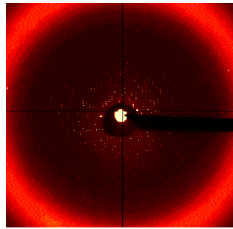


Transverse Coherence of a Vacuum Ultraviolet Free Electron Laser

Rasmus Ischebeck

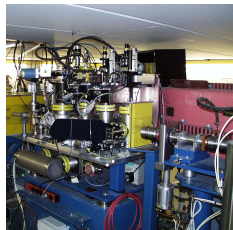
March 16, 2004

Transverse Coherence of a VUV Free Electron Laser



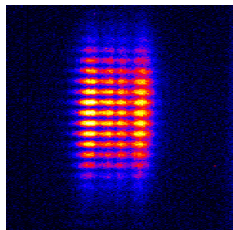
Introduction

- Relevance of Coherence
- Definition and Measurements



Measurements at the TTF FEL

- Challenges for the Measurements
- Experimental Setup



Results

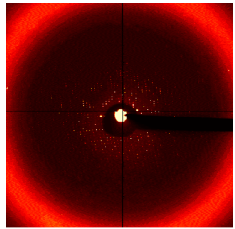
- Coherence as a function of the slit separation
- Development along the undulator



Outlook

- Phase 2 of the TTF FEL

Transverse Coherence of a VUV Free Electron Laser



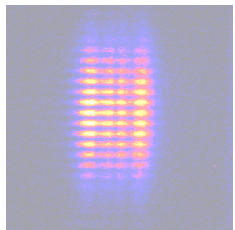
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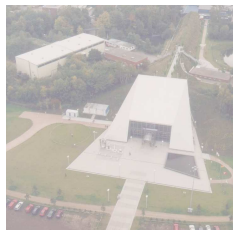
Measurements at the TTF FEL

- Challenges for the Measurements
- Experimental Setup



Results

- Coherence as a function of the slit separation
- Development along the undulator

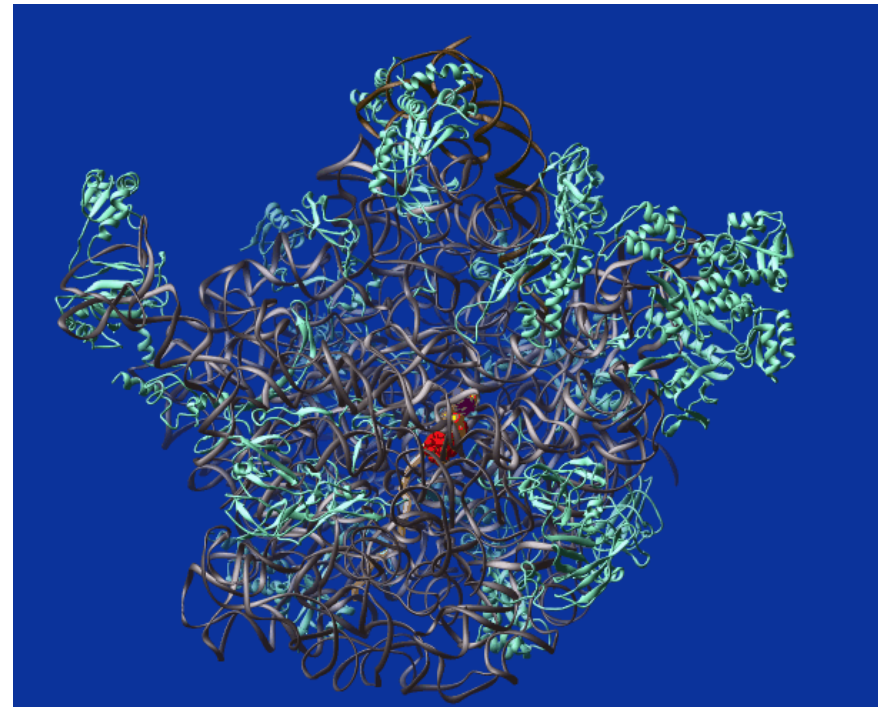
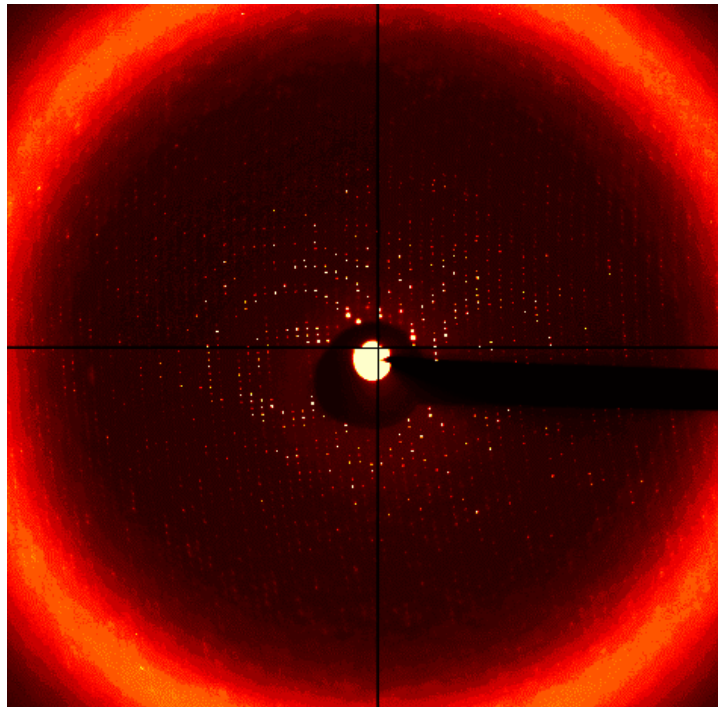


Outlook

- Phase 2 of the TTF FEL

Relevance of Coherence for Crystallography

- Diffraction pattern of a crystal \rightsquigarrow Structure of the molecule
here: Ribosome



Pictures: Jörg Harms, Arbeitsgruppe für Ribosomenstruktur, Max-Planck-Gesellschaft

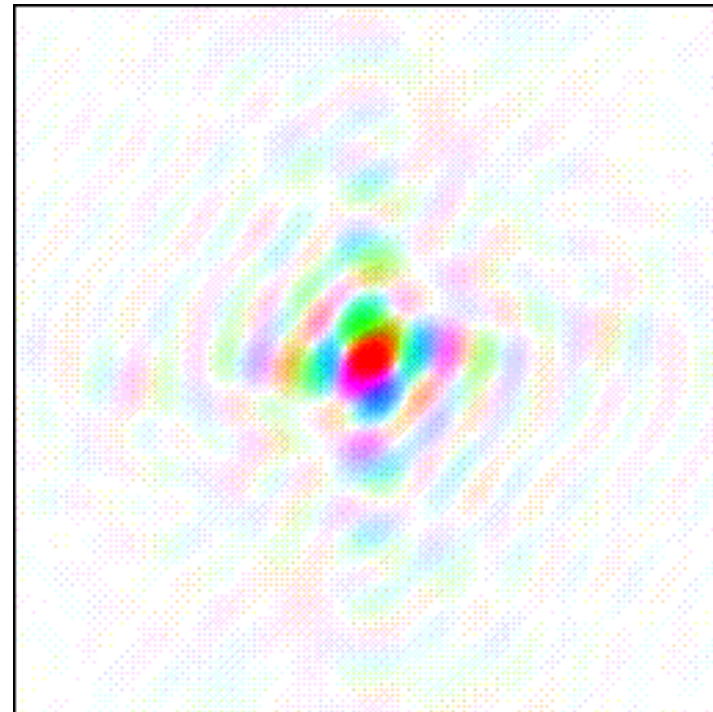
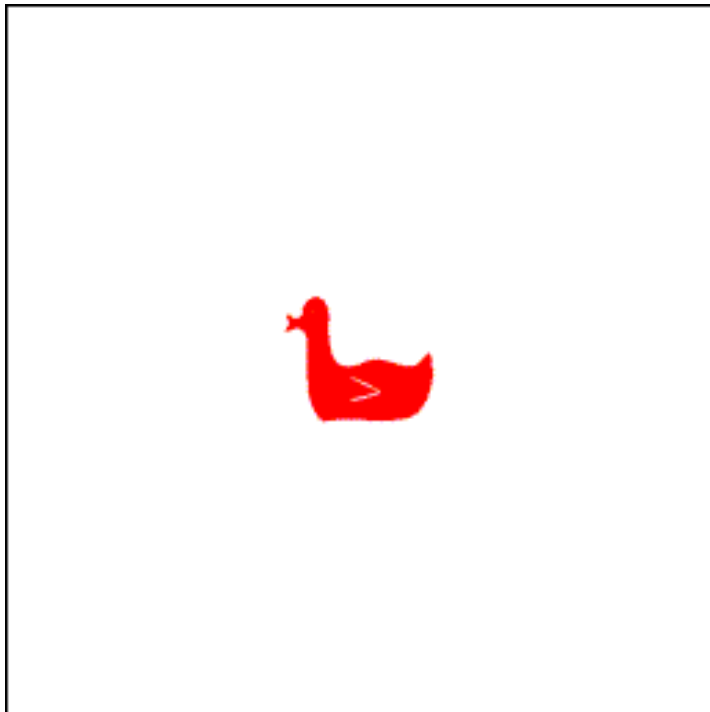
- Problem: Phase of the diffraction pattern is unknown

Relevance of Coherence

Diffraction Pattern of a Duck

- A (two-dimensional) duck

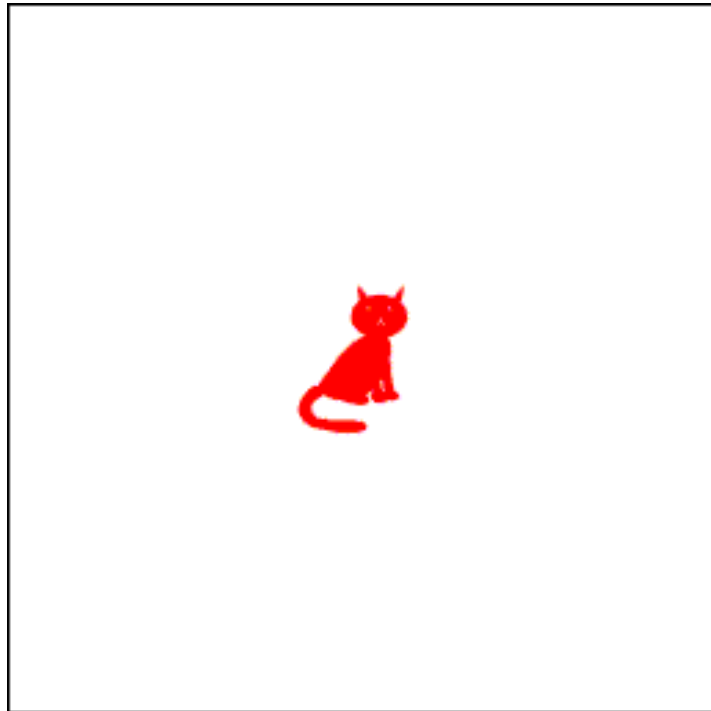
... creates this diffraction pattern
(the colors encode the phase)



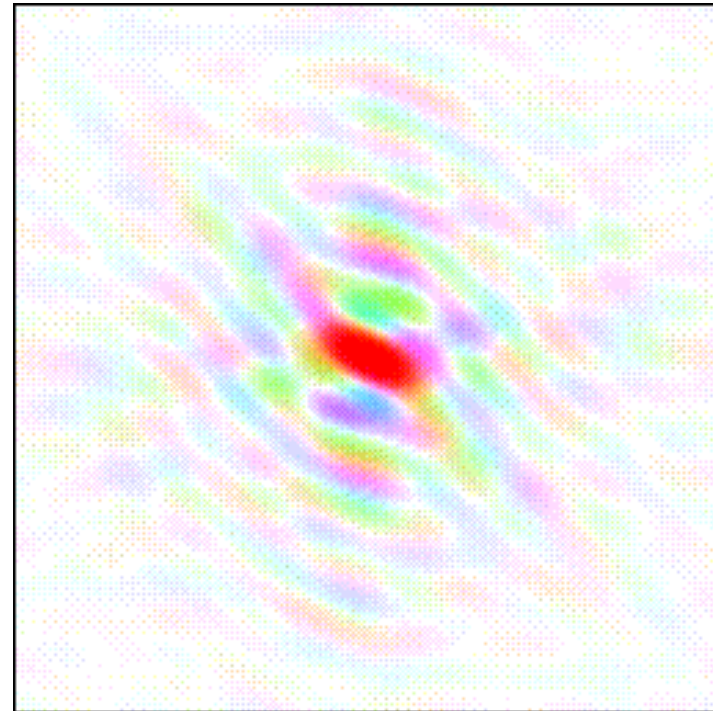
Relevance of Coherence

Diffraction Pattern of a Cat

- A cat



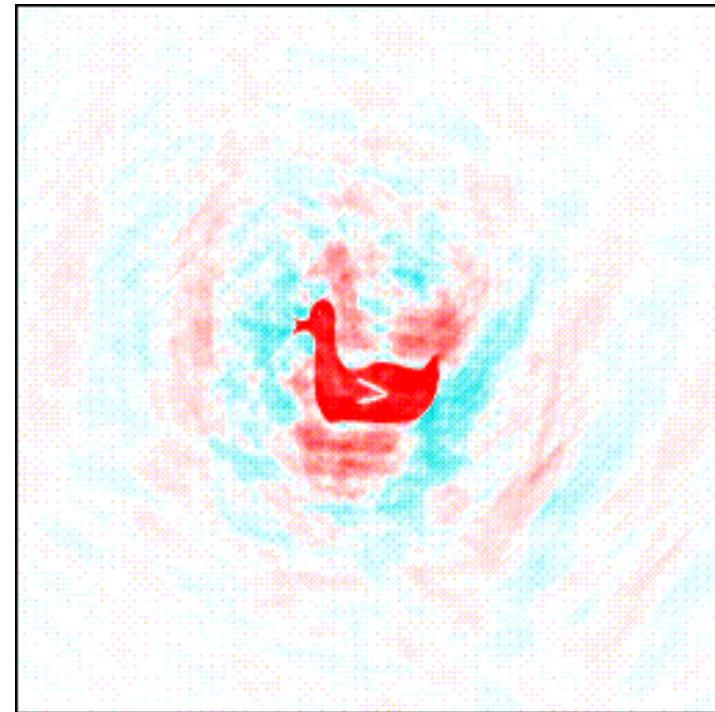
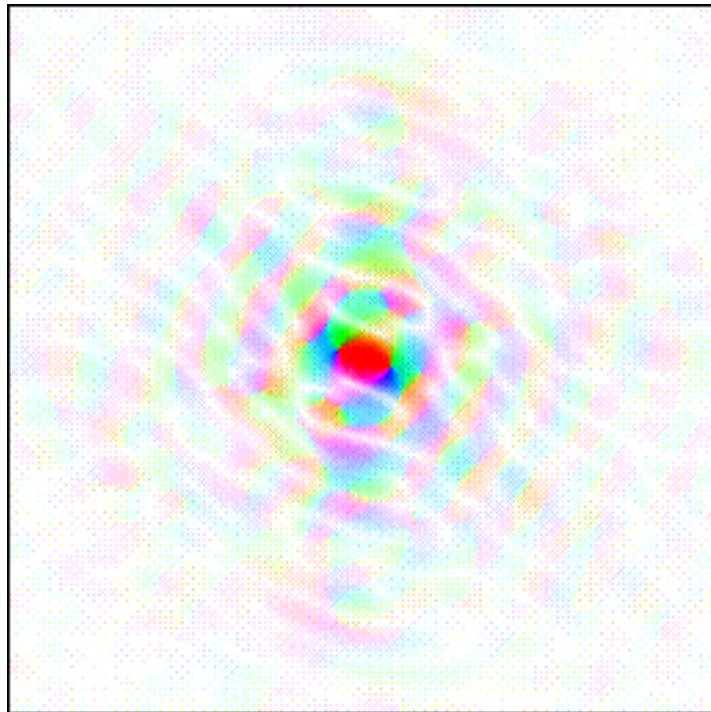
... and its diffraction pattern



Relevance of Coherence

Reconstruction

- Combine the amplitude of the diffraction pattern of the cat
- and the phase of the diffraction pattern of the duck

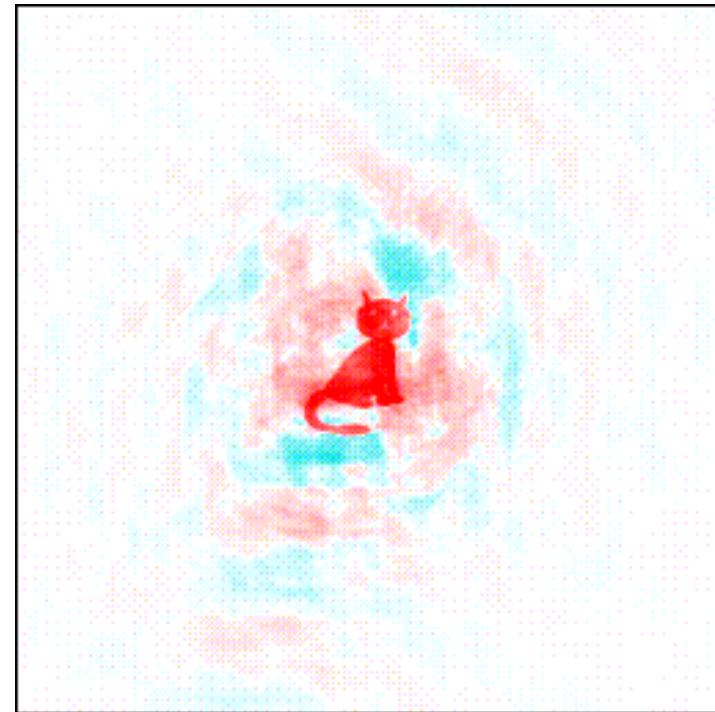
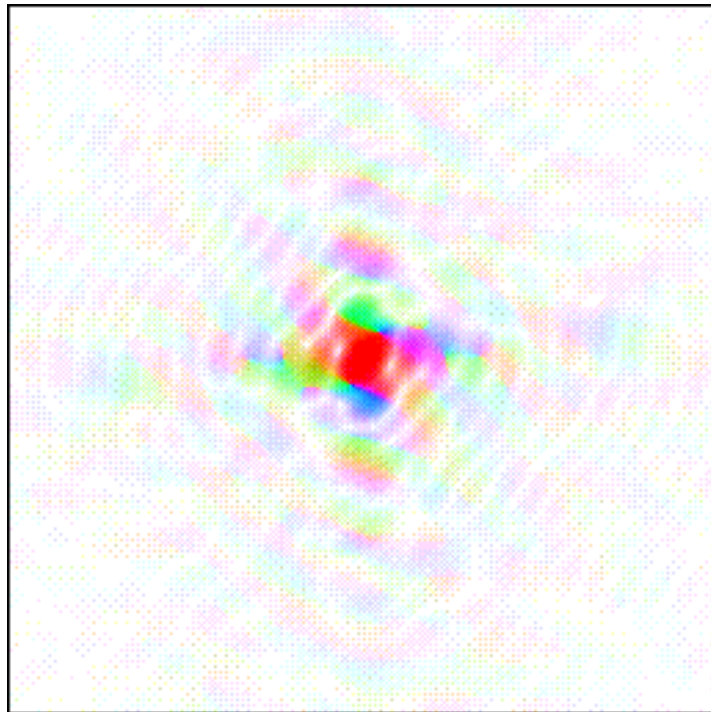


The result: a duck!

