Opacity Measurements in Warm Dense Matter

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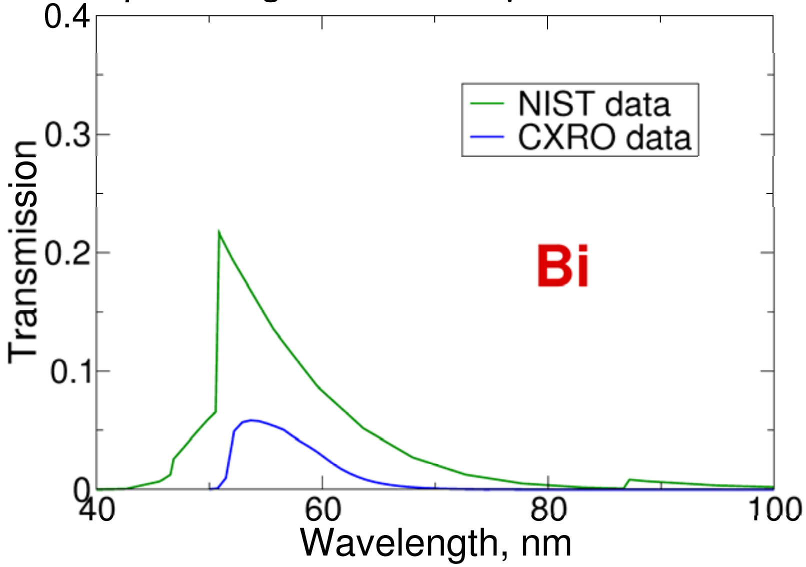
Why Opacities in the VUV – Regime?

“Cold” Matter

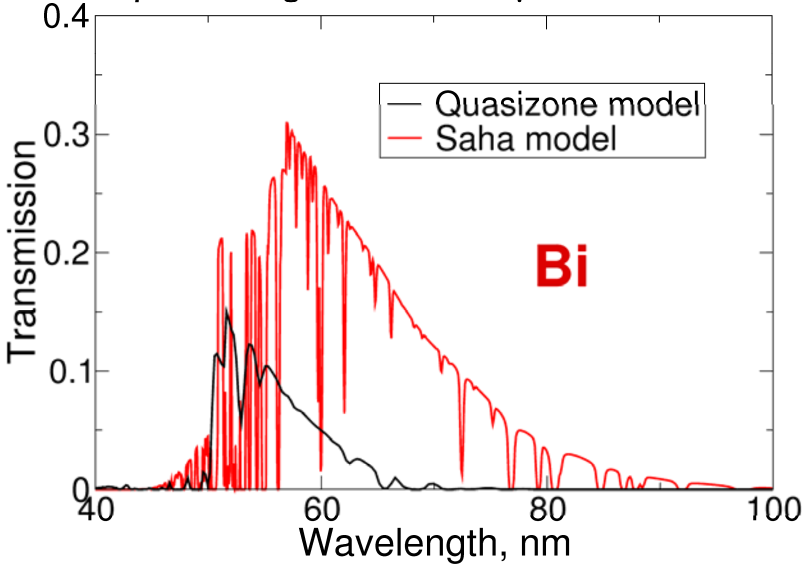
ρ= 9.73 g/cm^3, d = 0.2 µm, T = 300 K



Warm Dense Matter

Ion beam heated foil:

ρ = 0.05 g/cm^3, d = 39 µm, T = 1 eV



- **Lack of the measurements in “cold” matter, available data differs significantly**
- **Spectrally resolved opacity measurements in the XUV-range can benchmark theoretical approaches for the atomic physics of warm dense matter**

Optical Properties of Warm Dense Matter: Spectrally Resolved Opacity Measurements

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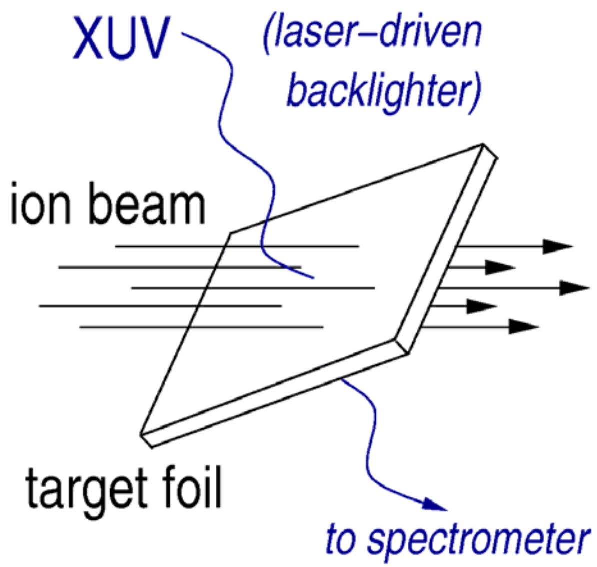
Conditions for an experiment at SIS-18:

- Beam intensity of SIS-18 limits target material to high-Z
- Interesting atomic physics processes of warm dense matter (few eV Temperatures) are expected for the interaction with few tens of eV radiation (XUV range)
- Due to the high absorption thin targets must be used

Backlighter source:

- laser-driven thermal source
- broad-band radiation required



Target:

- Constant temperature is prerequisite for precise opacity measurements
- Line density of the target must be known
- ➢ Target hydrodynamics must be controlled

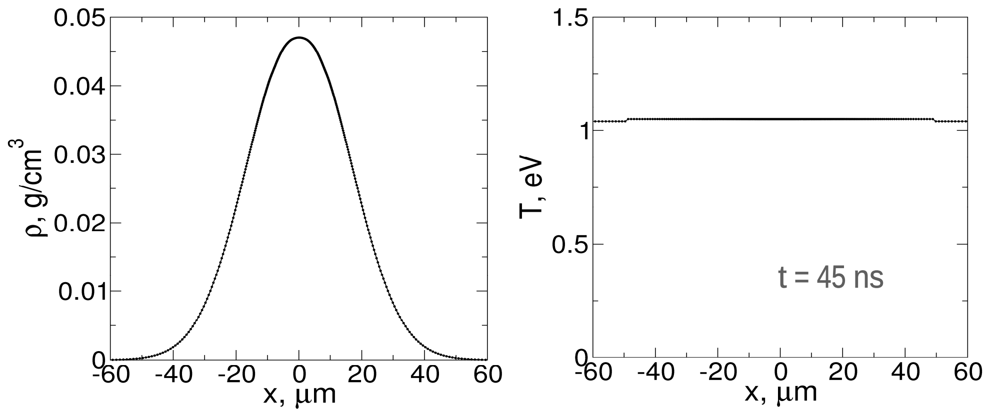
Perspectives for the WDM-collaboration at FAIR

