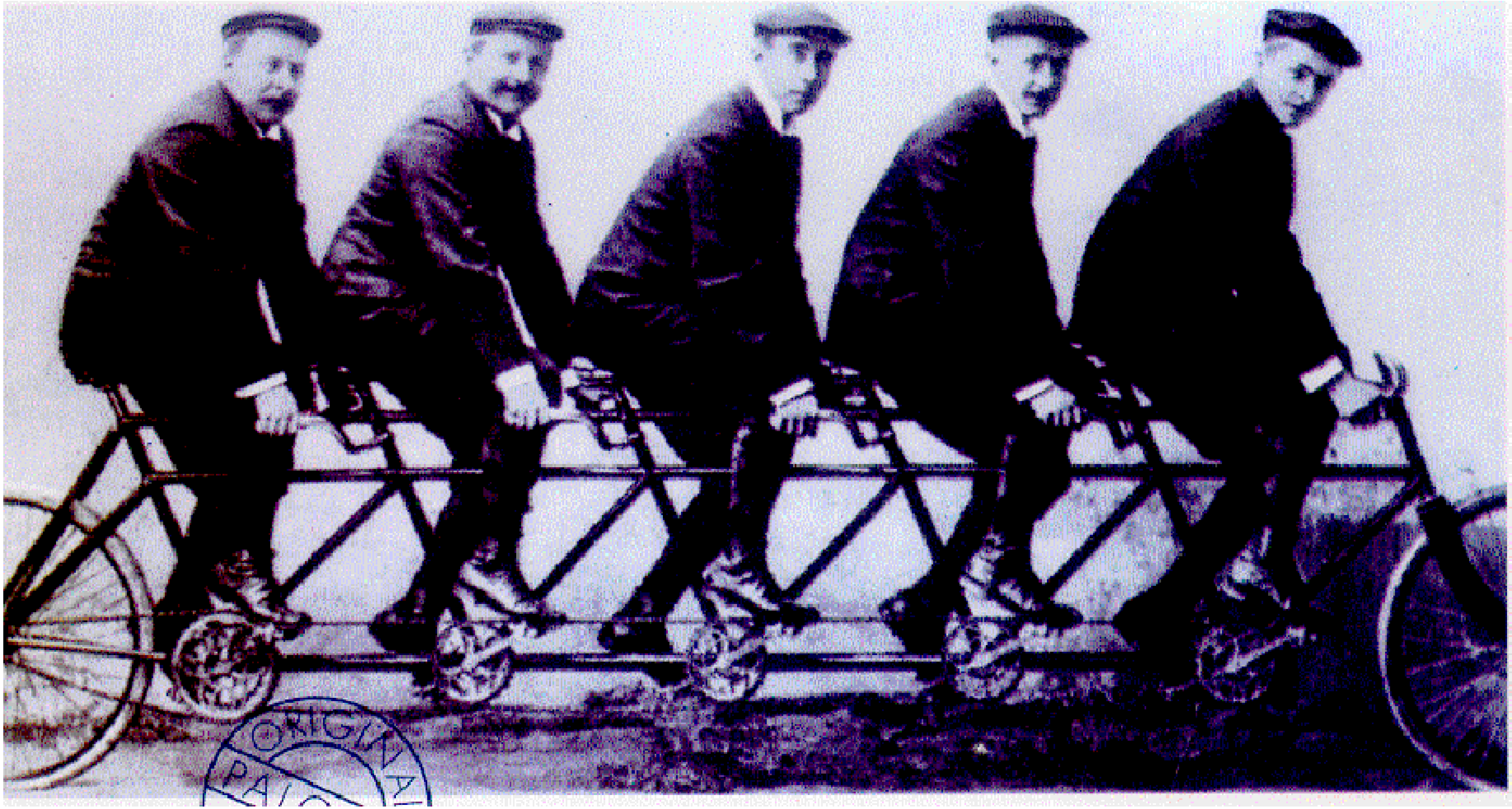
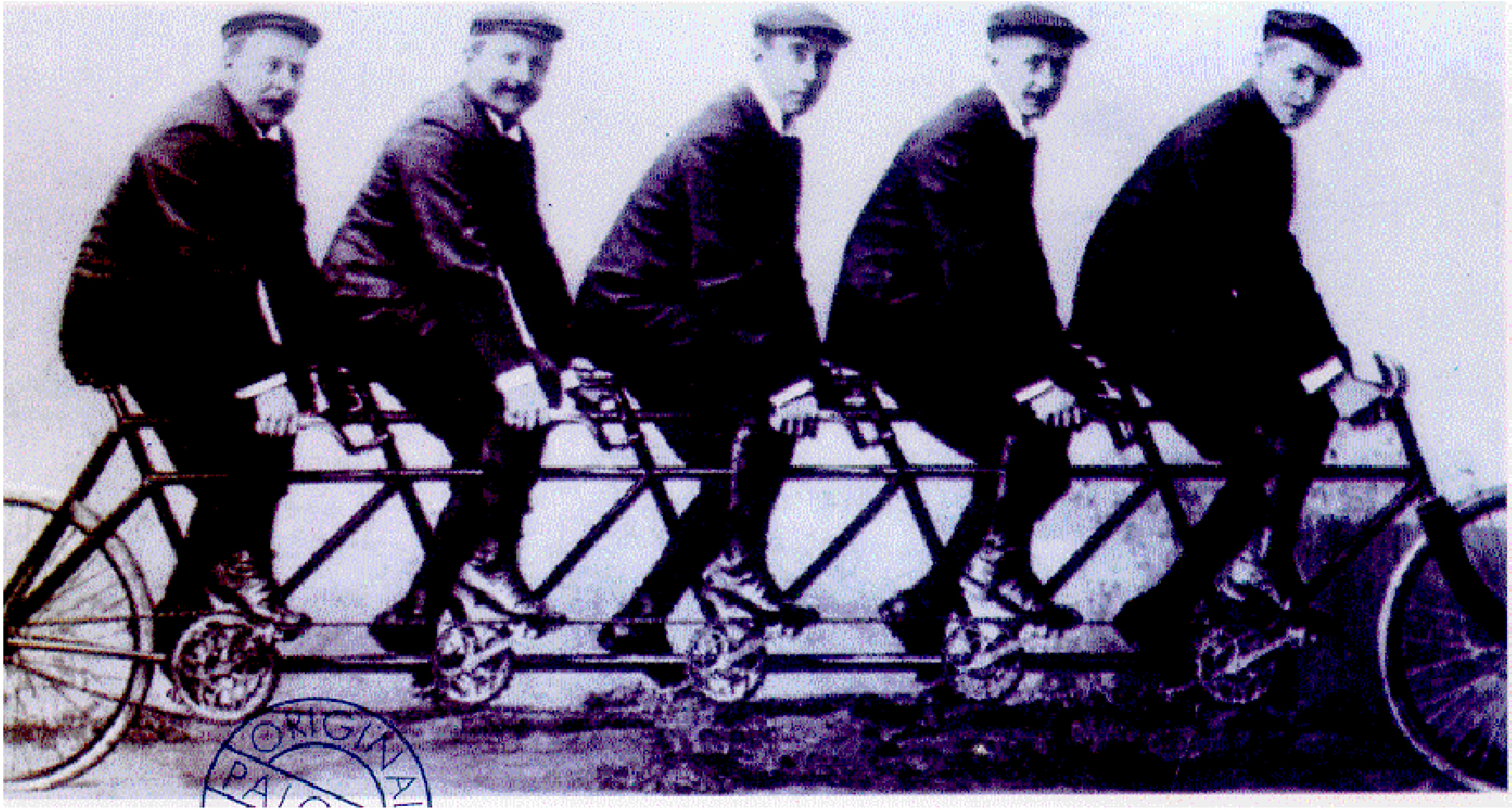
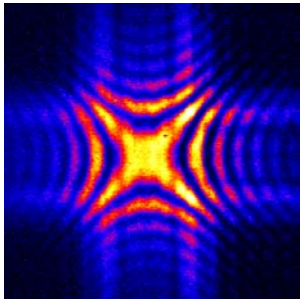
What do these people need?