Relevance of Coherence

Reconstruction

- Of course, one can also do the opposite trick:
- combine the amplitude of the duck and the phase of the cat

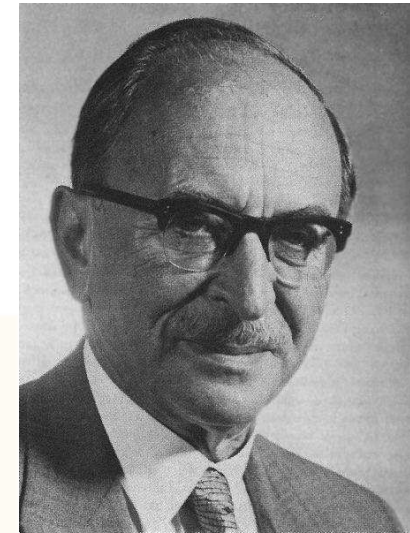
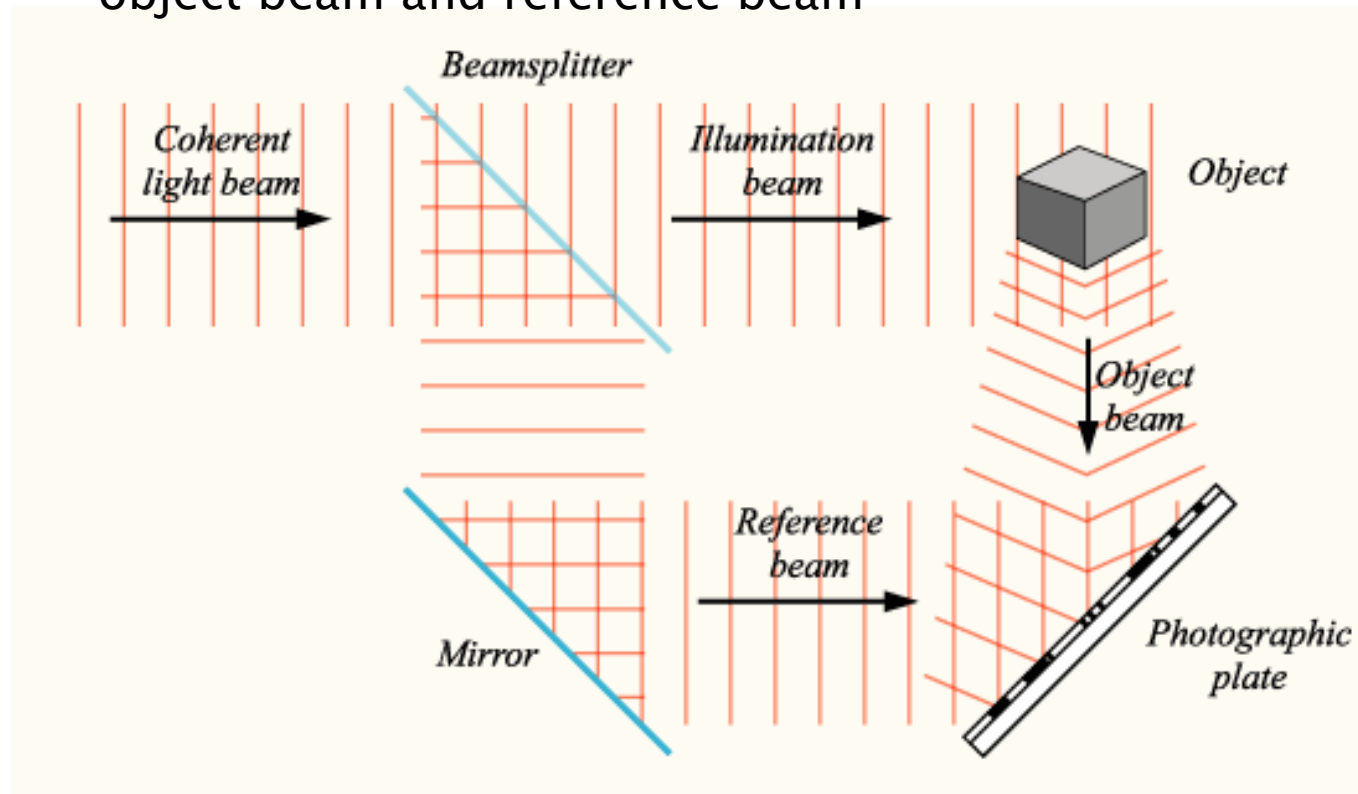


This is the famous **Phase Problem**

Phase Problem

A Possible Solution: Holography

- Record the interference between object beam and reference beam



Dennis Gabor

- Necessary prerequisite: coherence of the incoming wave

Definition of Coherence Properties

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

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

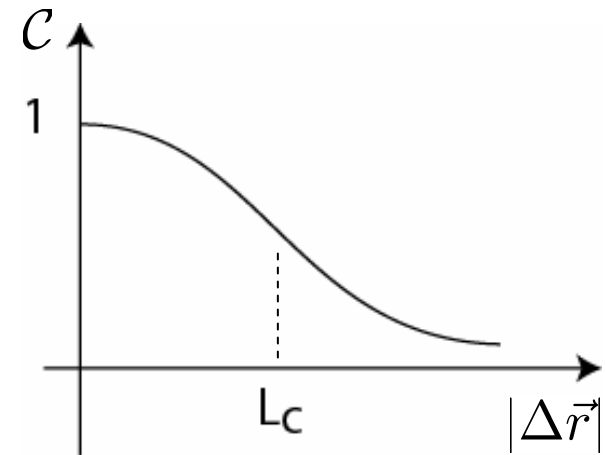
- Correlation function

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

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

- Coherence function

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



Coherence of Free Electron Lasers

- Decomposition of the radiation in its transverse modes

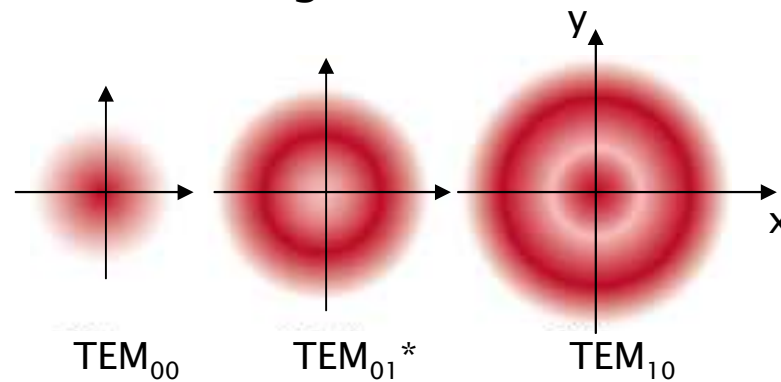
$$\tilde{E}(r, \vartheta, z) = \sum_{n,m} C_{nm}(z) \tilde{A}_{nm}(r, \vartheta)$$

- Development of the modes in the undulator

$$C_{nm}(z) = \exp\left(\frac{\Lambda_{nm}}{2} z\right)$$

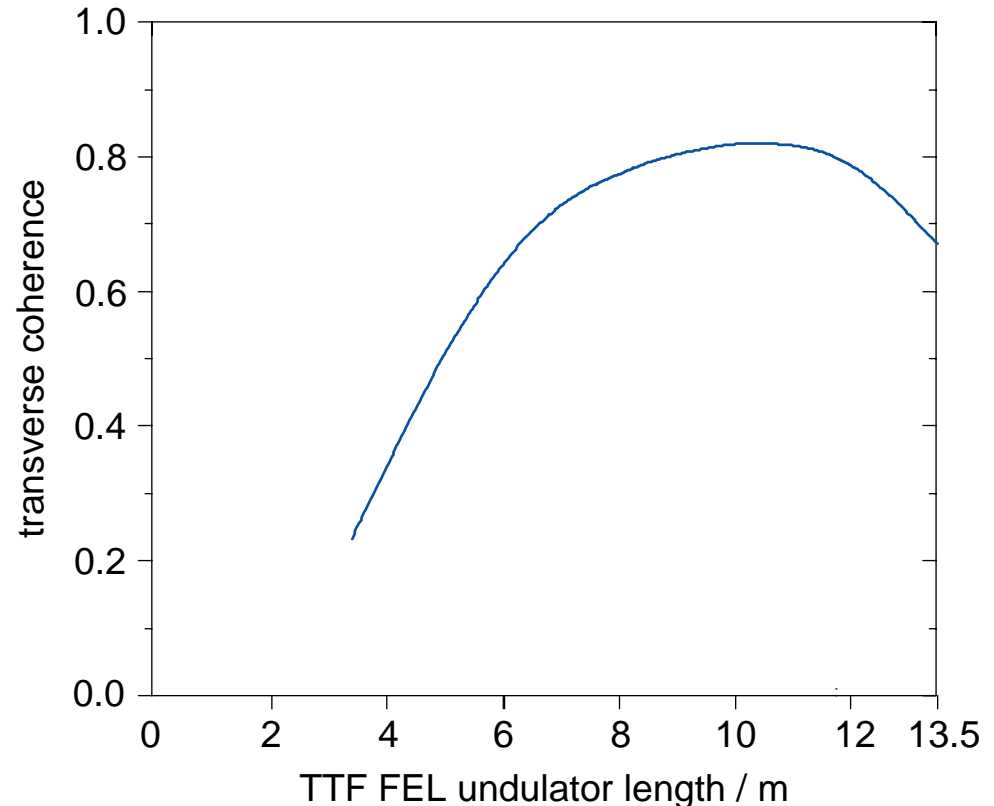
- TEM modes (transverse electric and magnetic field)

- Cross section of the first Gauß-Laguerre modes:



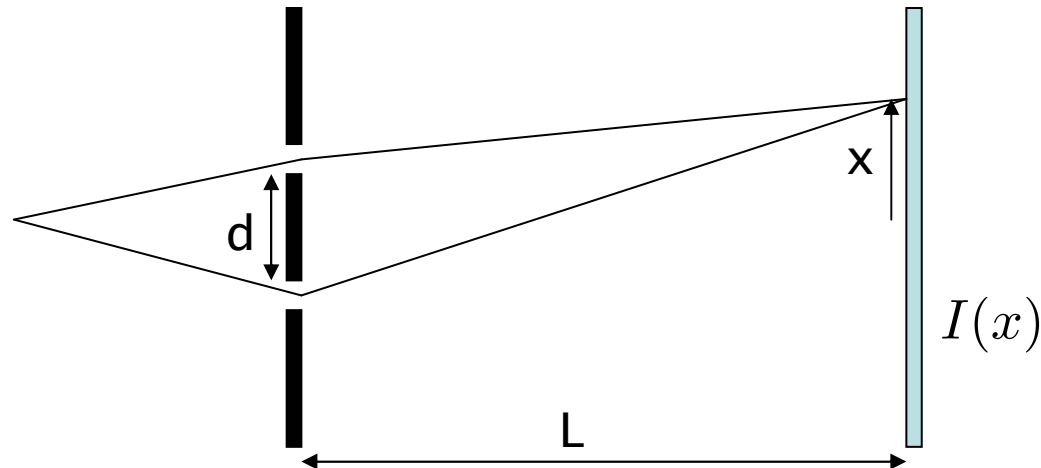
Development of the Coherence in a FEL

- Central mode TEM_{00} (Gaussian) has the best overlap with the electron beam
 - ↳ fastest growth
 - ↳ increase of coherence
- Saturation in the last part of the undulator
 - ↳ other modes gain importance
 - ↳ decrease of coherence



Measurement of Coherence by Interference Experiments

- Diffraction at a double slit:



- Visibility of the interference fringes:

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



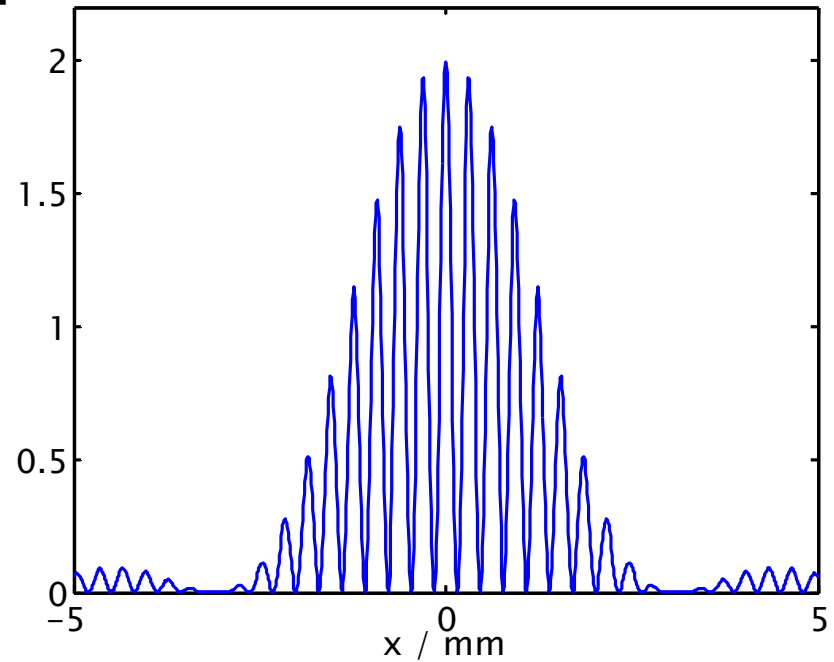
Thomas Young M.D.
F.R.S.

