International Workshop on Astronomical X-Ray Optics

Dec 02 - 06, 2019 | Prague, Czech Republic

Optical coherence tomography (OCT) with the use of soft X-rays as a tool for testing X-ray optics

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Outline

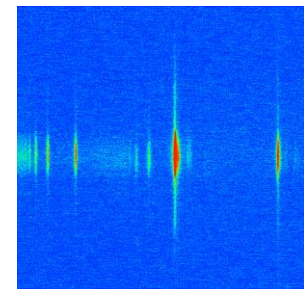
- **Introduction**
  - optical coherence tomography (OCT),
  - soft X-rays and extreme ultraviolet (EUV).
- **X-ray coherence tomography (XCT)**
  - XCT using synchrotron radiation,
  - XCT using high-order harmonic generation (HHG).

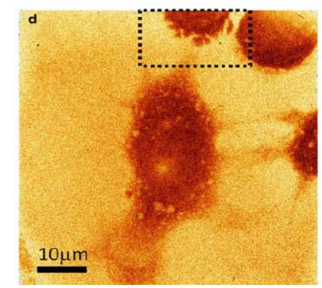
Jena

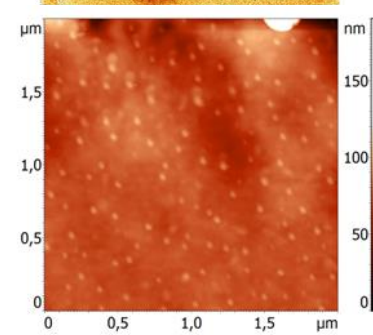
- **XCT using a laser plasma soft X-ray source**
  - laser plasma soft X-ray source with a gas puff target
  - XCT experimental setup,
  - XCT measurement results,
  - XCT setup design for 3-D imaging

Warszawa

- **Summary and conclusions**







Optical coherence tomography (OCT)

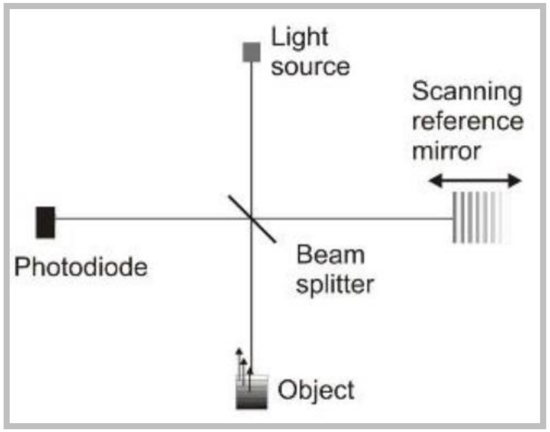
Optical coherence tomography (OCT) is a well-known imaging technique that uses low-coherent light to capture two- and three-dimensional images from optical scattering media.

OCT is **performed by splitting** an illumination beam into two, namely, a reference and an object beam. The object beam is scattered from the sample, while the reference beam, superimposed with the object beam, produces an interference pattern.

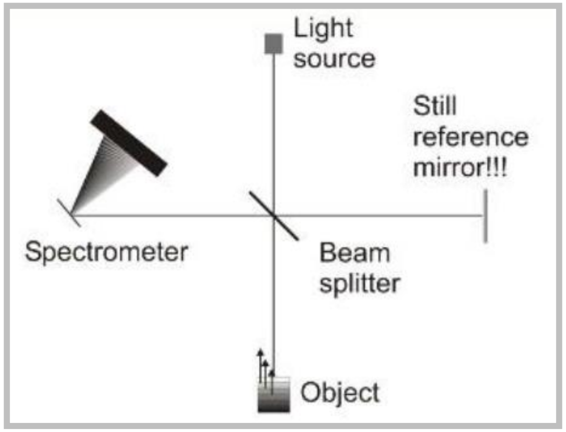
Due to a **broad bandwidth** of the light (**small coherence length**), the interference occurs only if the delay between the two beams is within a coherence time, related to the coherence length.

Thus it allows to probe the internal structure of the object by changing the delay between the beams (**time-domain OCT**) or by recording the interference in the spectral domain (**frequence-domain OCT**).

Time domain OCT (TD-OCT)



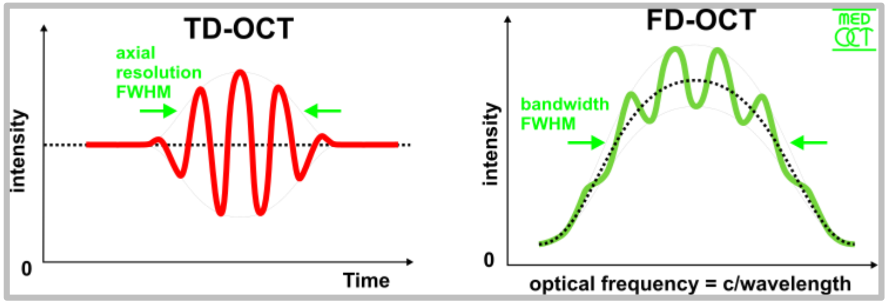
Frequency domain OCT (FD-OCT)



Optical coherence tomography (OCT)

The **axial resolution of OCT** is in the order of the coherence length of a light source l_c which depends on the central wavelength λ_0 and the spectral width (FWHM) of the source $\Delta\lambda_{FWHM}$.

For Gaussian shaped spectrum the **coherence length is defined**:



$$l_c = \frac{2\ln 2}{\pi}\frac{\lambda_0^2}{\Delta\lambda_{FWHM}}$$

Therefore, the **axial resolution only depends on the spectral** rather than geometrical properties of the radiation.

OCT with broadband visible and near-infrared sources typically reach axial (depth) resolutions in the **order of a few micrometers**.

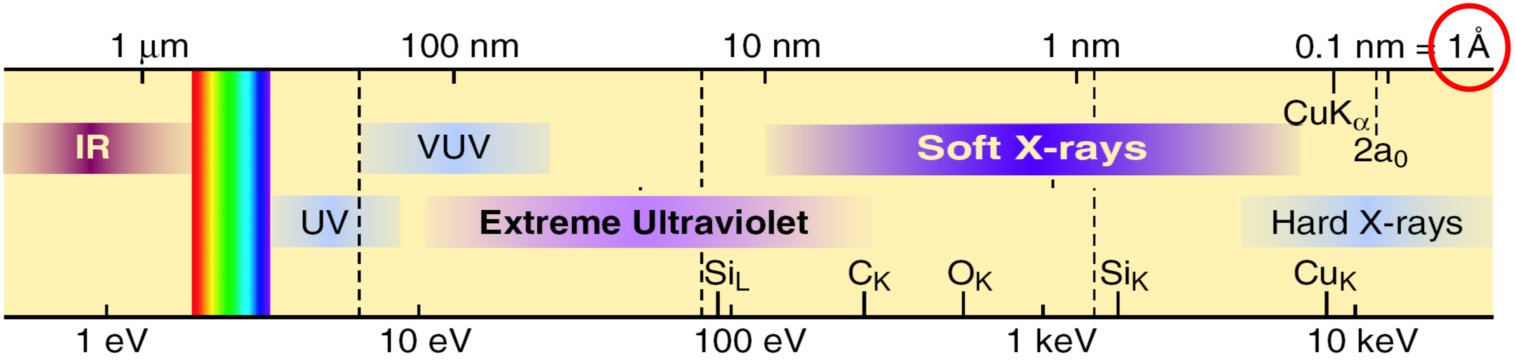
The axial resolution improvement has been proposed by extention of optical coherence tomography (OCT) to the **short-wavelength coherent tomography (XCT)** using extreme ultraviolet and soft X-rays.

G. Paulus & Ch. Rödel „Short-wavelength coherent tomography”
US Patent No.: US 7,656,538 B2

Soft X-rays and extreme ultraviolet (EUV)

ISO International Standard 21348 http://www.spacewx.com/ISO_solar_standard.html

Soft X-rays (XUV)	**$0.1 \leq \lambda < 10$ nm**
Extreme Ultraviolet (EUV)	**$10 \leq \lambda < 121$ nm (He Lyman-alpha)**



Motivations

- nanometer resolution (nanolithography & nanoimaging)
- nanometer penetration depth (processing of surfaces & nanoanalysis)
- elemental mapping (nanoscale)
- low inverse relative bandwith (IRB)

Generation

- synchrotrons, FELs
- plasma sources (discharge plasmas, laser plasmas)

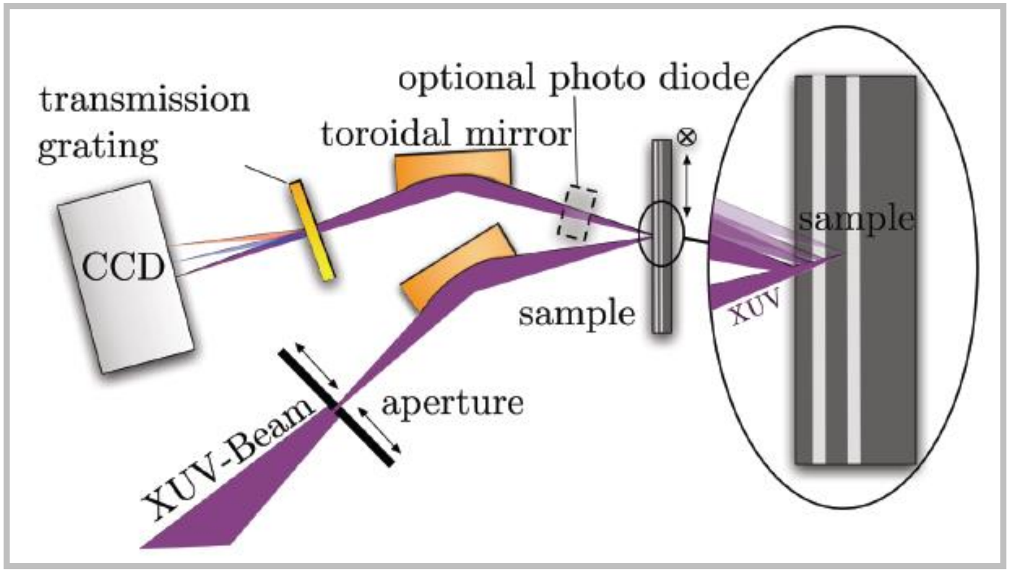
$$l_c \sim \frac{\lambda^2}{\Delta\lambda} = \lambda\, IRB$$

X-ray coherence tomography (XCT)

Realizing a classical **time-domain XCT (TD-XCT)** using a Michelson interferometer is highly demanding because of problems with optics.

In order to overcome these problems, the use of a variant of **Fourier-domain XCT** (FD-XCT) setup has been proposed.

A schematic of the proposed **FD-XCT setup**:



The **probing beam** is reflected at the layer surfaces of the sample. The beams interfere and cause a **modulated reflected spectrum** that can be measured with a grating spectrometer.

