Beam expander and homogenizer for 13.5 nm application

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Outline

- Motivation
- Applications
- EUV/SXR sources
- Properties of LPP, DPP and FEL radiation
- EUV/SXR optics
- Collector optics for EUV lithography
- Beam expansion and homogenisation

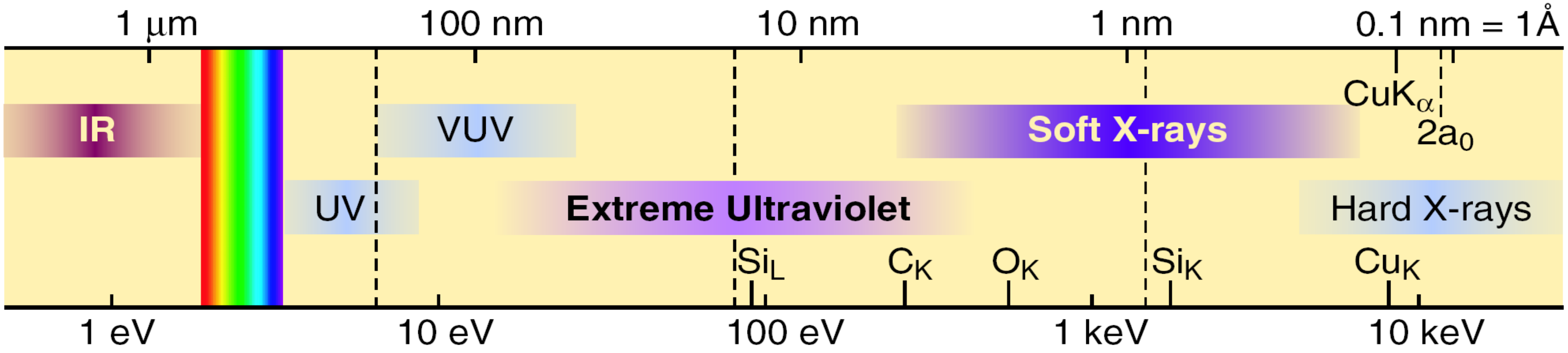
Motivation

- Collector optics for EUV/SXR lithography
- Experimental tools for EUV/SXR lithography
- Diagnostic tools for EUV/SXR lithography
- Novel optical systems for EUV/SXR lithography
- Novel optical systems for EUV/SXR/XR microscopy
- Novel optical systems for EUV/SXR/XR tomography

Applications

- EUV / SXR lithography
- EUV / SXR radiography
- EUV / SXR high contrast imaging
- EUV / SXR optics metrology
- EUV / SXR optics alignment

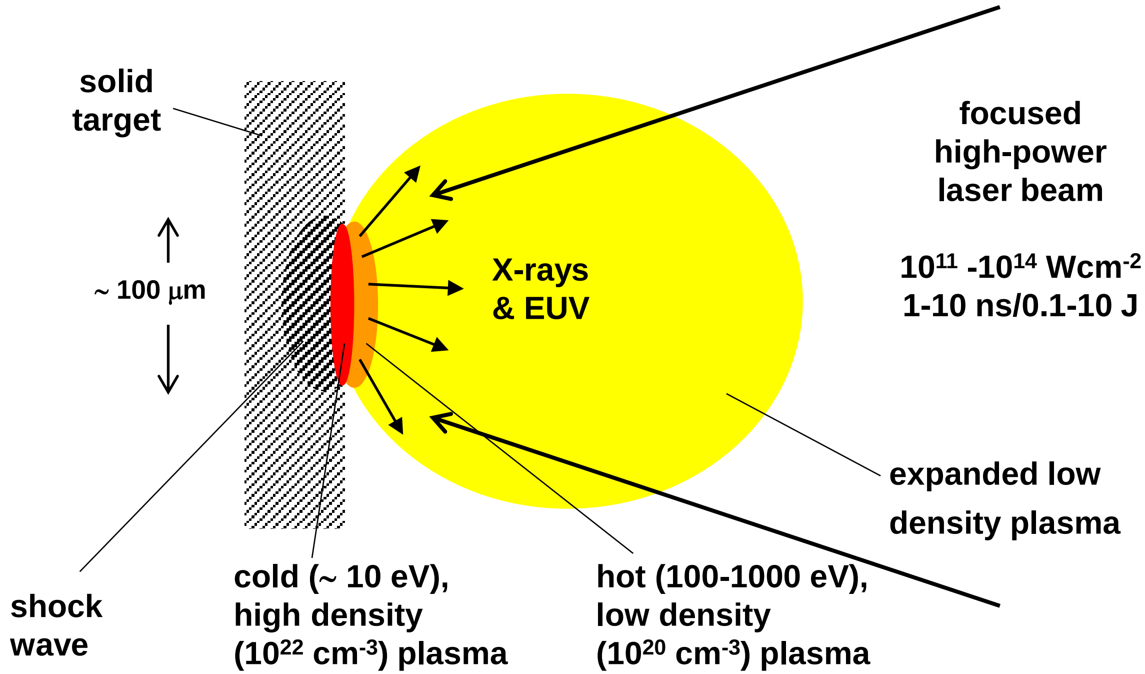
Electromagnetic radiation spectrum



D. T. Attwood *Soft X-rays and Extreme Ultraviolet Radiation: Principles and Applications* (Cambridge University Press, Cambridge, 1999)

13.5 nm – 92 eV

Laser Produced Plasma – solid (liquid) target

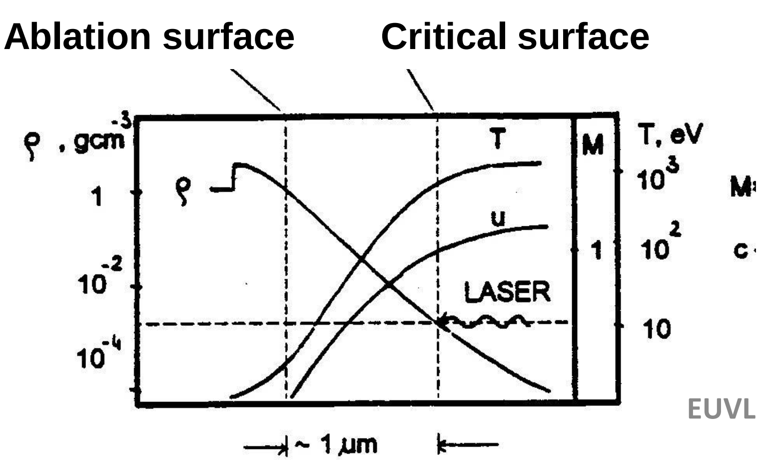


Nd:glass

Nd:YAG

KrF

CO_2

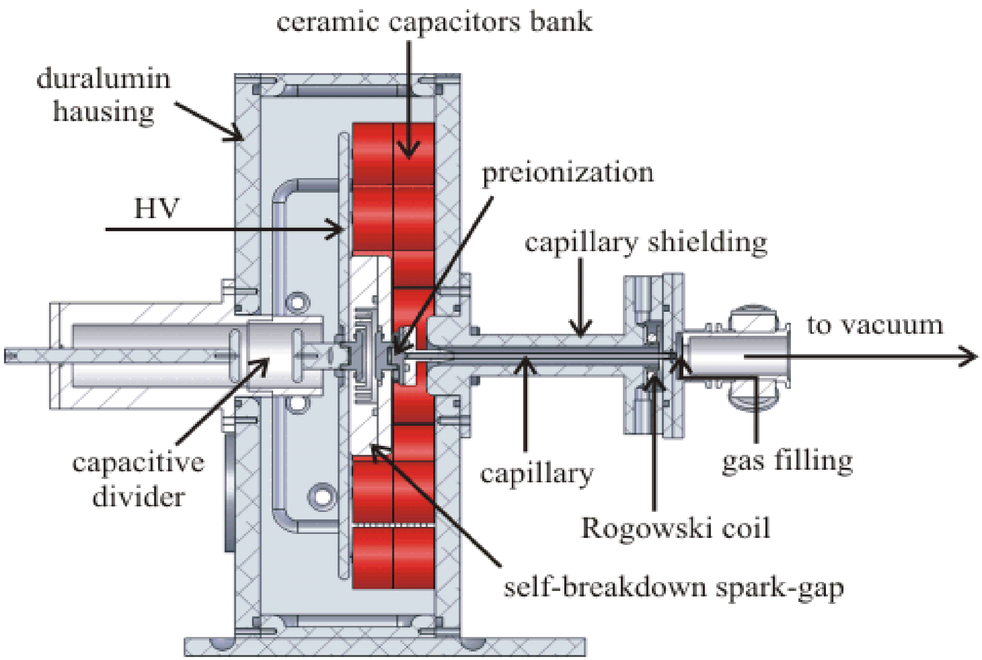


Laser plasma parameters for maximum EUV emission

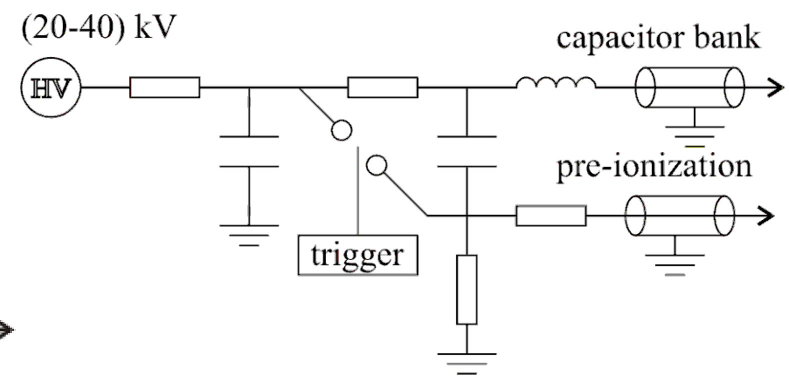
~ 40 eV, ~ 10^{19} cm^{-3}

Pinching Plasmas

Capillary Discharge Plasma



Main discharge unit

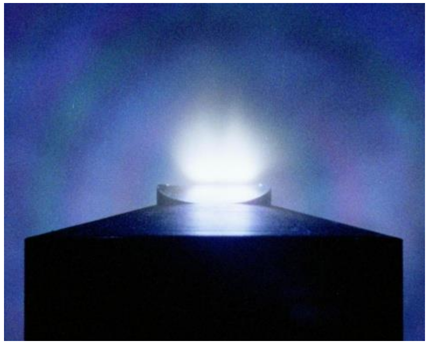


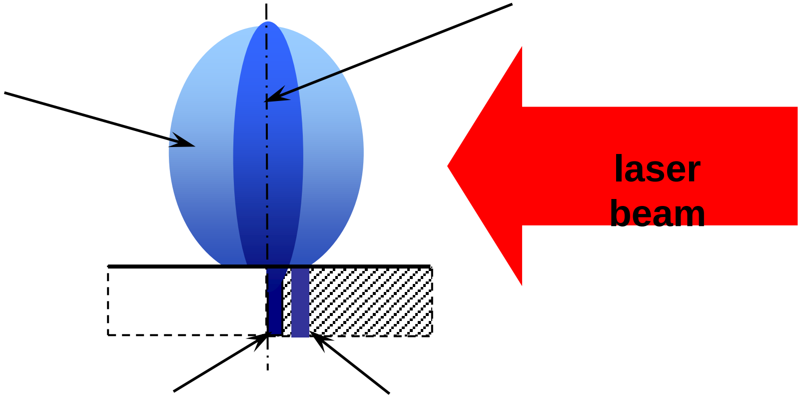
Charging circuit

- Ceramic Capacitors (1.25 ÷ 31 nF).
- Al_2O_3 capillary, 3.2mm dia., 20cm long.
- Low inductance -> high dI/dt.
- Pulse-charged: 1x Marx + coil.
- RL Rogowski coil.

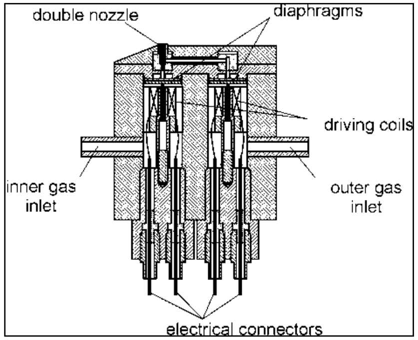
Design and construction of new experimental capillary discharge apparatus (A. Jancarek, M. Nevrkla)
CTU Prague, Faculty of Nuclear Sciences