Coherence…





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

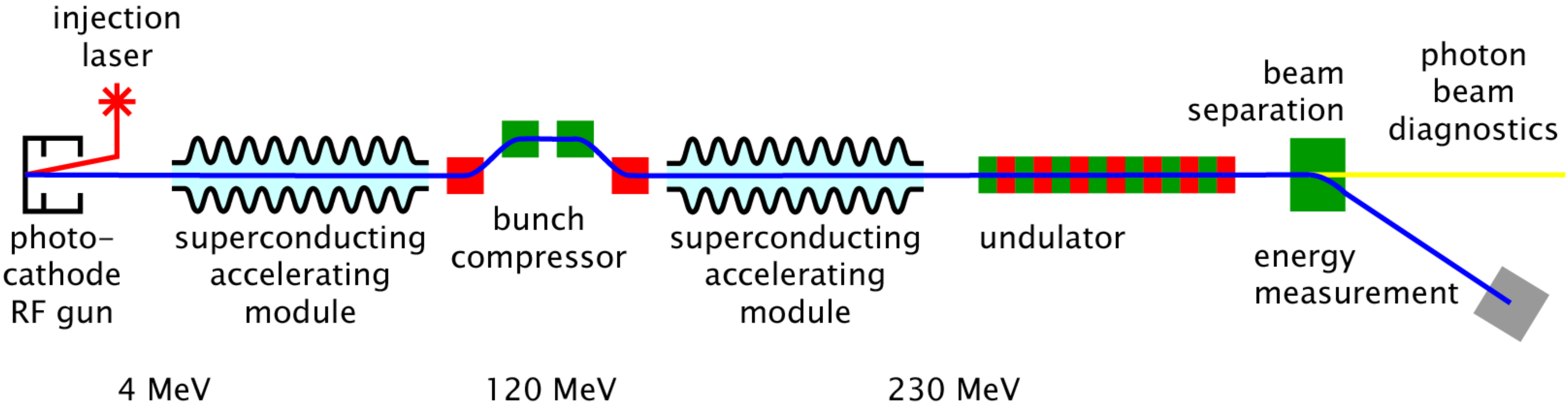
- Simulations

- Outlook

TTF FEL

Linear Accelerator

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

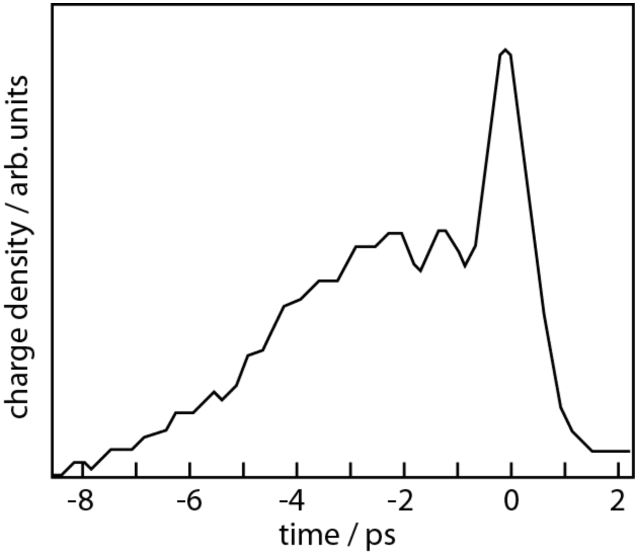


total length: 120 m

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

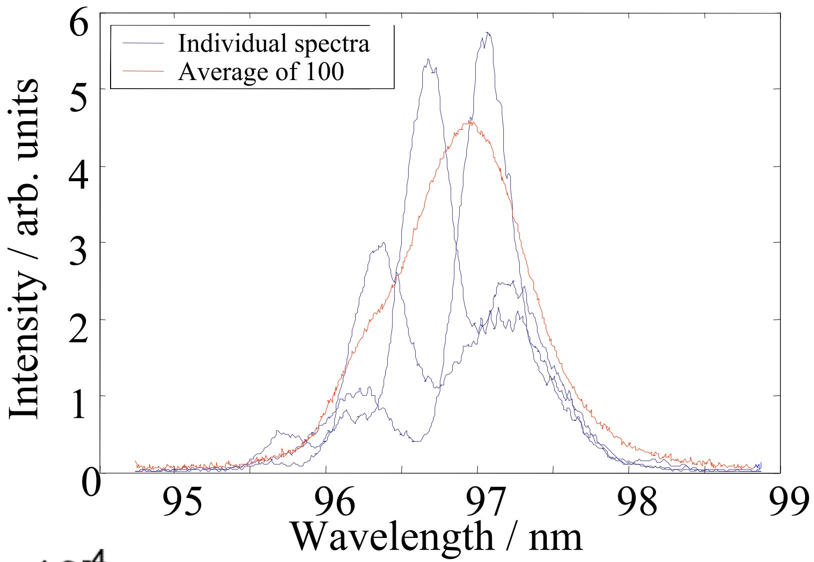
- Wavelength: 80 … 120 nm, depending on the electron energy
- Pulse energy: typically up to 10 μJ per pulse
- Peak power: 1 GW
- FEL starts from noise

