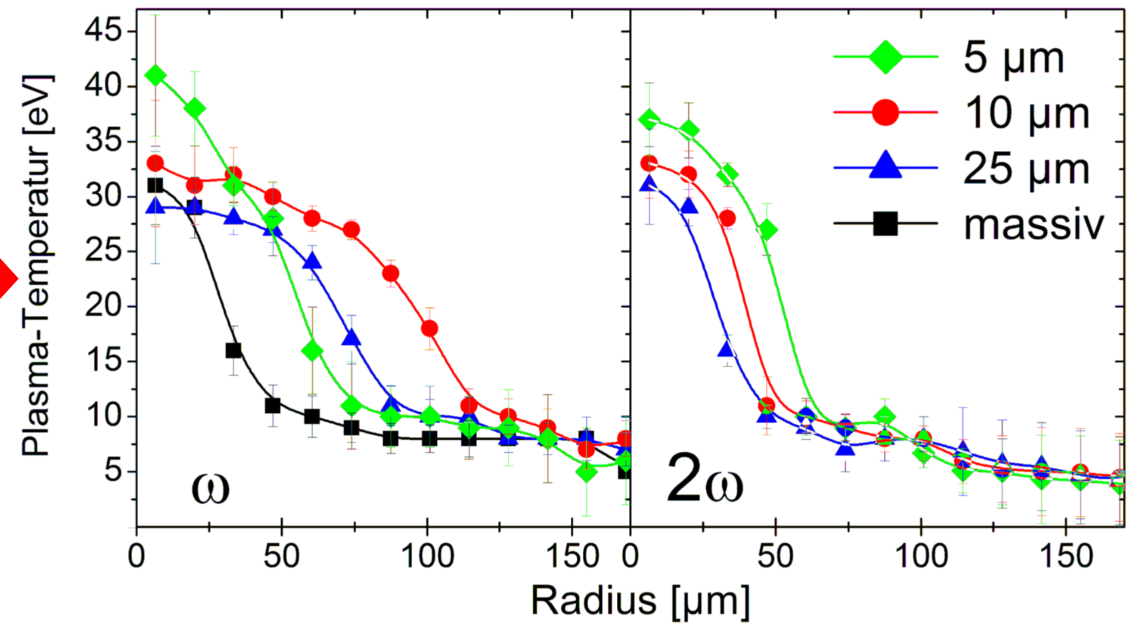
## radial Spectrum (*r*)




r =

# Radial Temperature Distribution

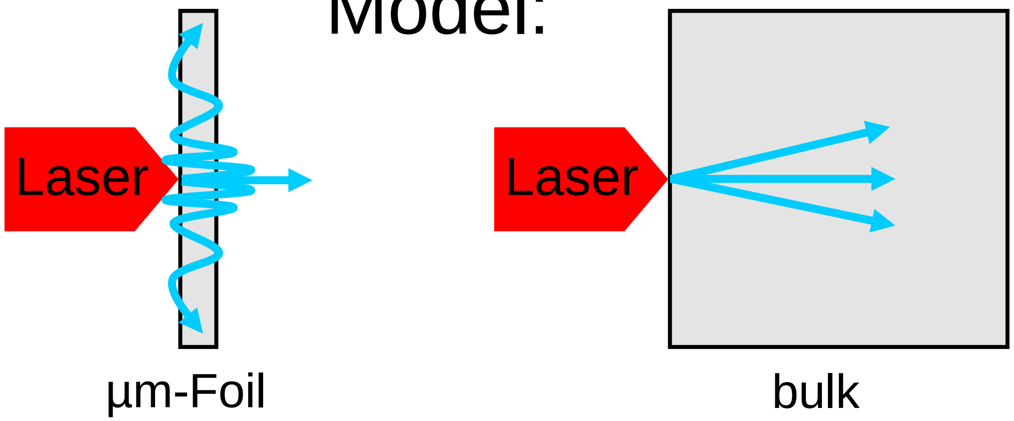



transition from cold
to warm Titanium plasma:

blue-shift due to thermal
M-shell ionization

Model:



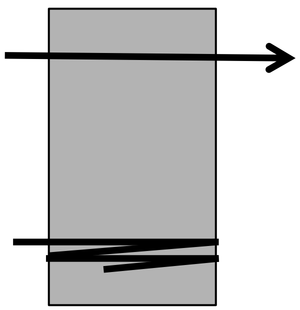

**Theoretical line shape models:**

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

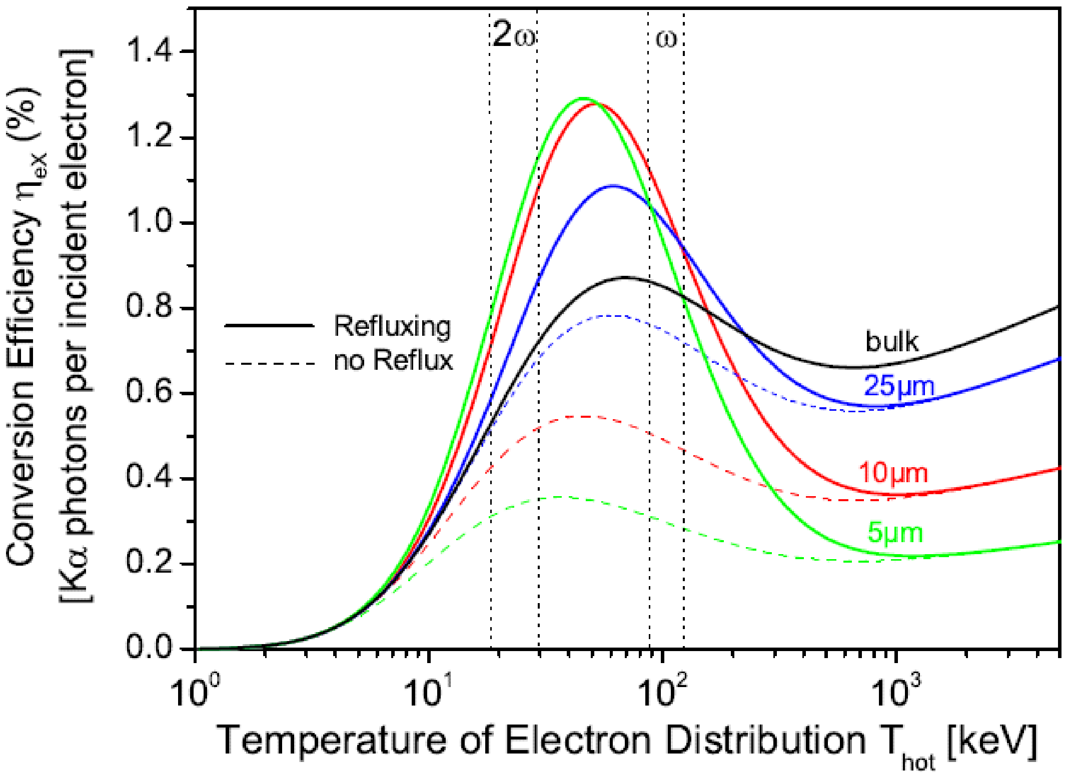
# Global Parameter: Kα-Yield and Refluxing

