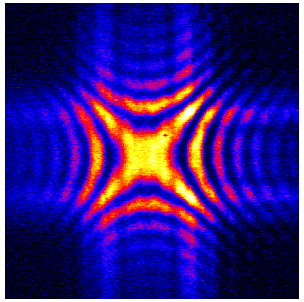

A Double Slit Experiment to Study the Transverse Coherence of the TTF Free Electron Laser

Rasmus Ischebeck

A Double Slit Experiment to Study the Transverse Coherence of the TTF FEL

- Introduction
    - TTF Linear Accelerator and Free Electron Laser
    - Photon Diagnostics
    - Near Field Diffraction Effects
- Measurements
- Image Processing
- Analysis
- Simulations
- Consistency of the Measurements
- Development of Transverse Coherence
- Outlook

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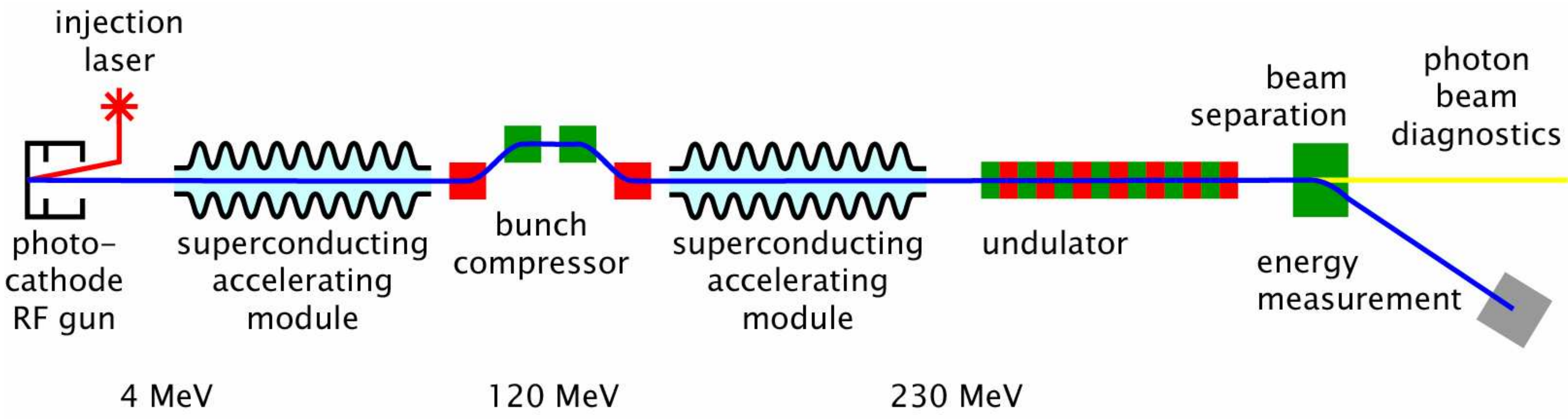
TTF FEL

Linear Accelerator

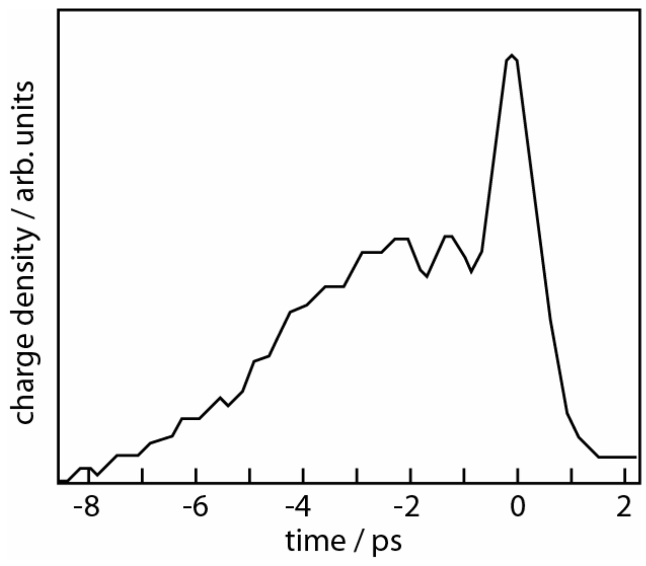
- Gun
- Superconducting RF Cavities
- Bunch Compressor
- Undulator
- SASE



total length: 120 m

Properties of the Electron Bunch

- Energy: 230 MeV per particle
- Bunch charge: 3 nC
  (Radiating bunch charge: 0.2 nC)
- Beam current > 1 kA
- Up to 70 bunches per second



Measurement by interferometry of coherent transition radiation

Experimental Set-Up

Properties of the FEL Light

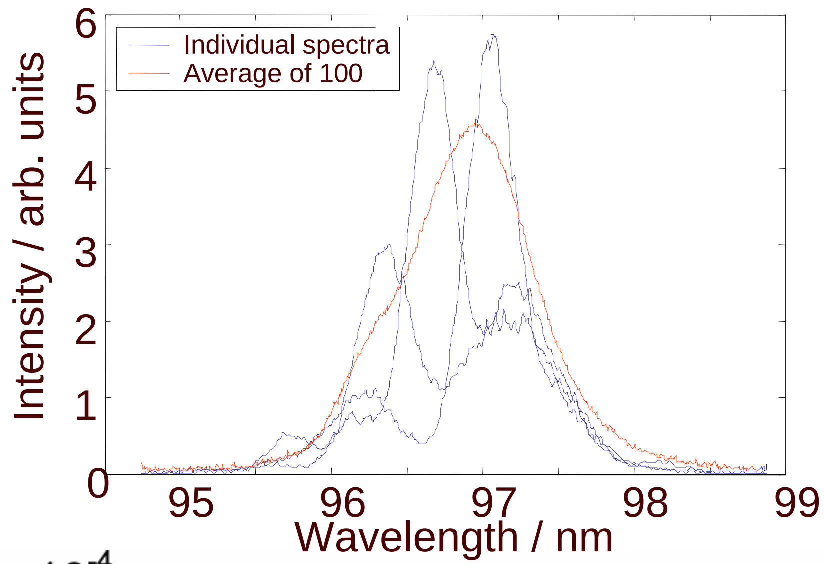
- Wavelength: 80 … 120 nm, depending on the electron energy
- Pulse energy: typically up to 10 μJ per pulse
- Peak power: 1 GW
- FEL starts from noise

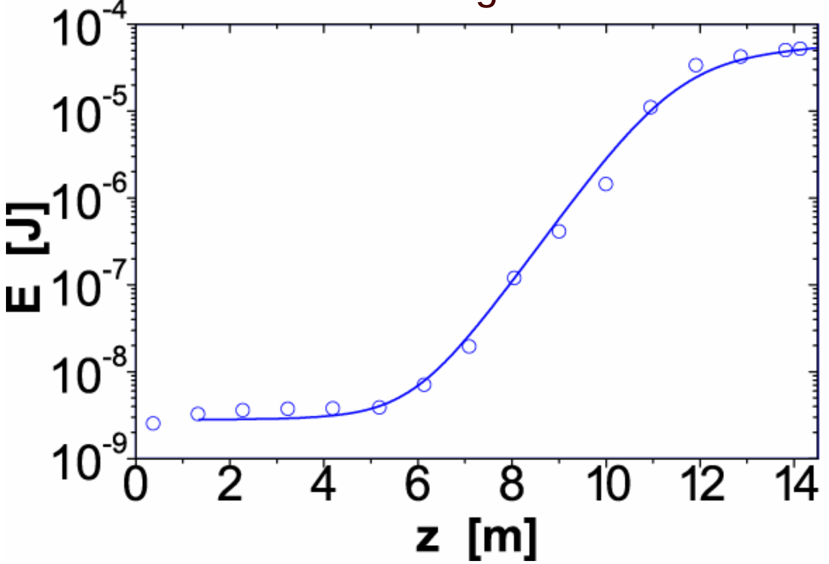
⇒ No input needed

- Single pass saturation

⇒ No mirrors needed

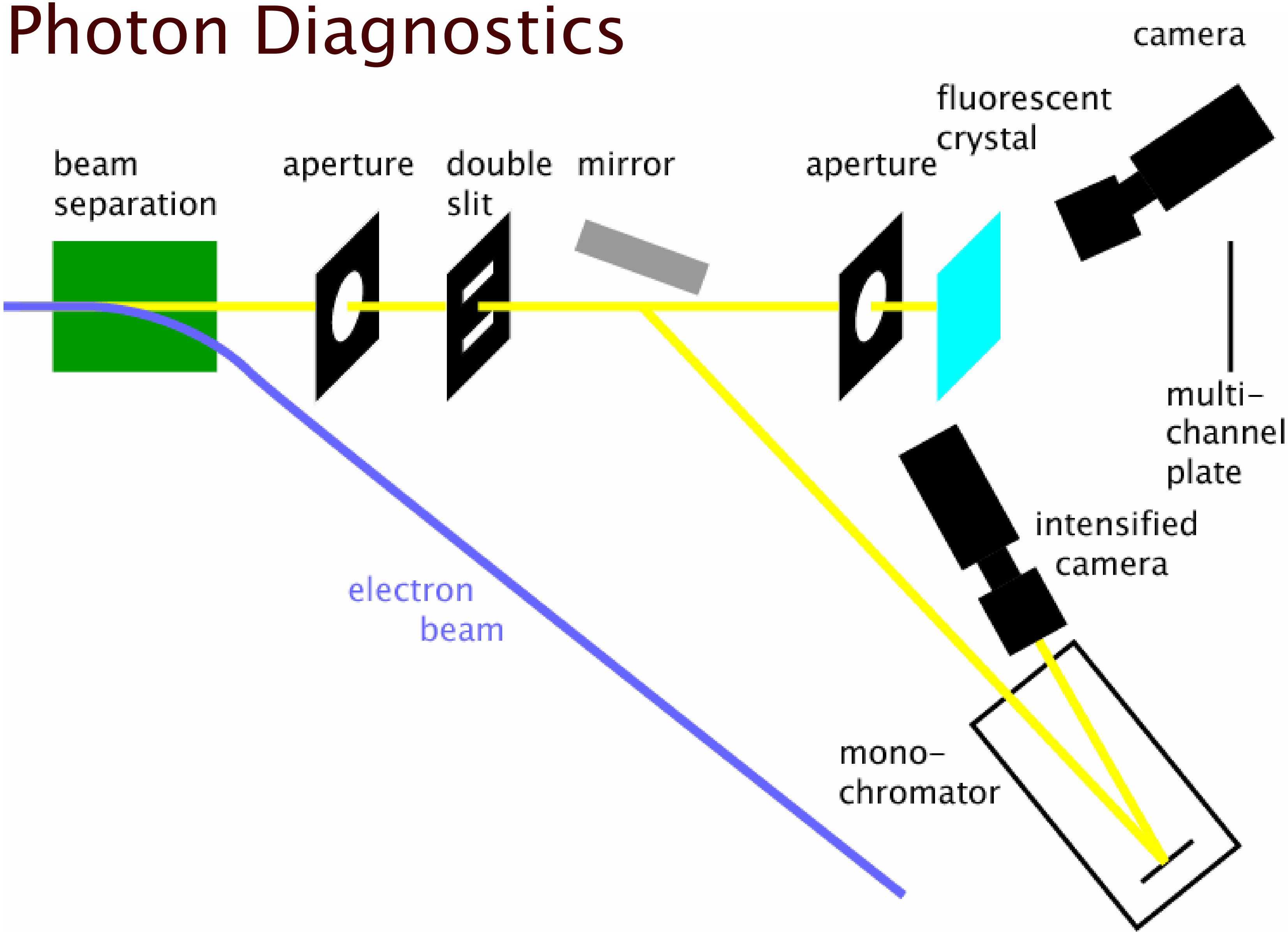
- Longitudinal and Transverse Coherence





Experimental Set-Up

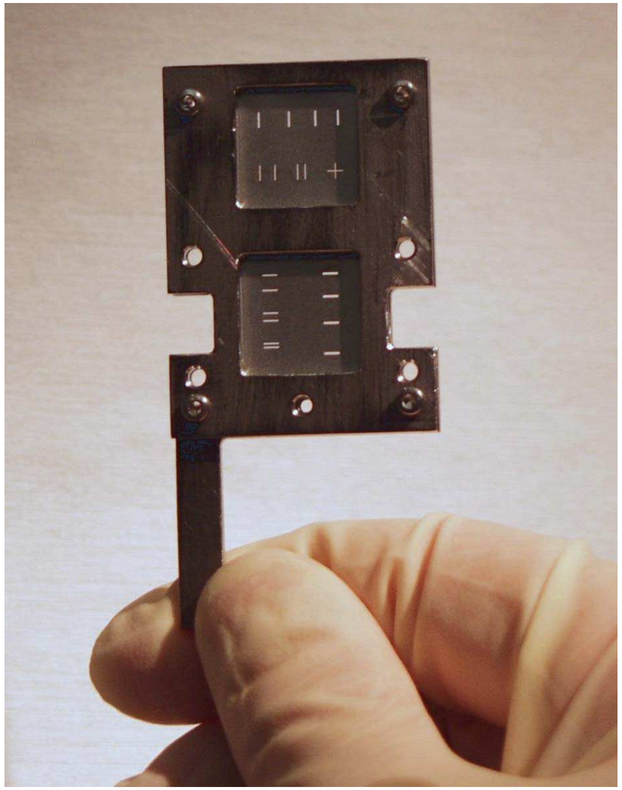
Photon Diagnostics

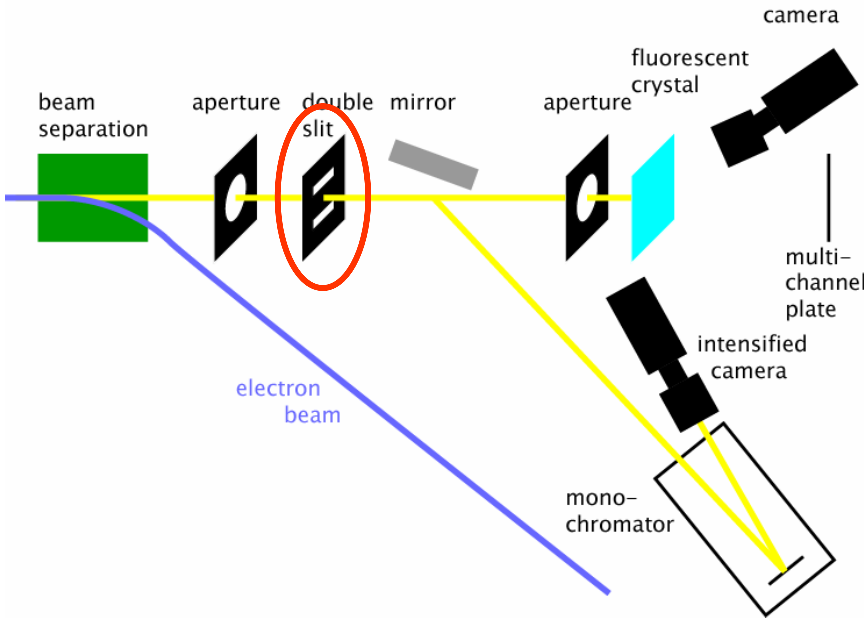


Experimental Set-Up

Double Slits

- Cut in stainless steel foil, using a laser



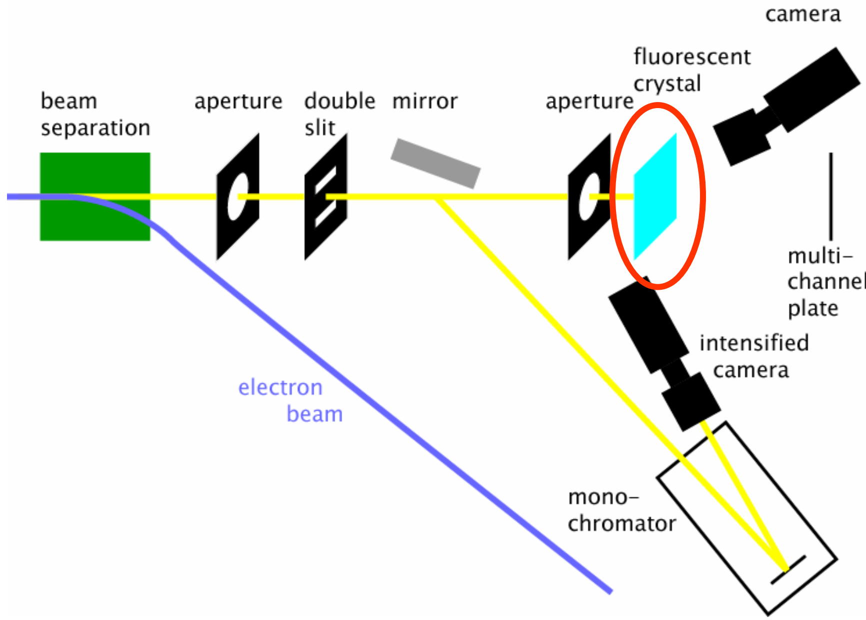


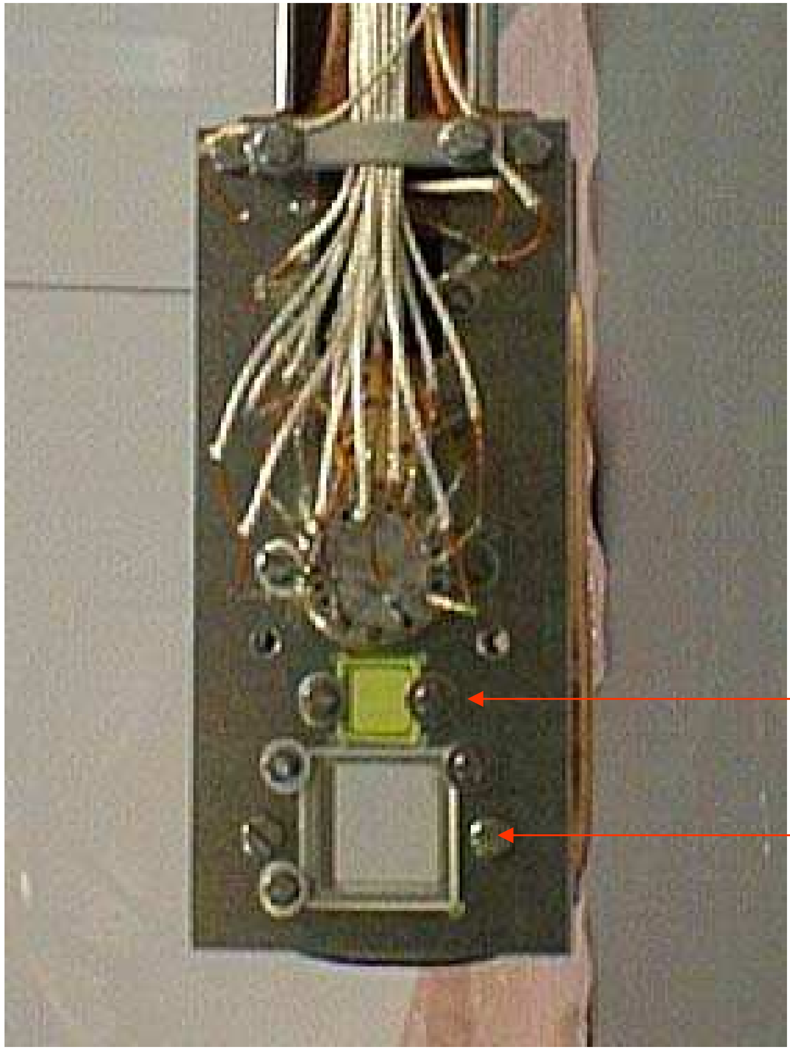
- Slit separations of 0.5, 1, 2 and 3mm available
- Slit width: 100µm
- Slit length: 2mm