- Higher beam intensities, shorter pulses: higher density / temperature plasmas
- No material restriction
- High power laser available to drive a hohlraum-backlighter

Target Hydrodynamics: Isothermal Expansion

RALEF-2D simulation: Isothermal expansion of ion beam heated foils

Target foil: 0.2 µm Bi, 10 kJ/g in 100 ns pulse (~10^{10} ions)



Interesting Target Properties:

- Isothermal target is condition for opacity measurements
- 1-D target expansion: constant line density
- Coupling parameter Γ ~ 1
- Average ionization Z ~ 1

Analytical solution of the hydro equations:

Isothermal, homogeneous expansion
⇒ self-similar solution*

For $t > d/c_s$: velocity

$$v = \left(\frac{dL/dt}{L}\right)x\,,$$

$L(t)$ – scale factor

Using equation-of-state of ideal gas:

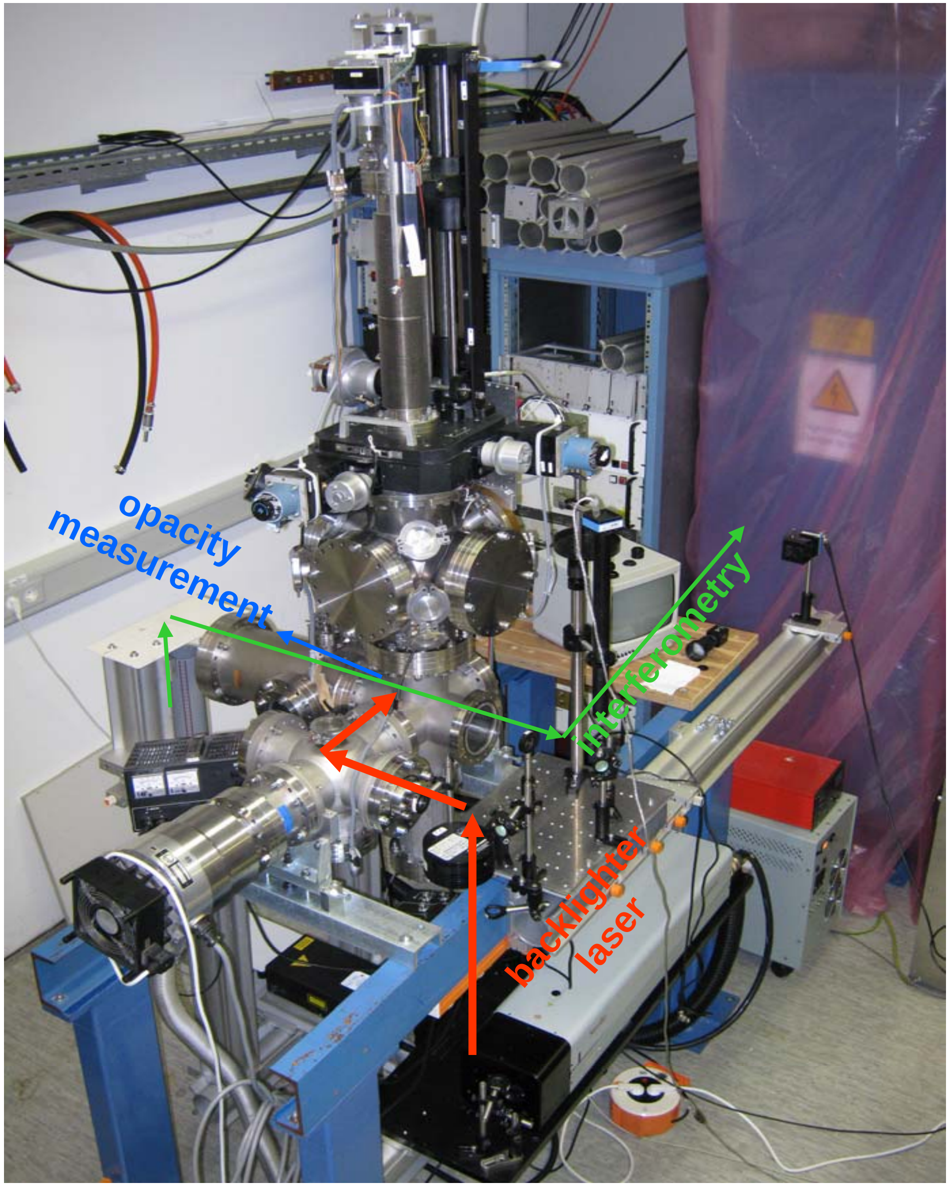
density

$$\rho = \frac{m}{\sqrt{2\pi}L}\exp\left(-\frac{x^2}{2L^2}\right),$$

$m = \rho_0 d$ – total column density

An. Tauschwitz et al., Appl. Phys. B, **95** (2009)

