Diagnostic Tools for the Transverse Coherence of an X-FEL

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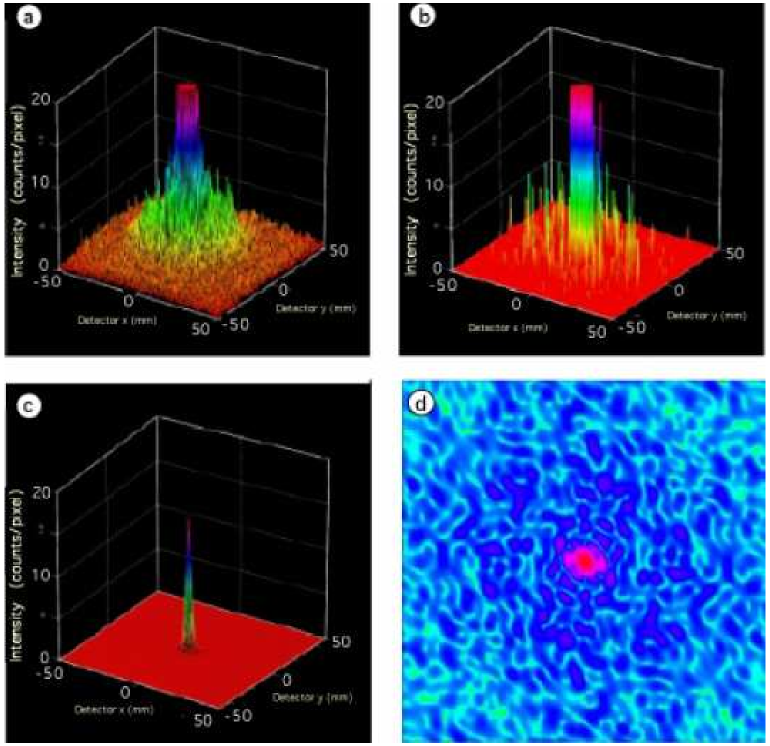
DESY

Diagnostic Tools for the Transverse Coherence of an X-FEL

- Importance of Coherence in an FEL
- Definition of coherence properties
- Coherence in an X-Ray FEL
- Evolution of the transverse coherence in a propagating beam
- Diagnostic tools for the coherence
- Coherence Measurements
- Measurement Concepts for an X-FEL

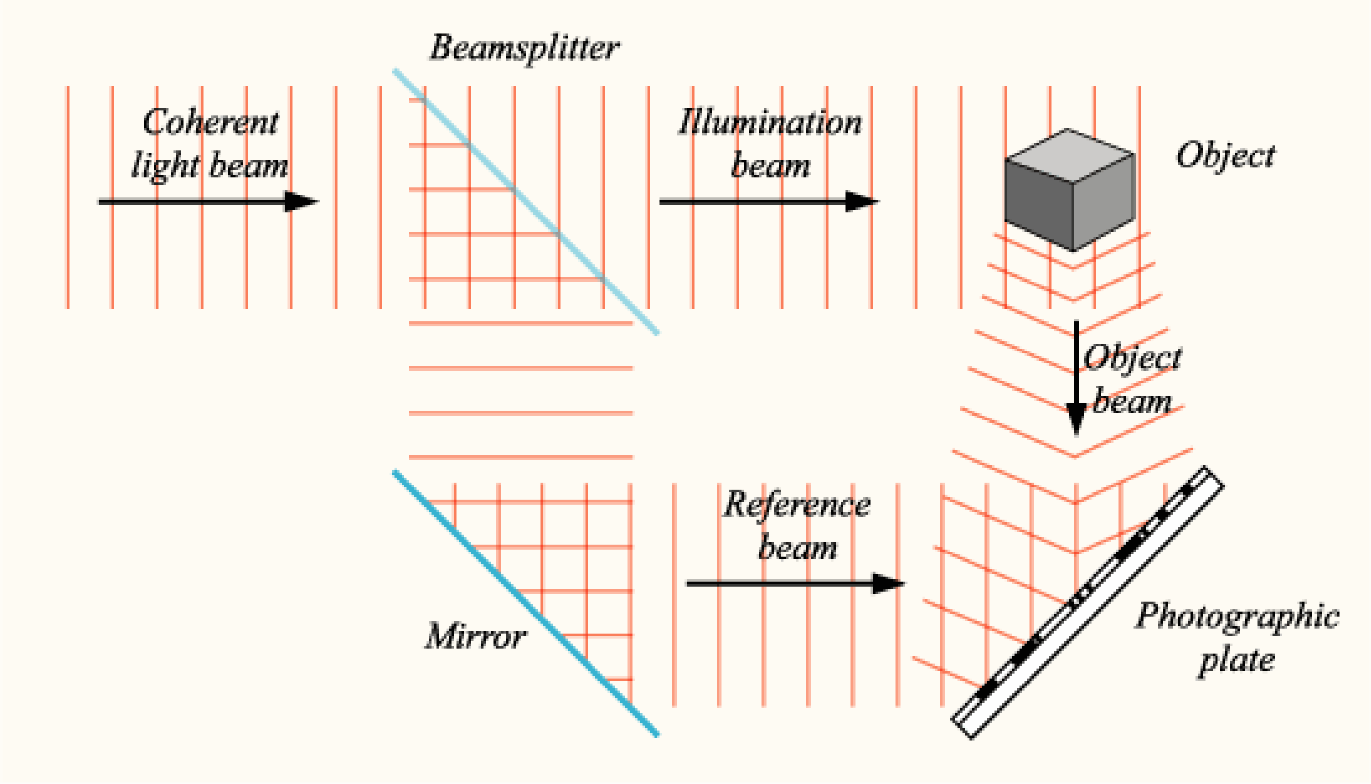
Importance of Coherence for X-FEL Experiments

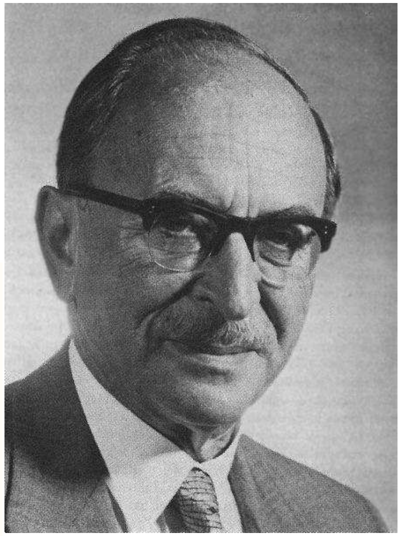
- Essential for experiments using interference methods
  - holography
  - coherent diffraction from a single molecule
- Can be employed for studies in condensed matter systems (XTGS technique)
- Needed to focus the beam to the diffraction limit



Holography

- Record the interference between object beam and reference beam



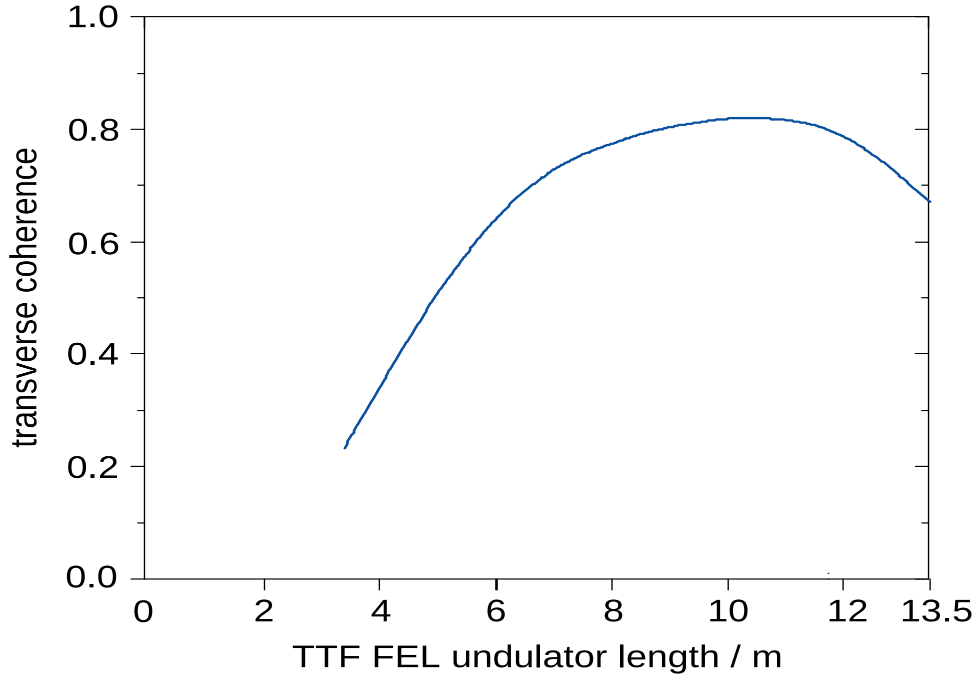


Dennis Gabor

- Allows to measure the phase of the diffracted wave
- Necessary prerequisite: coherence of the incoming wave

Importance of Coherence for FEL diagnostics

- Distinguish spontaneous radiation from FEL amplification
- Confirm theoretical models
- Indirect measurement of the size of the electron beam
- Measurement as a function of the undulator length