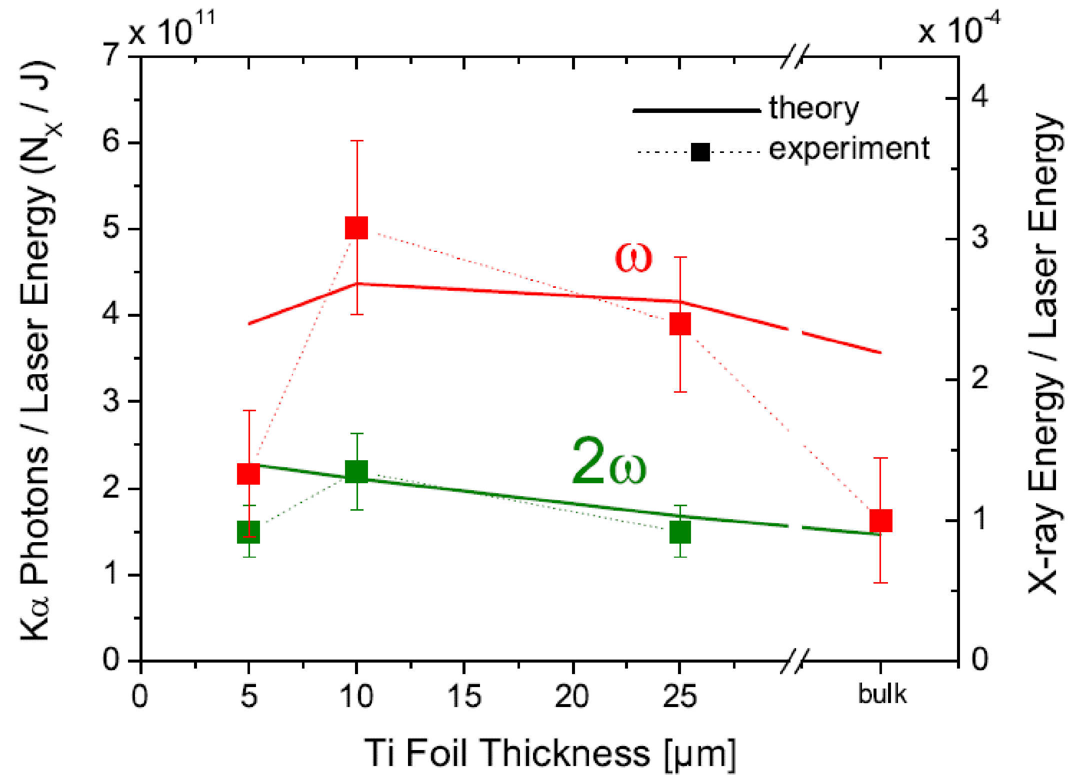


$E_e$ > 100 keV
→ $e^-$ leave the foil

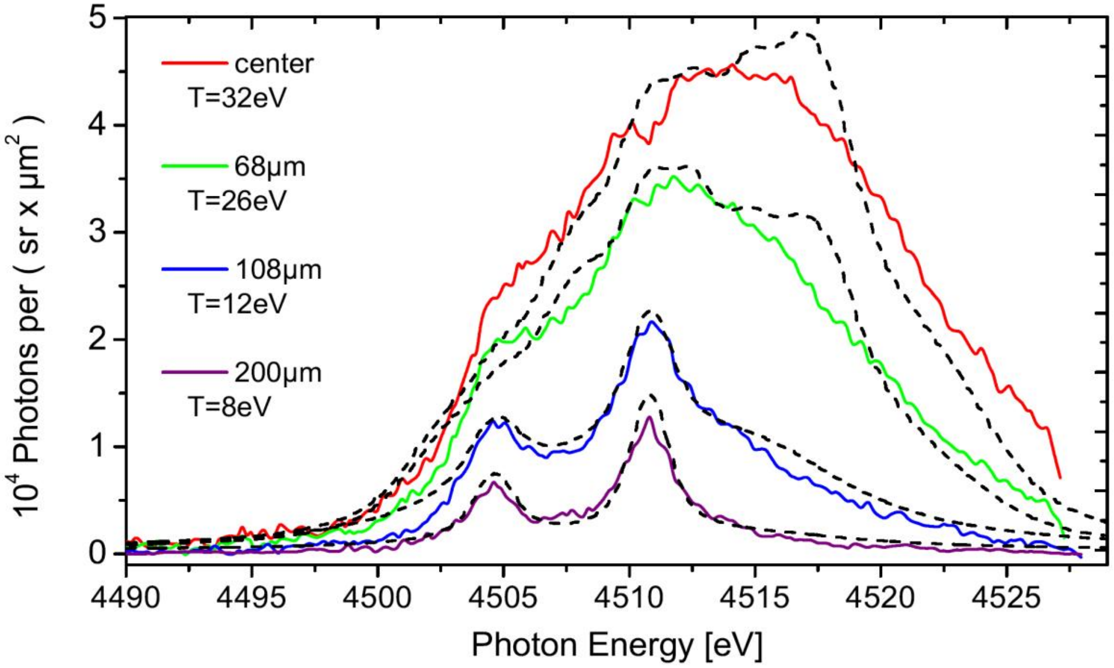
$E_e$ < 100 keV
→ $e^-$ stays in foil,
mean free path ~ 20µm