- Can be moved by two stepper motors

Experimental Set-Up

Fluorescent Crystals





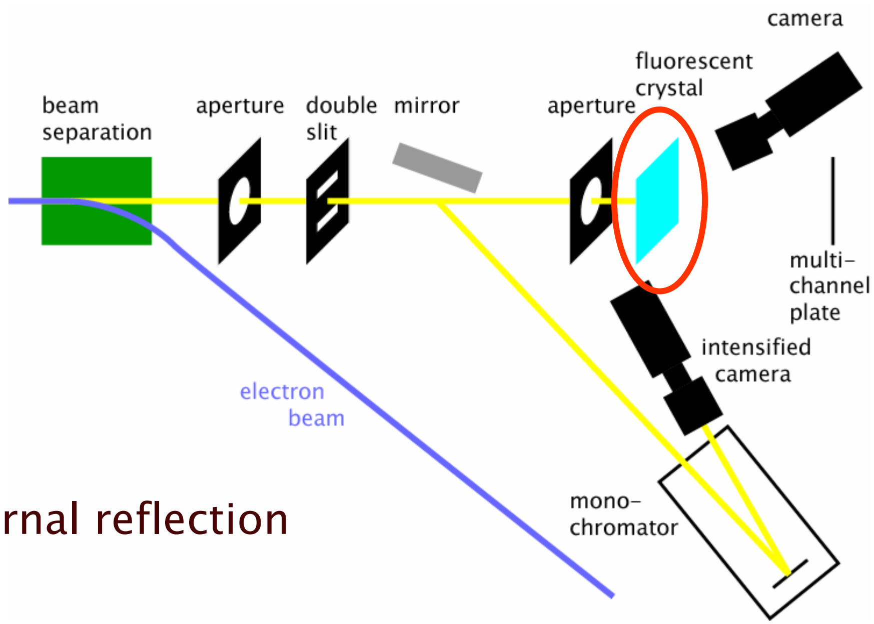
Ce:YAG crystal

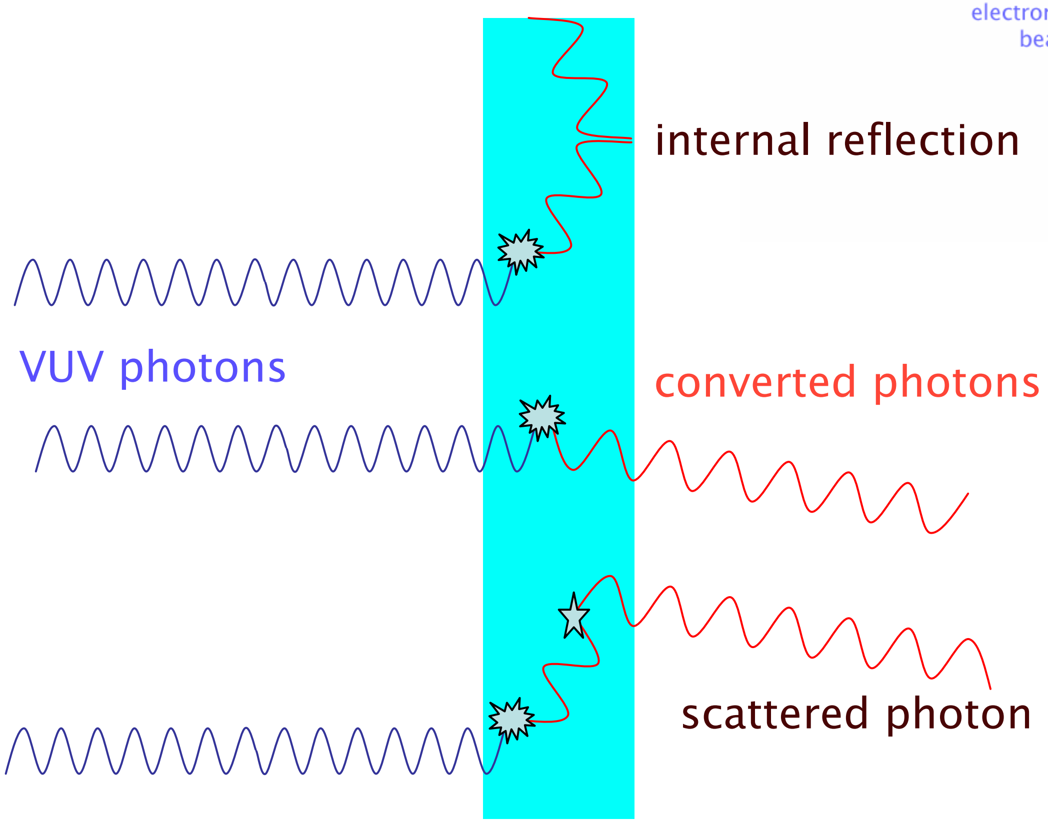
$PbWO_4$ crystal

placed on a watercooled frame

Experimental Set-Up

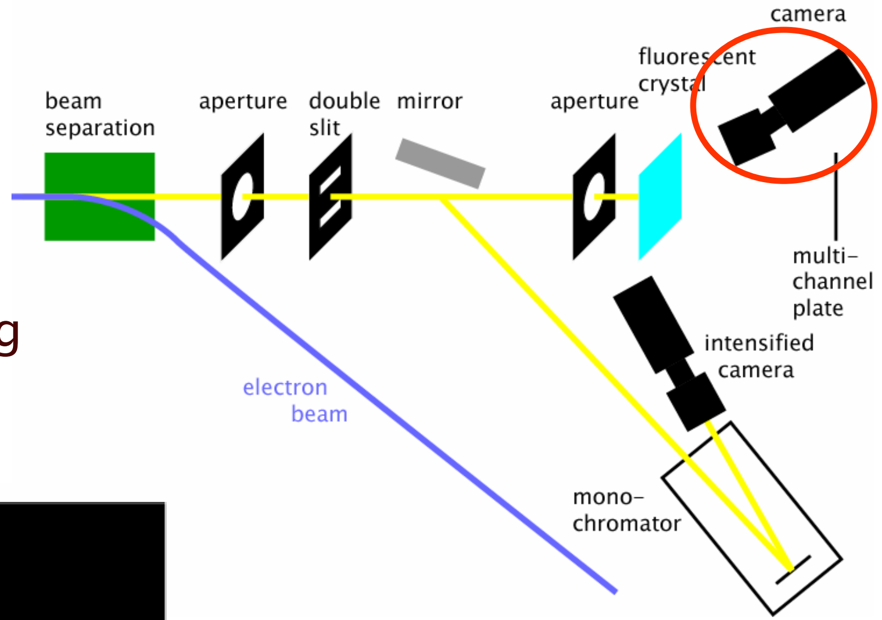
Fluorescent Crystals



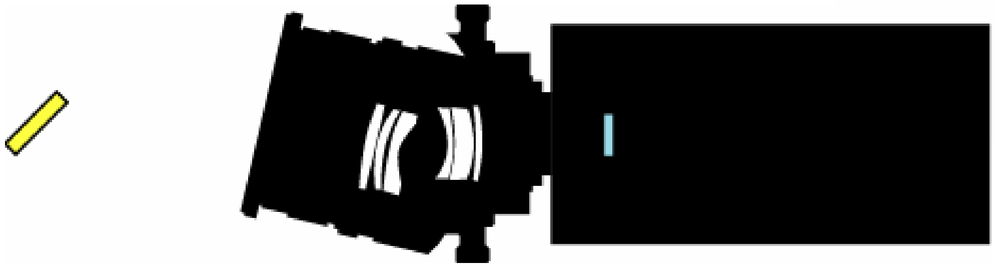


Experimental Set-Up

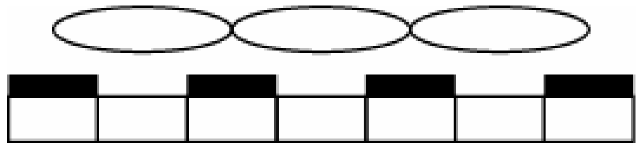
Camera



- Tilted lens to achieve good focusing over the inclined crystal



- Interline transfer CCD
  - ⇒ fast exposure times
  - ⇒ single-shot measurements
- Lens-on-chip technique
  - ⇒ good sensitivity
- Control and readout over fibre optical link



Experimental Set-Up

Coherence Measurements

- Diagnostics inside the accelerator tunnel
- Slits, crystal are in the UHV of the linear accelerator
- Distances fixed by set-up
- Near field diffraction
- compared to approx. 3 mm size of the radiation spot:
  slit length 2 mm

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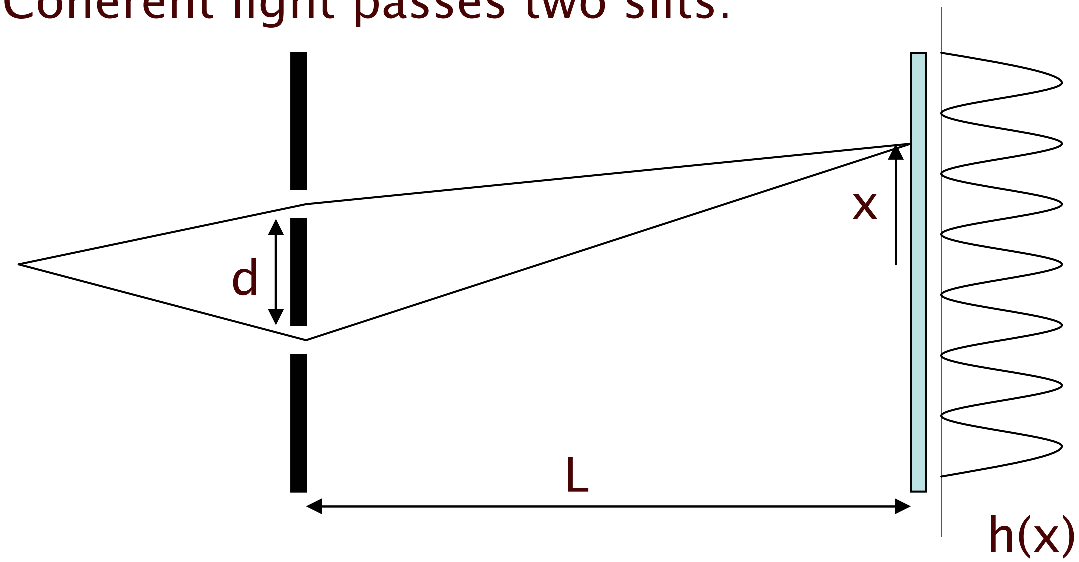
Young's Double Slit

- Coherent light passes two slits:



In the far field, we have:

$$h(x) = I_0 \left(1 + \cos\left(2\pi \frac{d}{L\lambda} x\right)\right)$$

Longitudinal (temporal) and transverse (spatial) coherence necessary!

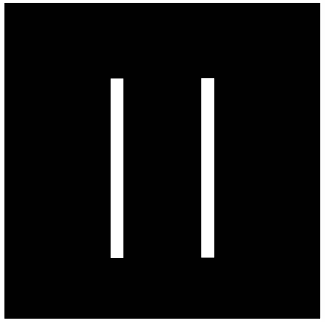
Near Field Effects

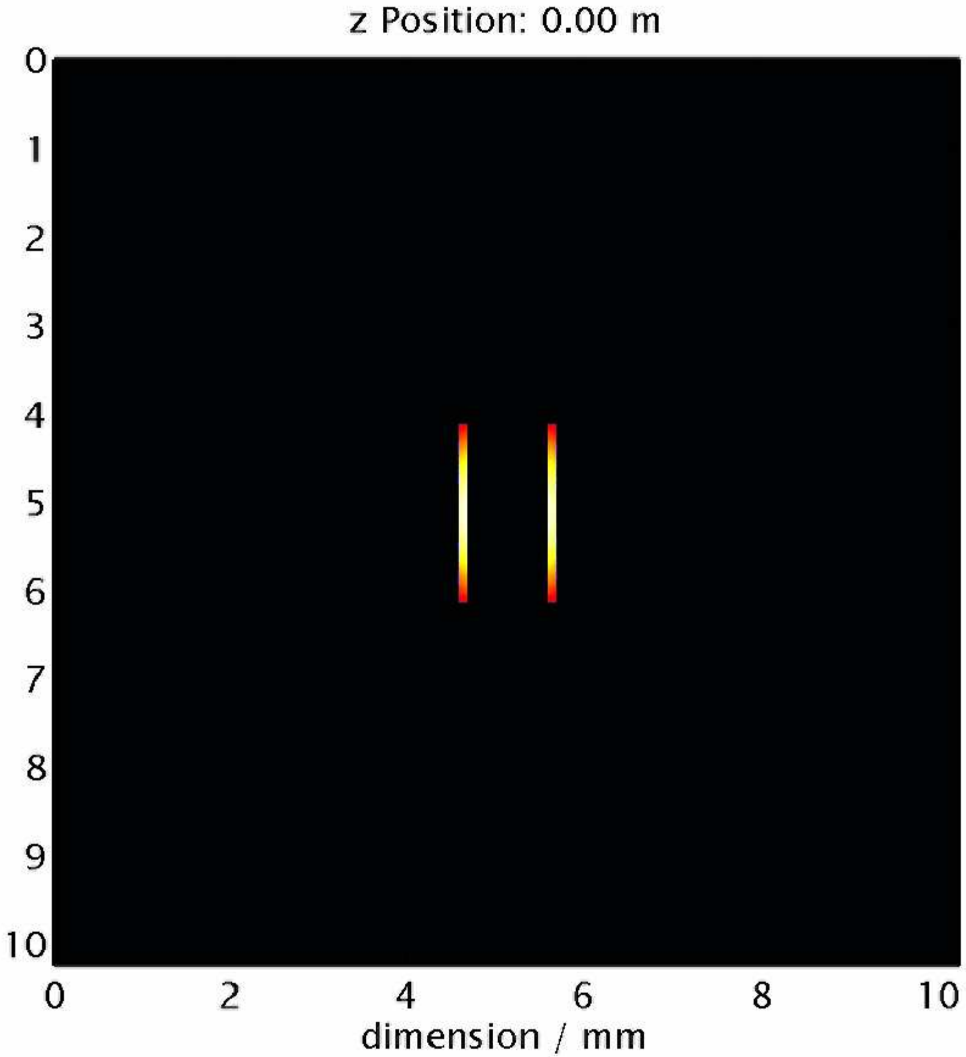
- Criterion for far field diffraction:

$$\frac{\lambda L}{d^2} >> 1$$

- d: distance between slits, λ: wavelength, L: distance slits—screen
- Here: L = 3.1m, d = 1mm, λ = 100nm ⇒ $\frac{\lambda L}{d^2} = 0.3$
- Near field effects ⇒ reduced modulation
- additional modifications to the far field formula:
  - finite width and length of slits

Simulation of Near Field Diffraction





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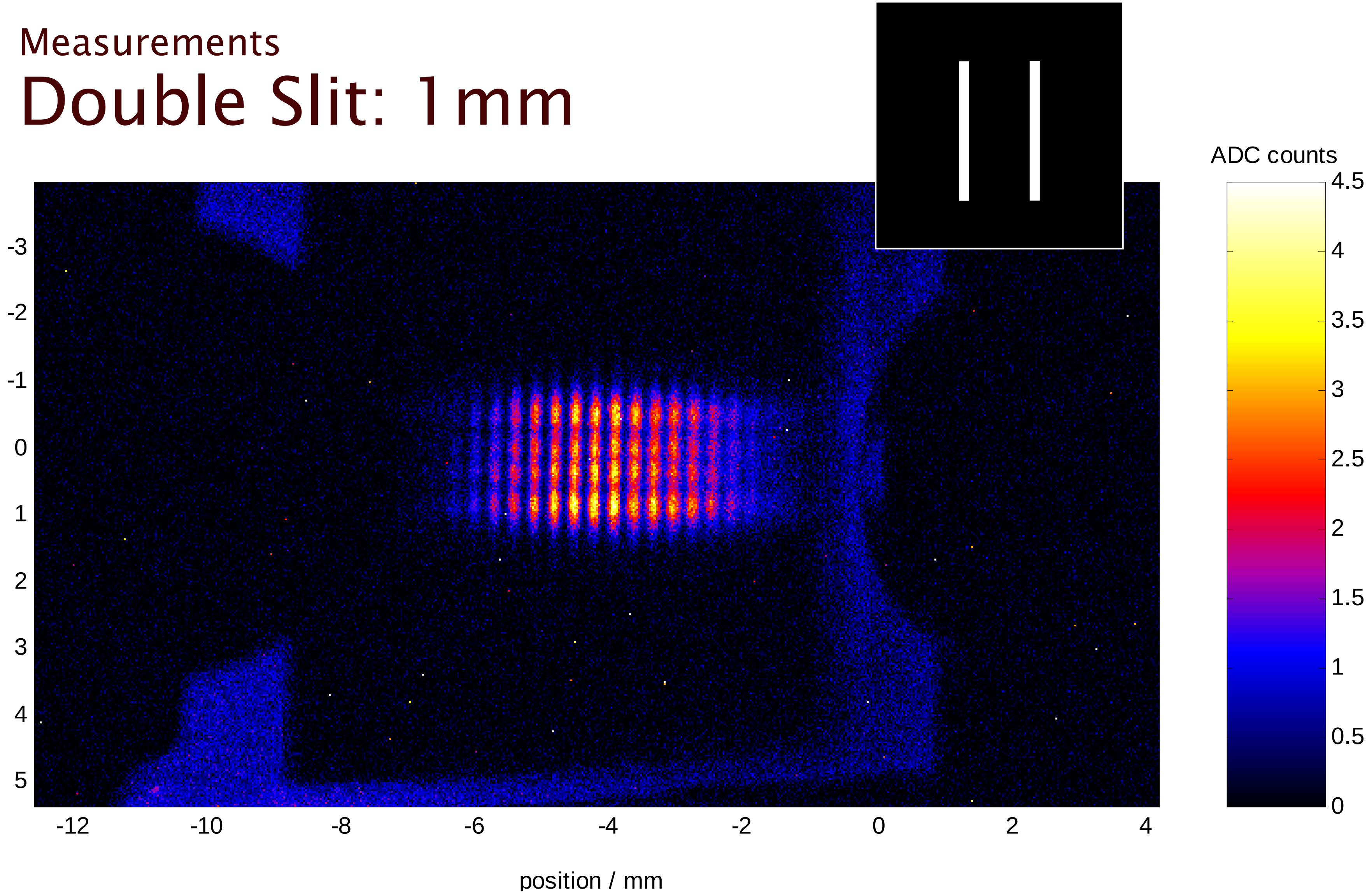
Measurements

