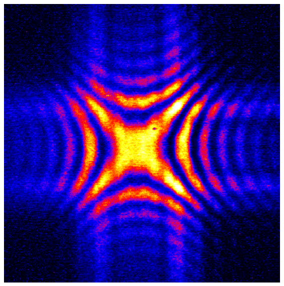


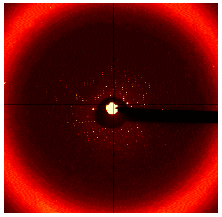
Transverse Coherence of a Vacuum Ultraviolet Free Electron Laser

Rasmus Ischebeck

February 12, 2004

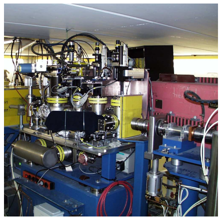
UHH Universität Hamburg
RWTH AACHEN
RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN
TESLA
DESY

Transverse Coherence of a VUV Free Electron Laser



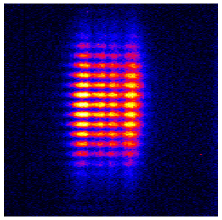
Introduction

- Relevance of Coherence
- Definition and Measurements



Measurements at the TTF FEL

- Challenges for the Measurements
- Experimental Setup



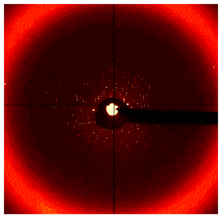
Results

- 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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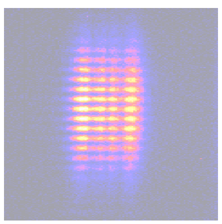

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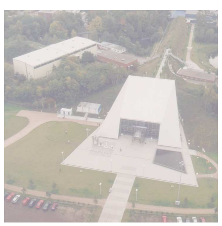
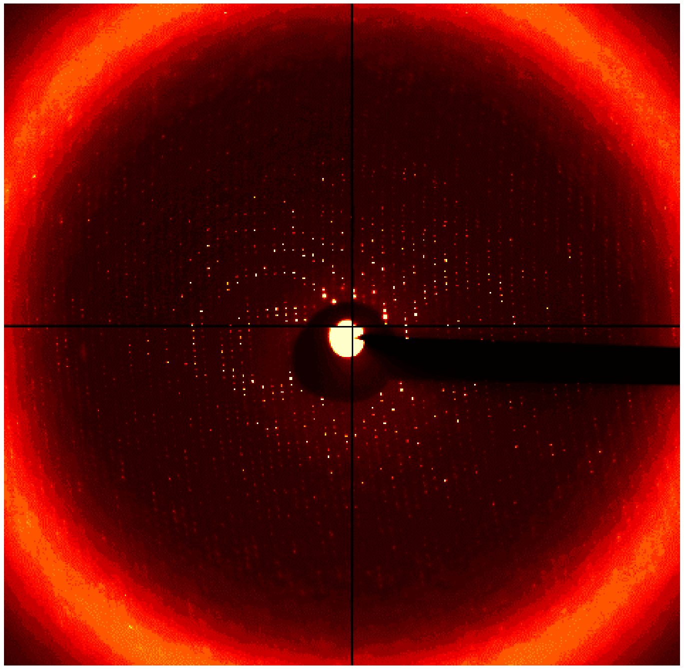


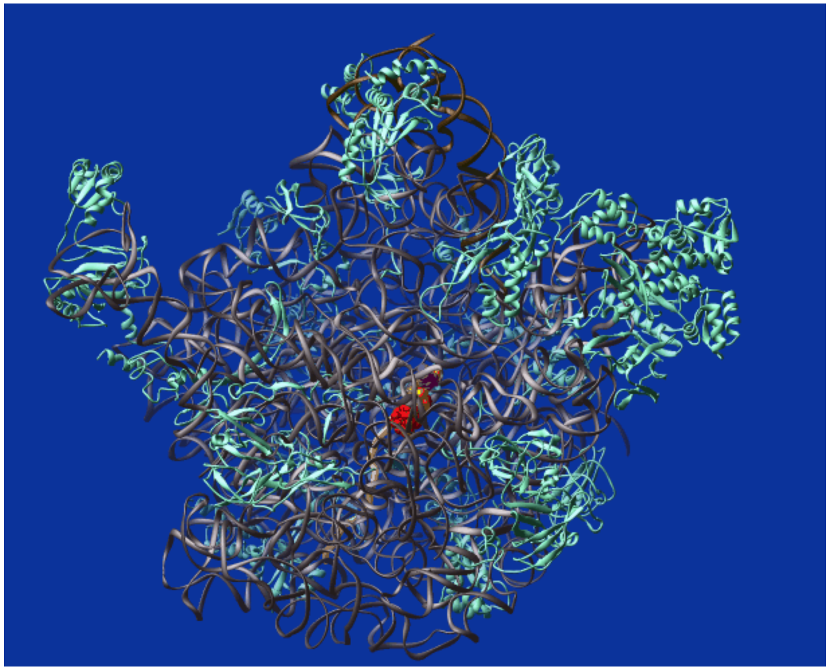
Outlook

- Phase 2 of the TTF FEL

Relevance of Coherence for Crystallography

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





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

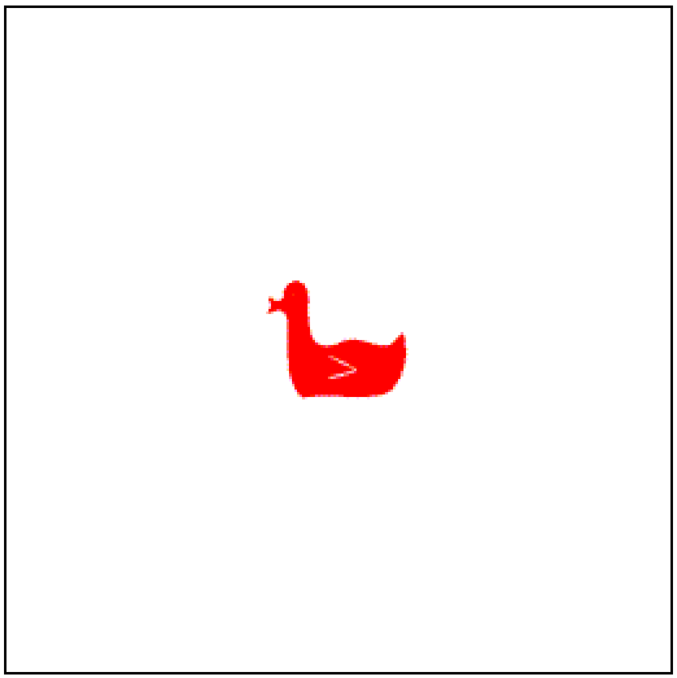
- Problem: Phase of the diffraction pattern is unknown

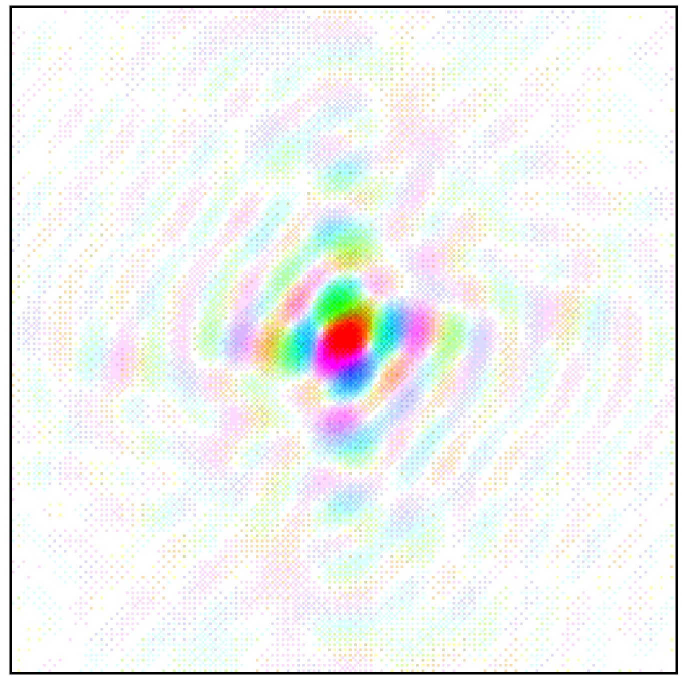
Relevance of Coherence

Diffraction Pattern of a Duck

- A (two-dimensional) duck

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





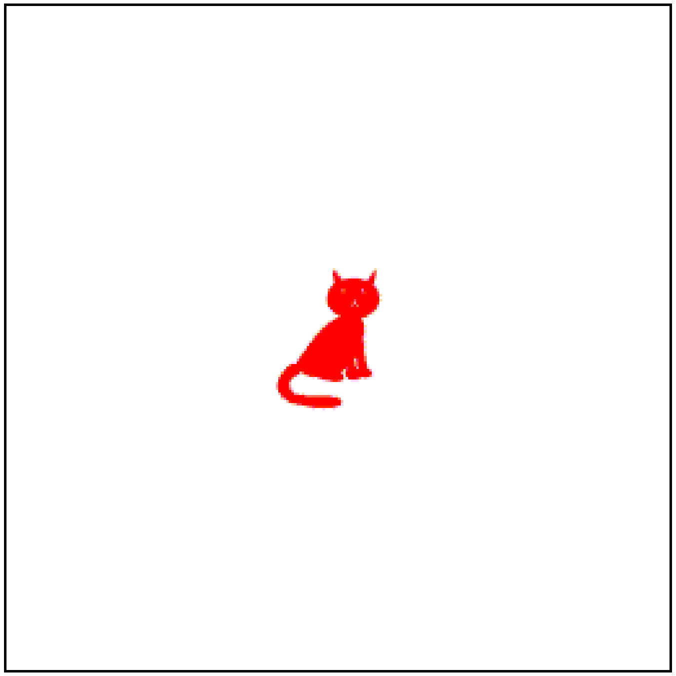
Images by Kevin Cowtan, Structural Biology Laboratory, University of York

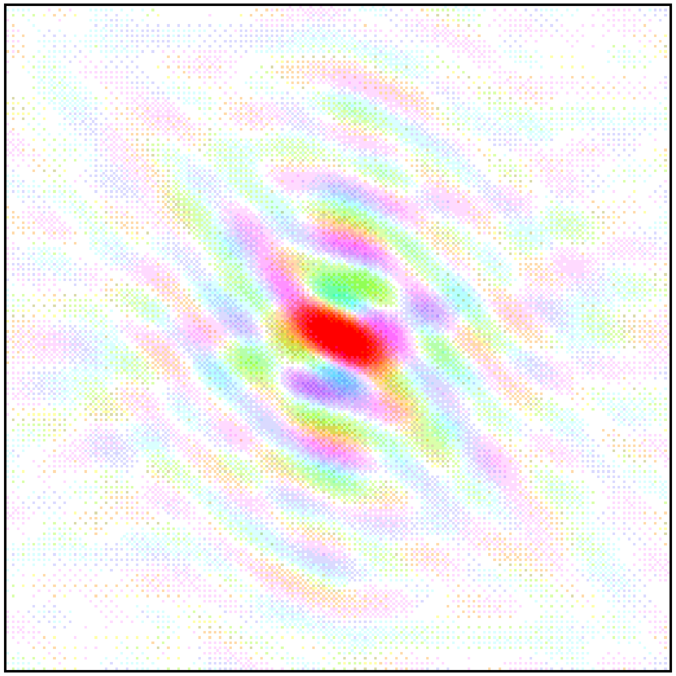
Relevance of Coherence

Diffraction Pattern of a Cat

- A cat

… and its diffraction pattern



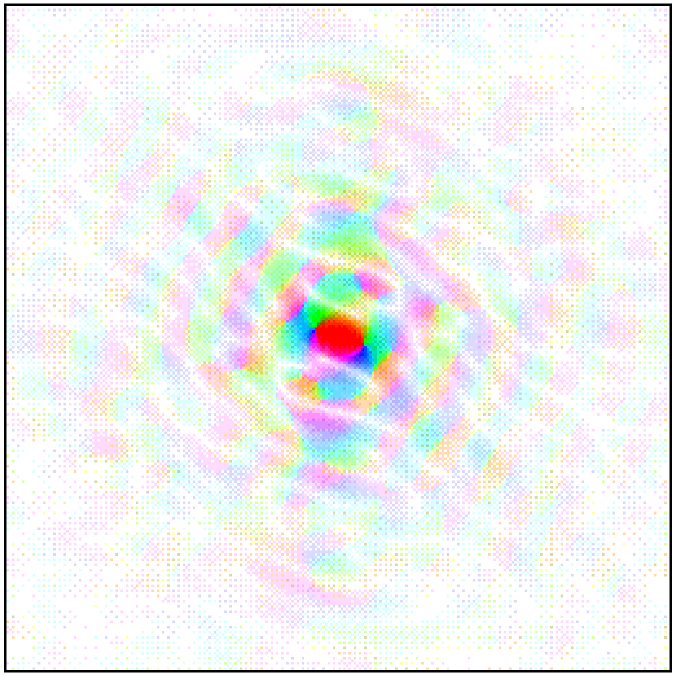


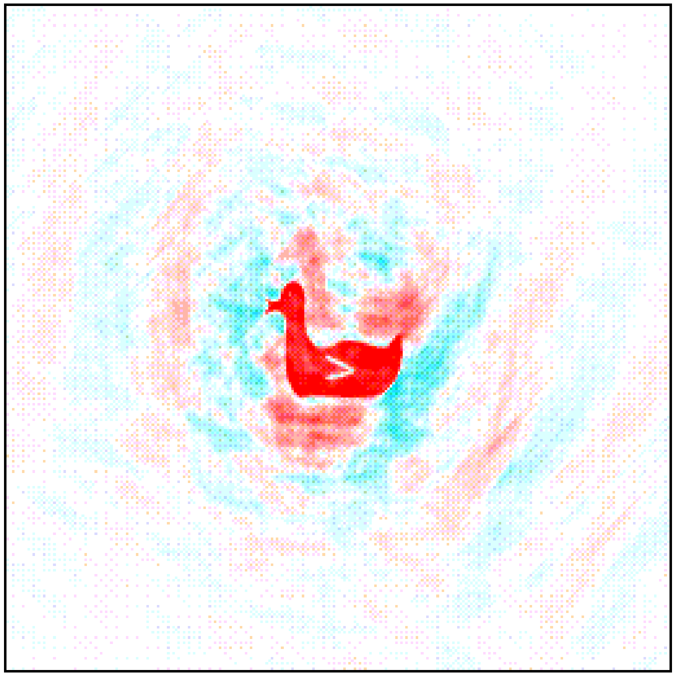
Images by Kevin Cowtan, Structural Biology Laboratory, University of York

Relevance of Coherence

Reconstruction

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





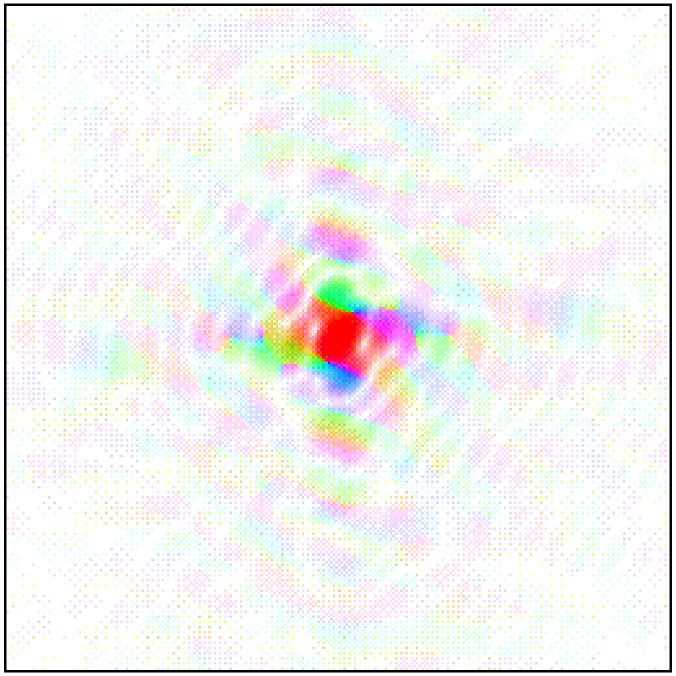
The result: a duck!