Definition of Coherence Properties

- Electromagnetic wave: representation of a wave in z direction in the Slowly Varying Amplitude (SVA) approximation

$$\vec{E}(\vec{r},t) = \mathrm{Re}\left[\tilde{E}(\vec{r},t)\exp\Big(i(\omega t - \vec{k}\cdot\vec{r})\Big)\right]\vec{u}_x$$

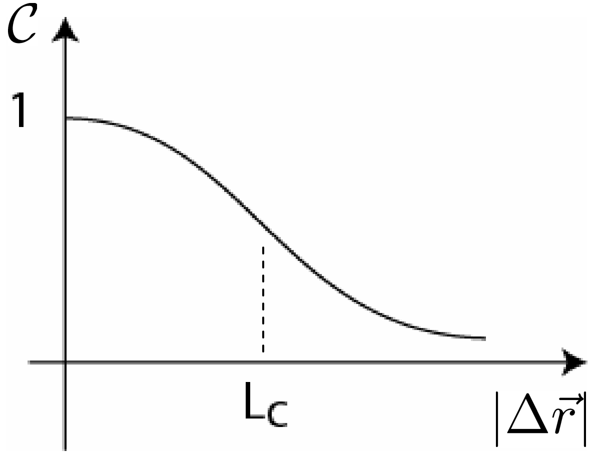
- Correlation function

$$\tilde{\Gamma}(\vec{r},\vec{r'}) = \left\langle \tilde{E}(\vec{r},t)\cdot\tilde{E}^*(\vec{r'},t)\right\rangle_t$$

$$\tilde{\gamma}(\vec{r}-\vec{r'}) = \frac{\tilde{\Gamma}(\vec{r},\vec{r'})}{\tilde{\Gamma}(\vec{r},\vec{r})}$$

- Coherence function

$$\mathcal{C}(\Delta\vec{r}) = |\tilde{\gamma}(\vec{r}-\vec{r'})|$$



Coherence of Free Electron Lasers

- Decomposition of the radiation in its transverse modes

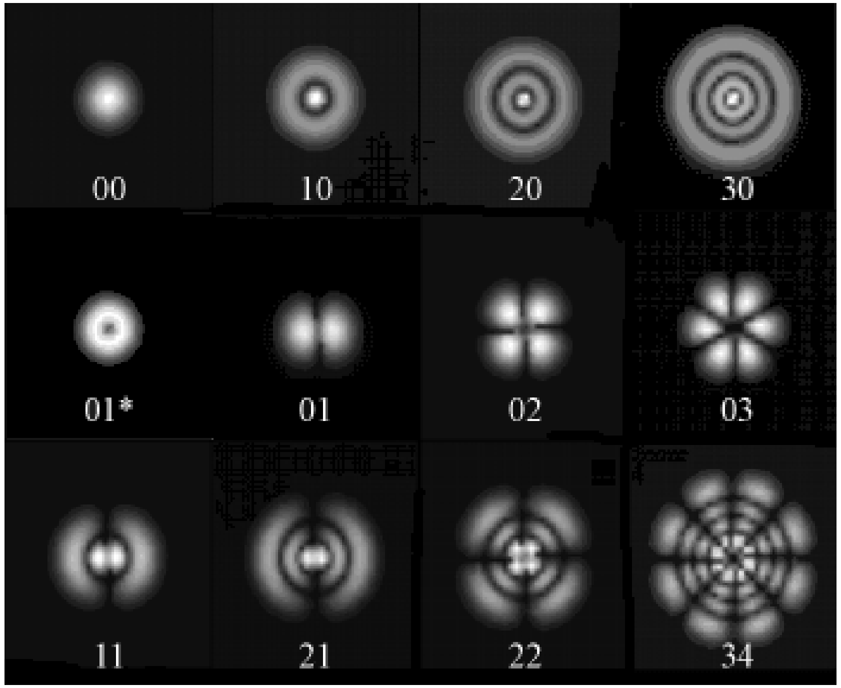
$$\tilde{E}(r,\vartheta,z) = \sum_{n,m} C_{nm}(z)\tilde{A}_{nm}(r,\vartheta)$$

- TEM modes (transverse electric and magnetic field)
- Cross section of the first Gauß-Laguerre modes:

$$\tilde{A}_{nm}(r,\varphi) =$$

$$r^{m/2} L_n^m(r)\cos(m\varphi)\mathrm{e}^{-r/2}$$

where L is the Laguerre polynomial



wikipedia.org

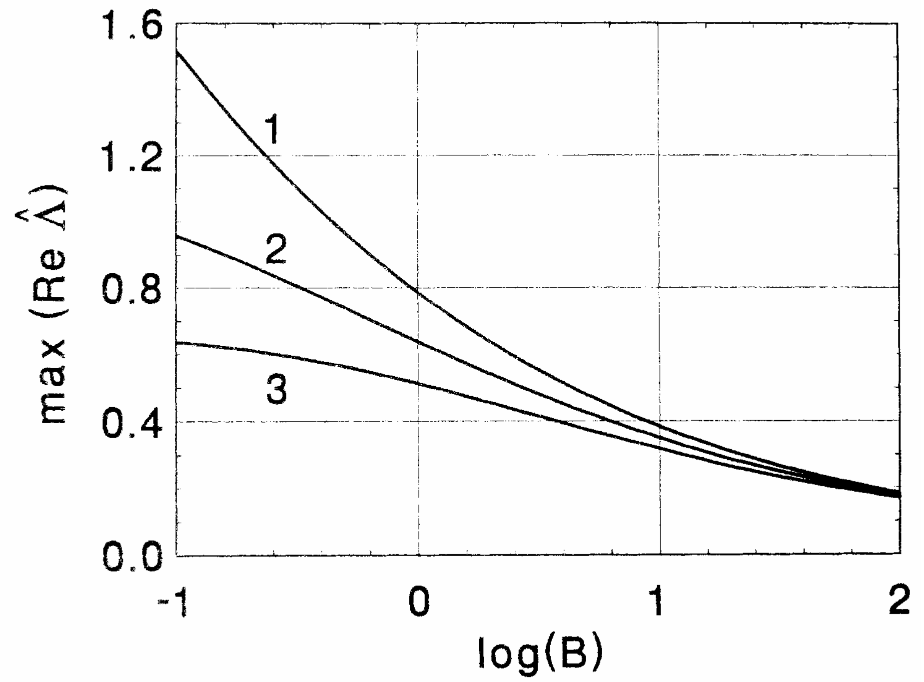
Coherence of an X-Ray FEL

- Coherence in the FEL process is determined by the diffraction parameter

$$B \approx \frac{\text{area that the } \gamma \text{ beam expands in } L_g}{\text{area of the e beam}}$$

- Growth rate of the three fundamental modes:
- Typical values:
  - TTF1: B ≈ 10
  - VUVFEL: B ≈ 20
  - XFEL: B ≈ 120

- What coherence results?



Saldin, Schneidmiller, Yurkov

Evolution of the transverse coherence in a propagating beam

- A fully coherent beam will retain its coherence along the propagation
- What about fully transversely incoherent beams?
- Partially coherent beams?

The van Cittert-Zernike Theorem

- Assume a source that has
  - zero transverse coherence (“pseudo-thermic”)
  - infinite longitudinal coherence (“monochromatic”)
- Then the transverse coherence in the far field is given by

$$\mathcal{C} \propto \iint \frac{I_S(x,y)}{L^2} \exp\left[i\frac{\omega}{c} \left(-\frac{x_1^2+y_1^2}{2L} + \frac{x_0 x_1 + y_0 y_1}{L} \right) \right] \mathrm{d}x\,\mathrm{d}y$$

  where I_S is the intensity at the source and L the distance to the observation plane
- This is equal to the normalized diffraction pattern that is formed by a fully coherent source behind an aperture
  - Replace the aperture function with the intensity distribution at the source
  - Normalize such that $\mathcal{C}(0) = 1$

The van Cittert-Zernike Theorem

- For a circular source, the coherence function is a Bessel function

$$\begin{aligned}\mathcal{C}(r) &= 4\left(\frac{J_1(2\pi Rr/(\lambda L))}{2\pi Rr/(\lambda L)}\right)^2 \\ L_C &= 0.26\frac{\lambda L}{R}\end{aligned}$$

- The van Cittert-Zernike Theorem can be used to infer the size of an incoherent source

Examples

- The light bulb over my desk
  - $\lambda = 500\text{nm}, L = 0.5\text{m}, r = 2\text{cm}$

  ⇒ $L_C = 3\mu\text{m}$
- A monochromatic portion of the sunlight, seen on earth
  - $\lambda = 500\text{nm}, L = 1.5 \cdot 10^{11}\text{m}, R = 7 \cdot 10^{8}\text{m}$

  ⇒ $L_C = 28\mu\text{m}$
- The star Betelgeuse
  - $\lambda = 500\text{nm}, L/R = 8.8 \cdot 10^{6}$

  ⇒ $L_C = 1.14\text{m}$
- synchrotron radiation source DORIS
  - $\lambda = 1\text{nm}, L = 10\text{m}, R = 1\text{mm}$

