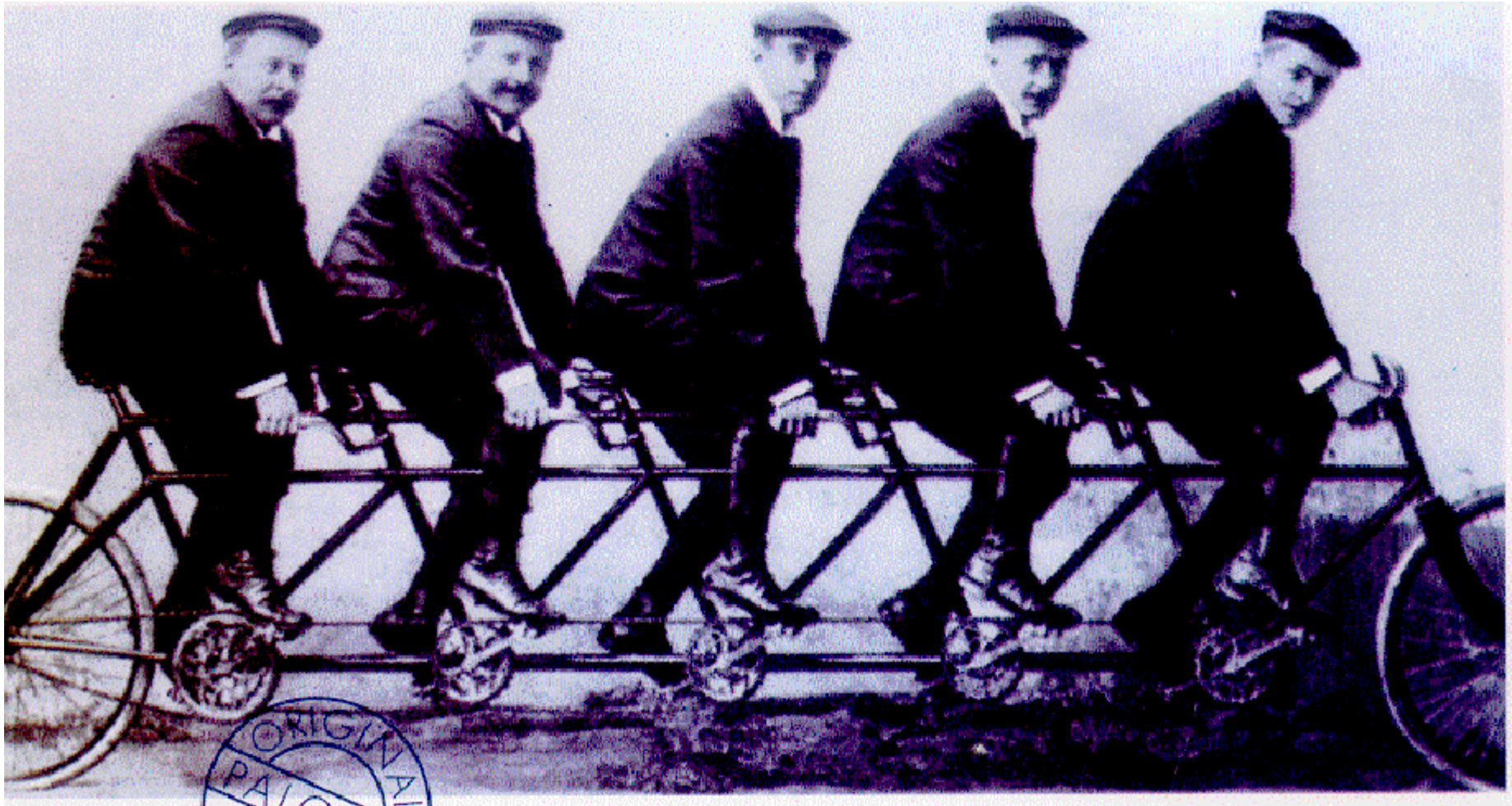
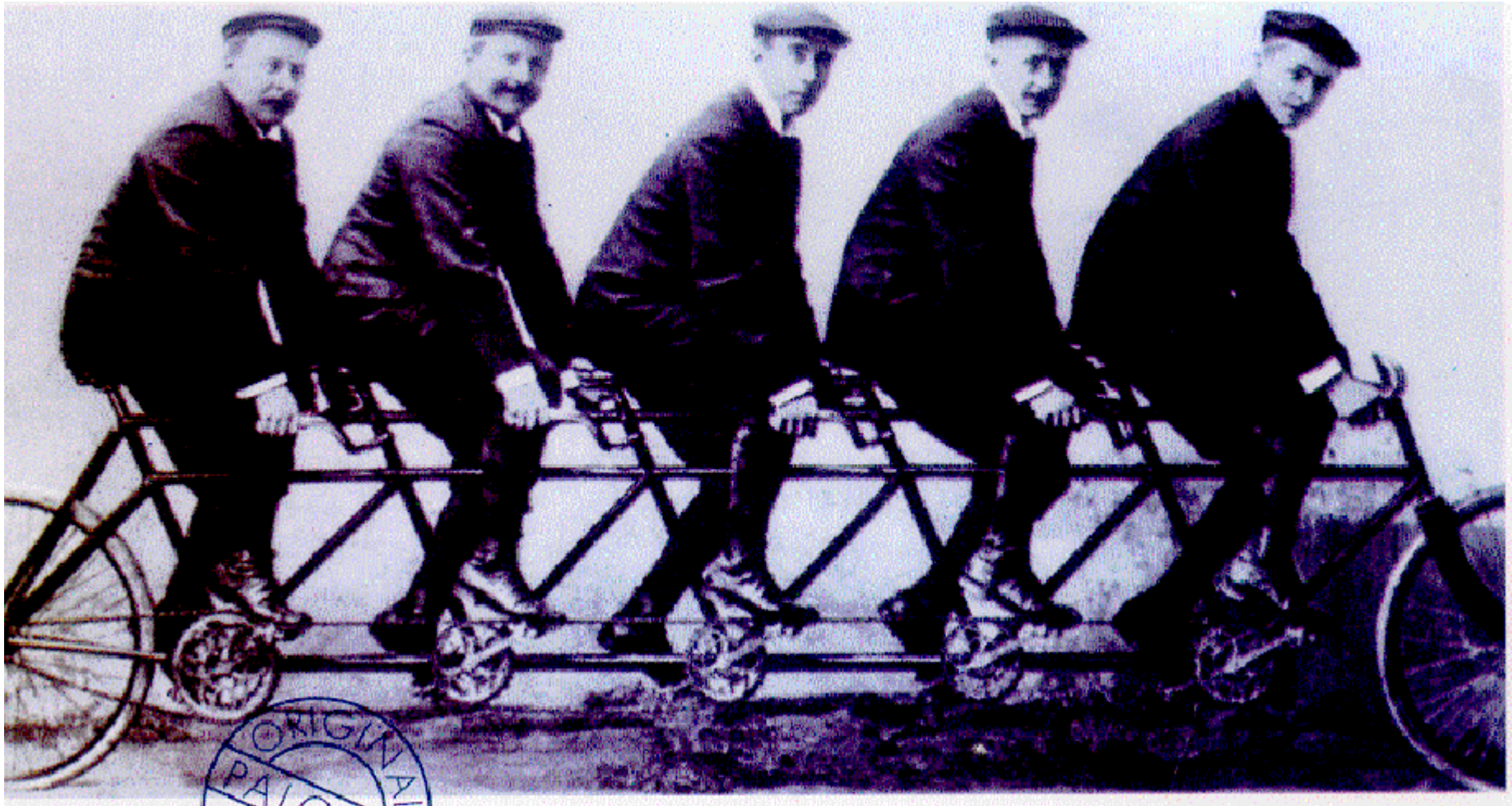


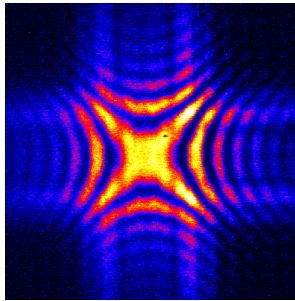
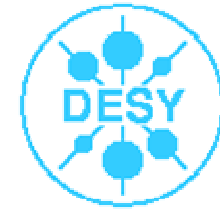
# What do these people need?



# Coherence...



**RWTH**



# Study of the Transverse Coherence at the TTF Free Electron Laser

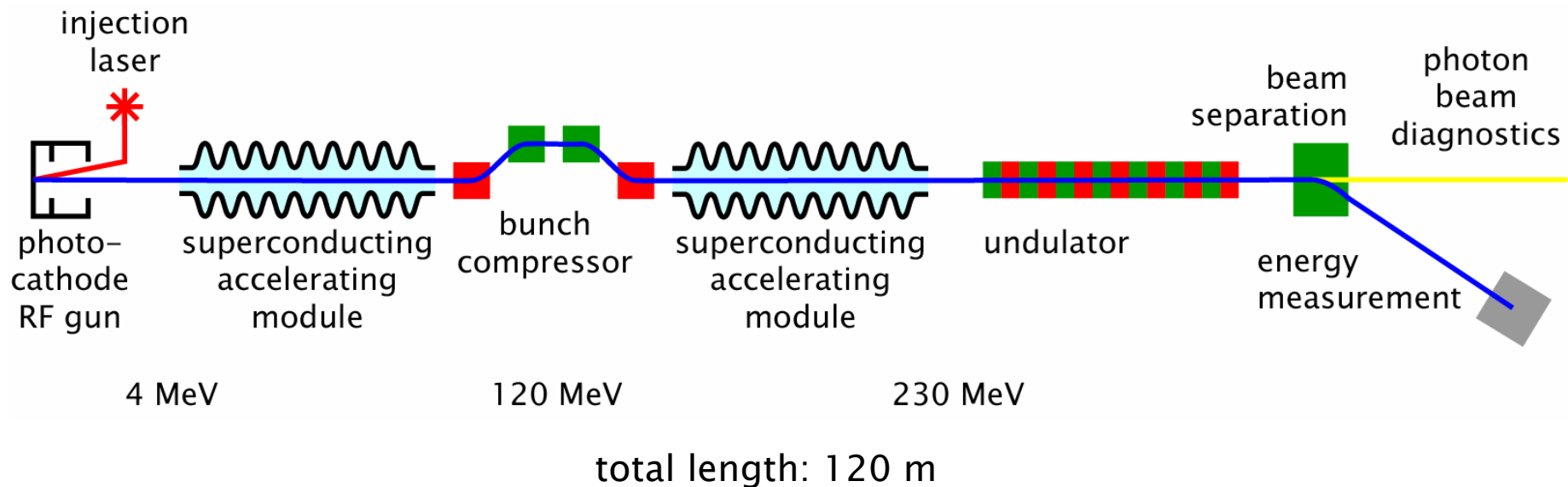
Rasmus Ischebeck

# Study of the Transverse Coherence at the TTF Free Electron Laser

- Experimental Setup
  - TTF Linear Accelerator and SASE FEL
  - Photon Diagnostics
- Measurements of the transverse coherence
- Image Processing
- Analysis
- Simulations
- Outlook

# TTF FEL Linear Accelerator

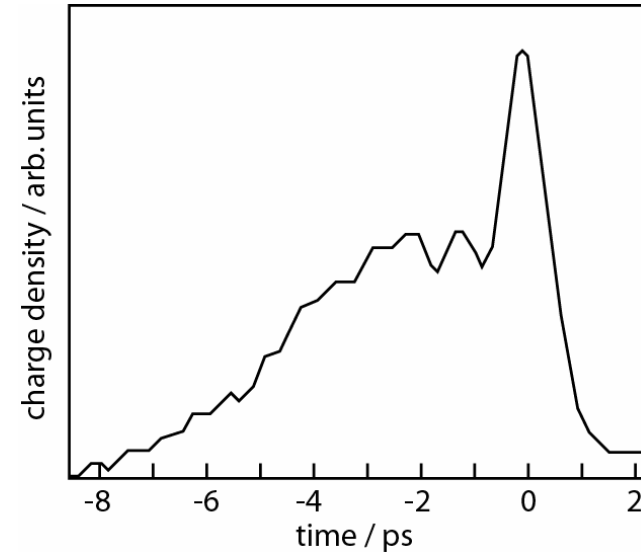
- Gun
- Superconducting RF Cavities
- Bunch Compressor
- Undulator
- SASE