The toroidal mirror images the sample surface onto the CCD camera. The reference wave and the sample wave share the same path. Moreover, using this variety of XCT, a **beam splitter can be completely avoided**.

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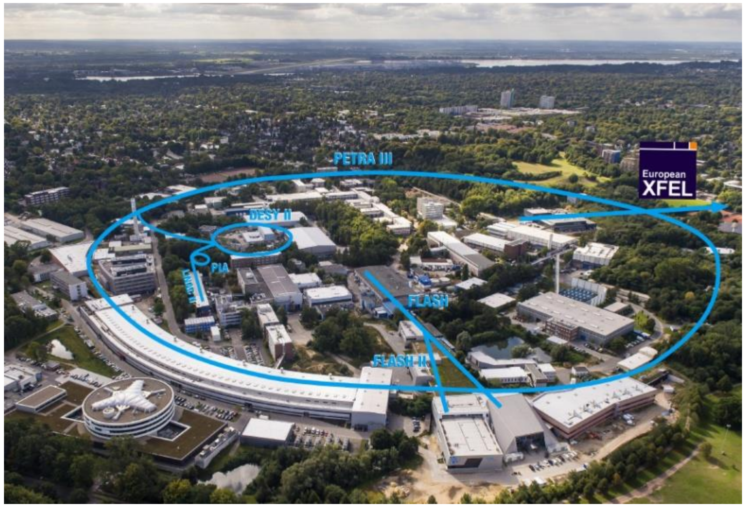
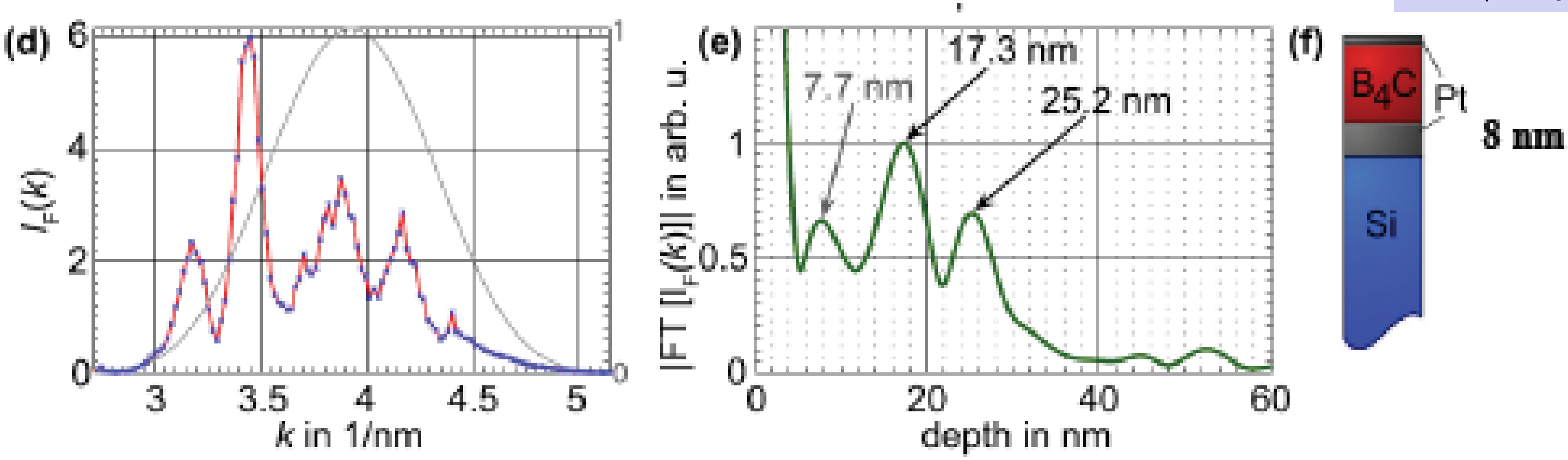
XCT using synchrotron radiation



A **proof-of-principle experiment** and the first demonstration of XCT has been recently performed using **synchrotron radiation** at DESY, Hamburg (PETRA III).

Silicon sample with Pt and B_4C layers

Soft X-ray „water window" 280 – 530 eV

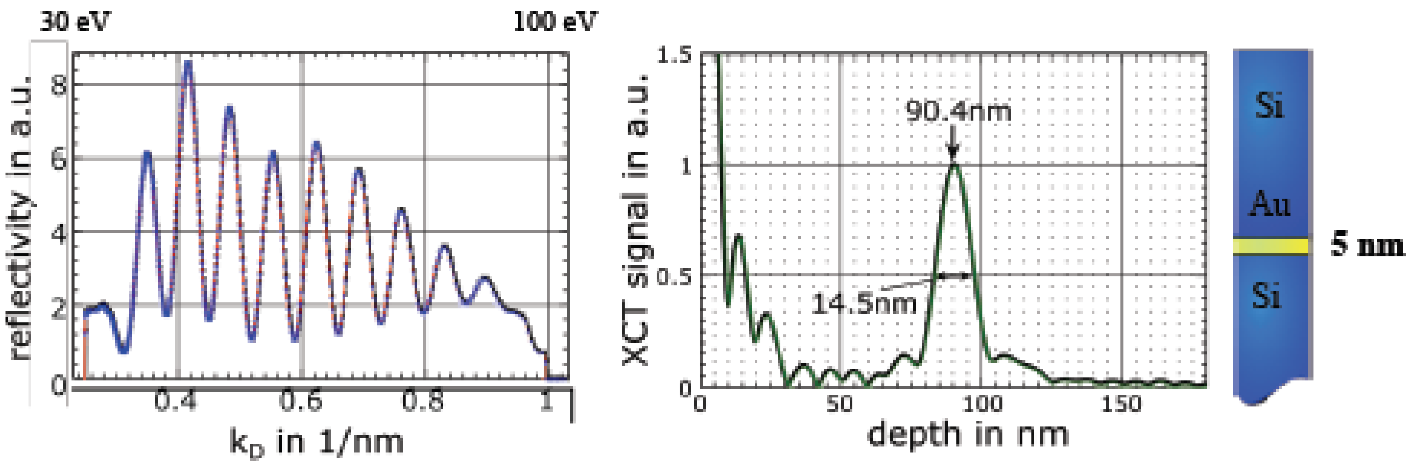


Front and back side of Pt layer resolved – resolution better than **8 nm**

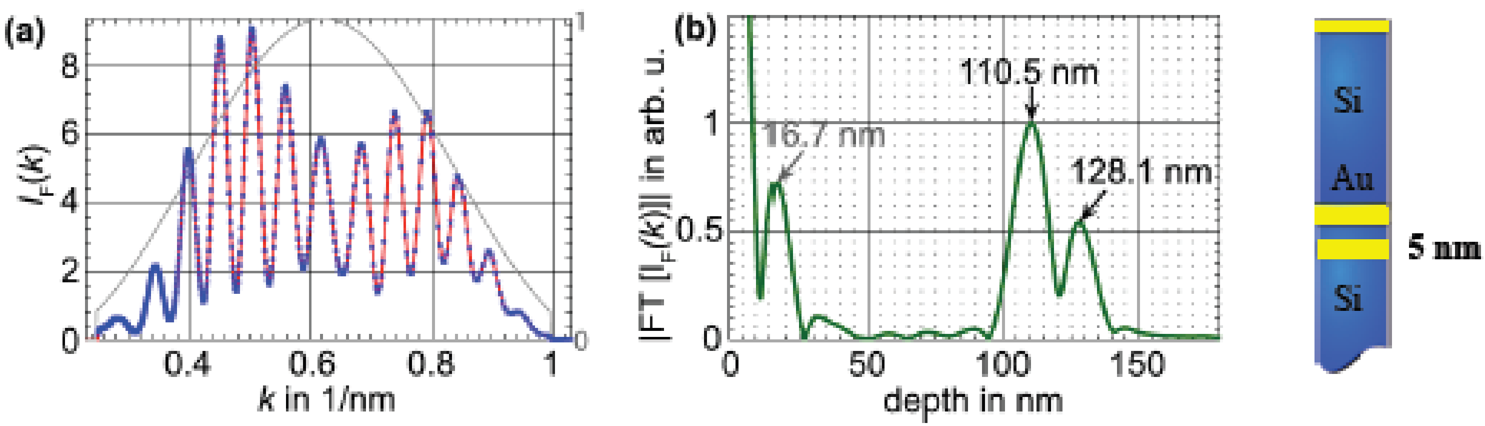
S. Fuchs et al. *Scientific Reports* **6**, 20658 (2016)

XCT using synchrotron radiation

XCT demonstration in the silicon window 30 eV – 100 eV using **synchrotron radiation** performed at DESY, Hamburg (BW3 DORIS III).



Silicon samples with buried gold layers



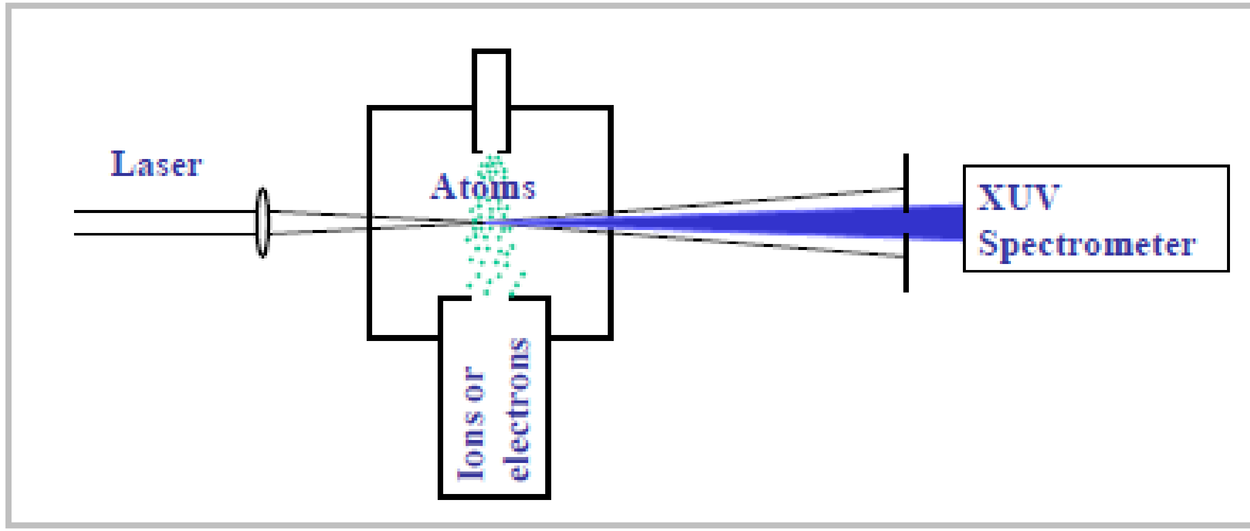
Axial resolution better than **18 nm**

S. Fuchs et al. *Scientific Reports* **6**, 20658 (2016)

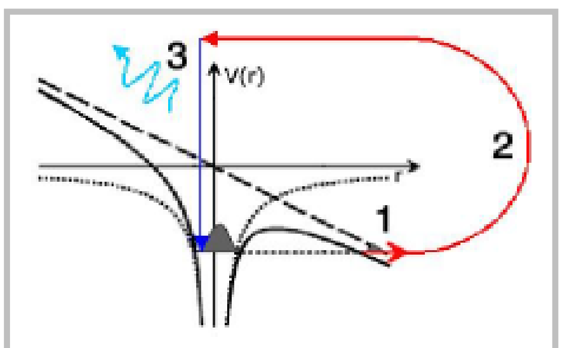
High-order harmonic generation (HHG) source