Optics Setup

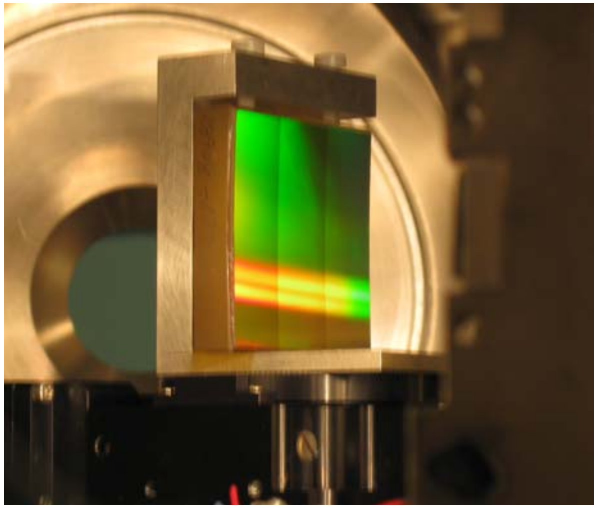


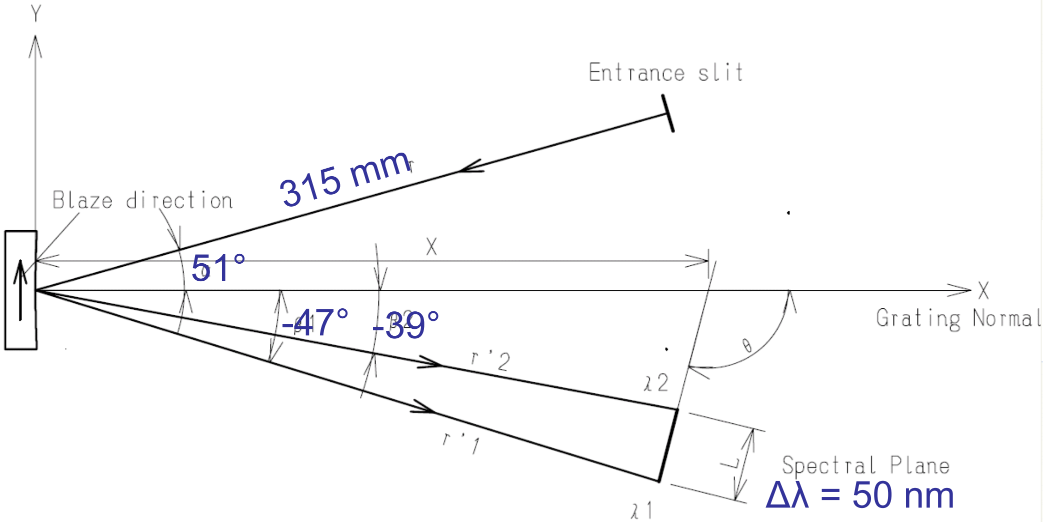
- simultaneous opacity measurement and plasma interferometry
- spectroscopic temperature measurement
- 300 mJ laser (ω / 2ω / 3ω) for backlighter
- 20 mJ laser (ω / 2ω) for interferometry
- 3-axis target manipulator

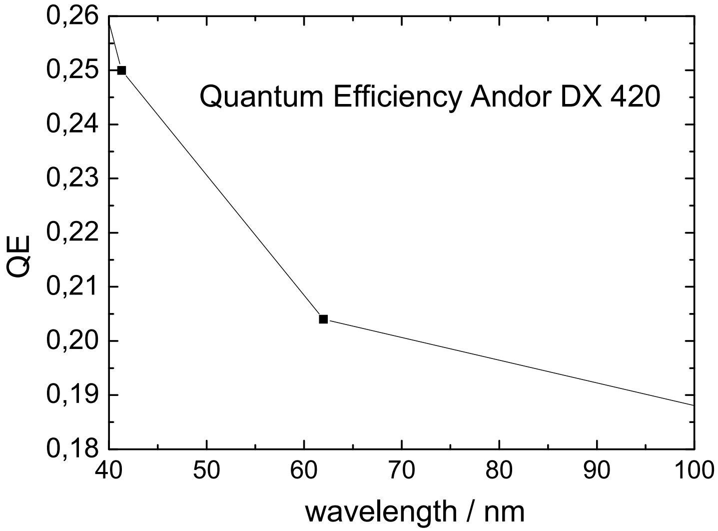
backlighter laser	**Nd:YAG**
wavelength	1064 nm
energy	300 mJ
pulse duration	7 ns
focal spot	~ 50µm -100 µm
backlighter target	gold

High Efficiency Spectrometer

- no entrance slit (backlighter in focal point)
- large solid angle (normal incidence, large blank, short focal length)
- concave flat field grating (Hitachi, 1200 l/mm) allows use of CCD detector
- efficient cooled x-ray CCD (Andor DX420, quantum efficiency 20%)
- noise immunity (90° geometry allows to place detector upstream of ion beam)
- resolving power: theoretical limit: $\lambda/\Delta\lambda = 5\cdot10^4$, limited to 0,5Å by CCD pixel size