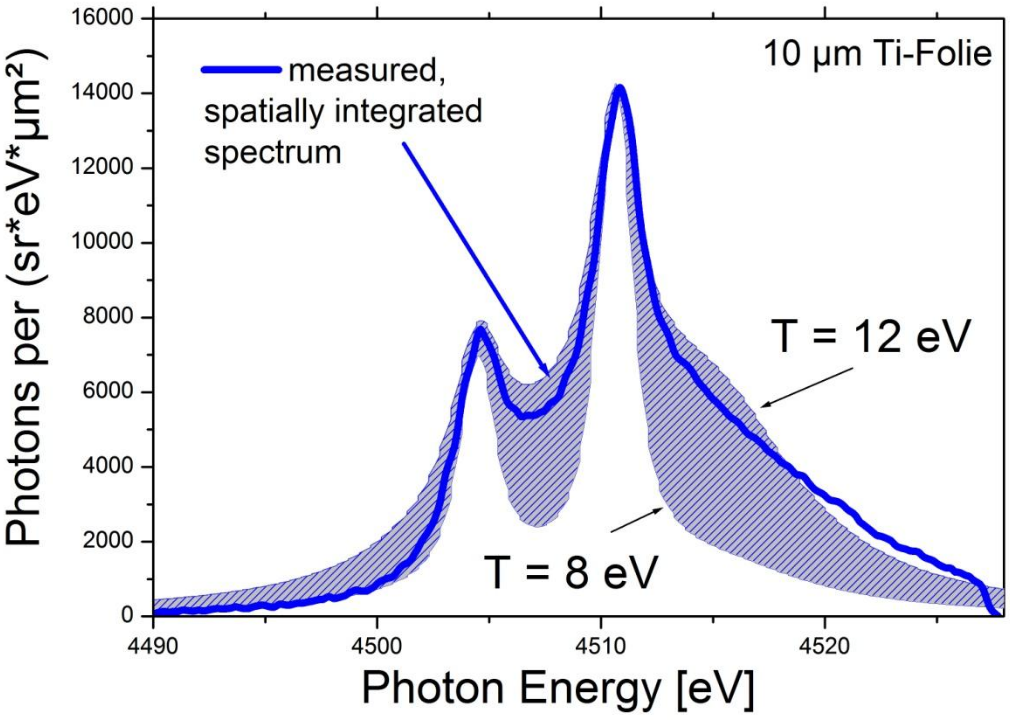
strong electric field ~ MeV/µm
hinders slow electrons
to escape from the foil.
Fit-Parameter: $E_e$ < 100 keV



# Spatially integrated spectra




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

# Summary

X-ray Spectroscopy reveals Properties of Extreme States of Matter:

- 10-channel monochromatic framing camera to measure time-resolved parameters of ICF capsules at GEKKO XII

- Polarization of ‘blue wings’ in K$\alpha$ emission from relativistic laser plasmas of thin Ti foils
  → anisotropy of relativistic electron beam.

- Radial temperature distribution of laser-heated foils, Homogeneous heating due to refluxing of electrons
  → center at 30 eV is significantly larger than laser focal spot.

# Thanks to international Collaborations

*High Energy Density Physics – Peak-Brightness Collaboration*

- **AG Röntgenoptik, IOQ, Universität Jena**
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  S. Höfer, T. Kämpfer, R. Loetzsch, O. Wehrhan, colleagues, workshop

- Universität Rostock
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- Weizmann Institute of Science, Israel
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  P. Audebert, E. Brambrink

HELMHOLTZ ASSOCIATION

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Laserlab Europe

HEPTAGON

GIF

IOQ Jena

*Thank you*
*for your attention.*