fs laser system

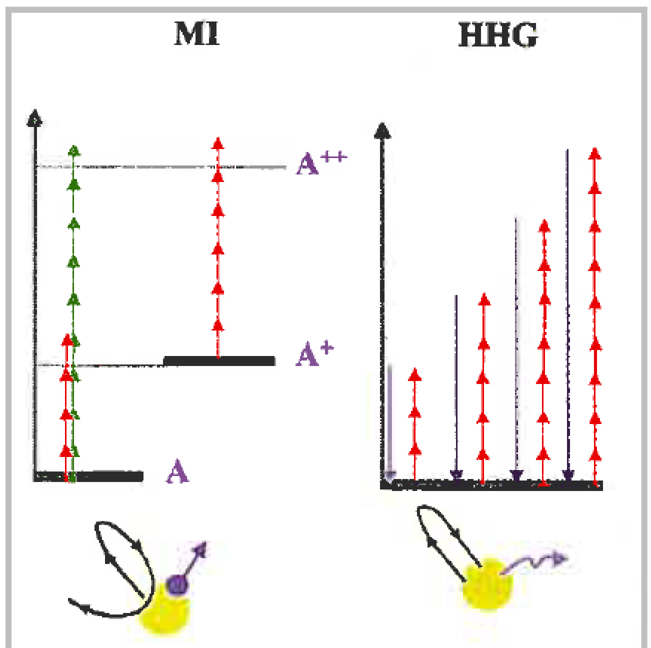
50 fs/500 mJ/10Hz



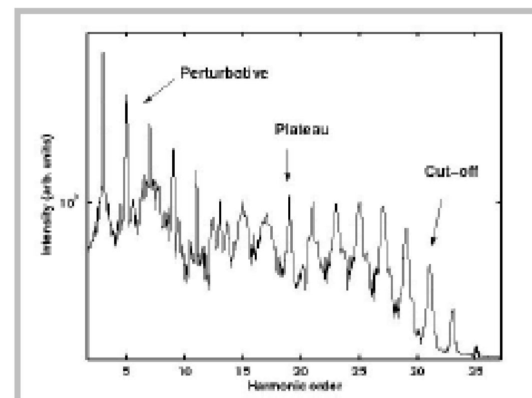
HHG process



M. Lewenstein



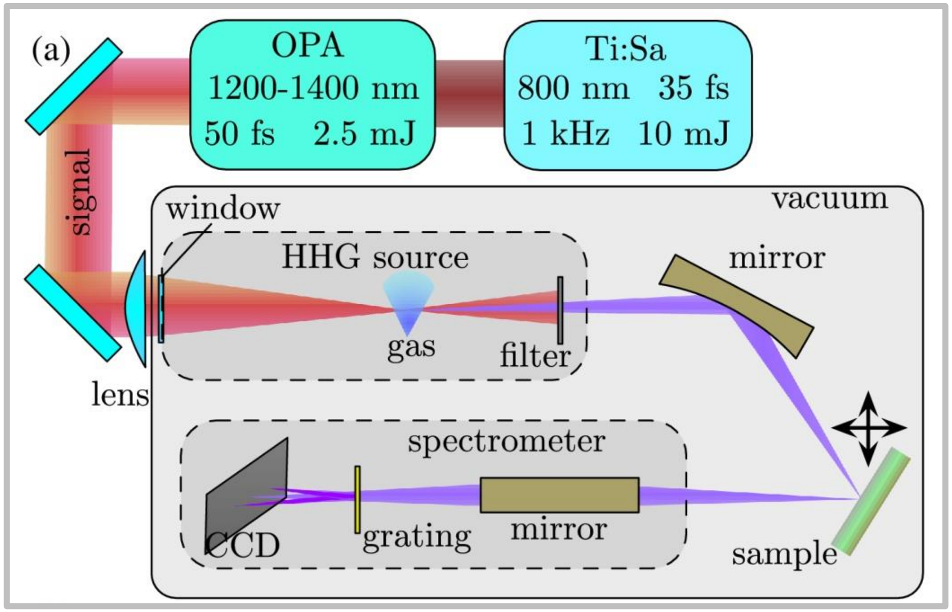
HHG spectrum

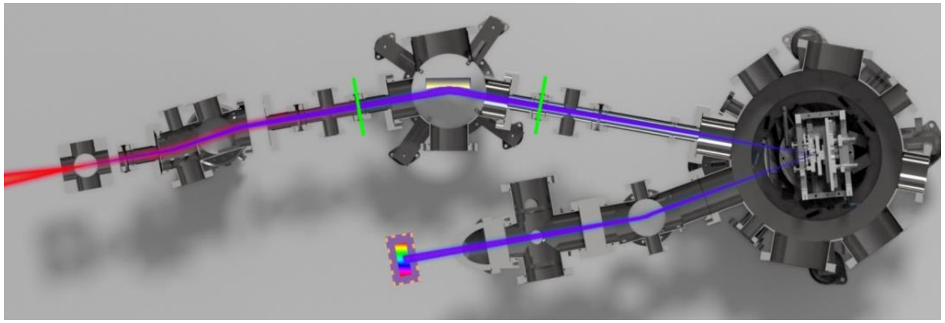


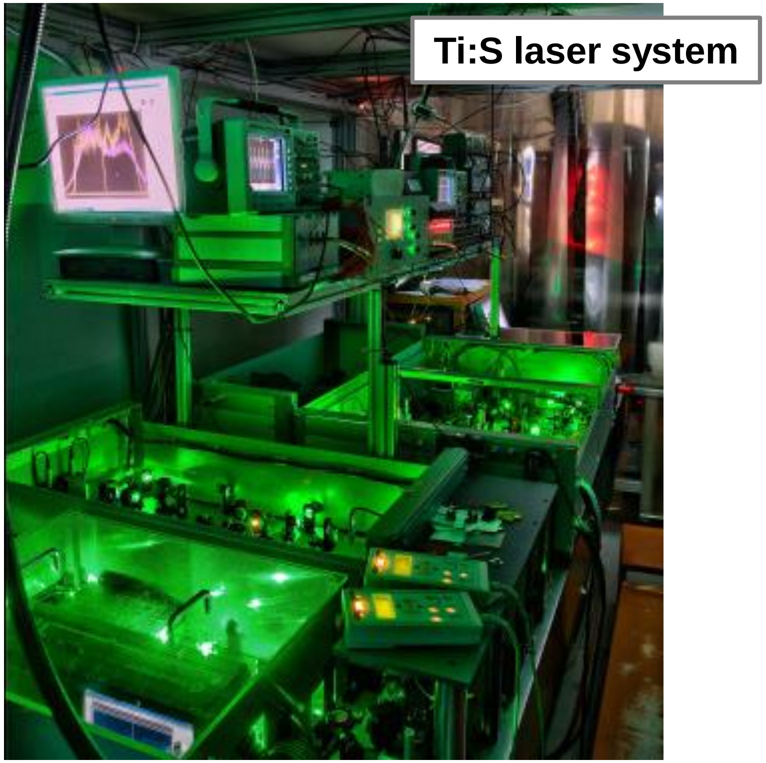
λ

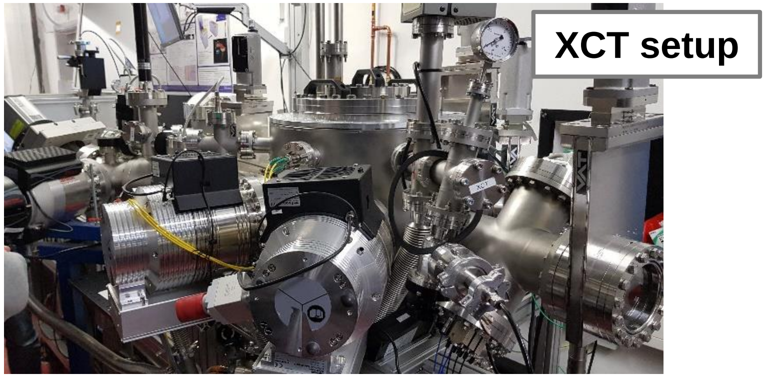
XCT using HHG radiation source

XCT experimental setup









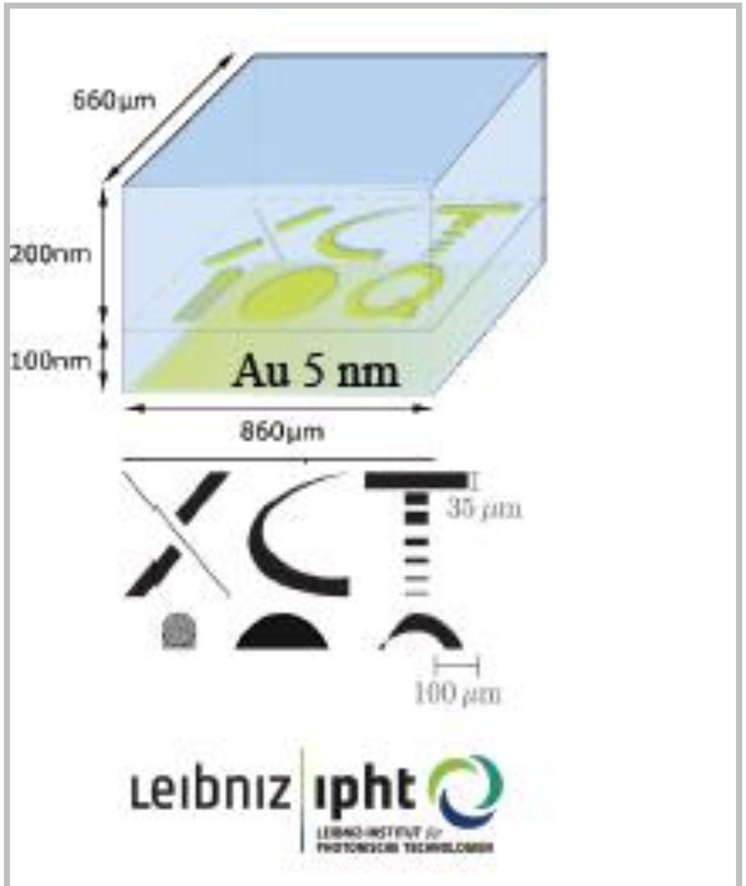
The XUV radiation from a HHG source is focused by a **toroidal mirror** (f = 40 cm) onto the sample's surface to a spot size of about 20 µm.