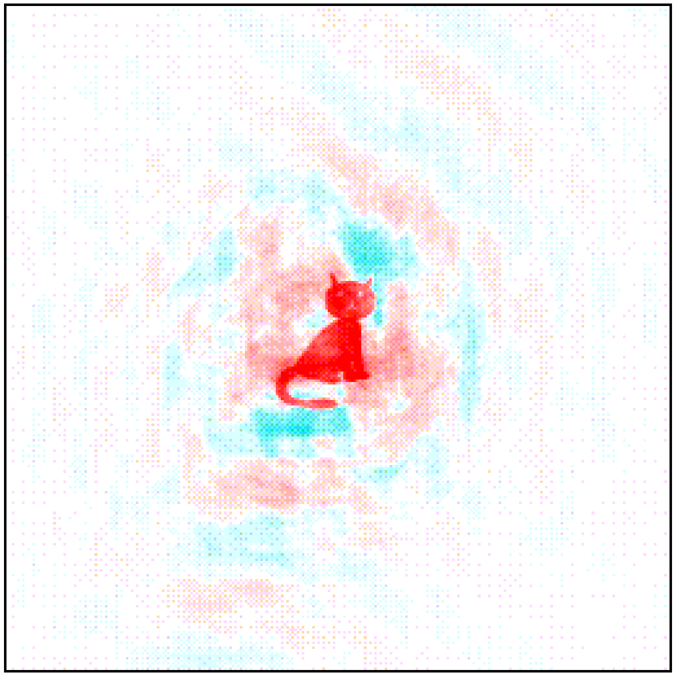
Images by Kevin Cowtan, Structural Biology Laboratory, University of York

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





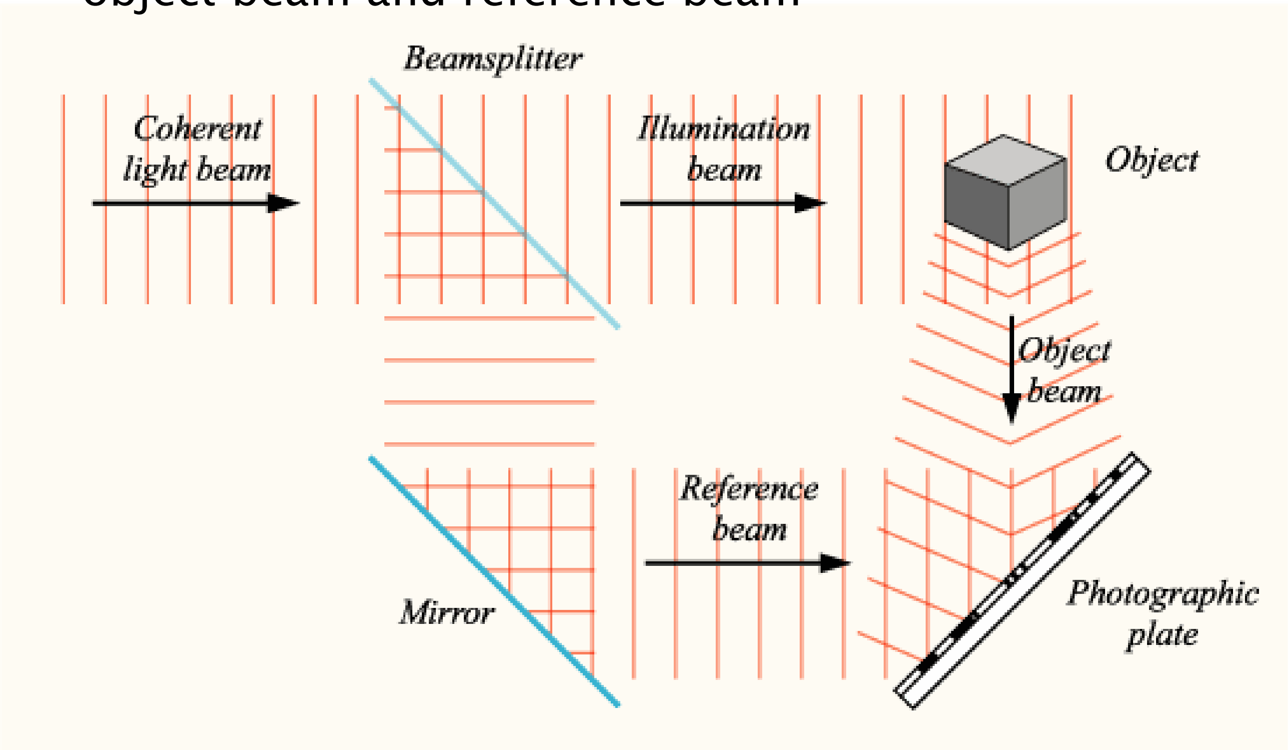
This is the famous **Phase Problem**

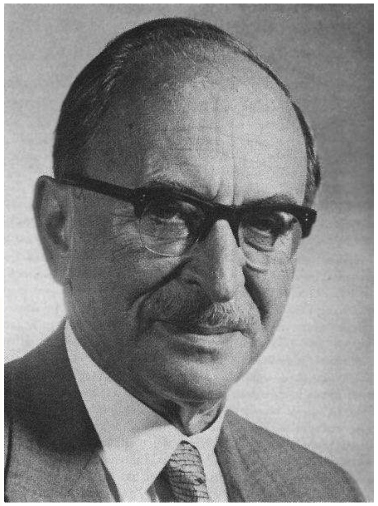
Images by Kevin Cowtan, Structural Biology Laboratory, University of York

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

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

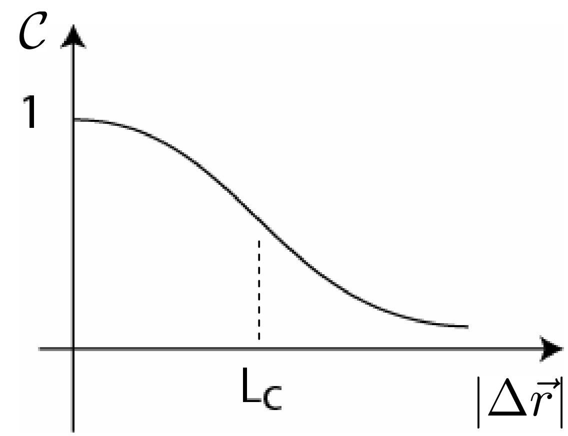
- Correlation function

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

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

- 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

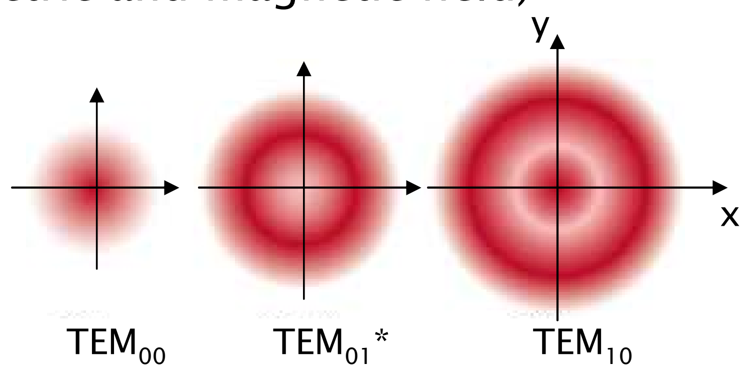
$$\tilde{E}(r,\vartheta,z) = \sum_{n,m} C_{nm}(z)\tilde{A}_{nm}(r,\vartheta)$$

- 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)

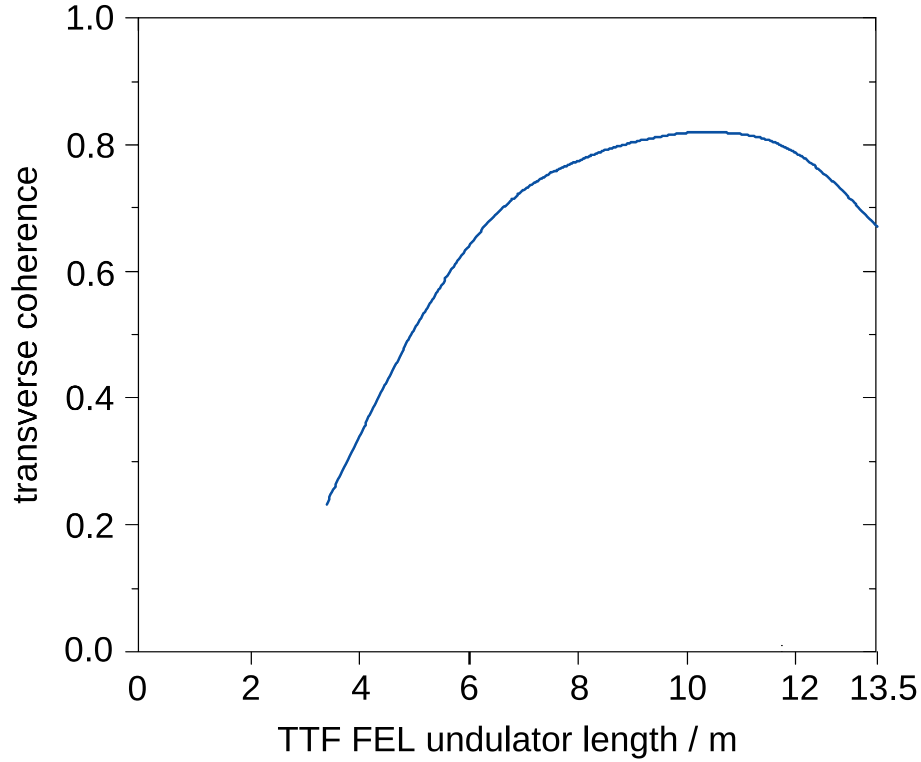
- Cross section of the first Gauß–Laguerre modes:



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

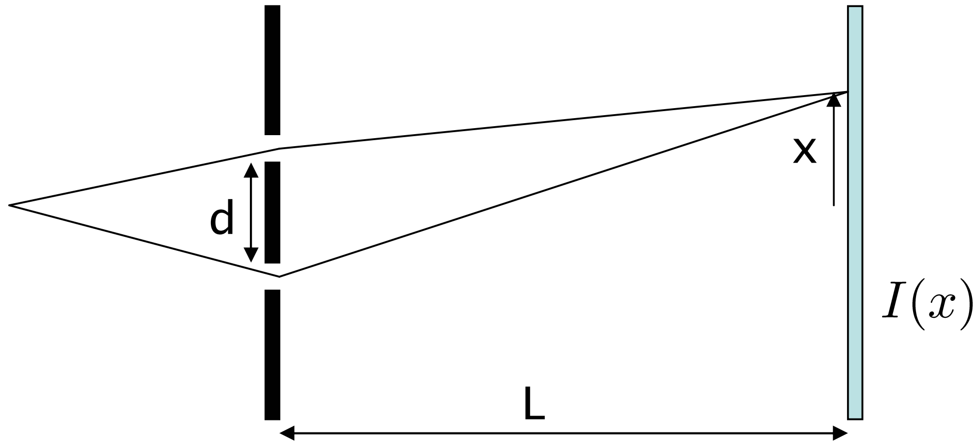
- Saturation in the last part of the undulator
  - ⇝ other modes gain importance
    - ⇝ decrease of coherence



Simulations by Saldin, Schneidmiller, Yurkov

Measurement of Coherence by Interference Experiments

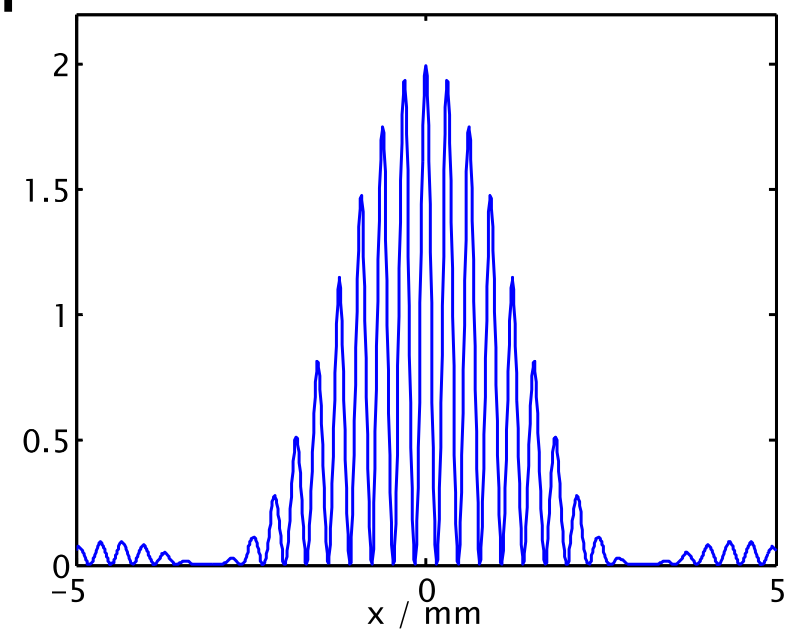
- Diffraction at a double slit:



- Visibility of the interference fringes:

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

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

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

- 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

Augustin Jean Fresnel

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

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

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

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

with

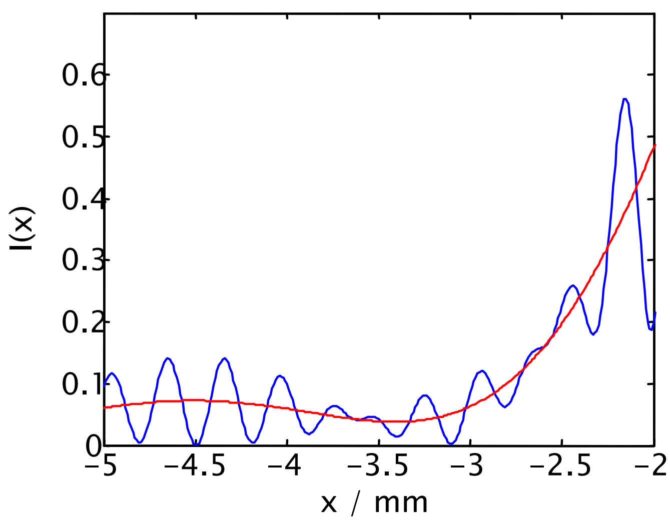
$$I_{1,2}(x) = \left(\frac{\sin(\pi w(x \pm d/2)/(\lambda L))}{\pi w(x \pm d/2)/(\lambda L)}\right)^2$$

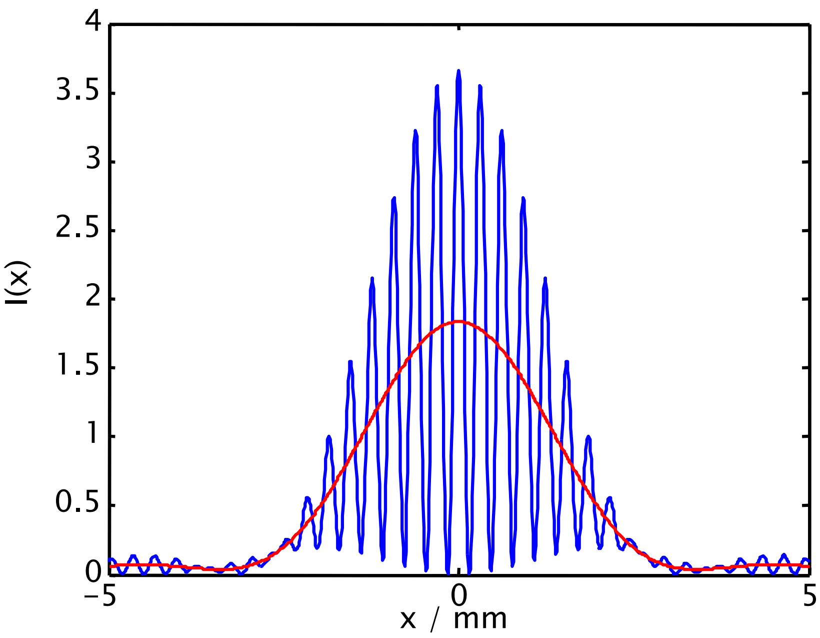
- The visibility $\mathcal{V}(x)$ is now a function of x