TTF FEL

# 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

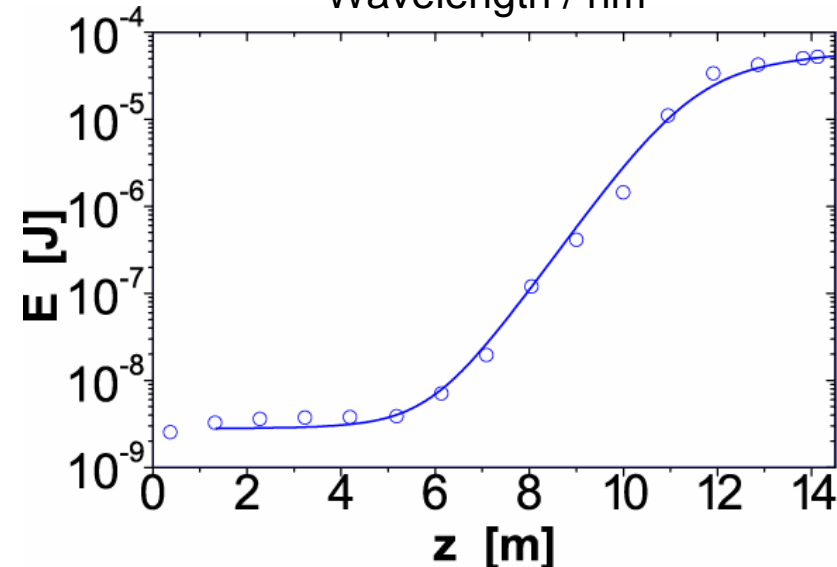
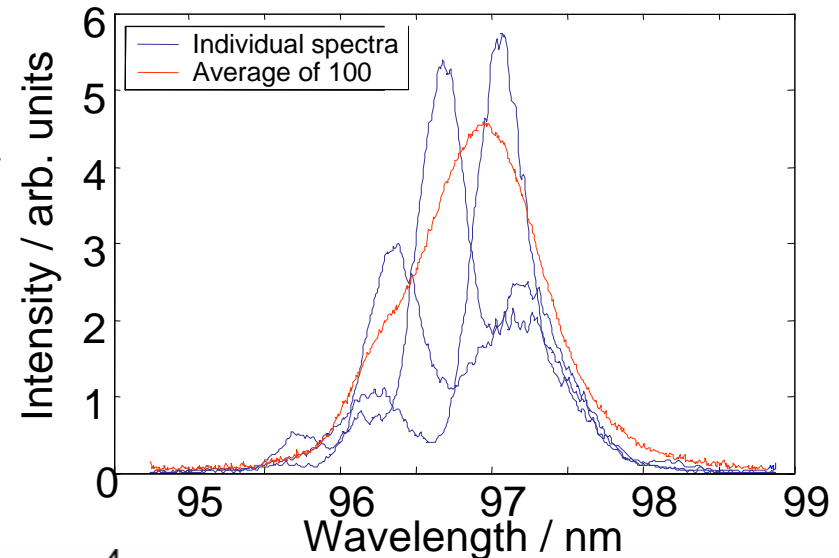


Measurement by  
interferometry of coherent  
transition radiation

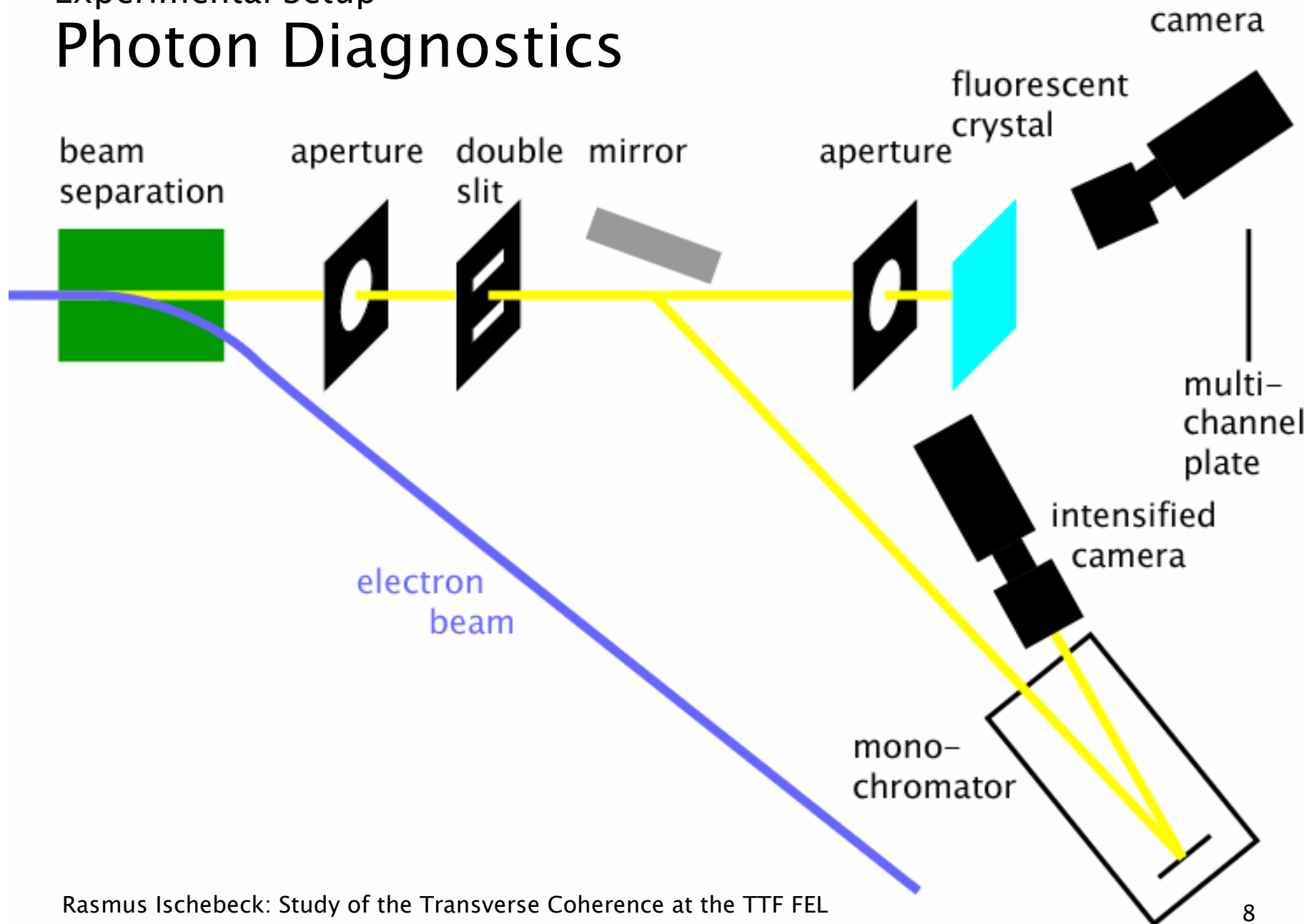
## Experimental Setup

# Properties of the FEL Light

- Wavelength: 80 ... 120 nm, depending on the electron energy
- Pulse energy: typically up to 10  $\mu\text{J}$  per pulse
- Peak power: 1 GW
- FEL starts from noise
- ⇒ No input needed
- Single pass saturation
- ⇒ No mirrors needed
- Longitudinal and Transverse Coherence

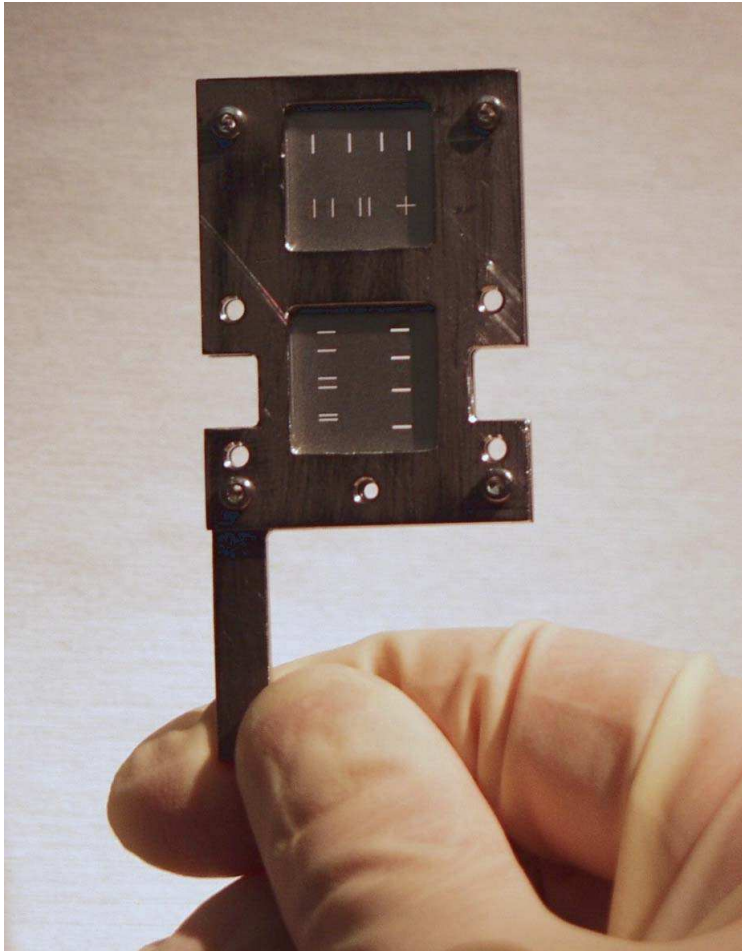


# Experimental Setup Photon Diagnostics



Experimental Setup

# Coherence Measurements



## Experimental Setup

# Coherence Measurements

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

## Experimental Setup

# Near Field Effects

- Criterion for far field diffraction:

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

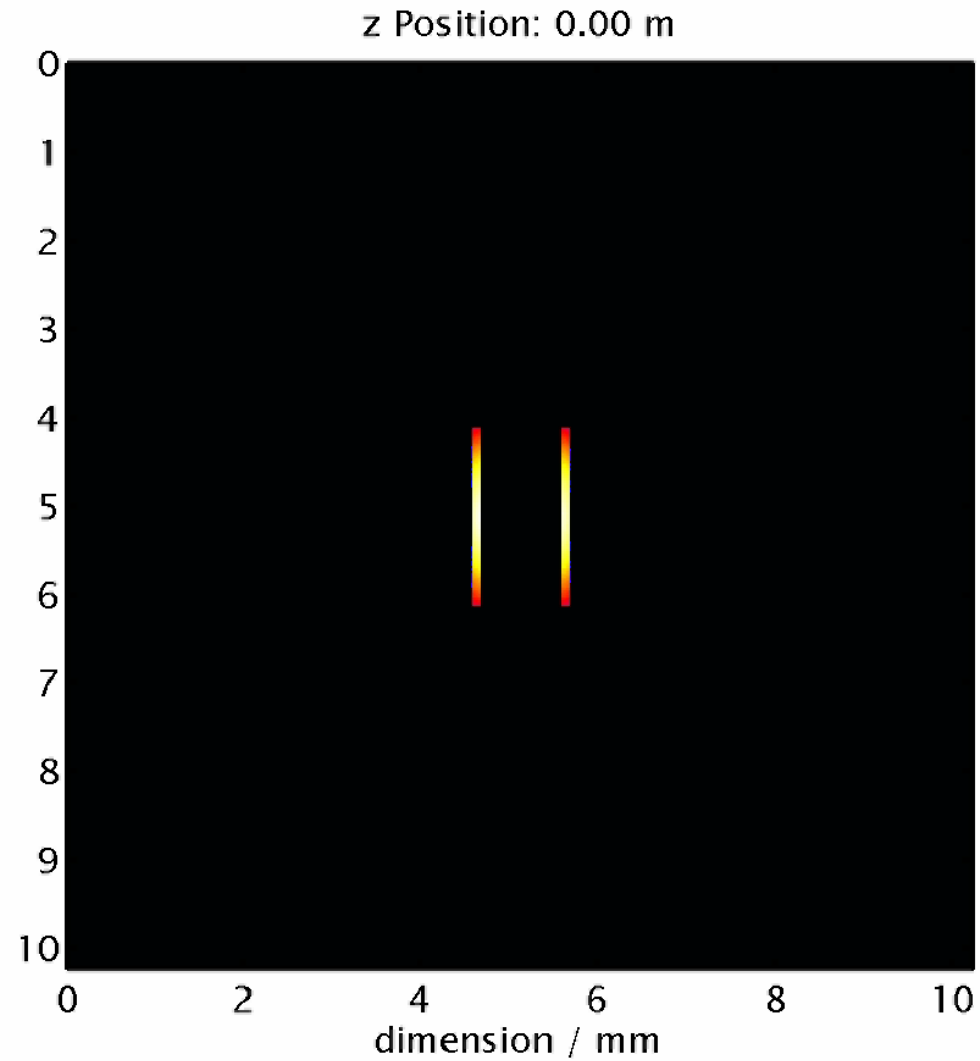
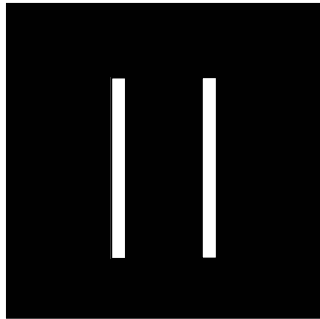
- $d$ : distance between slits,  $\lambda$ : wavelength,  $L$ : distance slits—screen

- Here:  $L = 3.1 \text{ m}$ ,  $d = 1 \text{ mm}$ ,  $\lambda = 100 \text{ nm} \Rightarrow \frac{\lambda L}{d^2} = 0.3$