  ⇒ $L_C = 2.6\mu\text{m}$

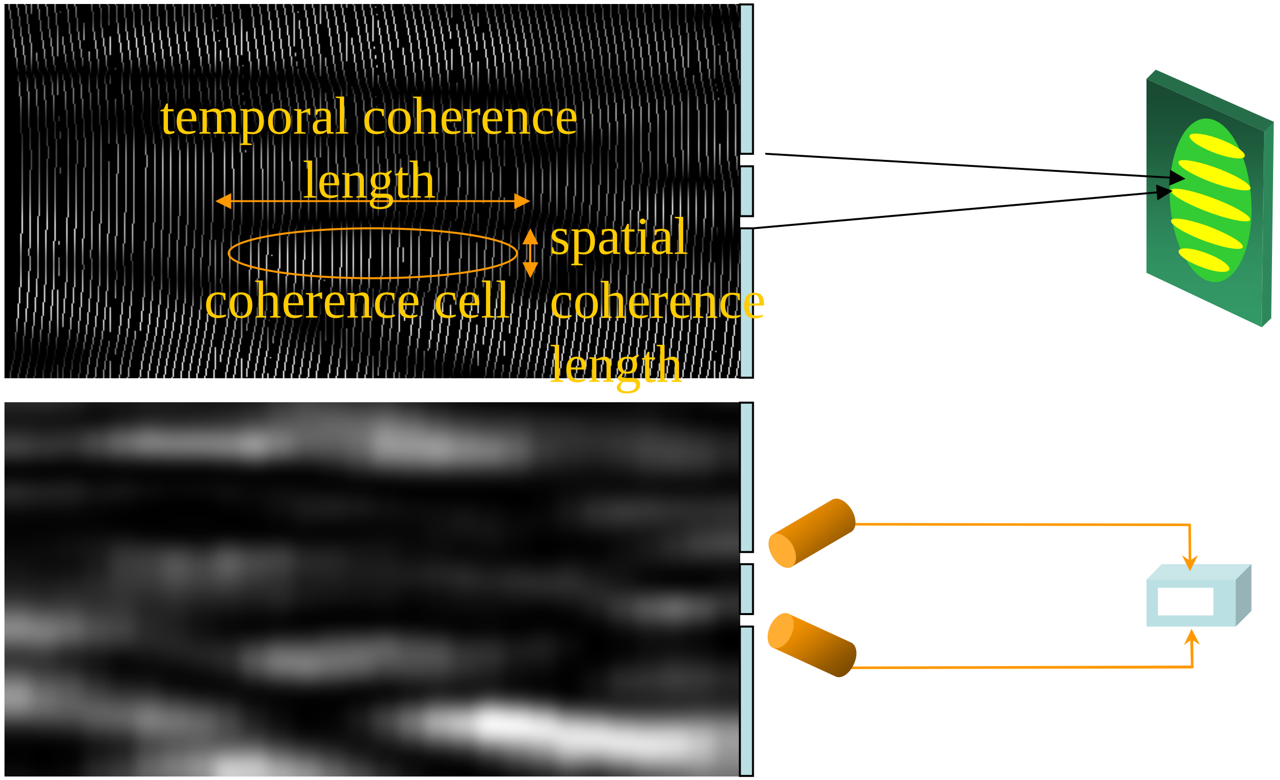
Evolution of the transverse coherence in a propagating beam

Implications for Coherence Measurements

- The FEL has a fairly small source size
- The radiation acquires a large coherence length by propagating from the undulator exit to the experiment
    - fortunate for the experiments
    - unfortunate to measure the coherence length as a diagnostics tool

Diagnostic tools for the coherence

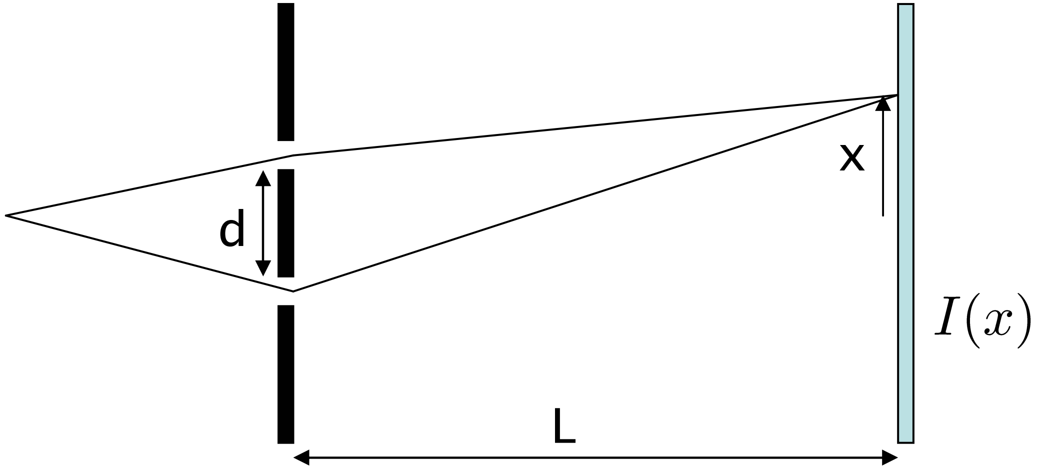
- Interference experiments with double slits or pinholes
- Coincidence experiments



Makina Yabashi

Measurement of Coherence by Interference Experiments

- Diffraction at a double slit:



- Visibility of the interference fringes:

$$\mathcal{V} = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

Experimental Setup

TESLA Test Facility and VUV FEL

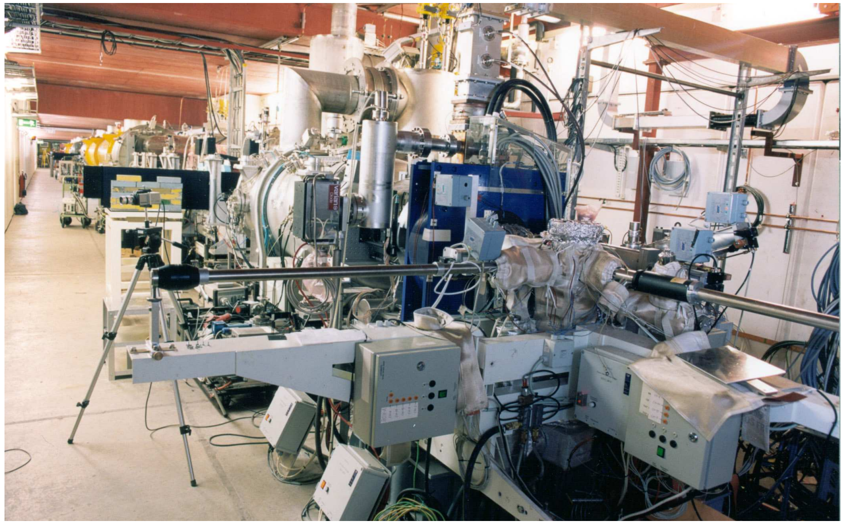
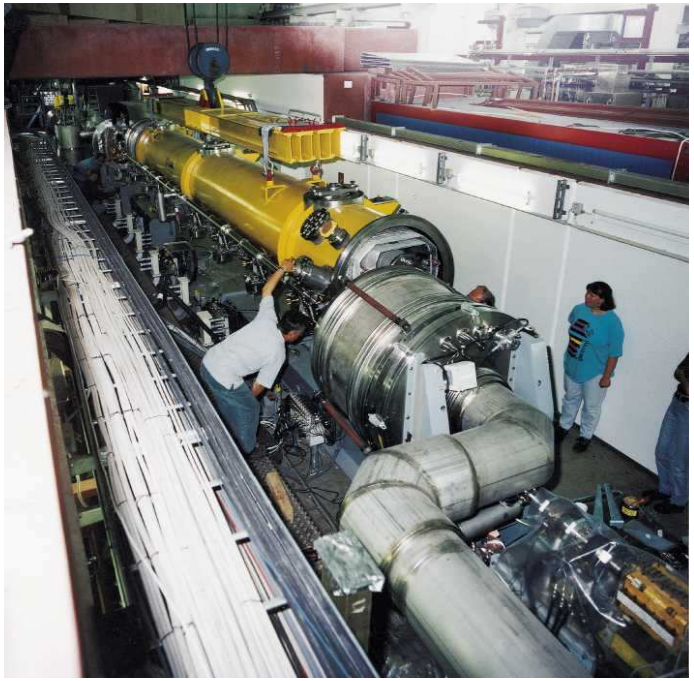