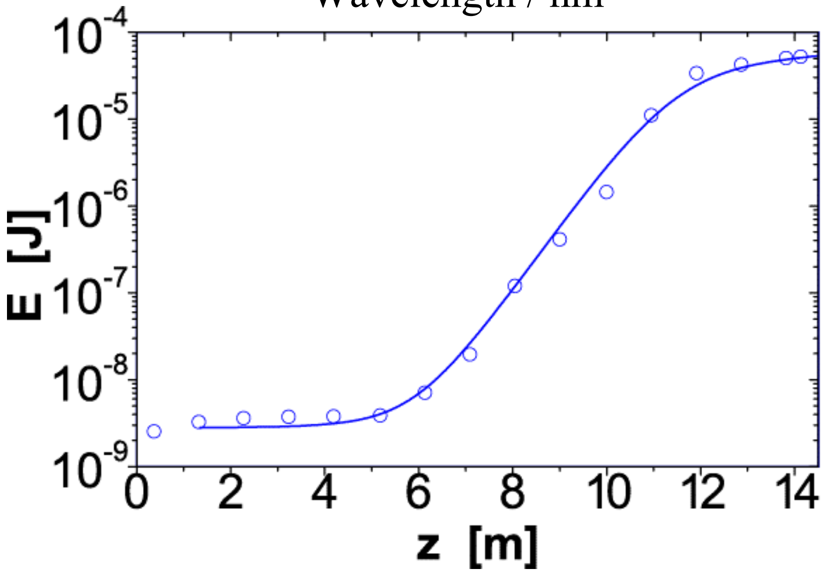
⇒ No input needed

- Single pass saturation

⇒ No mirrors needed

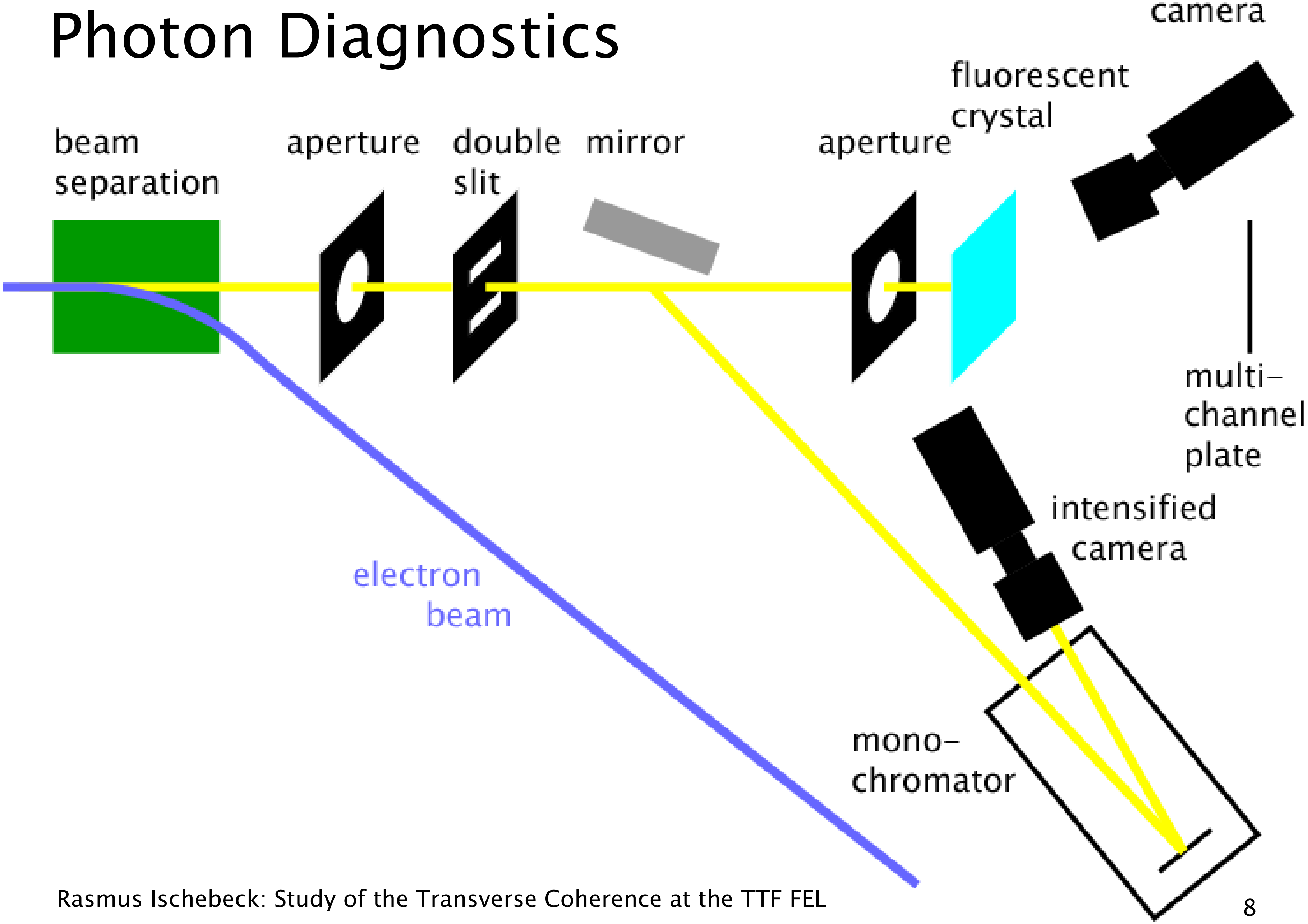