Another toroidal mirror (f = 36 cm) images this point through a **transmission grating** (1000 lines/mm) onto a CCD camera.

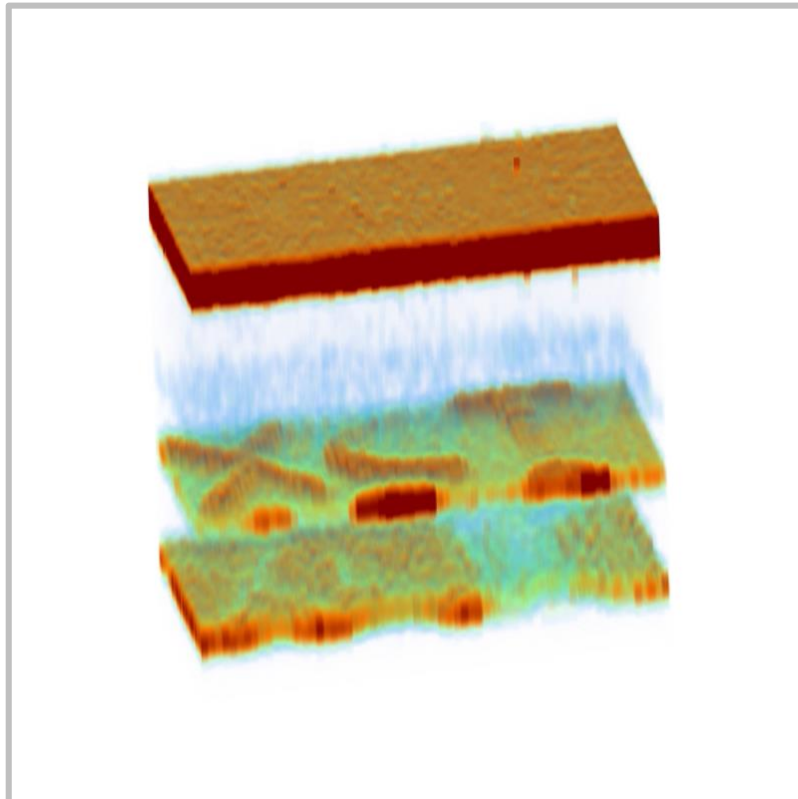
S. Fuchs et al. *Optica* **4**, 903 (2017)

XCT using HHG radiation source

3-D structured sample with two gold layers buried in silicon



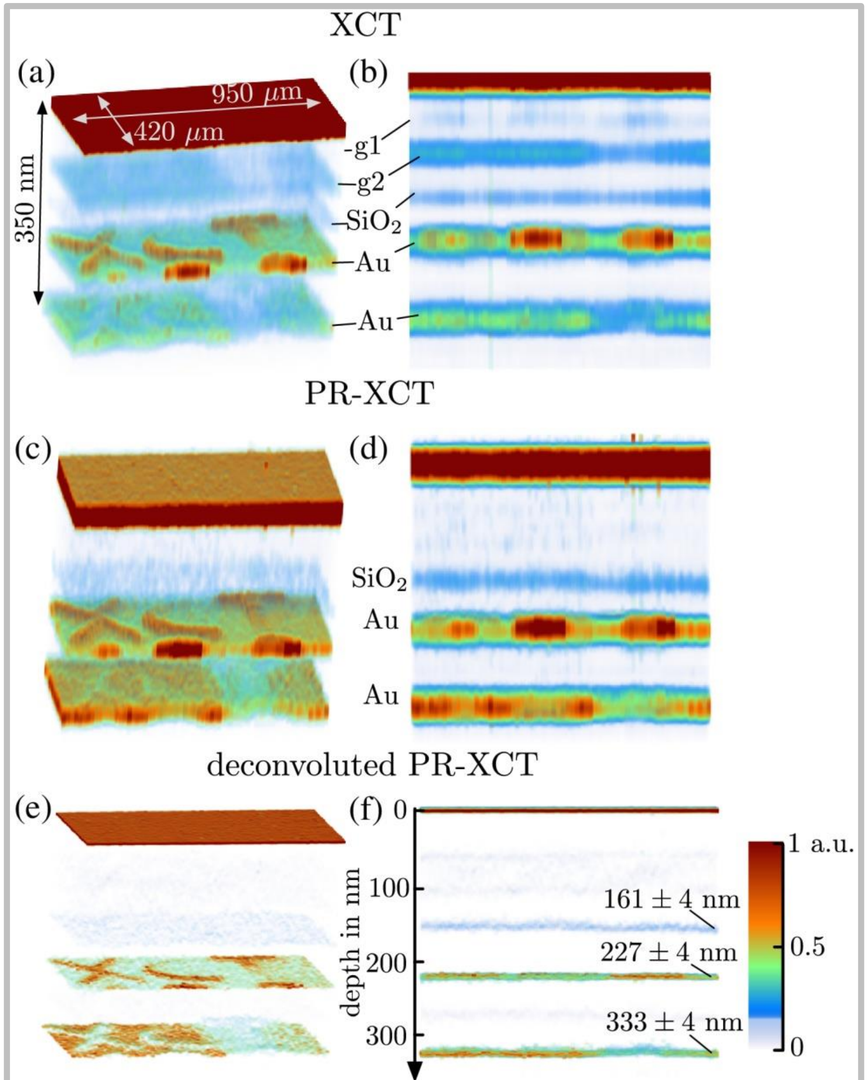
XCT tomogram
(Lab-Based HHG source)



S. Fuchs et al. *Optica* **4**, 903 (2017)

XCT using HHG radiation source

Tomogram of a 3-D structured sample with two gold layers buried in silicon



XCT measurements were performed on ≈1800 lateral scanning points in an area of 960 μm × 420 μm with 15 μm step size in approximately **6.5 h**.

(a) 3D image **reconstructed** by Fourier transformation.

(b) The same in the front view. Visible are **two gold layers (Au)**, where the upper one contains the letters "XCT" as well as three additional layers closer to the surface.

Panels (c) and (d) show the 3D image of the same data set reconstructed by a three-step **phase-retrieval algorithm**.

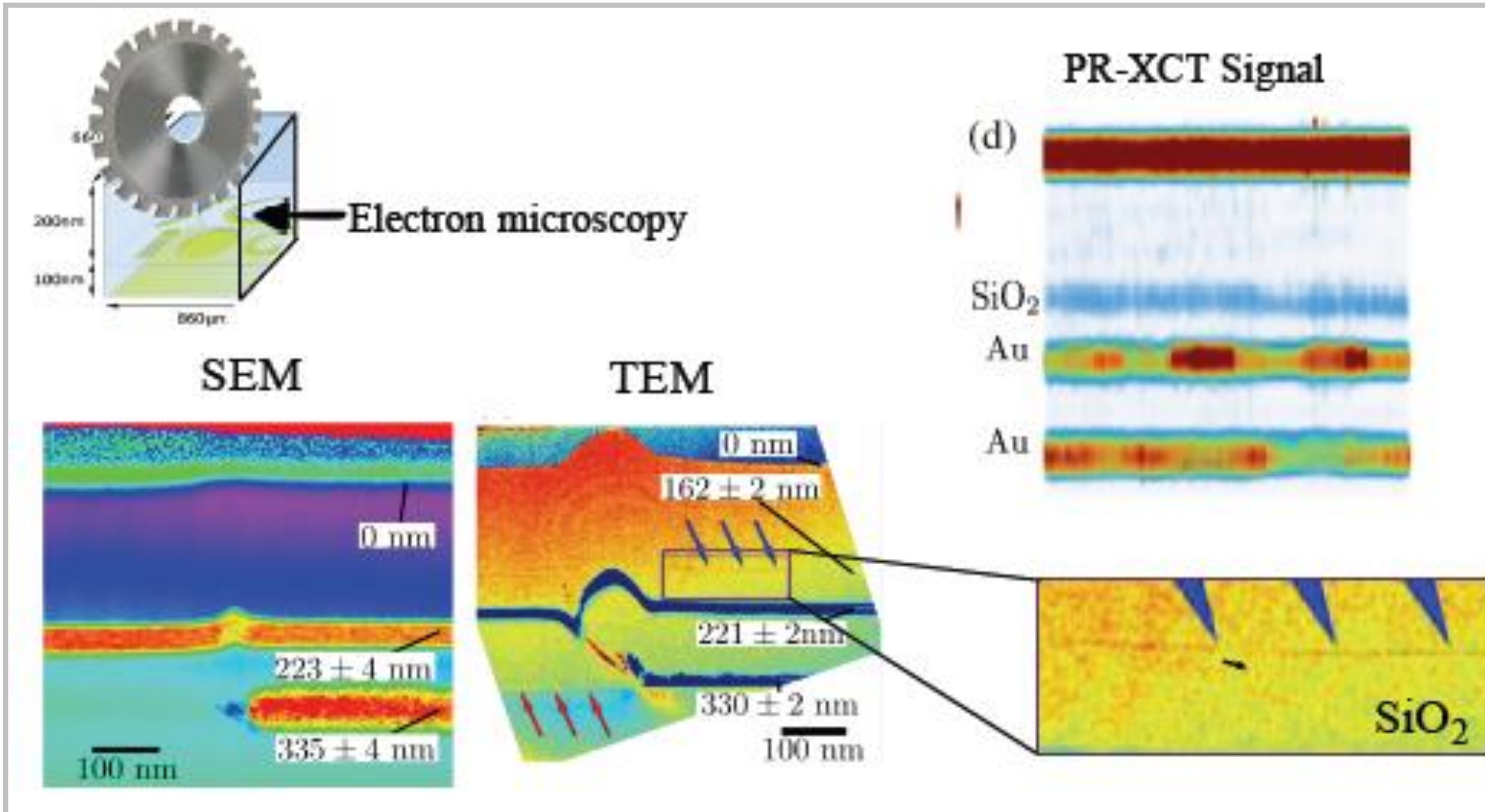
The images in panels (e) and (f) are **additionally deconvolved** by the point spread function.