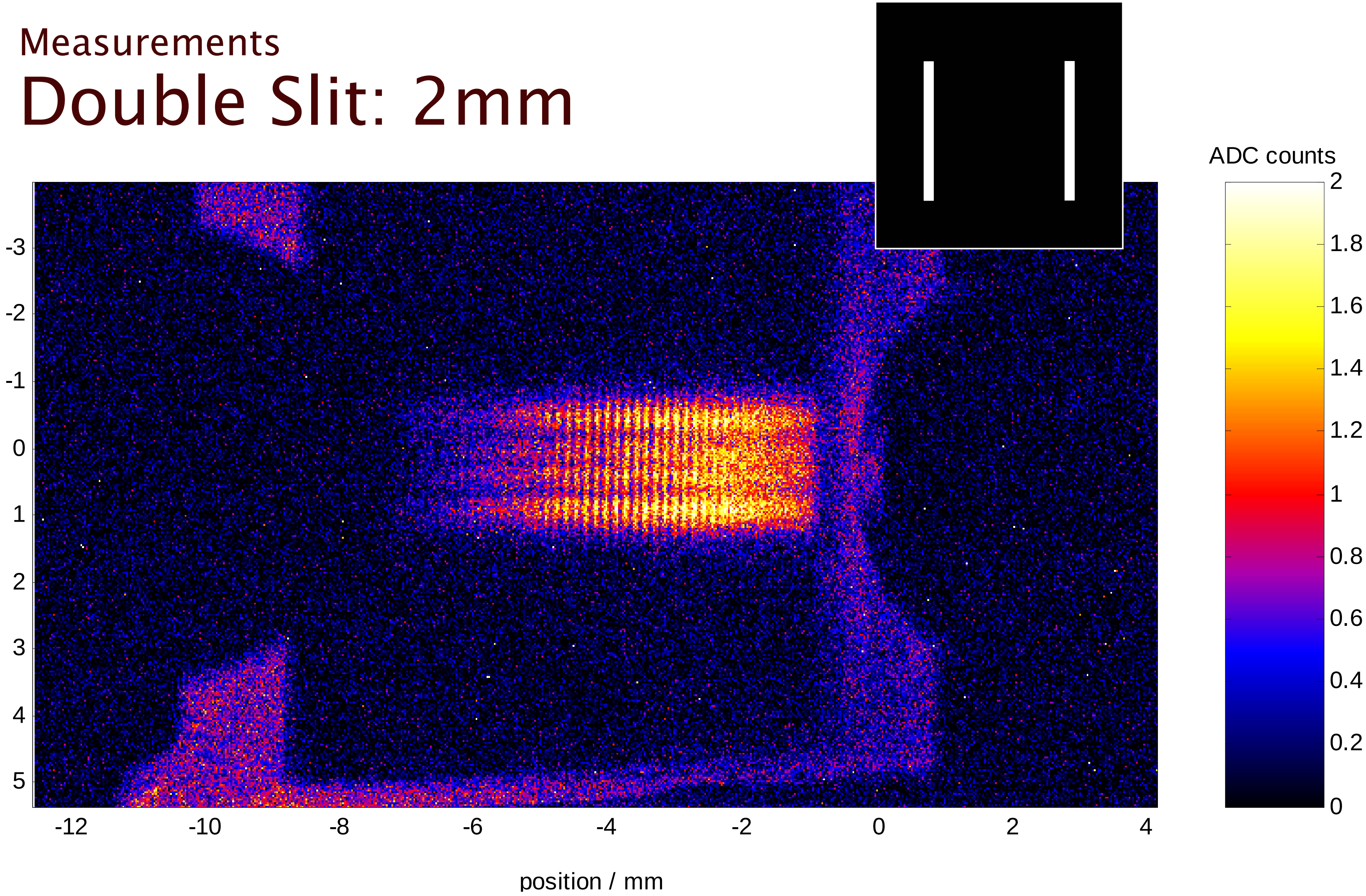
Double Slit: 1mm



Vertical slits, 1 mm separation. Average of 99 images with 3 bunches each

Measurements

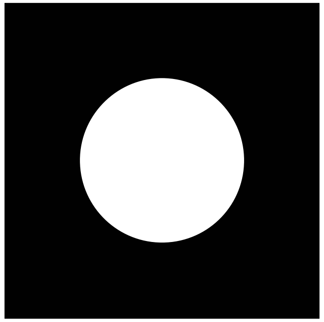
Double Slit: 2mm

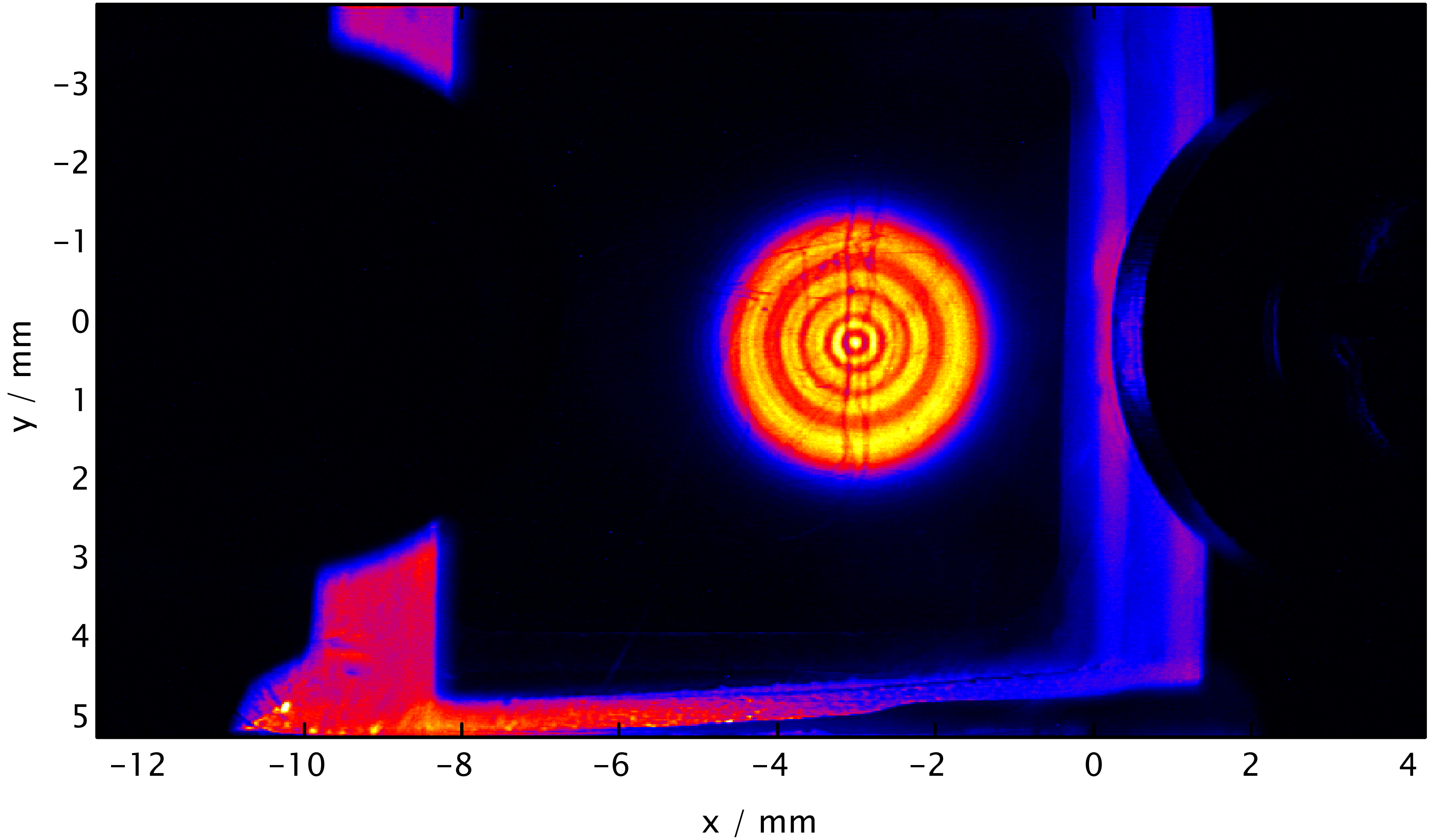


Vertical slits, 2 mm separation. Average of 99 images with 3 bunches each

Measurements

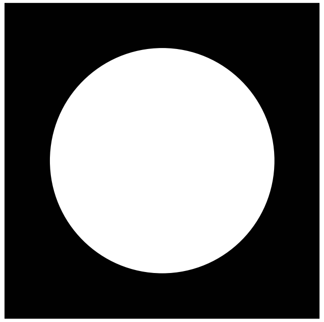
Circular Aperture: ∅ 3mm

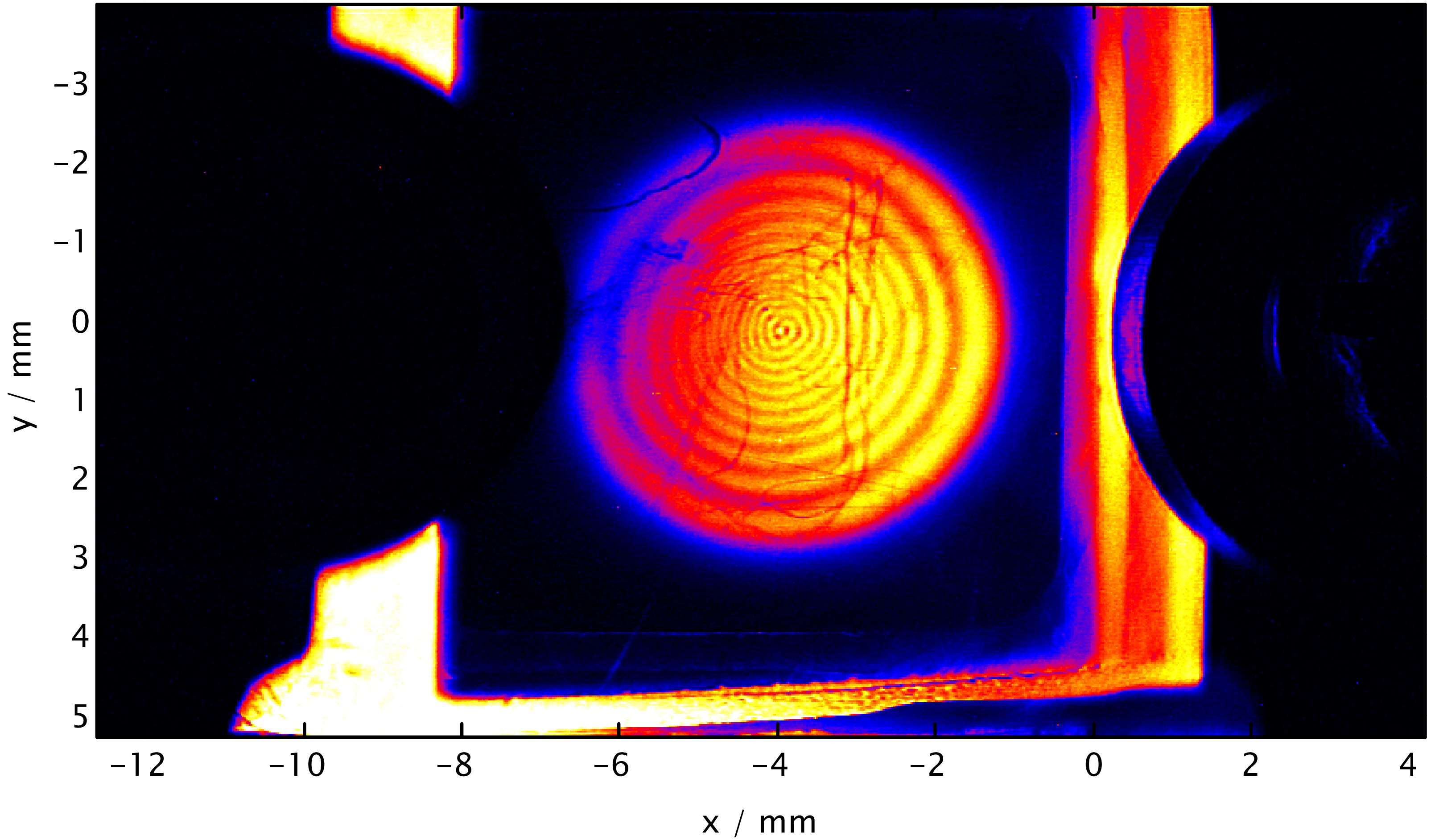




Measurements

Circular Aperture: ∅ 5mm





Measurements

Circular Apertures

- Number of rings that a circular aperture creates in near field approximation:

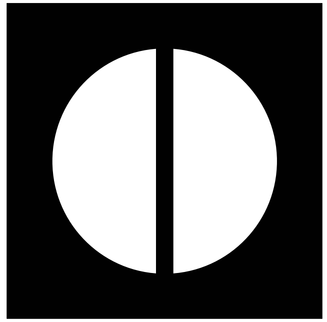
$$N_f = \frac{r^2}{\lambda}\left(\frac{1}{D} + \frac{1}{L}\right)$$

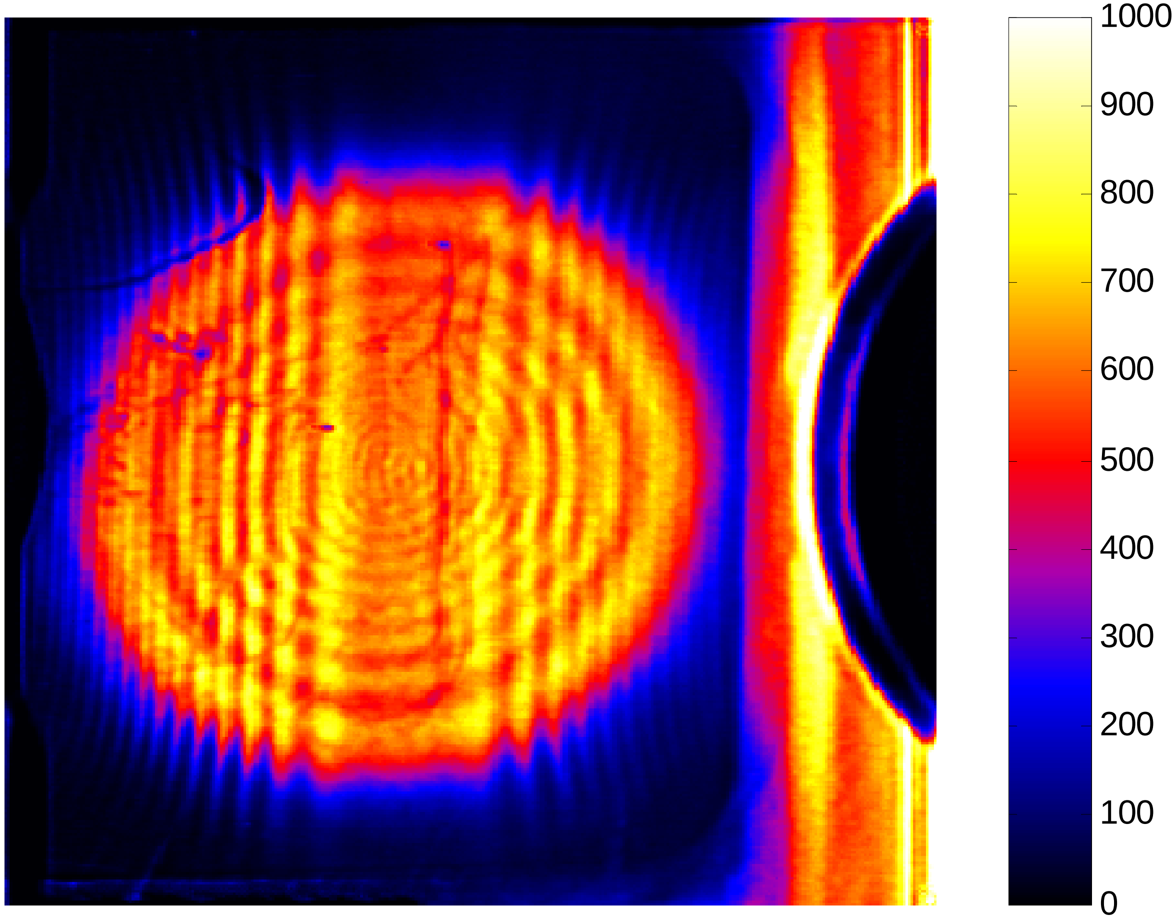
r: aperture radius, λ: wavelength, D: distance source—aperture, L: distance aperture—screen

Here:

Aperture	predicted	observed
3 mm	9.2	9
5 mm	25.5	23

Circular Aperture + Wire

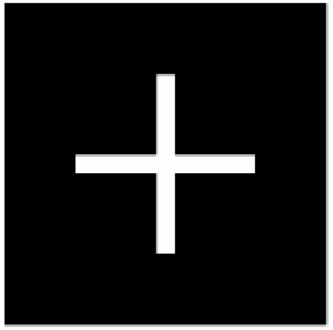


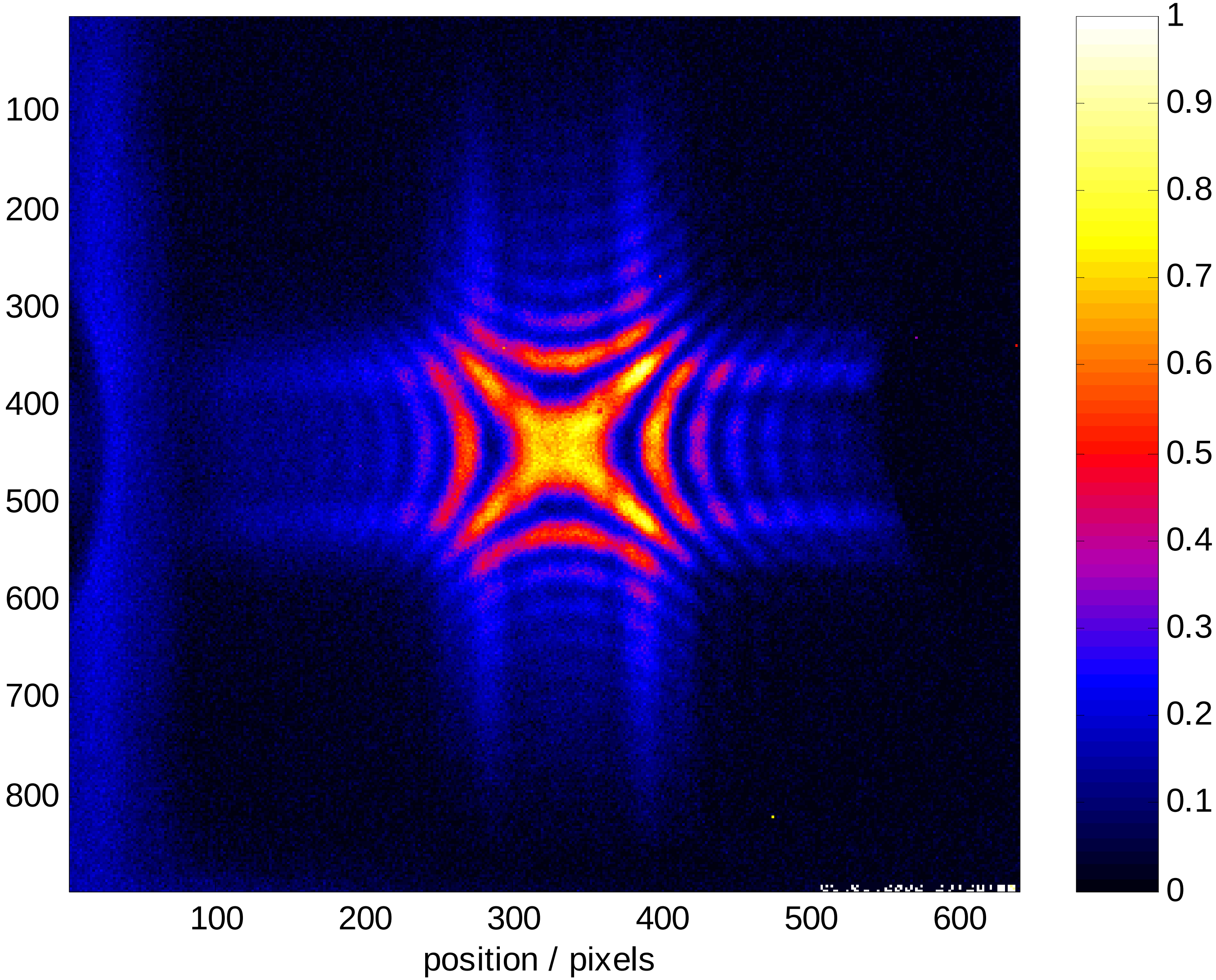


A wire in the beam path also creates diffraction

Measurements

Crossed Slits





A Double Slit Experiment to Study the Transverse Coherence of the TTF FEL

Image Processing

Deconvolution of the Camera Resolution

- Diffraction effects and lens errors affect the observed image: the real distribution Ψ is convoluted with the Point Spread Function P

$$\Phi(x,y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} P(x-u, y-v) \cdot \Psi(u,v) \mathrm{d}u \, \mathrm{d}v$$

- For discrete values:

$$\Phi_{i,k} = \sum_{m,n} P_{i-m,k-n} \cdot \Psi_{m,n}$$

⇒ Reduced contrast

⇒ apparently reduced FEL coherence

Image Processing

Deconvolution of the Camera Resolution

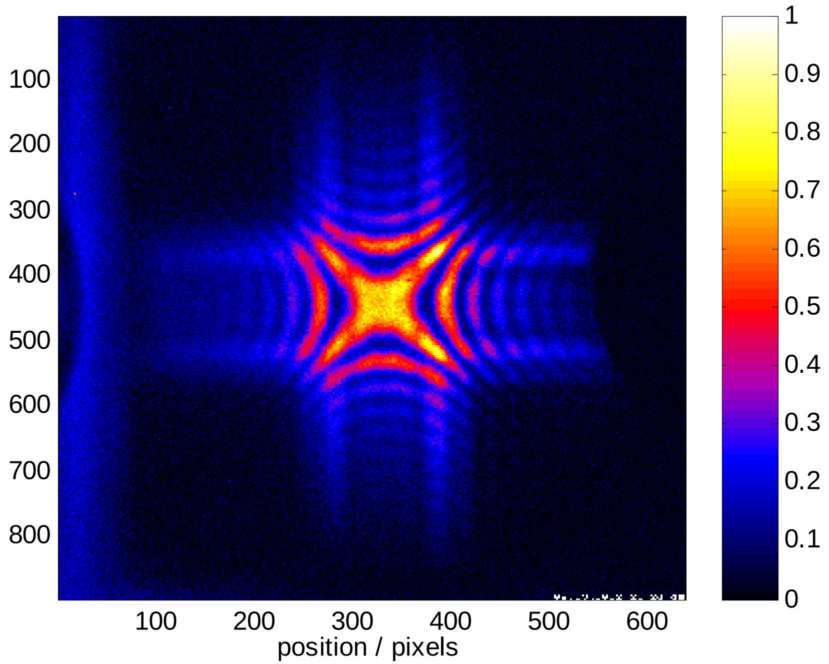
$$\Phi_{i,k} = \sum_{m,n} P_{i-m,k-n} \cdot \Psi_{m,n}$$

- If P is known, the system of equations can in principle be solved
- ➢ But: as a result of measurement errors (noise) in the measured image, negative values for the real intensities will appear!