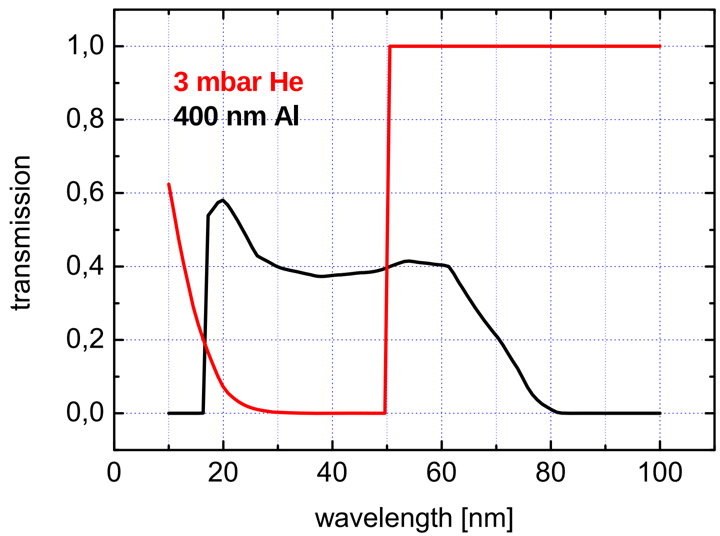




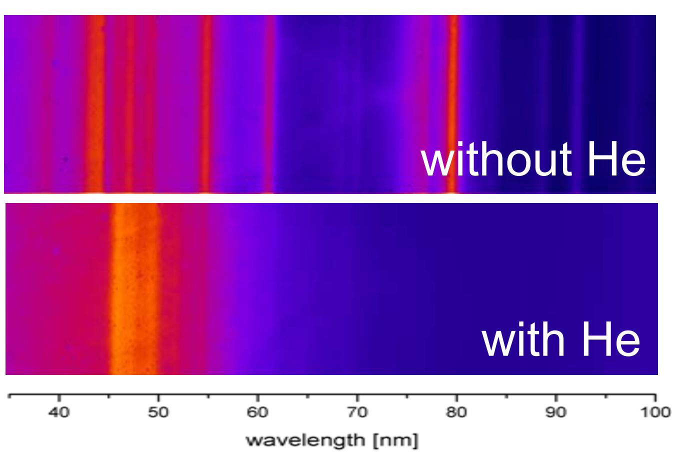


Spectral Filters

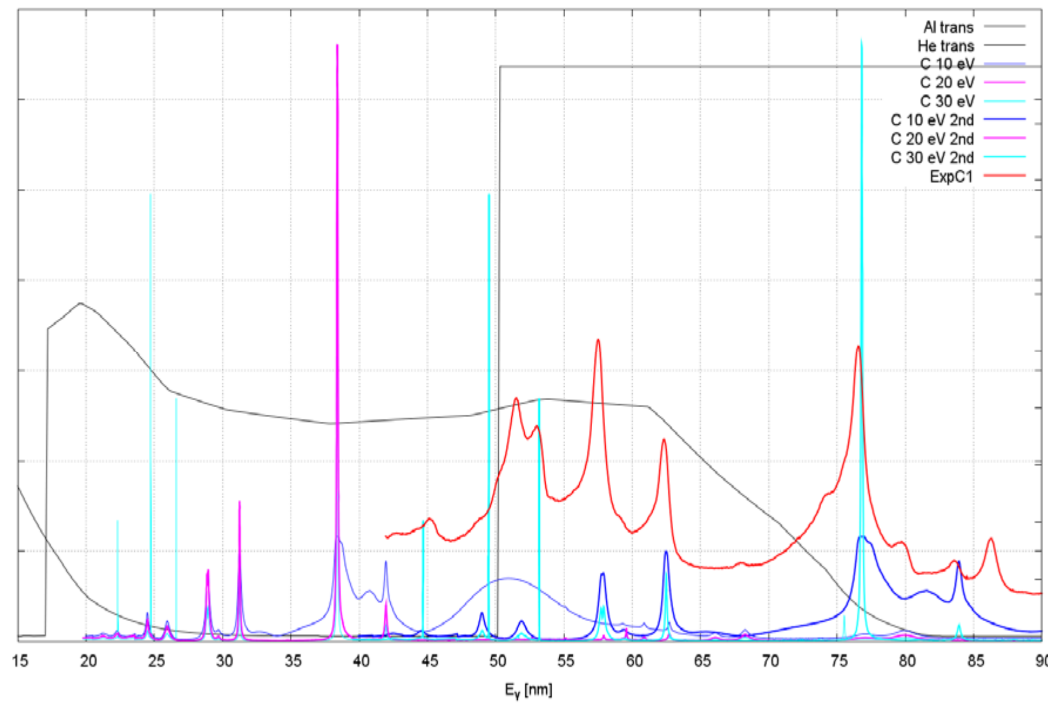
A combination of filters is used to suppress higher spectral orders