- Near field effects  $\Rightarrow$  reduced modulation

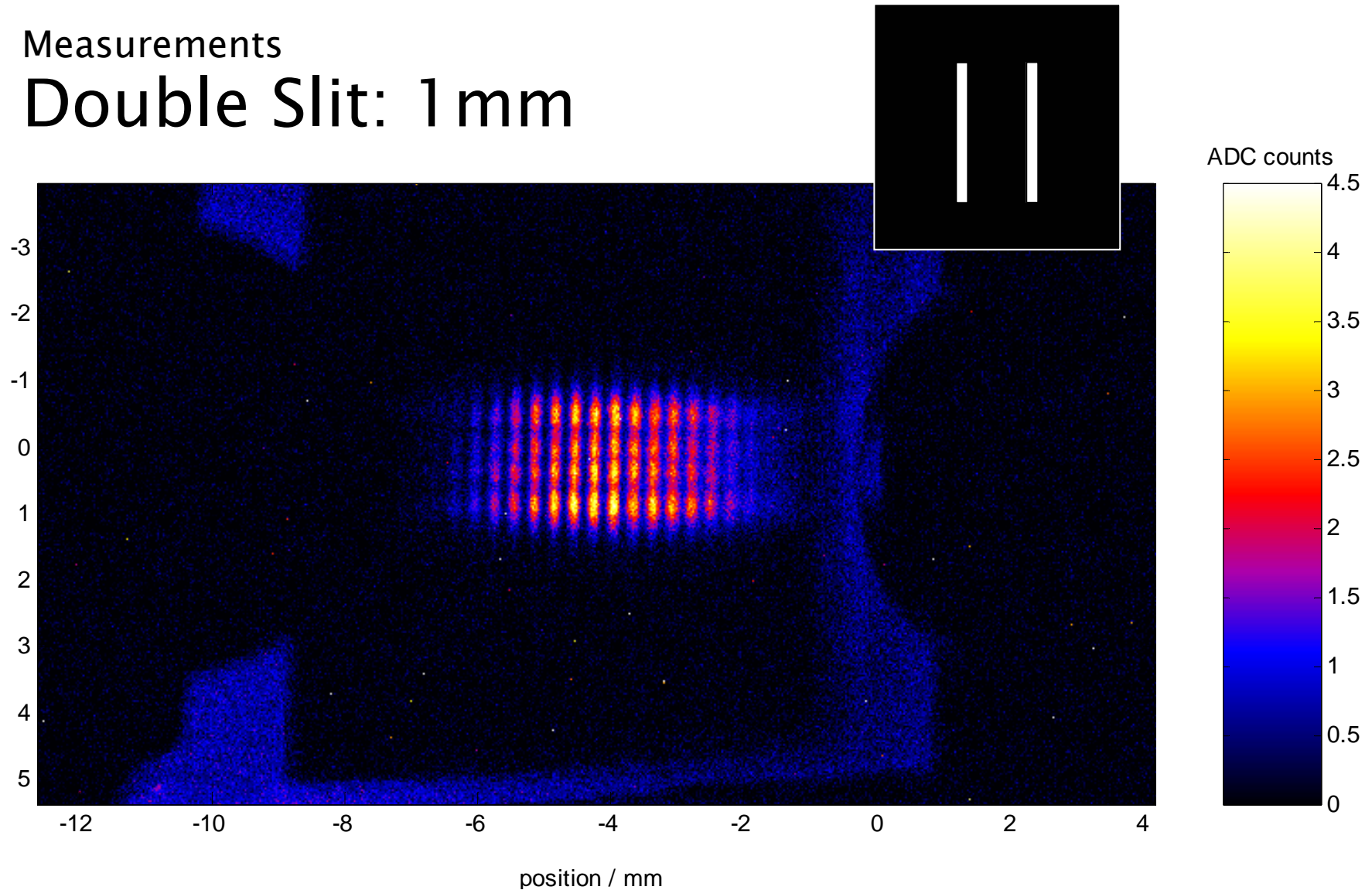
- additional modifications to the far field formula:
  - finite width and length of slits

# Simulation of Near Field Diffraction



Measurements

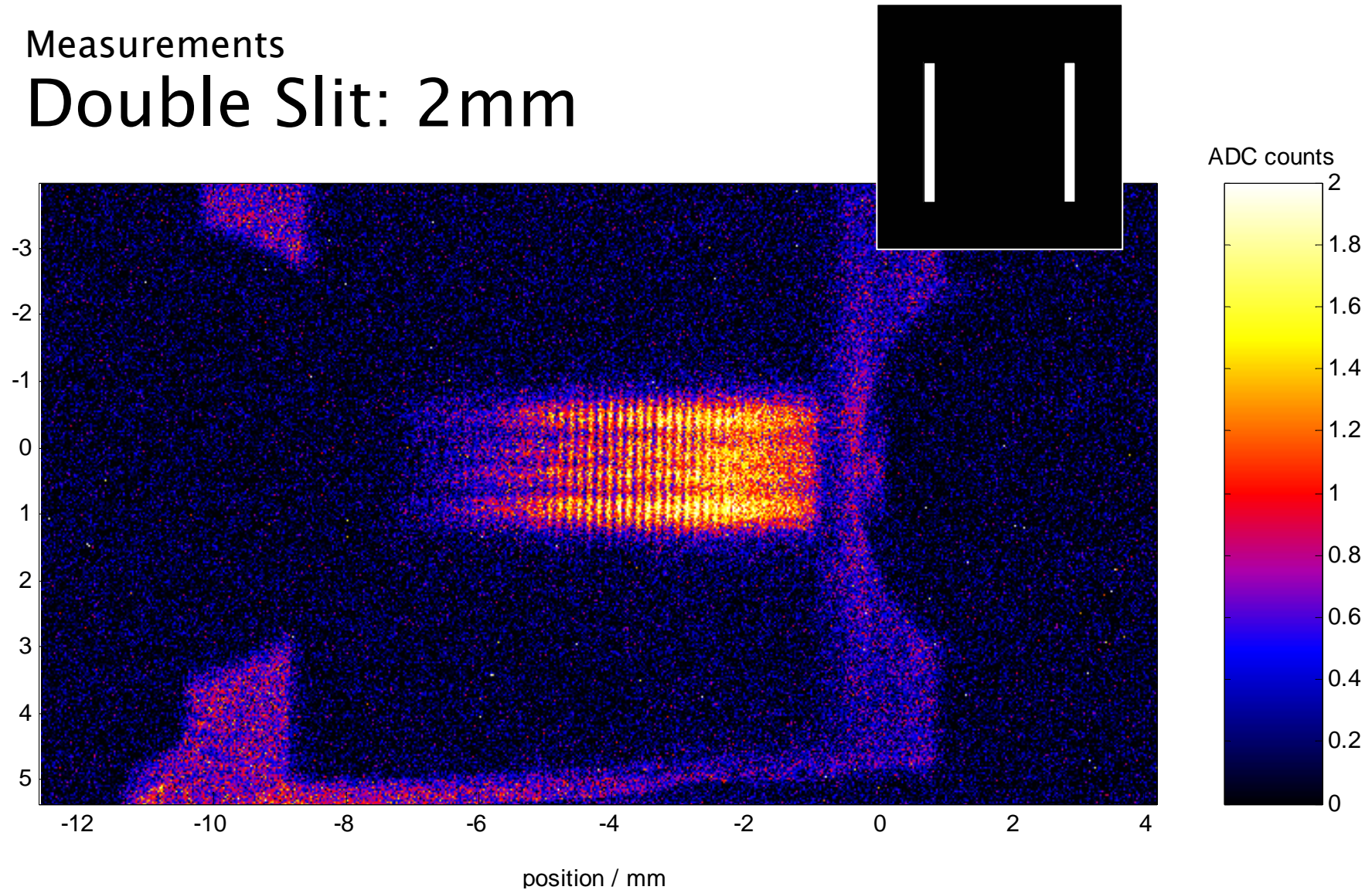
# Double Slit: 1 mm



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

Measurements

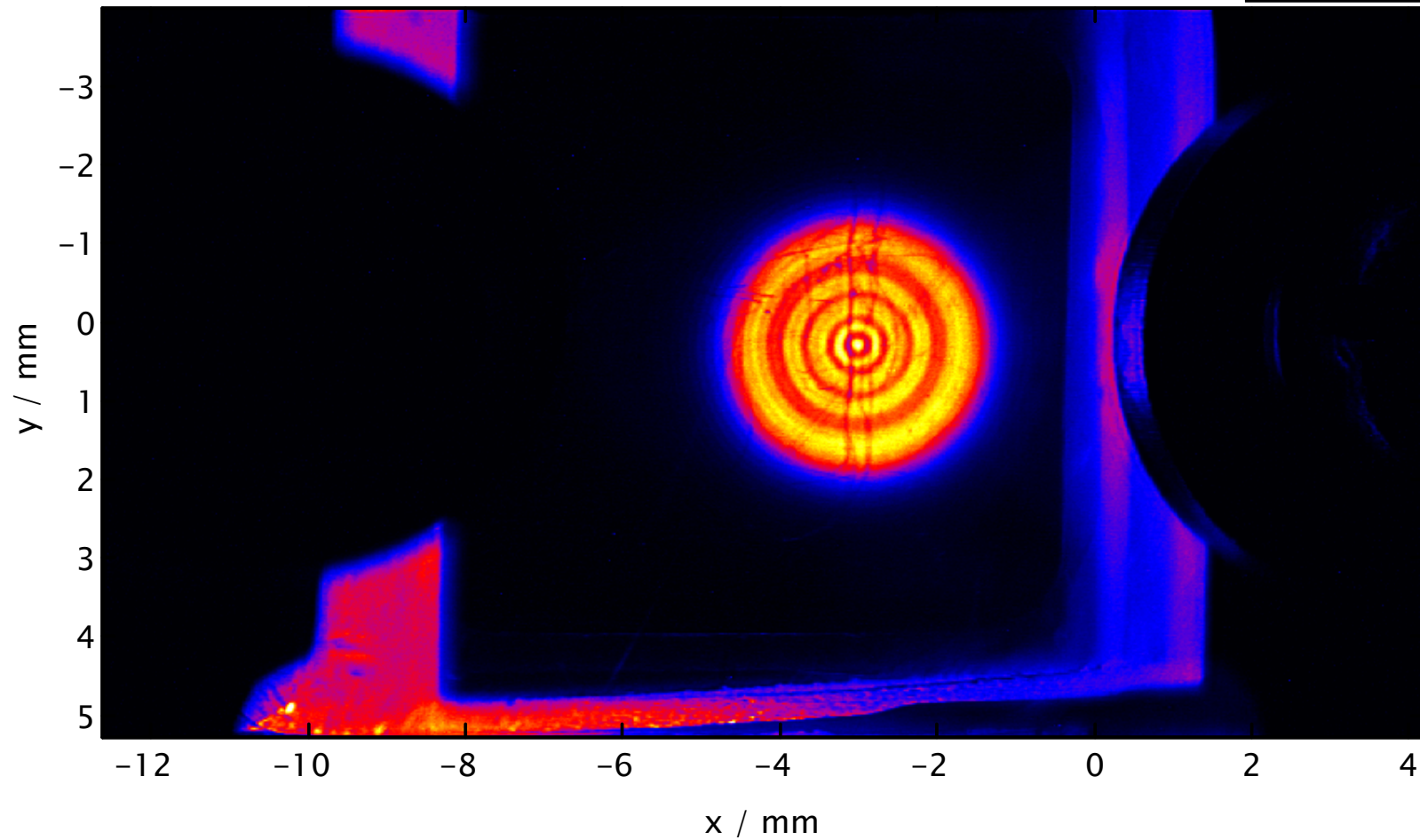
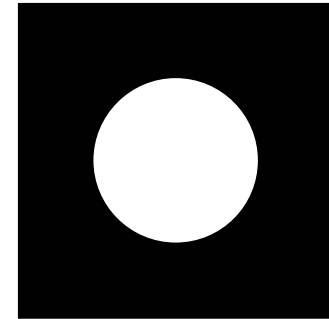
# Double Slit: 2mm



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

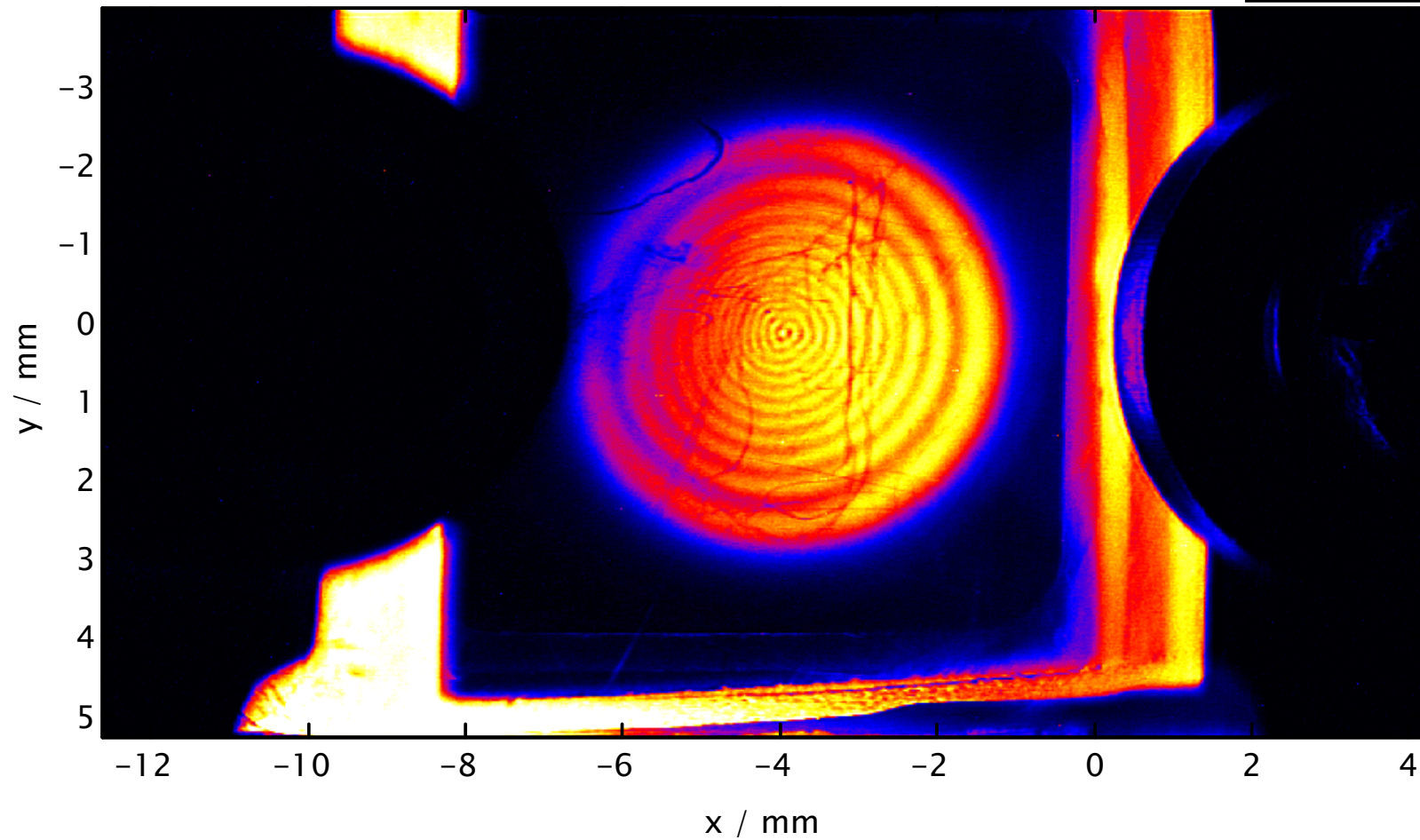
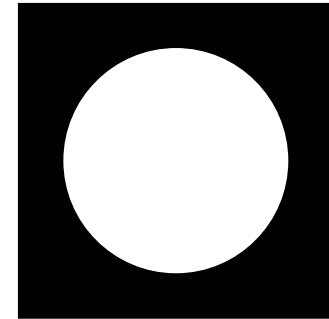
Measurements