Fraunhofer diffraction at the double slit

- Far field condition

$$L \gg \frac{\pi d^2}{\lambda}$$

- Diffraction at double slits with separation d and width w



$$I(x) = I_0 \left(\frac{\sin(\pi w x / (\lambda L))}{\pi w x / (\lambda L)} \right)^2 \left[1 + \cos \left(2\pi \frac{d}{\lambda L} x \right) \right]$$

Fraunhofer diffraction with partially coherent light

- Let \mathcal{C} be the value of the coherence function between the two slits

$$I(x) = I_0 \left(\frac{\sin(\pi wx/(\lambda L))}{\pi wx/(\lambda L)} \right)^2 \left[1 + \mathcal{C} \cos \left(2\pi \frac{d}{\lambda L} x \right) \right]$$

- One can calculate the following visibility of the interference fringes

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

Fresnel diffraction at the double slits

- The diffraction pattern is modulated with the total amplitude \mathcal{S} :

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



Augustin Jean Fresnel

- This is the sum of the intensities of the single slit diffraction patterns

$$\mathcal{S}(x) = I_1(x) + I_2(x)$$

with

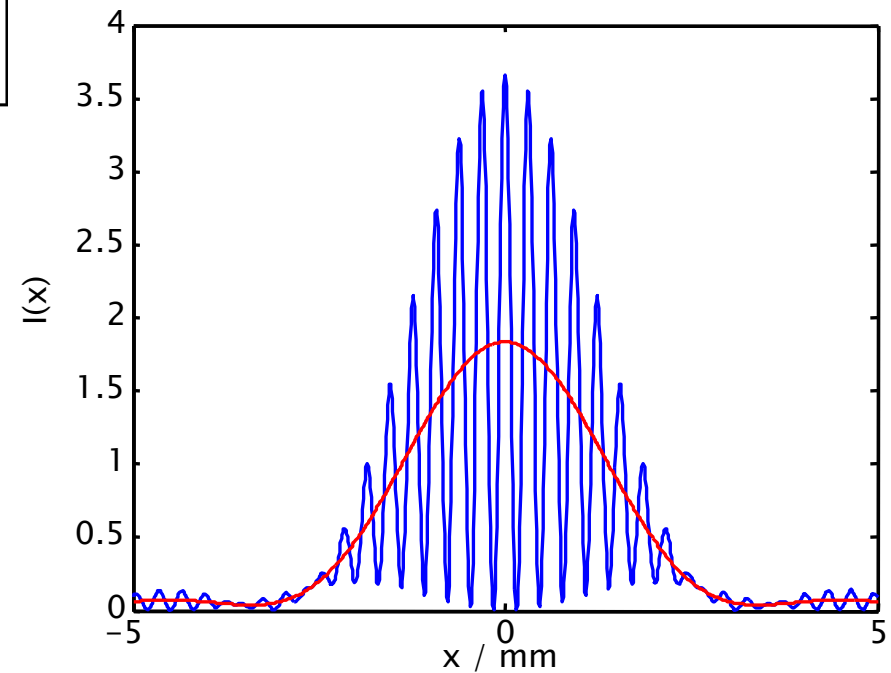
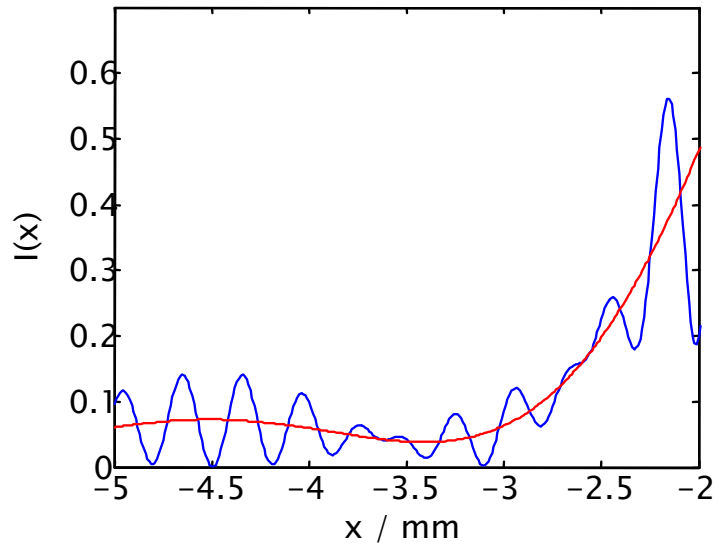
$$I_{1,2}(x) = \left(\frac{\sin(\pi w(x \pm d/2)/(\lambda L))}{\pi w(x \pm d/2)/(\lambda L)} \right)^2$$

- The visibility $\mathcal{V}(x)$ is now a function of x

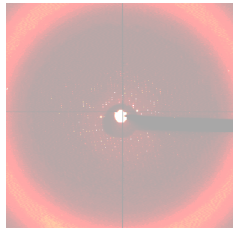
Fresnel diffraction at the double slit

- Interference pattern

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



Transverse Coherence of a VUV Free Electron Laser



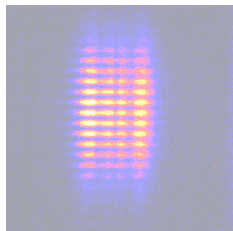
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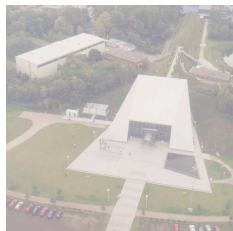
Measurements at the TTF FEL

- Challenges for the Measurements
- Experimental Setup



Results

- Coherence as a function of the slit separation
- Development along the undulator

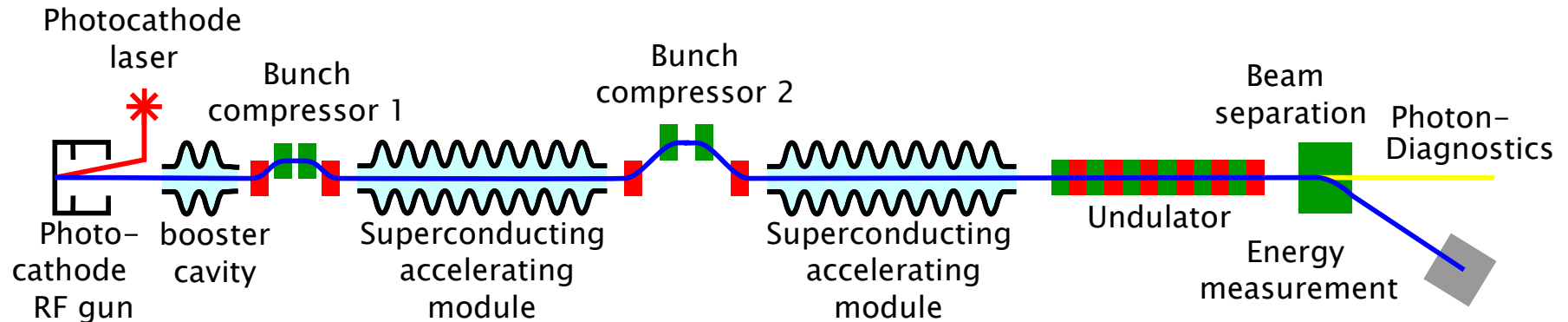


Outlook

- Phase 2 of the TTF FEL

Experimental Setup

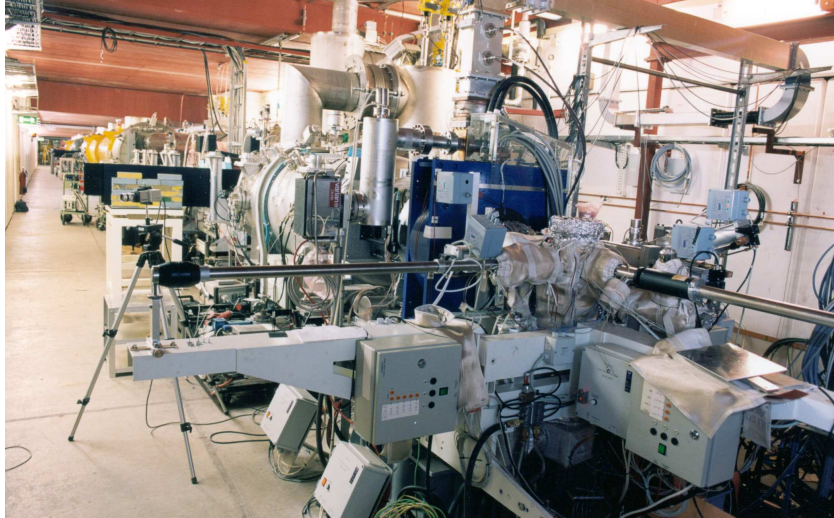
TESLA Test Facility and VUV FEL



- Length: 120m
- Electron energy: 260MeV
- Peak current: 1kA
- Transverse emittance in the undulator: $8 \pi \mu\text{m}$
- Wavelength of the FEL: 100nm
- Peak power of the FEL: 1GW
- Pulse energy: 10...100 μJ
- Brilliance of the FEL: $4 \cdot 10^{28}$ photons / (s mm² mrad² 0.1% bandwidth)

Experimental Setup

TESLA Test Facility and VUV FEL



Injector



Superconducting
accelerating module



Undulator

Experimental Setup

The TTF Free Electron Laser

Differences to conventional lasers:

- Large fluctuations in the intensity and wavelength because of
 - the stochastic nature of the radiation
 - instabilities of the electron beam
- There is no optical resonator which limits the radiation to the central mode
 - transverse coherence only within the modes
- Radiation is emitted in a single passage of the ultra-relativistic electron bunch
 - limited longitudinal coherence

Experimental Setup

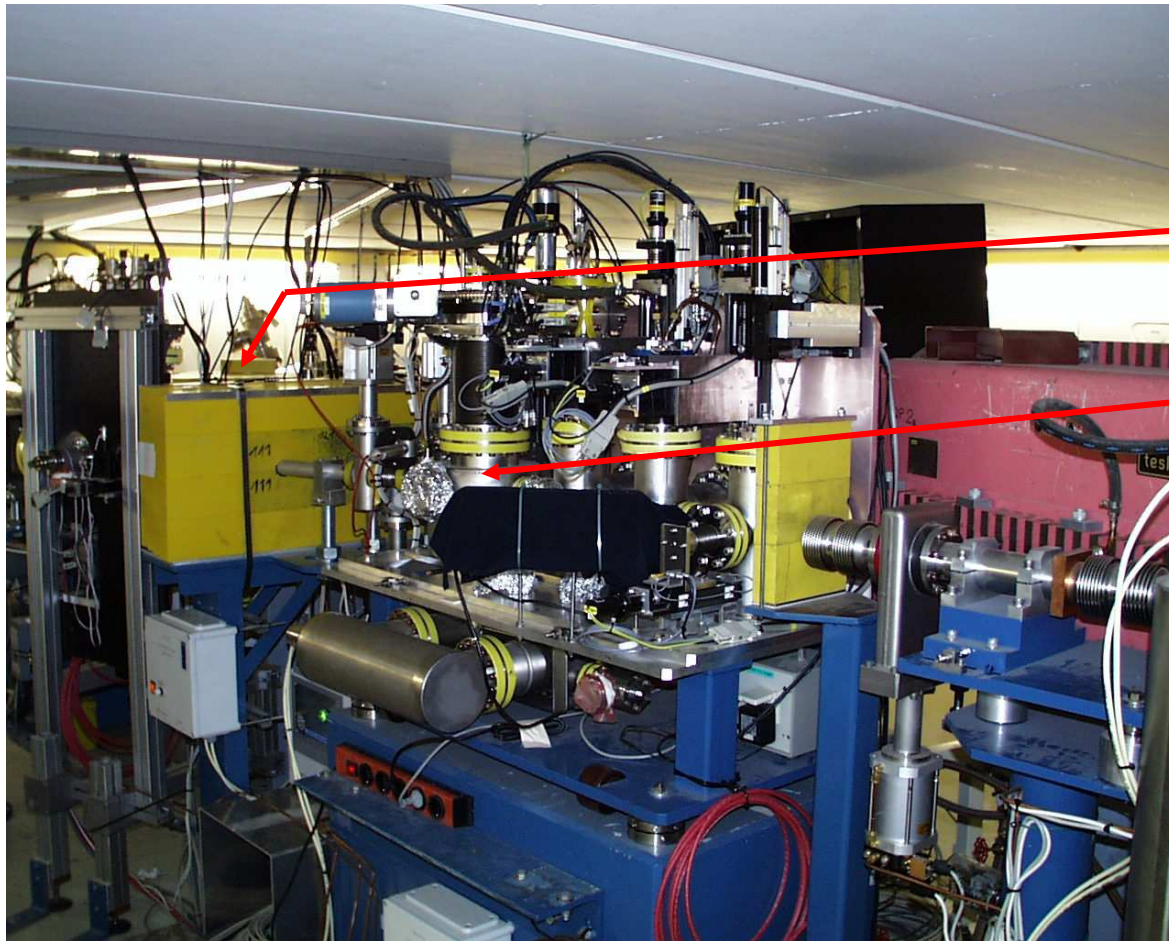
The TTF Free Electron Laser

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 10mm²
 - 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



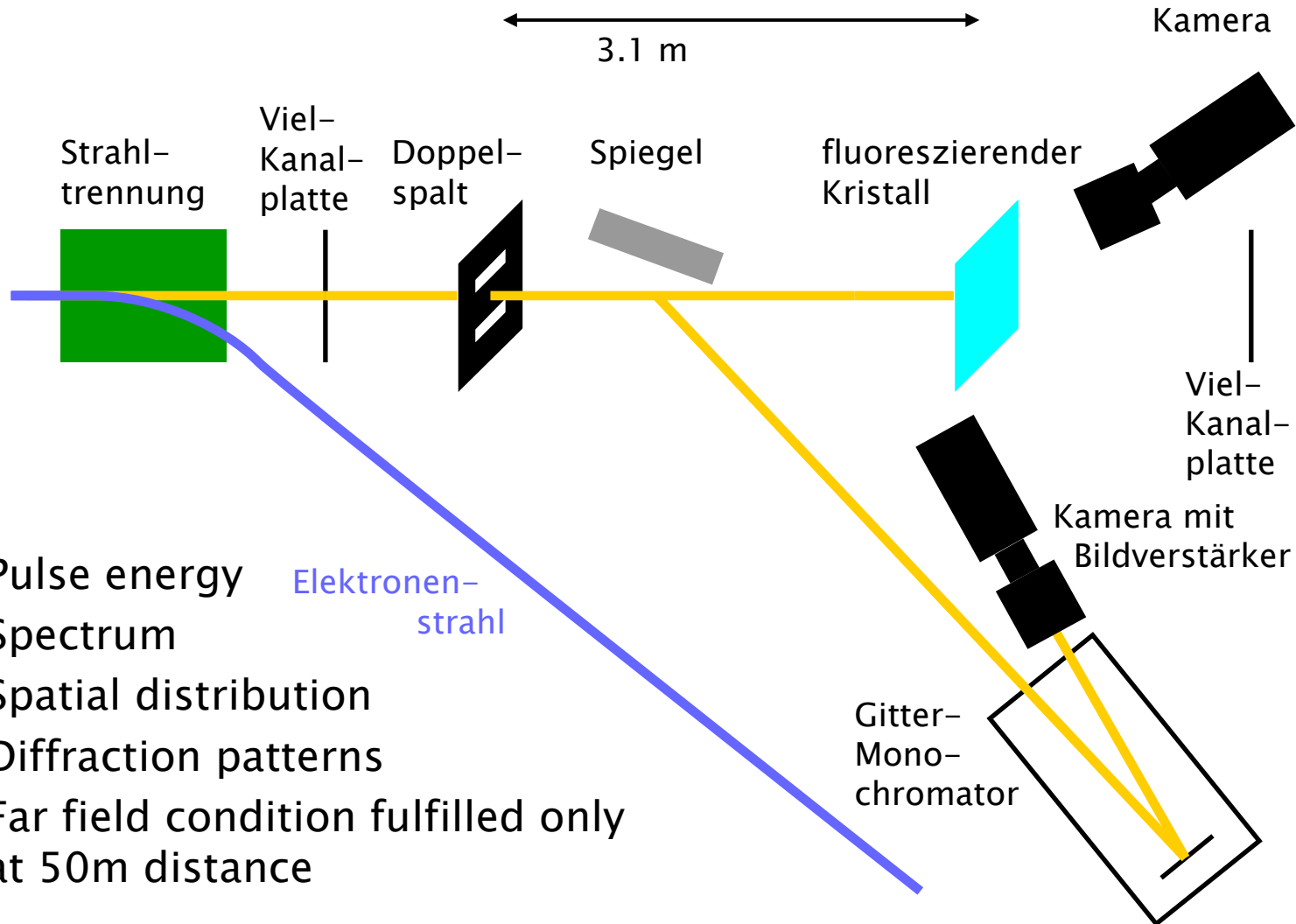
Crystal and camera

Double slit

Photons

Experimental Setup

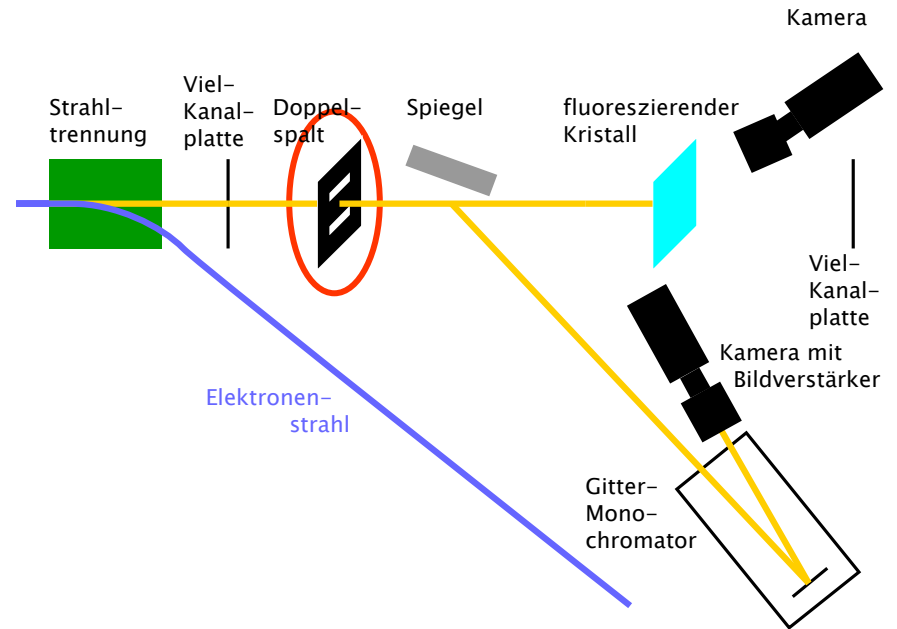
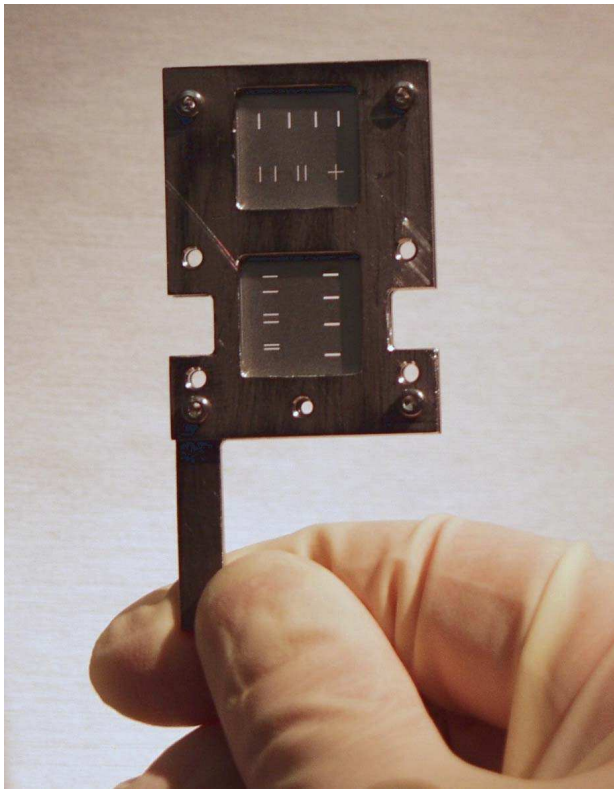
Photon Diagnostics at the TTF FEL