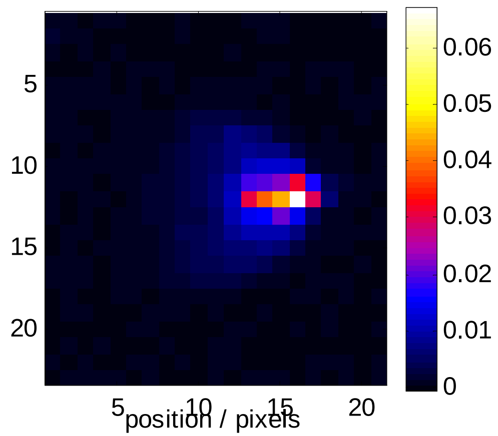
- The images can be reconstructed using the Lucy-Richardson algorithm
  - Maximize the likelihood of the measurement, with given boundary conditions
  - Widely used in image processing

Image Processing

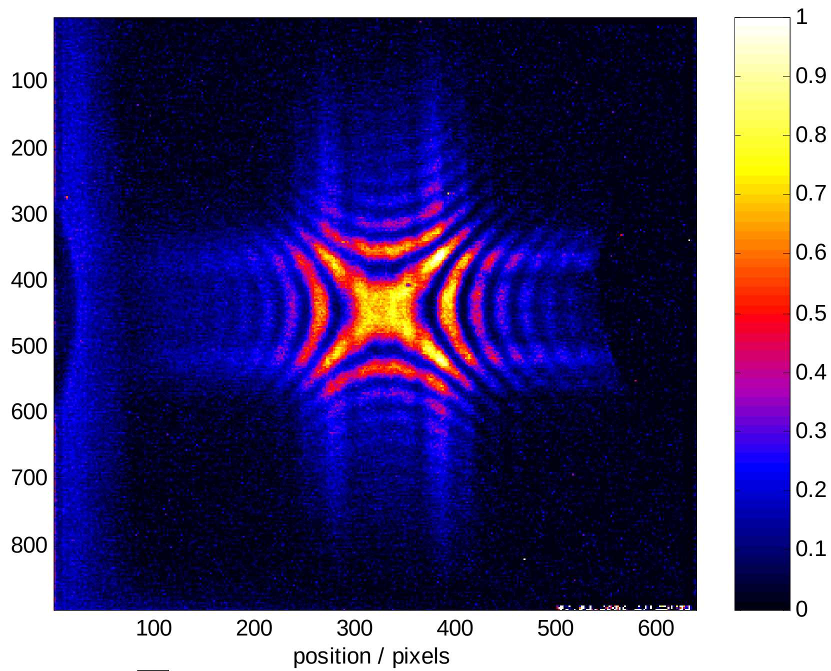
Deconvolution of the Camera Resolution



Measured distribution Φ



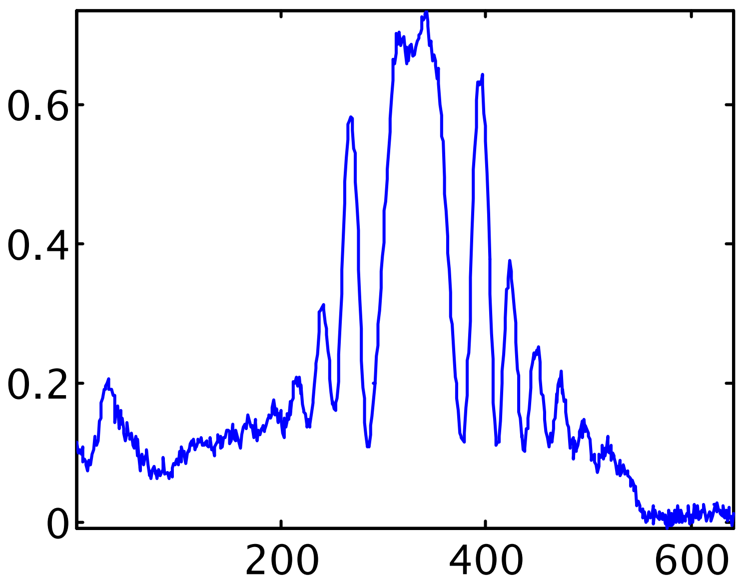
Point spread function P

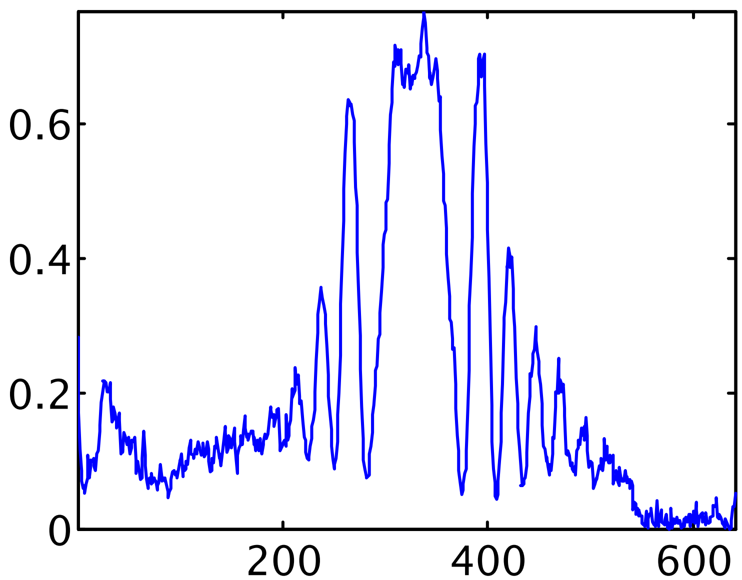


Reconstructed distribution Ψ

Image Processing

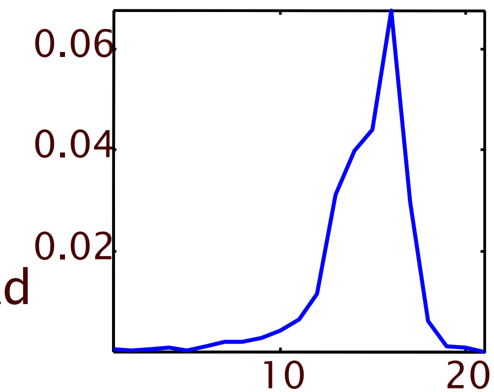
Deconvolution of the Camera Resolution





Measured distribution Φ

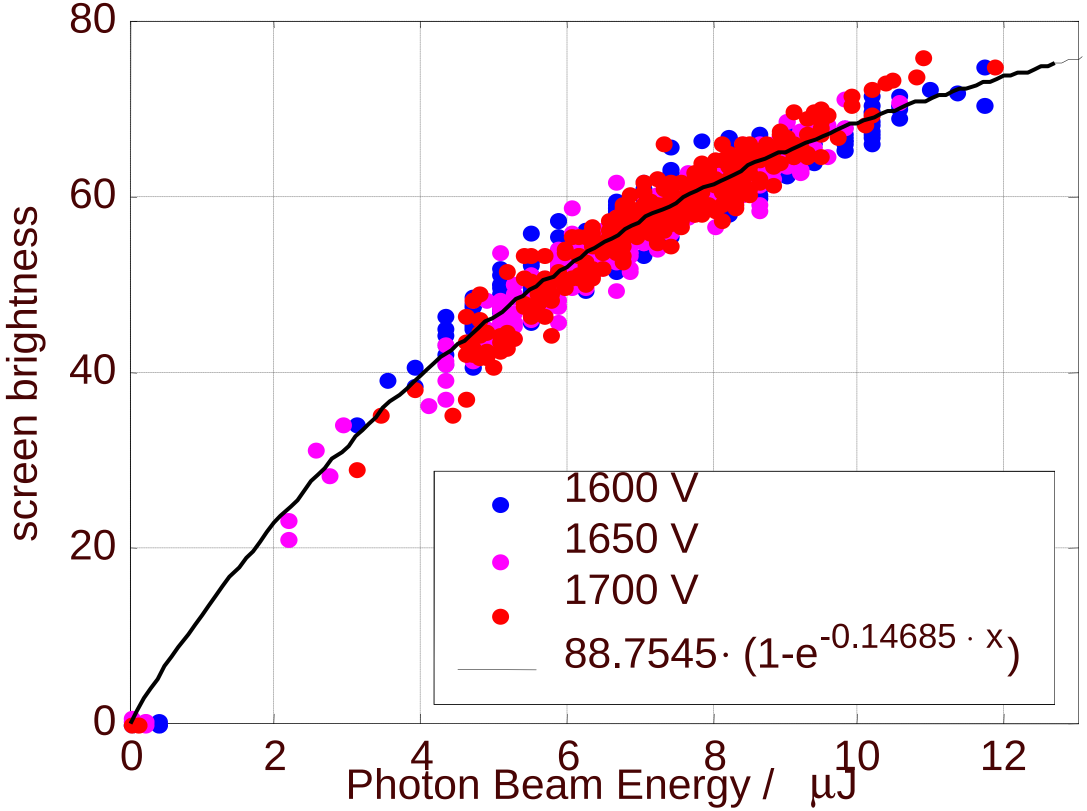
Reconstructed distribution Ψ



Point spread function P

Correction for Non-Linear Response

- Light emitted by the Ce:YAG crystal is not proportional to the incident energy
- Correction applied with the help of a calibrated multi-channel plate



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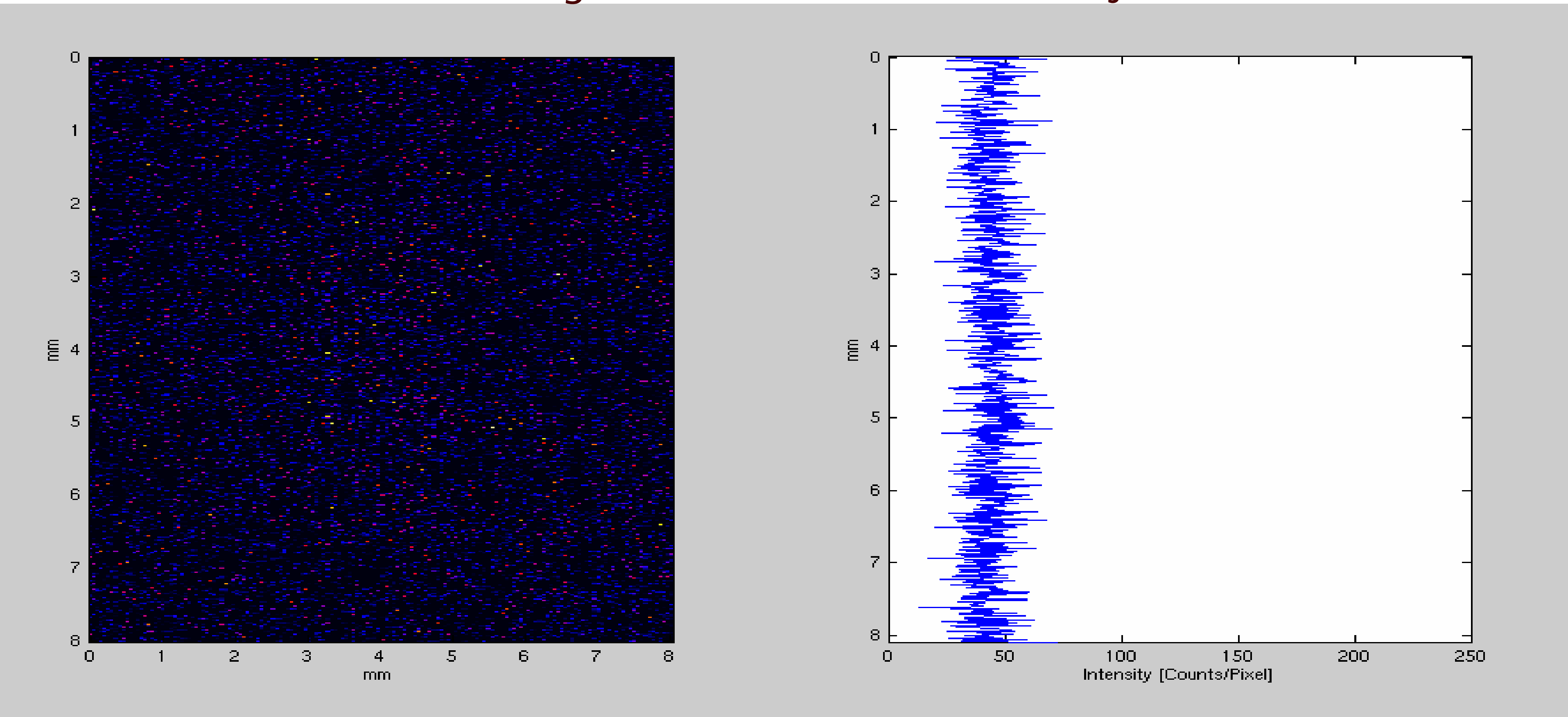
Experimental Data