Fresnel diffraction a the double slit

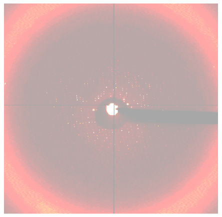
- Interference pattern

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





Transverse Coherence of a VUV Free Electron Laser



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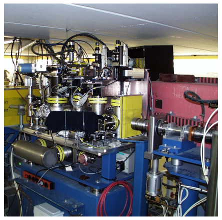
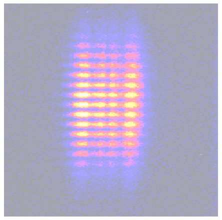


Measurements at the TTF FEL

- Challenges for the Measurements
- Experimental Setup



Results

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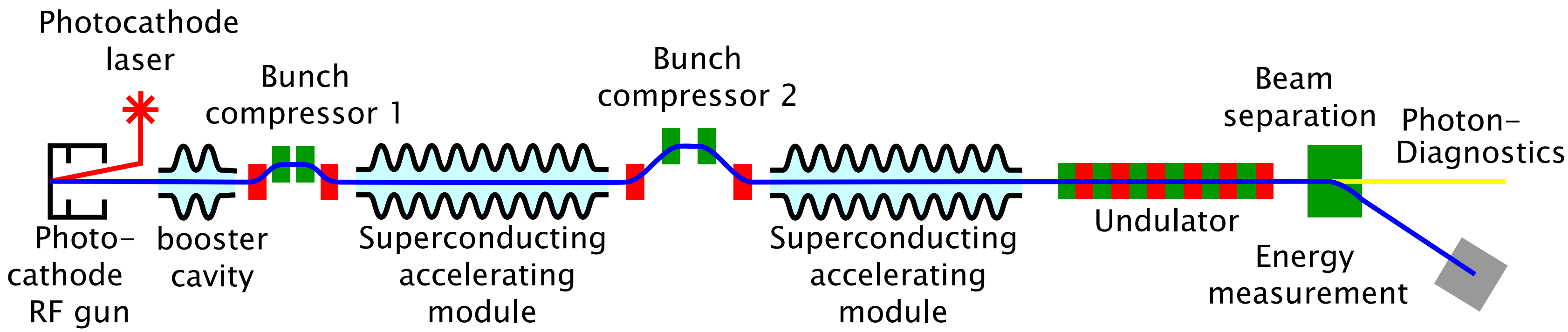
- Development along the undulator

Outlook

- Phase 2 of the TTF FEL

Experimental Setup

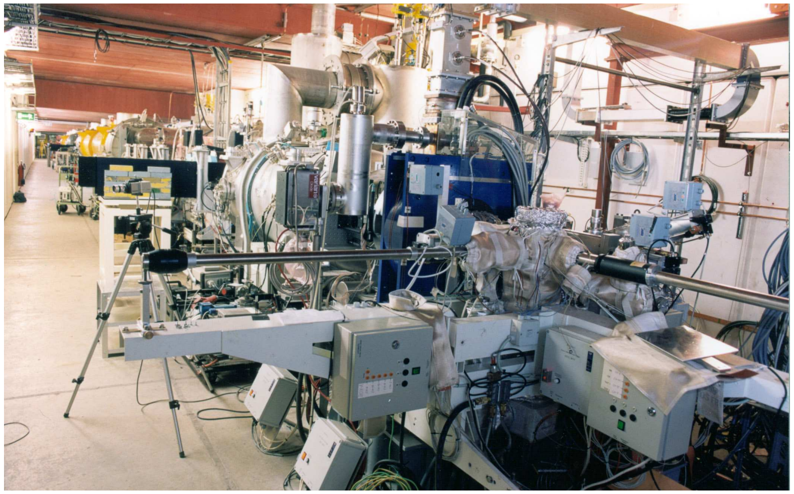
TESLA Test Facility and VUV FEL



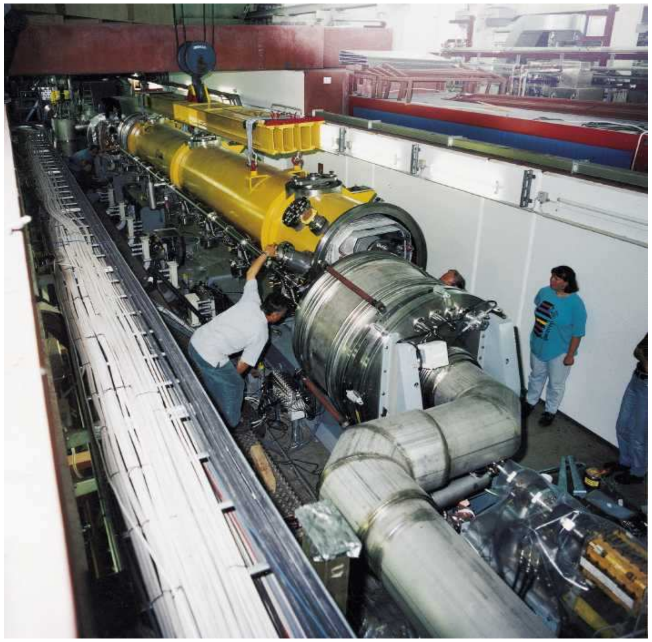
- Length: 120m
- Electron energy: 260MeV
- Peak current: 1kA
- Transverse emittance in the undulator: 8 πμm
- Wavelength of the FEL: 100nm
- Peak power of the FEL: 1GW
- Pulse energy: 10…100μJ
- Brilliance of the FEL: $4 \cdot 10^{28}$ photons / (s mm^2 mrad^2 0.1% bandwidth)

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

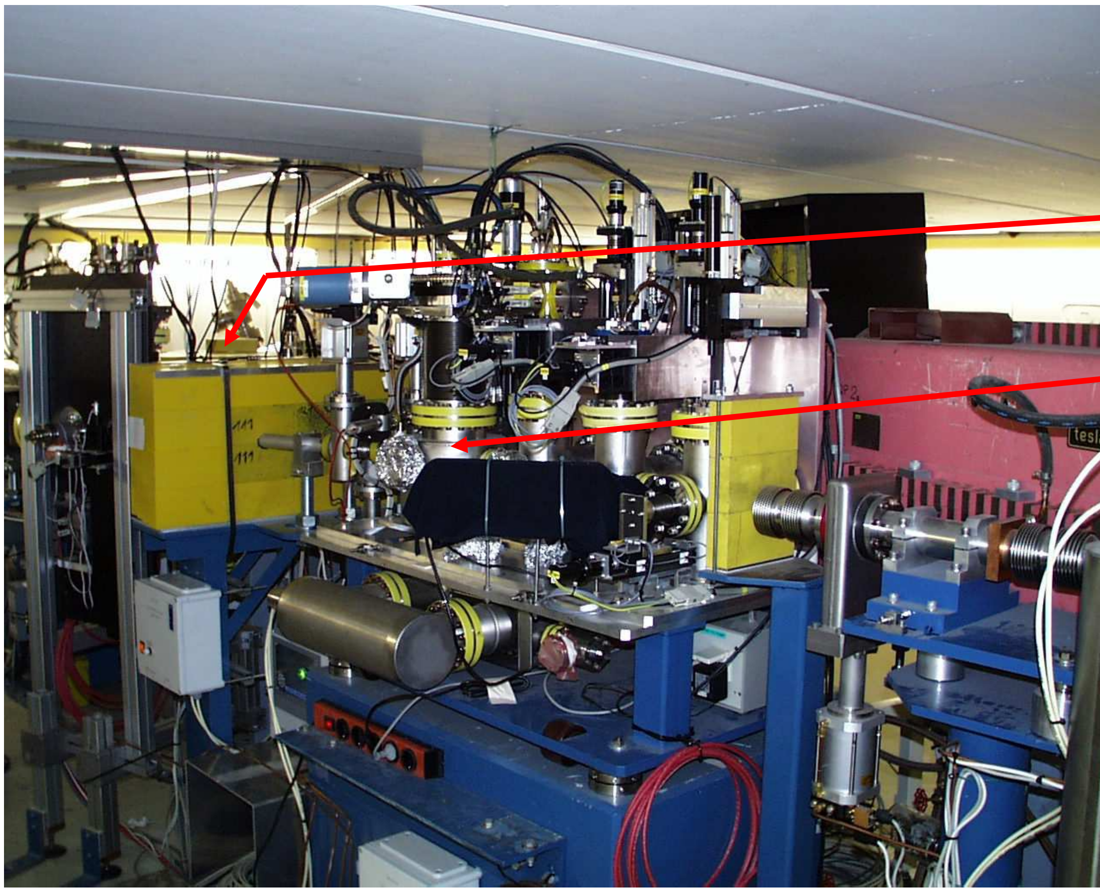
The TTF Free Electron Laser

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 $10 mm^2$
  - 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

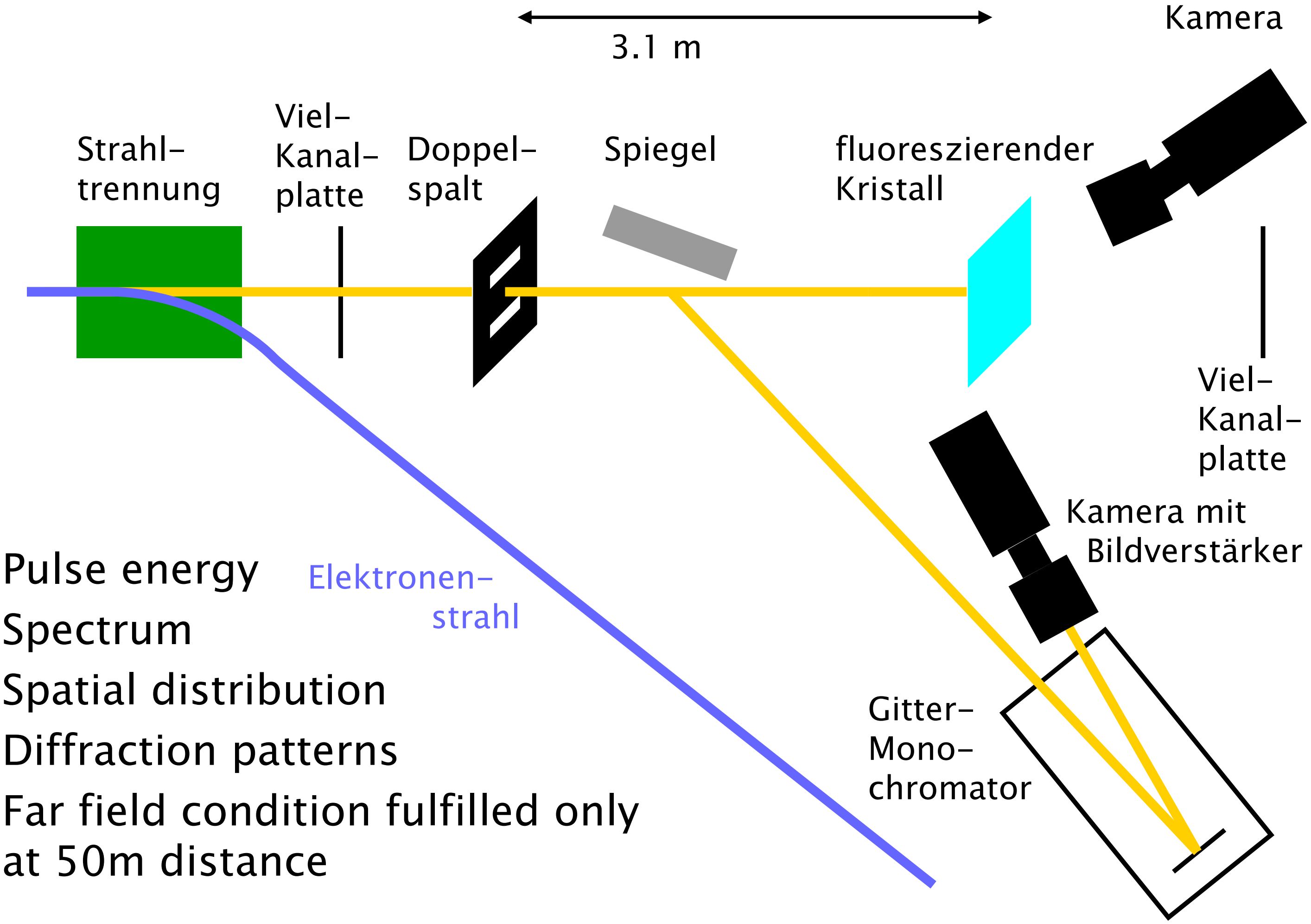
Experimental Setup

Photon diagnostics at the TTF FEL



Experimental Setup

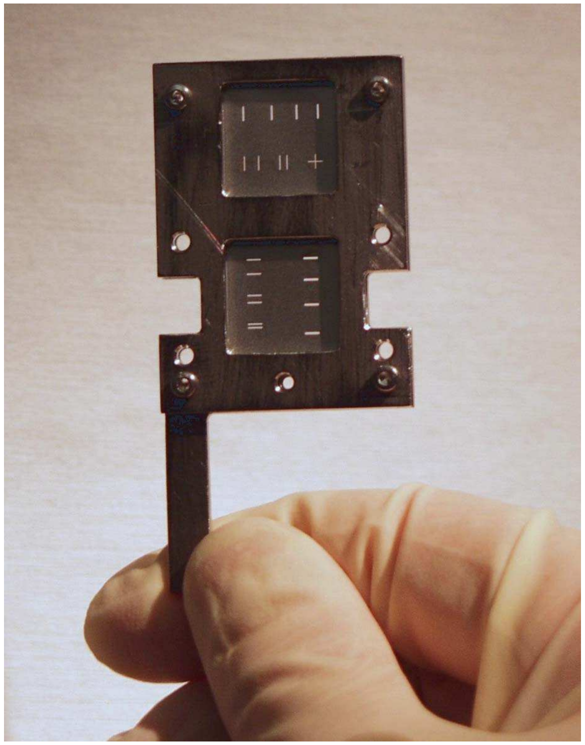
Photon Diagnostics at the TTF FEL

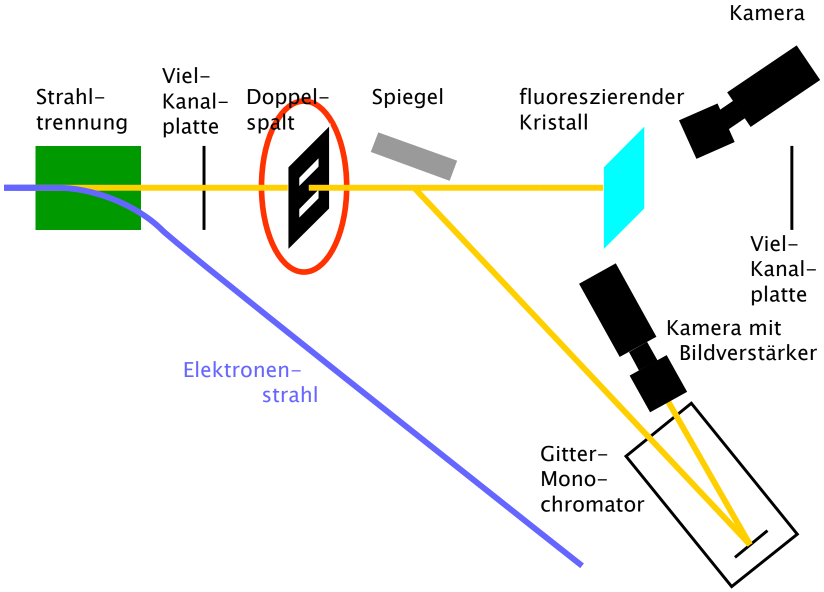


- Pulse energy
- Spectrum
- Spatial distribution
- Diffraction patterns
- Far field condition fulfilled only at 50m distance