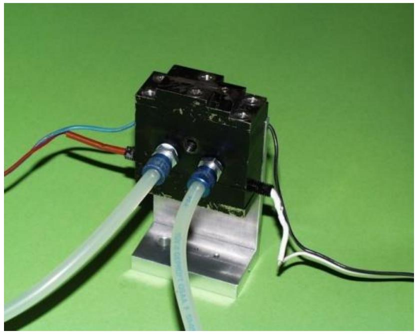
Laser Produced Plasma – gas puff target



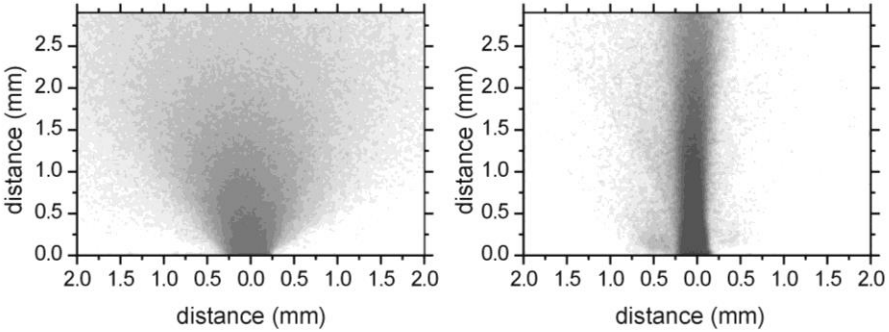


- **electromagnetic valve system**



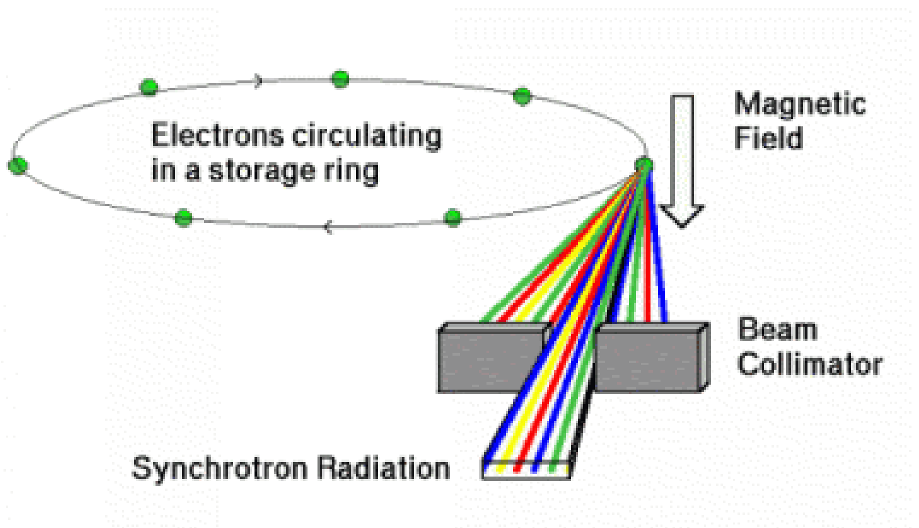


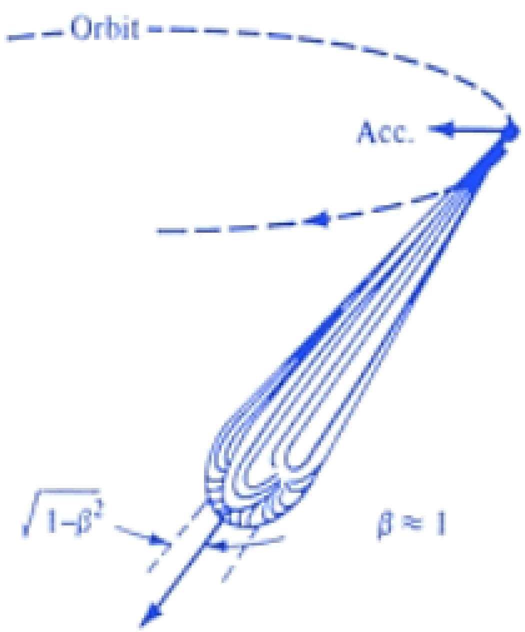
- **X-ray backlighting images**



H. Fiedorowicz *et al. Appl.Phys. B 70 (2000) 305; Patent No.: US 6,469,310 B1*
WAT , Warszaw

Synchrotron radiation

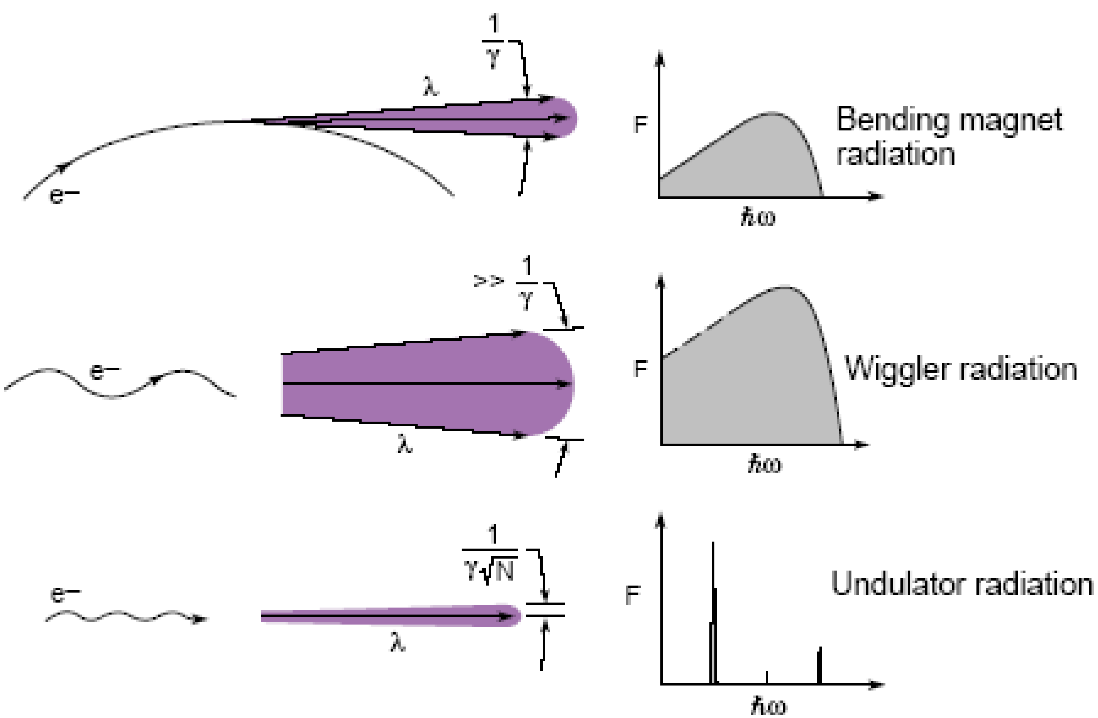


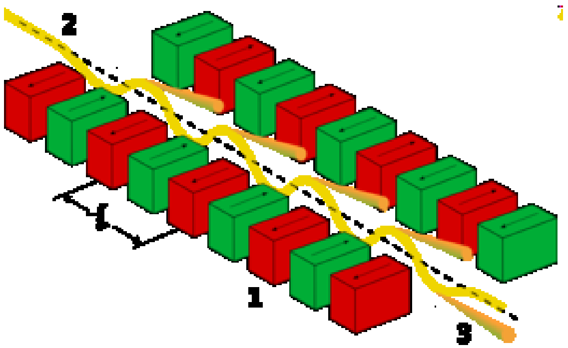


Characteristics of Synchrotron Radiation

- **High brightness: synchrotron radiation is extremely intense (hundreds of thousands of times higher than conventional X-ray tubes) and highly collimated.**
- **Wide energy spectrum: synchrotron radiation is emitted with a wide range of energies, allowing a beam of any energy to be produced.**
- **Synchrotron radiation is highly polarised.**
- **It is emitted in very short pulses, typically less that a nano-second.**

Synchrotron radiation



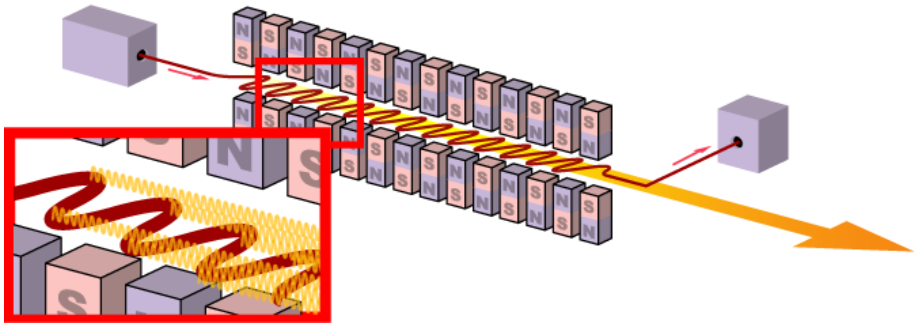


$$K = \frac{eB\lambda_u}{2\pi m_e c},$$

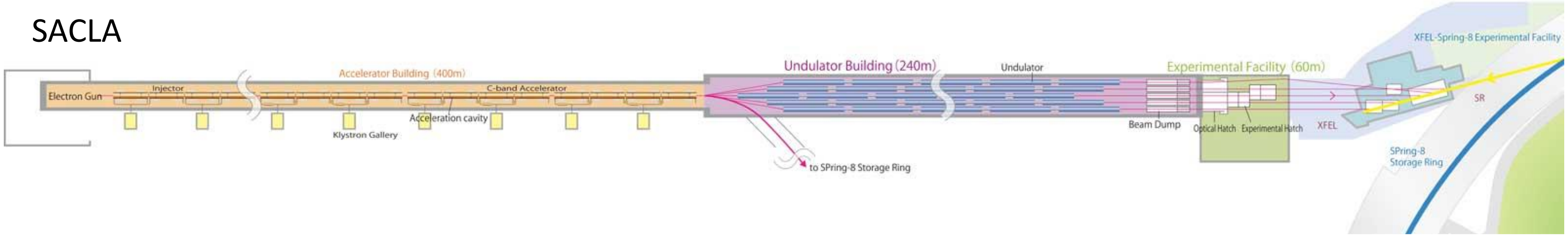
$K \gg 1$ wiggler

$K \ll 1$ undulator

Free Electron Laser radiation



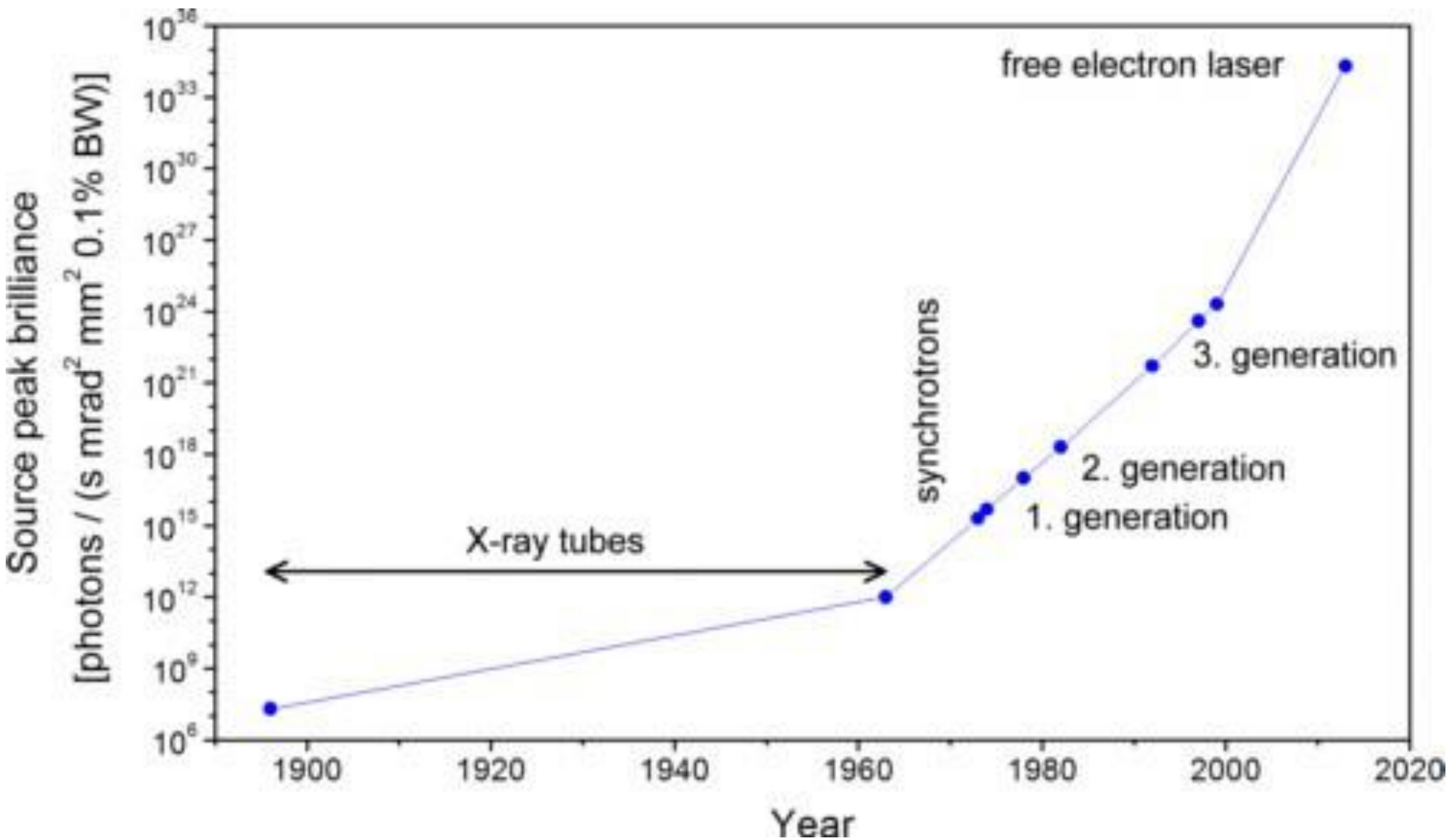
SACLA



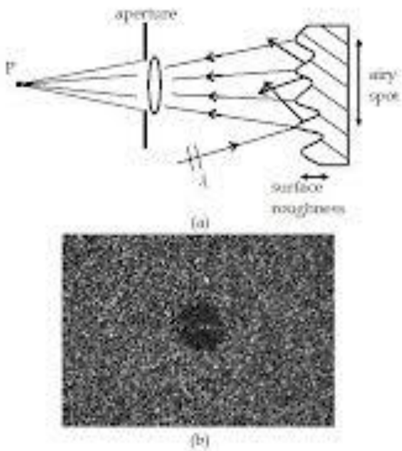
FEL Radiation characteristics:

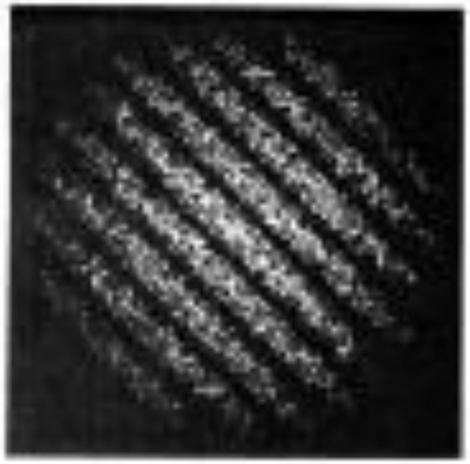
- **Highest brightness of all laboratory sources**
- **Collimation**
- **Polarisation**
- **Coherence**
- **Emitted in very short pulses, typically femto seconds.**

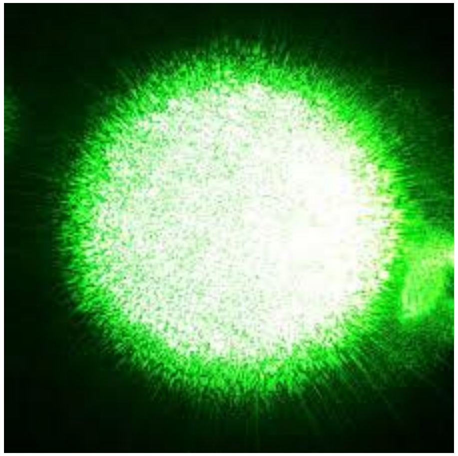
EUV/SXR/XR sources peak brilliance evolution



Diffraction and speckle patterns







Speckle pattern dependence on
- wavelength
- surface microroughness
- optical system geometry

surface microroughness << wavelength

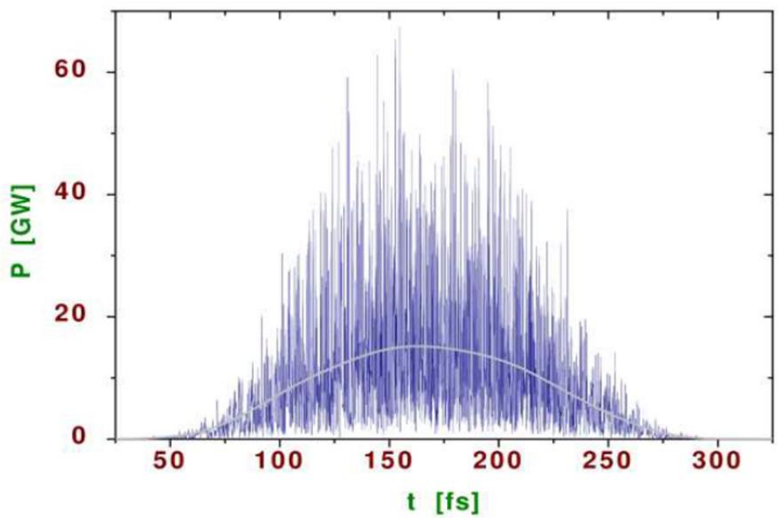
Speckle pattern intensities
exponential distribution

$$P(I)dI = \frac{1}{\mu}\exp(-I/\mu)$$

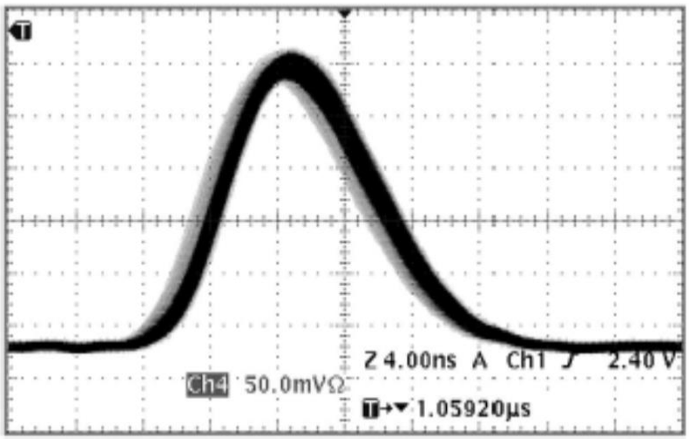
FEL and plasma source comparison

Temporal pulse structure

SASE FEL (FLASH)



LPP Sn plasma



Optimization of high average power FEL for EUV lithography application
Akira Endo, Kazuyuki Sakaue, Masakazu Washio (Waseda University), Hakaru Mizoguchi (Gigaphoton Inc.)
FEL Conference 2014 Basel, Switzerland