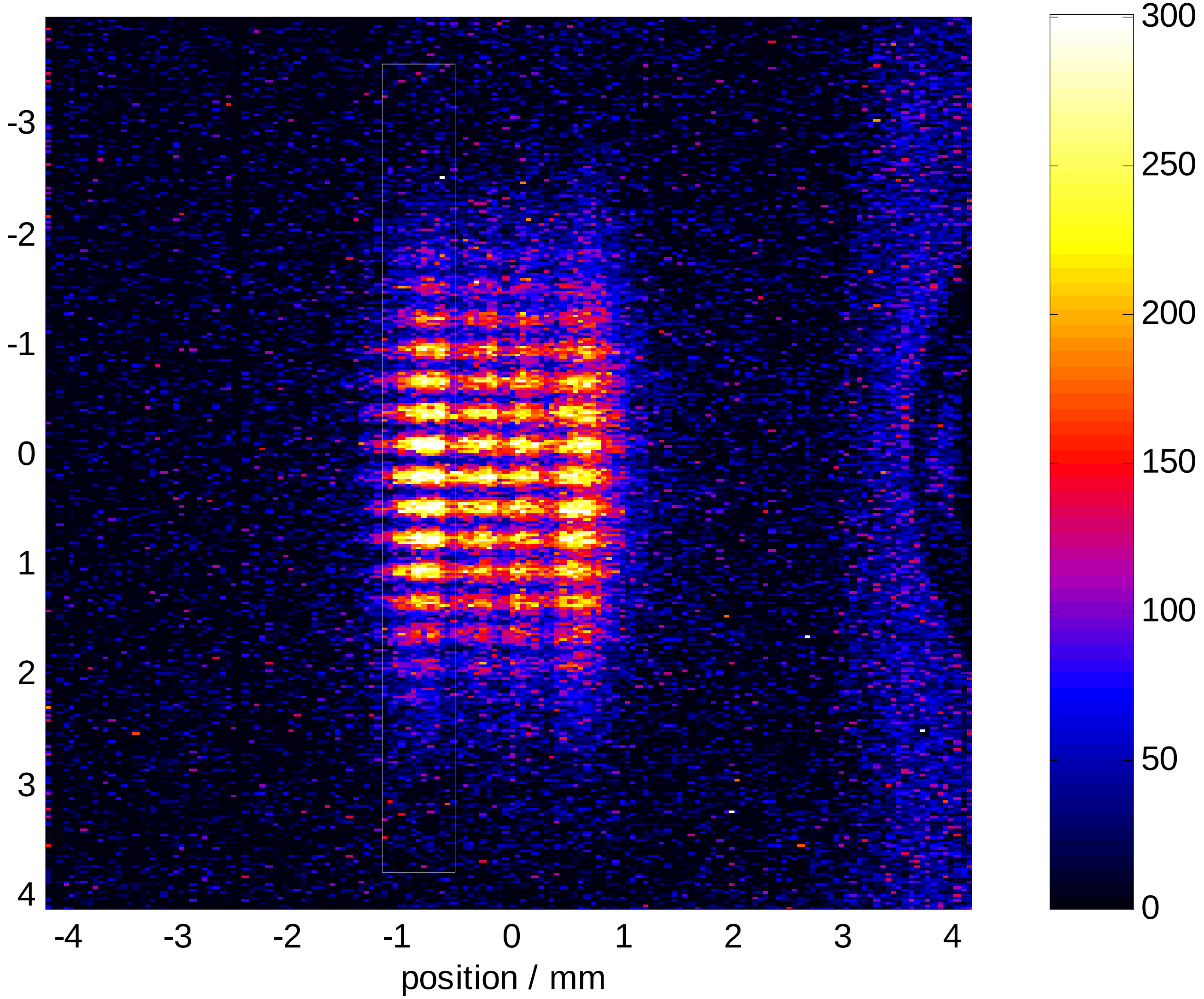
Double Slit — 1 mm separation

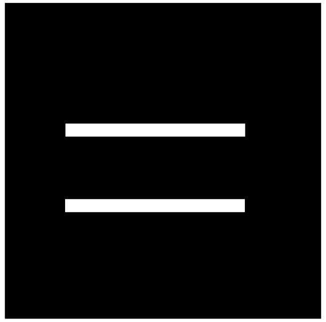
Reconstructed Image | Projection



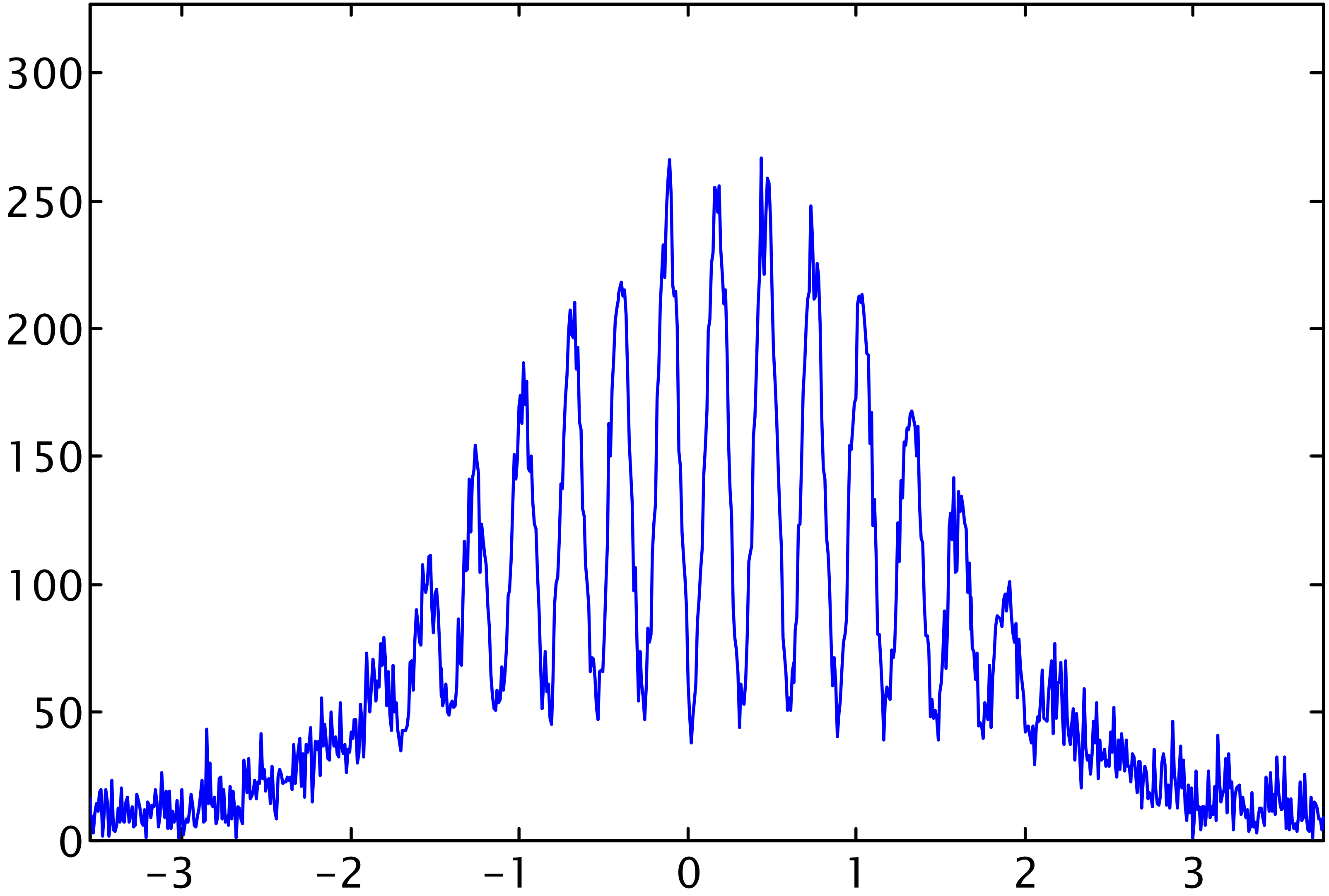
Analysis

Measurement, 1mm double slit



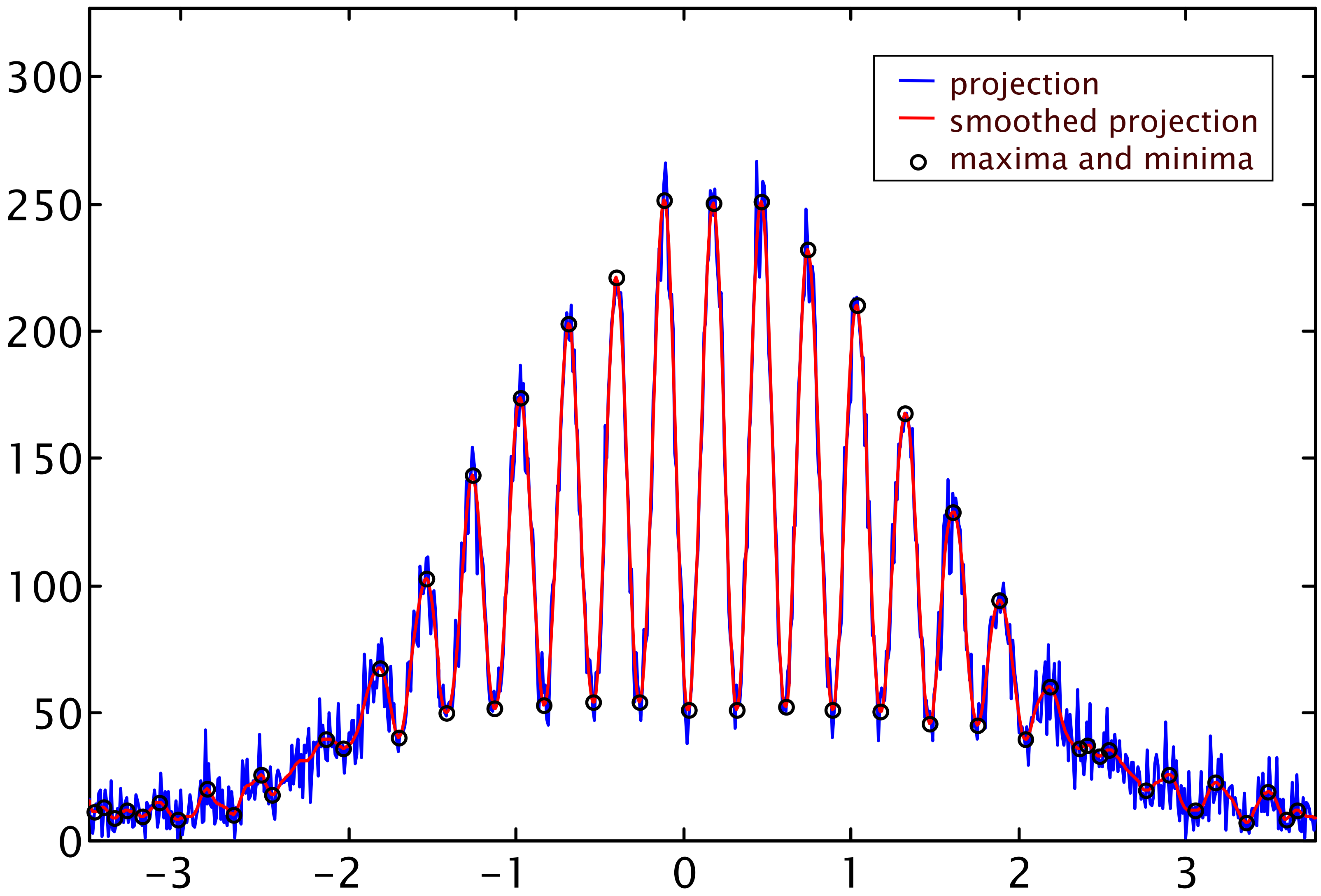


Projection of the Selected Area



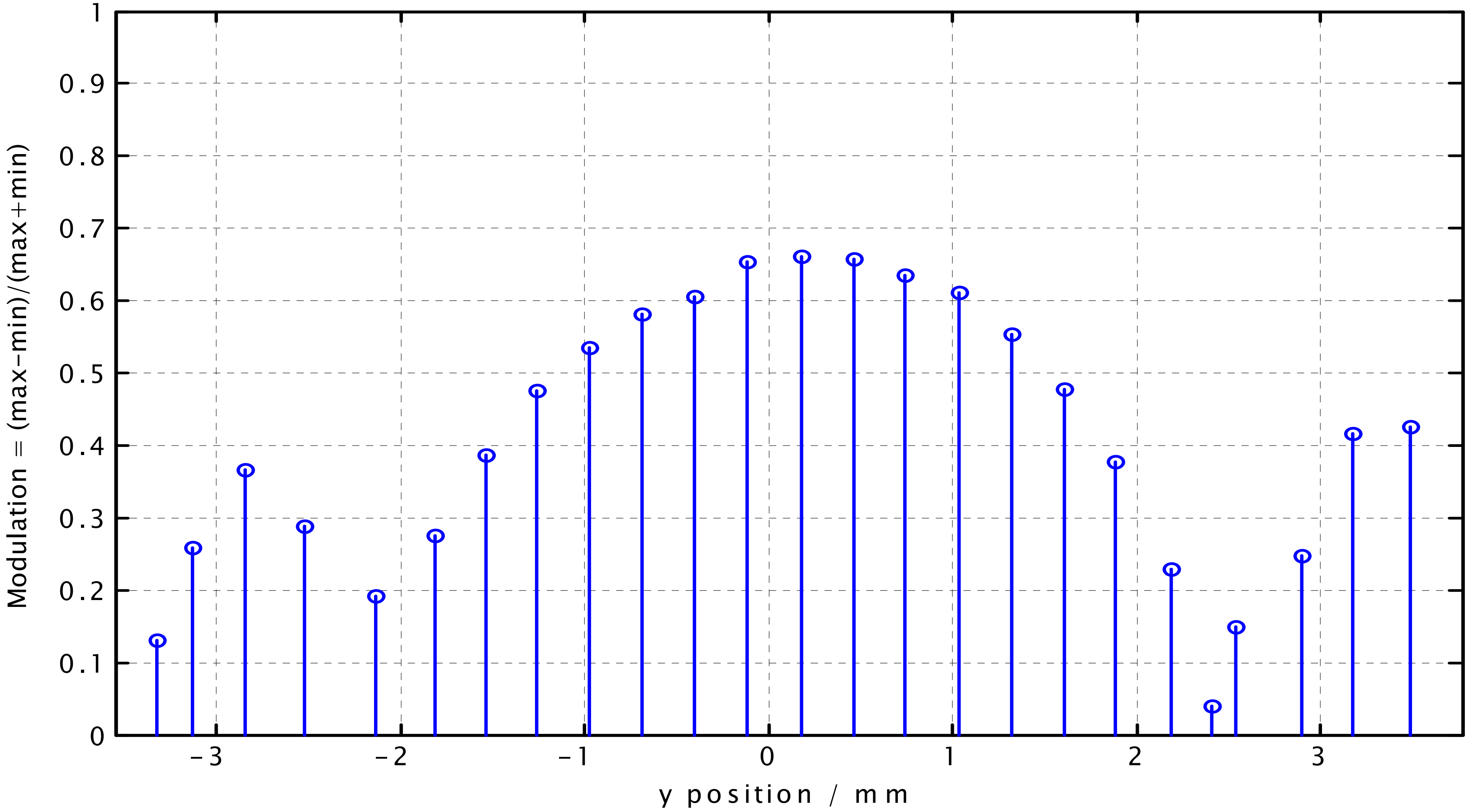
Analysis of Experimental Data

Smoothed Projection



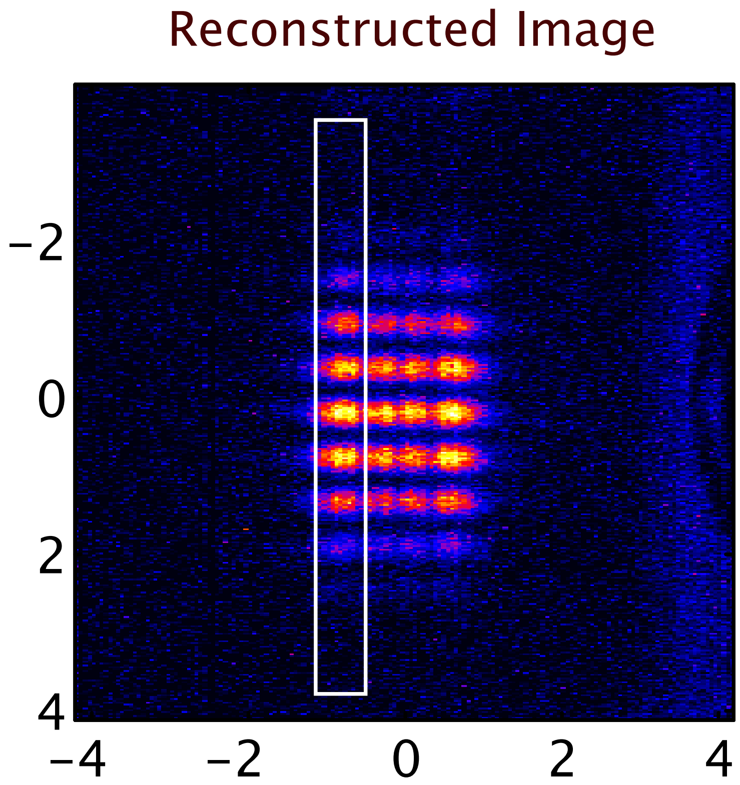
Modulation Depth

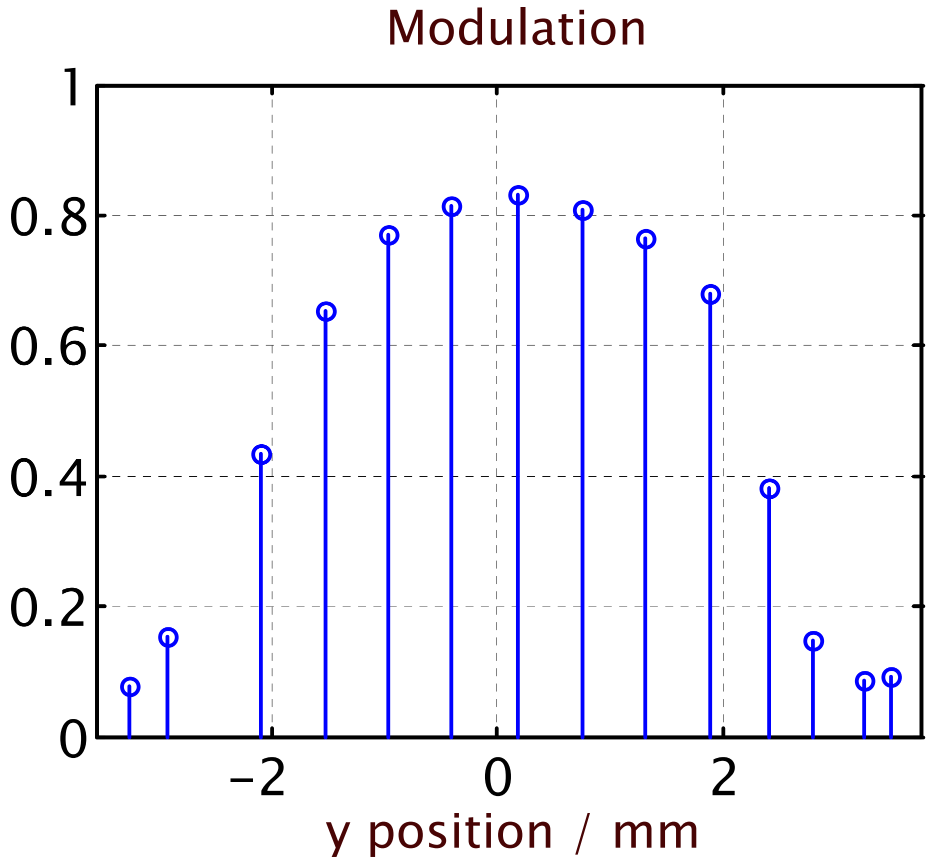
$$\text{modulation} = \frac{\text{max} - \text{min}}{\text{max} + \text{min}}$$