- Longitudinal and Transverse Coherence





Experimental Setup

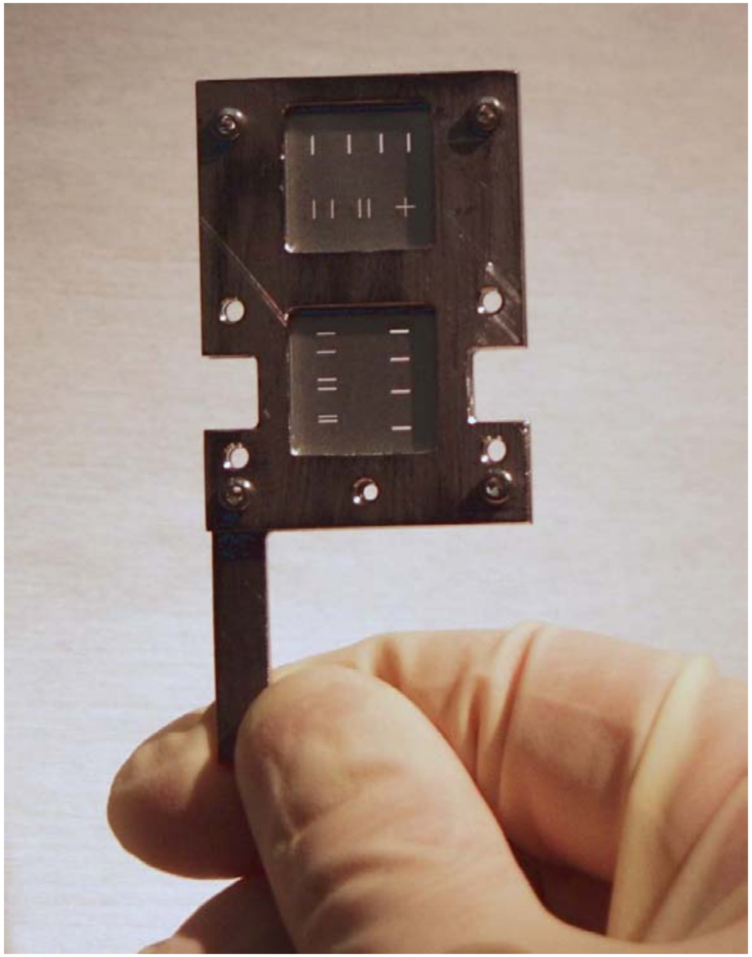
Photon Diagnostics