FEL and plasma source comparison

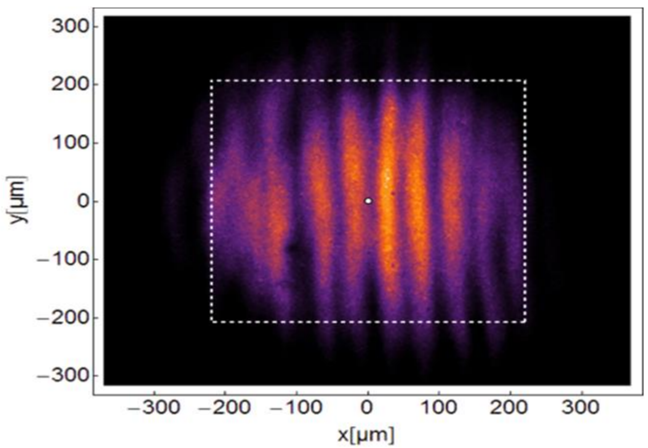
Spatial coherence

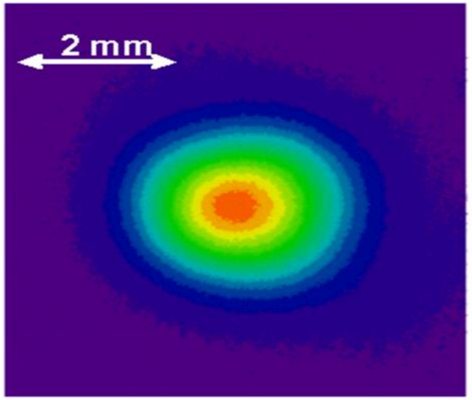
SASE FEL

~ 0.5

Plasma source

~ 3.2 x 10-9





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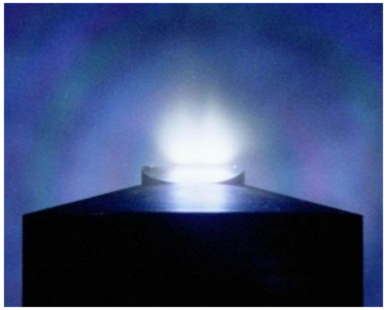
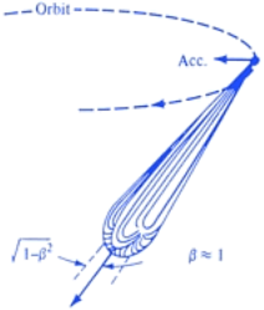
FEL and plasma source comparison

1. High divergence sources (LPP and DPP plasma sources)



Radiates in 2π steradian
ns – μs pulses typ., but …
Low repetition
Low spatial and temporal coherence

2. Low divergence (synchrotron, FEL, HHG, hot plasma laser)



Radiates in narrow beam
fs – ps pulses
High repetition
High spatial and temporal coherence

Next step – FEL as a EUV/SXR source for lithography

Subjects to be further studied:

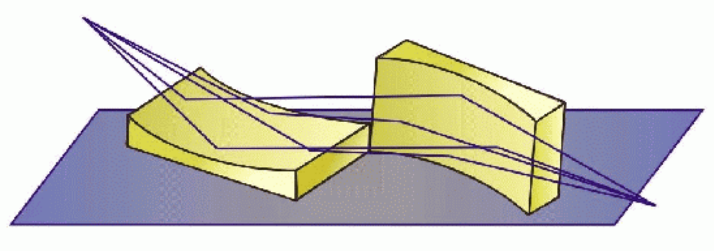
- Suppression of diffraction effects
- Suppression of speckle patterns
- Optics for quasi parallel input beam
- Sub micrometer IF
- High E field intensities phenomena with fs – ps pulses
- Photoresist exposure process physics with fs – ps pulses

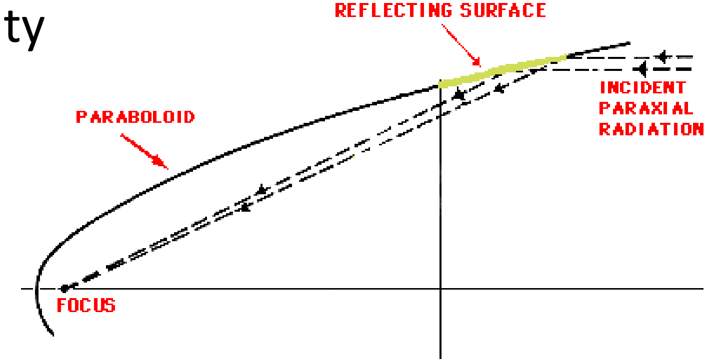
What optics is potentially relevant ?

- Grazing incidence mirrors
- ML mirrors
- Multi foil mirror systems

Kirpatrick-Baez system

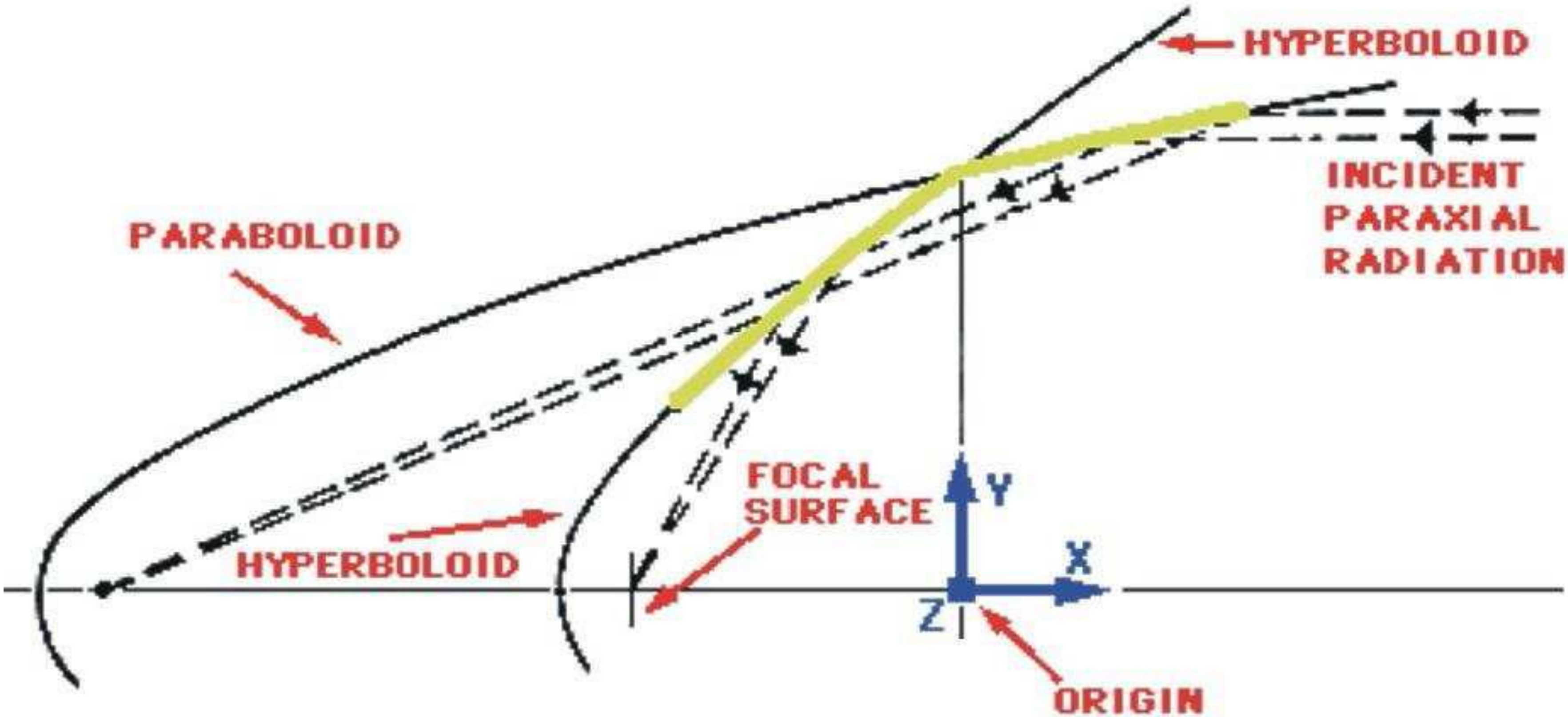
- Double reflection X-ray Optics
- Two mirror sets vertical and horizontal
- Mirrors in both sets have to be curved parabolically
- Single focal point is formed in the intersection of the horizontal and vertical focal planes
- Quality of the focal spot depends on quality of substrates (shape, microroughness)
- Technology is not necessarily based on precise and expensive mandrel
- Classical manufacturing technology of laboratory KB optics is expensive