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

Experimental Setup Double Slits

- Laser cut into stainless steel foil



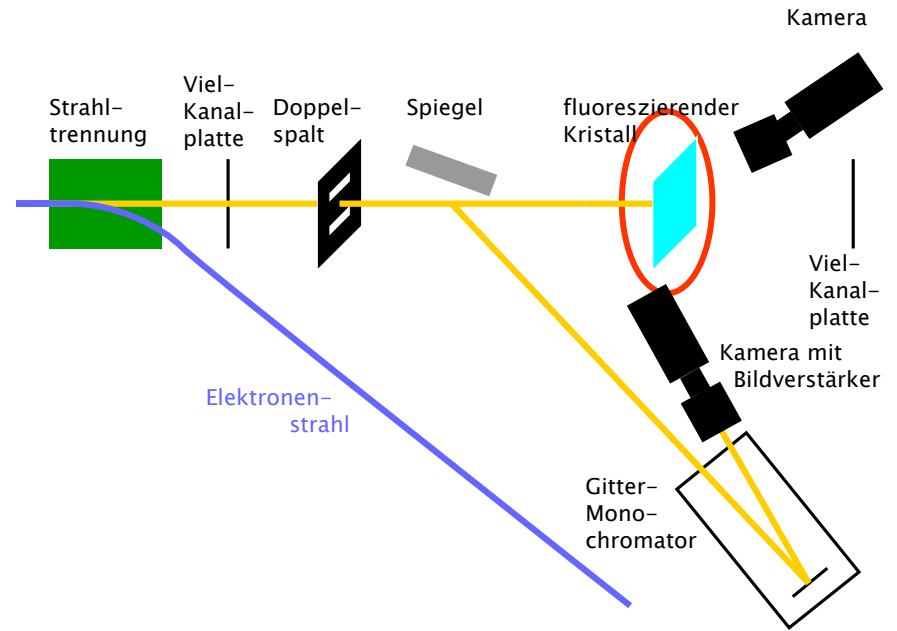
- Slit separations:
0.5, 1, 2 und 3mm
- Slit width: 100 μ m
- Slit length: 2mm
- Positioned by two stepper motors

Experimental Setup Fluorescent Crystal



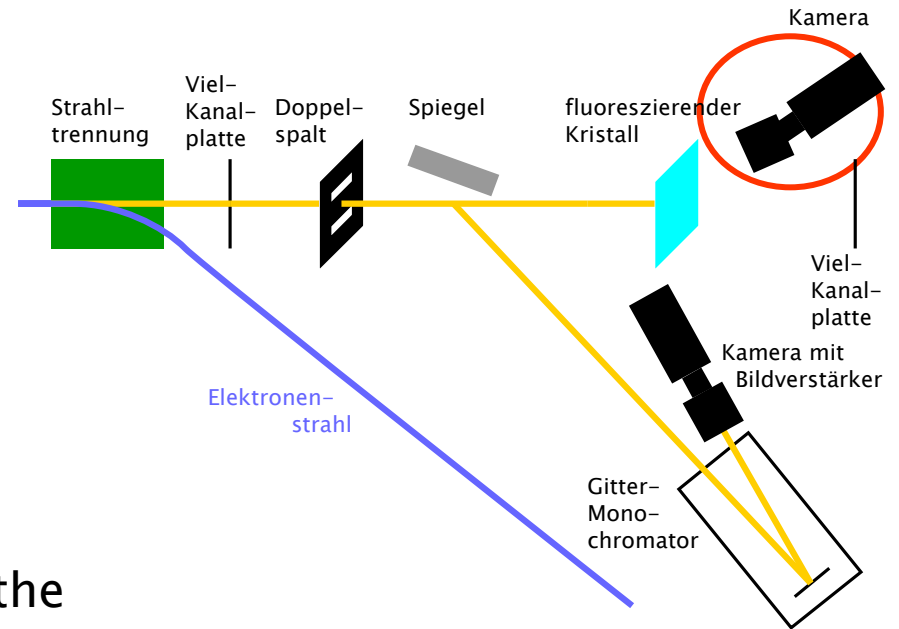
Ce:YAG crystal

on a watercooled frame

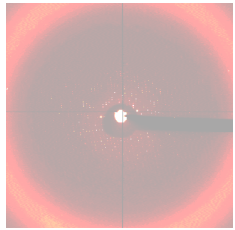


Experimental Setup Camera

- The space behind the crystal is occupied by another detector
- Camera looks on the crystal under an angle of 45°
- Tilted lens for good focusing over the inclined crystal



Transverse Coherence of a VUV Free Electron Laser



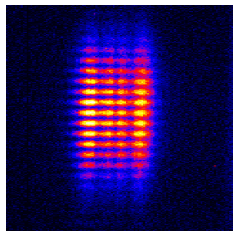
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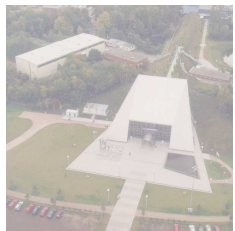
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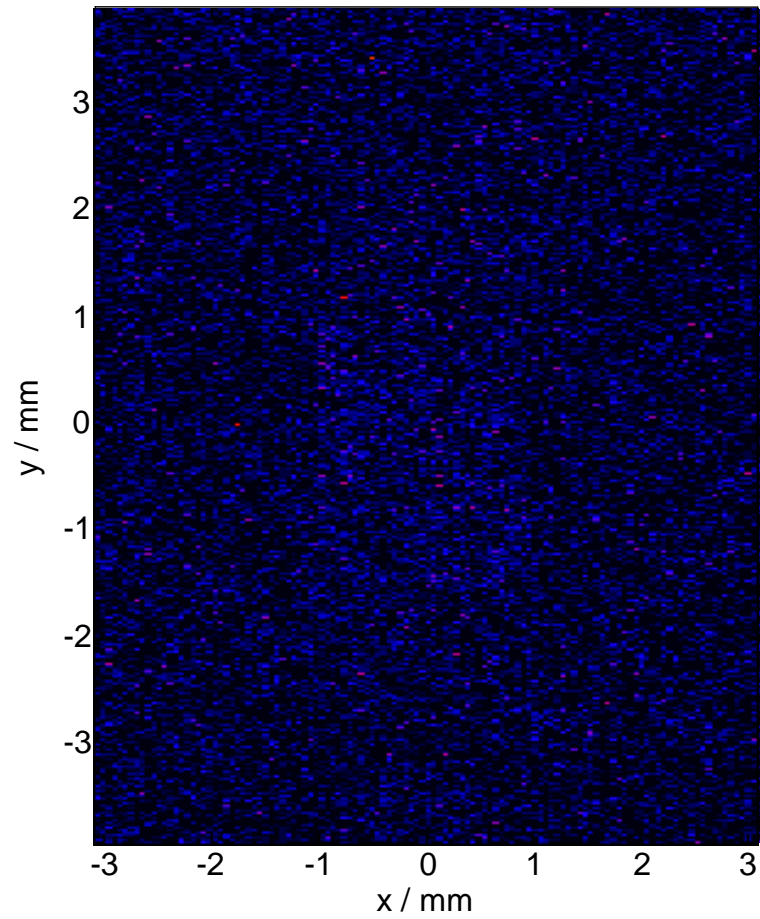


Outlook

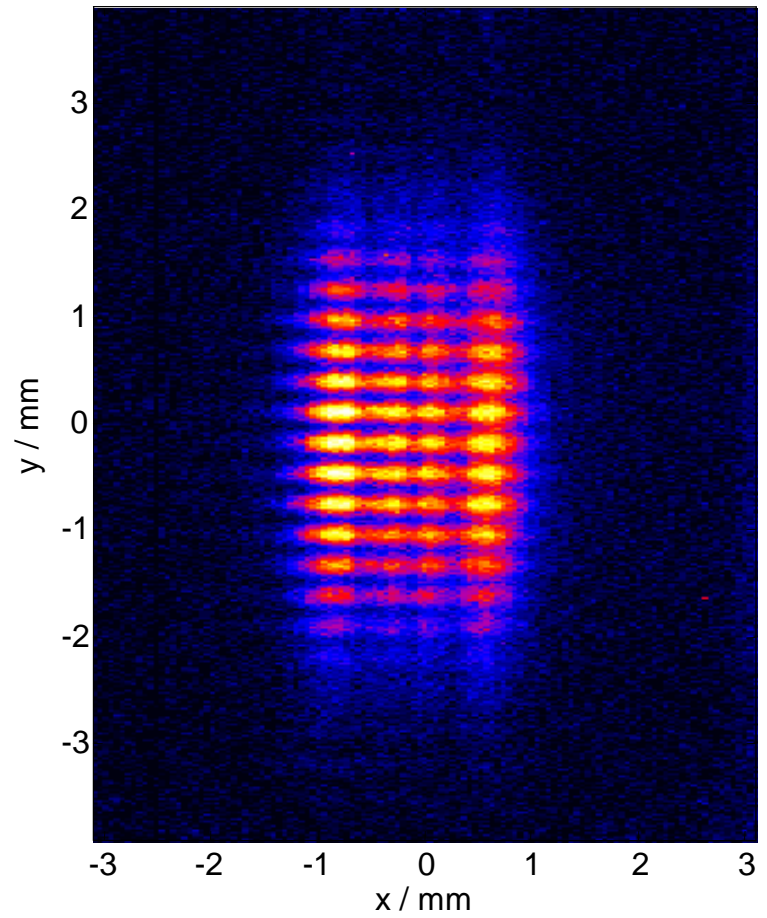
- Phase 2 of the TTF FEL

Diffraction Patterns

- Single images



- Average of 100 images



Effects of the Experimental Setup

- Fluorescent crystal (Ce:YAG):
 - Resolution: measured with the photo cathode laser
 - Saturation / non-linear response function: measured with the FEL
- Camera
 - Resolution: measured with a test pattern and a point-like light source
- CCD chip
 - Noise: measured on the unexposed chip

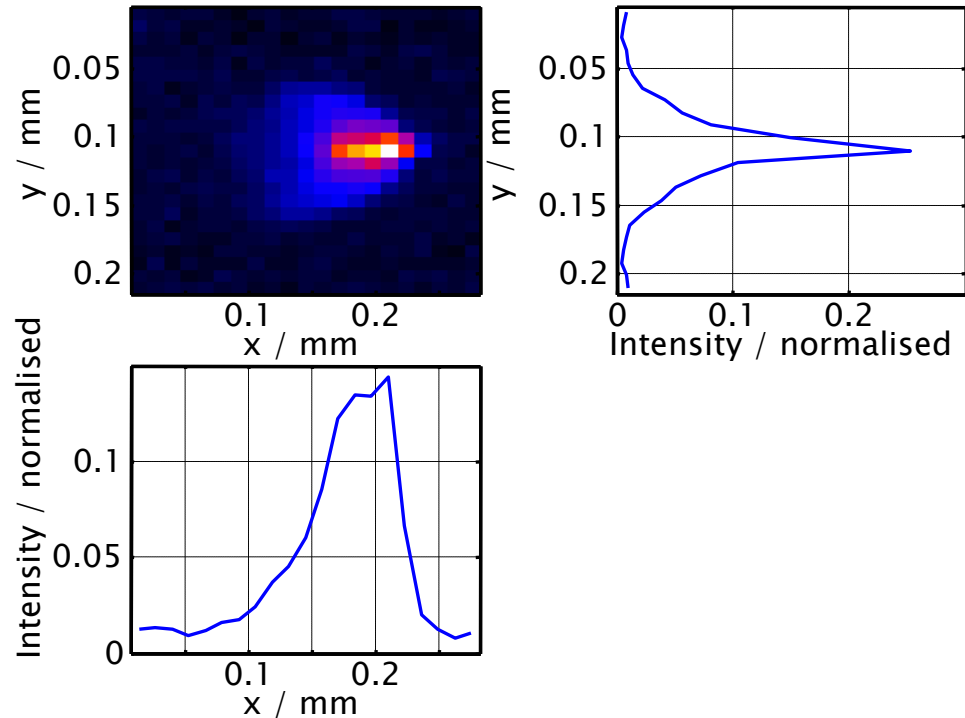
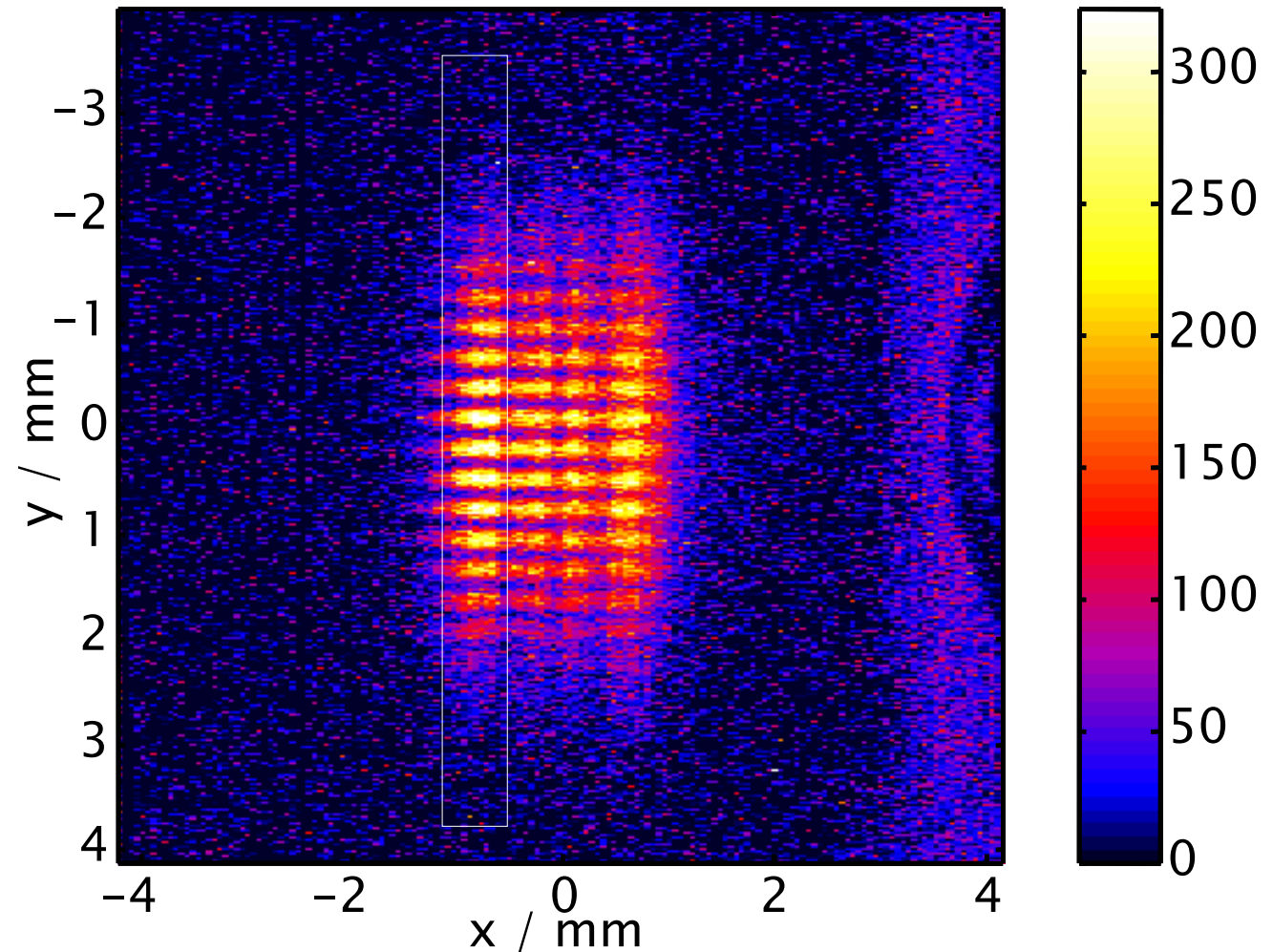