Photo-
Injector



Superconducting
accelerating module

Undulator

Experimental Setup

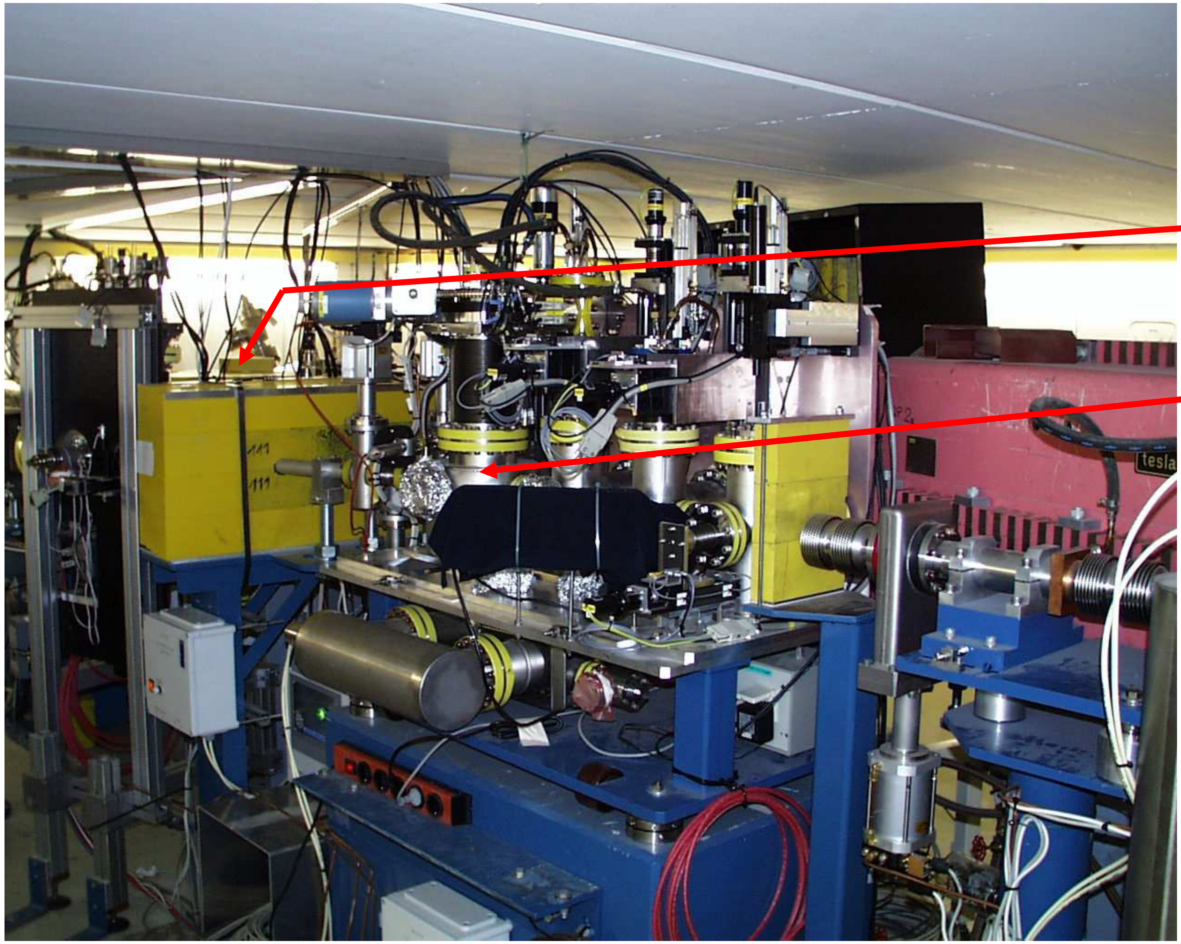
The TTF Free Electron Laser

Considerations for experiments using this radiation:

- Wavelength of 100nm: vacuum ultraviolet (VUV)
  - is absorbed by any material
  - no possibility to extract the beam from the vacuum chamber
  - the complete setup has to be enclosed in the dust-free ultra high vacuum of the accelerator
- High intensity of the FEL:
  - 10…100 µJ in 100fs, that is 1GW on 10mm^2
  - Usage of a two-step detector:
    - Conversion to visible light in a Ce:YAG crystal
    - Diffraction pattern is imaged onto a CCD chip
    - What is the resolution of this detector?
  - Cooling of apertures and fluorescent crystals

Experimental Setup

Photon Diagnostics at the TTF FEL



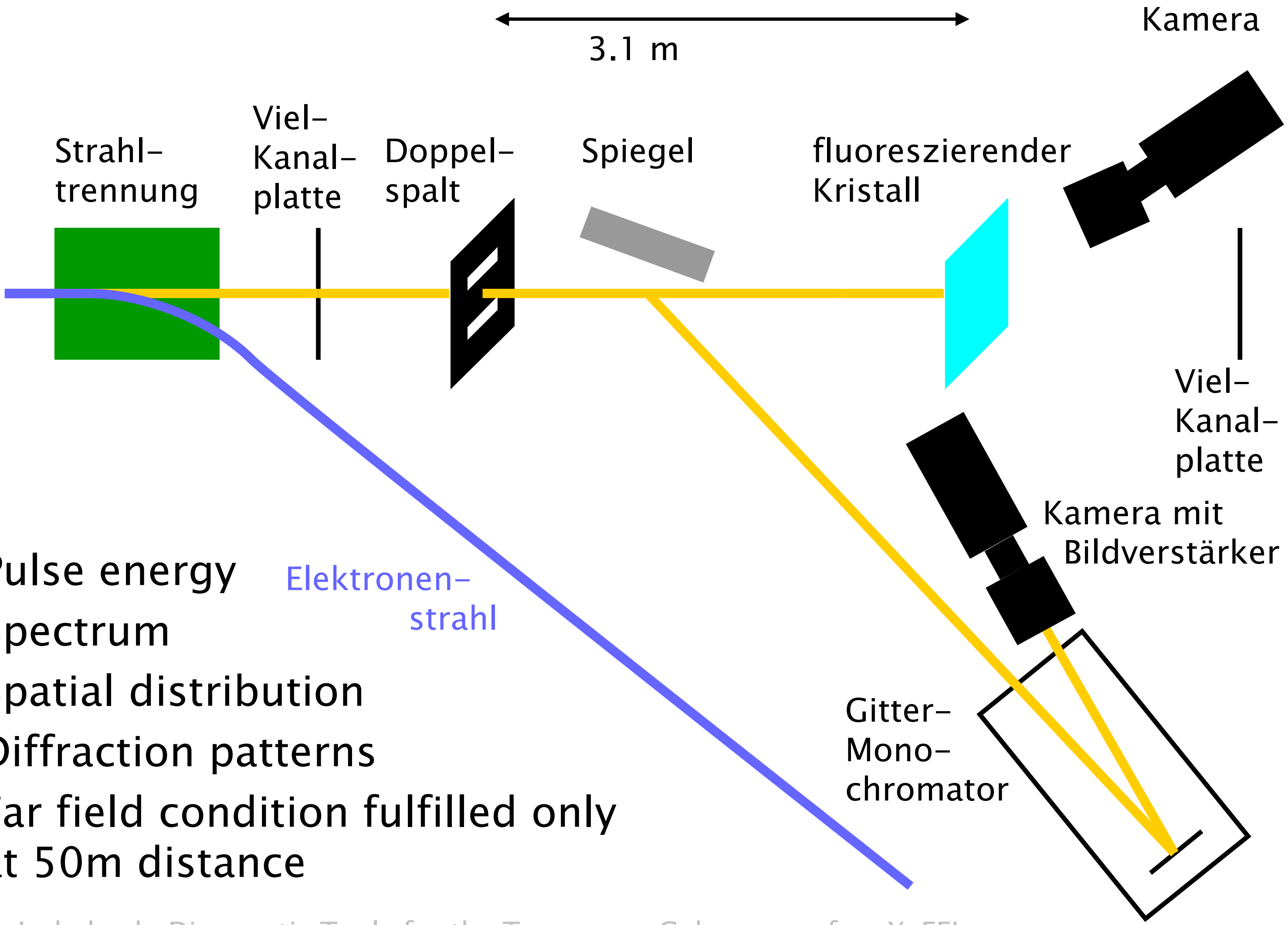
Crystal and camera

Double slit

Photons

Experimental Setup

Photon Diagnostics at the TTF FEL



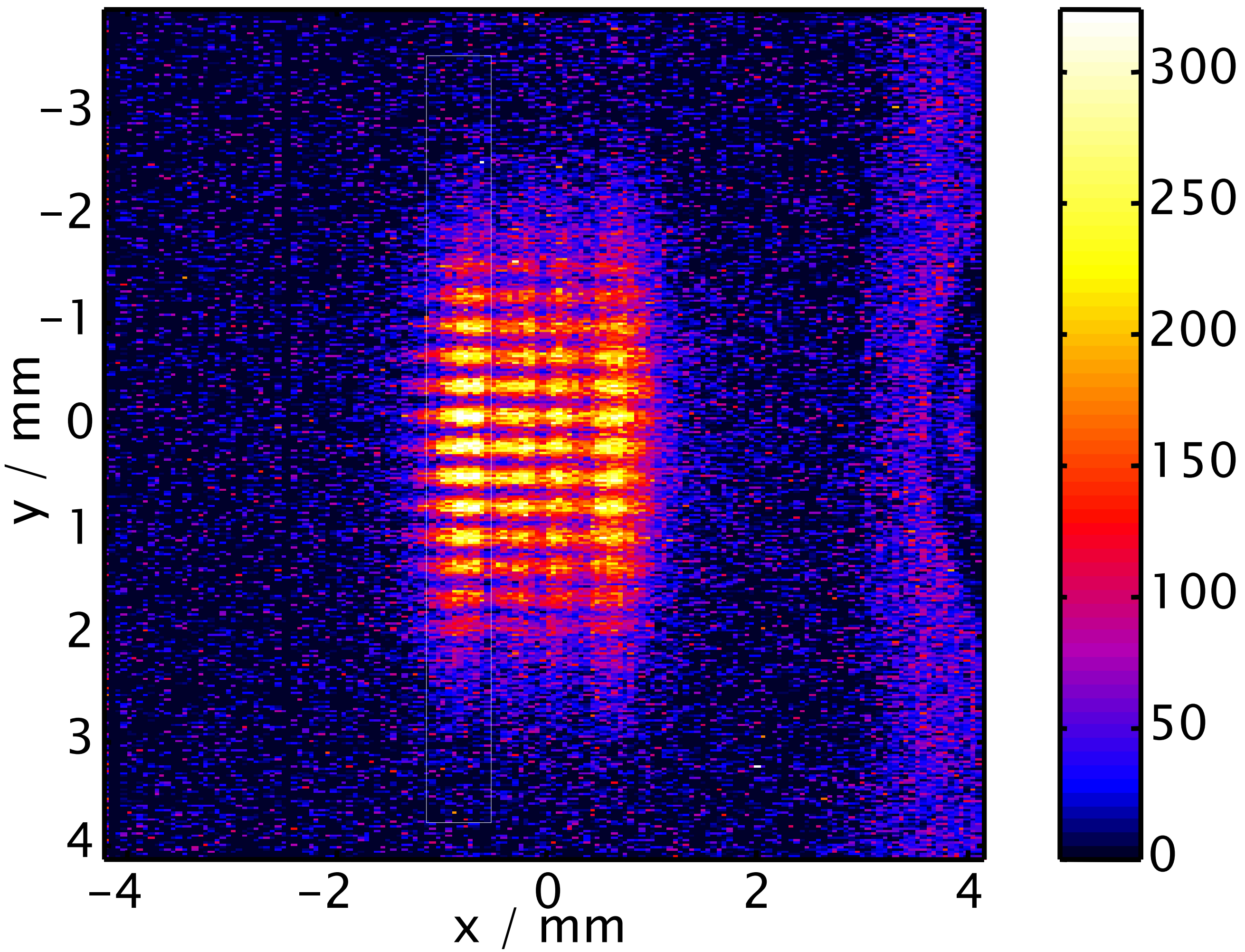
- Pulse energy
- Spectrum
- Spatial distribution
- Diffraction patterns
- Far field condition fulfilled only at 50m distance