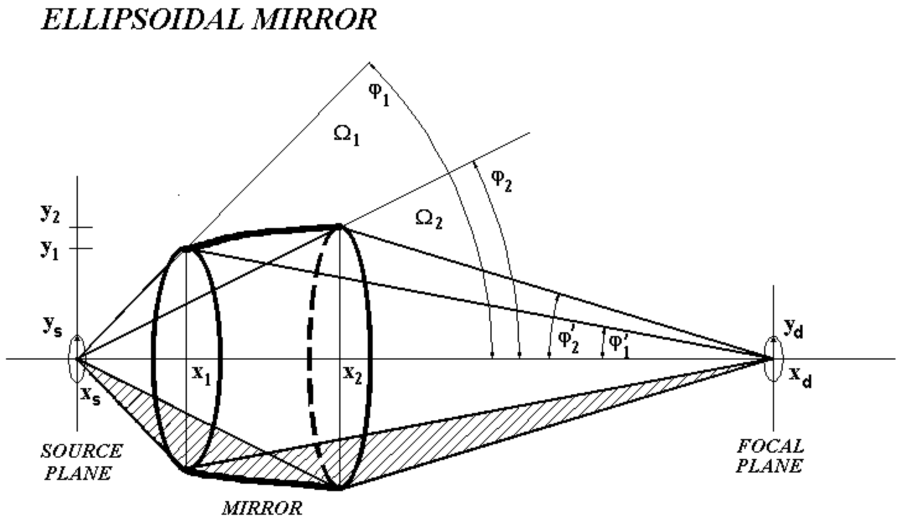


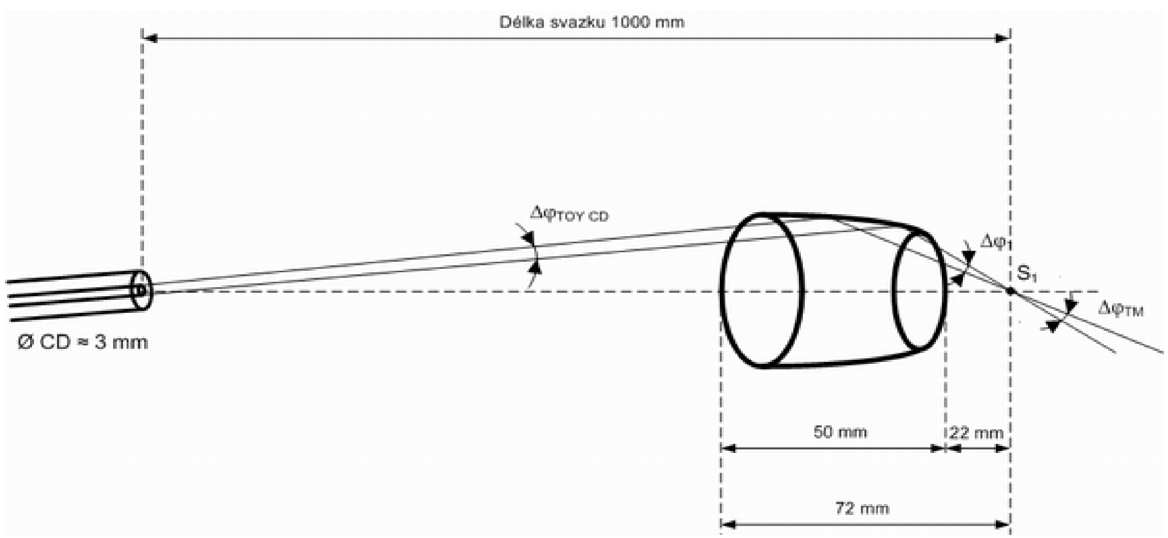
http://imagine.gsfc.nasa.gov/

Wolter system



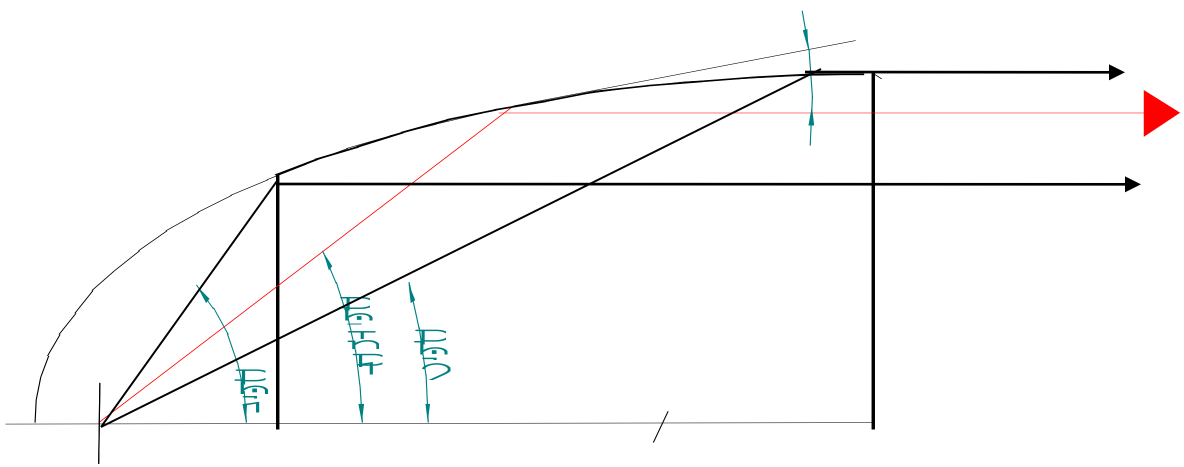
Ellipsoidal Mirror





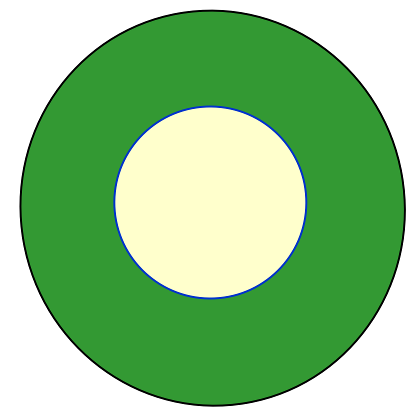
Paraboloidal Mirror

Highly parallel beam (< 1 mr)
Large area
Hole in the middle



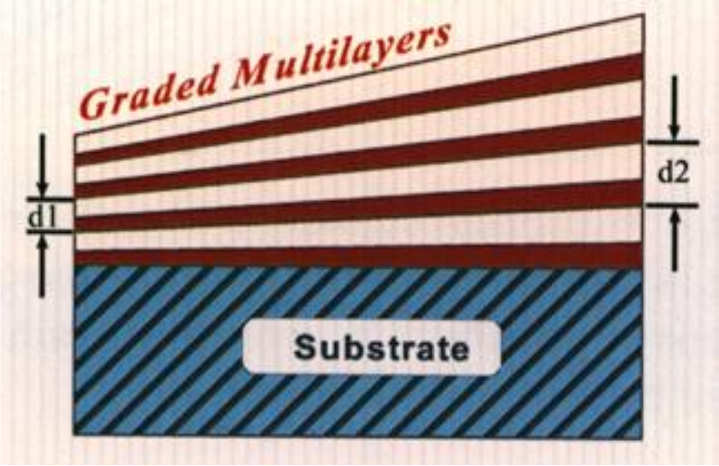
Source

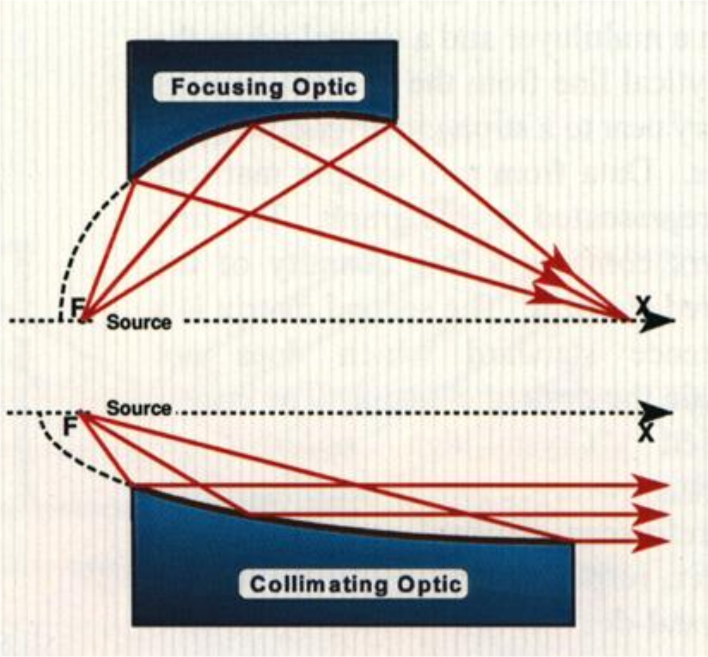
Beam profile



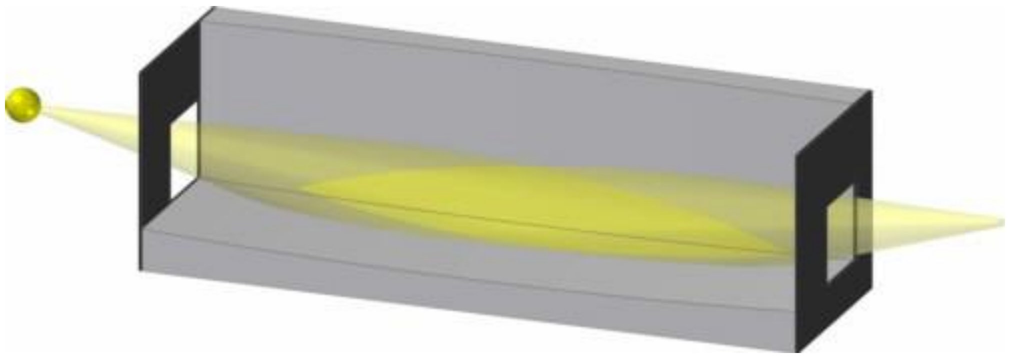
Multilayer optics

Multilayer Mirror



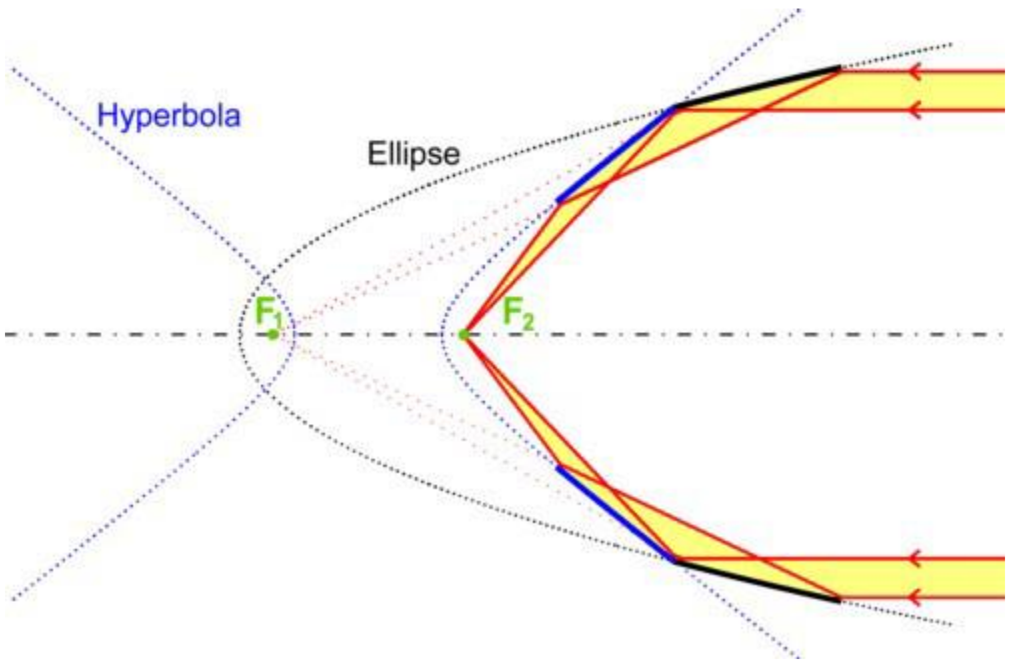


Montel system

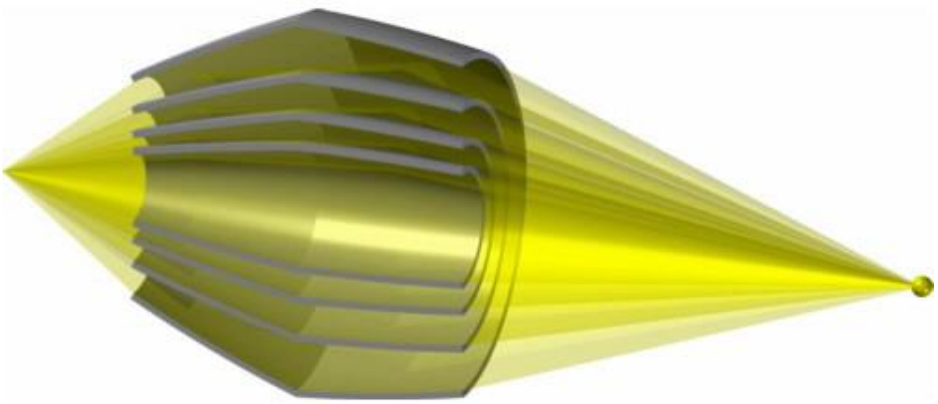


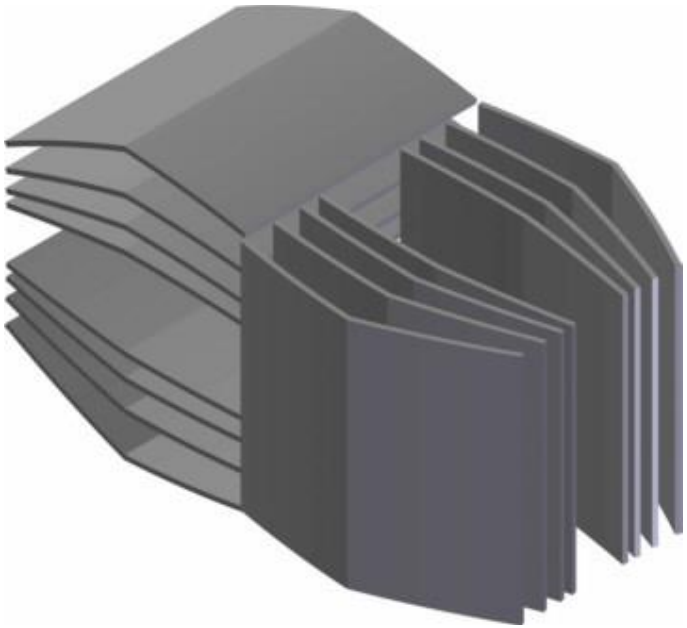
http://www.x-ray-optics.de

Wolter system



Wolter systems



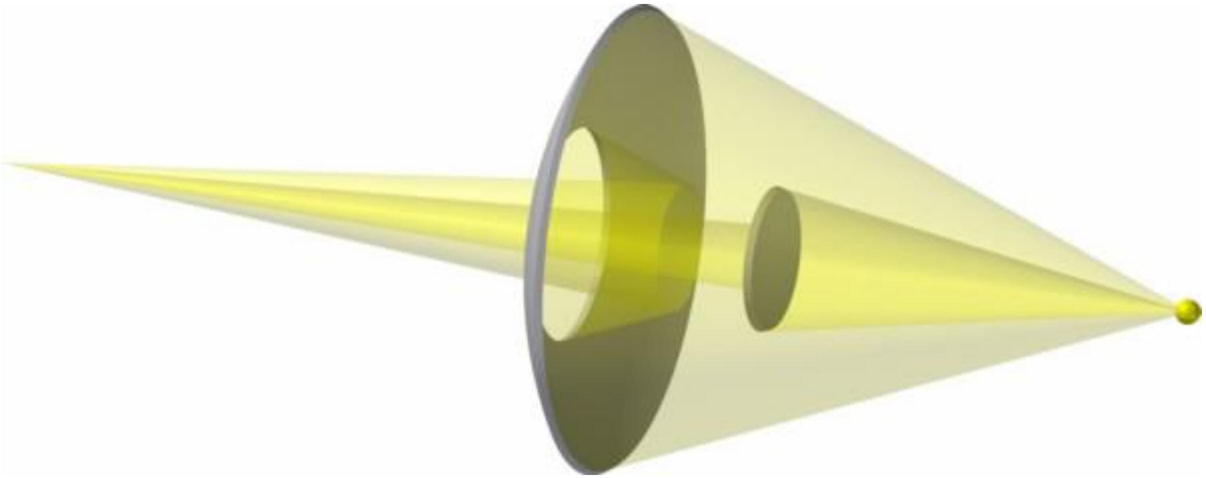


Rotationaly symmetric nested mirrors Wolter system

2D mirrors nested Wolter system

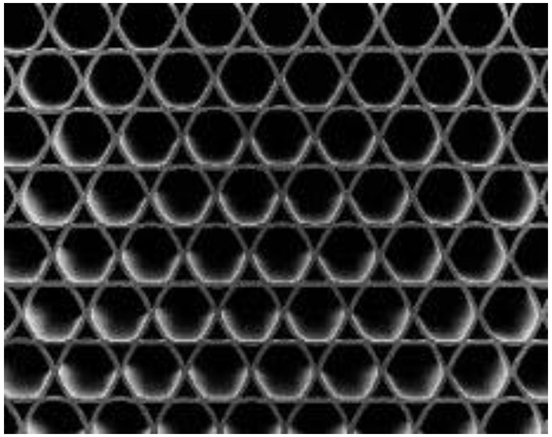
http://www.x-ray-optics.de

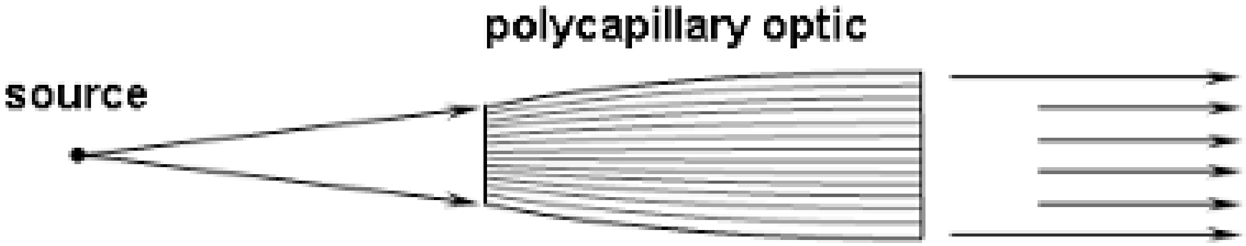
Schwarzschild-optics



http://www.x-ray-optics.de

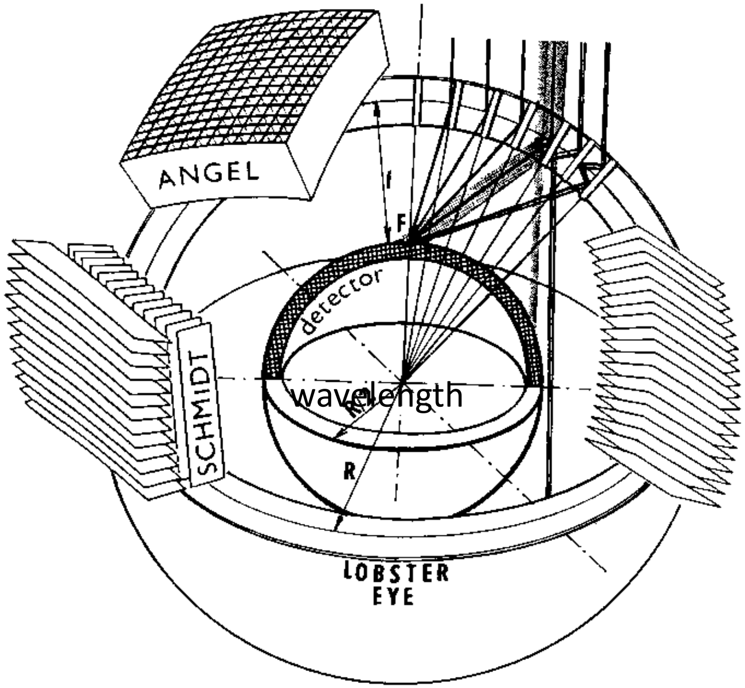
Polycapillary optics

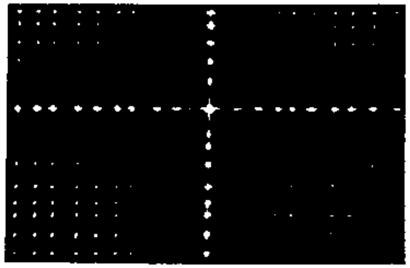


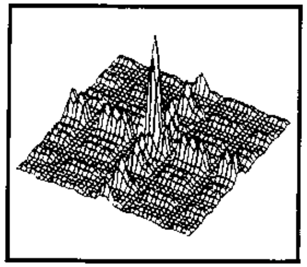


http://www.xos.com http://www.ifg-adlershof.de

Lobster Eye multifoil optics

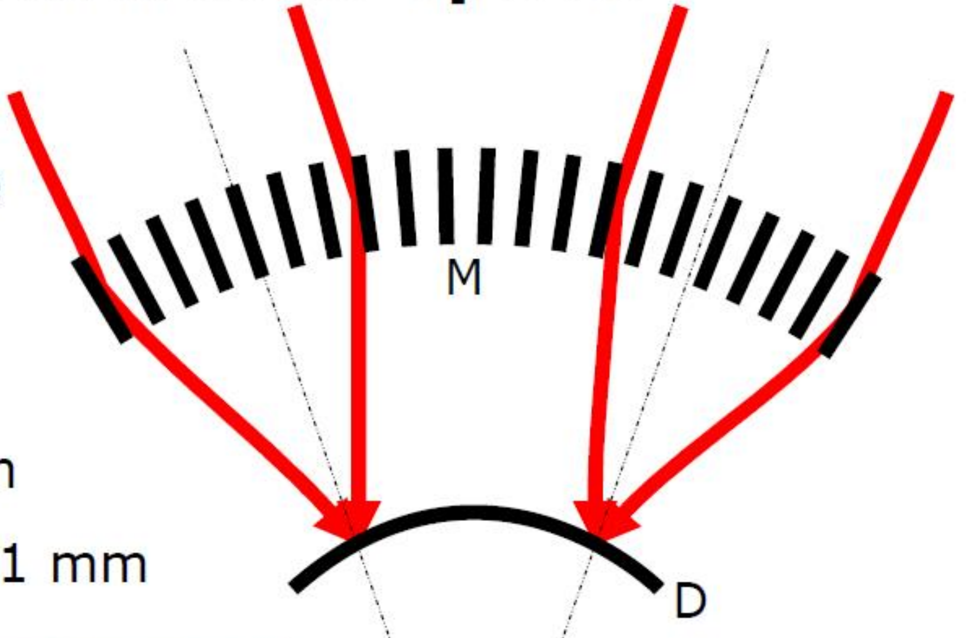


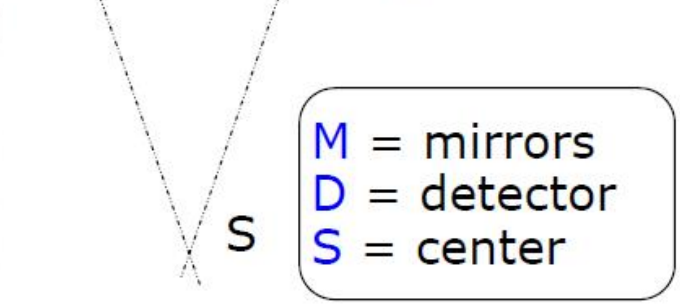


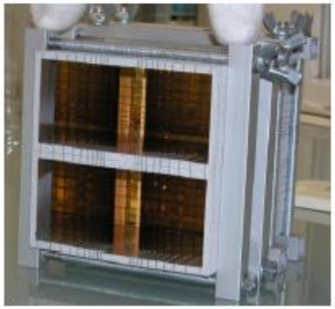


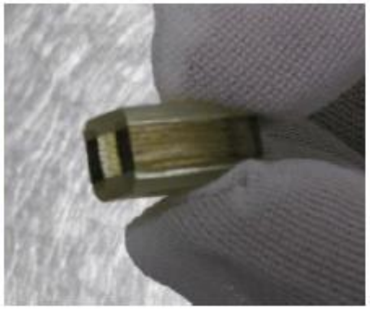
Lobster eye & multifoil optics

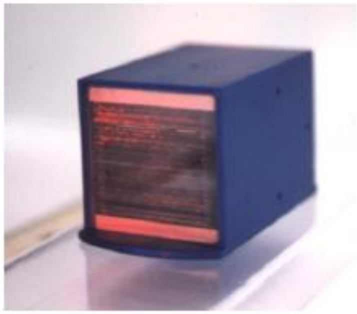
- Wide FOV
- Glass and/or silicon substrate for soft X-rays
- Planar & ellipsoidal mirrors
- Foils 3x3 mm to 300x300 mm
- Foil thickness from 30 µm to 1 mm