Image Processing

Corrected Diffraction Pattern

Corrections:

- Non-linearity
- Resolution



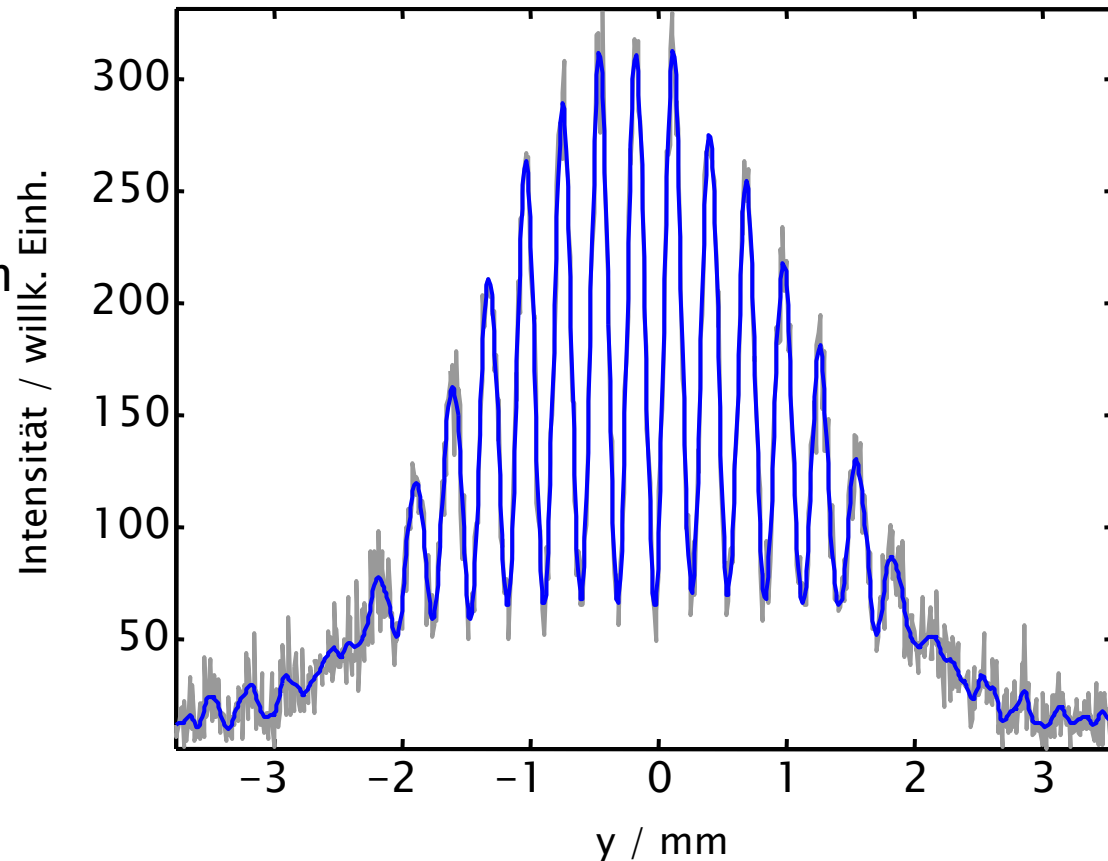
Analysis

- 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



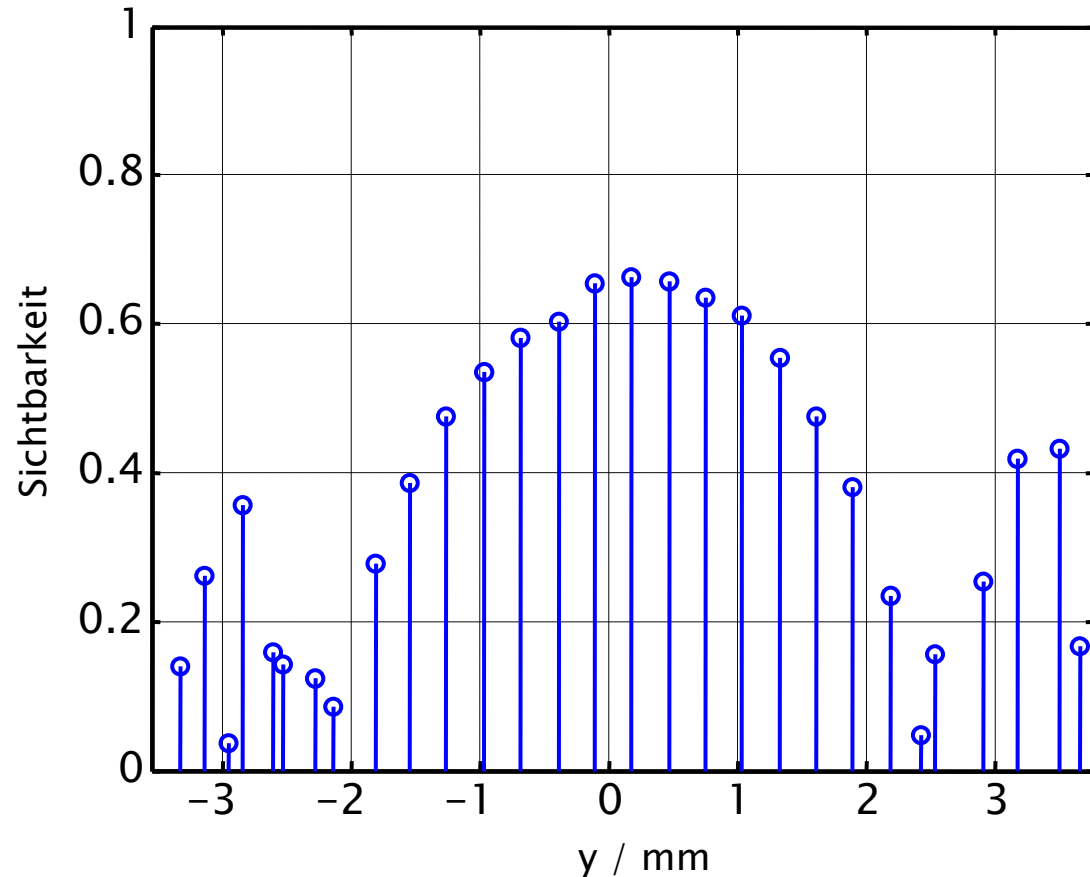
Analysis 1:

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

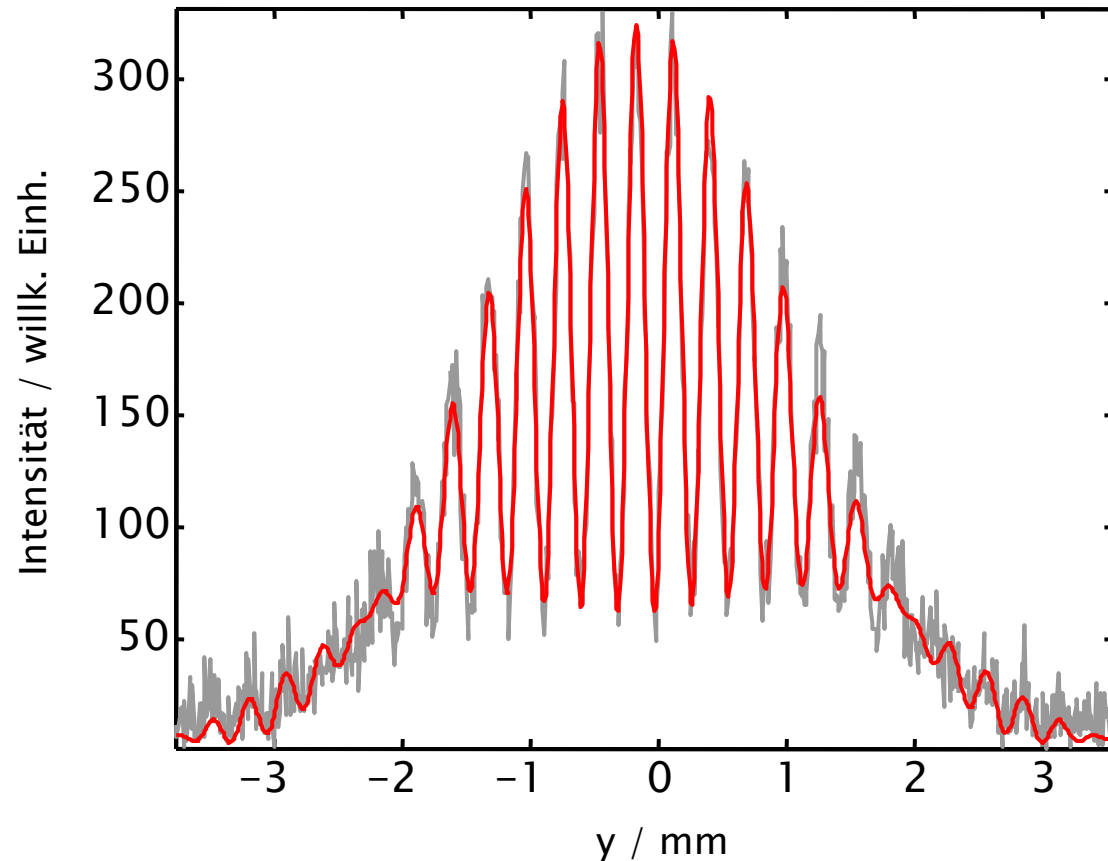


Analysis 2:

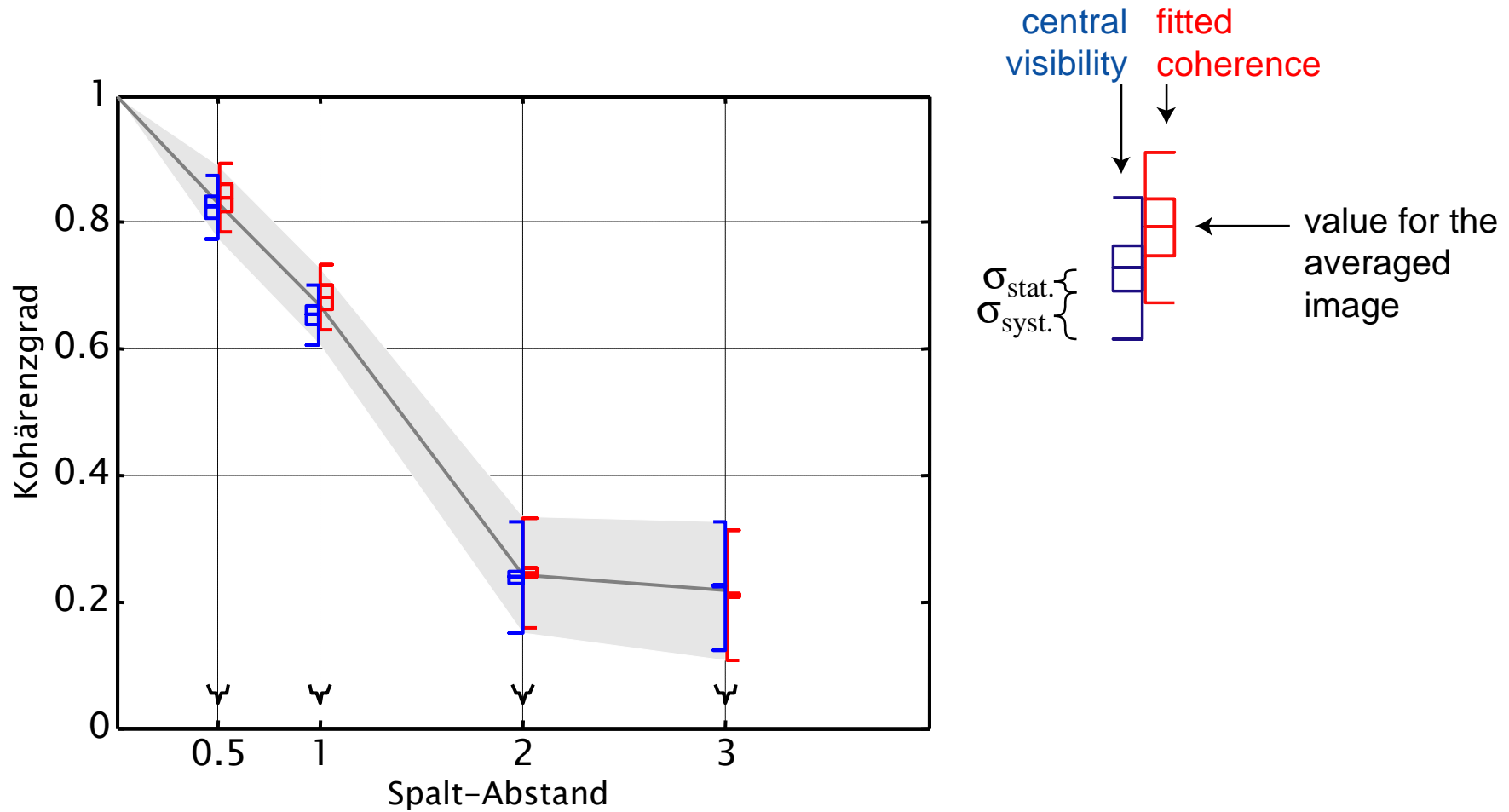
Fit to the Intensity Distribution

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



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



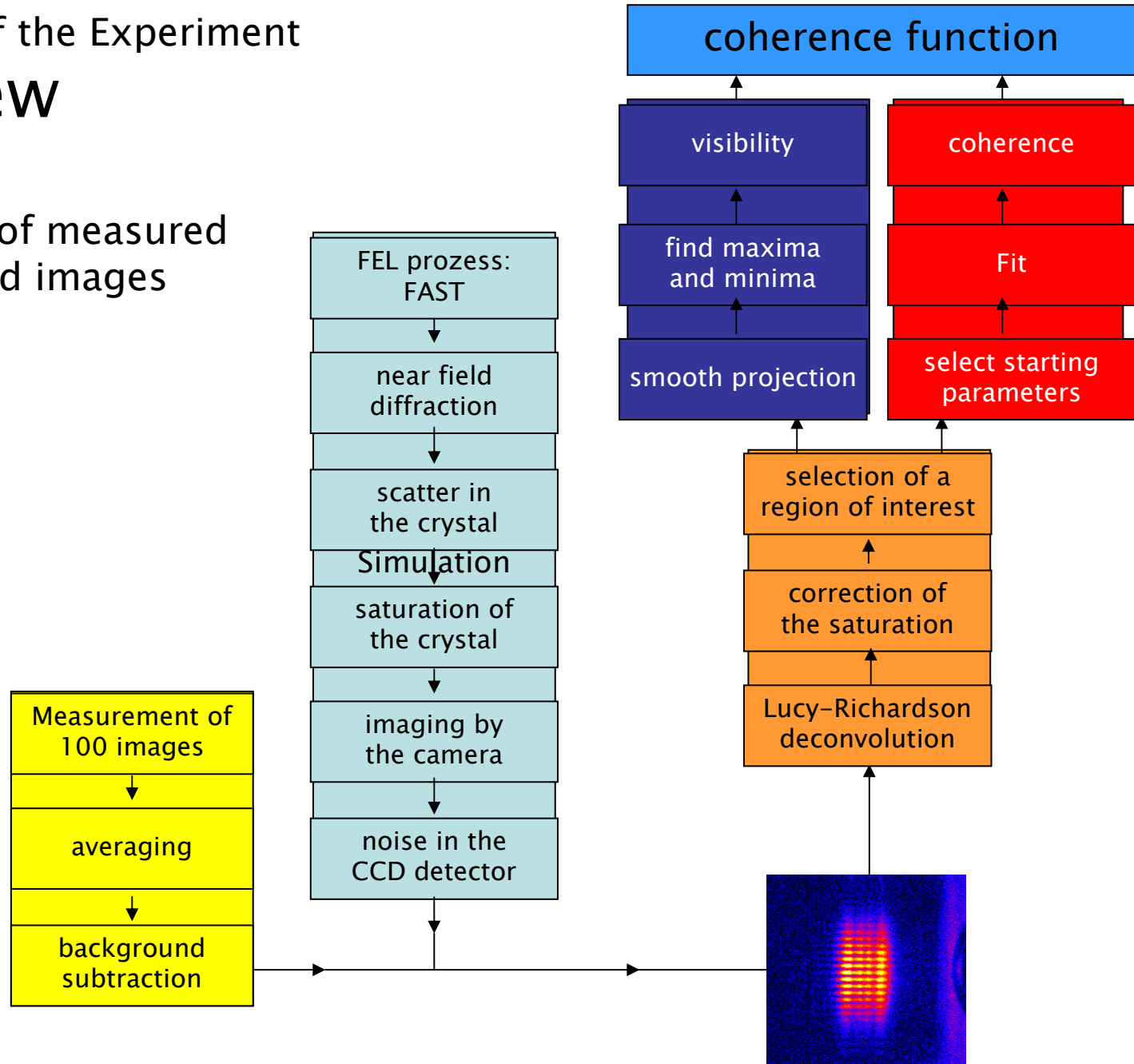
Simulation of the Experiment

- Goal of the simulations:
 - compare the simulation results to the measurements
 - review of the image processing and analysis routines
- Simulation of
 - FEL process (M. Yurkov)
 - near field diffraction
 - detrimental effects of the experimental setup
 - fluorescent crystal
 - scatter, measured with the photocathode laser
 - linearity, measured by comparing to a calibrated detector
 - camera lens, measured with test slide and pinhole aperture
 - CCD detector