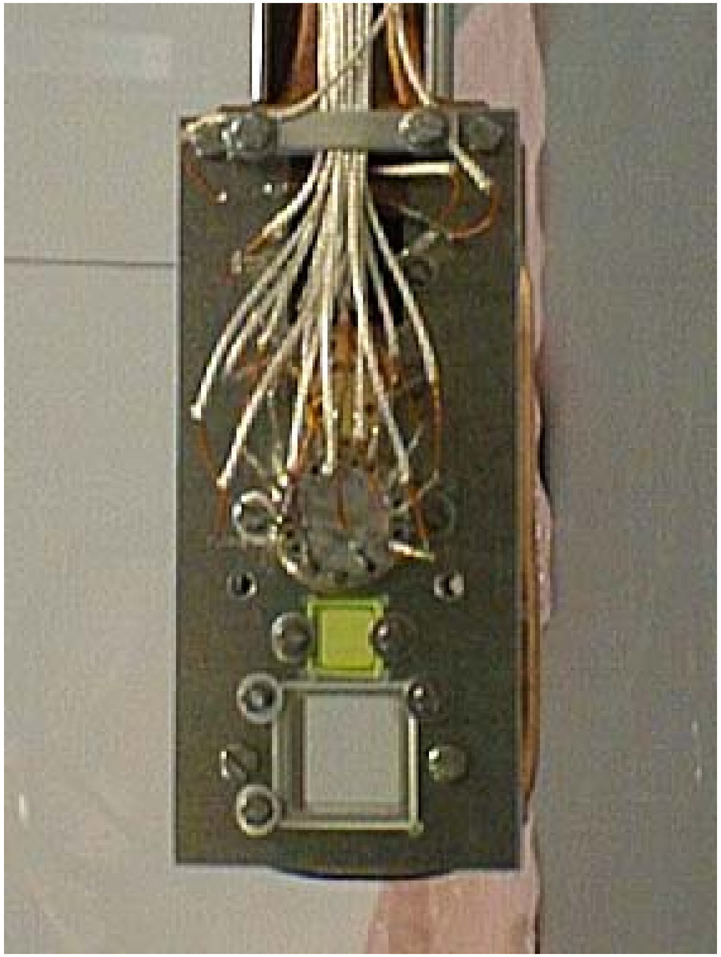


Rasmus Ischebeck: Study of the Transverse Coherence at the TTF FEL