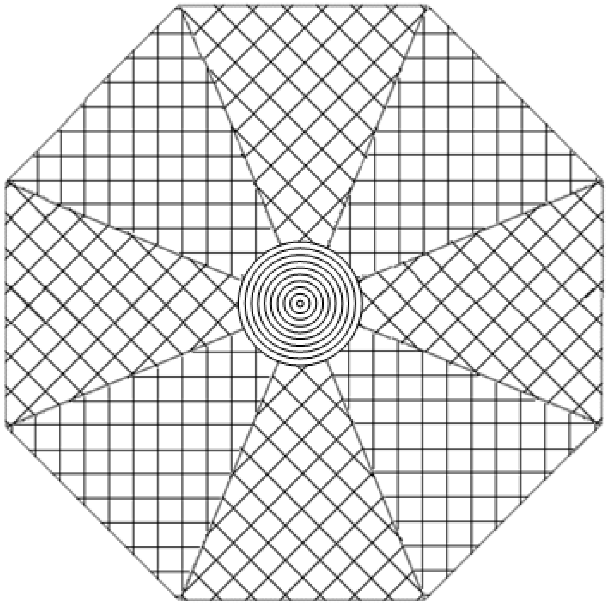




Combined MFO – nested paraboloids X-ray optical system

- Non-functional (blind) central area of **Flower** system can be filled with thin rotationally symmetric foils (classical nested mirrors with parabolic shape)

  => improvement of Flower optical system aperture effective area for higher energies

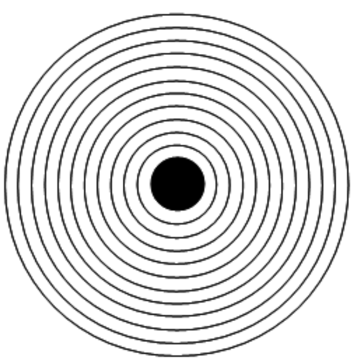


- Patent pending (PV 2011-297)
- Advantages:
  - the largest effective aperture in SXR region
  - higher efficiency in XR region
  - precise expensive mandrels are not needed for Flower part (silicon or glass thin planar mirrors can be used)
- Application in X-ray telescopes, XRF analysis, EUV/XUV microscopy, tomography and EUV/XUV lithography, focusing of electrons/neutrons, ...

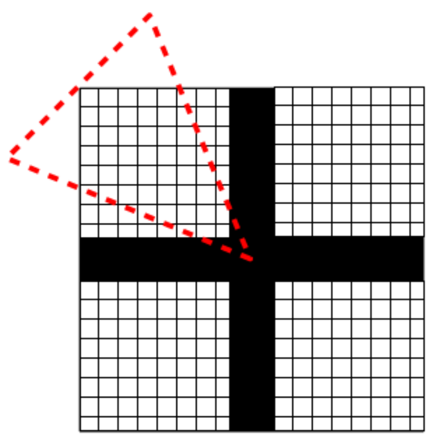
X-ray optical systems - comparison

- Size limited by the critical angle – the same maximum incident angle for all systems at a given photon energy

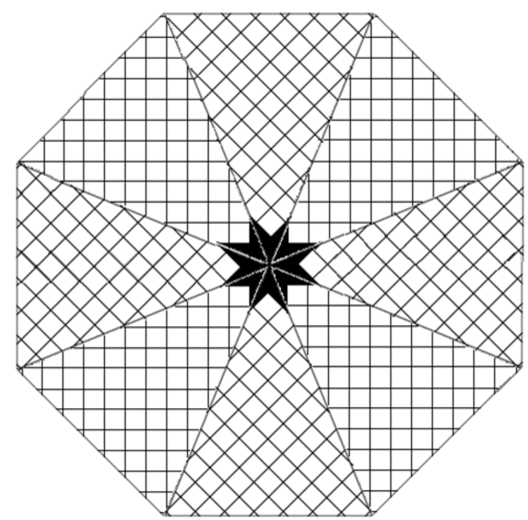
  (reflectivity 70% after 1^{st} reflection, 50% after 2^{nd} reflection)
- Wolter I and KB systems have the same aperture size
- KBF system has more than two times larger aperture than the others



Wolter system

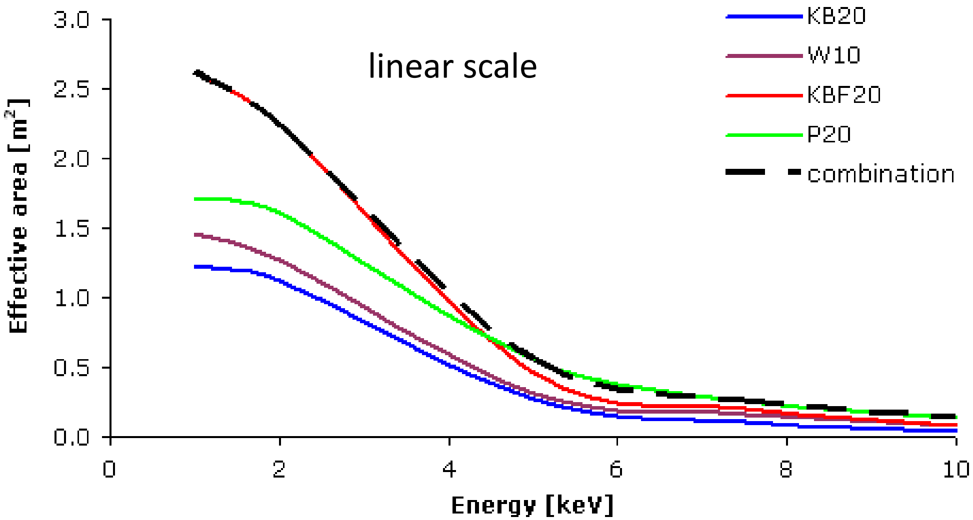


Kirkpatrick-Baez system

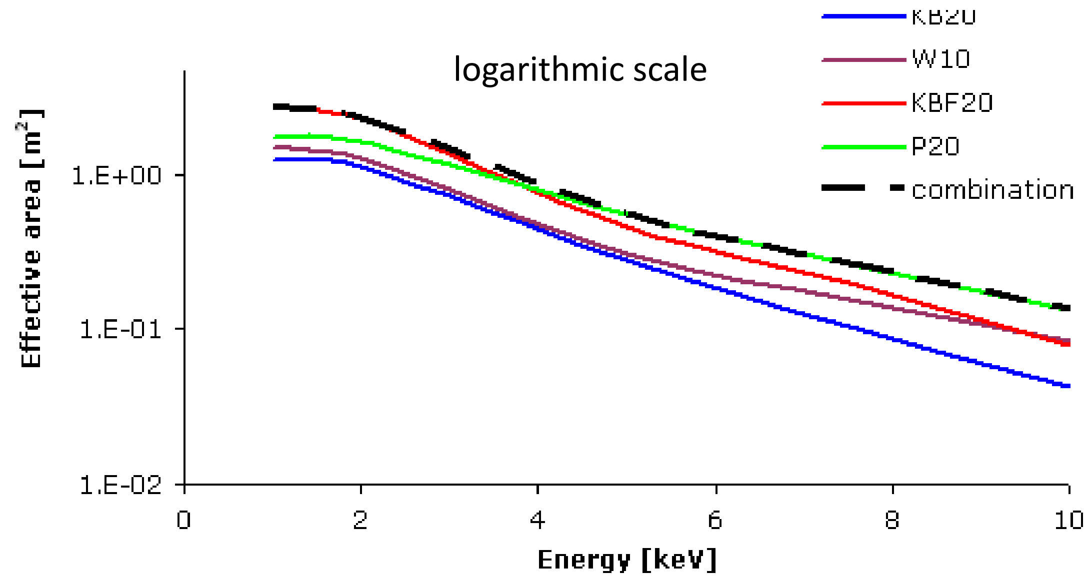


Flower system

X-ray optical systems - comparison



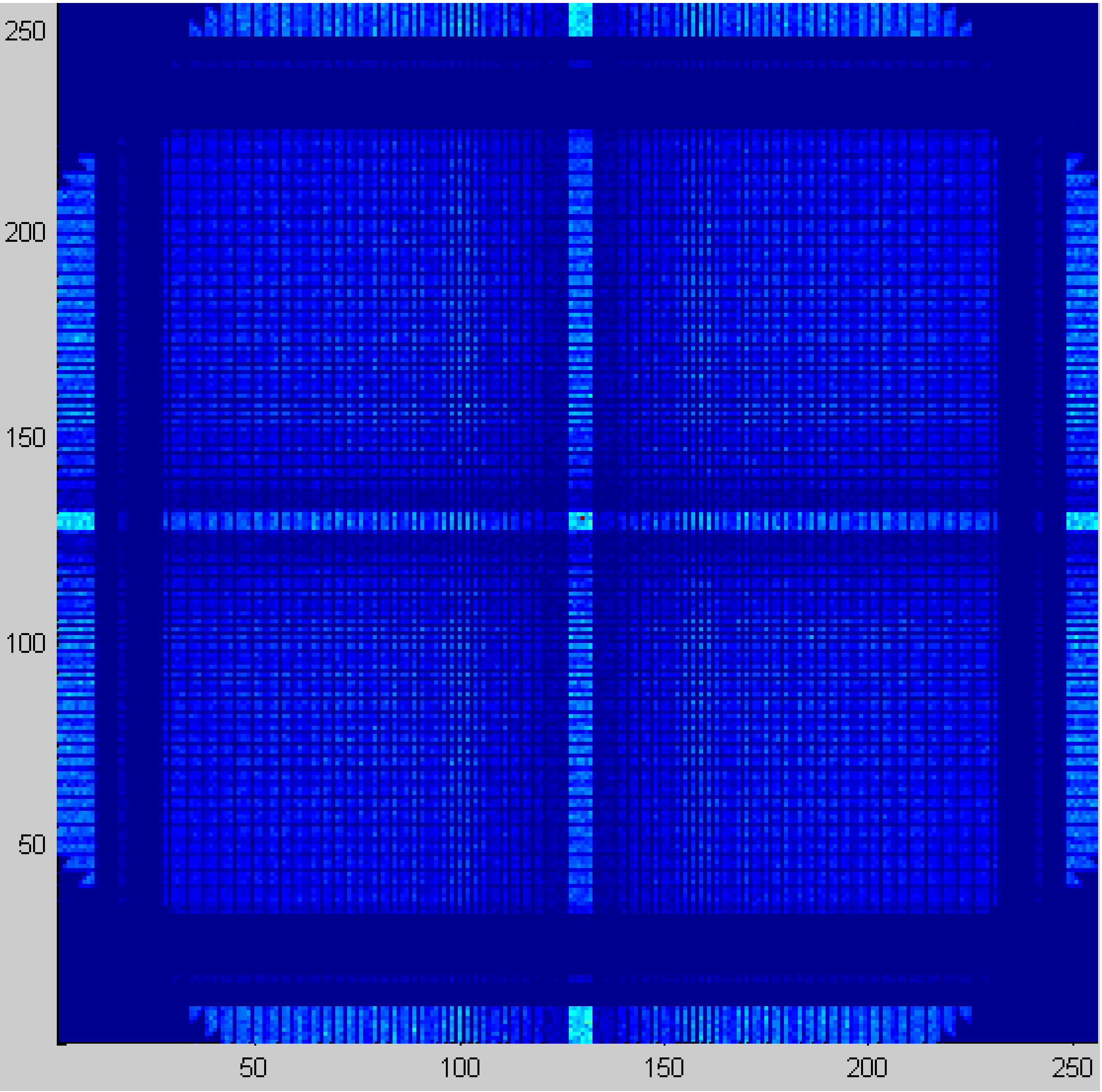
=> COMBINATION
KBF and P
(in SXR - XR region)



Ray tracing – intensity map behind the LE mirror

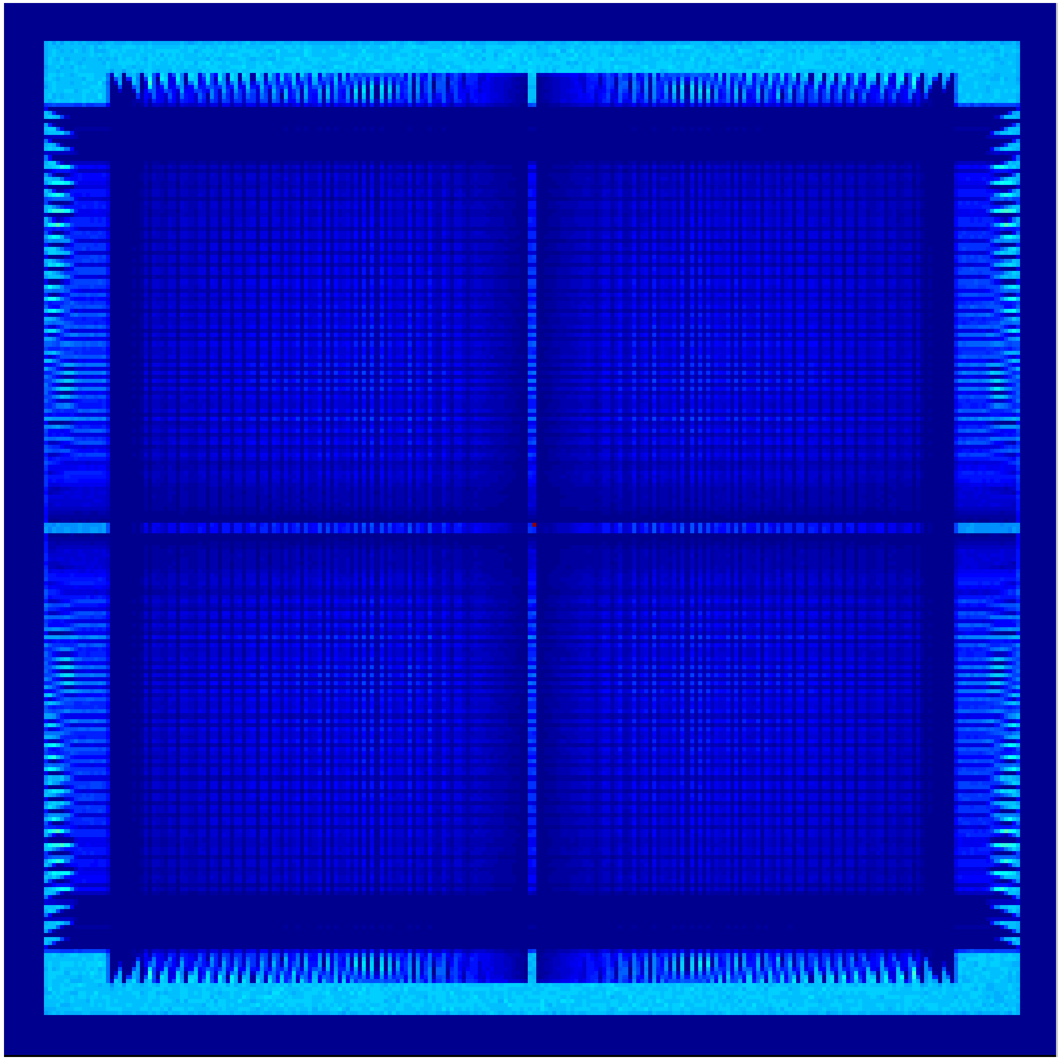
Ray tracing – Homogenization of X-ray beam