Circular Aperture:  $\varnothing$  3mm



Measurements

Circular Aperture:  $\varnothing$  5mm



## Measurements

# Circular Apertures

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

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

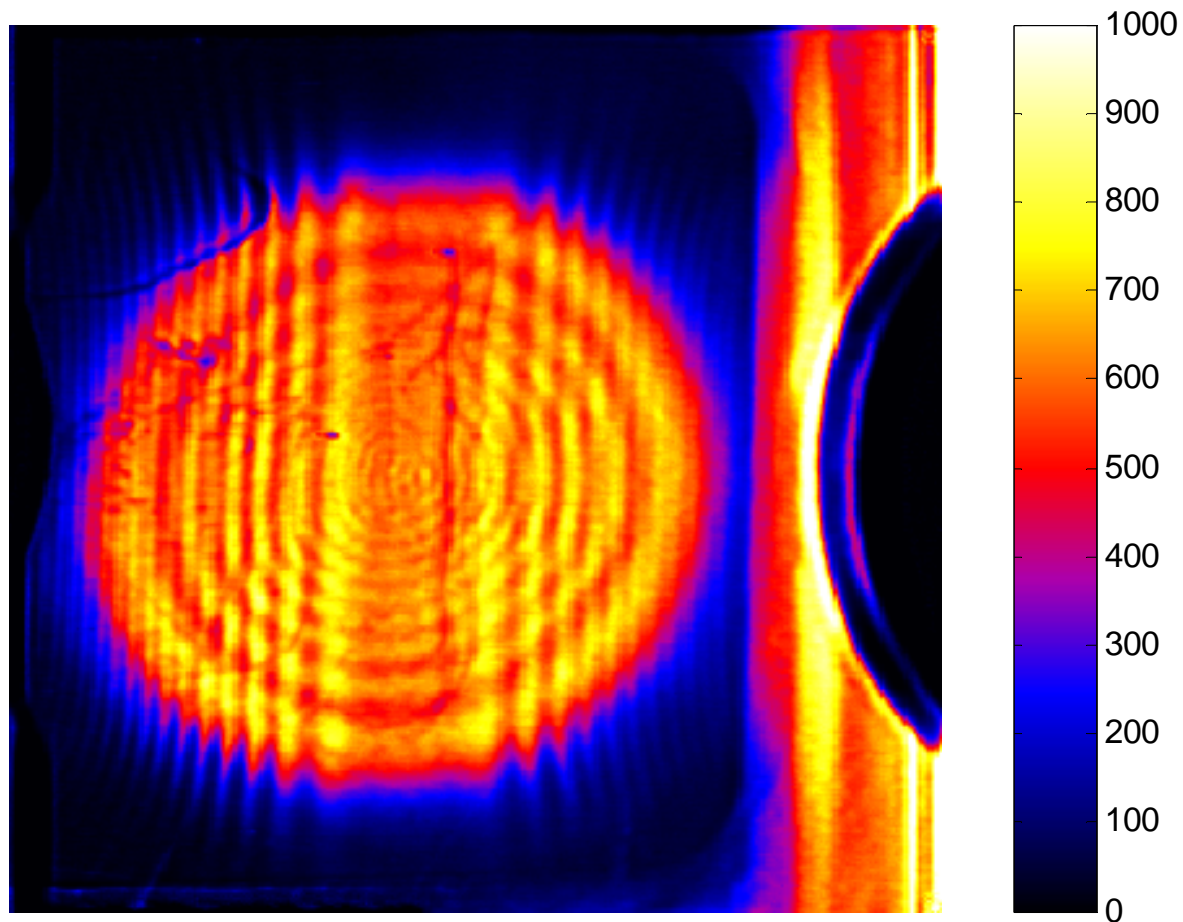
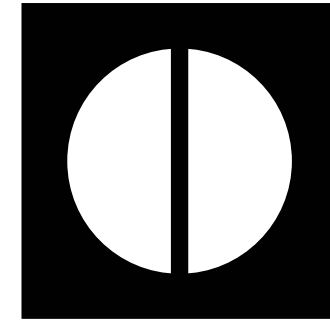
r: aperture radius,  $\lambda$ : wavelength, D: distance source—aperture, L: distance aperture—screen

Here:

Aperture	predicted	observed
3 mm	9.2	9
5 mm	25.5	23

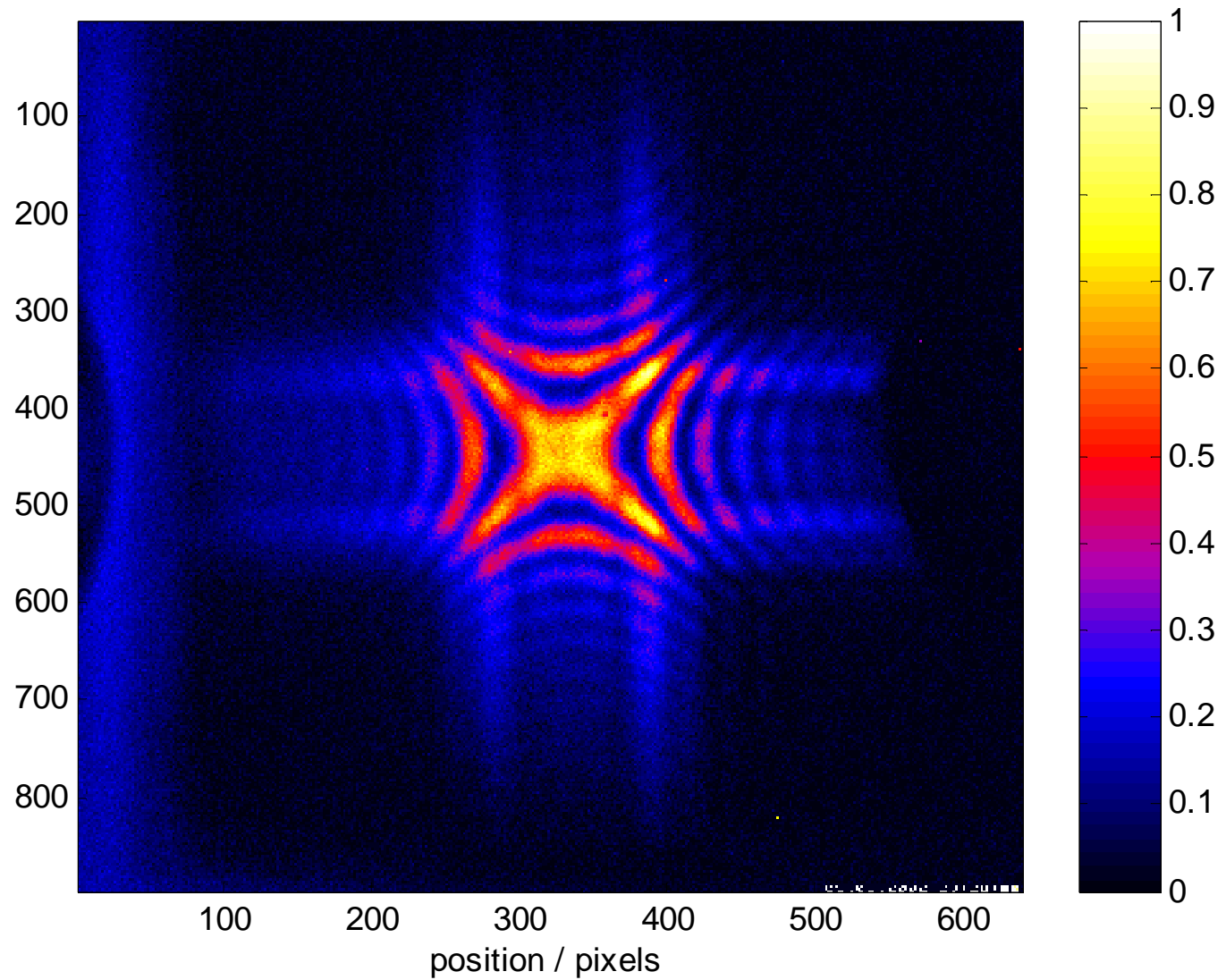
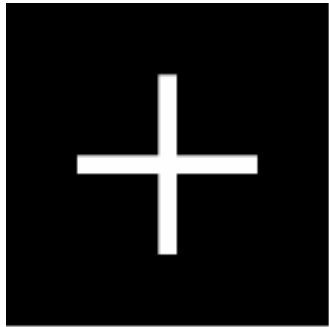
Measurements

# Circular Aperture + Wire



A wire in the beam path also creates diffraction

# Measurements Crossed Slits



# Deconvolution of the Camera Resolution

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

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

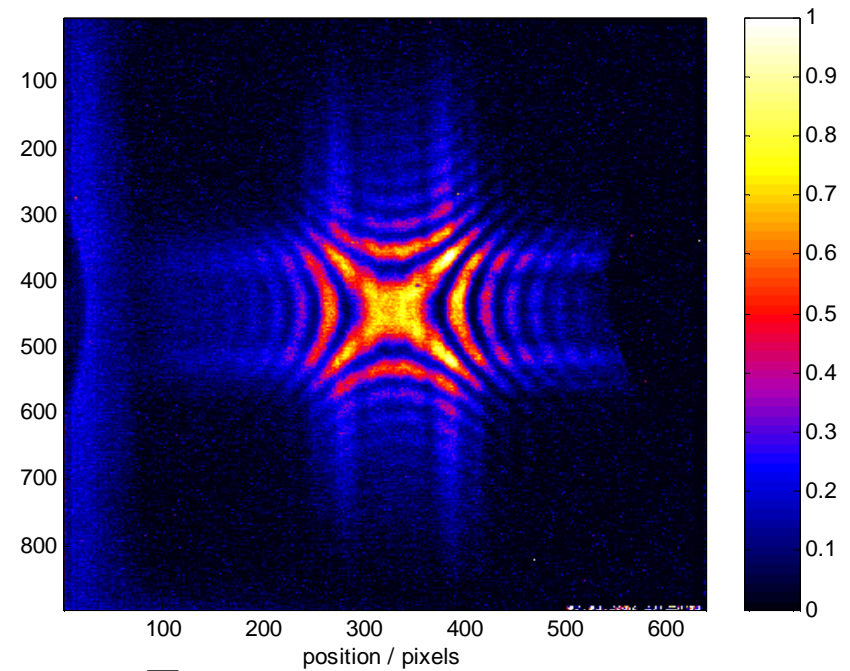
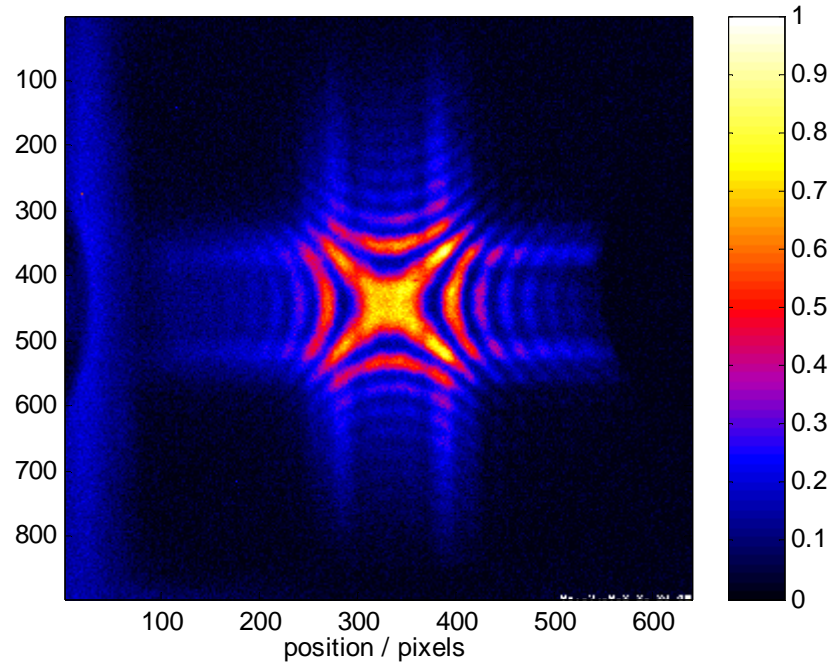
- For discrete values:

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

# Deconvolution of the Camera Resolution

- ⇒ Reduced contrast
  - ⇒ apparently reduced FEL coherence
- 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

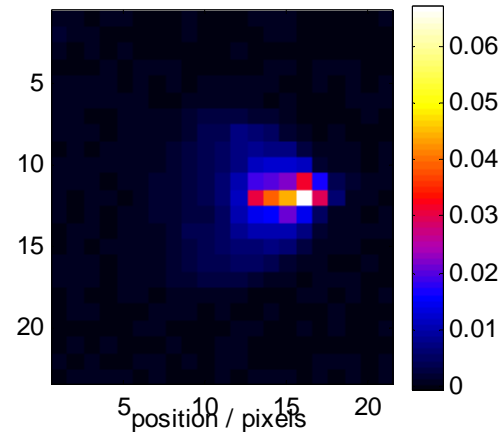
# Deconvolution of the Camera Resolution



Measured distribution  $\Phi$

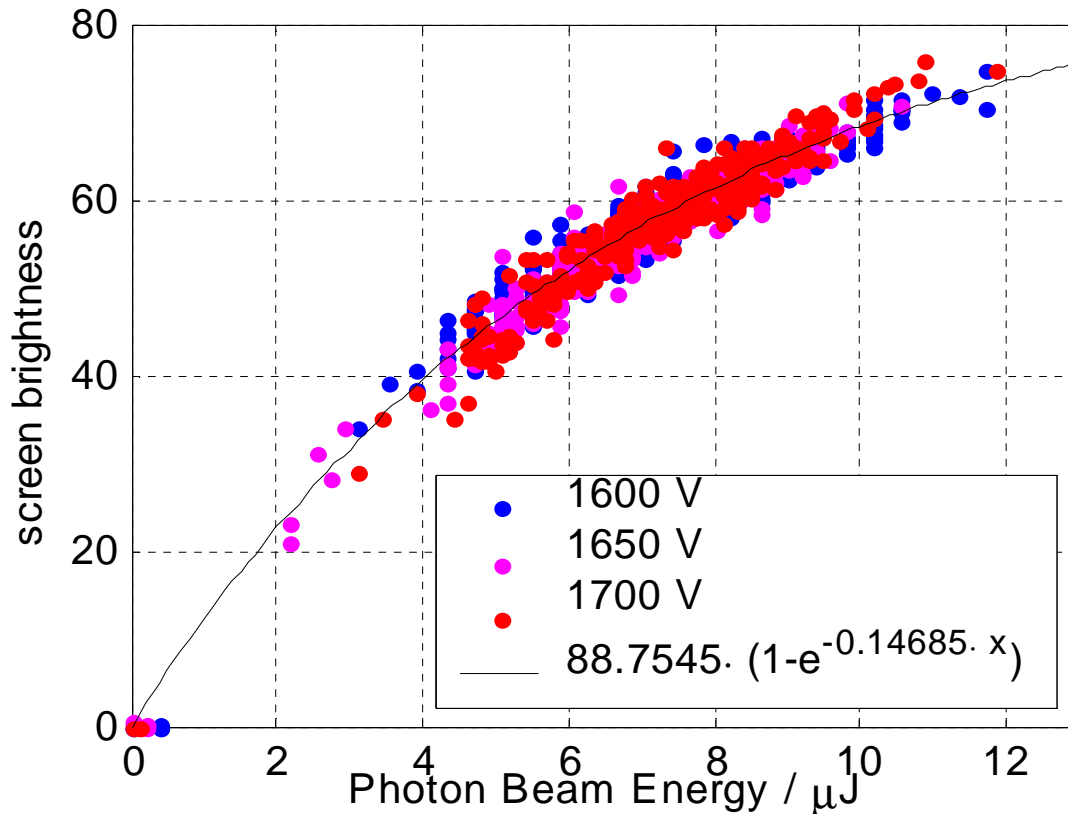
Reconstructed distribution  $\Psi$

Point spread function  $P$



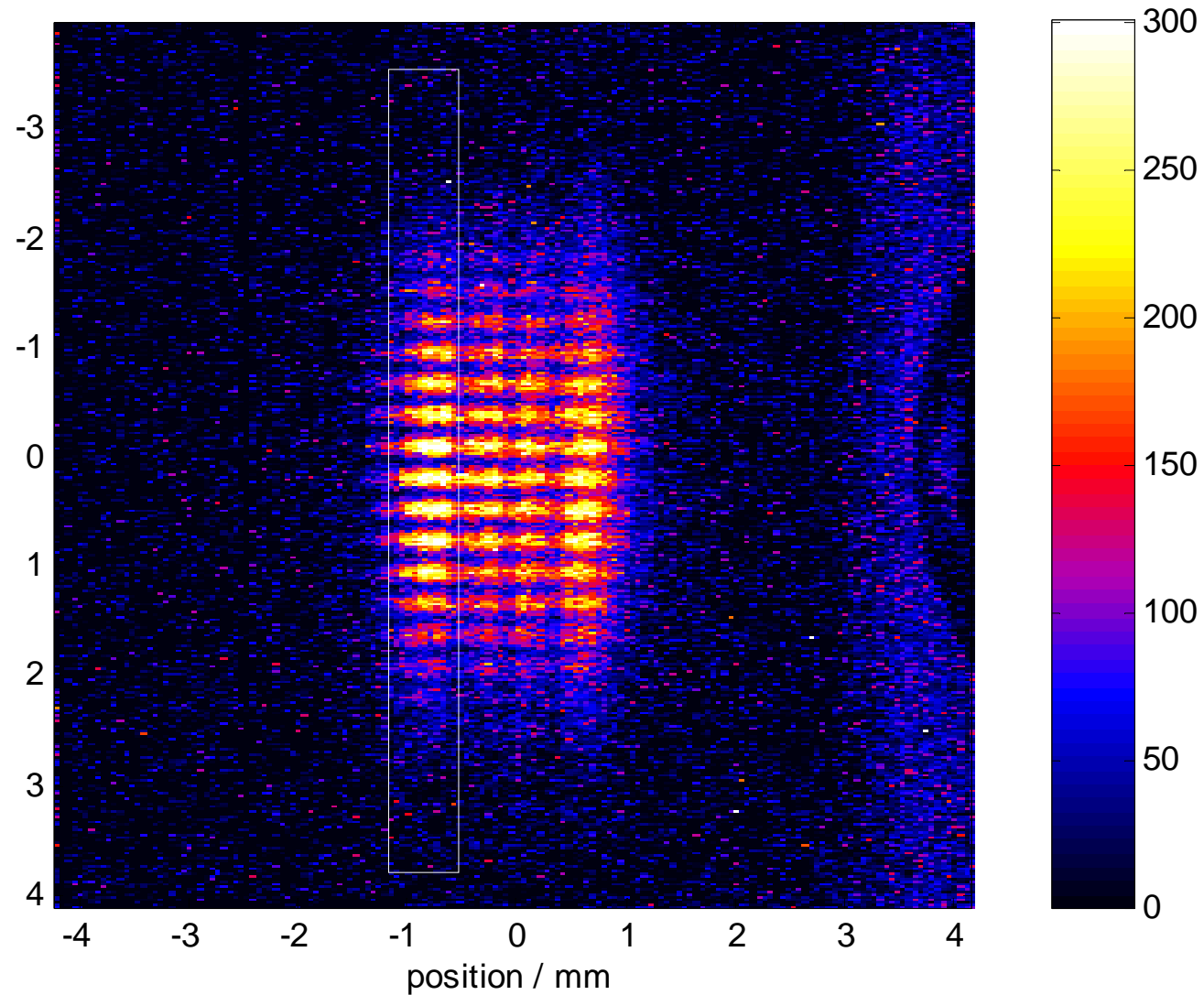
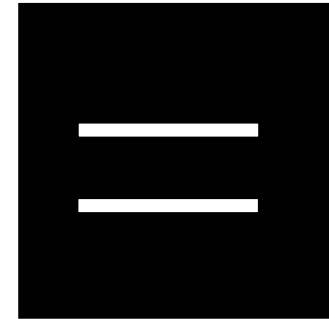
# Correction for Non-Linear Response