Image Processing

Corrected Diffraction Pattern

Corrections:

- Non-linearity
- Resolution



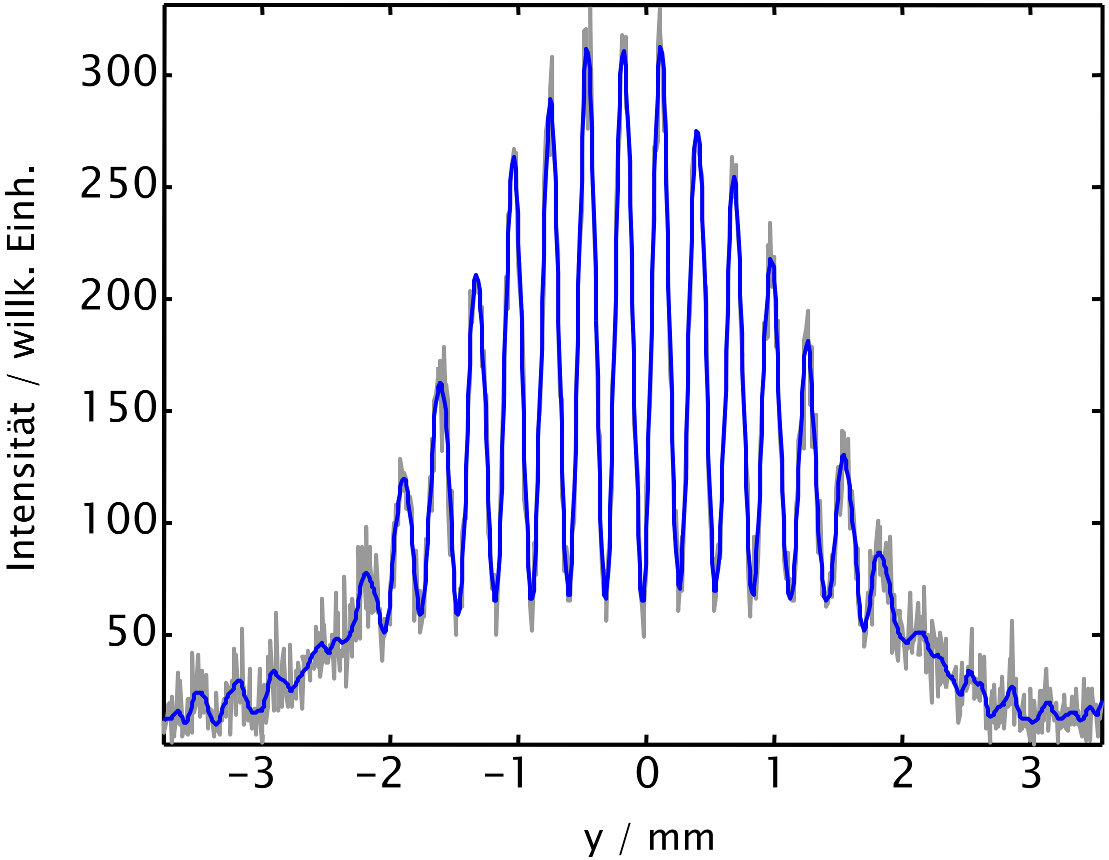
Analysis

- Goal of the analysis: determine the coherence function
- In the far field, with a perfect experimental setup:
  - coherence is equal to the visibility of the interference fringes: $\mathcal{C} = \mathcal{V}$
- Here:
  - near field effects
  - detrimental effects of the setup
- Two analysis methods will be presented:
  1. Visibility of the interference fringes
  2. Fit to the intensity distribution
- Simulation of the effects for comparison
  - Application of the analysis to simulated images

Analysis 1:

Visibility of the Interference Fringes

- Project the selected region of the diffraction pattern
- Smooth the projection with a digital filter
- Find maxima and minima



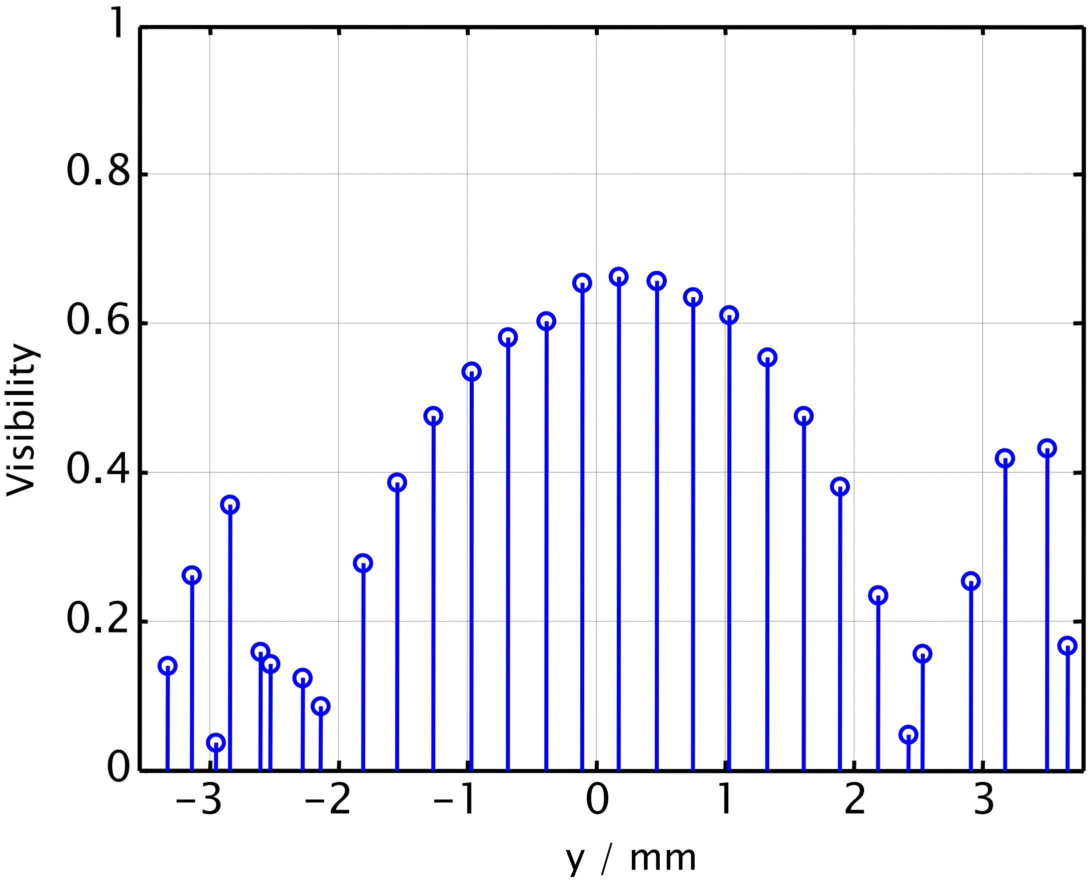
Analysis 1:

Visibility of the Interference Fringes

- Compute the visibility

  $$\mathcal{V} = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

  from the maxima and minima of the curve



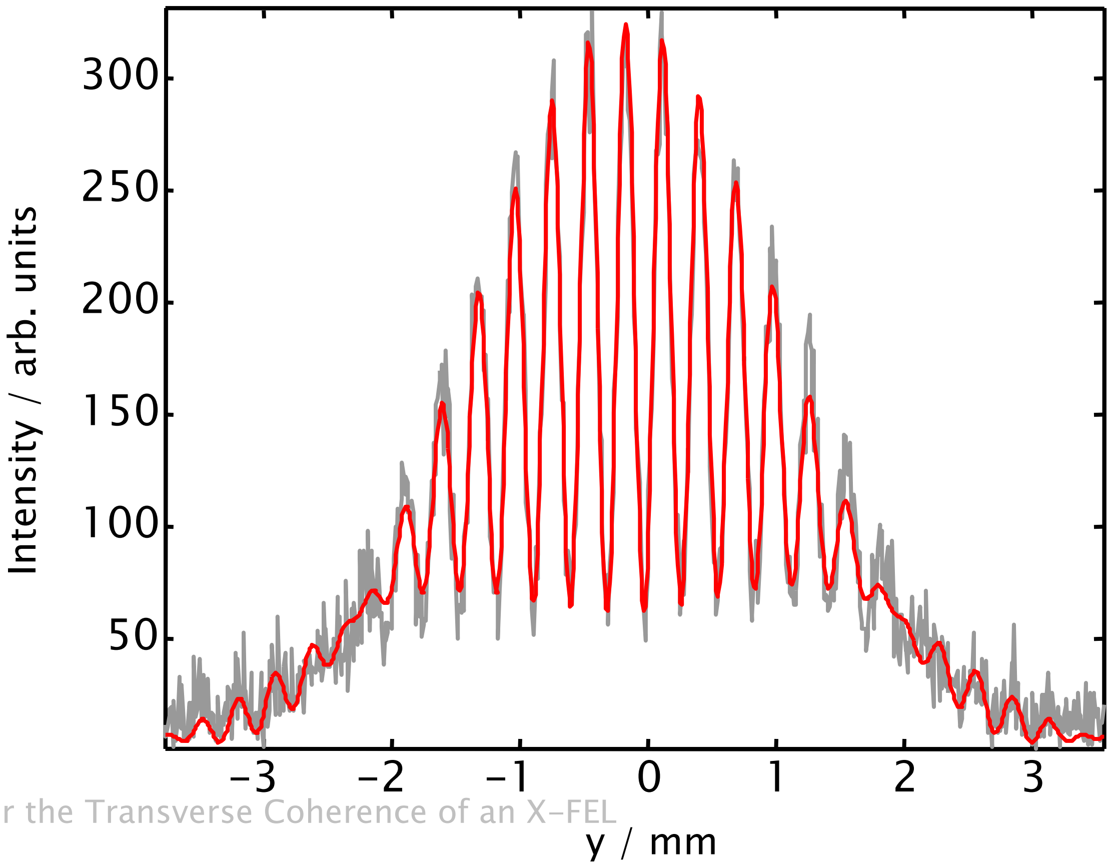
Analysis 2:

Fit to the Intensity Distribution

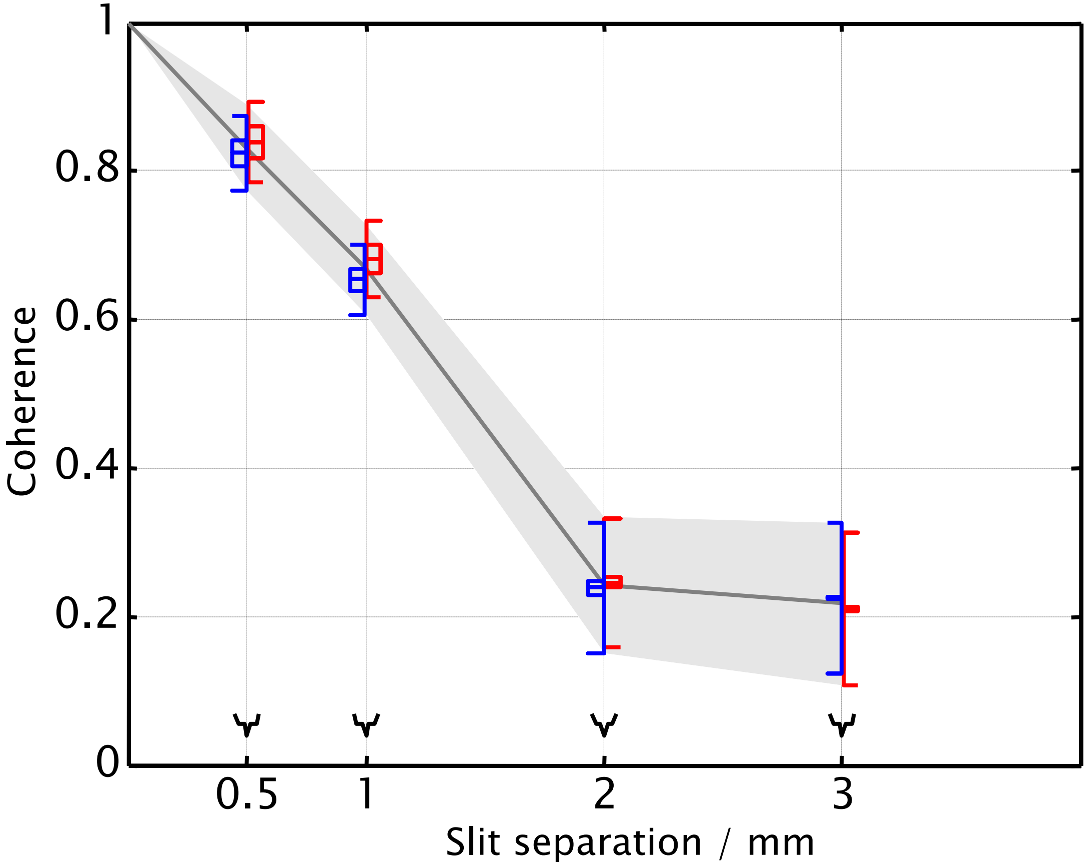
Fit 7 parameters:

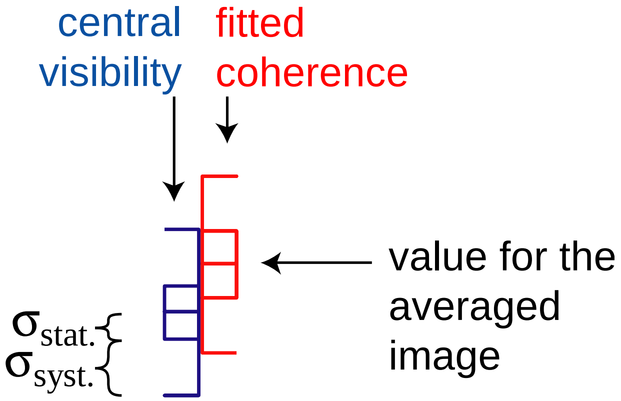
- degree of coherence
- middle
- intensity in front of the left slit
- intensity in front of the right slit
- direction of the wave vector in front of the left slit
- direction of the wave vector in front of the right slit
- wavelength

$$I(x) = \mathcal{S}(x)\left[1 + \mathcal{V}(x)\cos\left(\frac{2\pi d}{\lambda L}x\right)\right]$$