Experimental Setup
Double Slits

- Laser cut into stainless steel foil



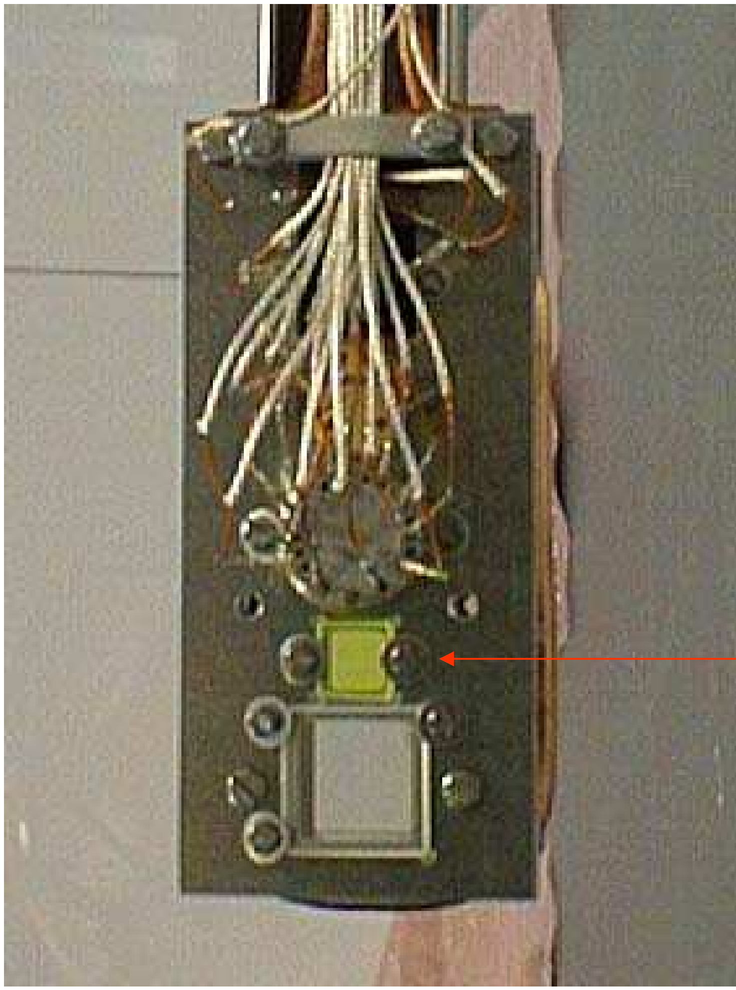


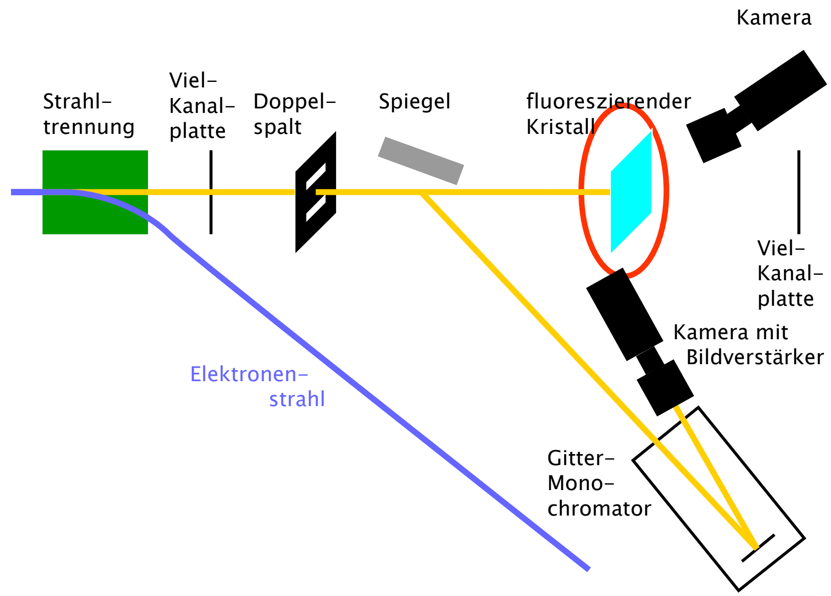
- Slit separations: 0.5, 1, 2 und 3mm
- Slit width: 100µm
- Slit length: 2mm

- Positioned by two stepper motors

Experimental Setup

Fluorescent Crystal

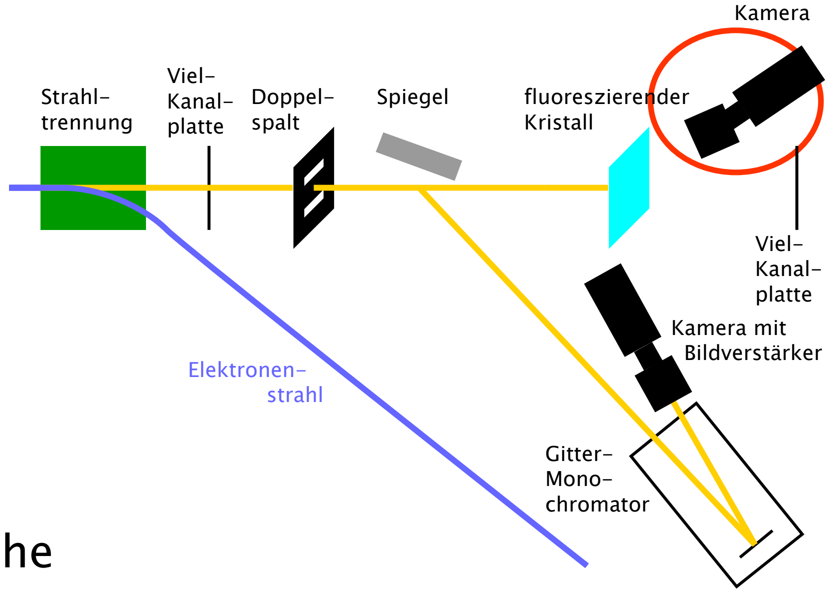




Ce:YAG crystal

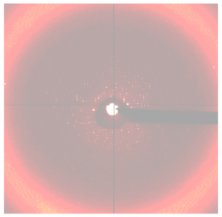
on a watercooled frame

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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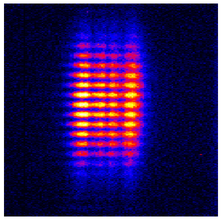

Results

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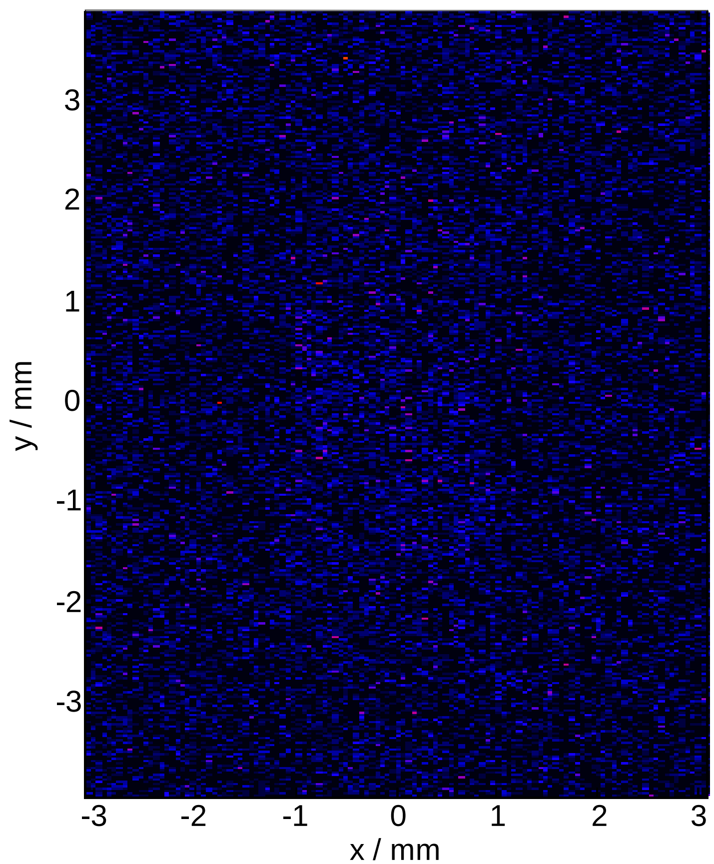
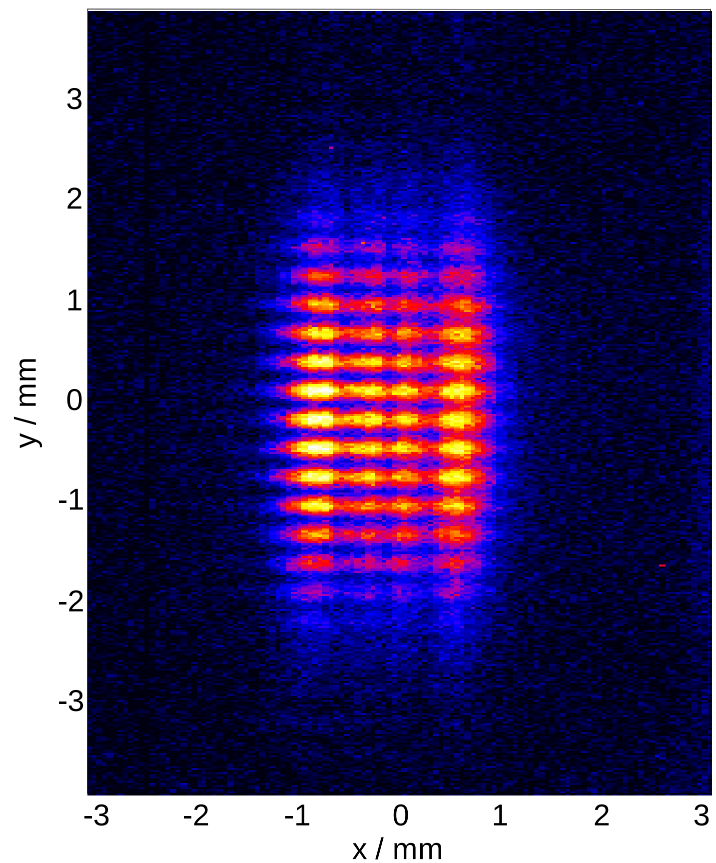
Diffraction Patterns

- 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

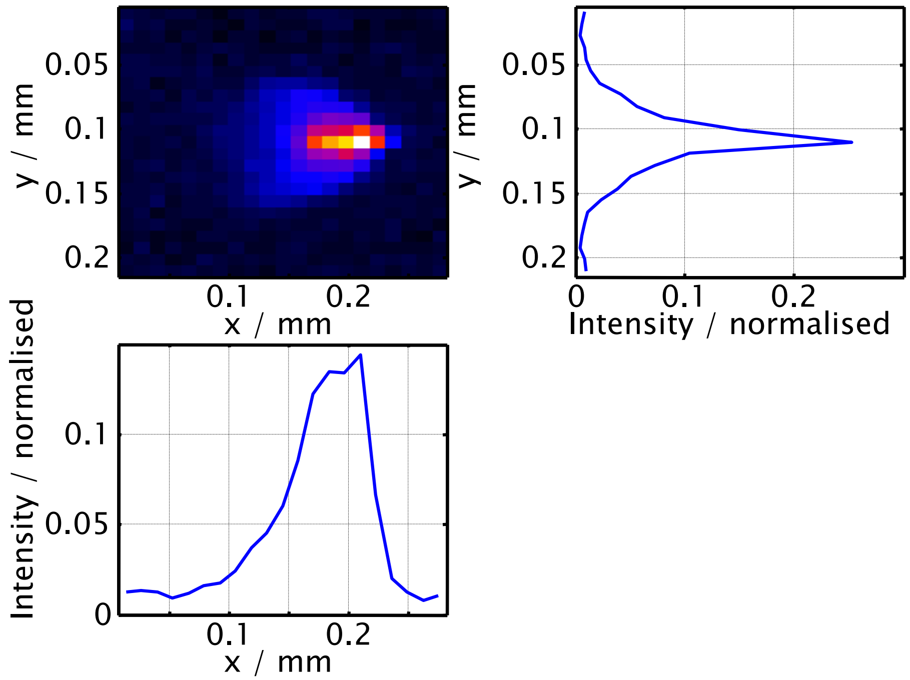
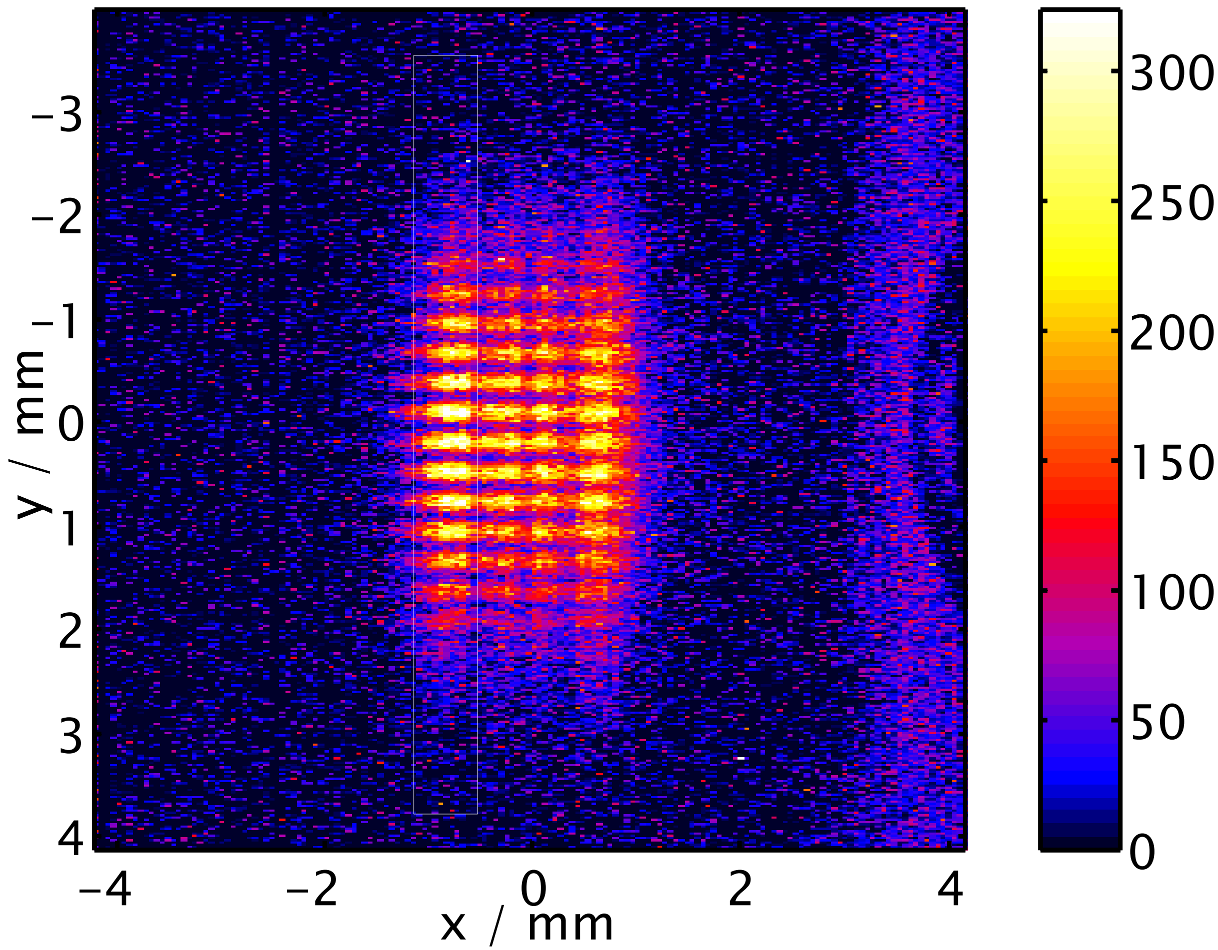