- 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



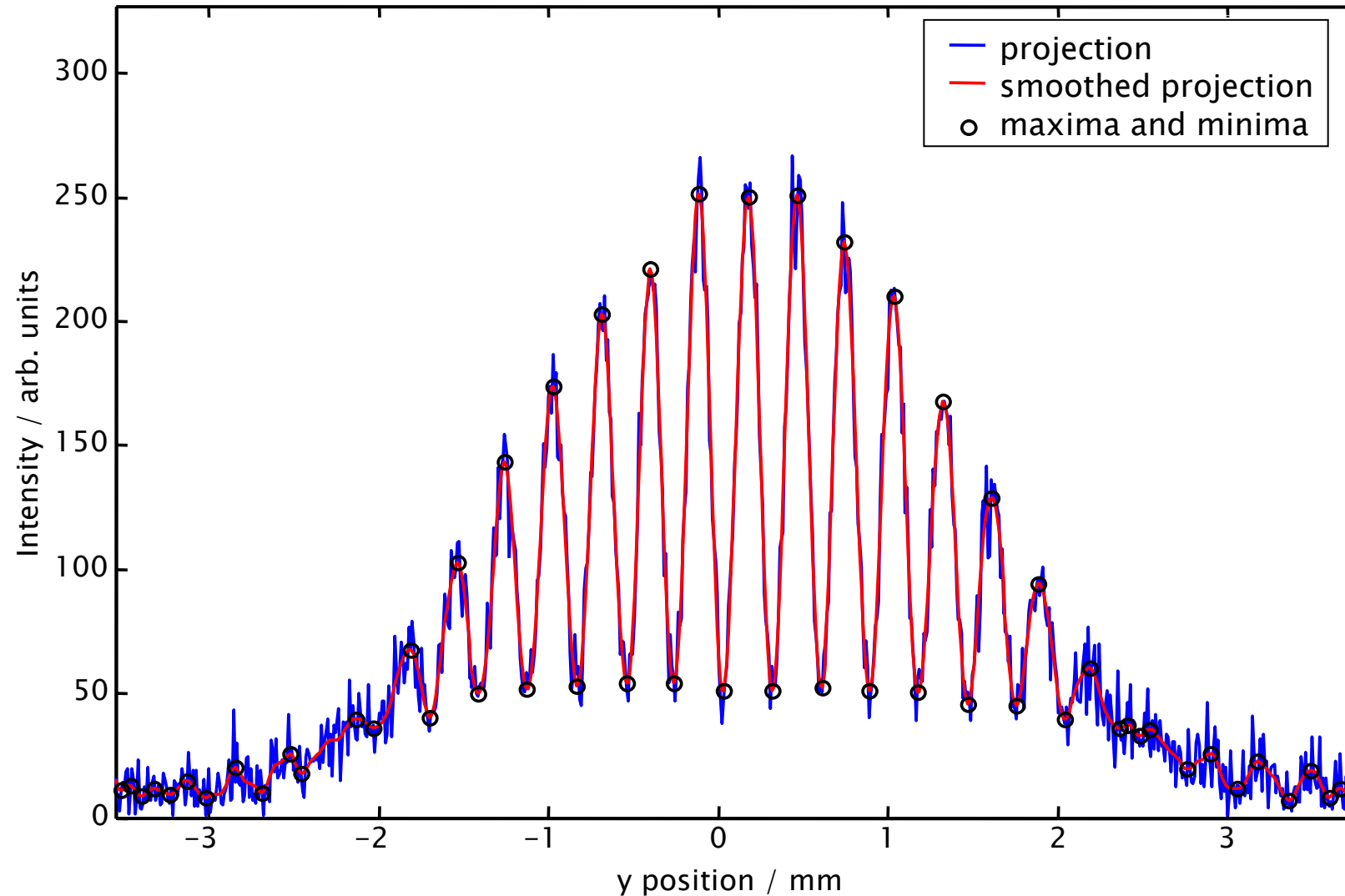
Analysis

# Measurement, 1 mm double slit



## Analysis of Experimental Data

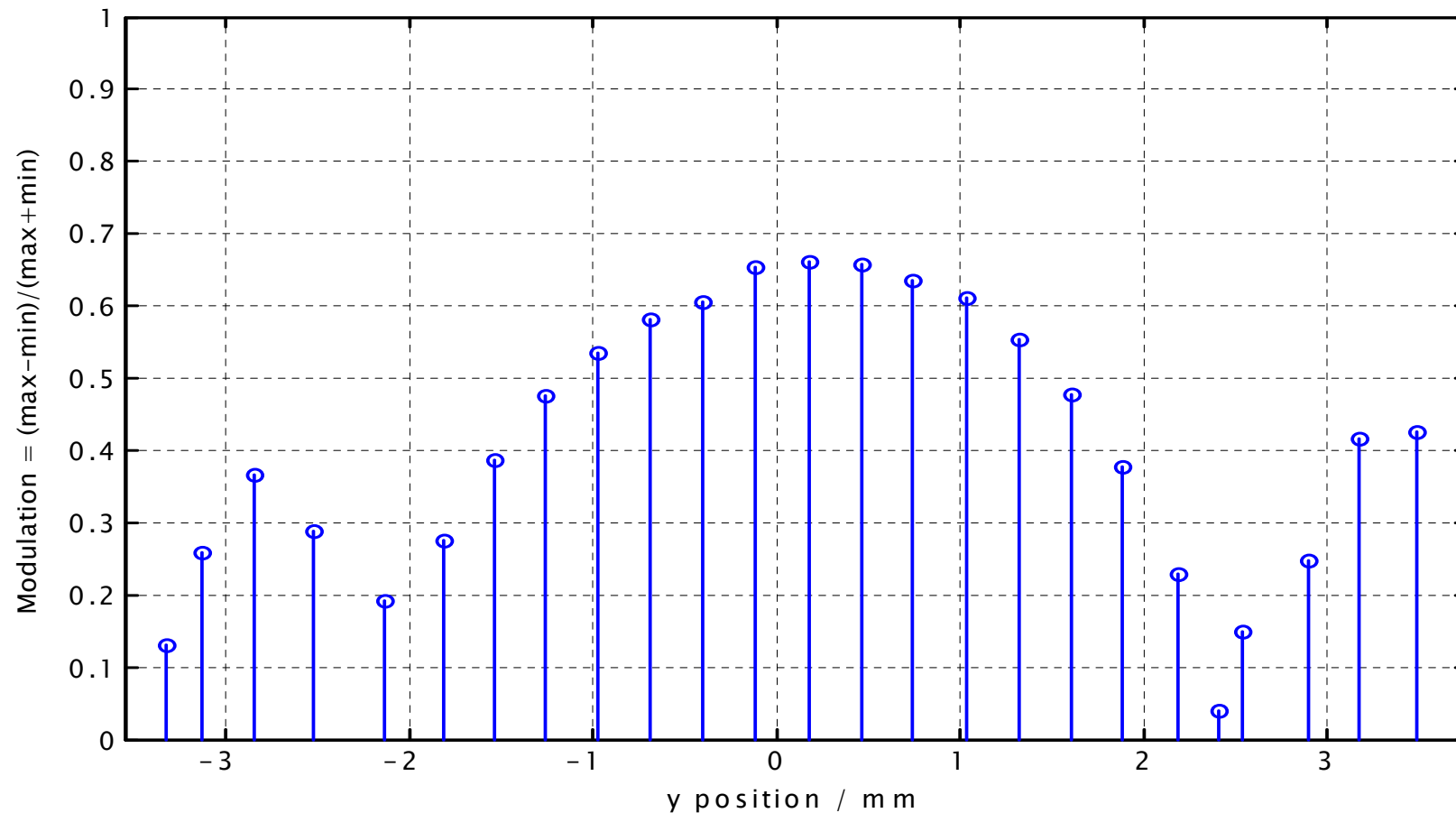
# Projection of the Selected Area



# Analysis of Experimental Data

## Modulation Depth

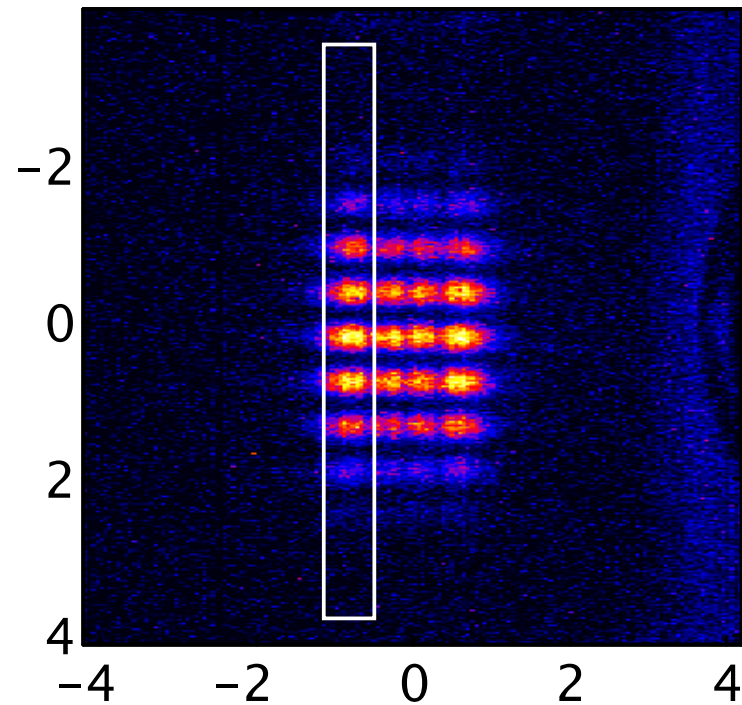
$$\text{modulation} = \frac{\text{max} - \text{min}}{\text{max} + \text{min}}$$