Results of the Measurements: Coherence as a Function of the Separation

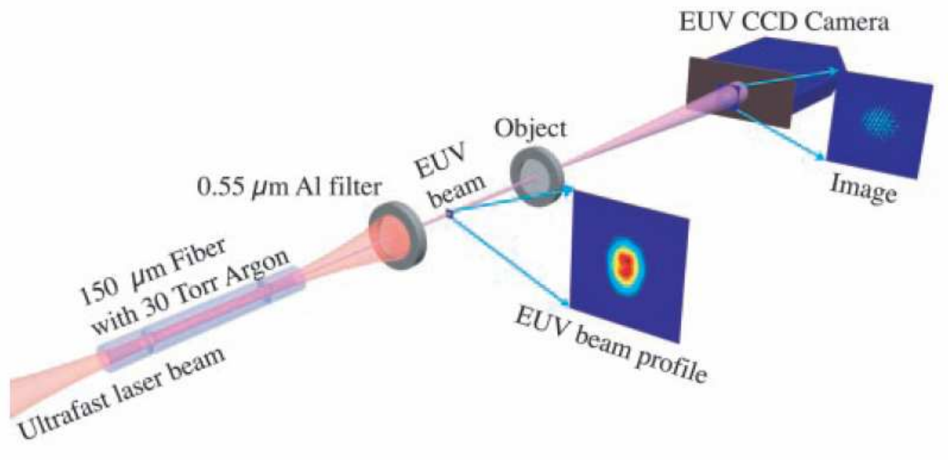


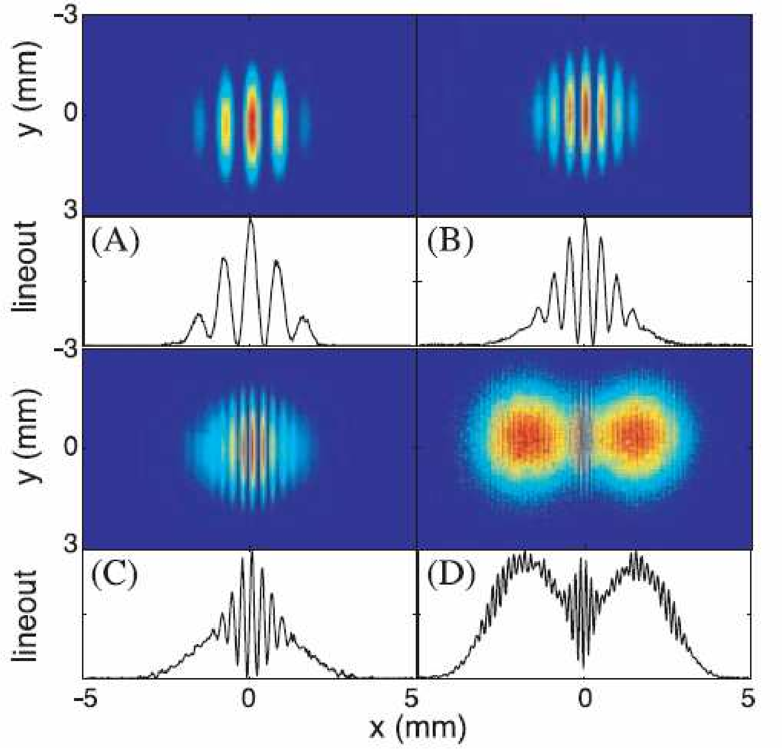


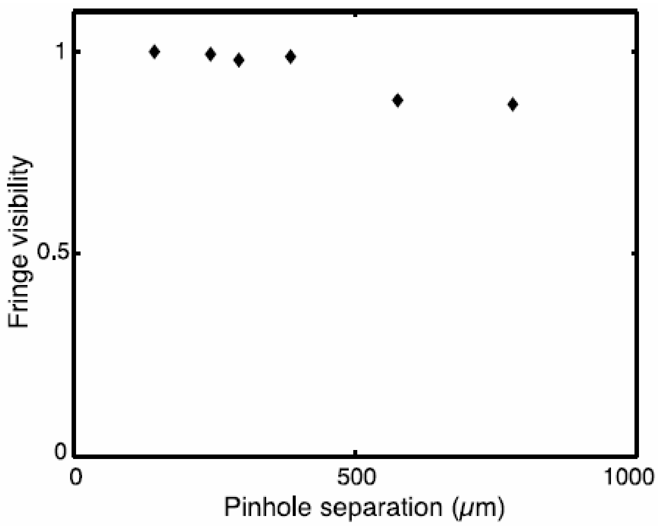
Randy A. Bartels, Ariel Paul, Hans Green, Henry C. Kapteyn, Margaret M. Murnane, Sterling Backus, Ivan P. Christov, Yanwei Liu, David Attwood, and Chris Jacobsen.

Generation of spatially coherent light at extreme ultraviolet wavelengths

Science, 297:376ff., July 2002



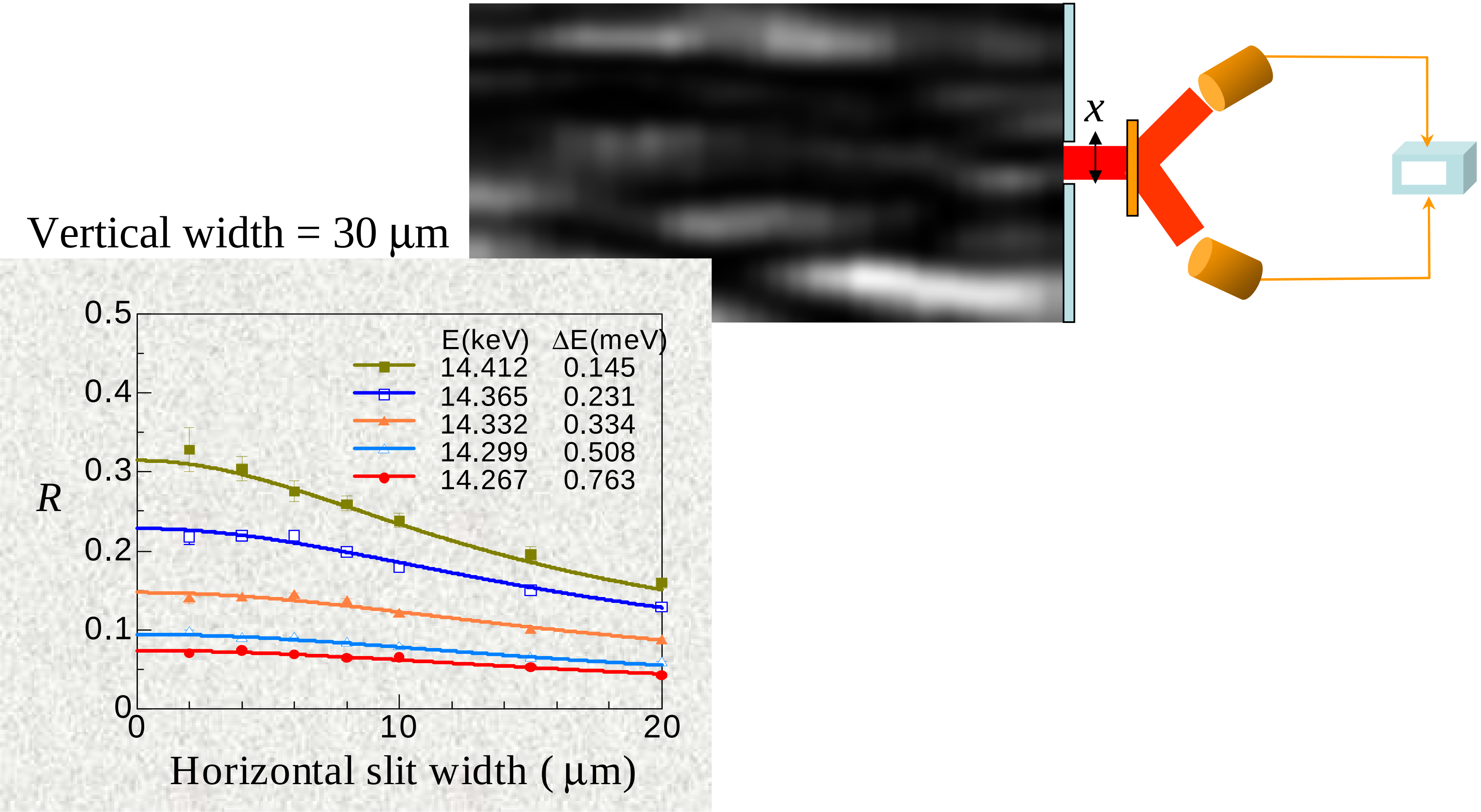




M. Yabashi, K. Tamasaku & T. Ishikawa

Intensity interferometry for the study of x-ray coherence

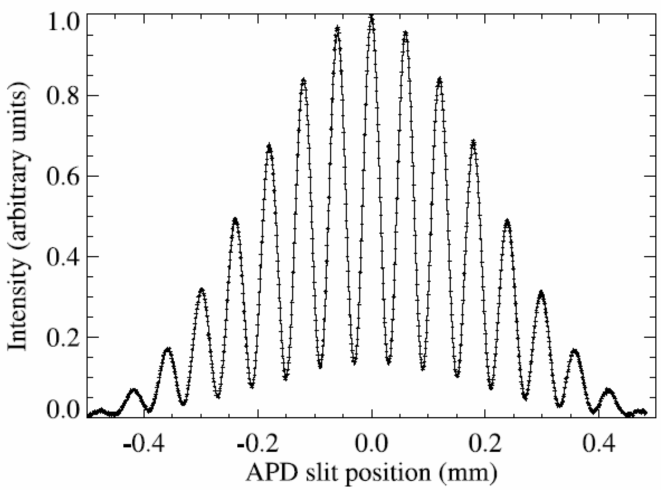
Phys. Rev. Lett. **87**, 140801 (2001); *Phys. Rev.* A **69**, 023813 (2004).

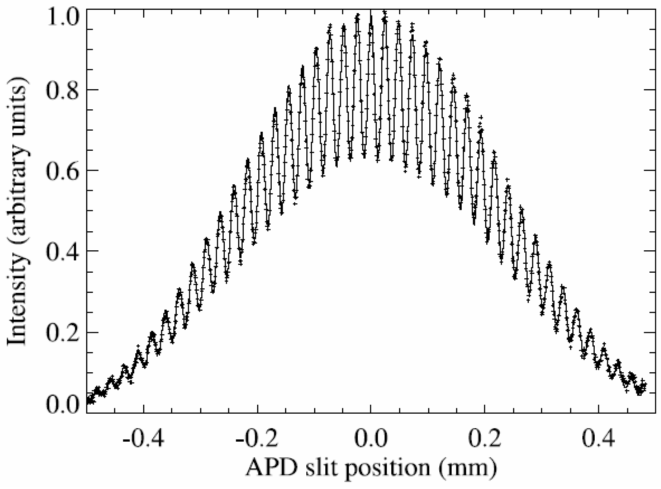


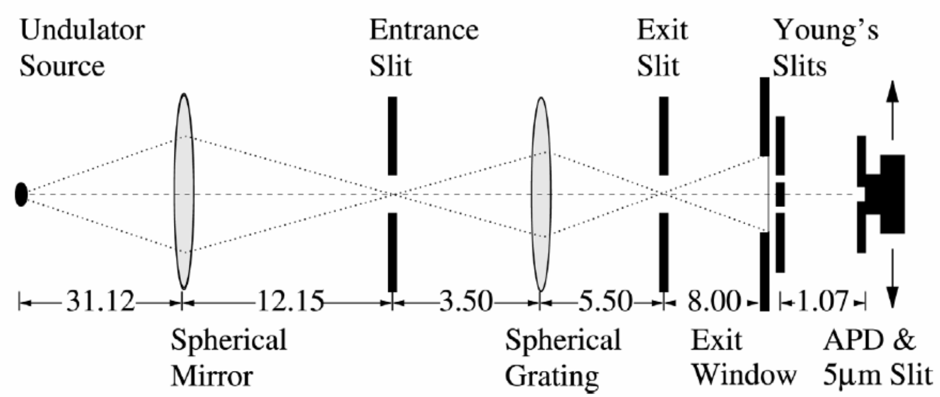
D. Paterson, B.E. Allman, P.J. McMahon, J. Lin, N. Moldovan, K.A. Nugent, I. McNulty, C.T. Chantler, C.C. Retsch, T.H.K. Irving, and D.C. Mancini.