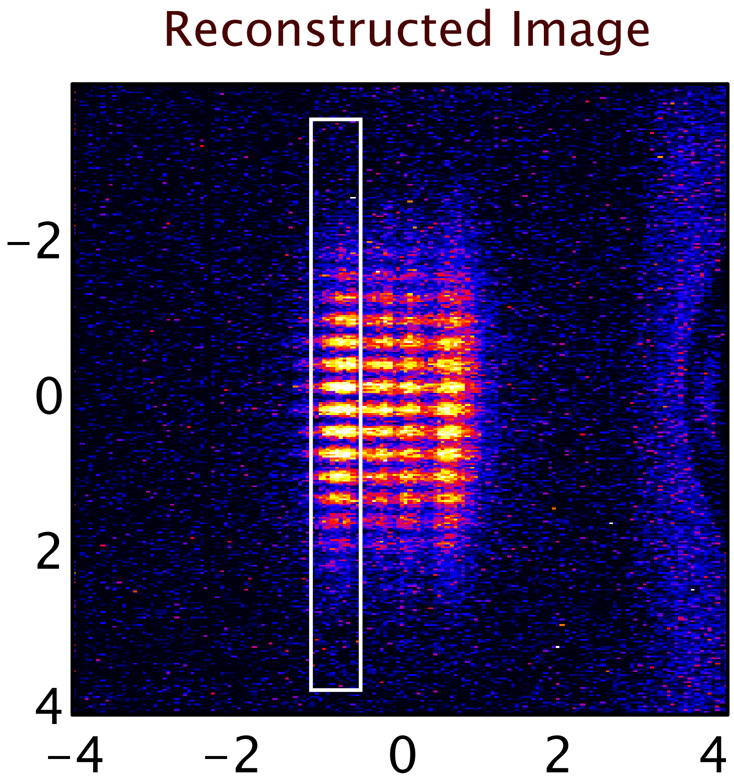
Analysis of Experimental Data

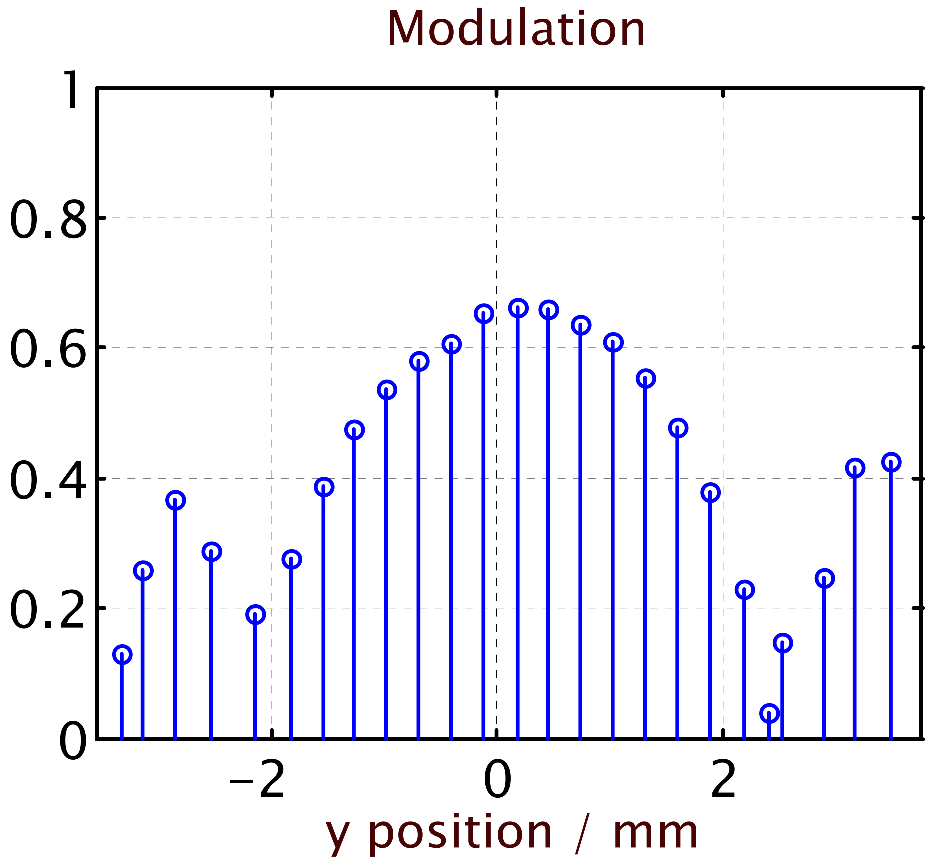
Double Slit — 0.5 mm separation





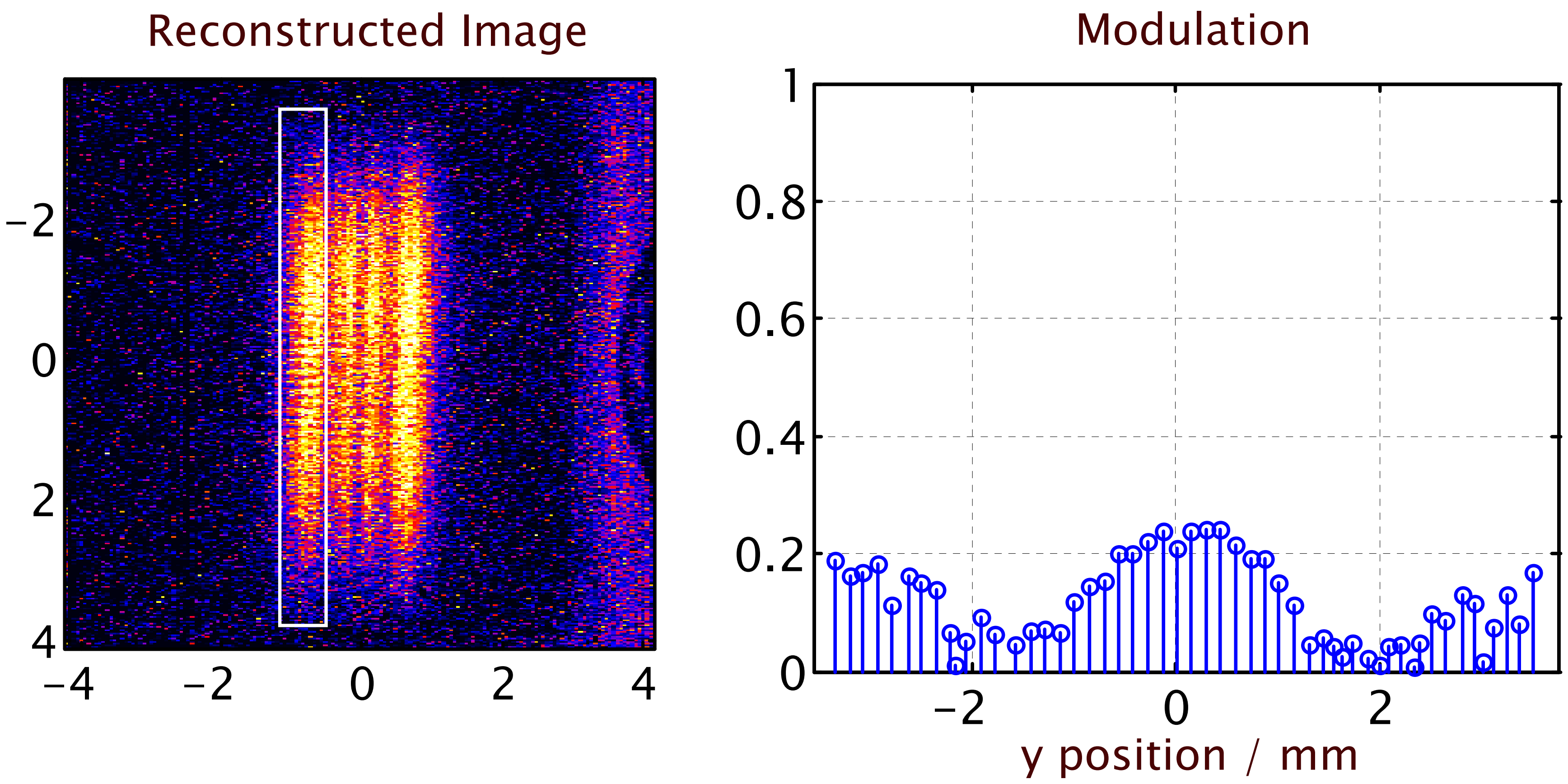
Double Slit — 1 mm separation





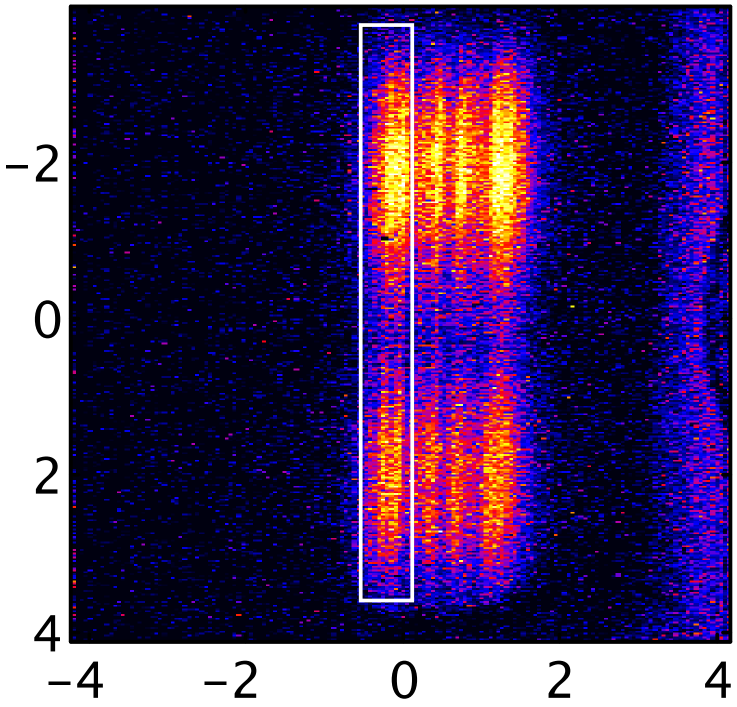
Analysis of Experimental Data

Double Slit — 2 mm separation

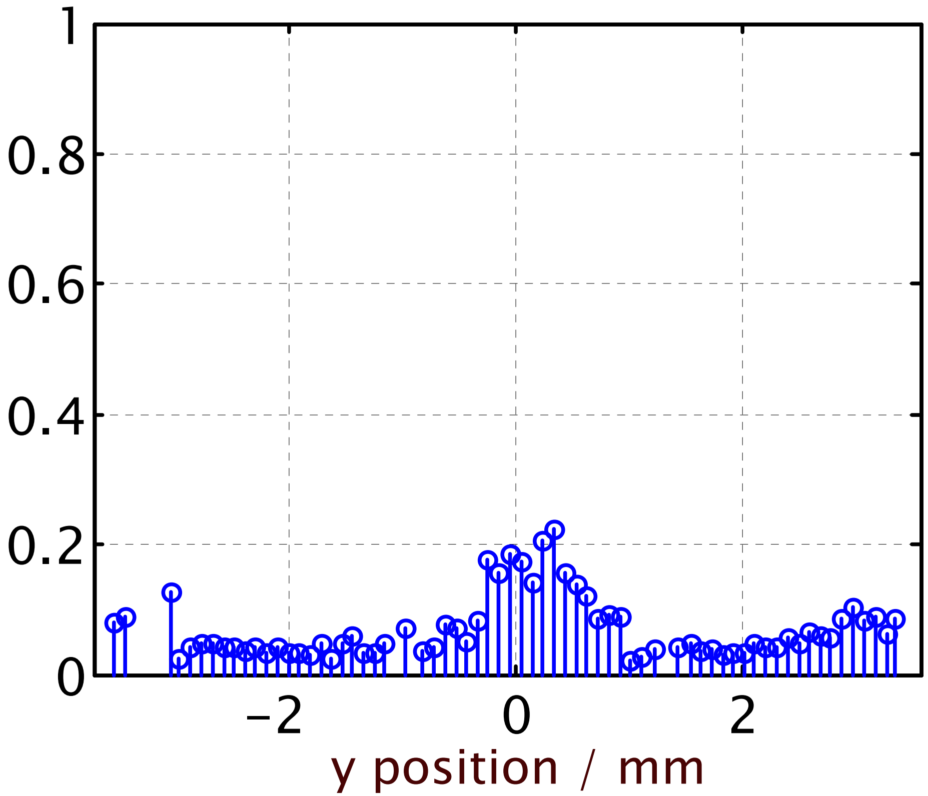


Double Slit — 3 mm separation

Reconstructed Image

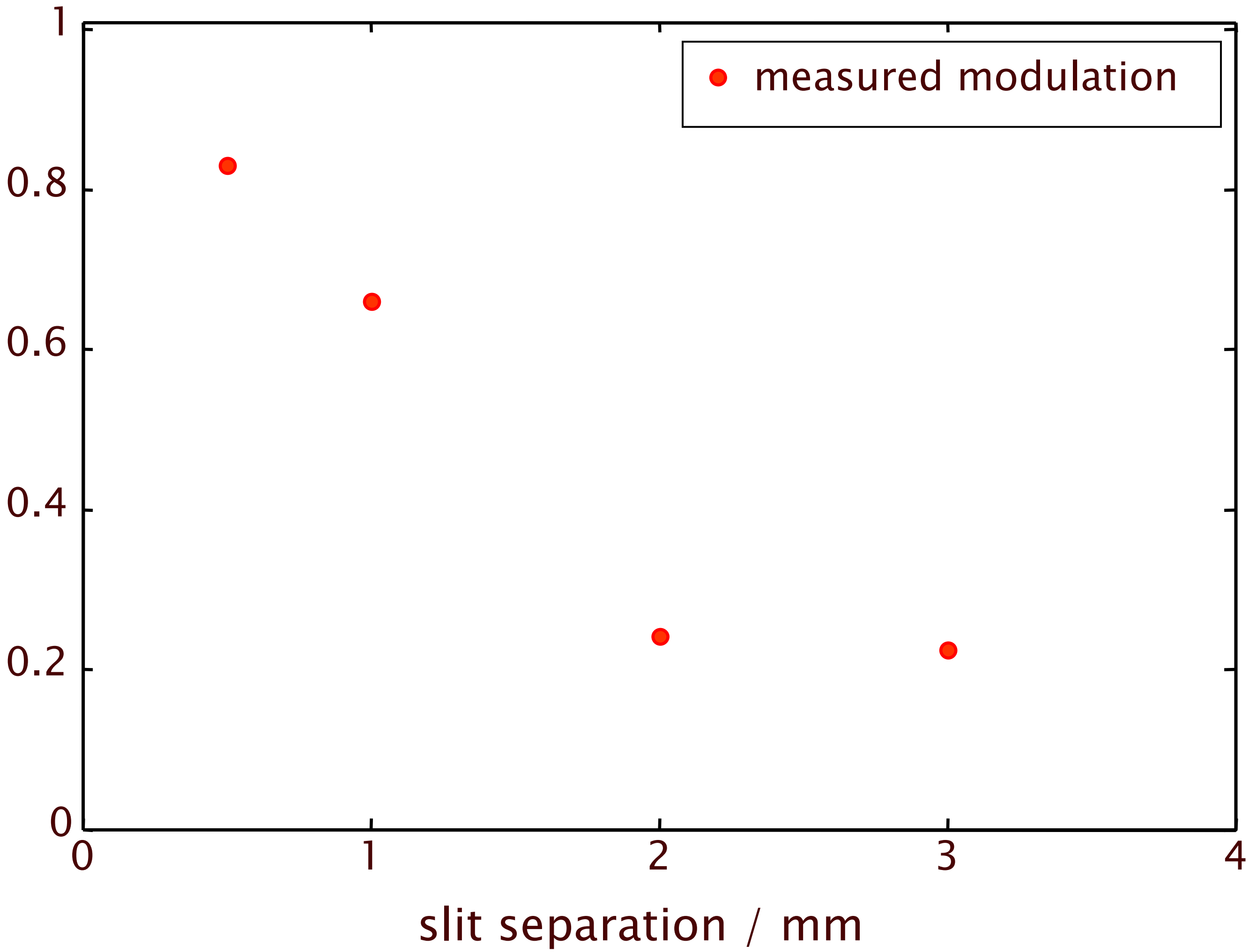


Modulation



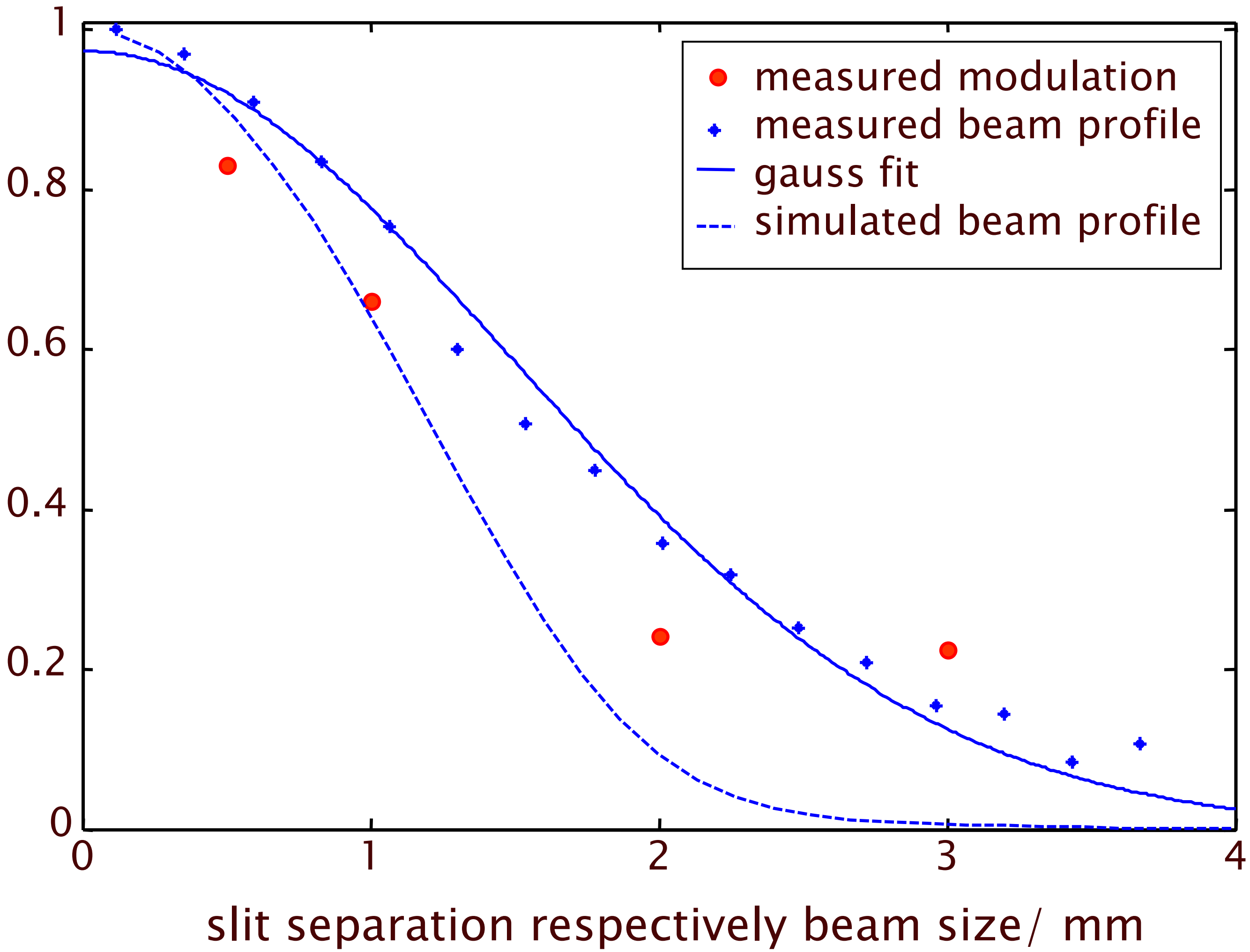
Analysis of Experimental Data

Slit Separation → Modulation



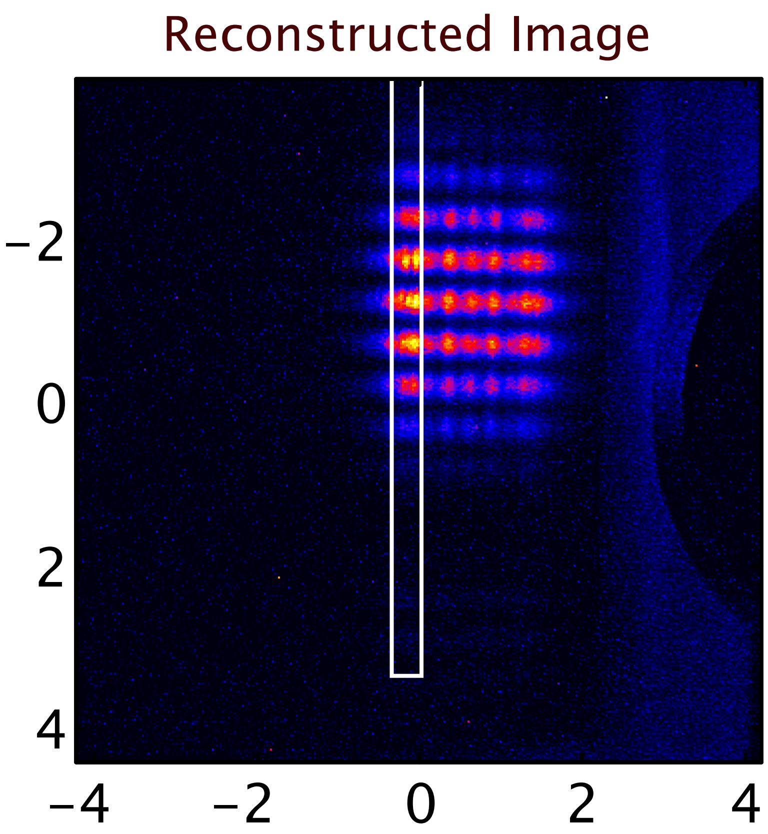
Analysis of Experimental Data

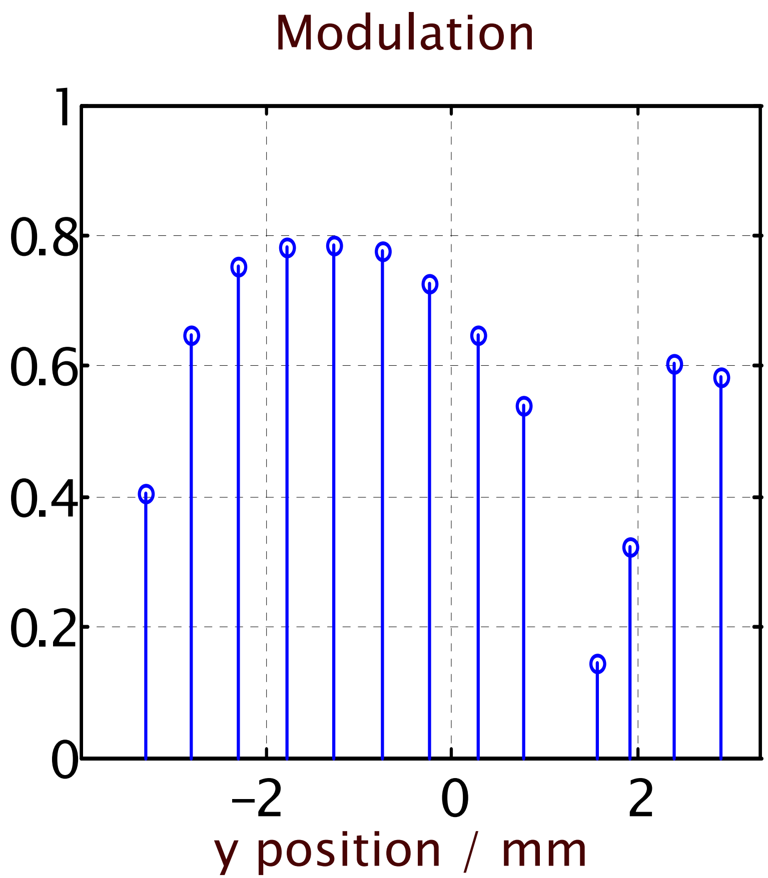
Slit Separation → Modulation



Analysis of Experimental Data at 87 nm

Double Slit — 0.5 mm Separation

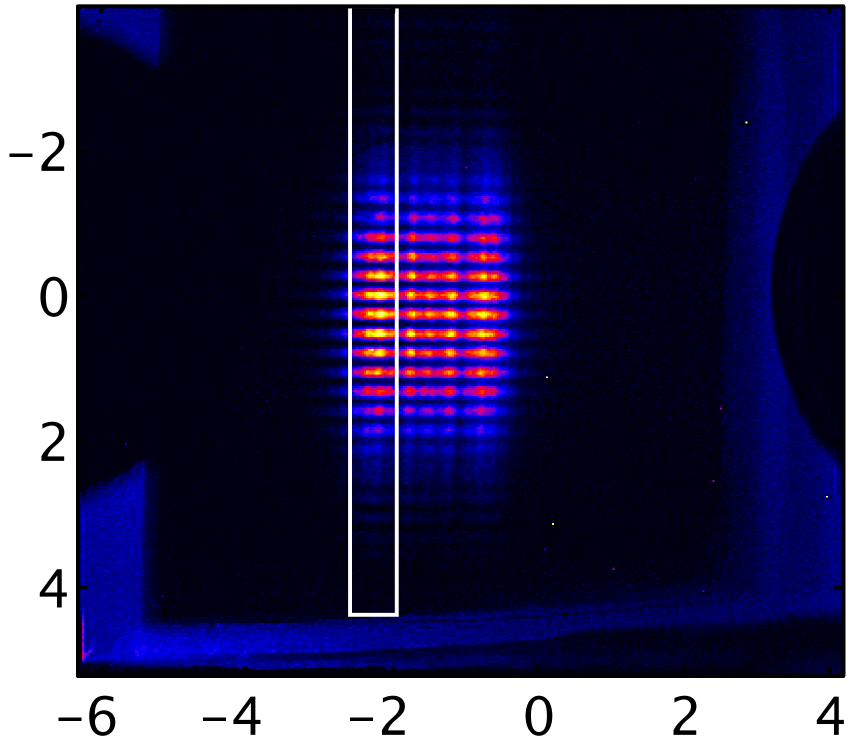




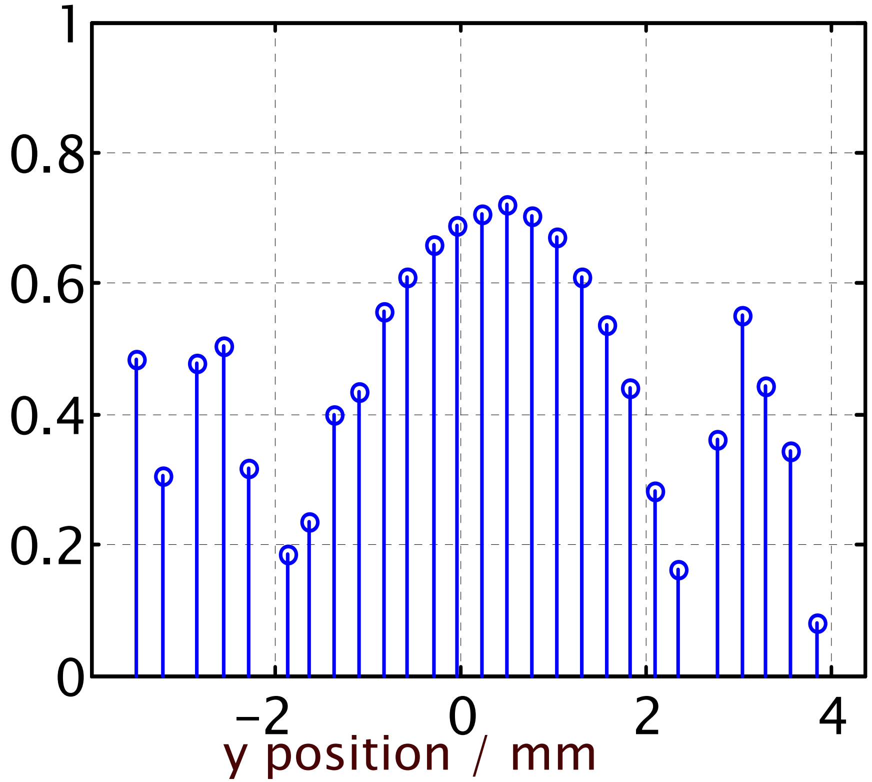
Analysis of Experimental Data at 87 nm

Double Slit — 1 mm Separation

Reconstructed Image

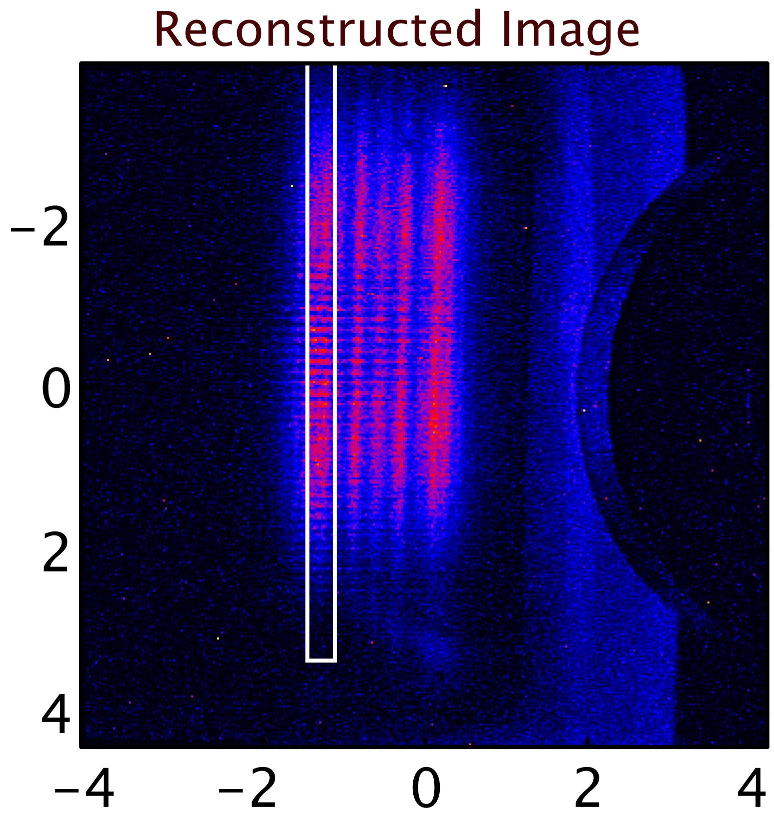


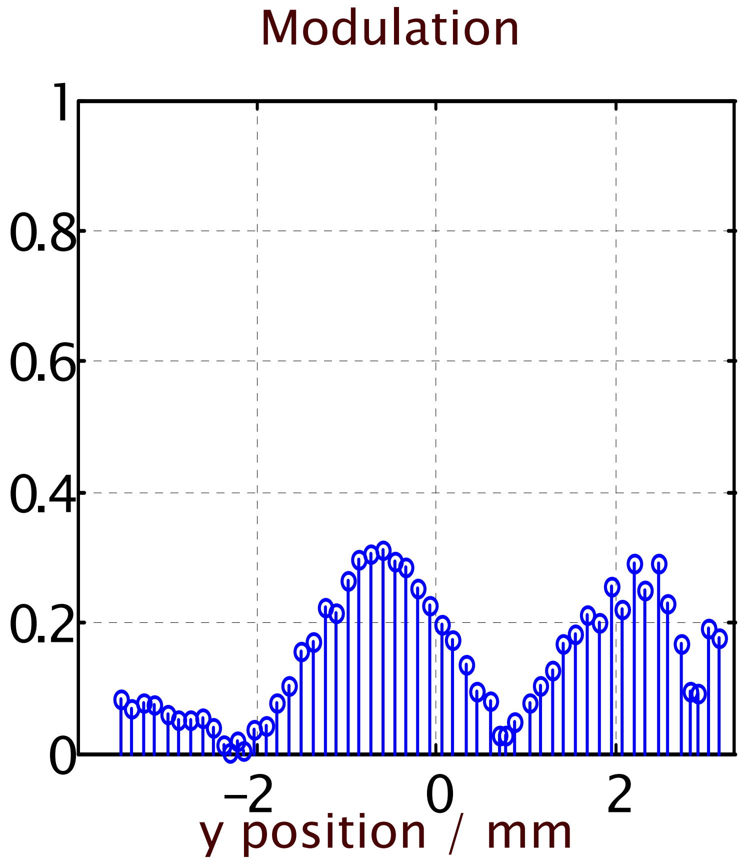
Modulation



Analysis of Experimental Data at 87 nm

Double Slit — 2 mm Separation

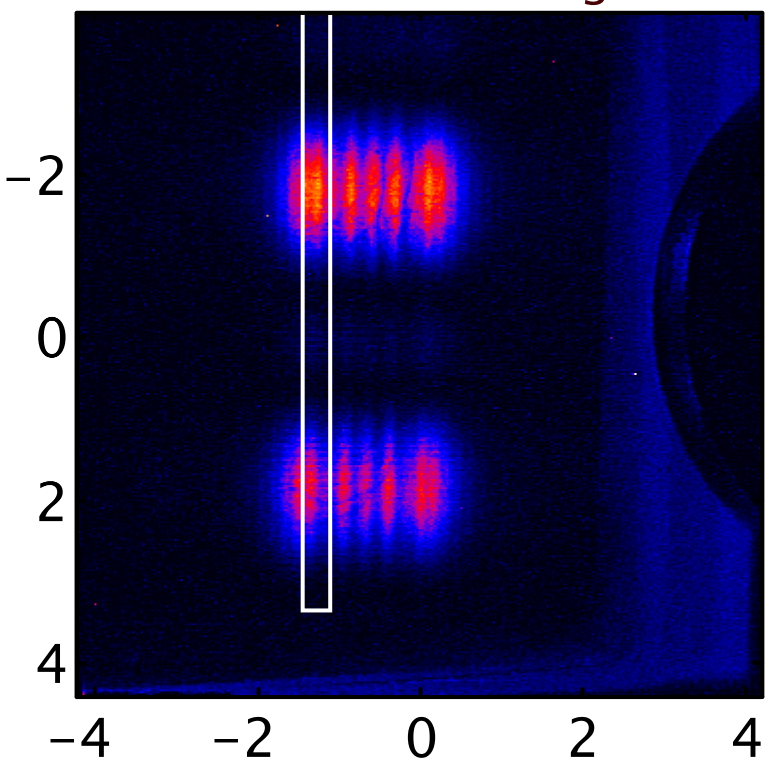




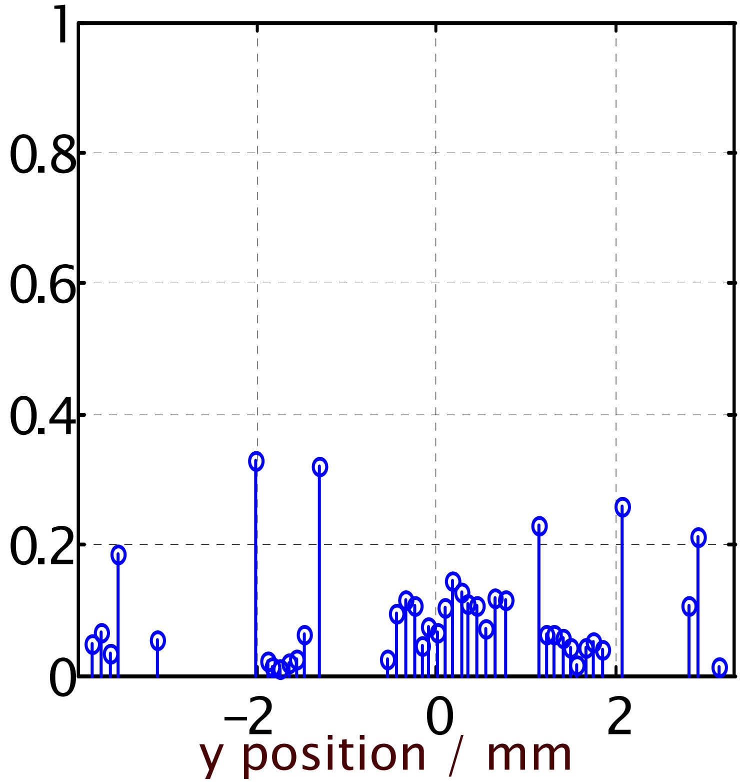
Analysis of Experimental Data at 87 nm

Double Slit — 3 mm Separation