Simulation of the Experiment

Overview

Comparison of measured and simulated images

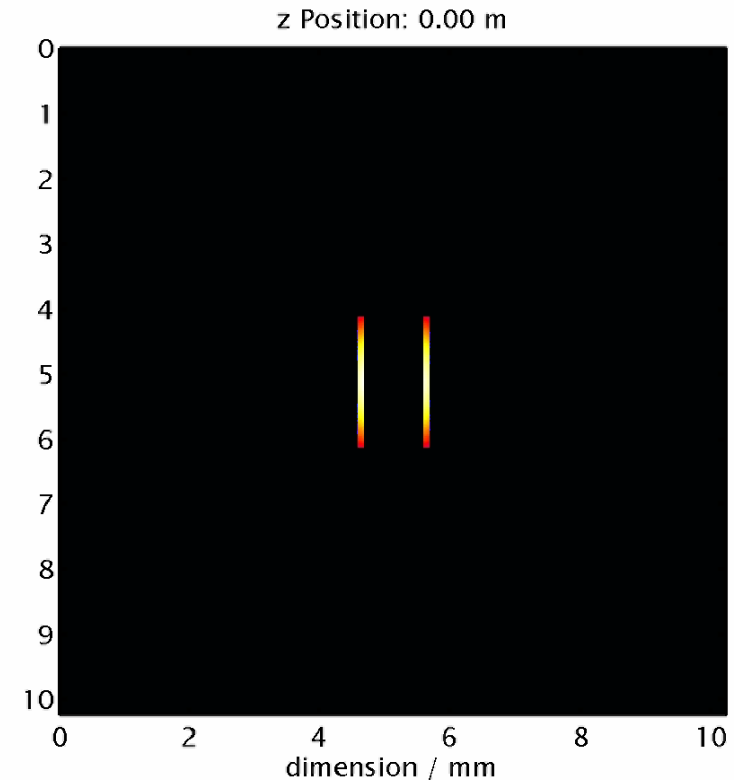


Simulation of the Experiment

Interference Effects

Near field diffraction (GLAD)

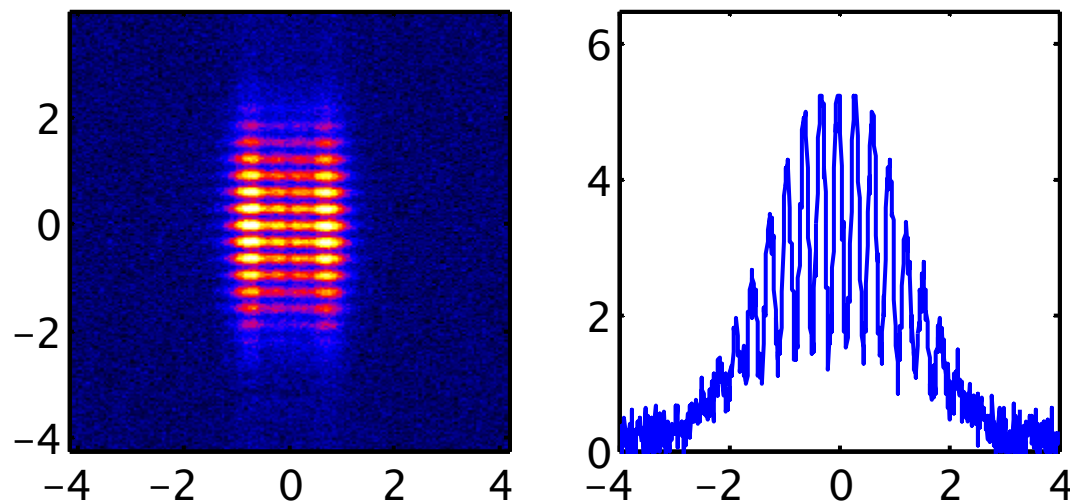
- Representation as classic electromagnetic field with a slowly varying amplitude
- Computation of diffraction effects
 - in Fourier space
 - on a grid



Simulation of the Experiment

Simulation of the Experimental Setup

- Fluorescent crystal
 - scatter: convolution with a Gaussian distribution
 - Non-linearity
- Imaging by the camera: convolution with the measured point spread function
- CCD detector: addition of pixel noise



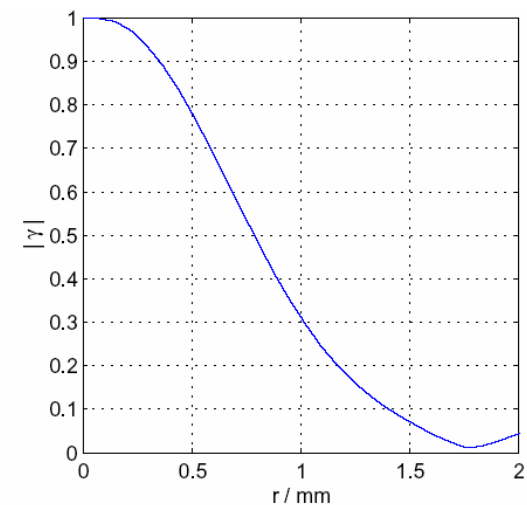
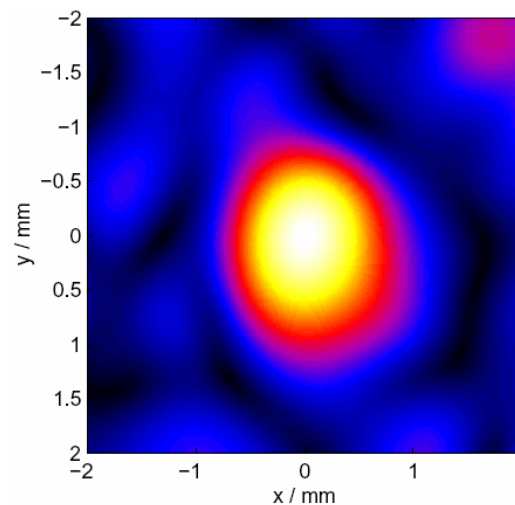
Simulation of the Experiment

Analysis of Simulated Images

- Deconvolution of the resolution
- correction of the non-linearity of the fluorescent crystal
- Projection of a selected region
- Application of the analysis methods
 - visibility of the interference fringes
 - fit to the intensity distribution

- The correlation function of the wave can be calculated directly in front of the double slit

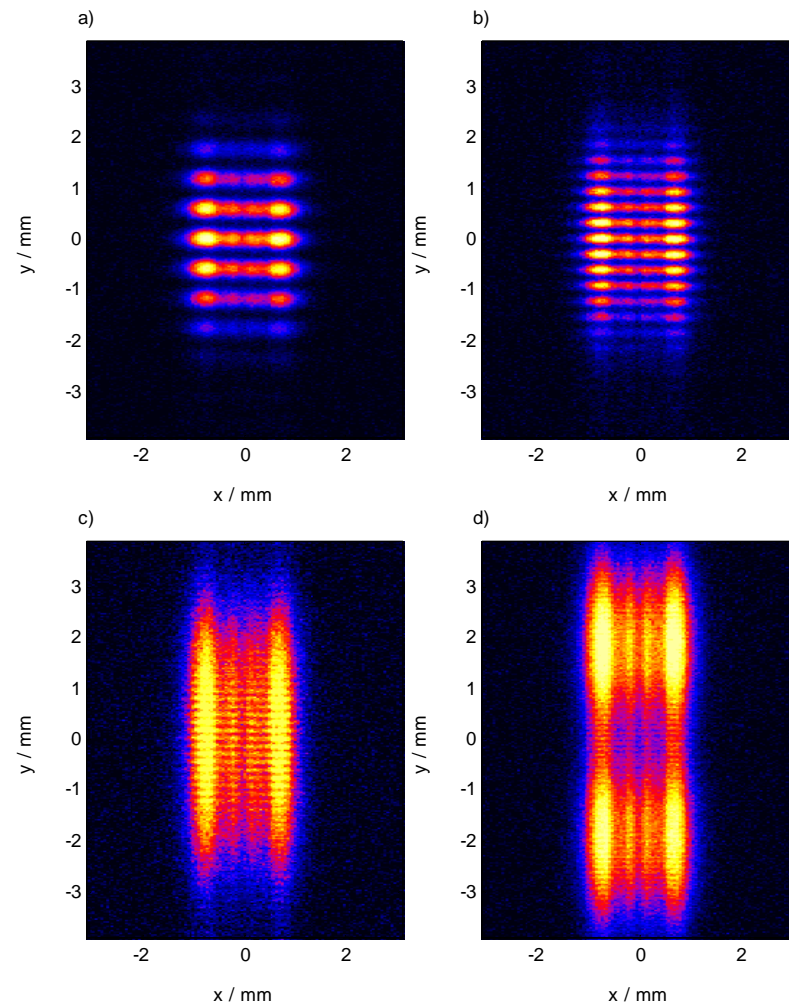
⇒ Compare the results of the analysis with the correlation function



Simulations: Summary

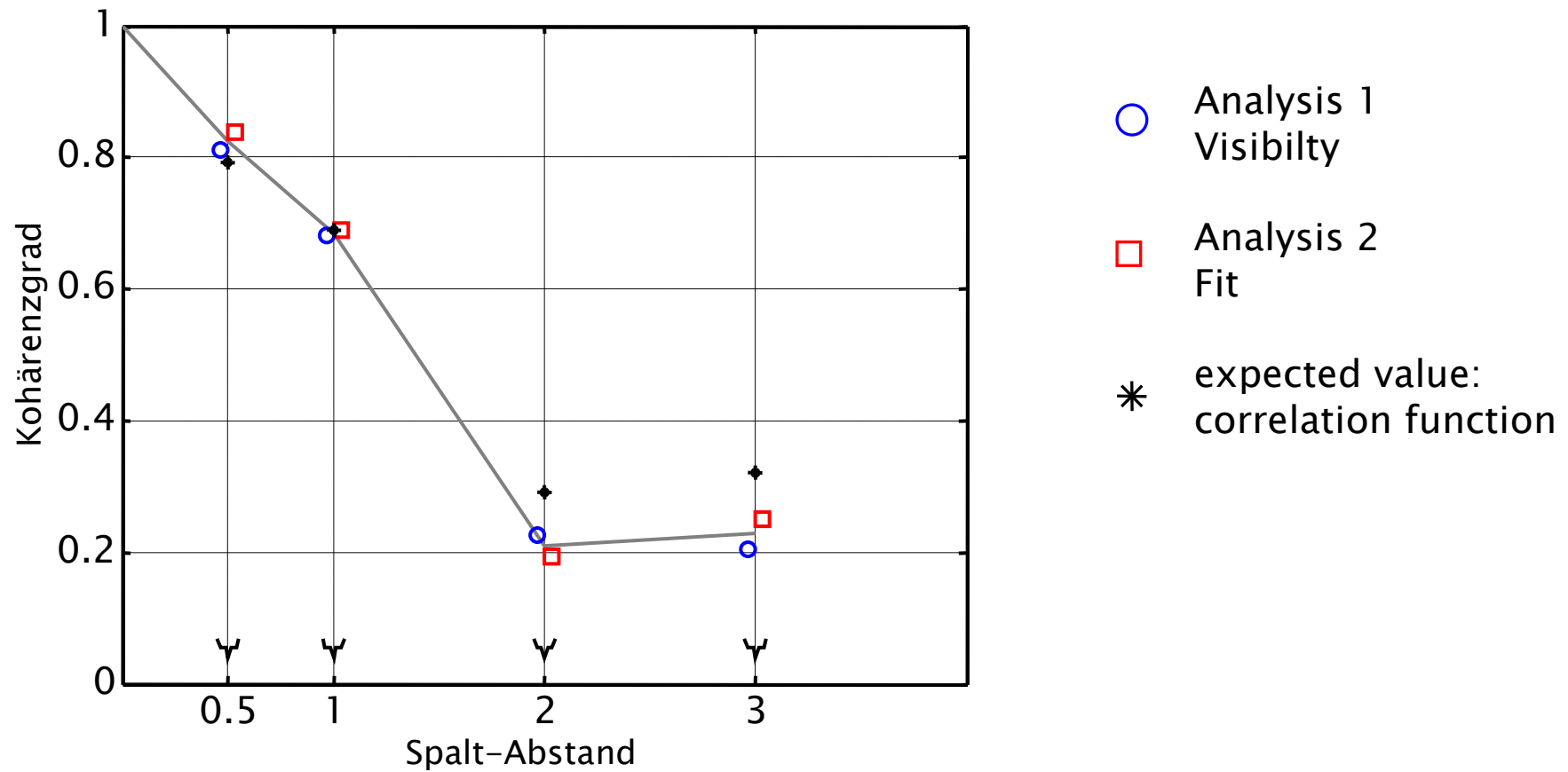
Simulations of

- FEL process
- Adjustment of the coherence function by distortion of the wave fronts
- Near field (Fresnel) diffraction
- Detrimental effects of the experimental setup

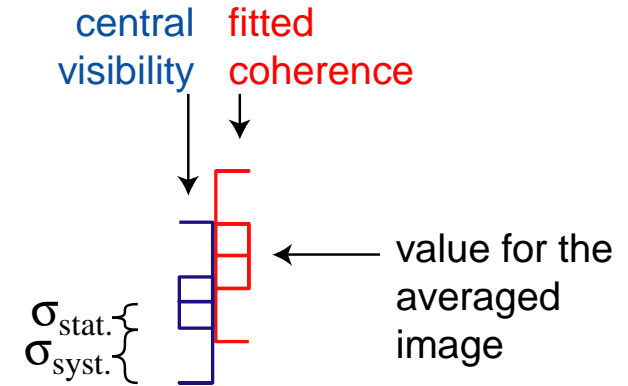
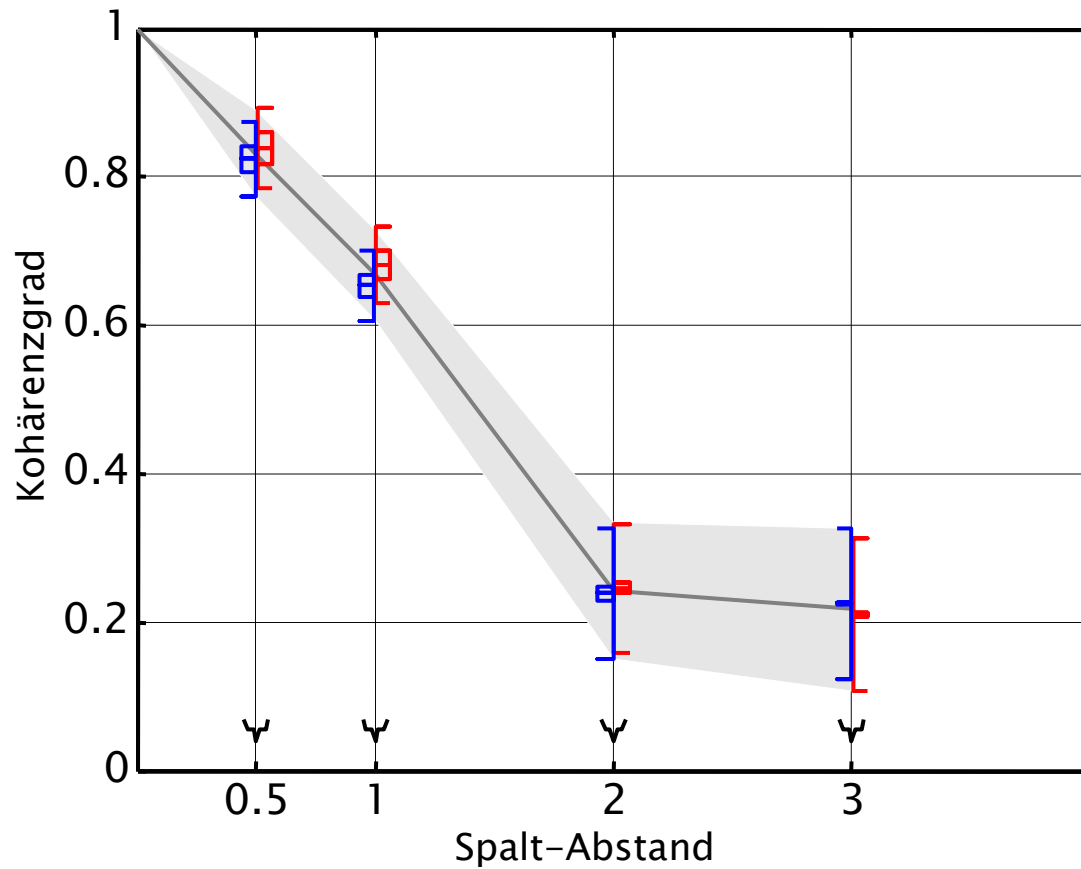