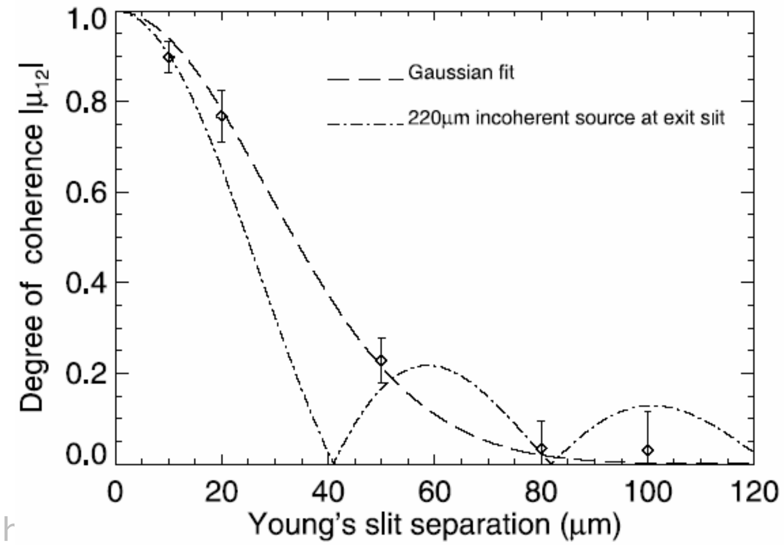
Spatial coherence measurement of X-ray undulator radiation

Optics Communications, 195:79–84, 2001









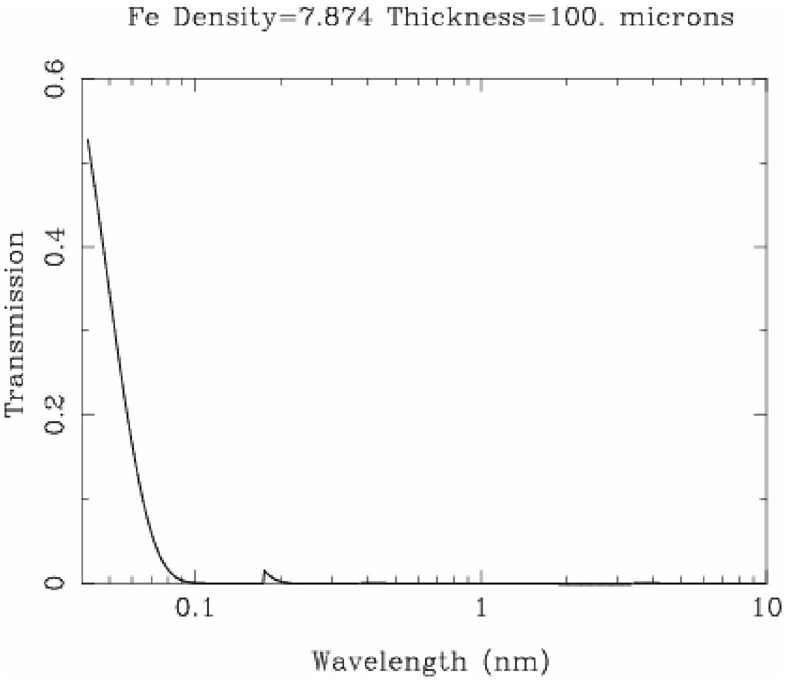
Measurement Concepts for the XFEL

- To measure the coherence for experiments
    - place the pinholes where the experiment would be located
- To measure the coherence in the undulator
    - place the pinholes in the near field of the undulator

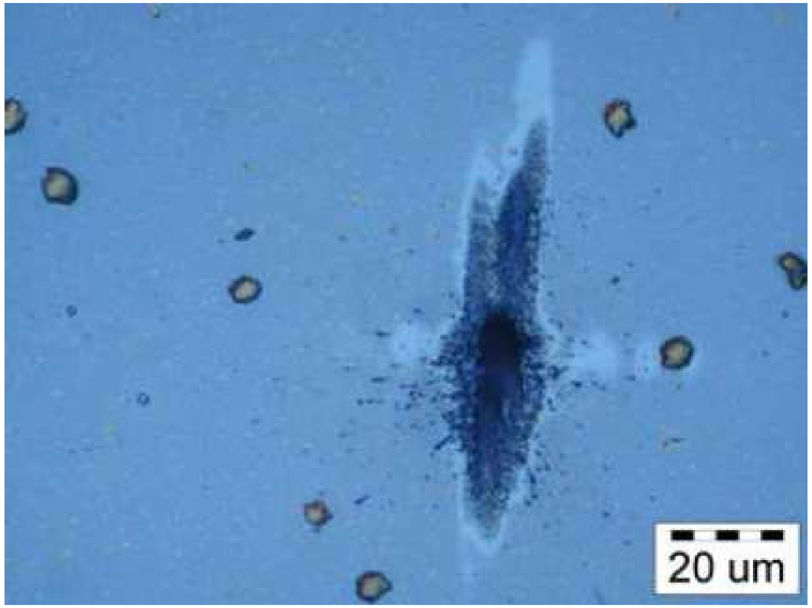
- Optimum position for aperture and detector
- Aperture material
- Detector technology

Aperture

- High absorption for the wavelength
- Withstands the power density of the FEL



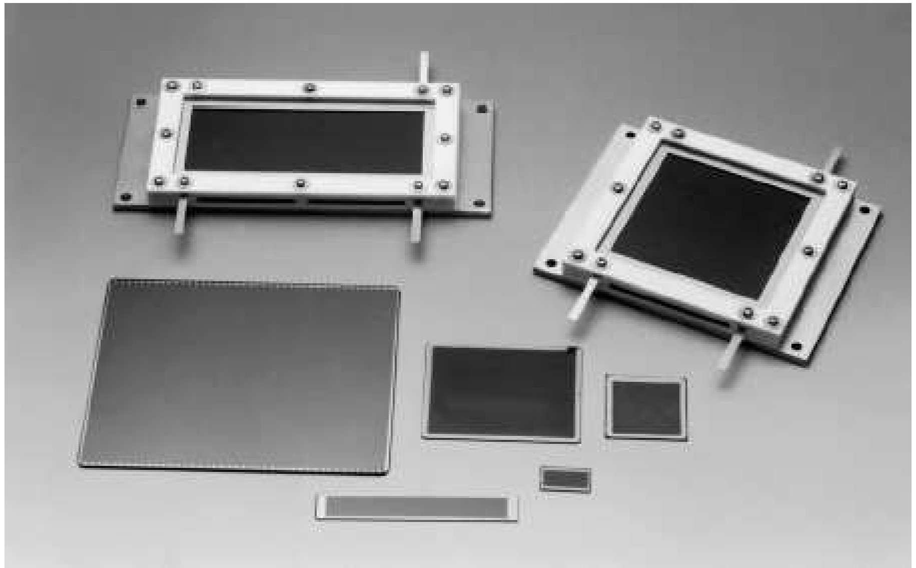
(Eric Gullikson)



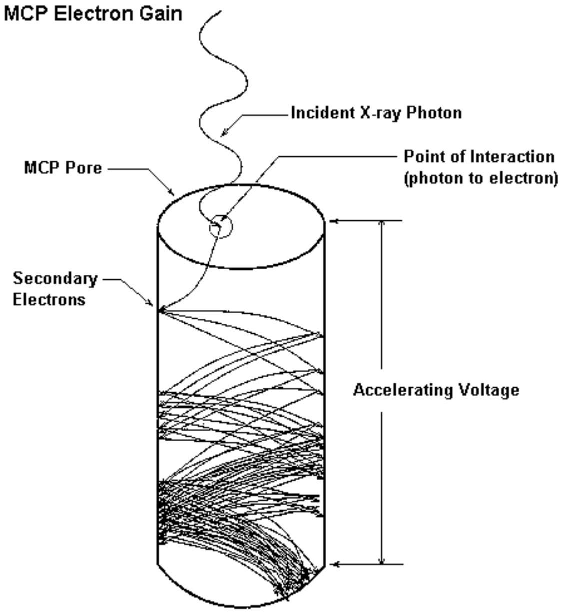
J. Krzywinsky: Ablation of a gold target after one pulse of the TTF FEL at 98nm, pulse duration 40fs, peak power density 10^{18} W/m^2

Detector

- High dynamic range needed to cover the range from spontaneous radiation to saturated FEL
- Amplification in a microchannel plate (MCP) can be varied by several orders of magnitude by changing the voltage



(Hamamatsu)



(Martin V. Zombeck)

Summary

- Measurement of coherence is of importance for
  - experiments using the FEL radiation
  - diagnostics of the FEL process
- Coherence of an X-FEL is expected to be
  - higher than 3rd-generation synchrotron sources
  - lower than FELs in the UV region
- Coherence of the TTF FEL has been measured using interferometry

Many thanks to…