Ray tracing – intensity map behind the LE mirror



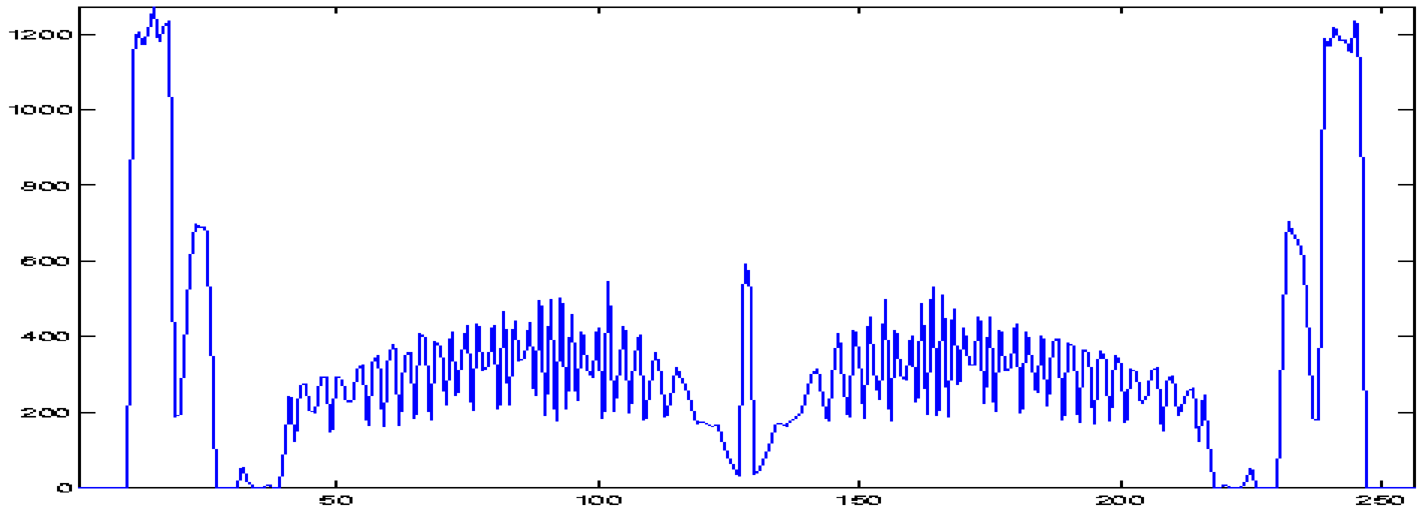
LE Ray tracing – Typical intensity map just behind the mirror

Ray tracing – intensity map behind the LE mirror



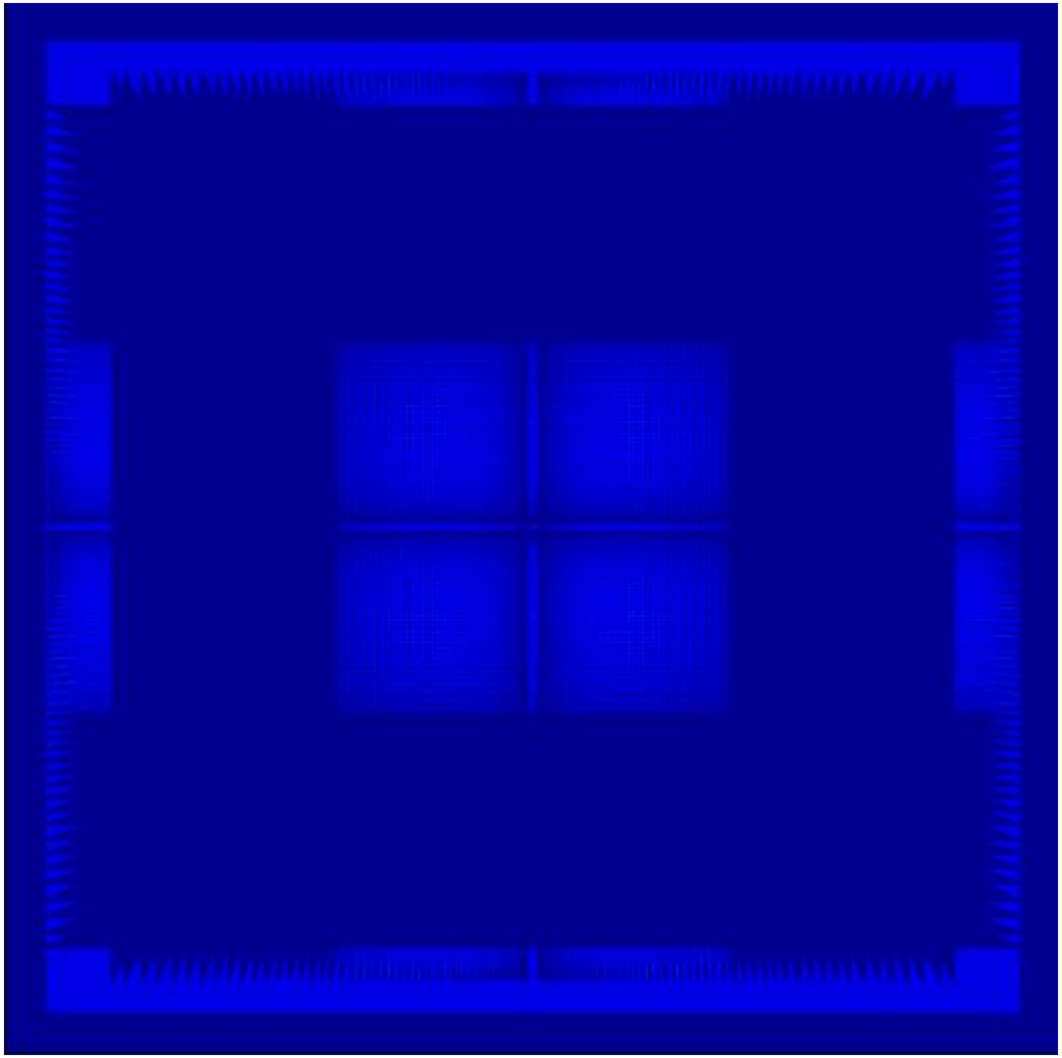
INTENSITY MAP LE-18 L =6 X1 = 85 Xd = 90

Ray tracing – intensity map behind the LE mirror



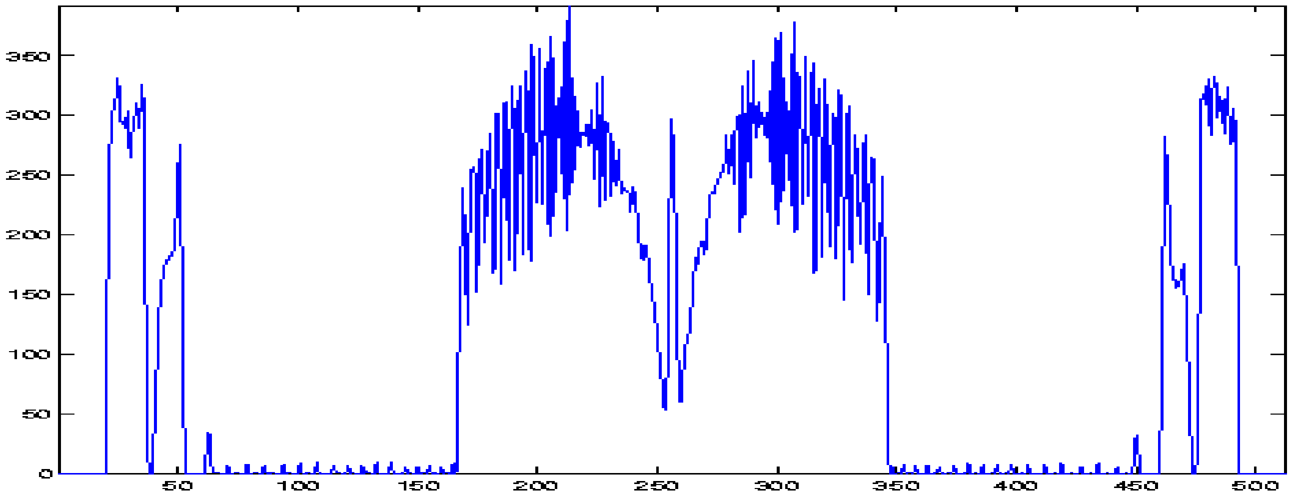
INTENSITY PROFILE LE-18 L =6 X1 = 85 Xd = 90

Ray tracing – intensity map behind the LE mirror



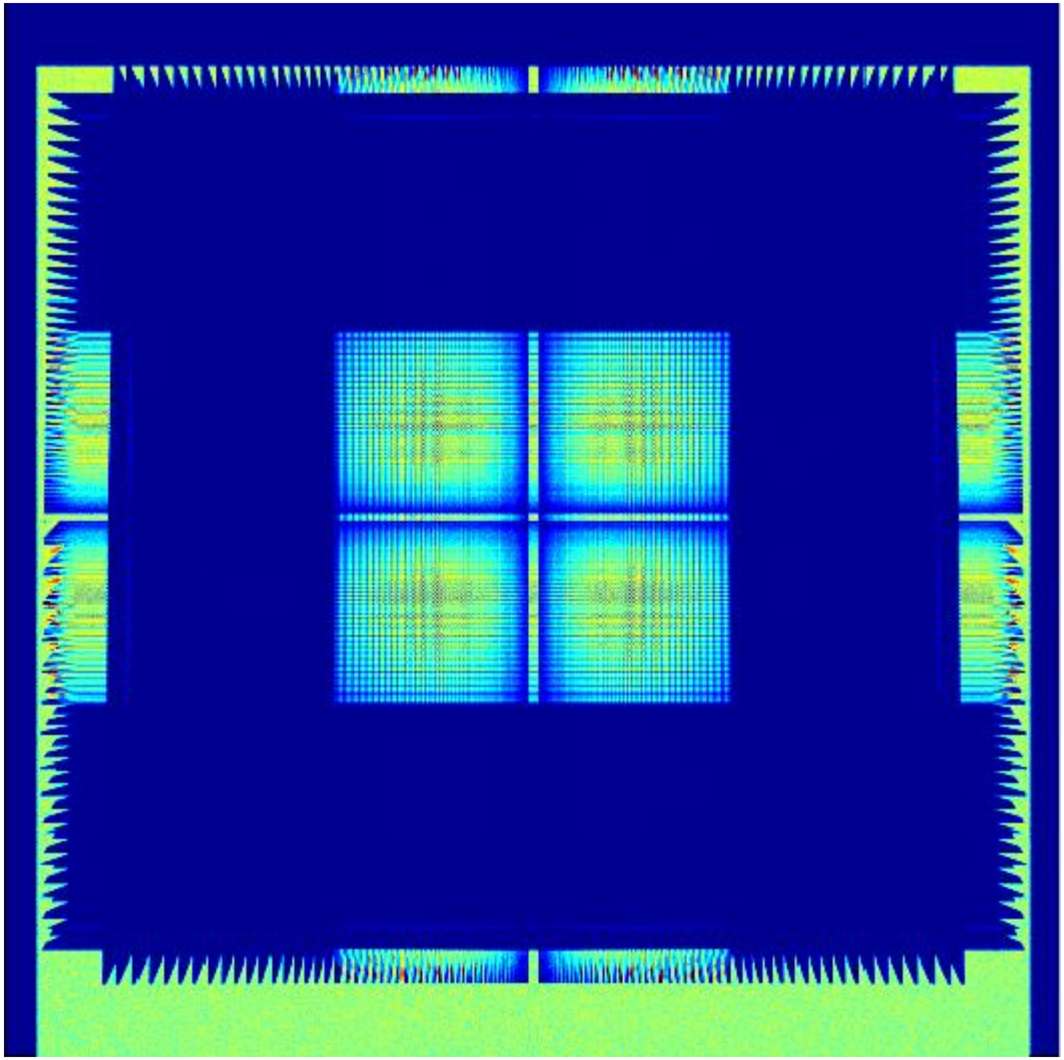
INTENSITY MAP LE-18 L =6 X1 = 85 Xd = 200

Ray tracing – intensity map behind the LE mirror



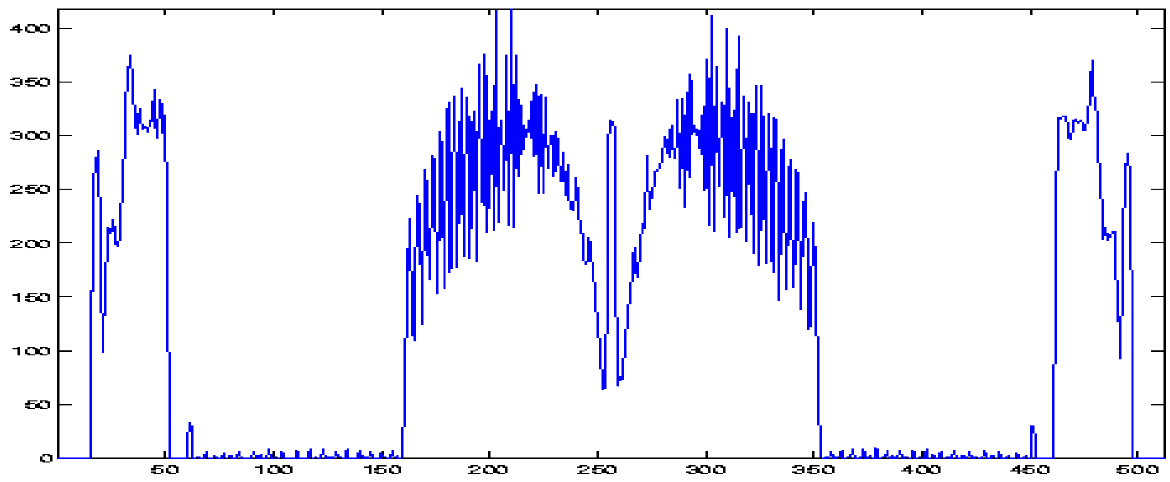
INTENSITY PROFILE LE-18 L =6 X1 = 85 Xd = 200

Ray tracing – intensity map behind the LE mirror



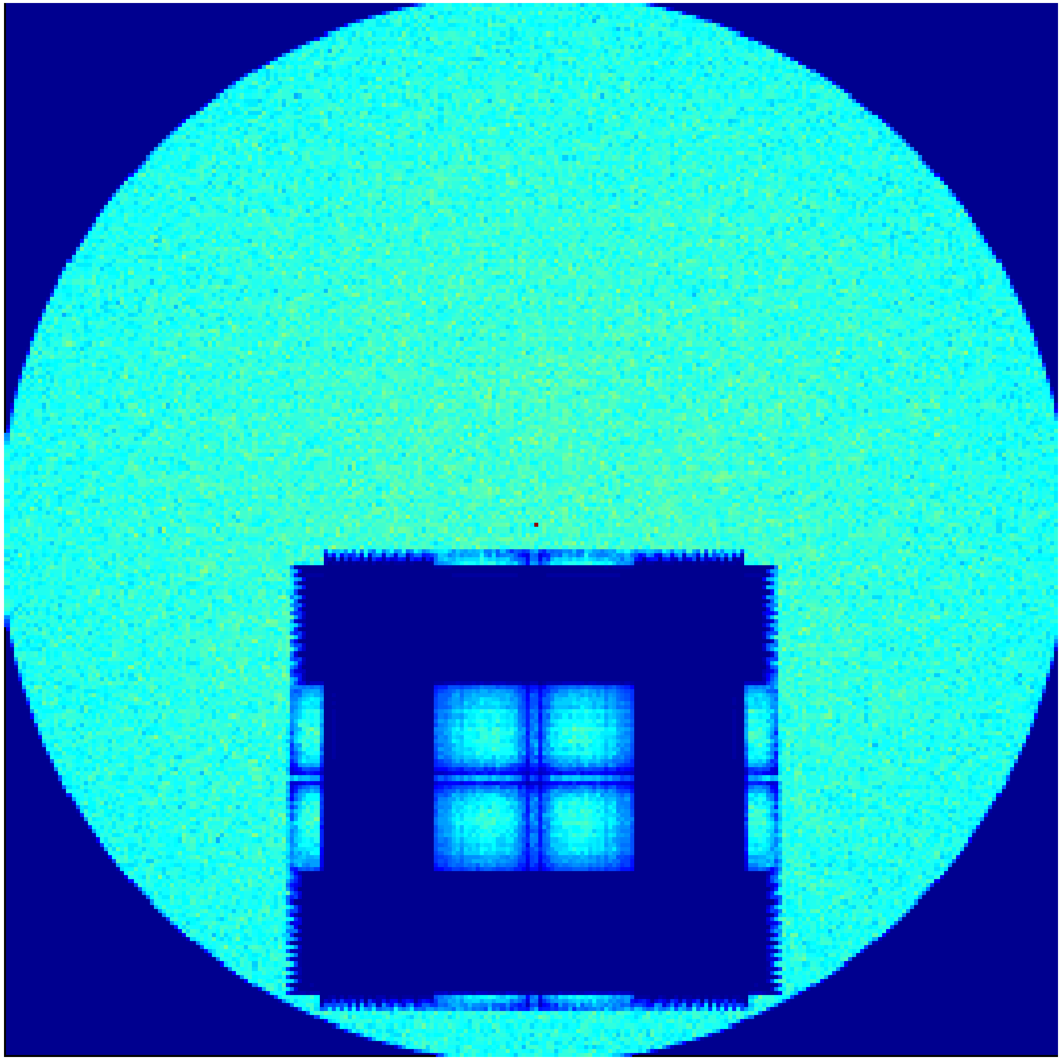
INTENSITY MAP LE-18 inclined L =6 X1 = 85 Xd = 200