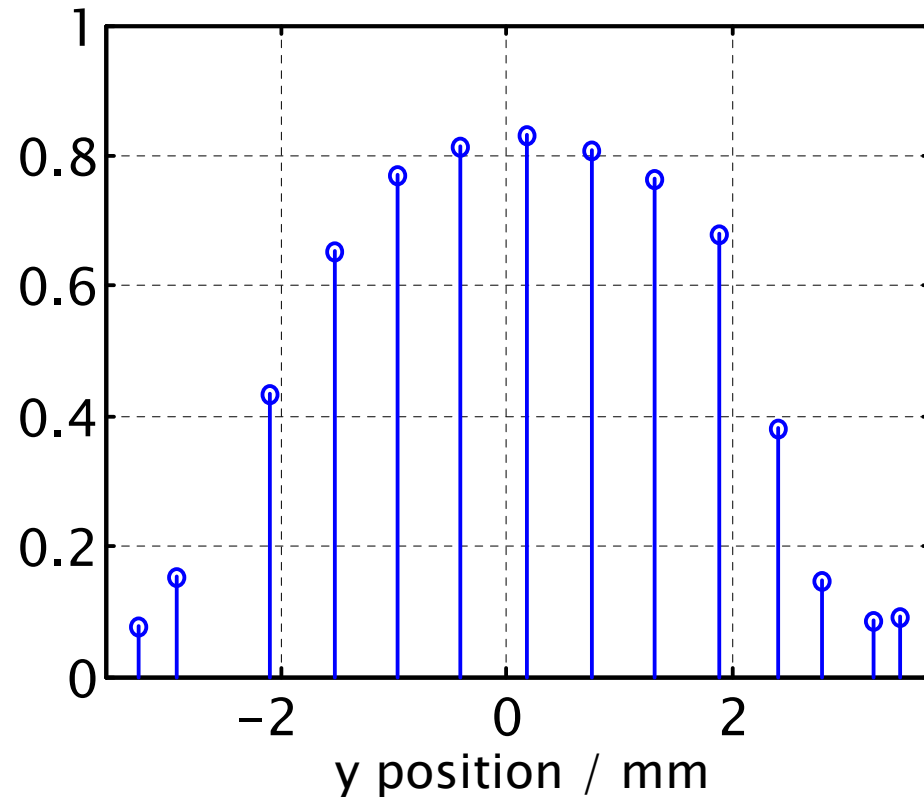
## Analysis of Experimental Data

# Double Slit — 0.5 mm separation

Reconstructed Image



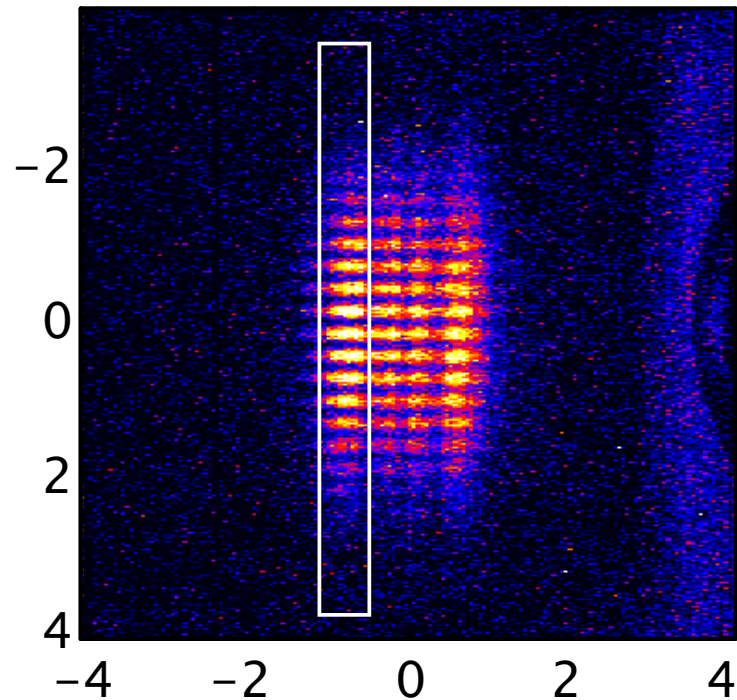
Modulation



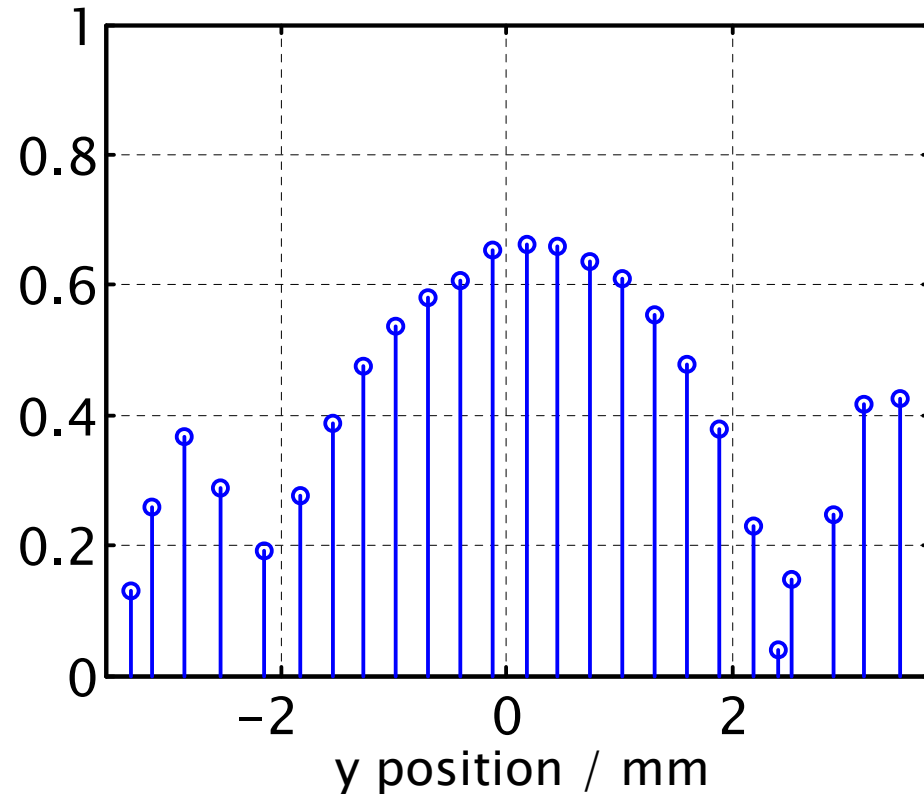
## Analysis of Experimental Data

# Double Slit — 1 mm separation

Reconstructed Image



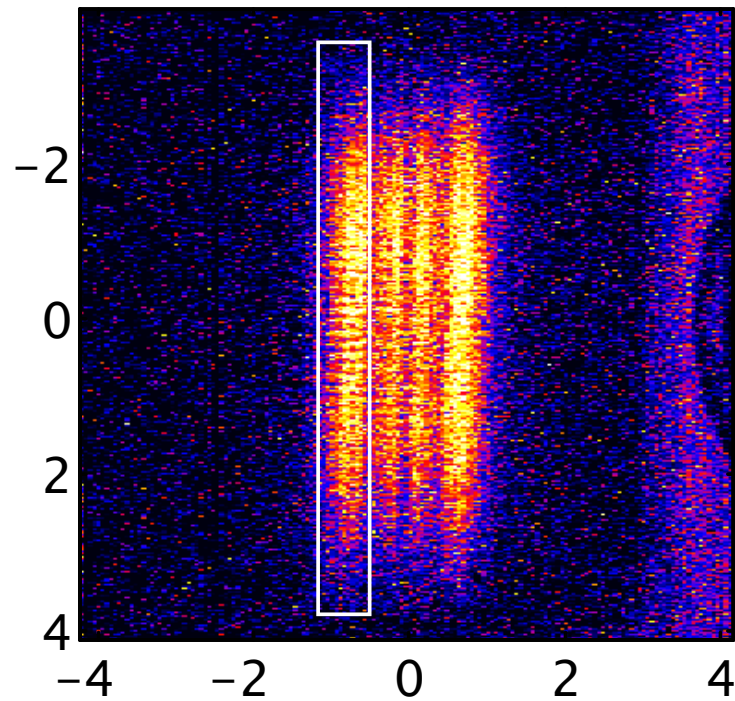
Modulation



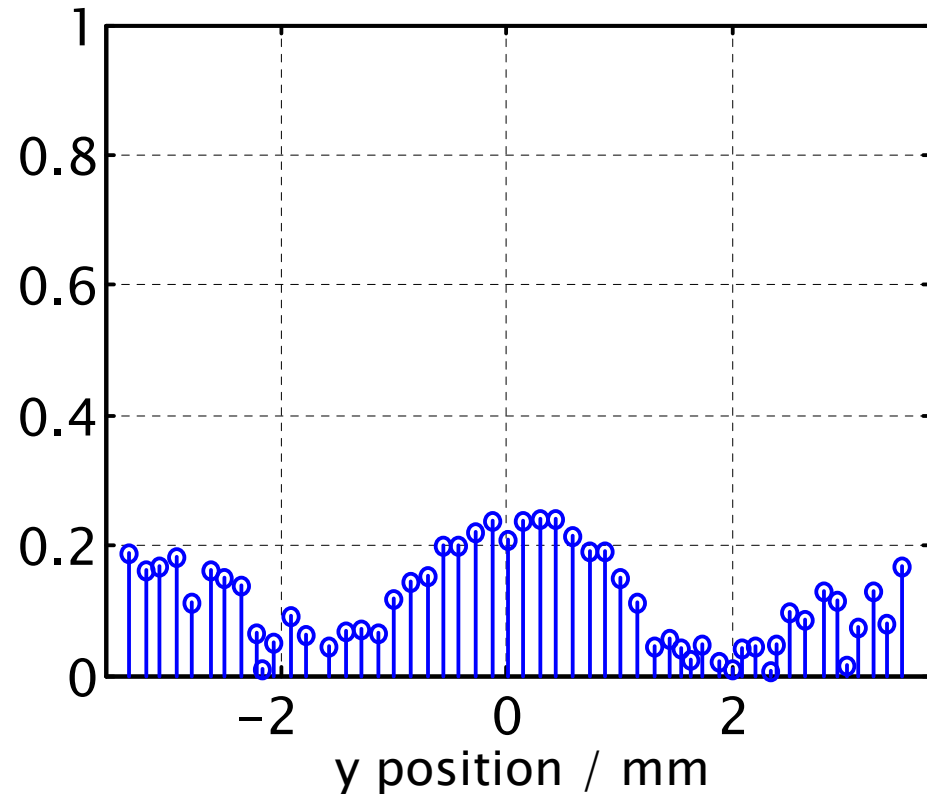
Analysis of Experimental Data

# Double Slit — 2 mm separation

Reconstructed Image



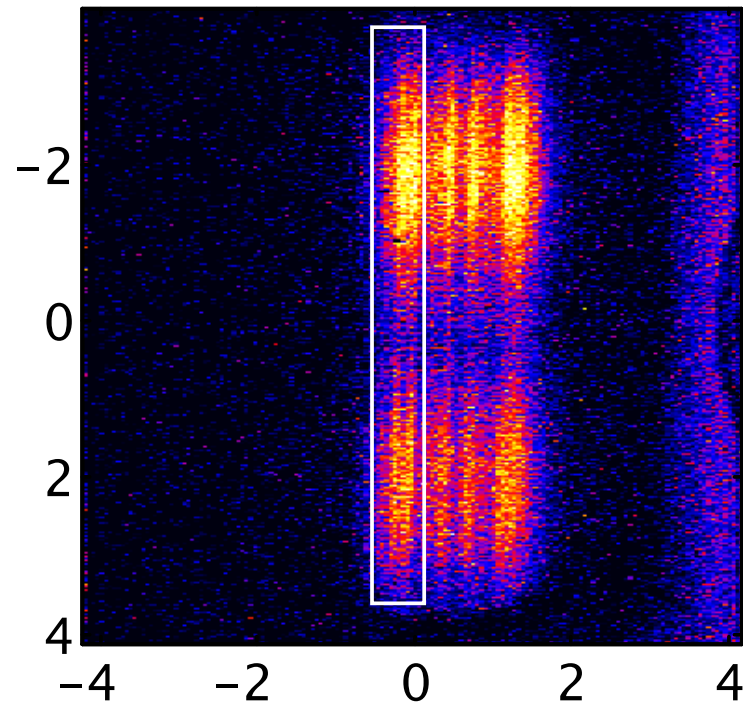
Modulation



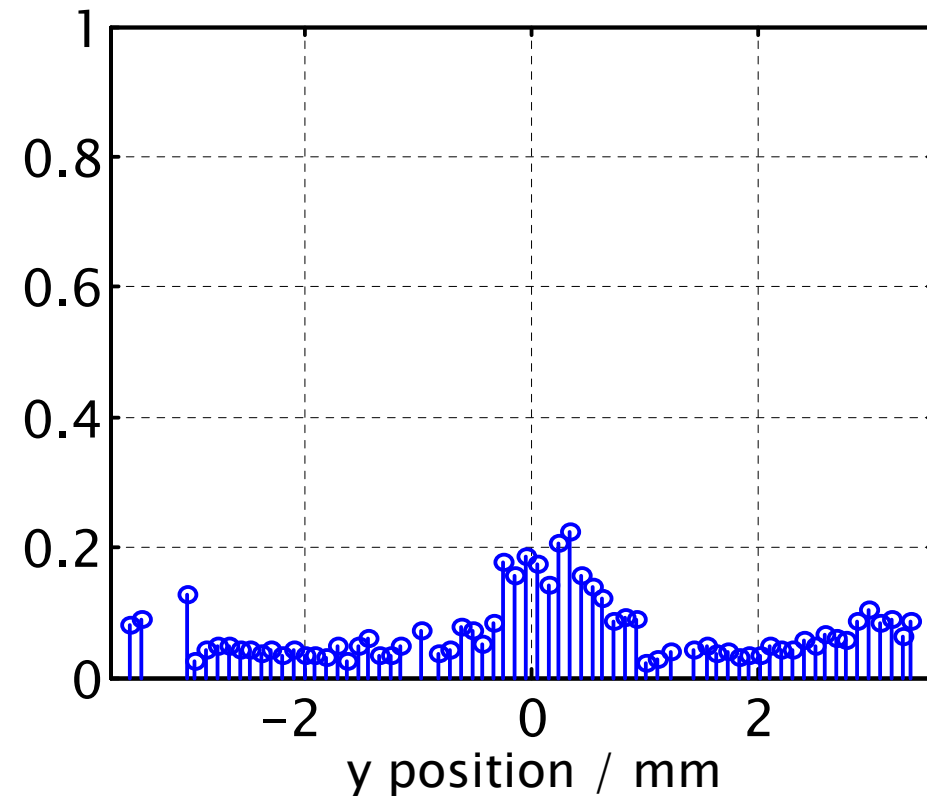
Analysis of Experimental Data

# Double Slit — 3 mm separation

Reconstructed Image

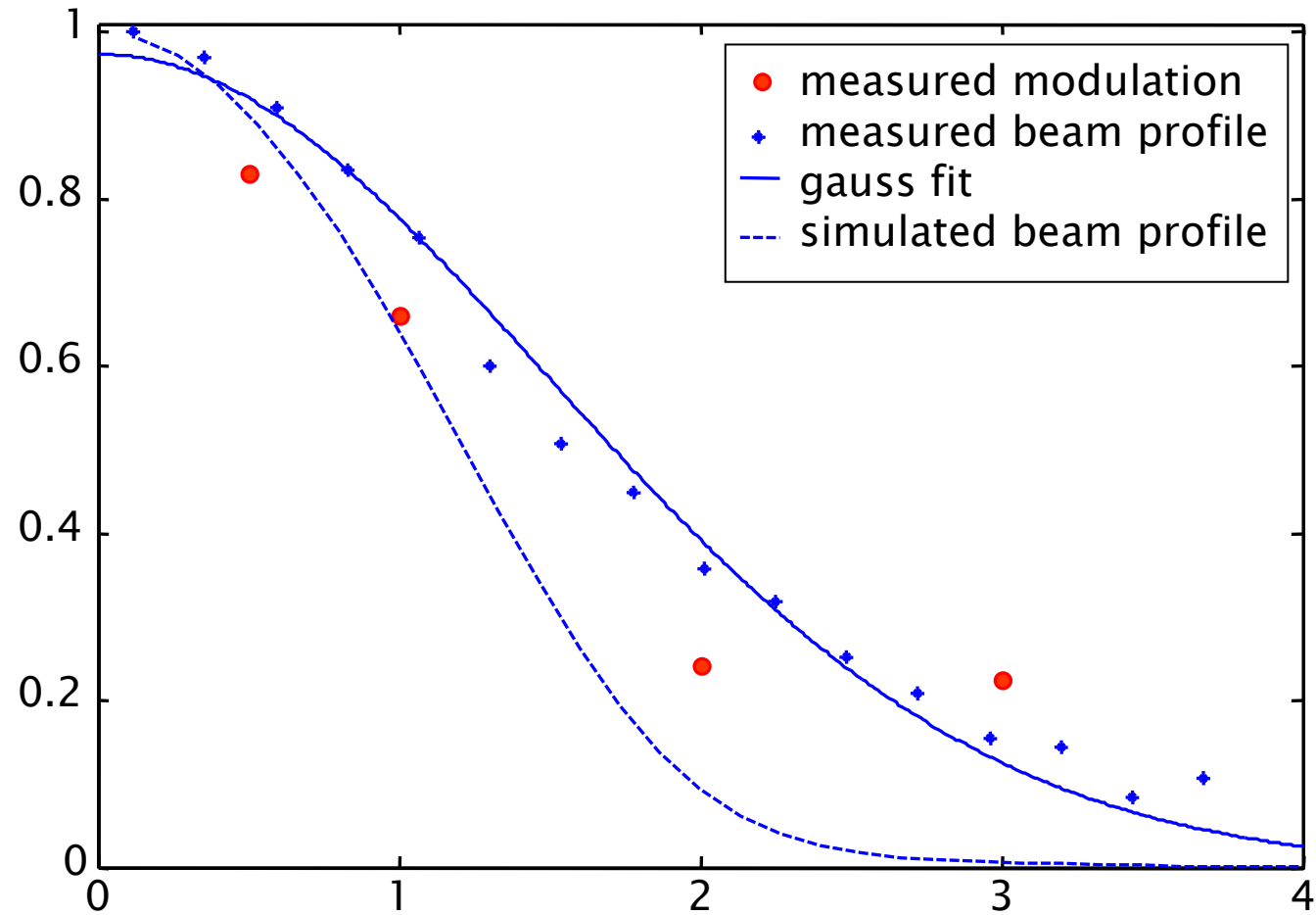


Modulation



Analysis of Experimental Data

# Slit Separation $\rightarrow$ Modulation



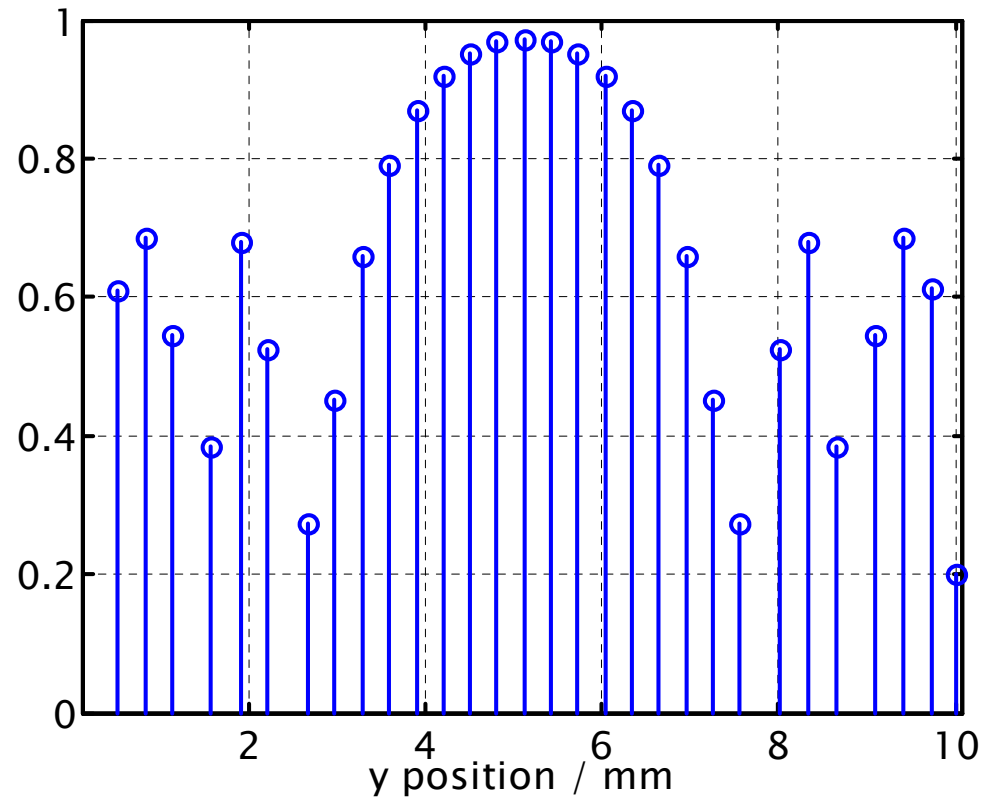
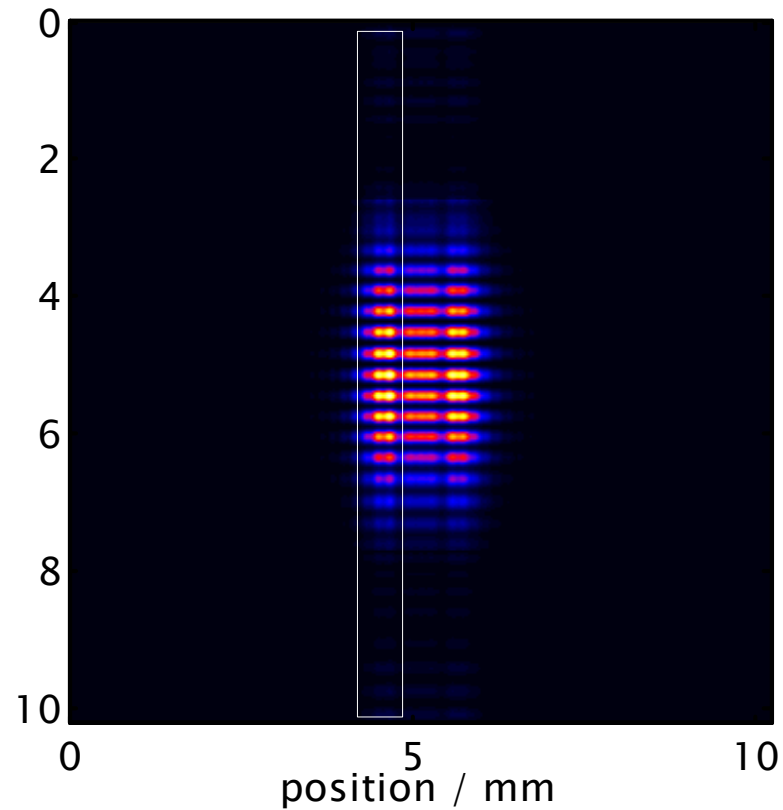
## Simulations