The **axial resolution** (the ability to resolve two layers) is approximately **24 nm.**

S. Fuchs et al. *Optica* **4**, 903 (2017)

XCT using HHG radiation source

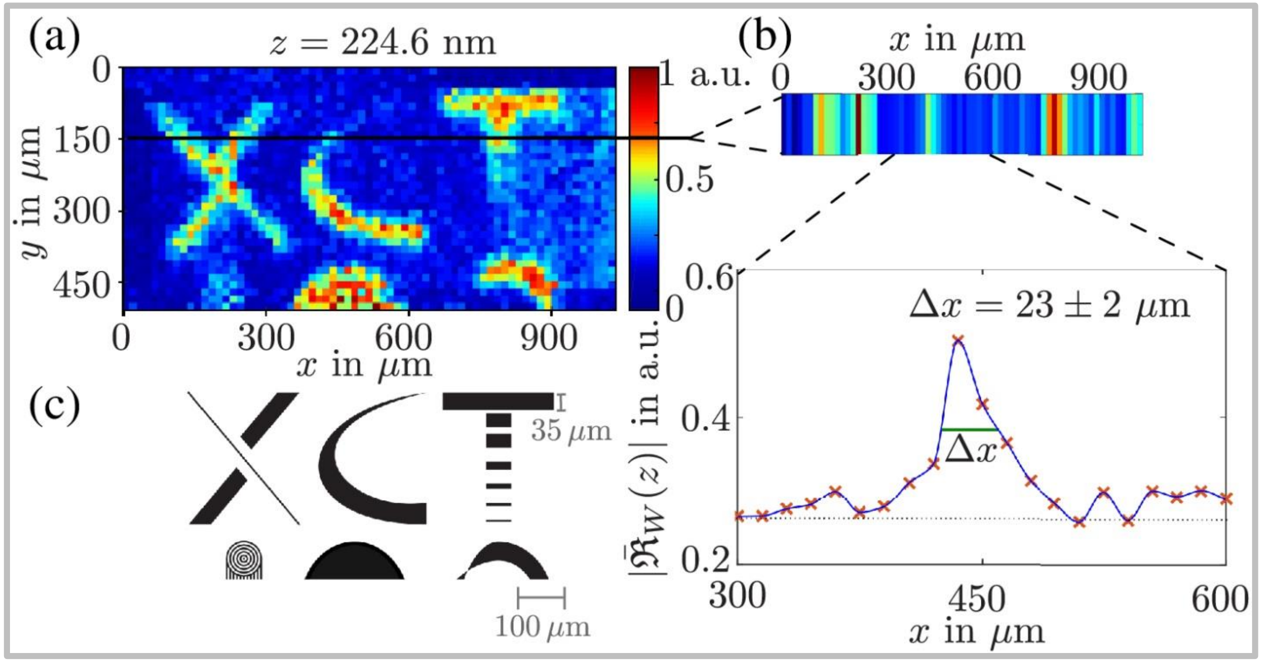
XCT competing with SEM and TEM



S. Fuchs et al. *Optica* **4**, 903 (2017)

XCT using HHG radiation source

Lateral resolution of the XCT tomogram obtained using a HHG source.



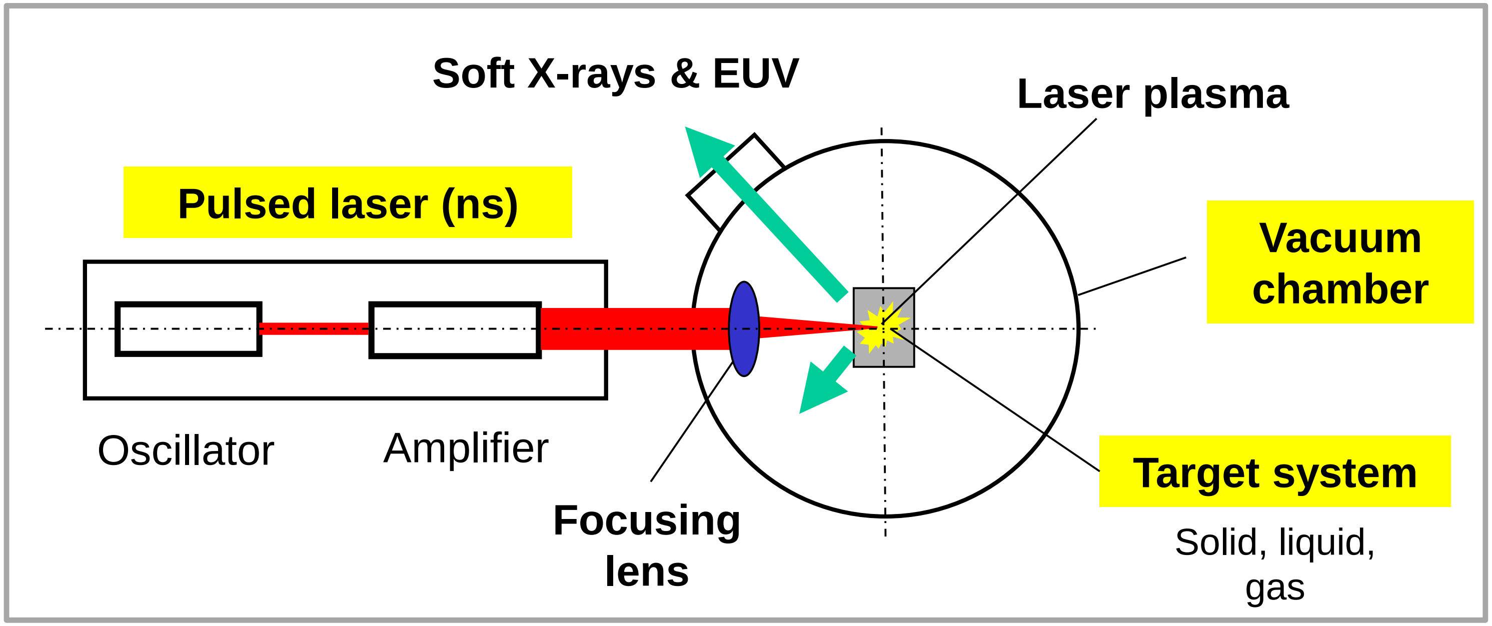
(a) Cross section through the sample at the depth of the upper gold layer (225 nm) in comparison with the designed structure in (c). Most features can be resolved, except for the smallest structures of the vertical bar of the letter "T."

(b) A line out at y = 150 μm. The width (FWHM) of the upper part of the letter "C" is approximately **23 μm and defines the lateral resolution**.

S. Fuchs et al. *Optica* **4**, 903 (2017)

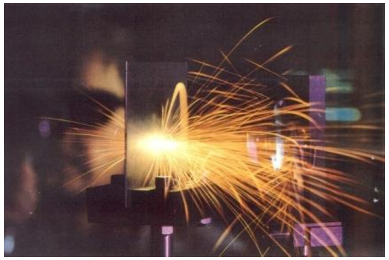
Laser plasma source of EUV and soft X-rays

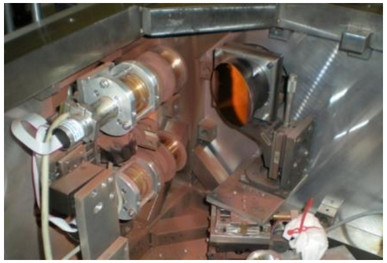
Schematic of a laser plasma source



Source characteristics:
- high single-pulse brightness
- short-pulse duration (ns)
- point-like shape
- easy tuning of wavelength
- low investment costs

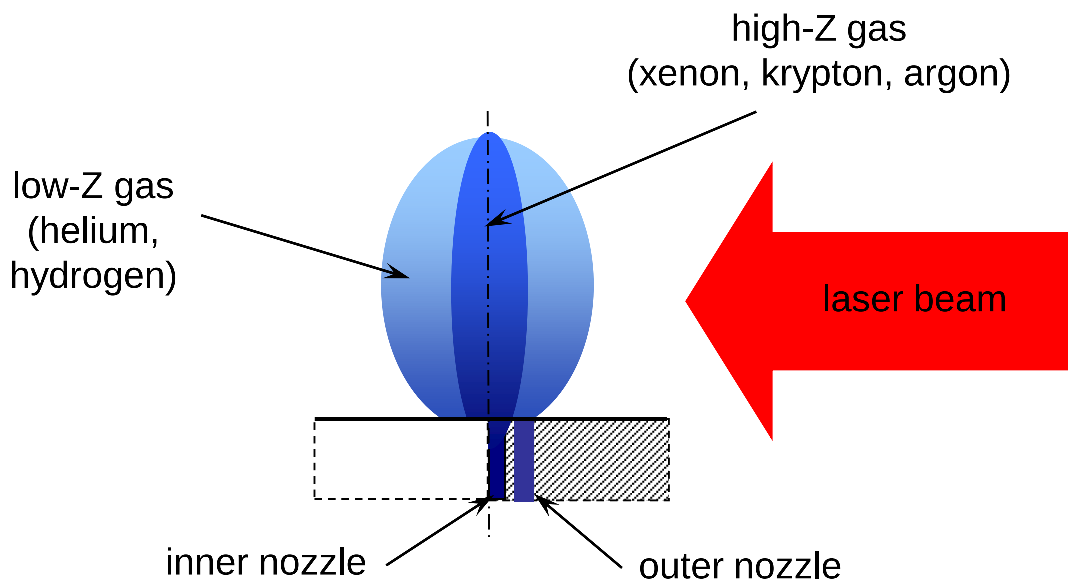
Main disadvantages:
- laser target operation
- **target debris production**