Carbon spectra for wavelength calibration

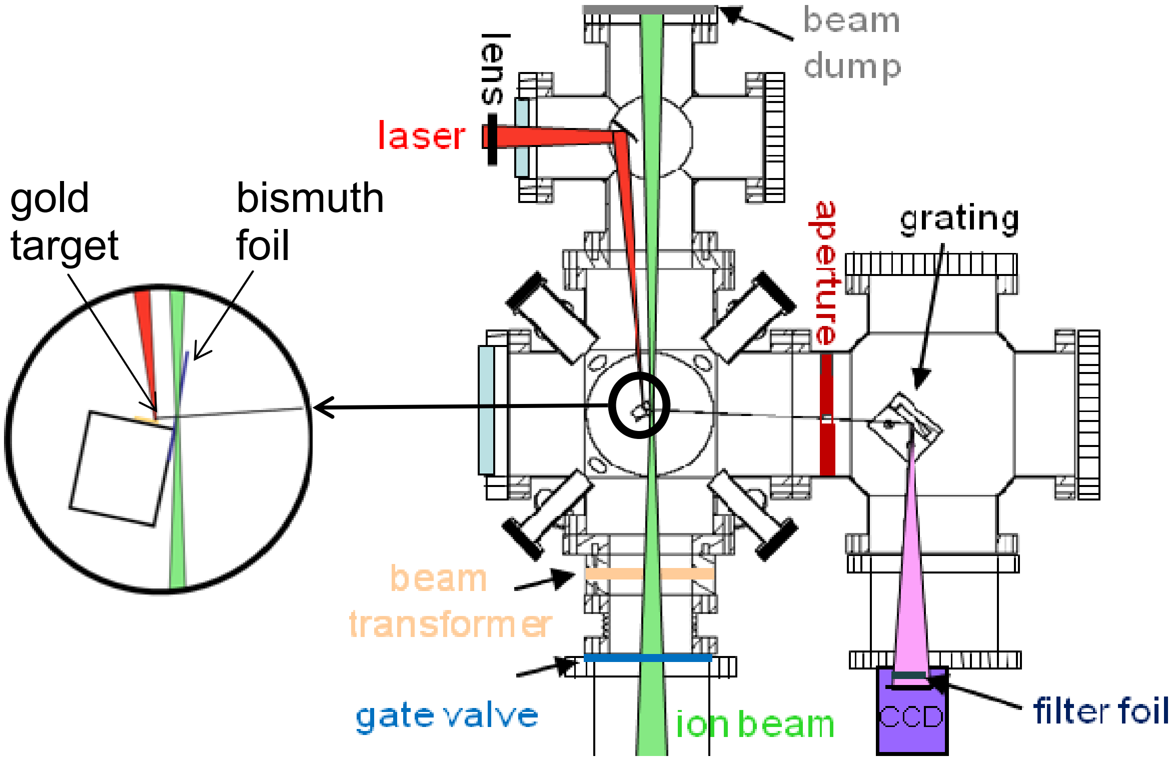


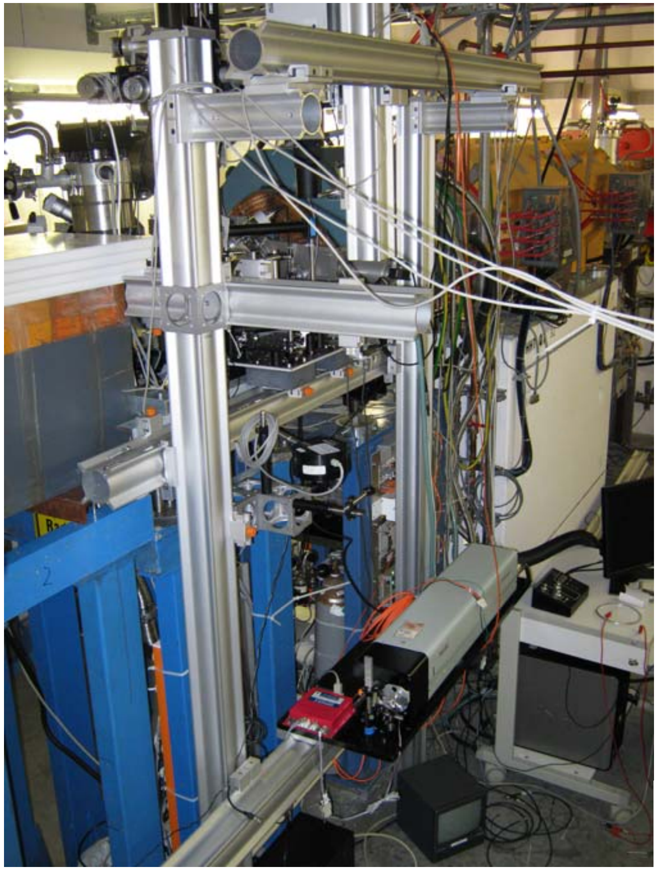
Flychk-simulation of Carbon spectra in the range of 10 to 30 eV are used for the wavelength calibration of the spectra



All intense lines are second order from the 20 – 50 nm wavelength region an can be suppressed with the He-filter

Integration into the Beamline





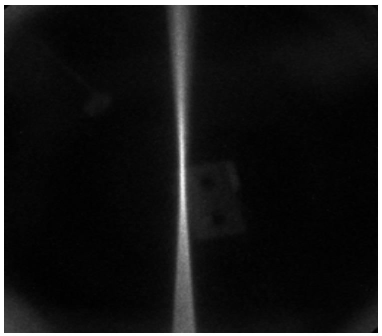
Vacuum chamber

- chamber base pressure: < 1E-6 mbar
- entrance window of chamber can be removed after evacuation
- beam current transformer integrated in front of target
- can be run detached from beamline
- setup can be tranported, installed and aligned at the HHT-cave within 3-4 days

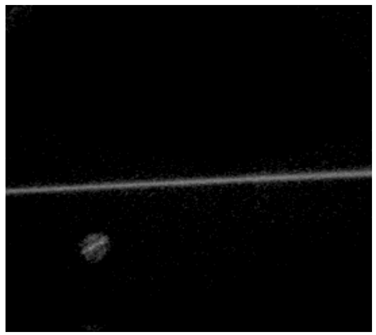
Ion Beam Manipulation

spatial bunch control

emission of the He filter gas in the target chamber



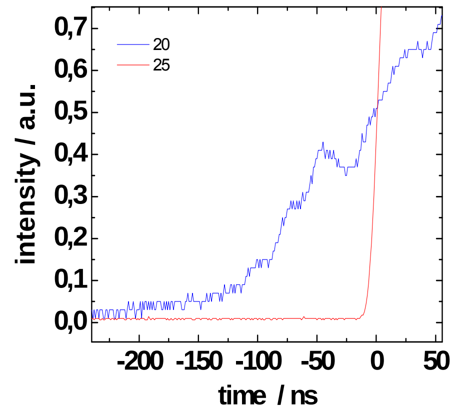
horizontal (x)



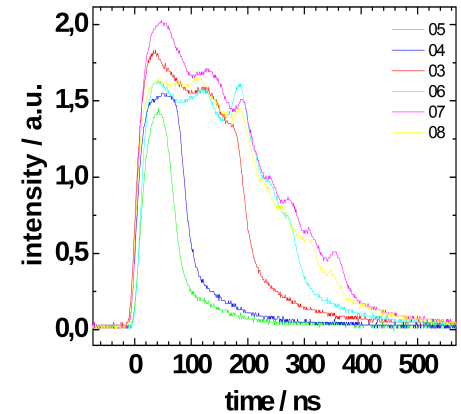
vertical (y)