Ray tracing – intensity map behind the LE mirror



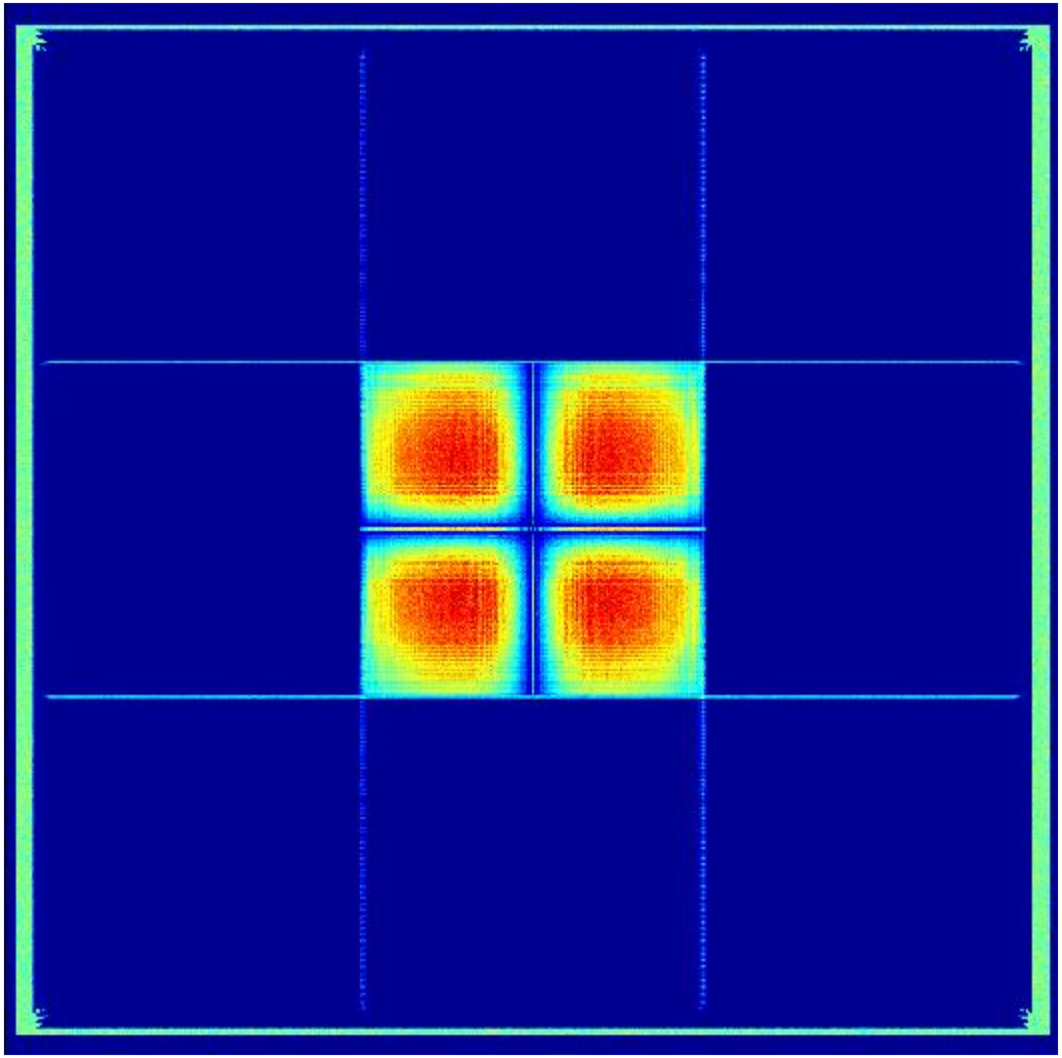
INTENSITY PROFILE LE-18 inclined L =6 X1 = 85 Xd = 200

Ray tracing – intensity map behind the LE mirror



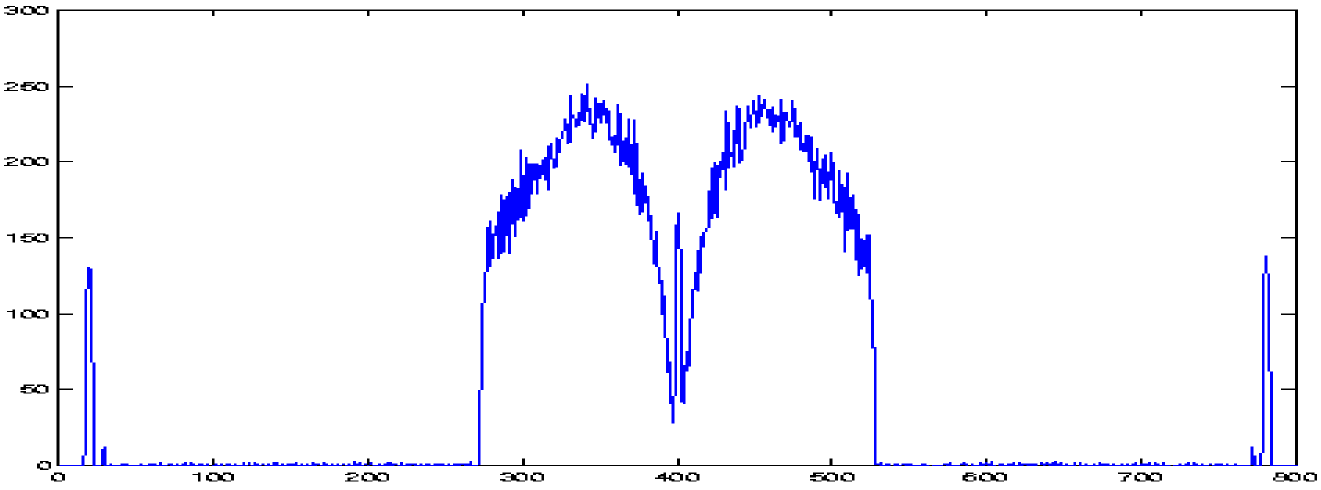
INTENSITY MAP TRUE POSITION LE-18 inclined L =6 X1 = 85 Xd = 200

Ray tracing – Homogenization of X-ray beam



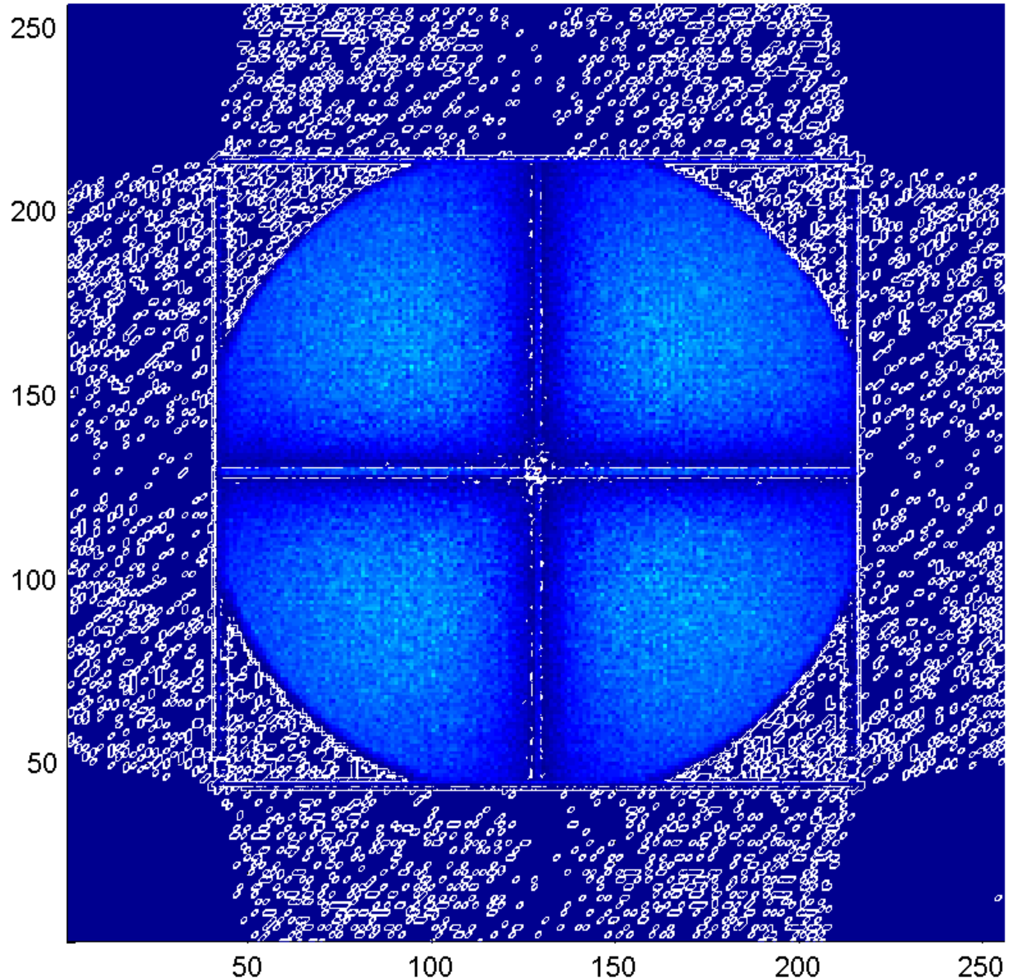
INTENSITY MAP LE-50 L =6 X1 = 250 Xd = 750

Ray tracing – Homogenization of X-ray beam



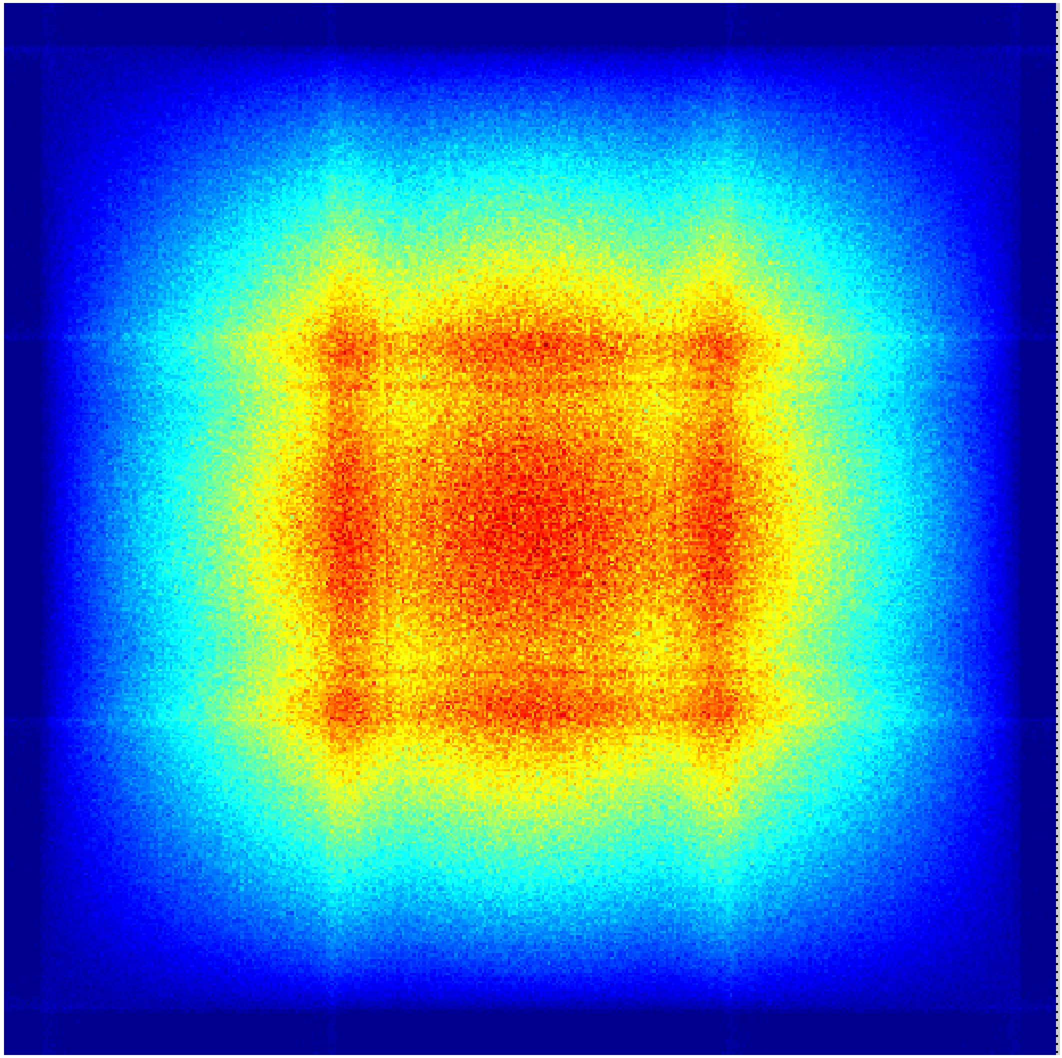
INTENSITY PROFILE LE-50 L =6 X1 = 250 Xd = 265

Ray tracing – Homogenization of X-ray beam



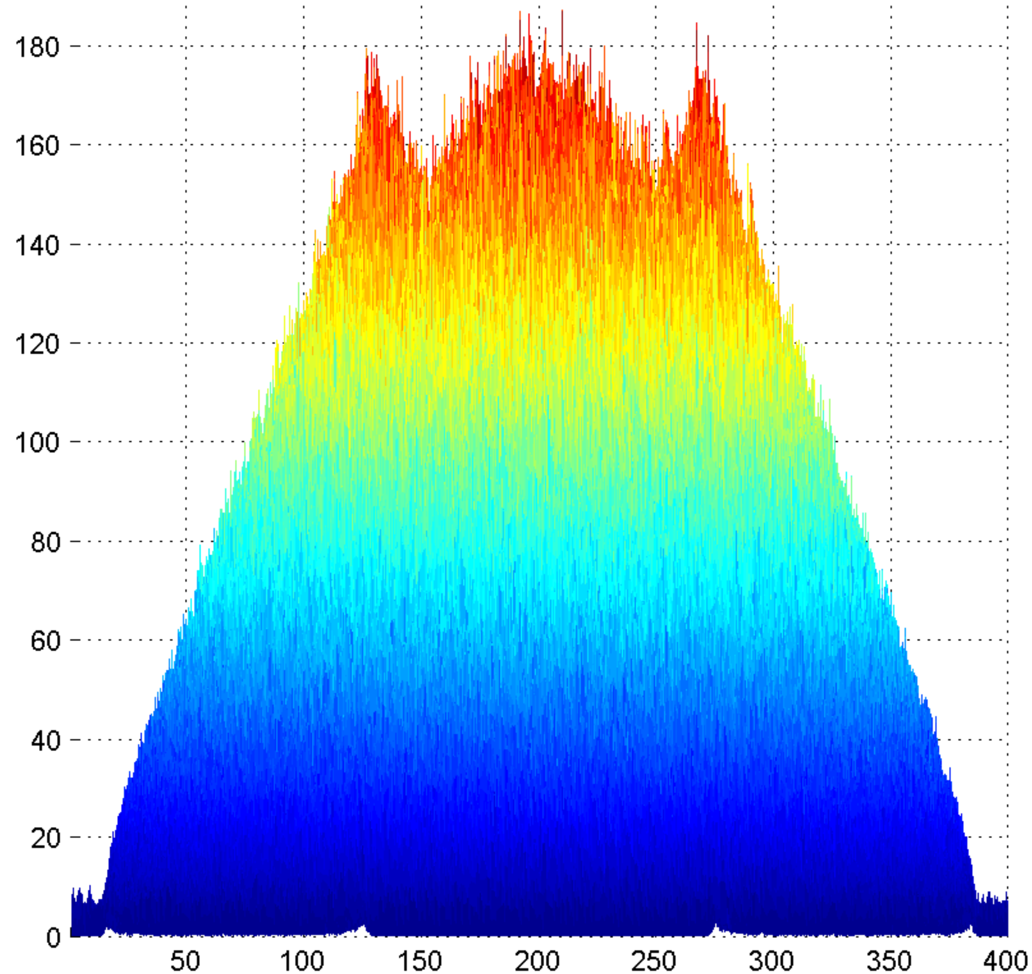
INTENSITY MAP LE-50 L =6 X1 = 250 Xd = 750