Image Processing

Corrected Diffraction Pattern

Corrections:

- Non-linearity
- Resolution



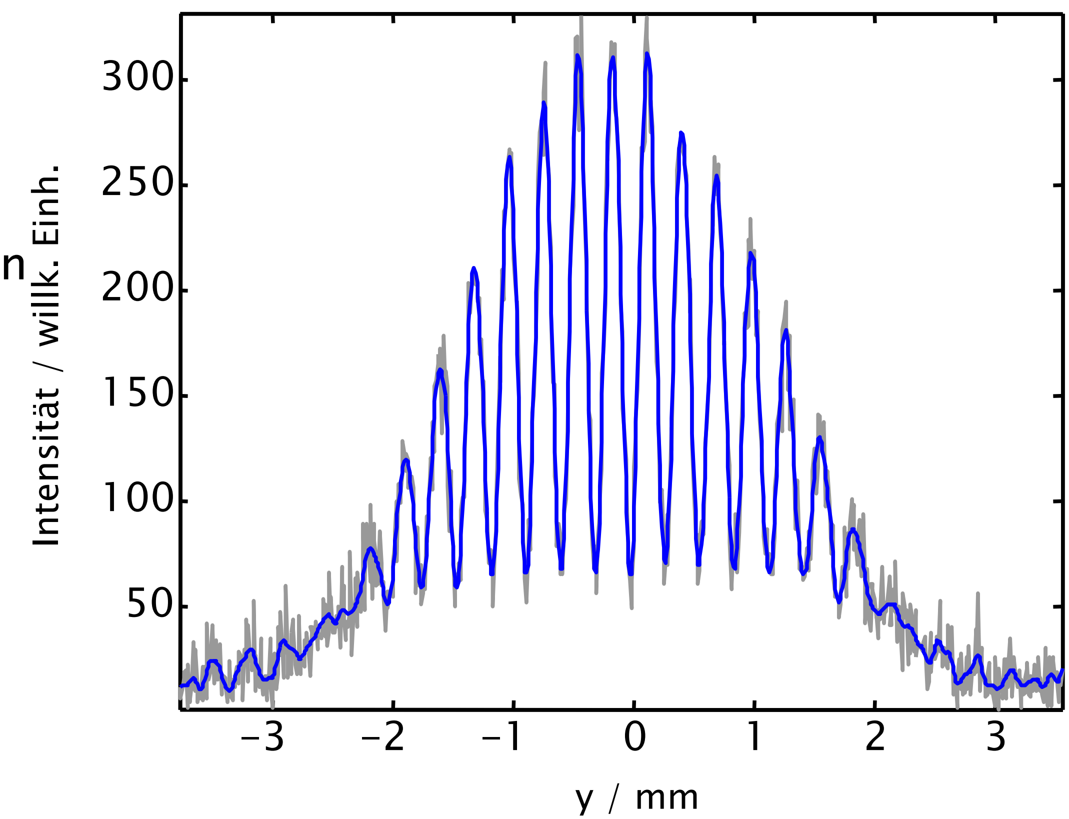
Analysis

- 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

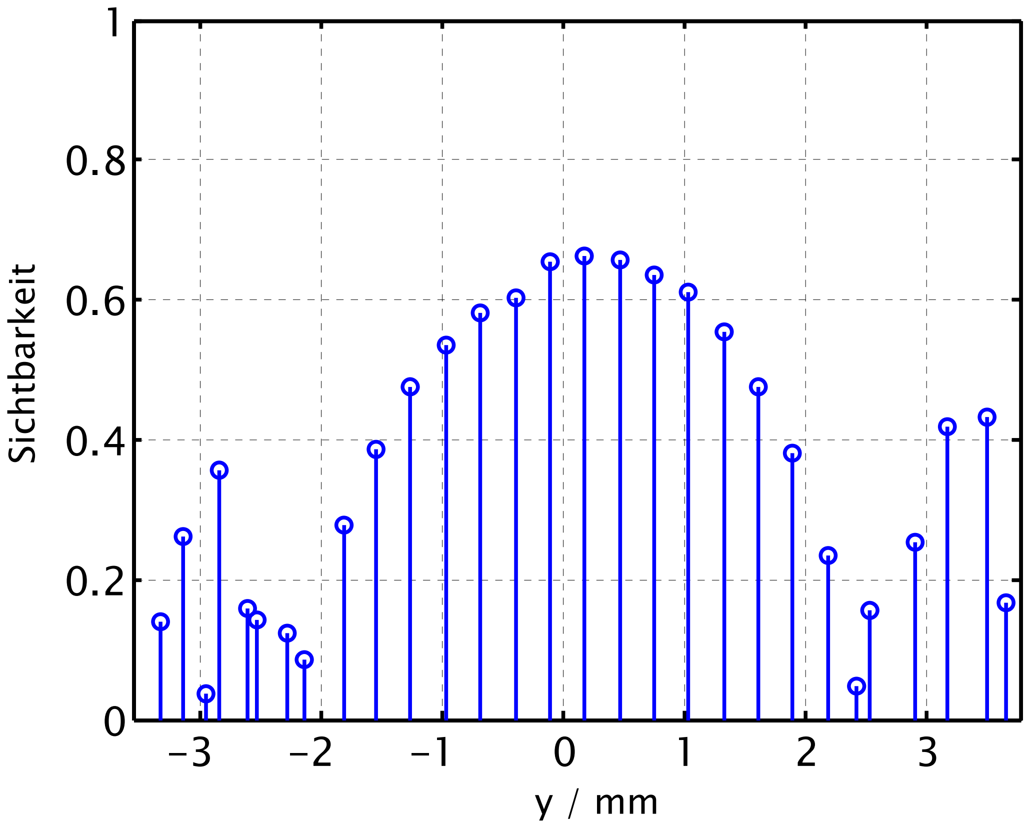


Analysis 1:
Visibility of the Interference Fringes

- Compute the visibility

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

from the maxima and minima of the curve

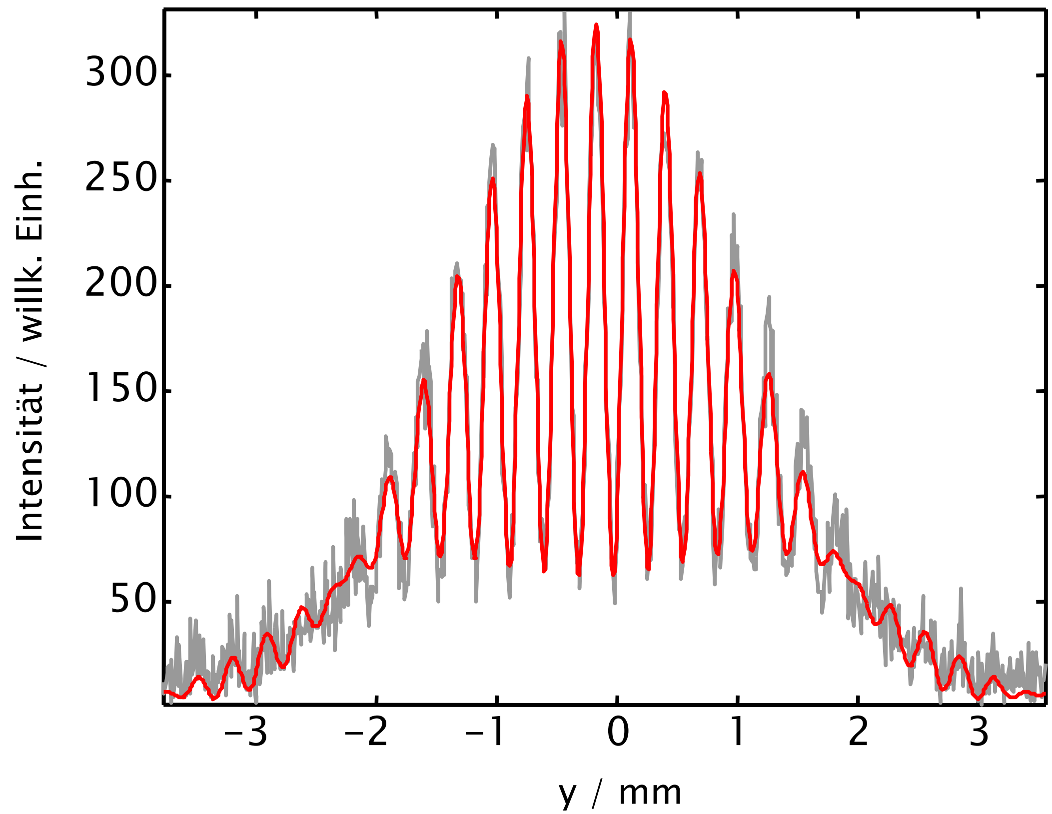


Analysis 2:

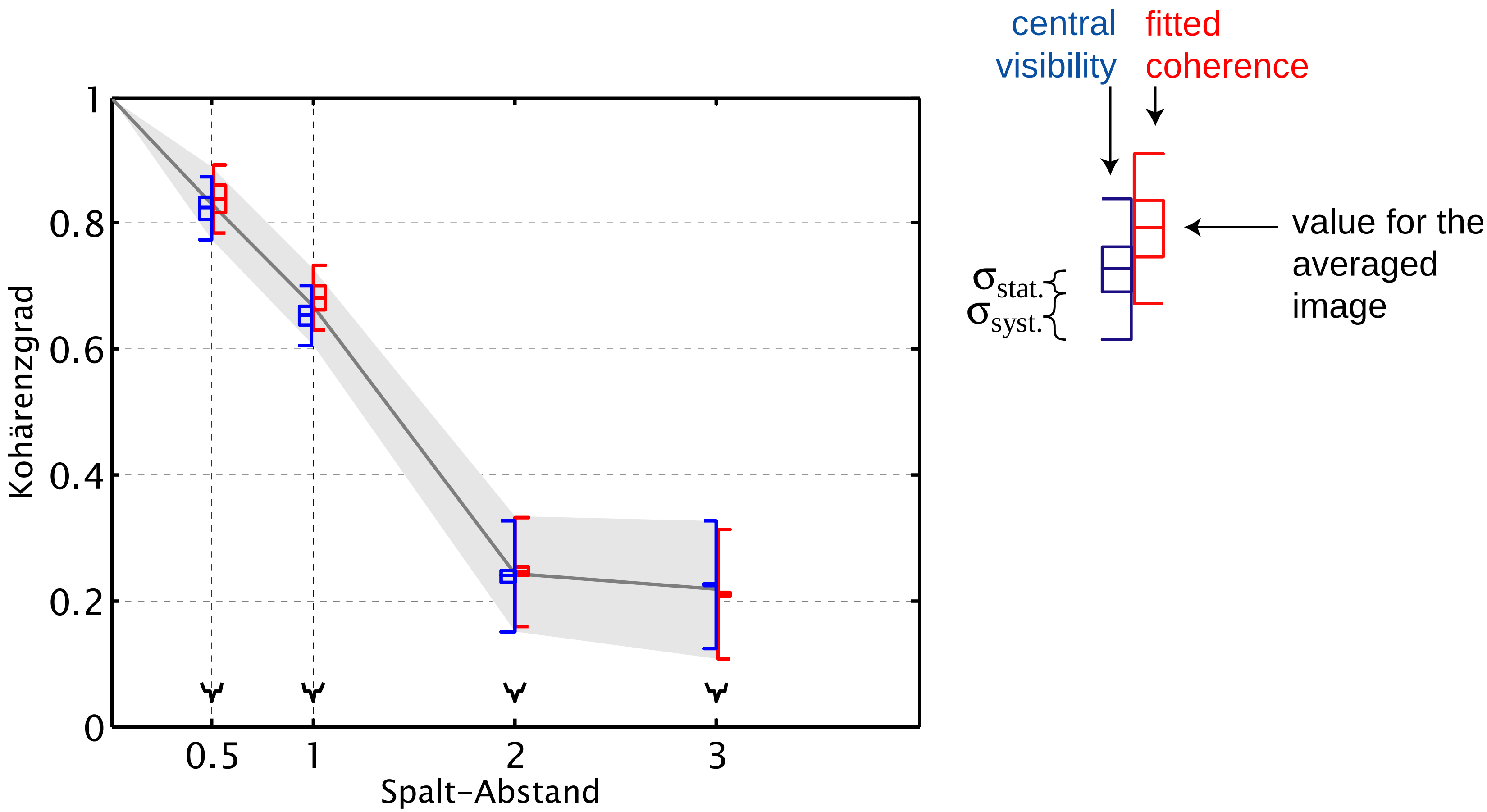
Fit to the Intensity Distribution

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



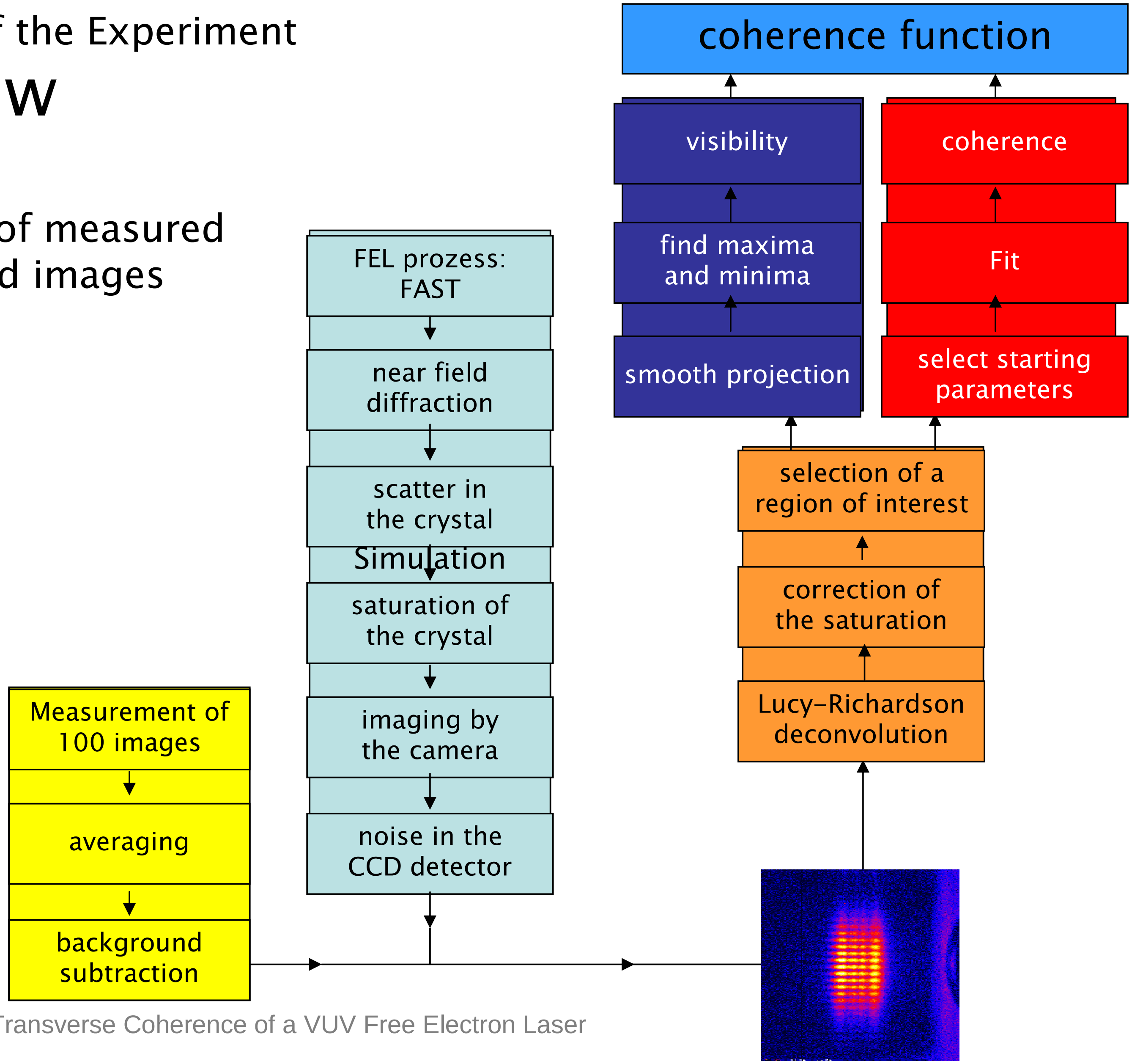
Simulation of the Experiment

- 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

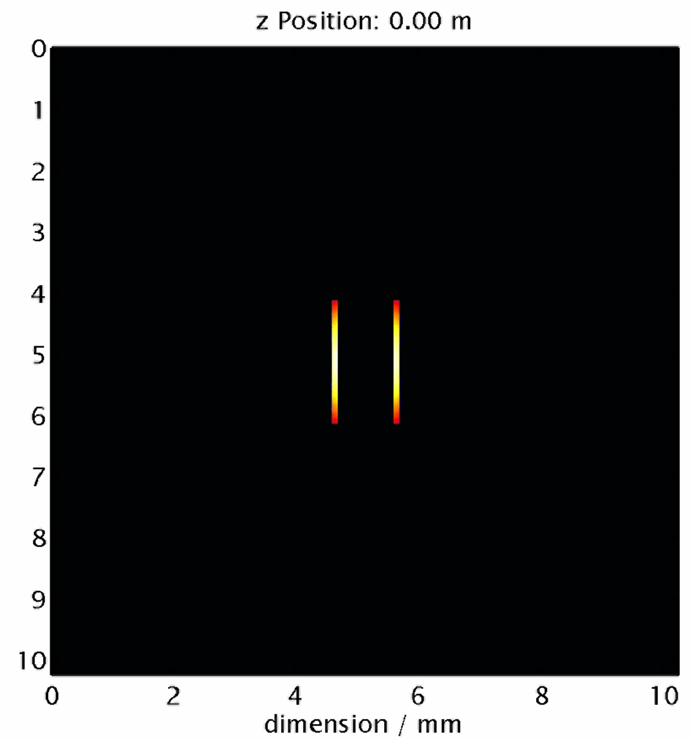
Comparison of measured and simulated images



Simulation of the Experiment
Interference Effects

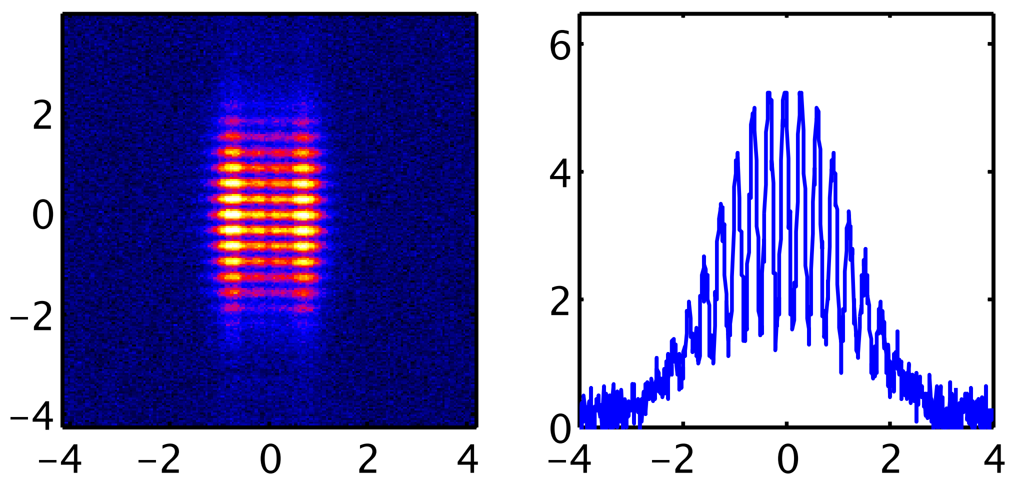
Near field diffraction (GLAD)

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



Simulation of the 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



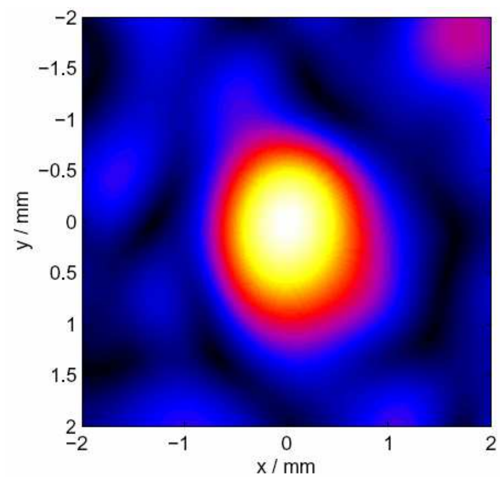
Simulation of the Experiment

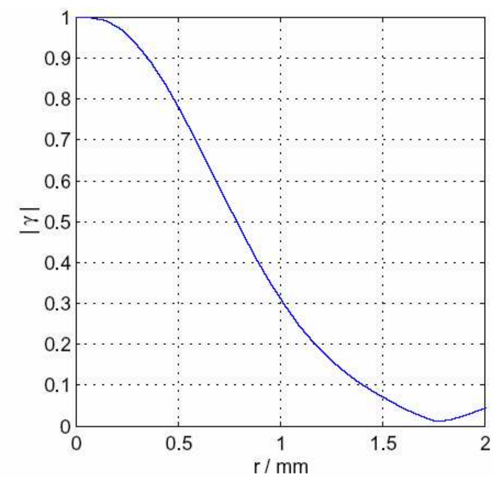
Analysis of Simulated Images

- 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

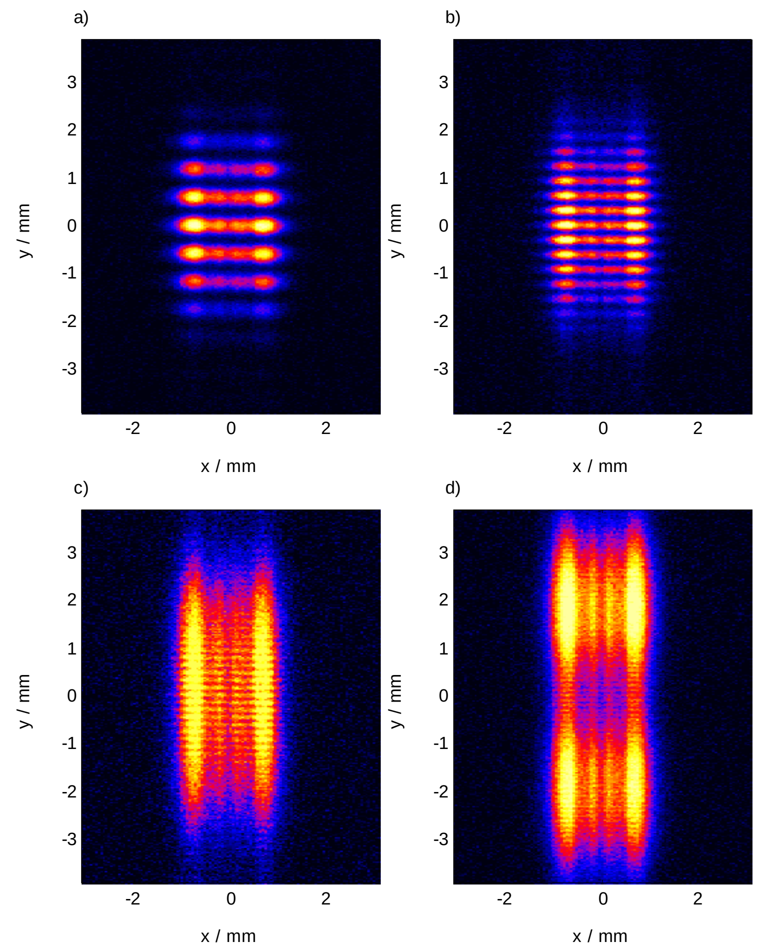




Simulations: Summary

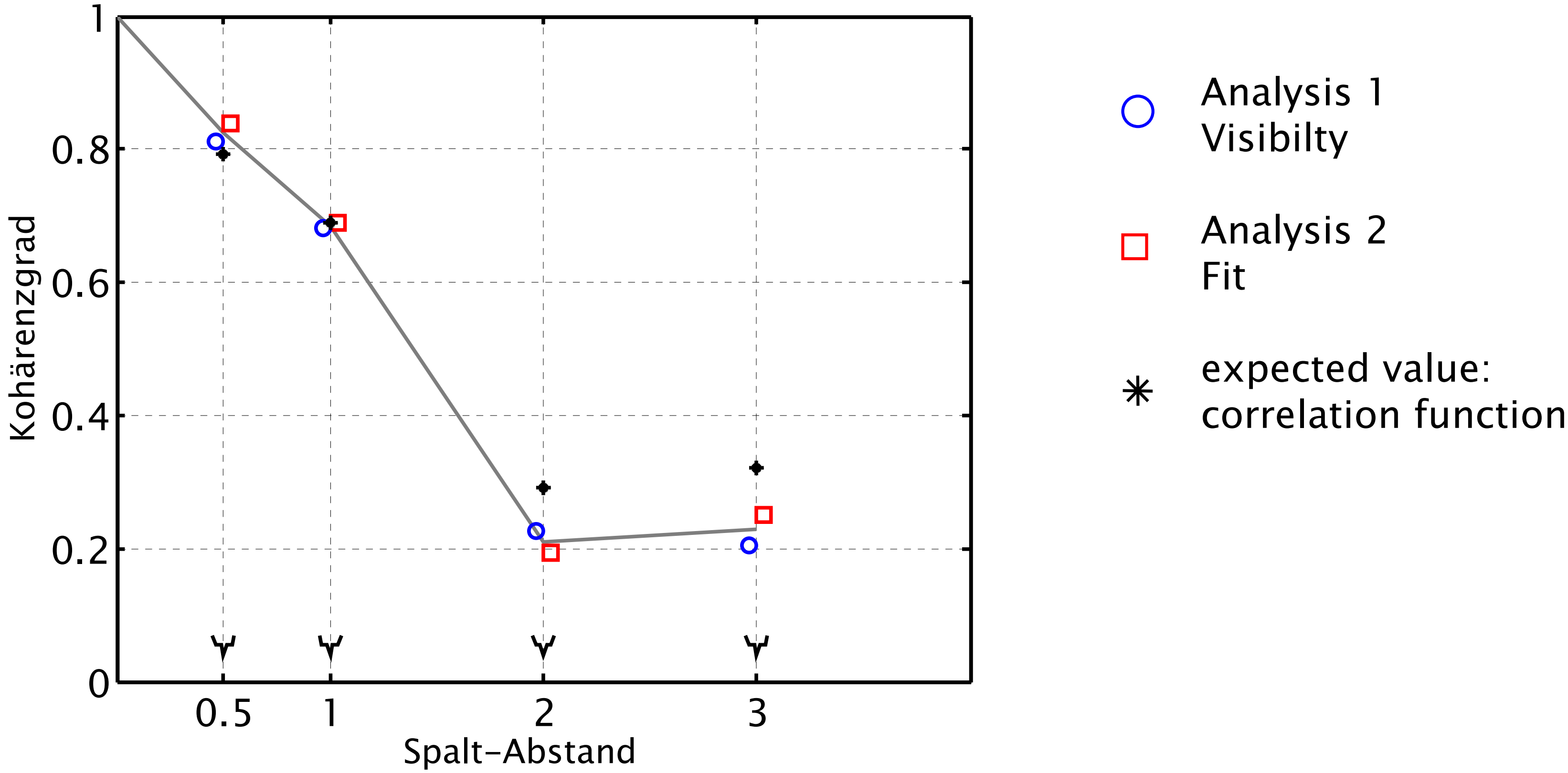
Simulations of

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

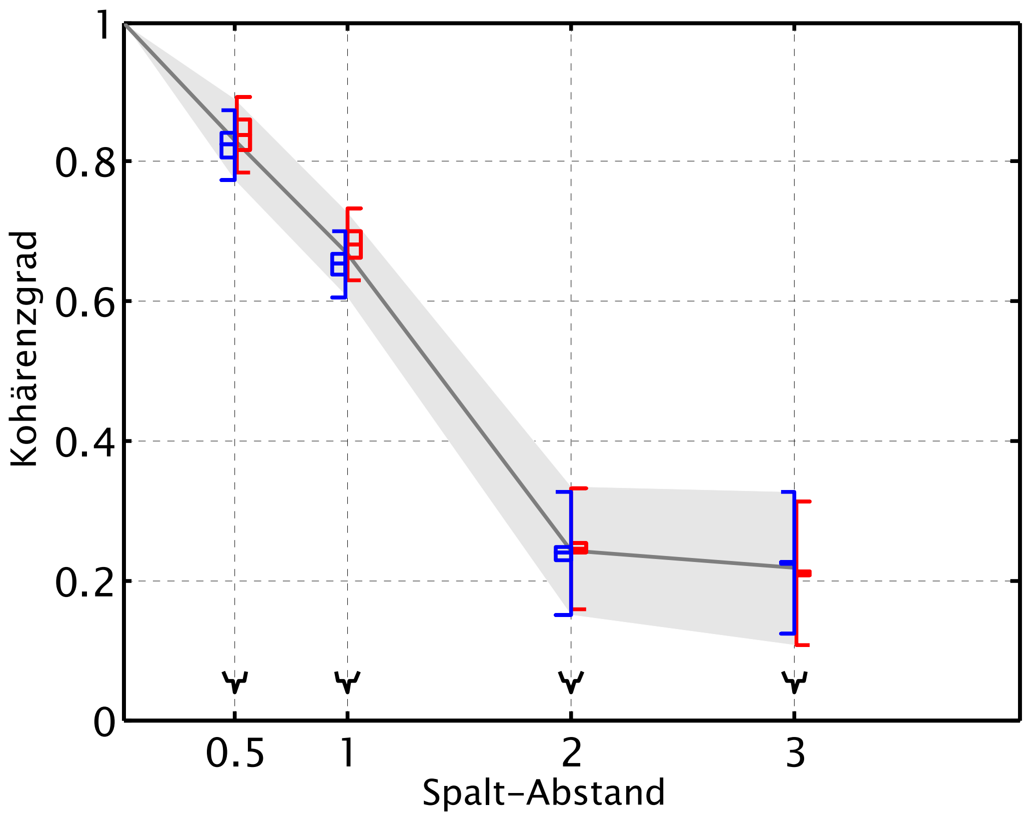


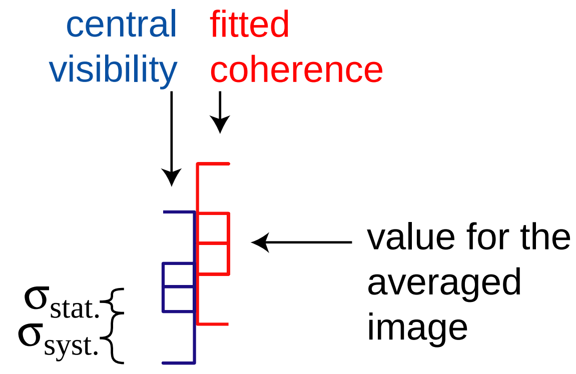
Simulations:

Spatial Coherence as a function of Slit Separation



Reminder:
Result of the Measurements

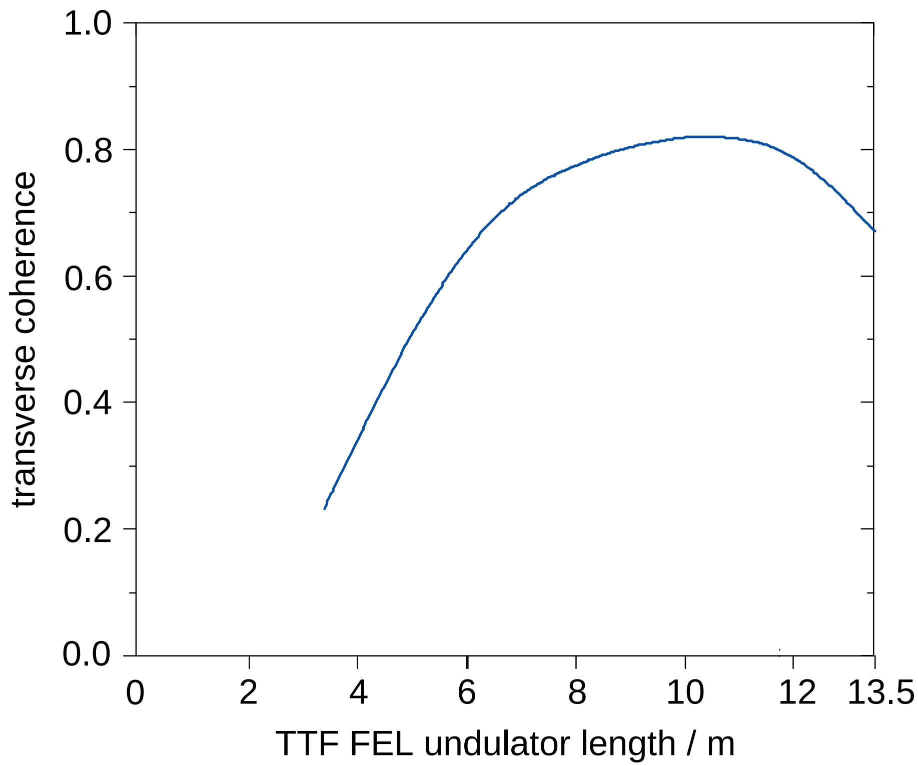




Evolution of the Coherence along the Undulator

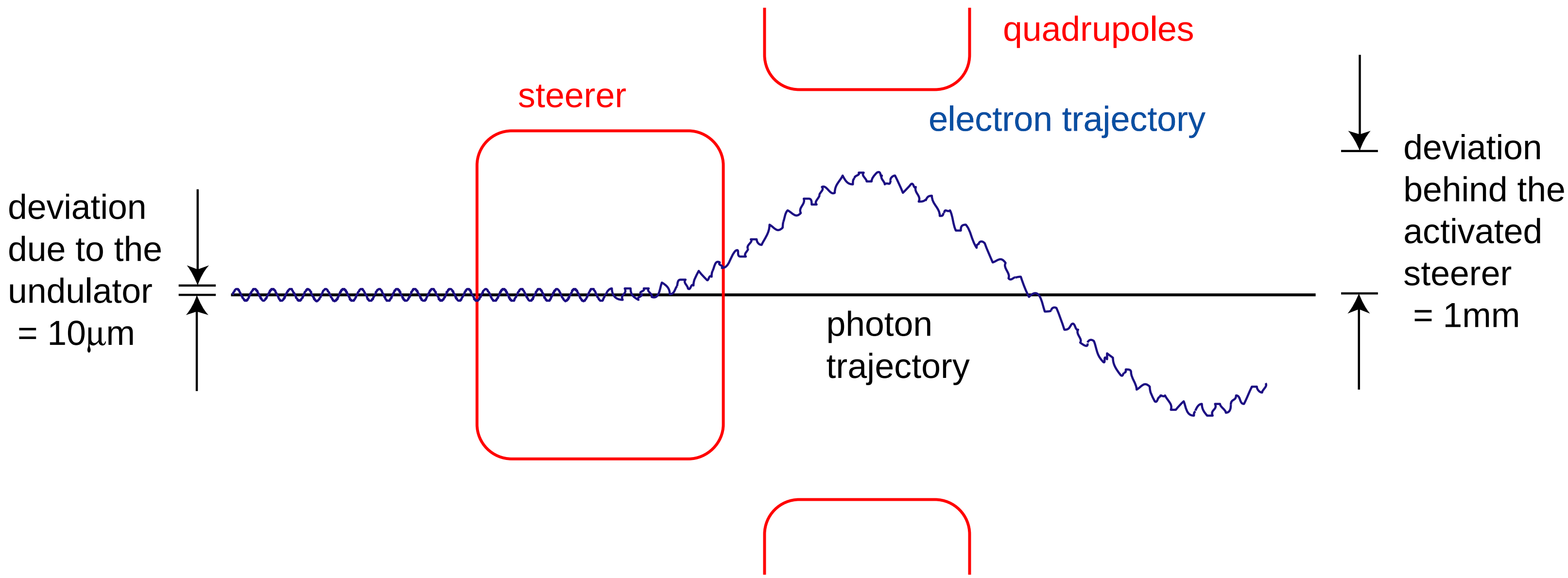
- Reminder: theoretic prediction

- How can the undulator length be adjusted?



Evolution of the Coherence along the Undulator

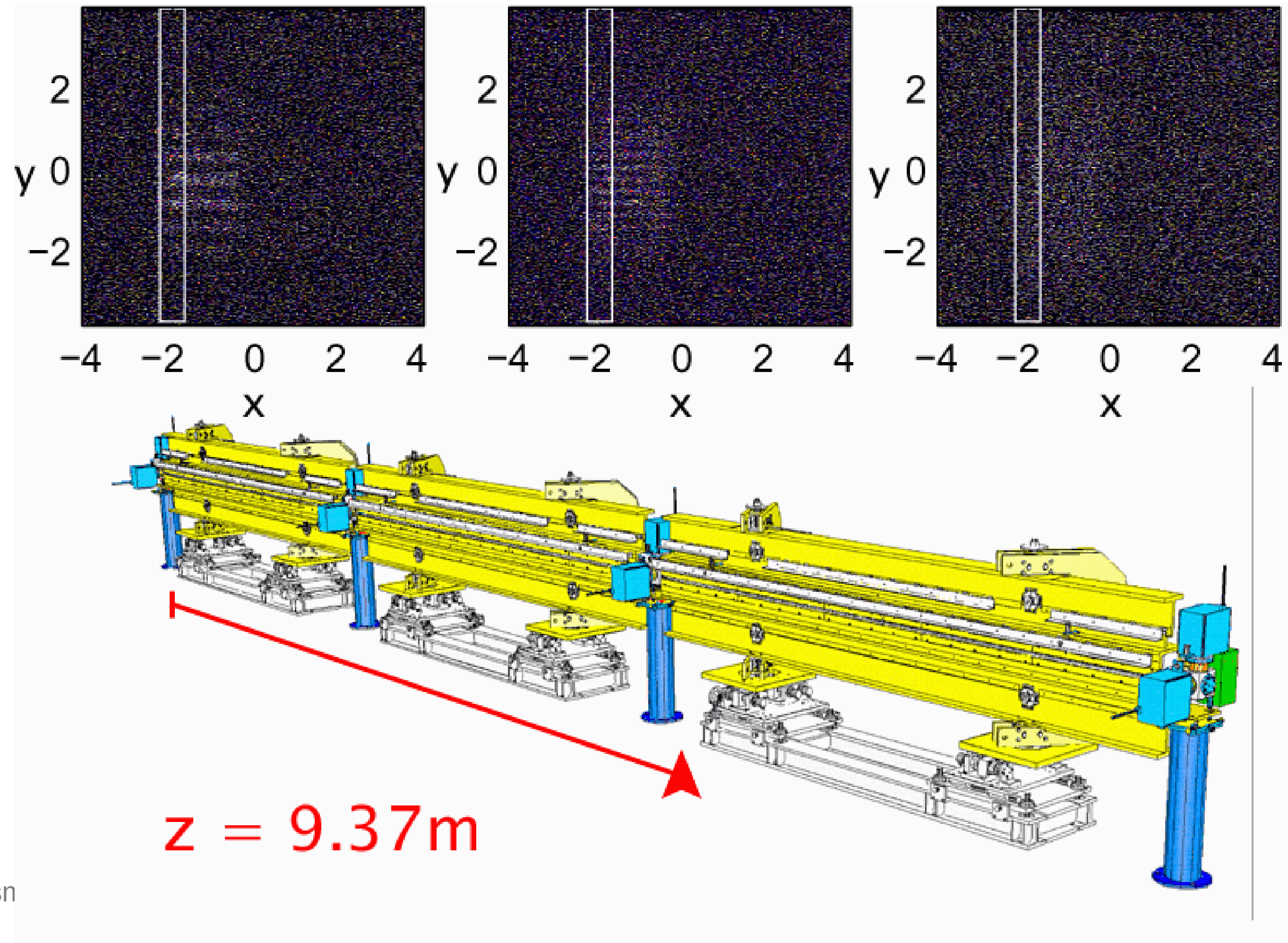
- Undulator can be virtually shortened by displacing the beam from the ideal trajectory
- Measurements possible in the last third of the undulator



Evolution of the Coherence along the Undulator

Diffraction patterns

Slit separation: 0.5mm 1mm 2mm

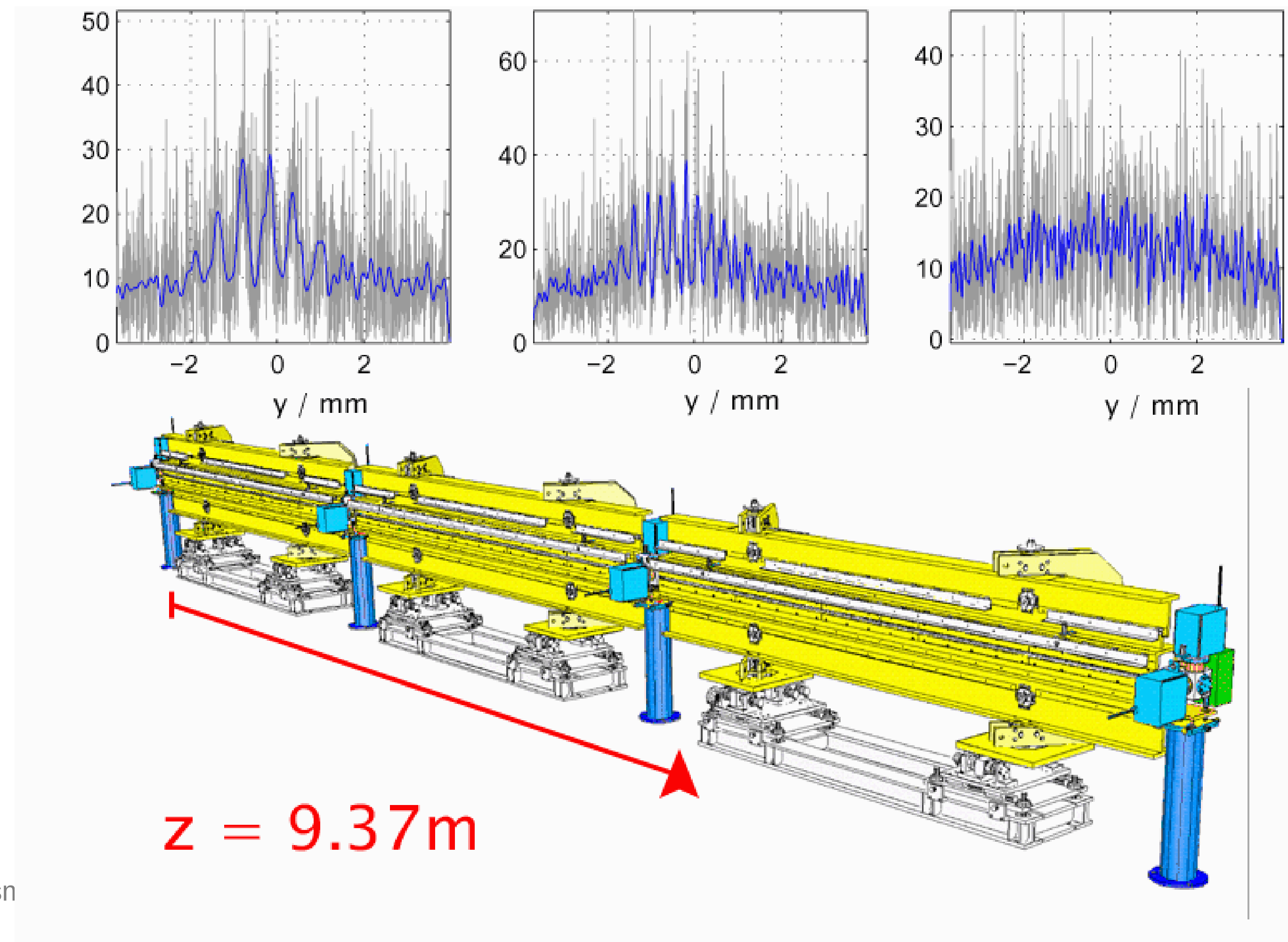


Rasn

Evolution of the Coherence along the Undulator

Filtered Projection

Slit separation: 0.5mm 1mm 2mm



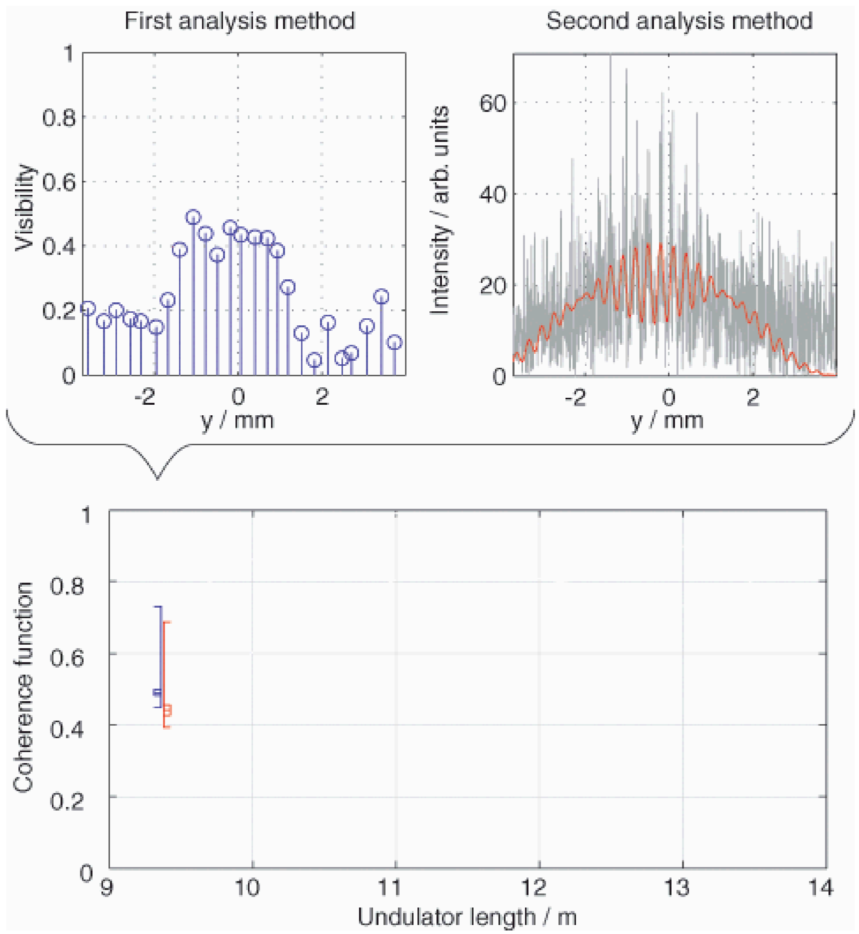
Rasn

Evolution of the Coherence along the Undulator

Results

Results of the analysis:

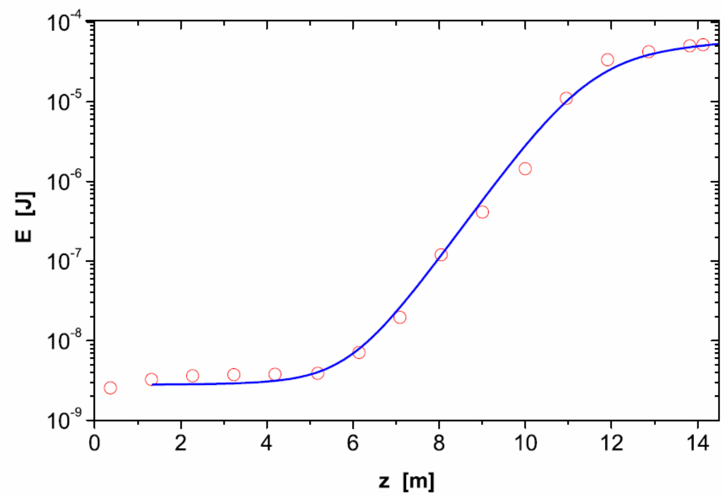
- Visibilty determined from the maxima and minima of the smoothed projection
- Fit of the near field diffraction pattern to the intensity distributions

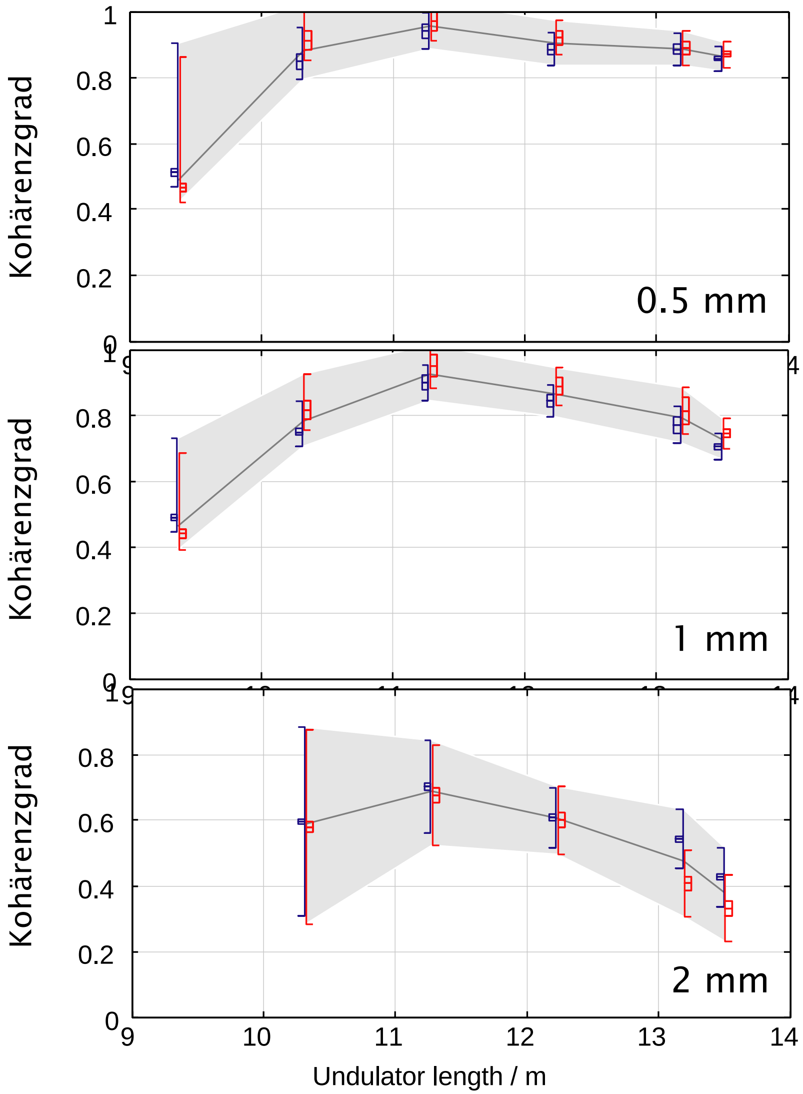


Evolution of the Coherence along the Undulator

Results

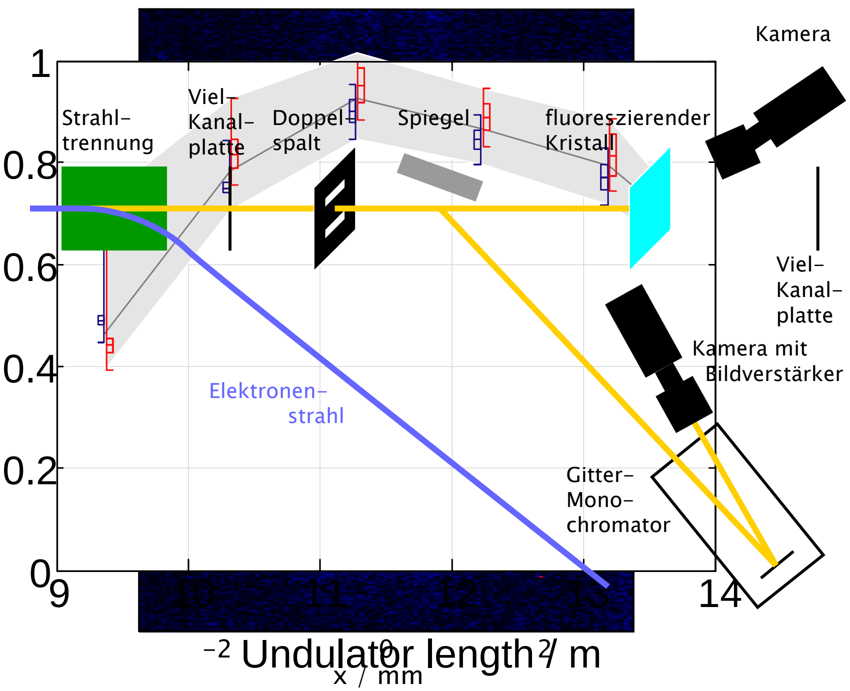
- Coherence function for slit separations of 0.5, 1 and 2 mm
- Compare the intensity of the FEL (measured with the MCP detector)



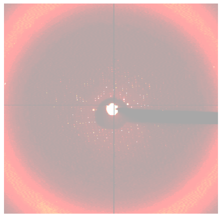


Summary

- 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

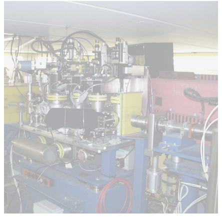


Transverse Coherence of a VUV Free Electron Laser



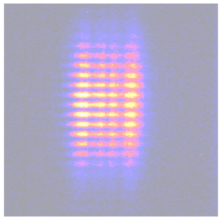
Introduction

- 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

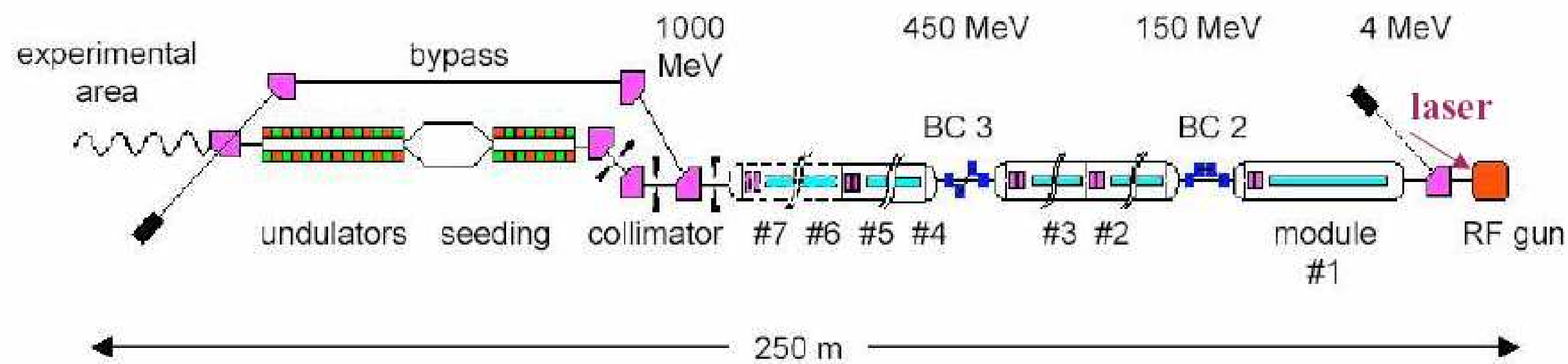
⇒ FEL wavelengths down to 6 nm

- Operation with the electron beam will start March 8, 2004

Outlook

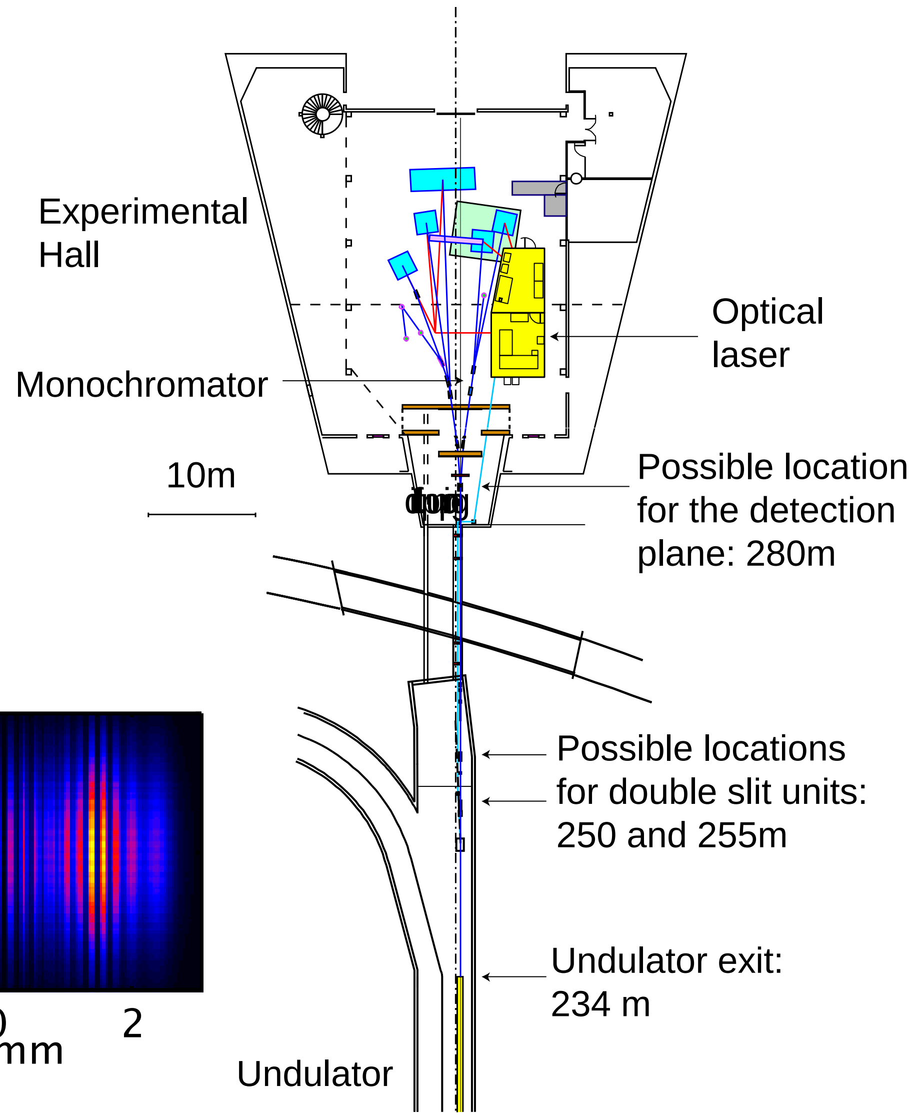
As compared to TTF1:

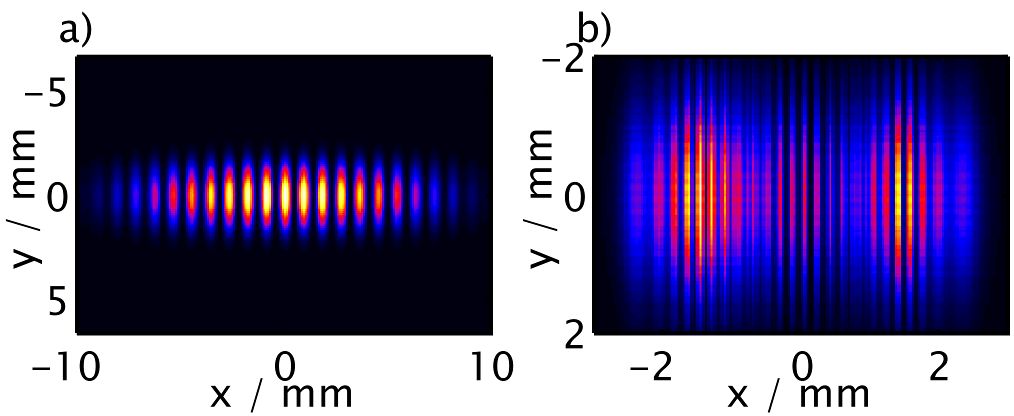
- higher electron energy by more superconducting accelerating modules, operating at higher electric field
- improved gun design
- smaller distance between gun and first acceleration module
- a bypass for the undulator
- undulator with external focusing
- much more space for experiments with the FEL radiation!



Outlook

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





30nm

6nm

Thank you to the TTF Team!

V. Ayvazyan, N. Baboi, I. Bohnet, R. Brinkmann, M. Castellano, P. Castro, L. Catani, S. Casalbuono, S. Choroba, A. Cianchi, M. Dohlus, H.T. Edwards, B. Faatz, A.A. Fateev, J. Feldhaus, K. Flöttmann, A. Gamp, T. Garvey, H. Genz, Ch. Gerth, V. Gretchko, B. Grigoryan, U. Hahn, C. Hessler, K. Honkavaara, M. Hüning, M. Jablonka, T. Kamps, M. Körfer, M. Krassilnikov, J. Krzywinski, P. Kulinski, C. Lackas, M. Liepe, A. Liero, T. Limberg, H. Loos, M. Luong, C. Magne, J. Menzel, P. Michelato, M. Minty, U.-C. Müller, D. Nölle, A. Novokhatski, C. Pagani, F. Peters, J. Petrowicz, J. Pflüger, P. Piot, L. Plucinski, K. Rehlich, I. Reyzl, A. Richter, J. Rossbach, E. Saldin, W. Sandner, H. Schlarb, G. Schmidt, P. Schmüser, J.R. Schneider, E. Schneidmiller, H.-J. Schreiber, S. Schreiber, D. Sertore, S. Setzer, S. Simrock, R. Sobierajski, B. Sonntag, B. Steffen, B. Steeg, F. Stephan, N. Sturm, K.P. Sytchev, K. Tiedtke, M. Tonutti, R. Treusch, D. Trines, D. Türke, V. Verzilov, R. Wanzenberg, T. Weiland, H. Weise, M. Wendt, T. Wilhein, I. Will, A. Winter, K. Wittenburg, S. Wolff, M. Yurkov, K. Zapfe