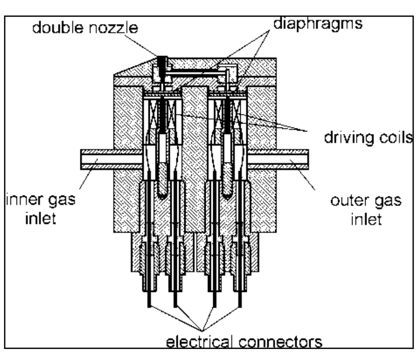


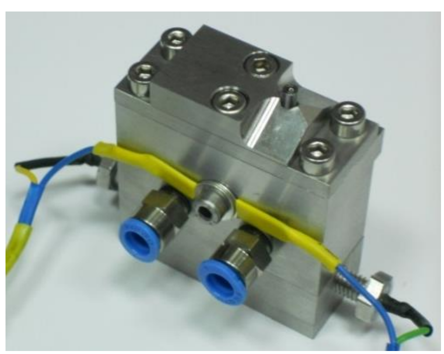
Double-stream gas puff target

• schematic of a double-stream gas puff target

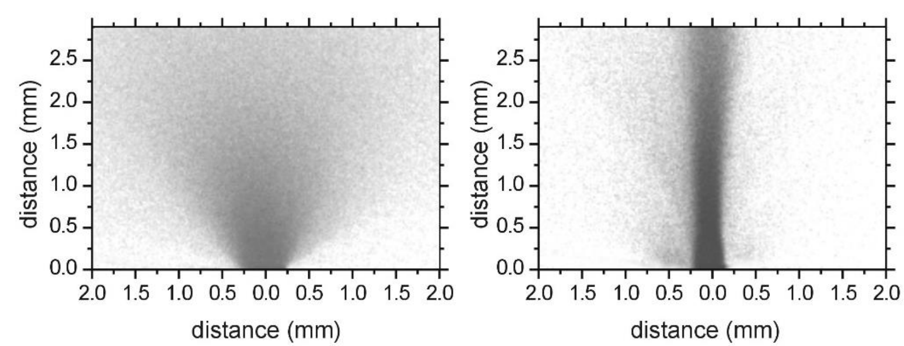


• electromagnetic valve system





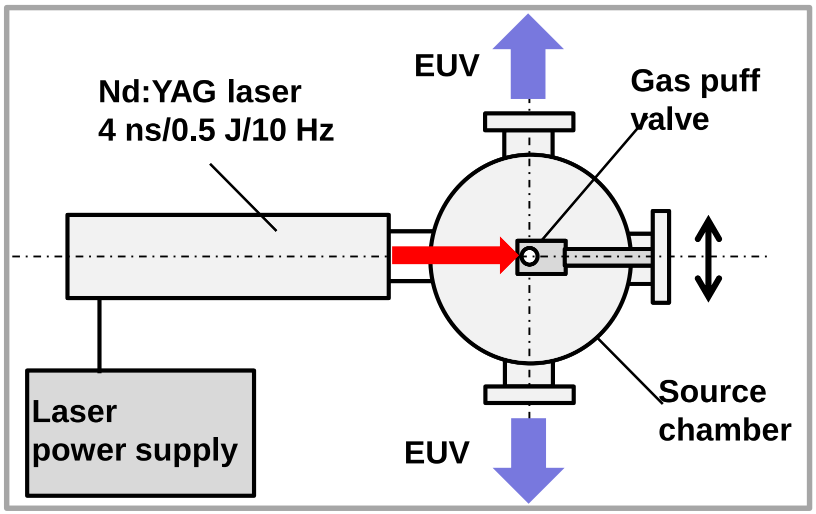
• X-ray backlighting images



HF al. *Appl. Phys. B* **70** (2000) 305; Patent No.: US 6,469,310 B1

Compact laser plasma EUV source

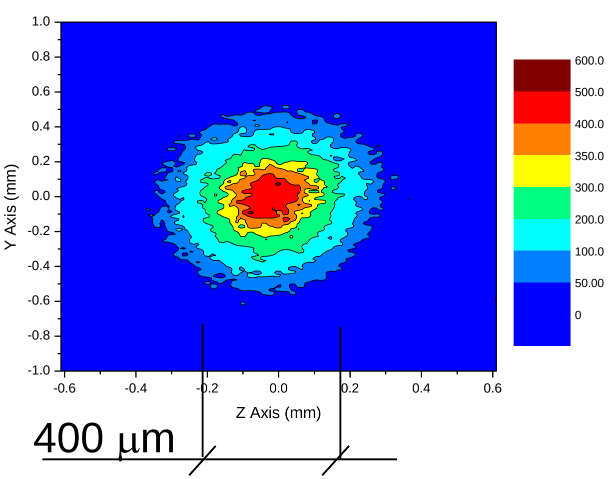
- schematic of the source



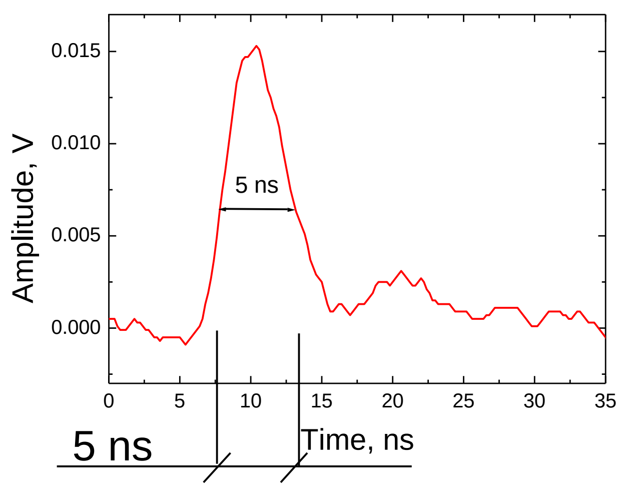
EUV lamp

10 cm

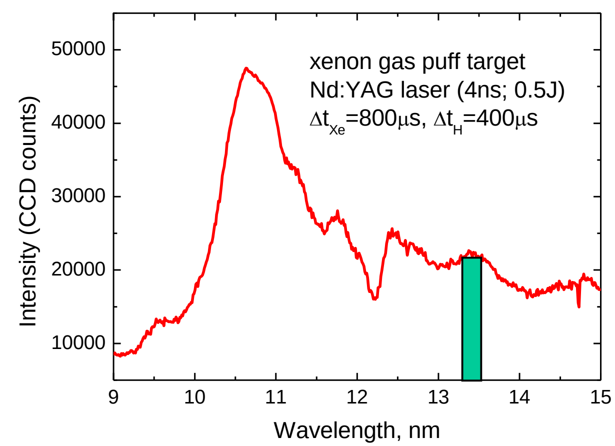
- spectral image at 13.5 nm



- time profile



- EUV spectrum

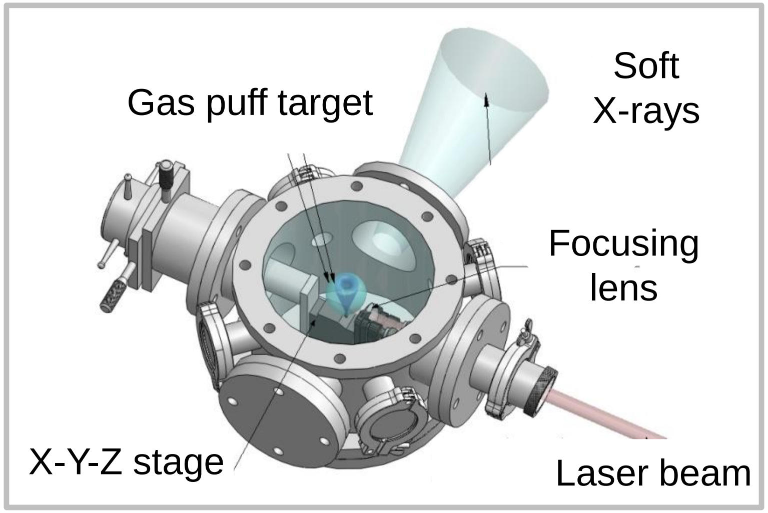


~ 1.5 % CE at 13.5 nm

H.F. et al., *J.Alloys&Compounds* ***401*** *(2005) 99*

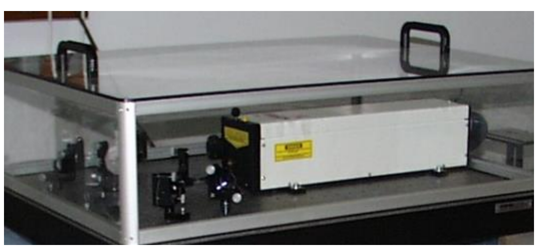
Laser plasma soft X-ray source

Source chamber



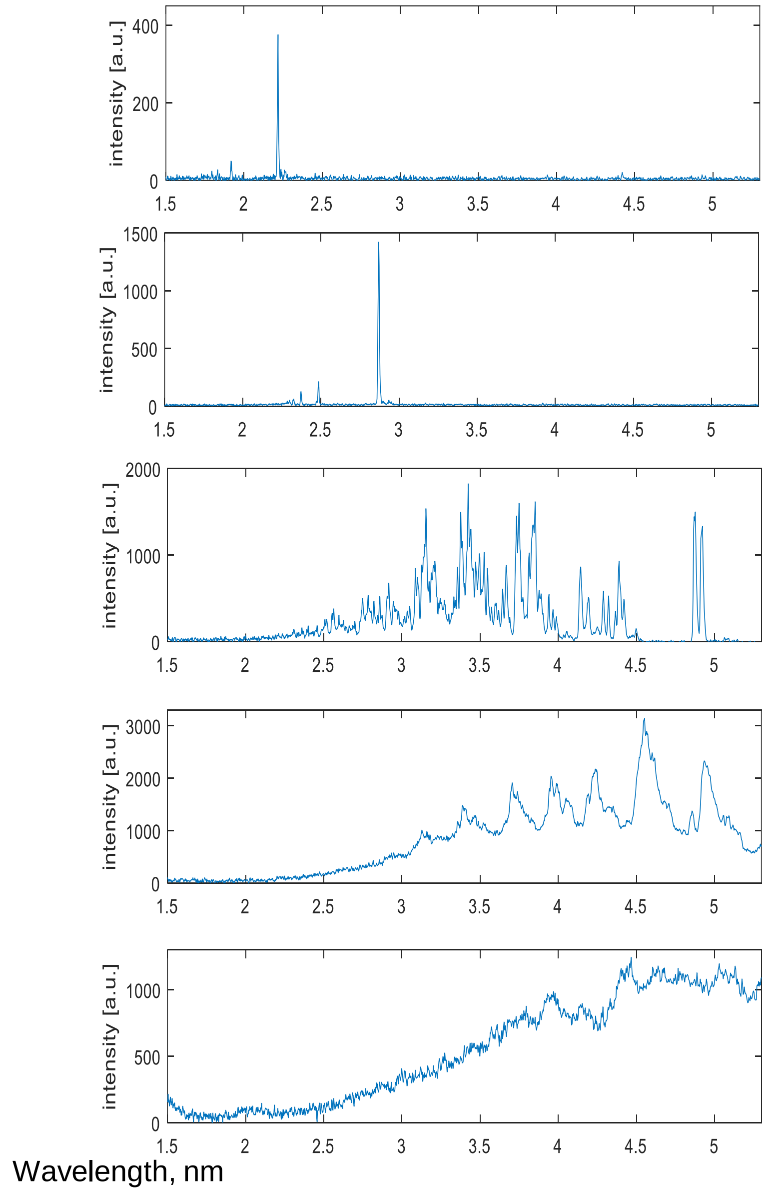
We use commercial Nd:YAG lasers

4 ns
0.5-0.8 J
10 Hz



2-10 ns
10 J
10 Hz

Soft X-ray spectra



oxygen

nitrogen

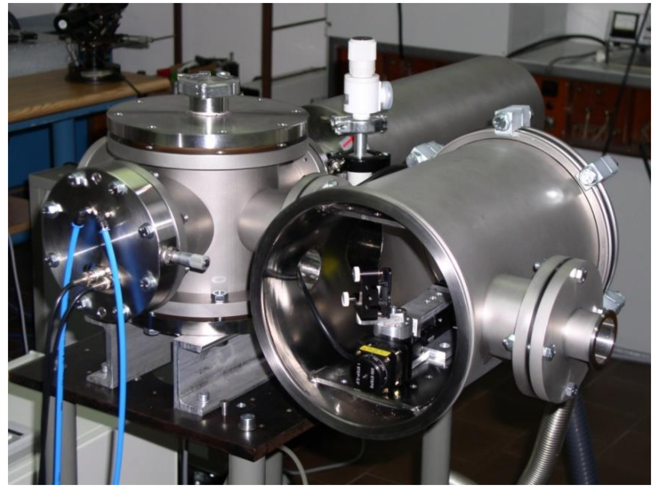
argon

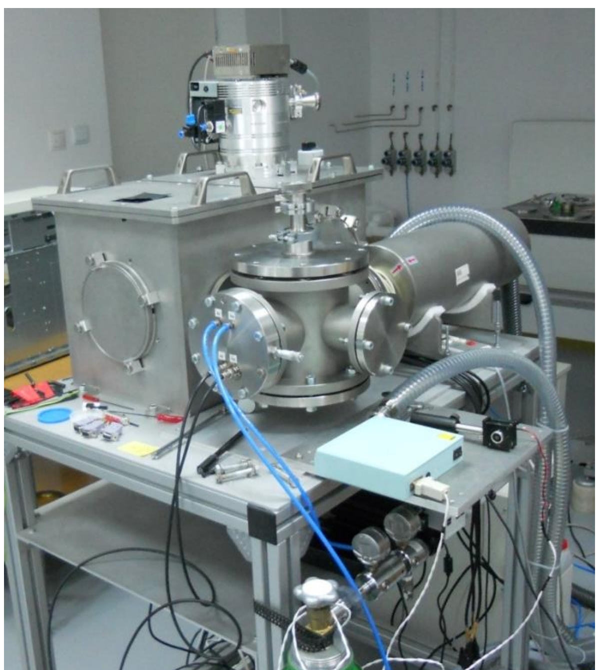
krypton