Ray tracing – Homogenization of X-ray beam



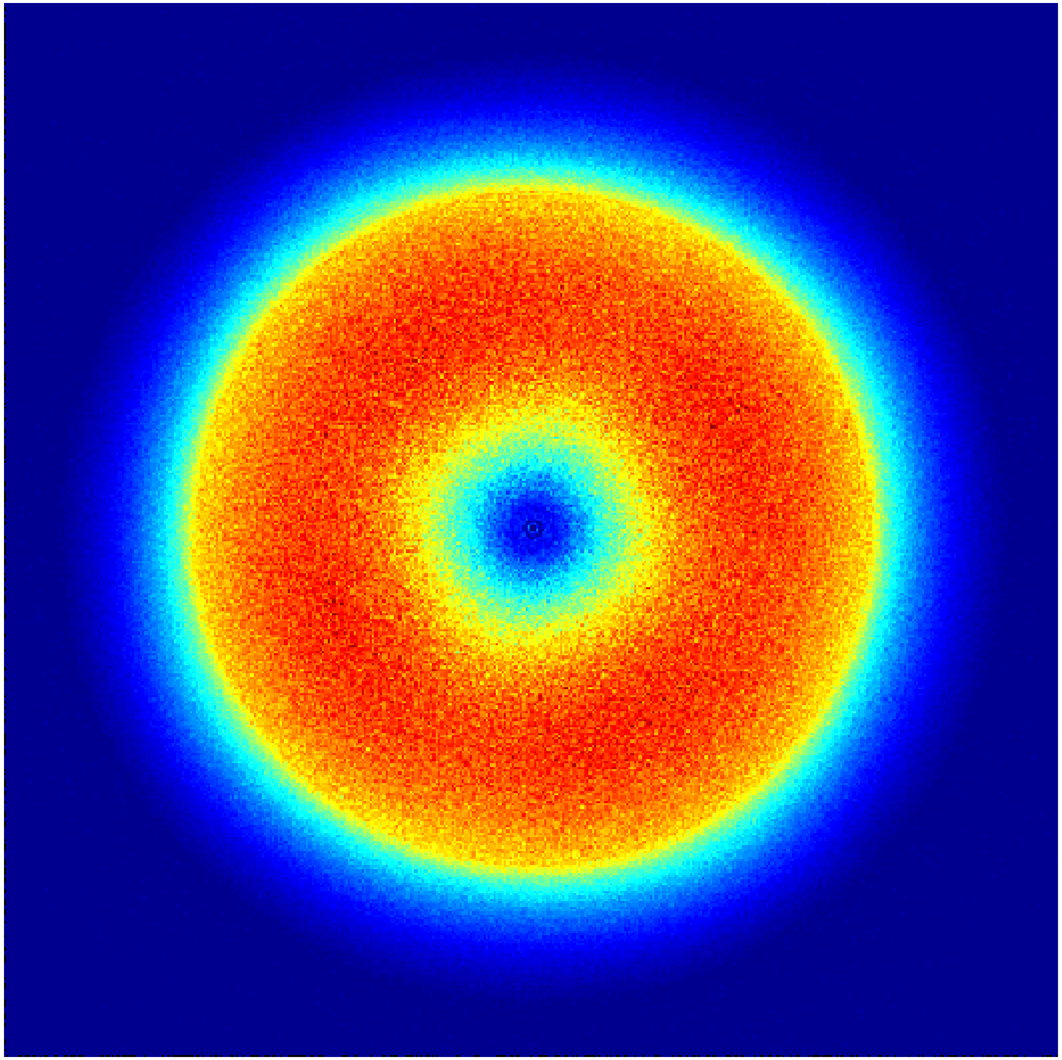
INTENSITY MAP (11 mm detector sweep) LE-50 L =6 X1 = 250 Xd = 750

Ray tracing – Homogenization of X-ray beam



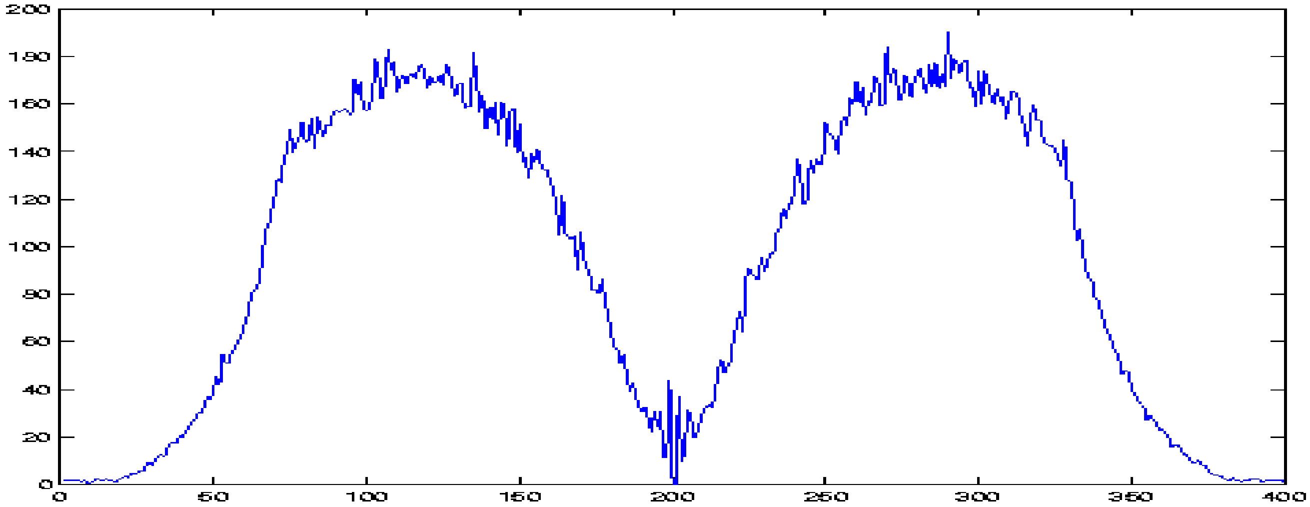
INTENSITY PROFILE (11 mm detector sweep) LE-50 L =6 X1 = 250 Xd = 750

Ray tracing – Homogenization of X-ray beam



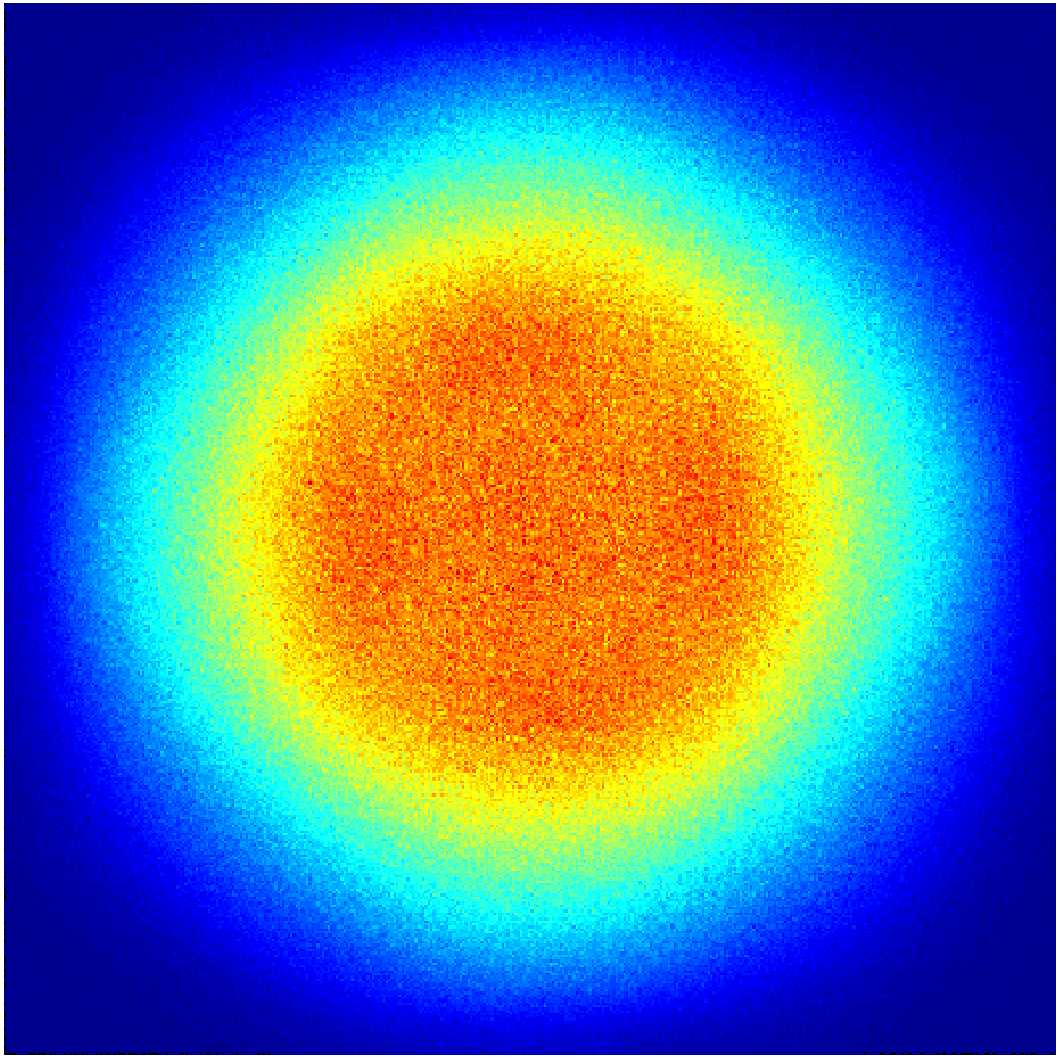
INTENSITY MAP (rotating LE mirror) LE-50 L =6 X1 = 250 Xd = 750

Ray tracing – Homogenization of X-ray beam



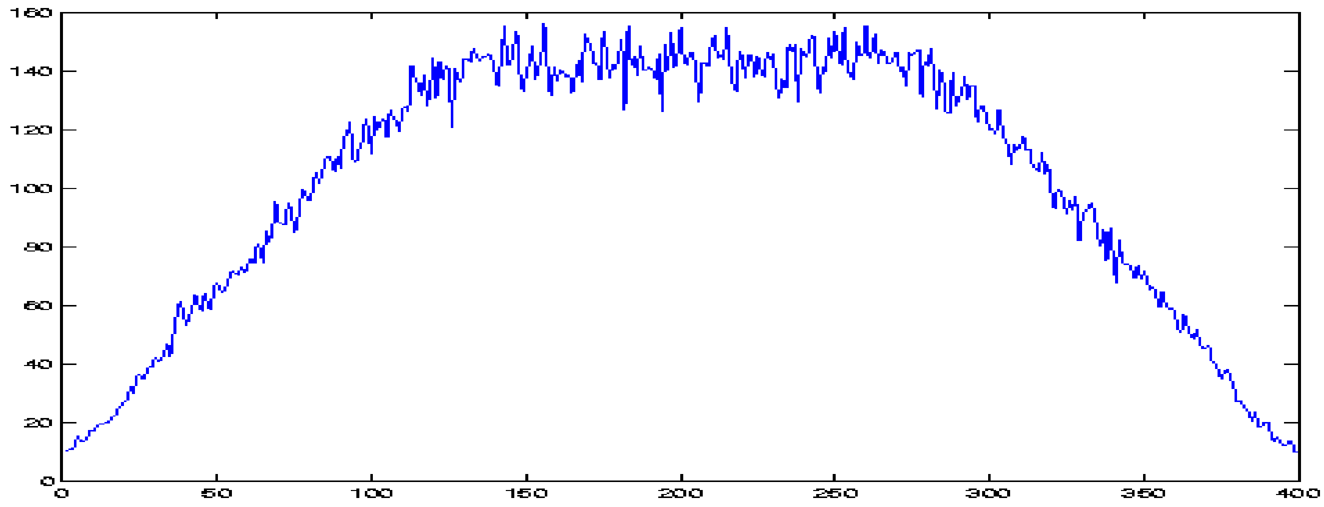
INTENSITY PROFILE (rotating LE mirror) LE-50 L =6 X1 = 250 Xd = 750

Ray tracing – Homogenization of X-ray beam



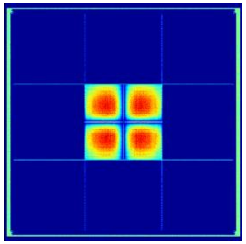
INTENSITY MAP (rotating LE mirror + sweeping detector) LE-50 L =6
X1 = 250 Xd = 750

Ray tracing – Homogenization of X-ray beam

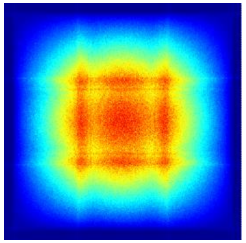


INTENSITY Profile (rotating LE mirror + sweeping detector) LE-50 L =6
X1 = 250 Xd = 750

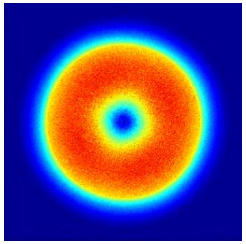
Ray tracing – intensity map behind the LE mirror
Homogenization of X-ray beam
Summary



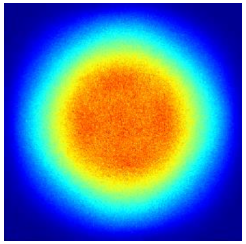
Lobster Eye INTENSITY MAP LE-50 L =6 X1 = 250 Xd = 750



Lobster Eye INTENSITY MAP LE-50 L =6 X1 = 250 Xd = 750
(11 mm detector sweep)



Lobster Eye INTENSITY MAP LE-50 L =6 X1 = 250 Xd = 750
(rotating LE mirror)



Lobster Eye INTENSITY MAP LE-50 L=6 X1 = 250 Xd = 750
(rotating LE mirror + sweeping detector)

Potential optical scheme for FEL based EUV lithography

Key components:

- Grazing incidence Kirkpatrick-Baez collector or better
- Axisymmetric ellipsoidal collector grazing incidence mirror
- Pinhole spatial filter at IF
- Optics for diffraction effects and speckle suppression (optional)
- Optics for beam homogenization (optional)
- Mask illumination optics
- Demagnifying imaging optics

Summary

- Possible optical systems for FEL based EUV lithography were studied.
- Key features of FEL radiation were compared to LPP and DPP radiation
- Quasi parallel input beam, small beam size and possibly submicron size IF make potential optics solutions different from plasma source solutions.
- Diffraction effects and speckle suppression are needed.
- Homogenization of the beam was studied and one example of relevant optical system was modeled.
- Main building blocks of the FEL lithography optical system were identified.

THANK YOU FOR ATTENTION

Prague