temporal bunch control with the SIS-kicker

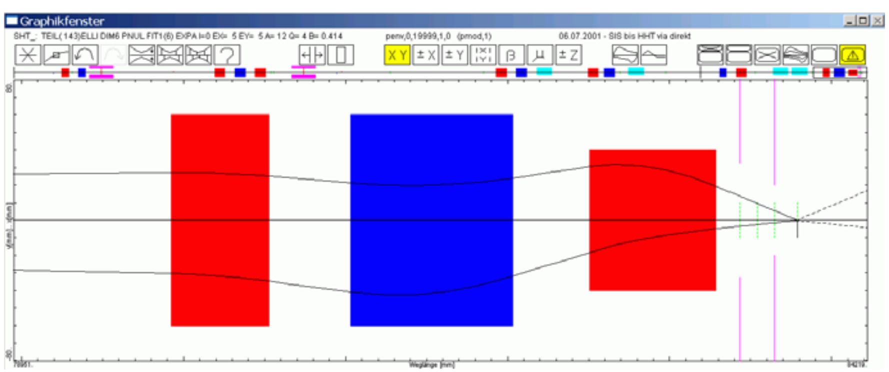
prepulse suppression



bunch length control



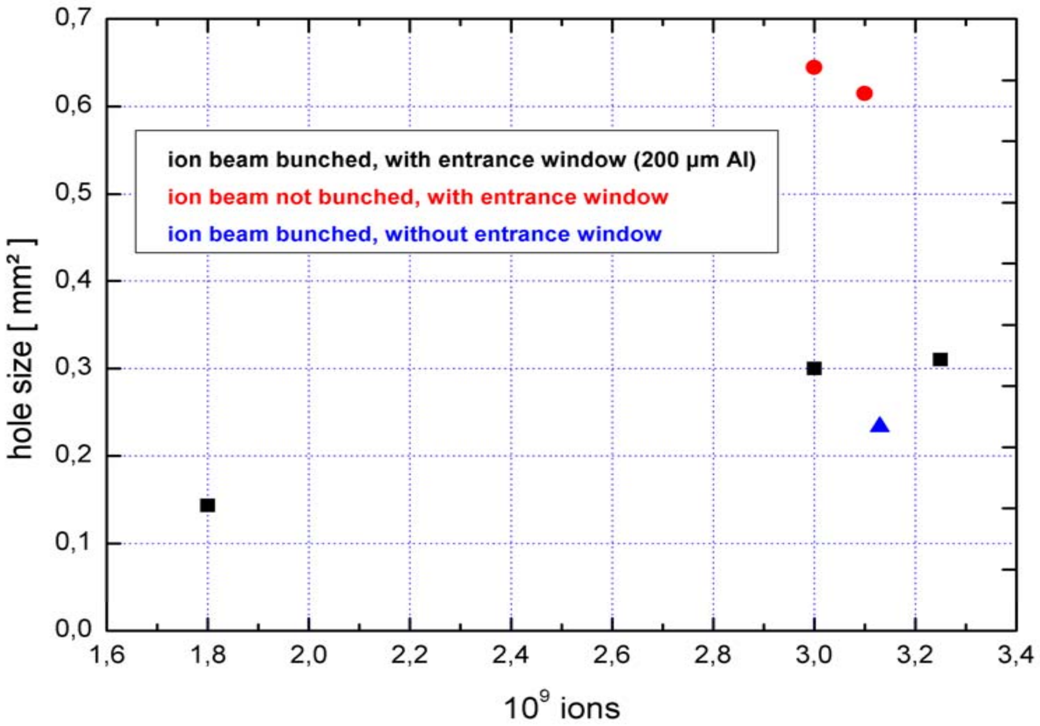
magnet settings for focus control



heavy ion particles	U^{73+}
energy	250 MeV/u
pulse rise time	~ 15 ns
pulse duration	~ 100 ns
bunch intensity	$3*10^9$ per bunch
focal spot	~ 500 µm
energy deposition (Bi)	~ 1 kJ/g

Ion Beam Focus

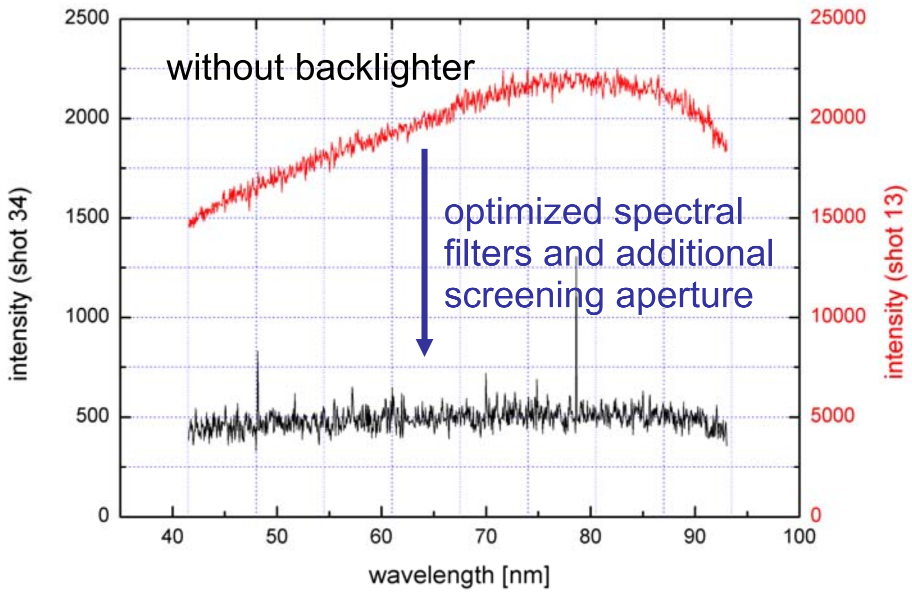
There is no precise established method for the focus measurement of intense beams



A gold witness foil is used to estimate ion beam focus:

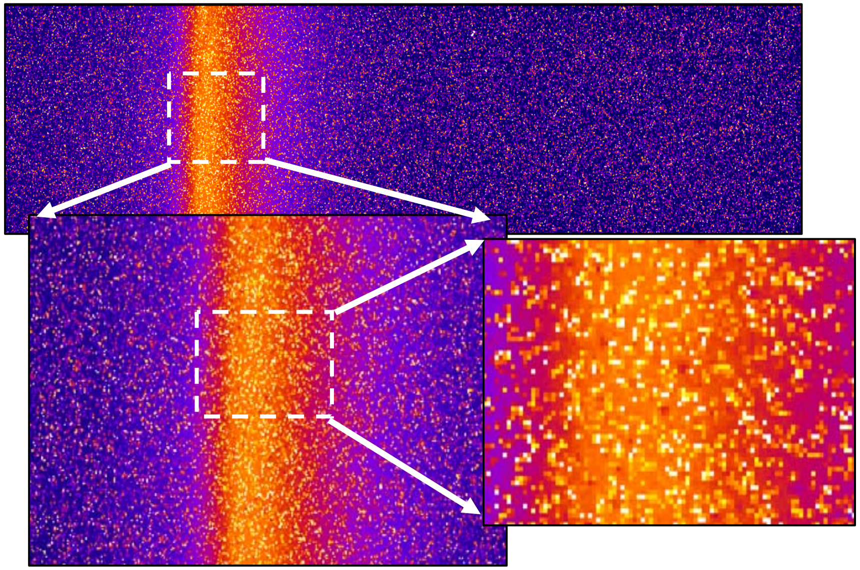
- use of the bunch compressor has reduced the beam line transmission
- removing the entrance foil window has improved the beam focus
- for most measurements (with bunch compressor and entrance window) energy deposition was ~1 kJ/g
- the corresponding temperature in Bi is ~3500 K