Reconstructed Image

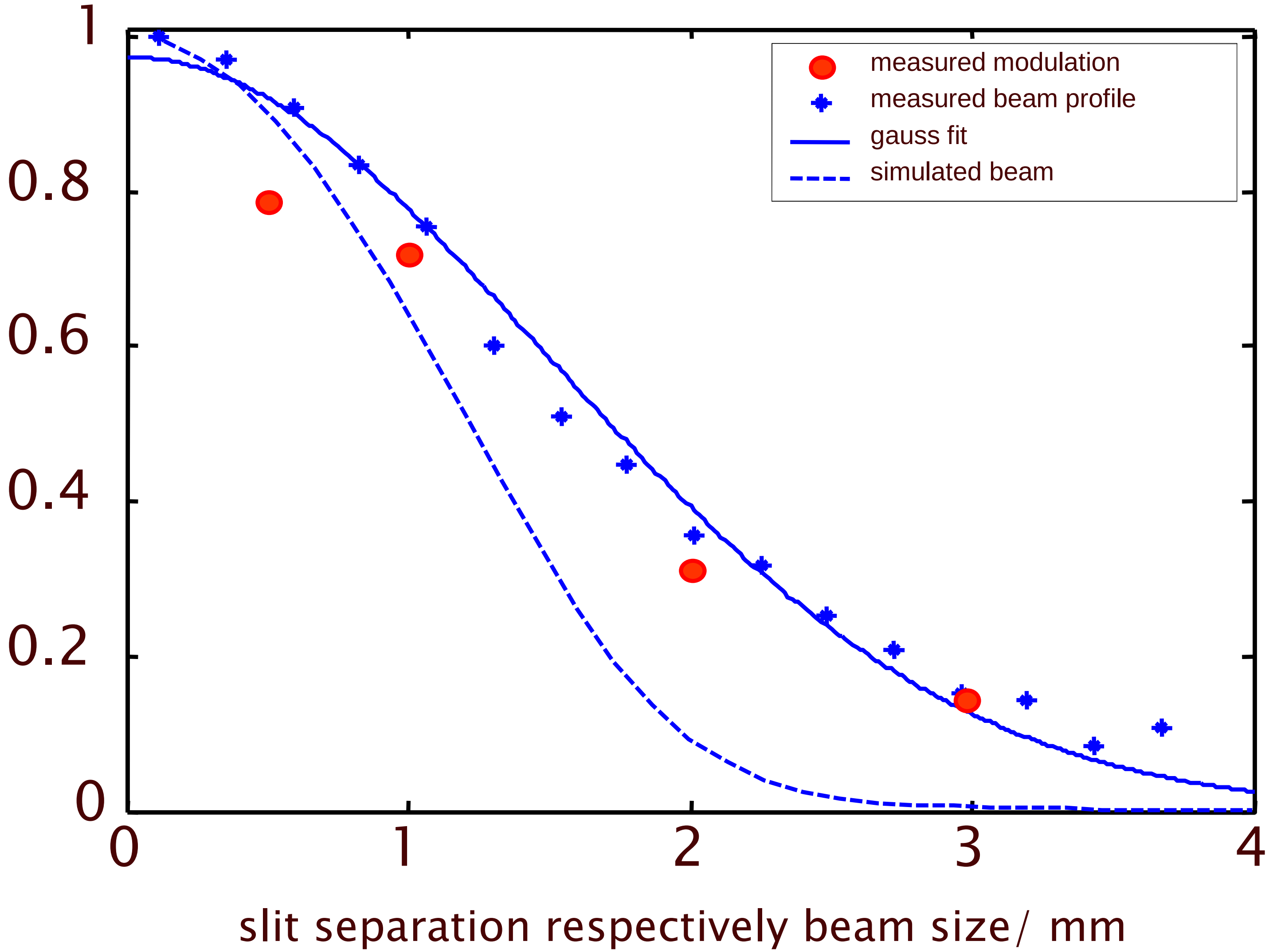


Modulation

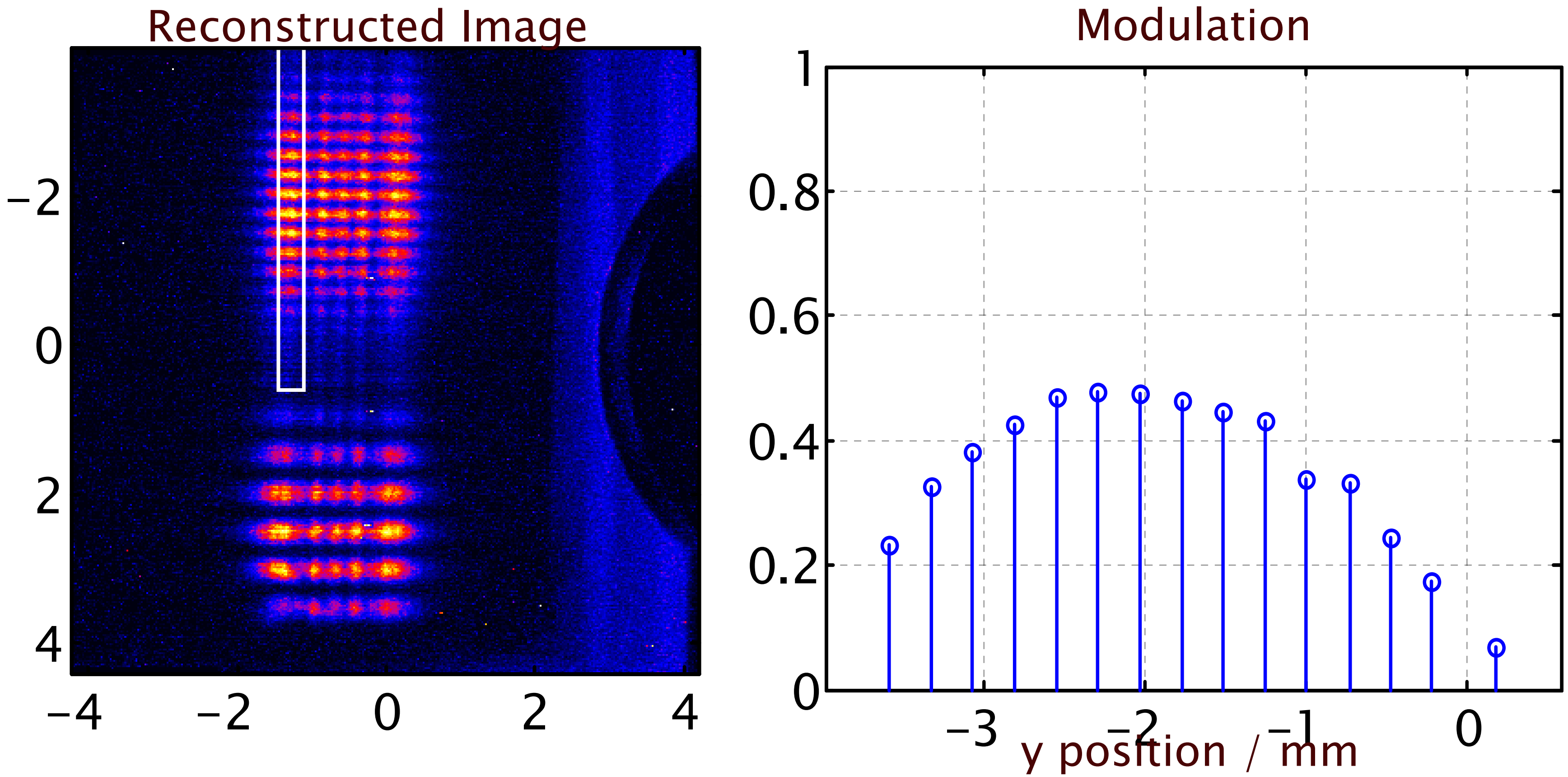


Analysis of Experimental Data at 87 nm

Dependence on Slit Separation



Coherence in the Outer Part of the Beam



A Double Slit Experiment to Study the Transverse Coherence of the TTF FEL

- Introduction
  - TTF Linear Accelerator and Free Electron Laser
  - Photon Diagnostics
  - Near Field Diffraction Effects
- Measurements
- Image Processing
- Analysis
- Simulations
- Consistency of the Measurements
- Development of Transverse Coherence
- Outlook

Simulations

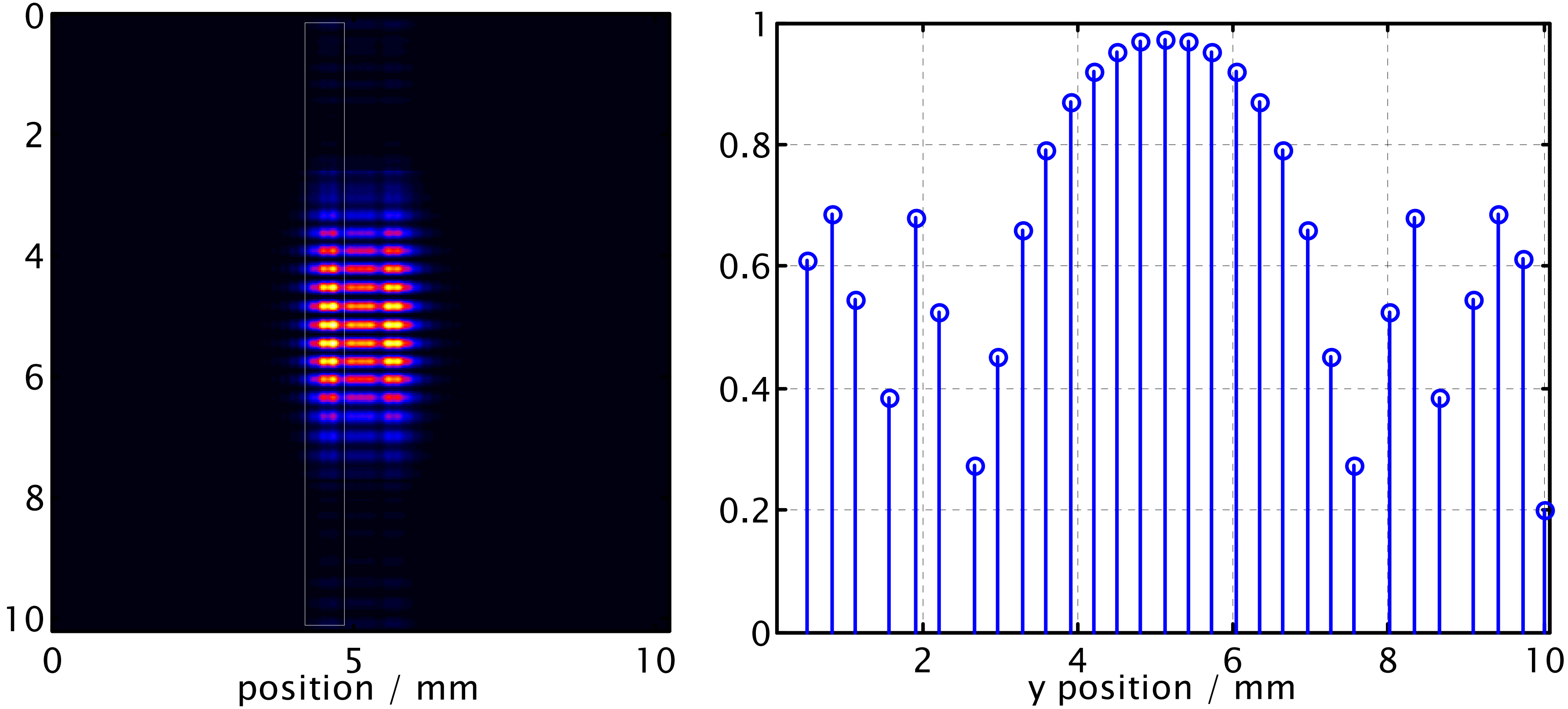
GLAD

- “General Laser Analysis and Design”
- Calculates the diffraction in the near field
- Propagates arbitrarily shaped wave packets, defined by slowly varying amplitude
- Various optical elements
- Import and export of the electric field

- Limitations
  - Assigned memory not sufficient to propagate 3-dimensional beam (defined on 1024x1024x512 points)

Simulations

Plane Wave Input



Simulations

FAST

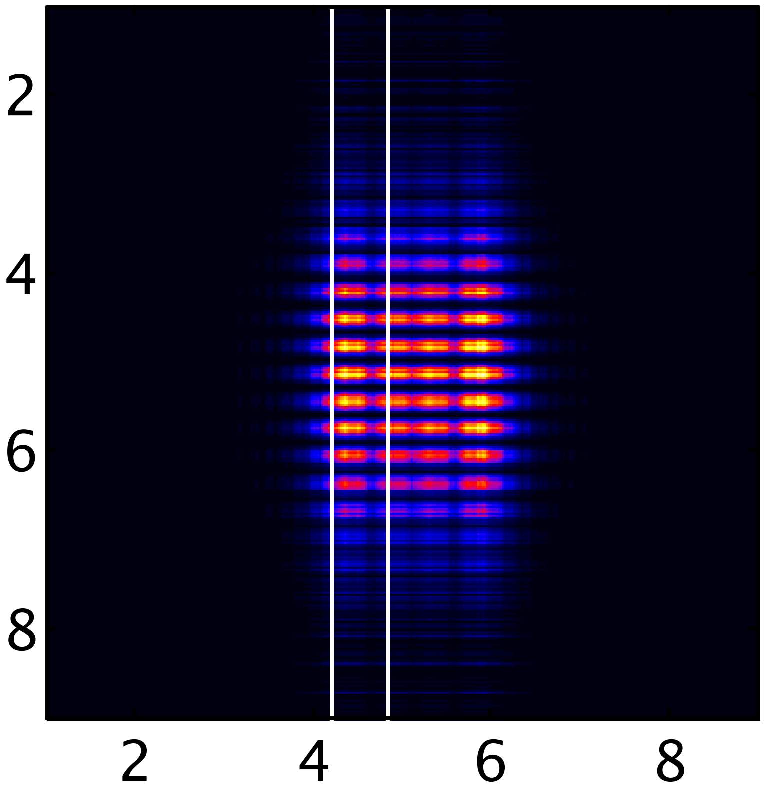
- Saldin, Schneidmiller, Yurkov
- 3-dimensional Free Electron Laser code
  - Start from shot noise
  - Numerical solution of the initial-value problem
  - Non-Linear Dynamics of the FEL process