# 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)

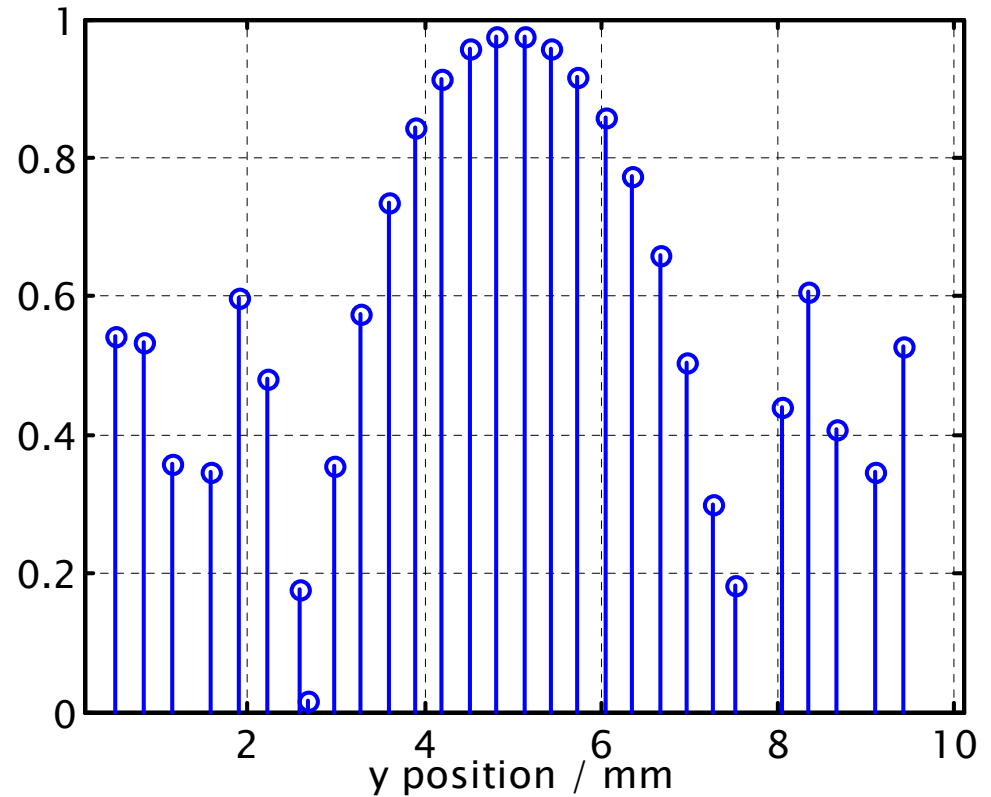
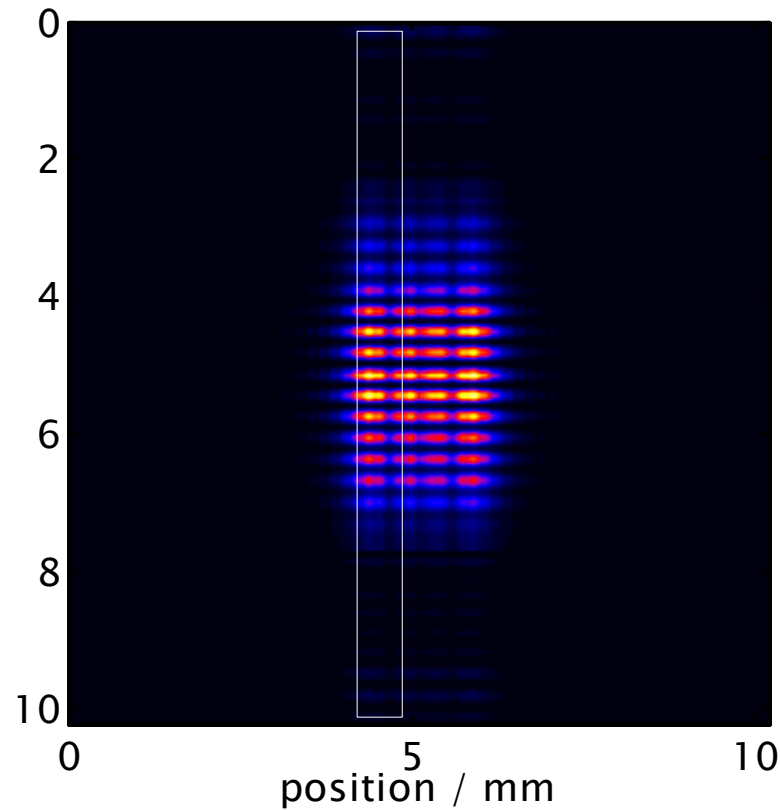
Simulations

# Plane Wave Input



Simulations

# Gaussian Beam Input



# Comparison with other Methods

- For any beam, we have at the waist:

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

where  $\sigma_r$  is the beam diameter,  $\sigma_\theta$  the angular divergence

- For a perfectly coherent gaussian beam, this becomes an equality:

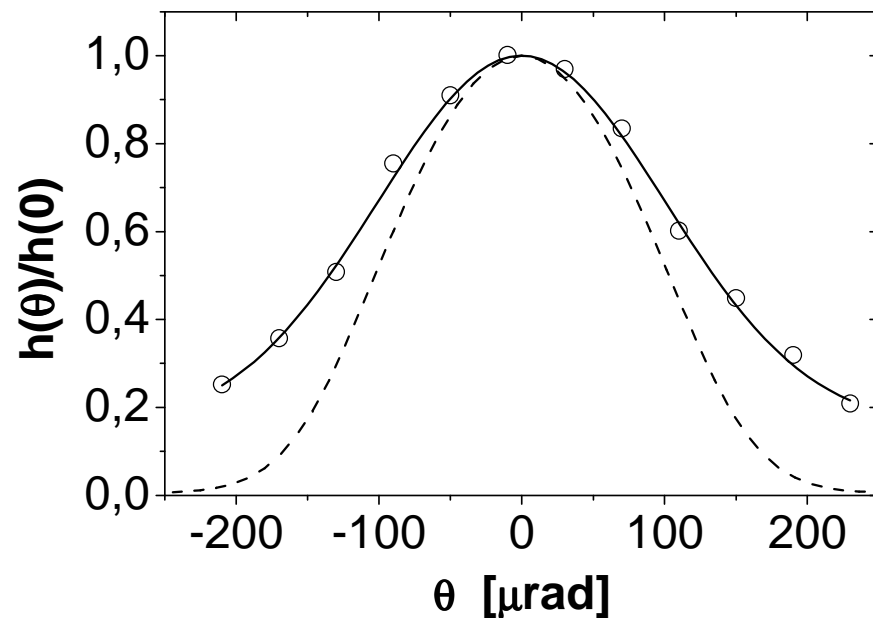
$$\sigma_r \sigma_\theta = \lambda/4\pi$$

## Coherence Measurements

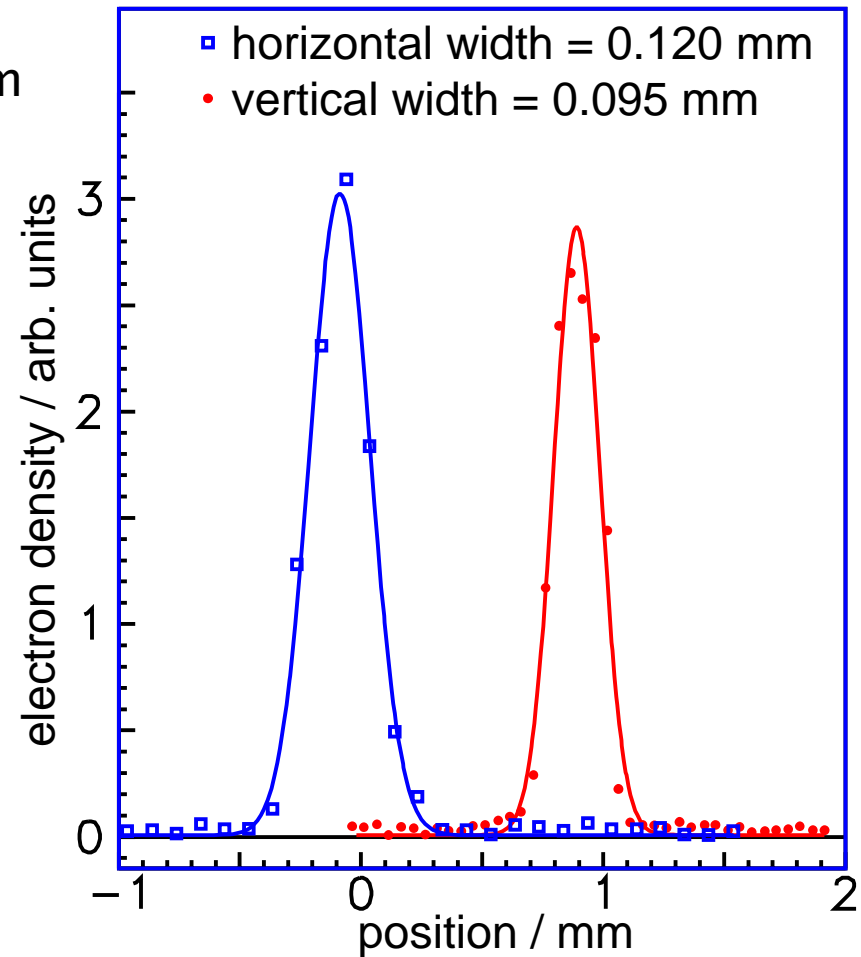
# Comparison with other Methods

- Here:  $\sigma_r = 100 \dots 150 \mu\text{m}$

$$\sigma_\theta = 120 \mu\text{rad}$$



$$\Rightarrow \sigma_r \sigma_\theta = 15 \text{ nm} \approx 8 \text{ nm} = \lambda/4\pi$$



Outlook

# Development along Undulator

- Beyond the saturation of the FEL:  
growth of the number of transverse modes
- ⇒ decrease of transverse coherence!  
(See FEL2002: Saldin, Schneidmiller, Yurkov)
- TTF FEL can be virtually shortened by kicking the beam off the undulator axis
  - measure coherence at different effective undulator lengths

# Conclusion

- Obtained double slit diffraction patterns of a SASE FEL at 100 nm
  - Setup in ultra high vacuum
  - Fluorescent crystal read out with CCD camera
- Double slit create diffraction images similar to near field theory:
  - Modulation depth decreases outwards
- Determined Modulation
  - at various slit separations
  - with different electron bunch properties

# Contributions by

- J. Feldhaus, Ch. Gerth, E. Saldin, P. Schmüser, E. Schneidmiller, B. Steeg, K. Tiedtke, M. Tonutti, R. Treusch, M. Yurkov

# Thank You to the TTF Team

- V. Ayvazyan, N. Baboi, I. Bohnet, R. Brinkmann, M. Castellano, P. Castro, L. Catani, S. Choroba, A. Cianchi, M. Dohlus, H.T. Edwards, B. Faatz, A.A. Fateev, J. Feldhaus, K. Flöttmann, A. Gamp, T. Garvey, H. Genz, 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, W. Sandner, H. Schlarb, G. Schmidt, J.R. Schneider, H.-J. Schreiber, S. Schreiber, D. Sertore, S. Setzer, S. Simrock, R. Sobierajski, B. Sonntag, B. Steeg, F. Stephan, N. Sturm, K.P. Sytchev, D. Trines, D. Türke, V. Verzilov, R. Wanzenberg, T. Weiland, H. Weise, M. Wendt, T. Wilhein, I. Will, K. Wittenburg, S. Wolff, K. Zapfe