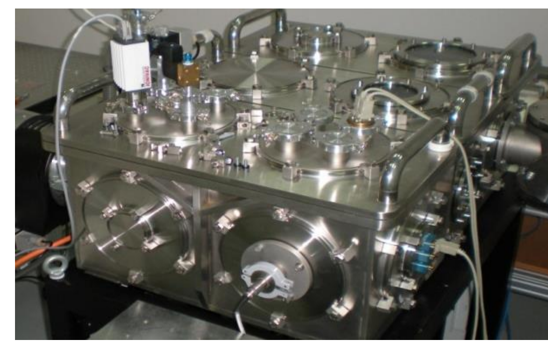
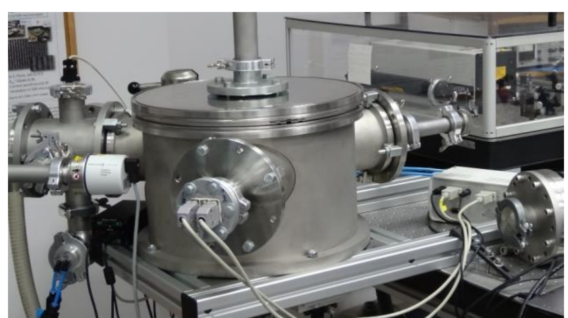
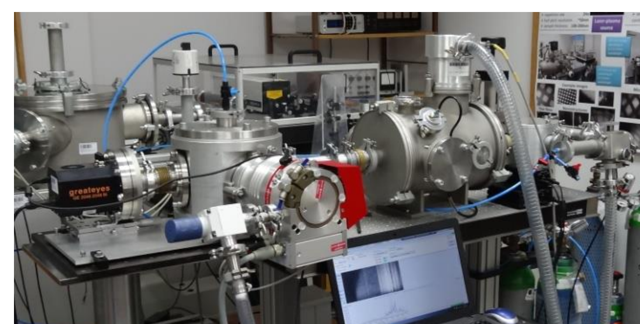
xenon

Laser plasma EUV/soft X-ray sources based on a gas puff target



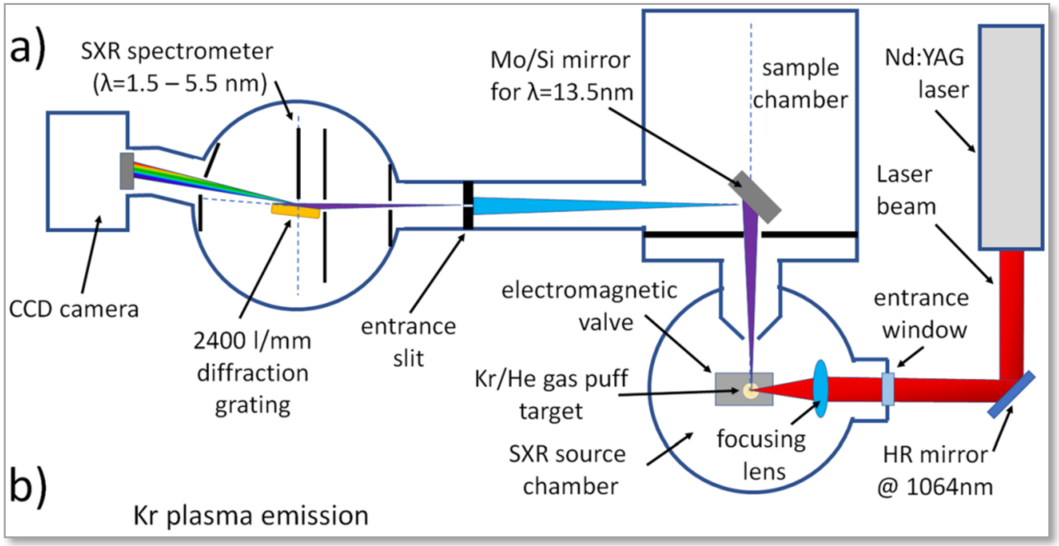





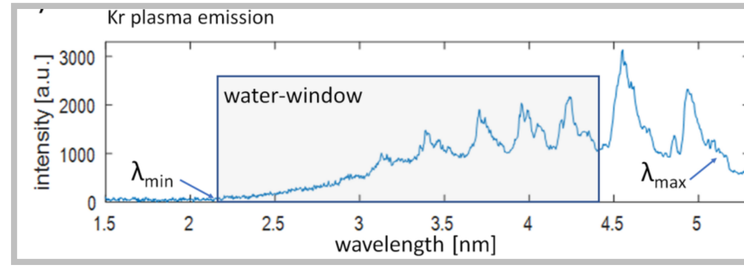




XCT using laser plasma soft X-ray source

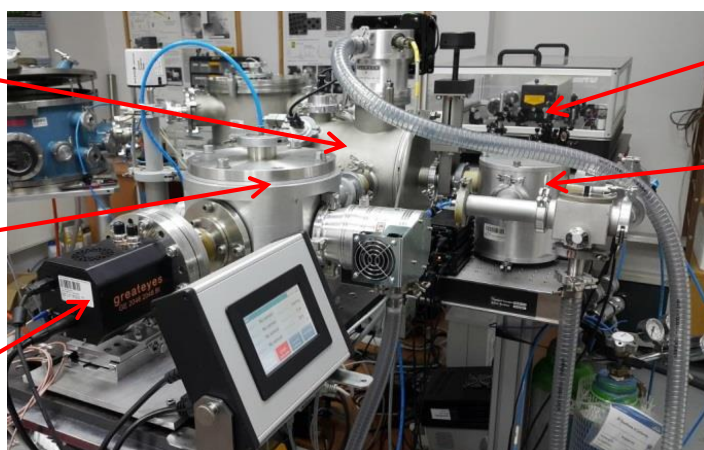
Schematic of the XCT setup



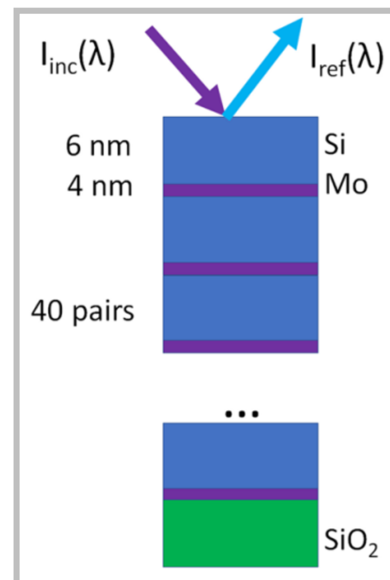
Soft X-ray spectrum



Experimental arrangement of the XCT setup

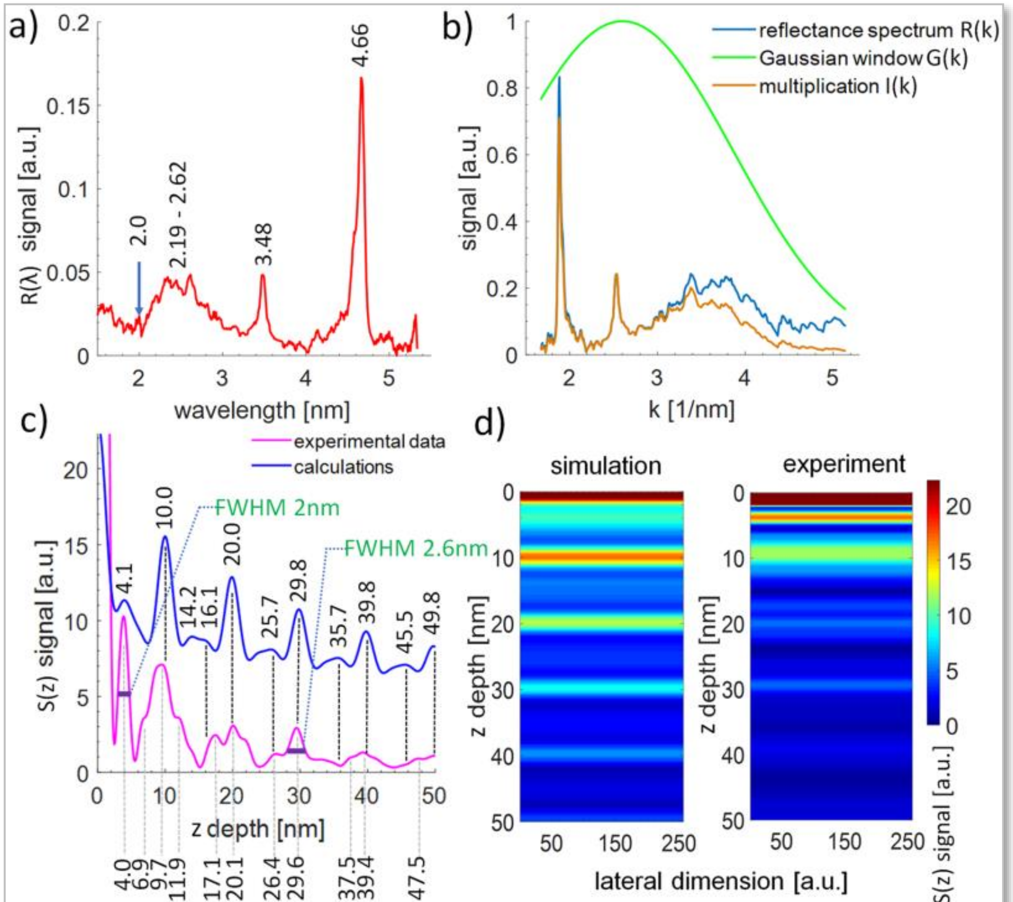


Sample (Mo/Si mirror)



XCT using laser plasma soft X-ray source

Results of the preliminary XCT measurements



(a) **Measured reflectivity** of the Mo/Si multilayer structure in the wavelength range from 1.5 nm to 5.5 nm.

(b) ***k*-space reflectivity spectrum** with a Gaussian-type window applied

(c) Reconstruction of a **depth information** from the Mo/Si structure, experimental data (bottom, pink curve) and simulation (top, blue curve).

(d) Visualization of **depth structure** of the sample; a comparison between theoretical and experimental data.

Axial spatial resolution was estimated.