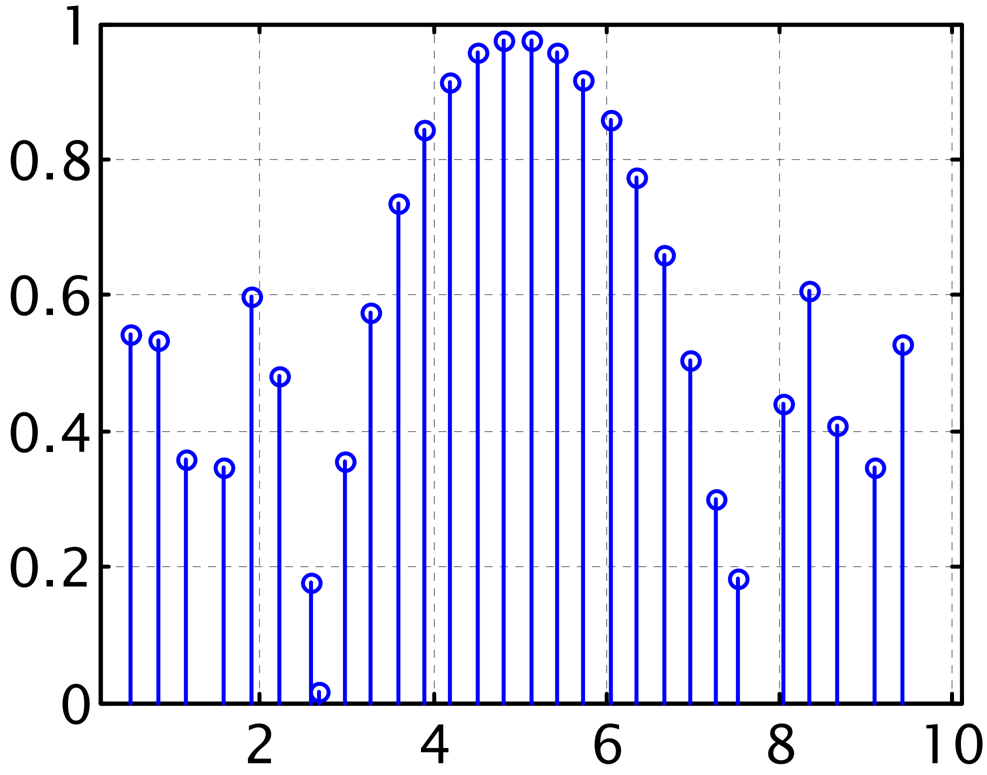
    ⇒Predicts
    - Transverse mode selection
    - Saturation
- Delivers the electric field (in Slowly Varying Amplitude approximation) at the exit of the undulator

⇝ Input file for GLAD

Simulations

FAST





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Consistency of the Measurements

Comparison with other Methods

- Coherence of the FEL is given by the number of independent modes
- Here: transverse coherence ↔ number of transverse modes
- For the fundamental gaussian mode, we have at the waist:

$$\sigma_r \sigma_\theta = \lambda / 4\pi$$

where σ_r is the beam diameter, σ_θ the angular divergence

- For higher order modes:

$$\sigma_r \sigma_\theta \geq \lambda / 4\pi$$

Consistency of the Measurements

Comparison with other Methods

- Consider a perfectly coherent beam, where only the fundamental gaussian mode is present:

$$\sigma_r \sigma_\theta = \lambda / 4\pi$$

λ: easy to measure

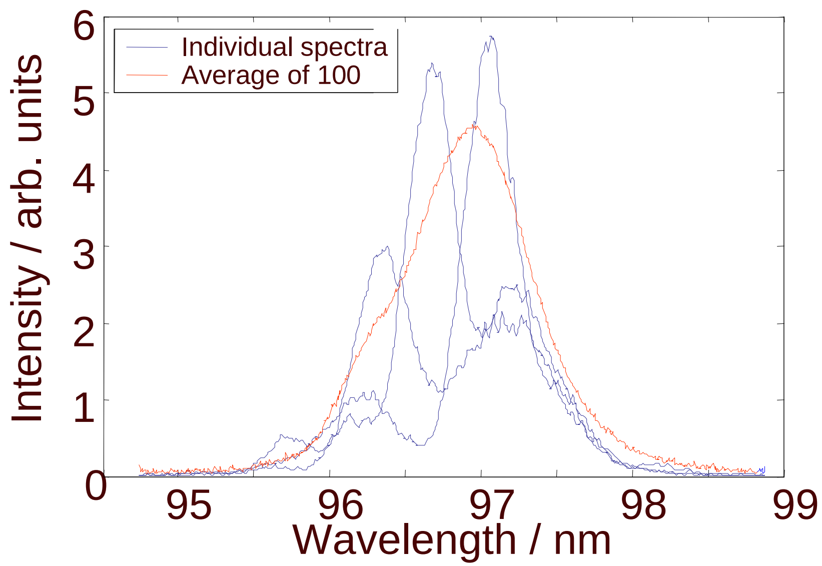
σ_θ: easy to measure (distribution in the far field)

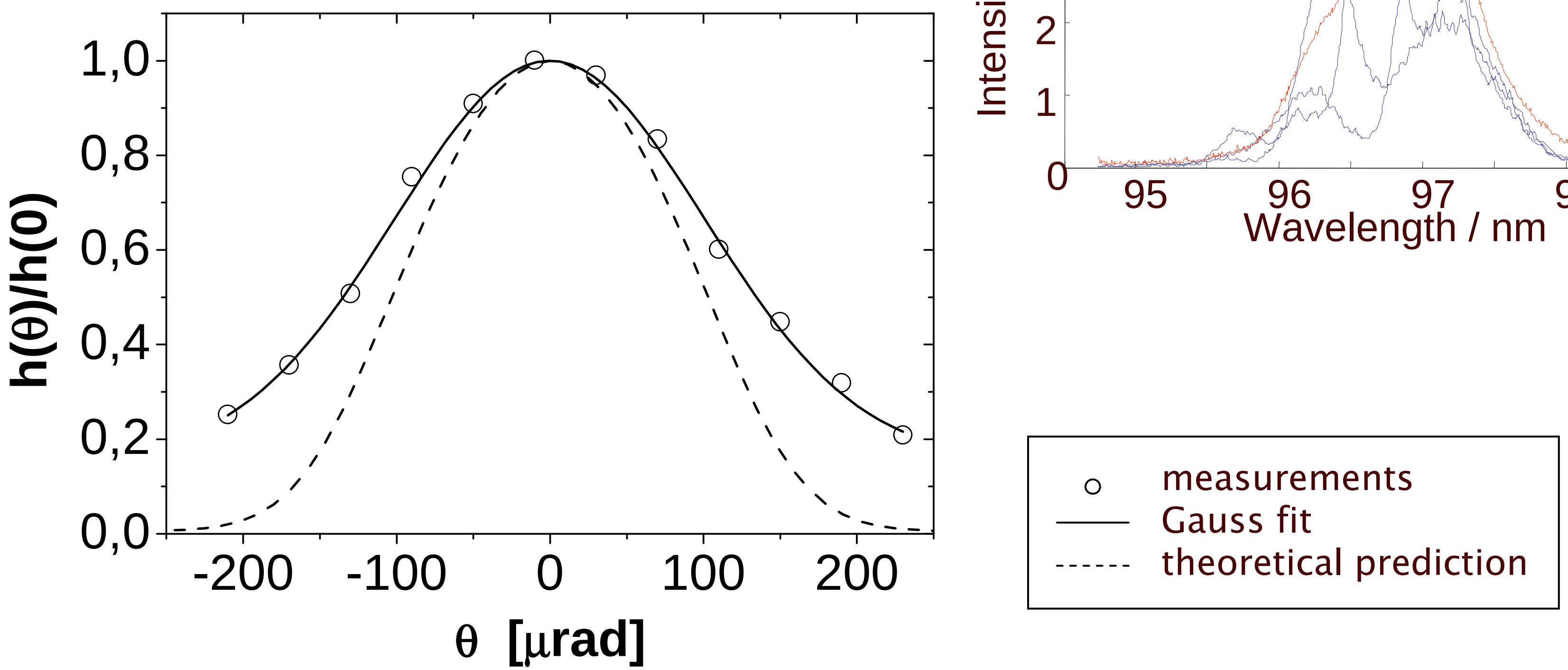
σ_r: determine photon beam size in the undulator

Comparison with other Methods

Measurement: λ = 97 nm

σ_θ = 120 µrad:



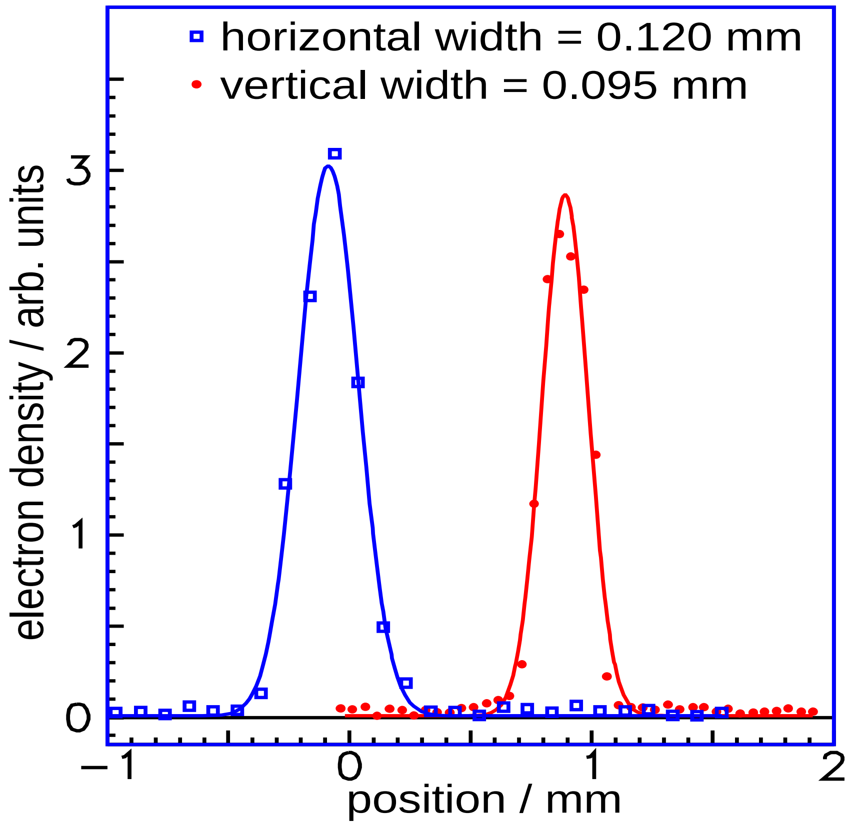


Comparison with other Methods

⇒ For the fundamental transverse mode, we expect a photon beam width

$\sigma_r = 64\ \mu m$

• Compare to the electron beam in the undulator:



A Double Slit Experiment to Study the Transverse Coherence of the TTF FEL

Outlook

Development along Undulator

- Beyond the saturation of the FEL:
  growth of the number of transverse modes

⇒ decrease of transverse coherence!

- TTF FEL can be virtually shortened by kicking the beam off the undulator axis
  - measure coherence at different effective undulator lengths

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Coherence Measurements

Outlook

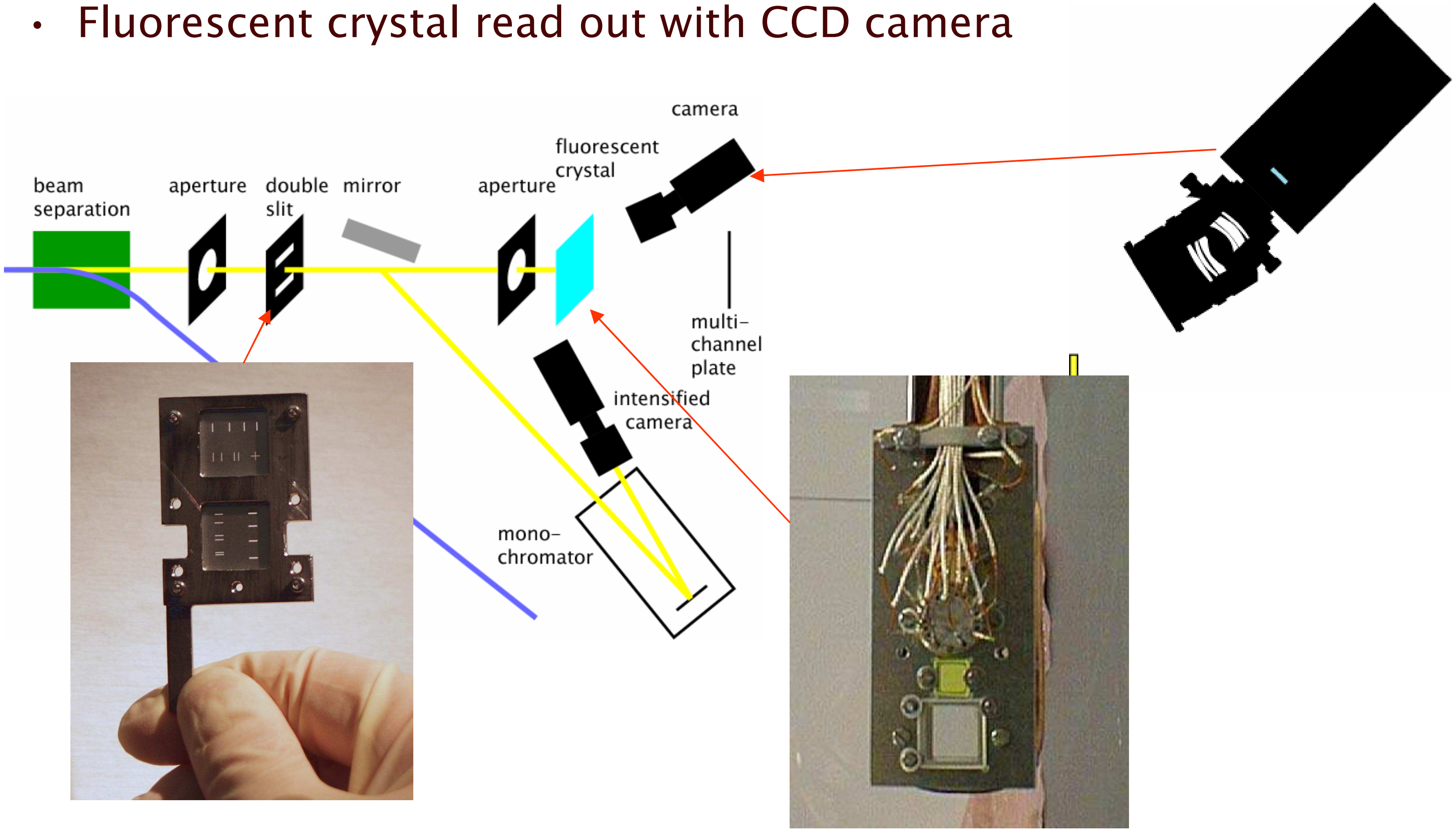
- Refinement of the Analysis
  - Consider influence of multiple scattering in the fluorescent crystal
  - What is the effect of the averaging over many pulses?

- Expansion of the Analysis
  - Degree of coherence at various Undulator lengths

- Can this device be installed at X-Ray wavelengths?

Conclusion (1)

- Obtained double slit diffraction patterns of a SASE FEL at 100 nm
  - Set-Up in ultra high vacuum
  - Fluorescent crystal read out with CCD camera



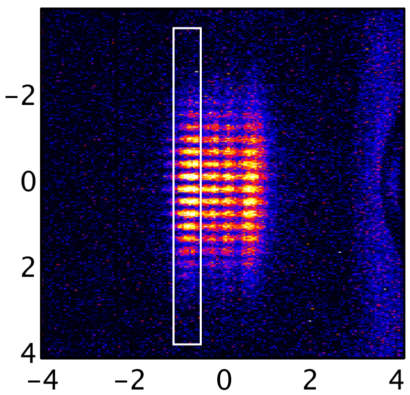
Conclusion (2)

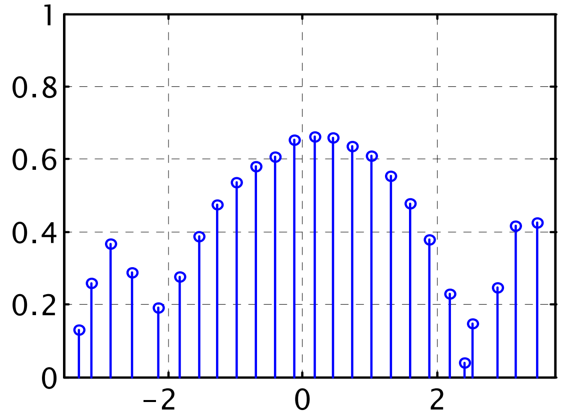
- Double slit create diffraction images similar to near field theory:
  - Modulation depth decreases outwards

Image

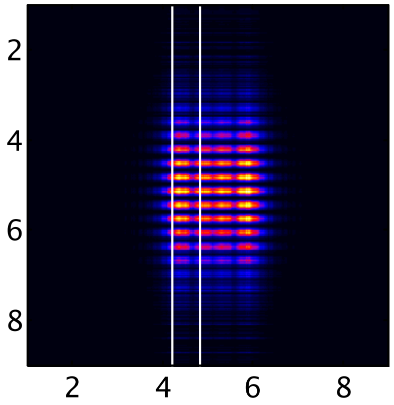
Modulation

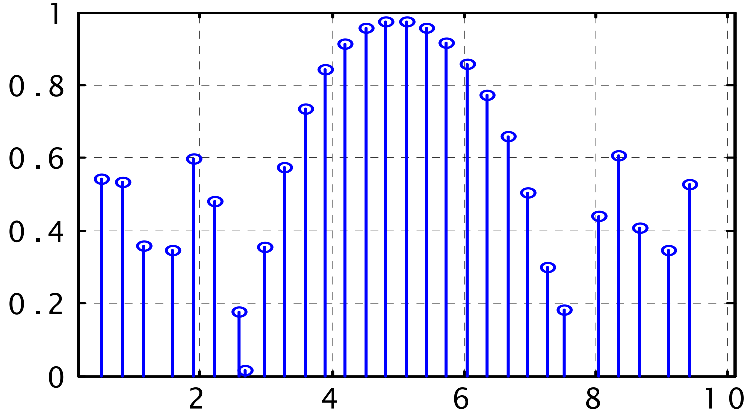
experimental data





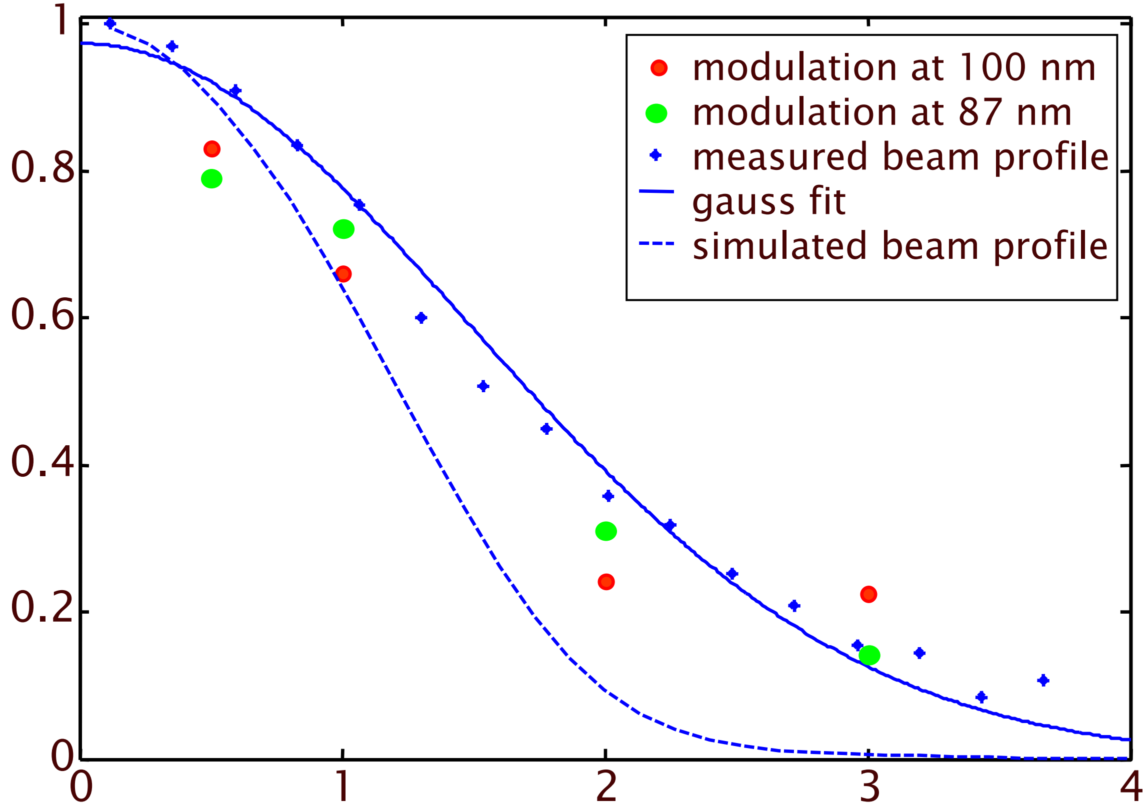
simulations





Conclusion (3)

- Determined Modulation
    - at various slit separations
    - with different electron bunch properties



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Thank You to the TTF Team

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