Ion Beam Induced Background

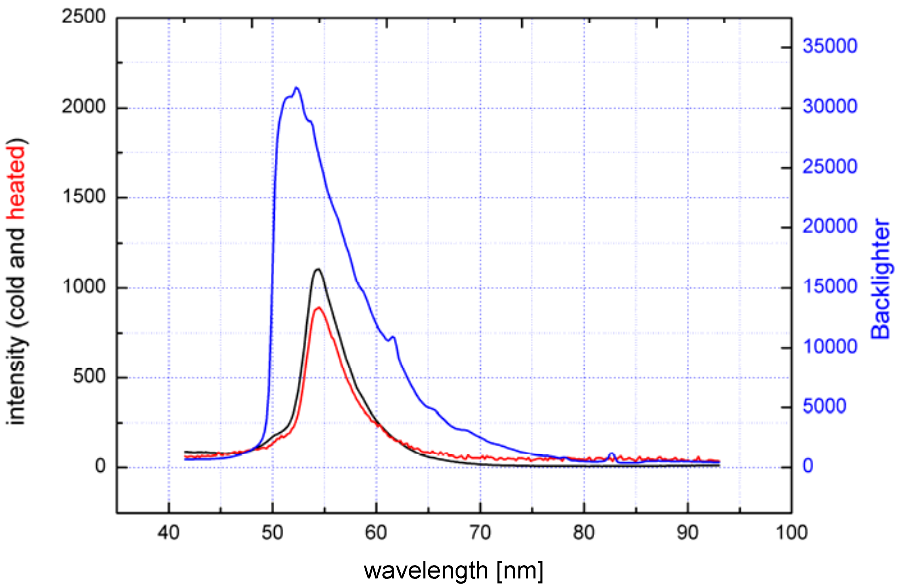


source of noise	rel. intensity
Bi-foil self emission	1
entrance window (200 µm Al)	4E-2
beam dump	4E-3
Ion beam halo on Al target frame	2,5

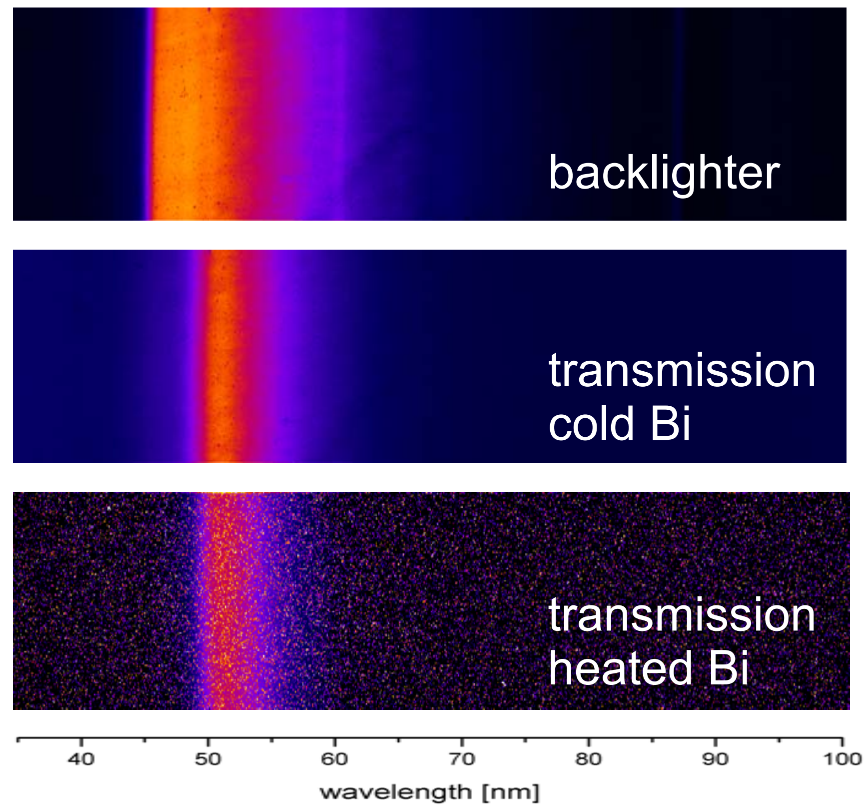
- main source of background noise are probably low-energy electrons
- neutrons originating from the beam dump can be neglected
- a beam halo that hits the target frame increases the background significantly
- the noise can only partially eliminated by binning and filtering



Transmission Spectra



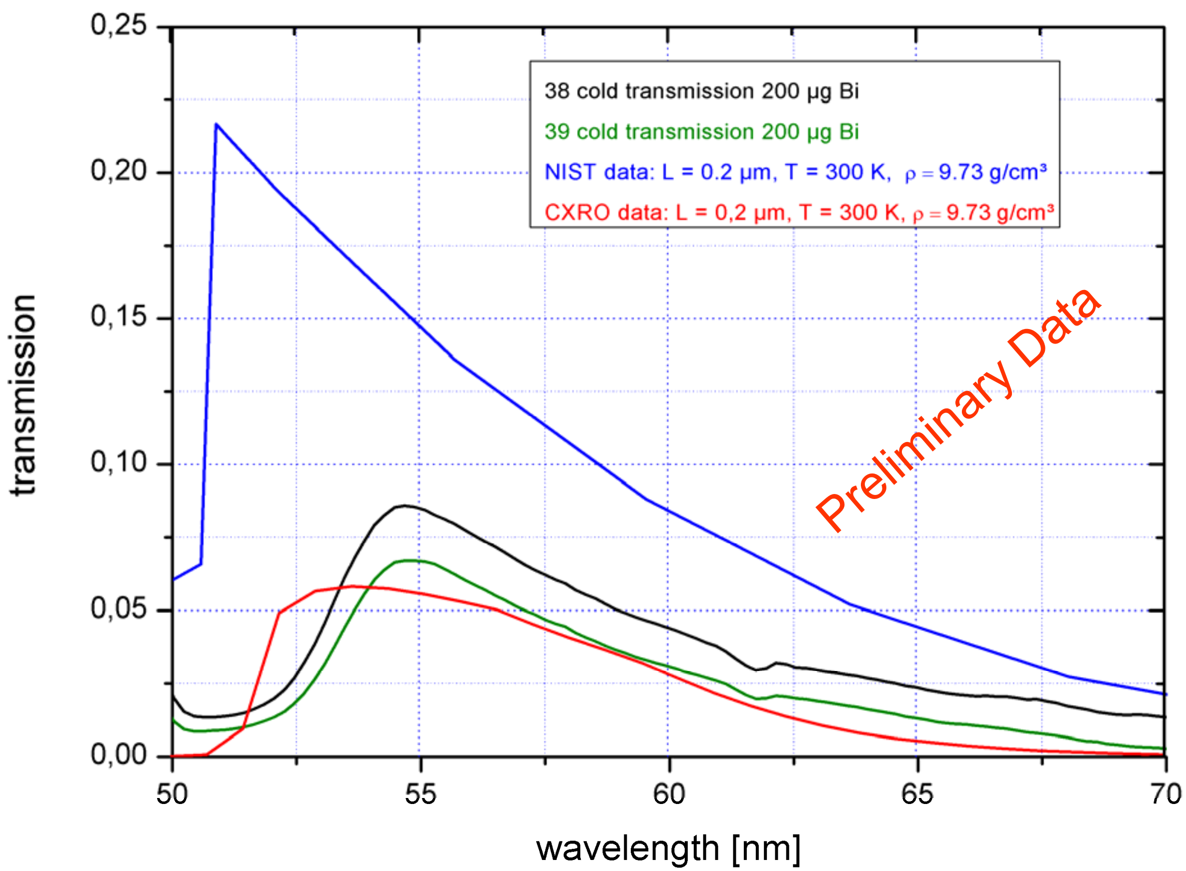
The transmission spectra have sufficient signal to noise ratio