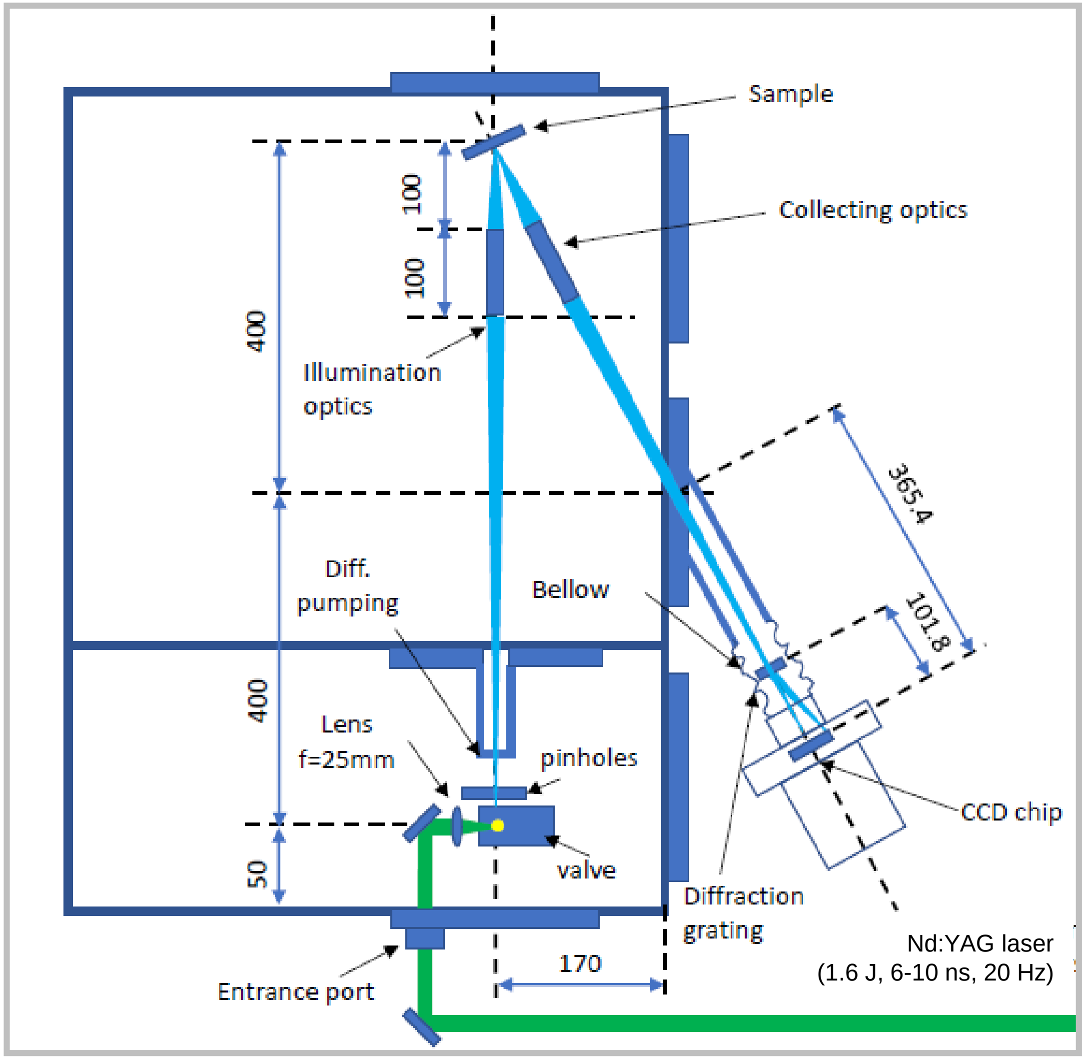
The FWHM of the peak, related to the first Si-Mo interface equals to ~2 nm. Taking into account another, well defined experimental spectral peak at 30 nm depth, the FWHM is estimated to be ~2.6 nm.

The **axial spatial resolution** in XCT can be comparable to FWHM values and is of the order of **2–2.6 nm**.

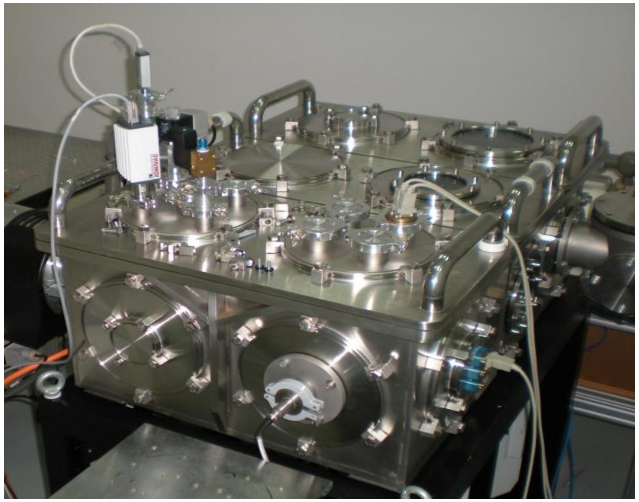
P. Wachulak, A. Bartnik, H. Fiedorowicz,
Optical coherence tomography (OCT) with 2 nm axial resolution using a compact laser plasma soft X-ray source
Scientific Reports **8**, 8494 (2018)

XCT setup for 3-D imaging

Schematic of the XCT setup for 3-D imaging using a laser plasma light source



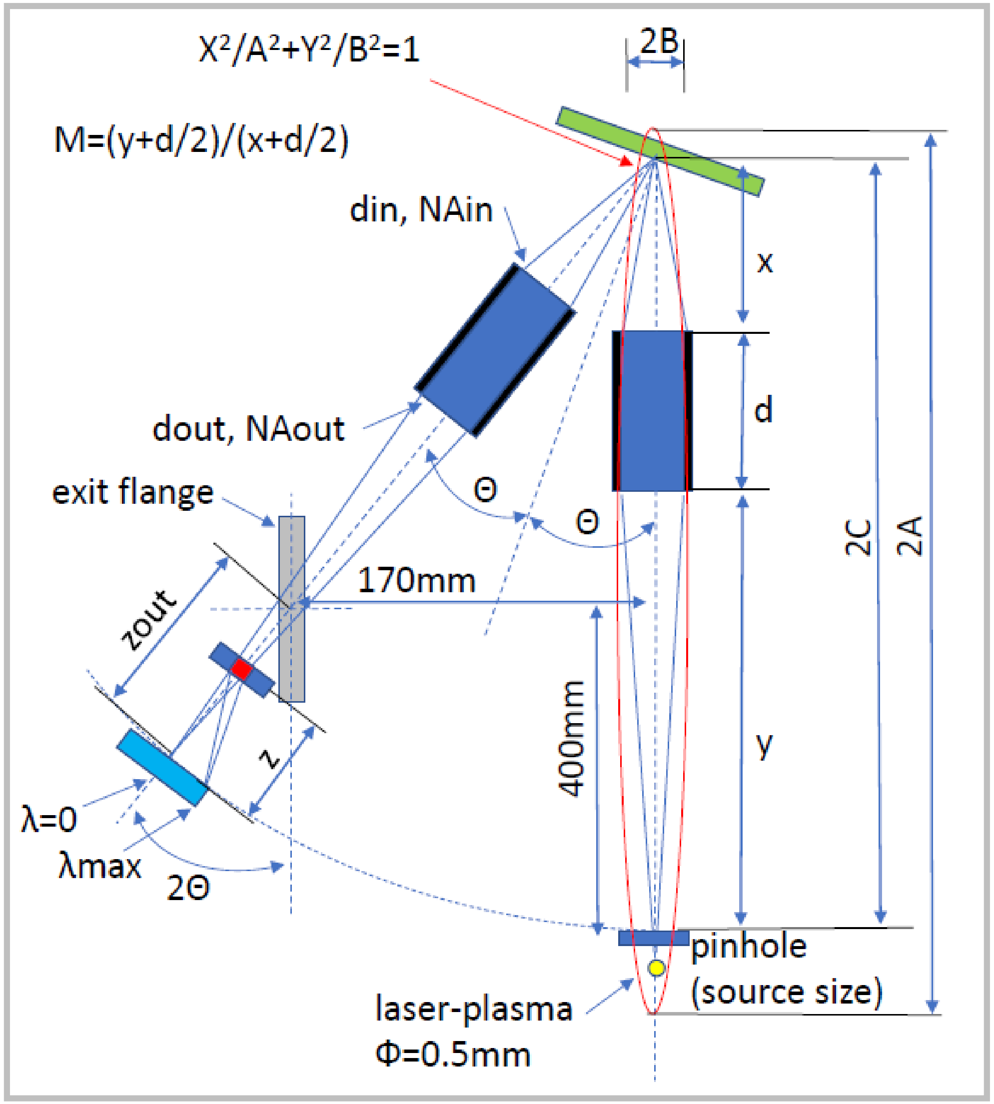
Experimental vacuum chamber



Nd:YAG laser system

XCT setup for 3-D imaging

Optical scheme of the XCT setup for 3-D imaging using a laser plasma light source



Optics and system parameters:

length of the optics d = 100.00 mm
object-image distance x = 800.00 mm
magnification = 4.3333
angle θ = 11.51 deg,
object distance x = 100.00 mm
image distance y = 600.00 mm
critical angle = 2.58 deg

Ellipsoidal mirrors parameters:

A = 400.177 mm, B = 11.906 mm
d_{in} = 15.759 mm, d_{out} = 20.625 mm
NA_{in} = [0.0786, 0.0515],
NA_{out} = [0.0172, 0.0113

Rigaku

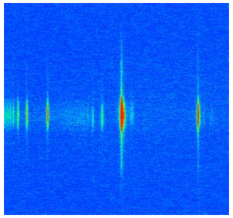
Detection system:

grating width = 2.0 mm,
grating period = 200.0 nm
grating - CCD distance z = 58.18 mm
CCD chip size = 13.0 mm,
number of pixels = 1024×1024
max wavelength = 22.2 nm,
dispersion = 0.043 nm/pix
source size = 0.10 mm,

greateyes

Summary and conclusions

- **optical coherence tomography (OCT)** in the short-wavelength range (soft X-rays and EUV) has been proposed (XCT),
- **demonstration experiments on XCT** was performed using synchrotron and high-order harmonic generation (HHG) sources,
- **axial resolution** of 18 nm for EUV and 8 nm for soft X-rays was achieved,
- a compact **laser plasma soft X-rays and EUV source** based on a gas puff target was presented,
- **preliminary XCT experiment** with the use of the laser plasma source has been performed,
- **axial resolution** of about 2 nm was measured,
- design of a new **XCT setup for 3-D imaging** was presented.



Possible application of XCT – defect inspection of multilayer optics

Narodowe Centrum Nauki
Beethoven program
DFG Deutsche Forschungsgemeinschaft
Laserlab Europe

Laser-Matter Interaction (LMI) Group

Research goals: Development of laser-driven sources of X-rays and EUV for application in science and technology

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