Simulations:

Spatial Coherence as a function of Slit Separation

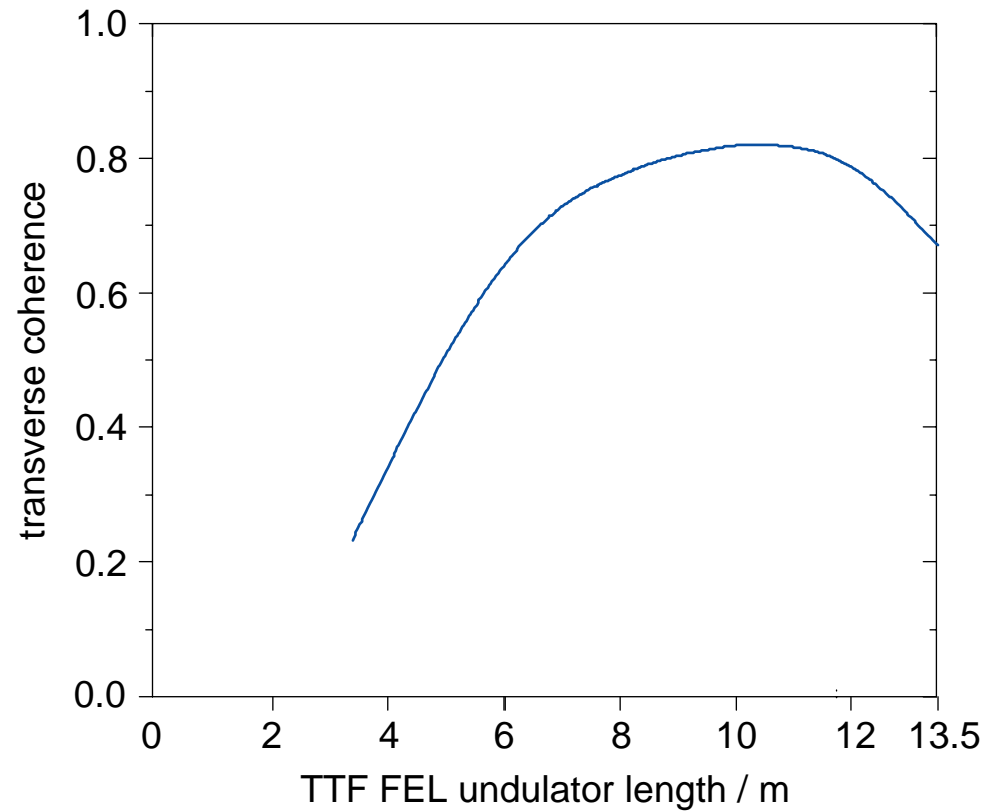


Reminder: Result of the Measurements



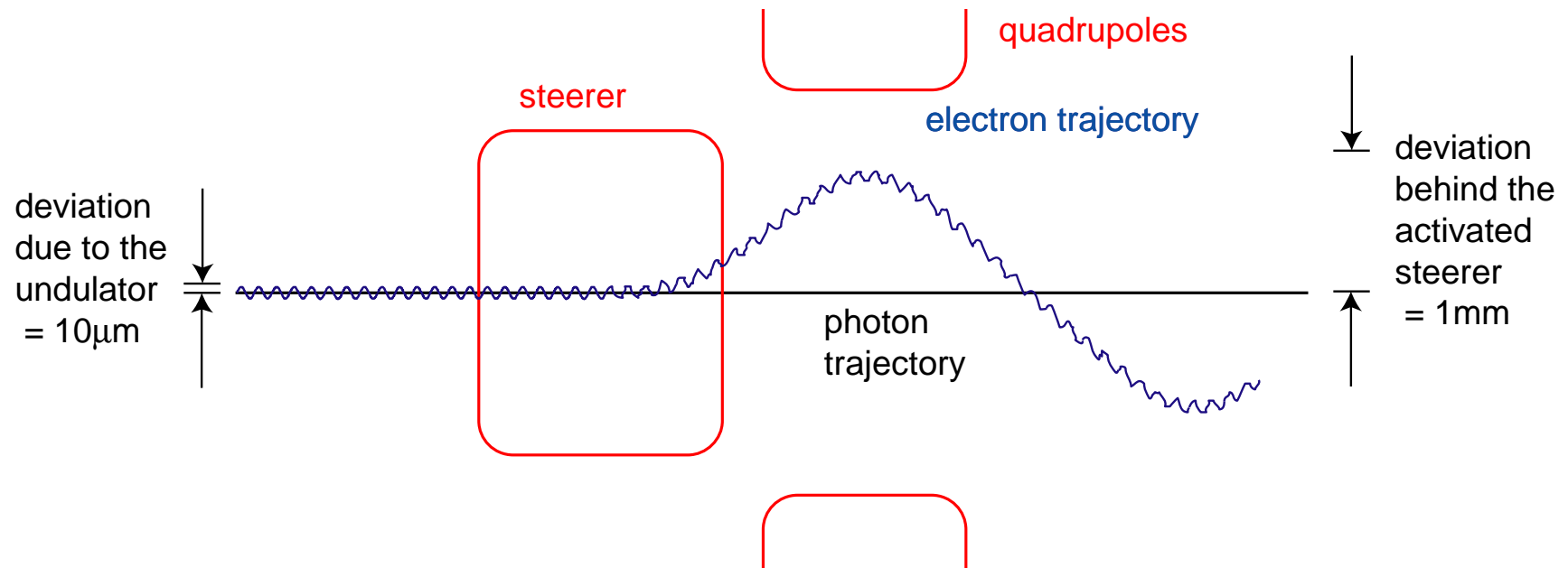
Evolution of the Coherence along the Undulator

- Reminder: theoretic prediction
- How can the undulator length be adjusted?



Evolution of the Coherence along the Undulator

- Undulator can be virtually shortened by displacing the beam from the ideal trajectory
- Measurements possible in the last third of the undulator



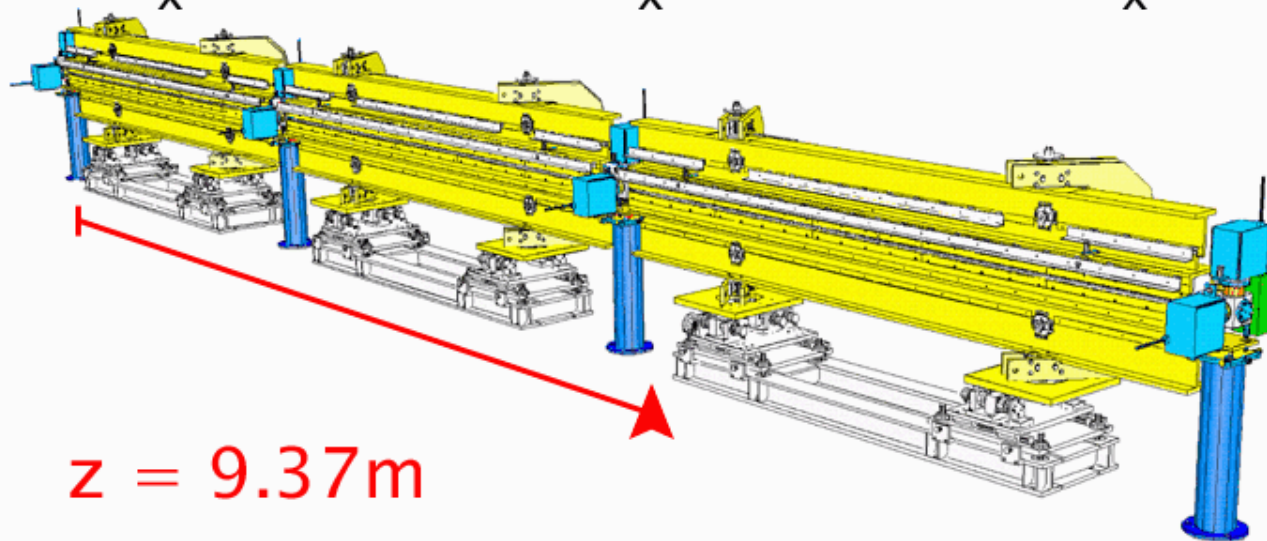
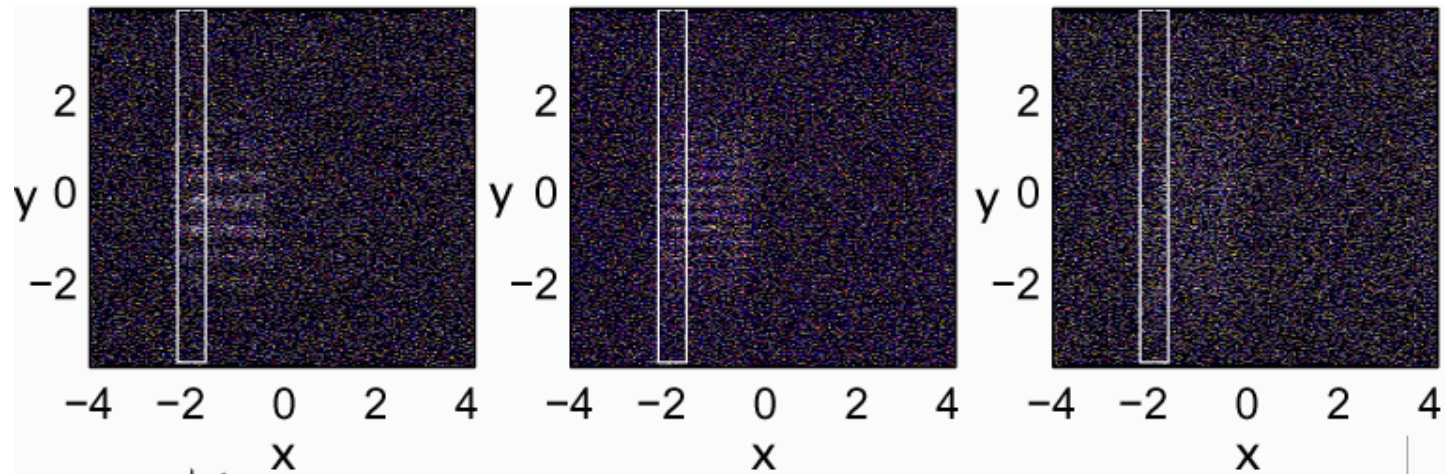
Evolution of the Coherence along the Undulator

Diffraction patterns

Slit separation: 0.5mm

1mm

2mm



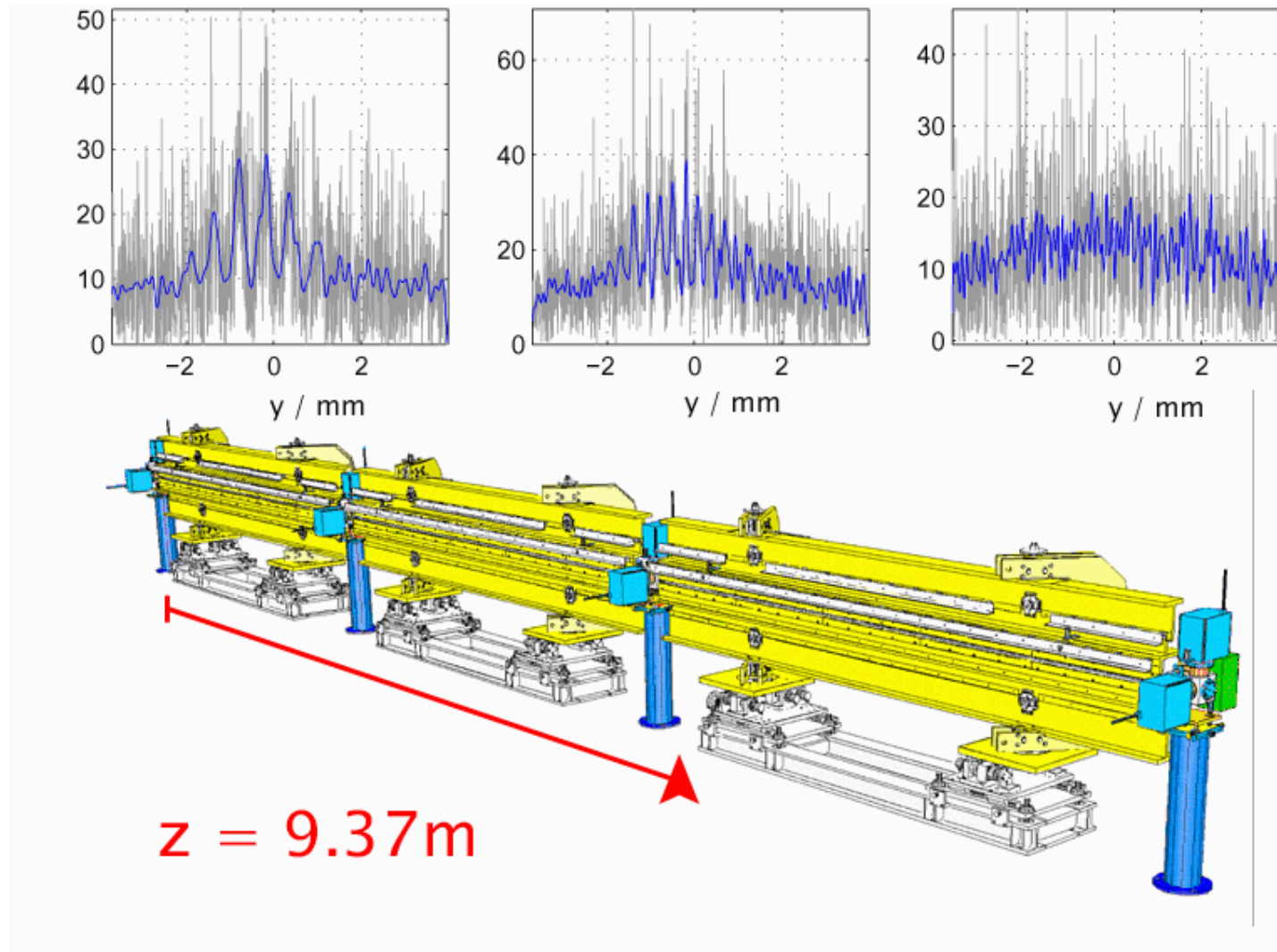
Evolution of the Coherence along the Undulator

Filtered Projection

Slit separation: 0.5mm

1mm

2mm

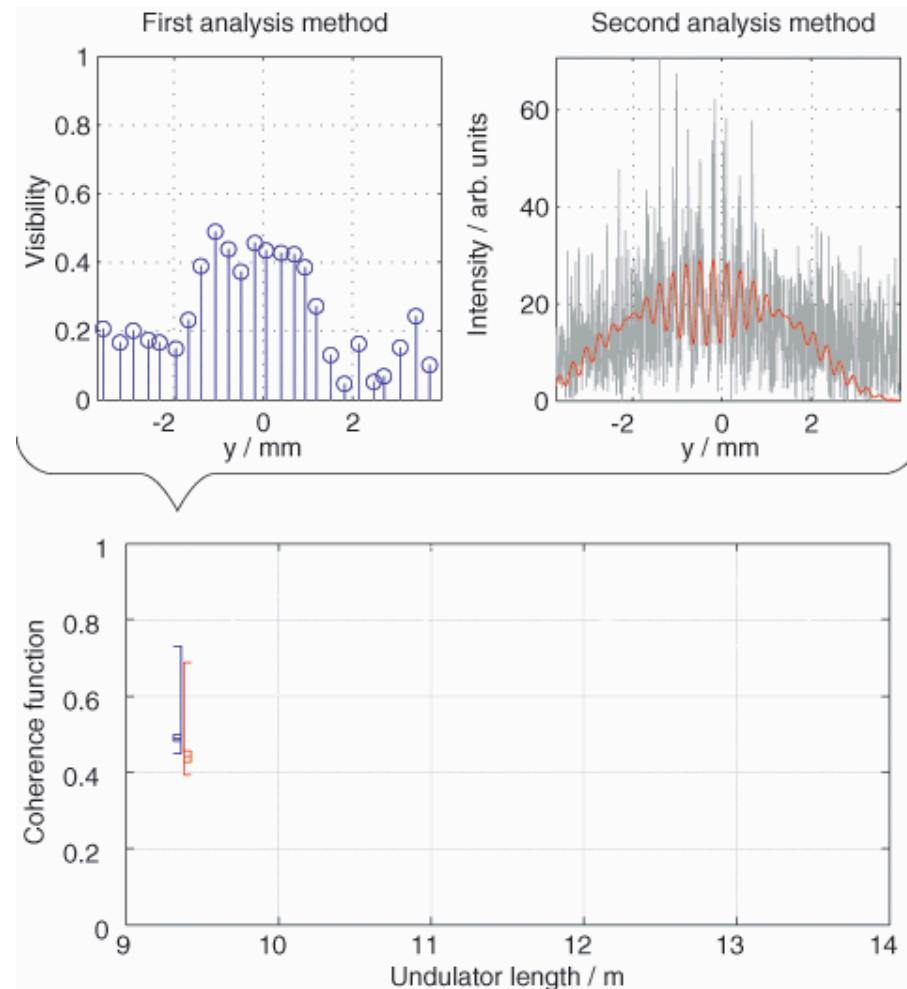


Evolution of the Coherence along the Undulator

Results

Results of the analysis:

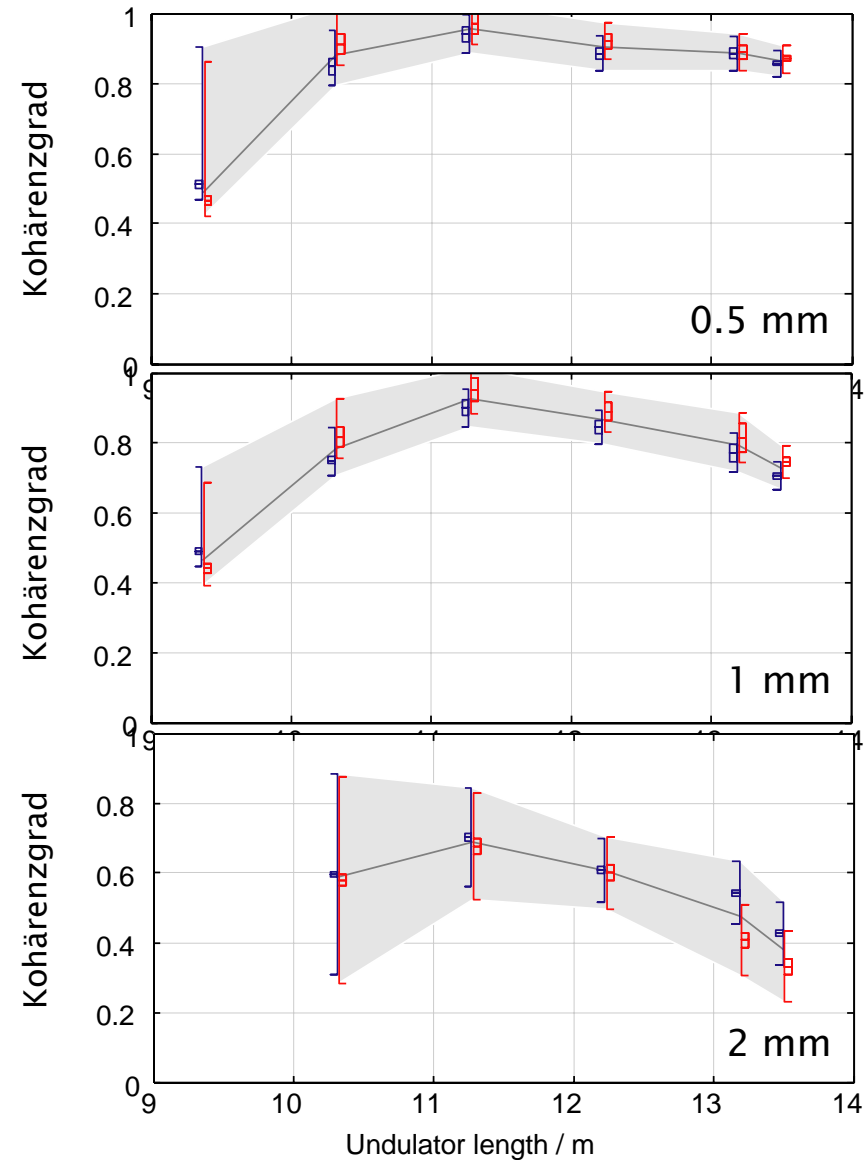
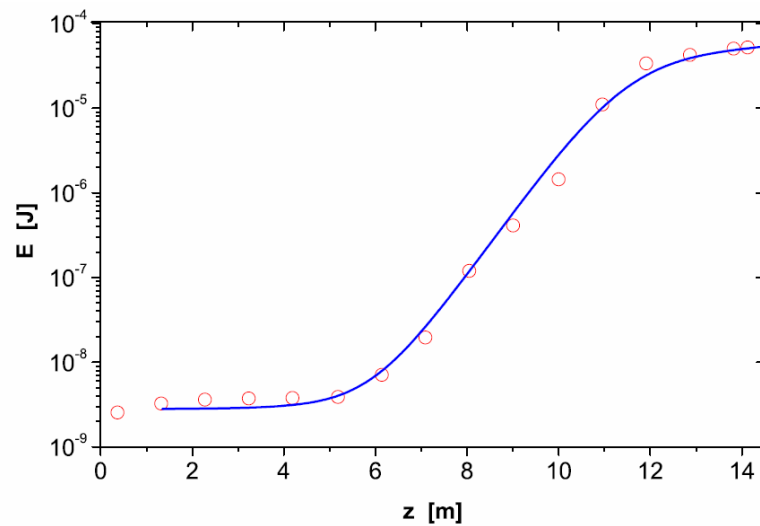
- Visibility determined from the maxima and minima of the smoothed projection
- Fit of the near field diffraction pattern to the intensity distributions



Evolution of the Coherence along the Undulator

Results

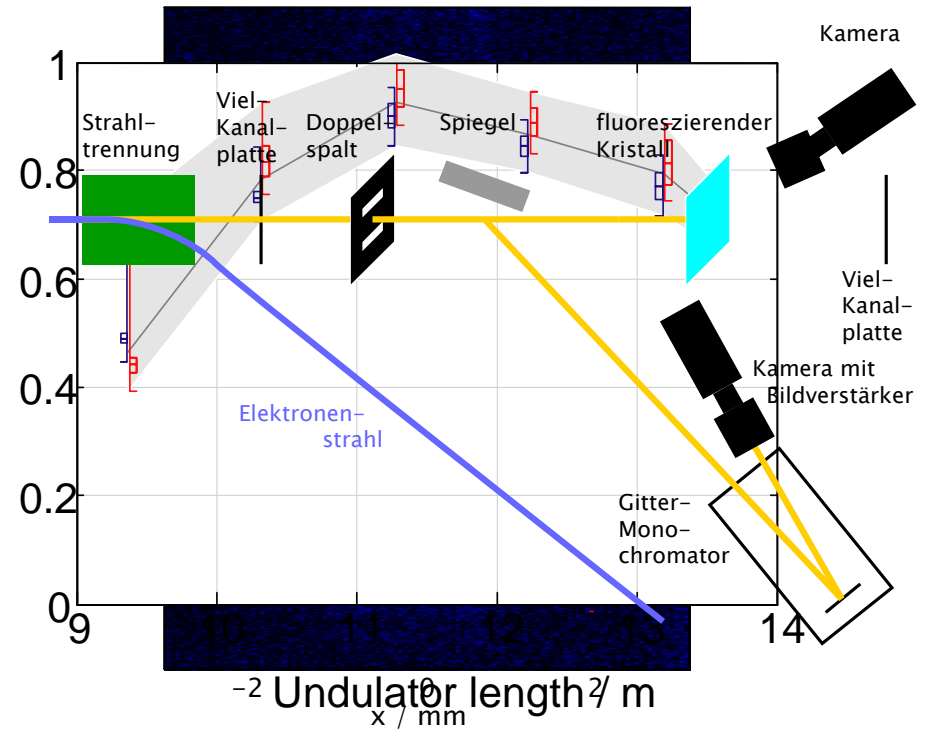
- Coherence function for slit separations of 0.5, 1 and 2 mm
- Compare the intensity of the FEL (measured with the MCP detector)



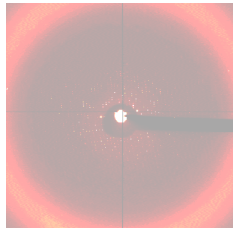
Transverse Coherence of a VUV Free Electron Laser

Summary

- Experimental setup in the ultra high vacuum of the accelerator
- Measurement of diffraction patterns
- Correction of the detrimental effects of the setup
- Evolution of the coherence along the undulator



Transverse Coherence of a VUV Free Electron Laser



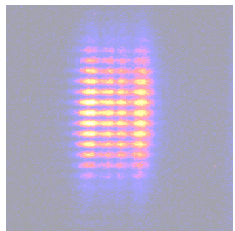
Introduction

- Relevance of Coherence
- Definition and Measurements



Measurements at the TTF FEL

- Challenges for the Measurements
- Experimental Setup



Results

- Coherence as a function of the slit separation
- Development along the undulator



Outlook

- Phase 2 of the TTF FEL

Outlook

TTF Phase 2:

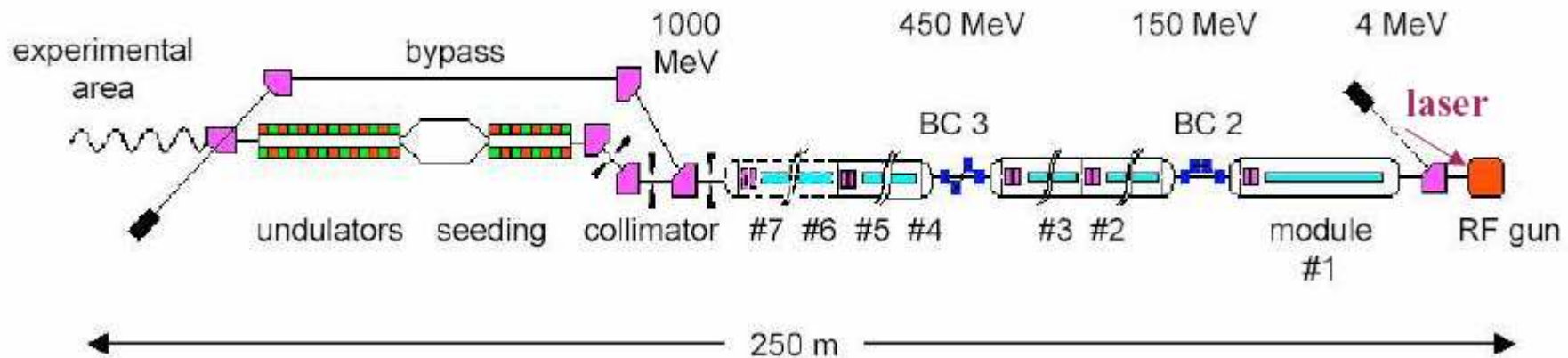
- Extension of the accelerator to a length of 250 m
 - Increase of the electron energy to 1 GeV
- ⇒ FEL wavelengths down to 6 nm
- Commissioning of the components is just starting now



Outlook

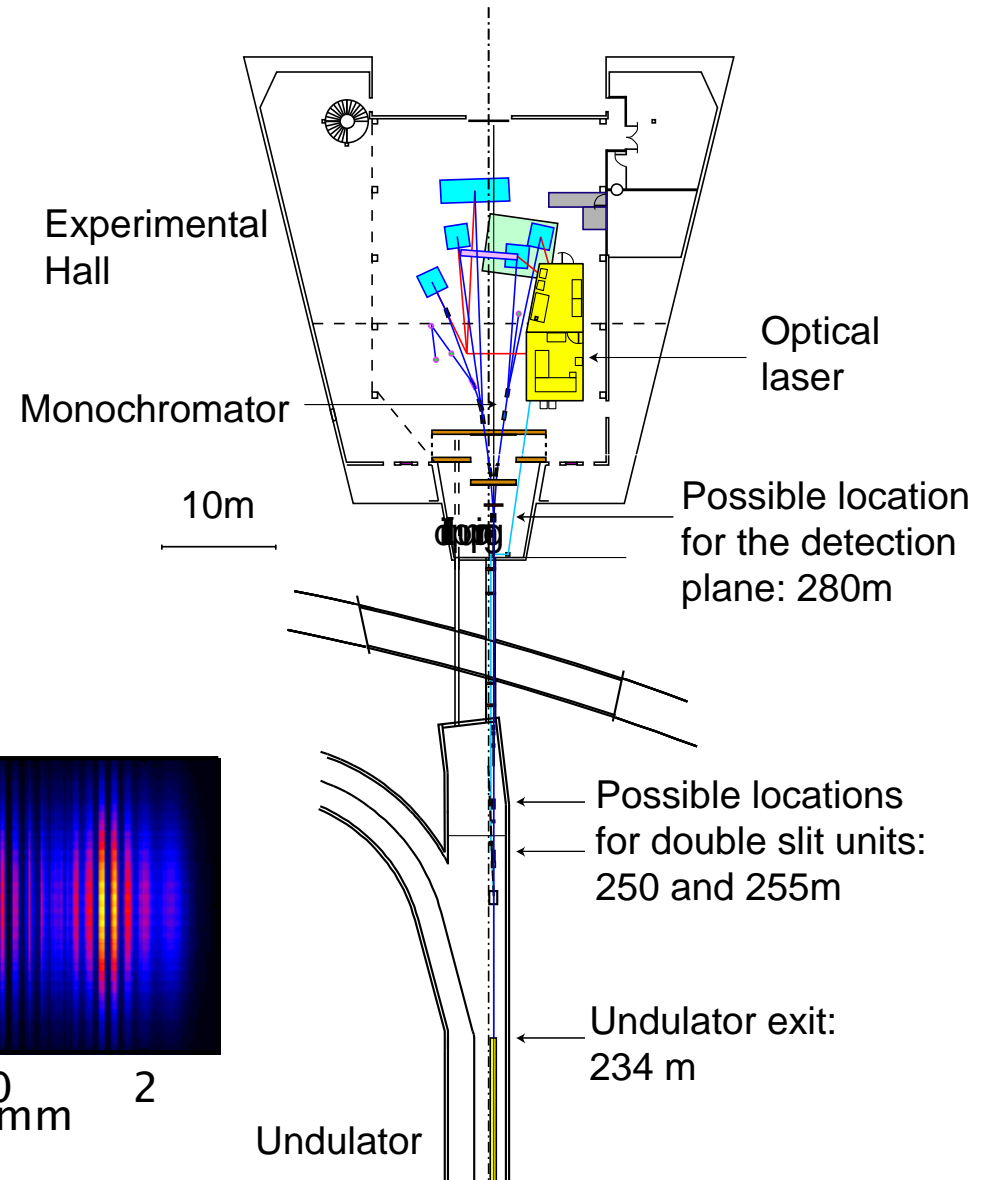
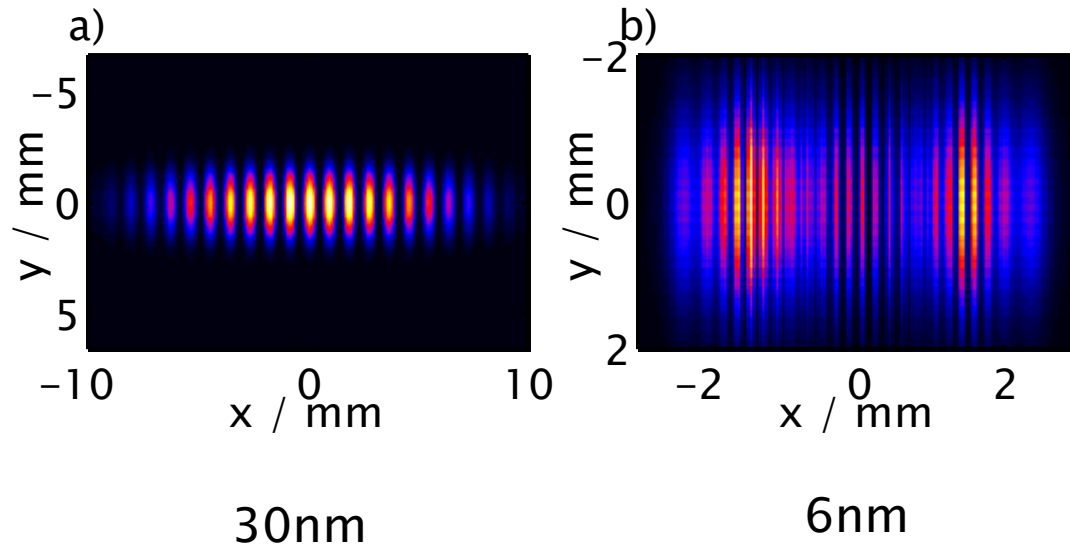
As compared to TTF1:

- higher electron energy by more superconducting accelerating modules, operating at higher electric field
- improved gun design
- smaller distance between gun and first acceleration module
- a bypass for the undulator
- undulator with external focusing
- much more space for experiments with the FEL radiation!



Outlook

- Diffraction patterns
- Challenges:
 - Damage to apertures and detectors



Many thanks to...