The backlighter spectra have relatively large intensity fluctuations caused by surface contaminations on the Au target.

Cleaning shots with the laser will be used in the future to remove this error.

Transmission through Cold Foil

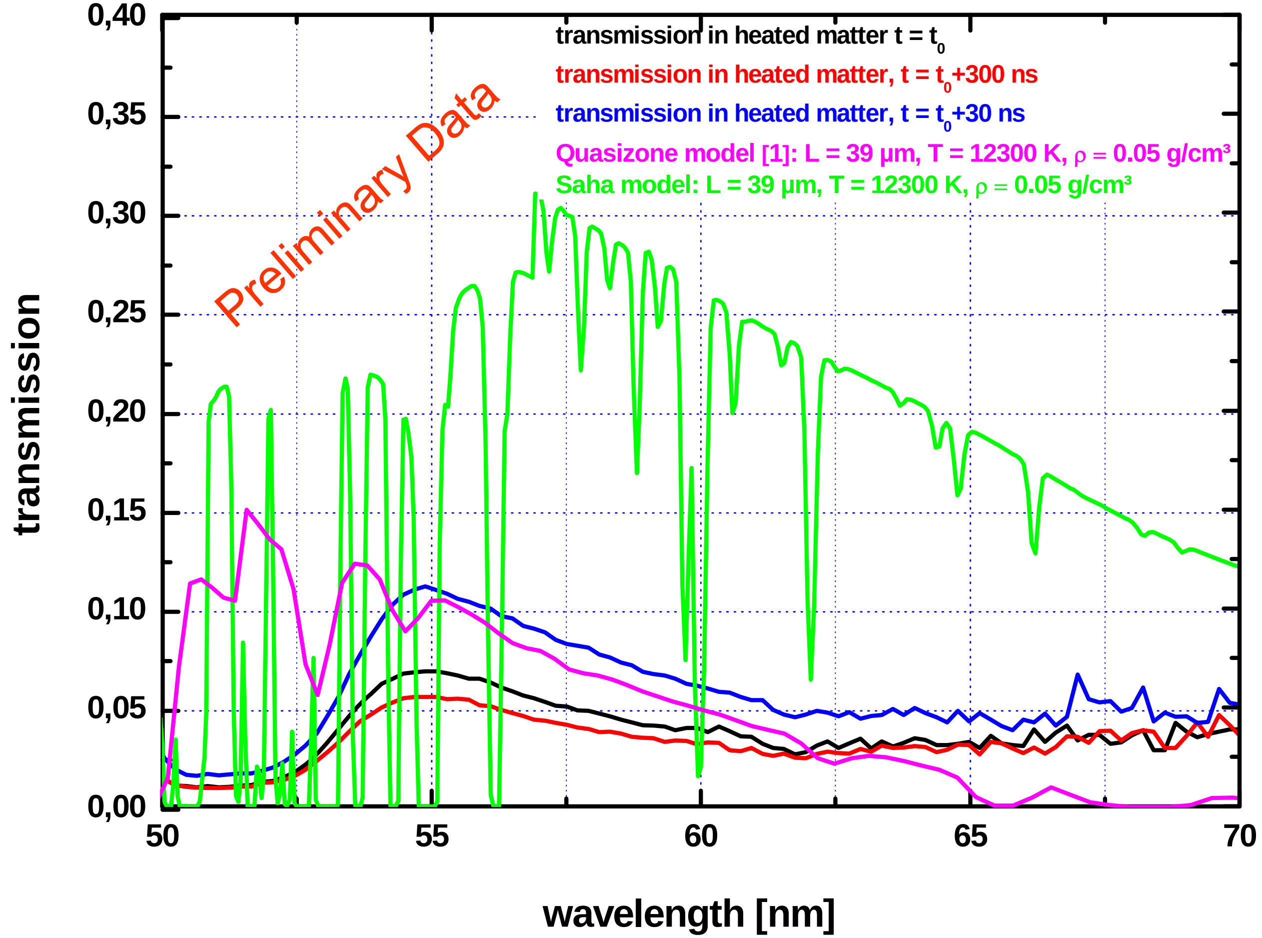


The Center of X-Ray Optics
http://www.cxro.lbl.gov/

National Institute of Standards and Technology
http://www.nist.gov

The measured transmissions in cold matter is in the range of the tabulated data given by NIST and CXRO

Transmission through Heated Foil



[1] A.F. Nikiforov, V.G. Novikov, V.B. Uvarov: 'Quantum-statistical models of hot dense matter: methods for computation opacity and equation of state', Birkhäuser Verlag, 2005

The achieved Bi temperatures are well below the envisioned 1eV range and agreement with the theoretical predictions cannot be expected.

The first results show that the transmission data have sufficient quality to discriminate between different models.

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Summary

- ✓ A broad-band backlighter could be realized with a table top laser
- ✓ The highly efficient spectrometer and detector guarantee sufficient intensity for spectrally resolved measurements
- ✓ A combination of filters reduce unwanted higher spectral orders to a large extend
- ✓ Different measures have allowed to reduce ion beam induced noise to a tolerable level
- ✓ Measured transmission data are precise enough to discriminate between different opacity models

- ➢ Influence of surface contaminations on target and backlighter source have to be controlled
- ➢ On-line measurements of target density and temperature as well as backlighter intensity have to be set up