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

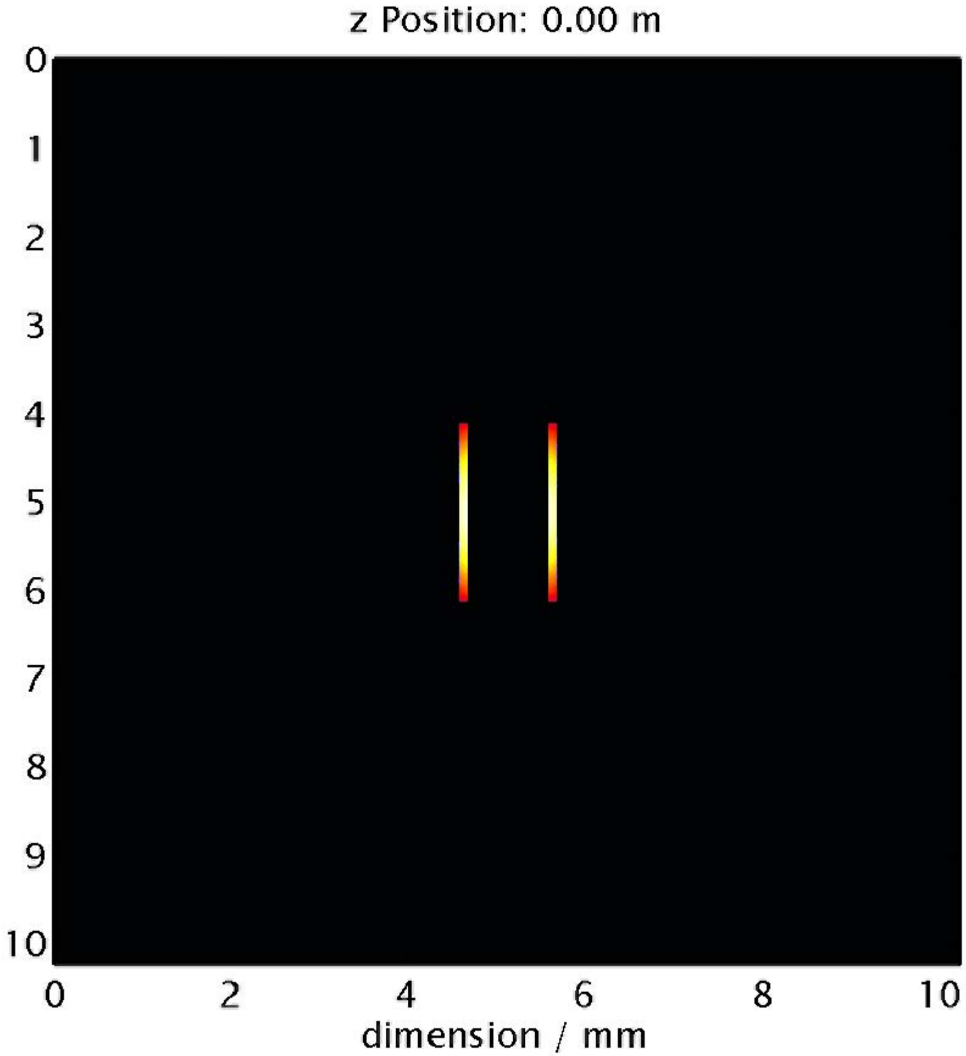
Near Field Effects

- Criterion for far field diffraction:

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

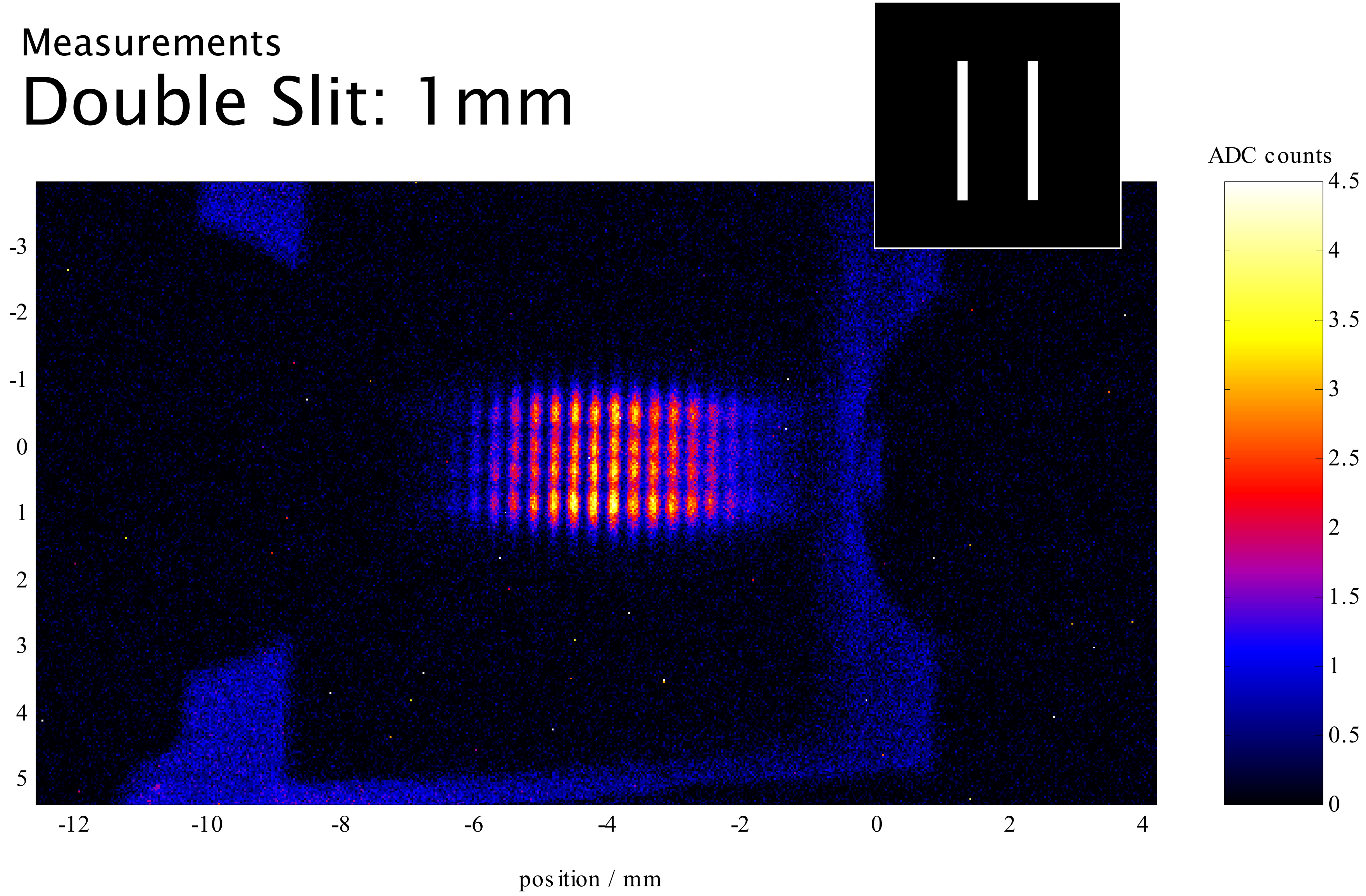
- d: distance between slits, λ: wavelength, L: distance slits—screen
- Here: L = 3.1m, d = 1mm, λ = 100nm ⇒ $\frac{\lambda L}{d^2} = 0.3$
- Near field effects ⇒ reduced modulation
- additional modifications to the far field formula:
  - finite width and length of slits

Simulation of Near Field Diffraction



Measurements

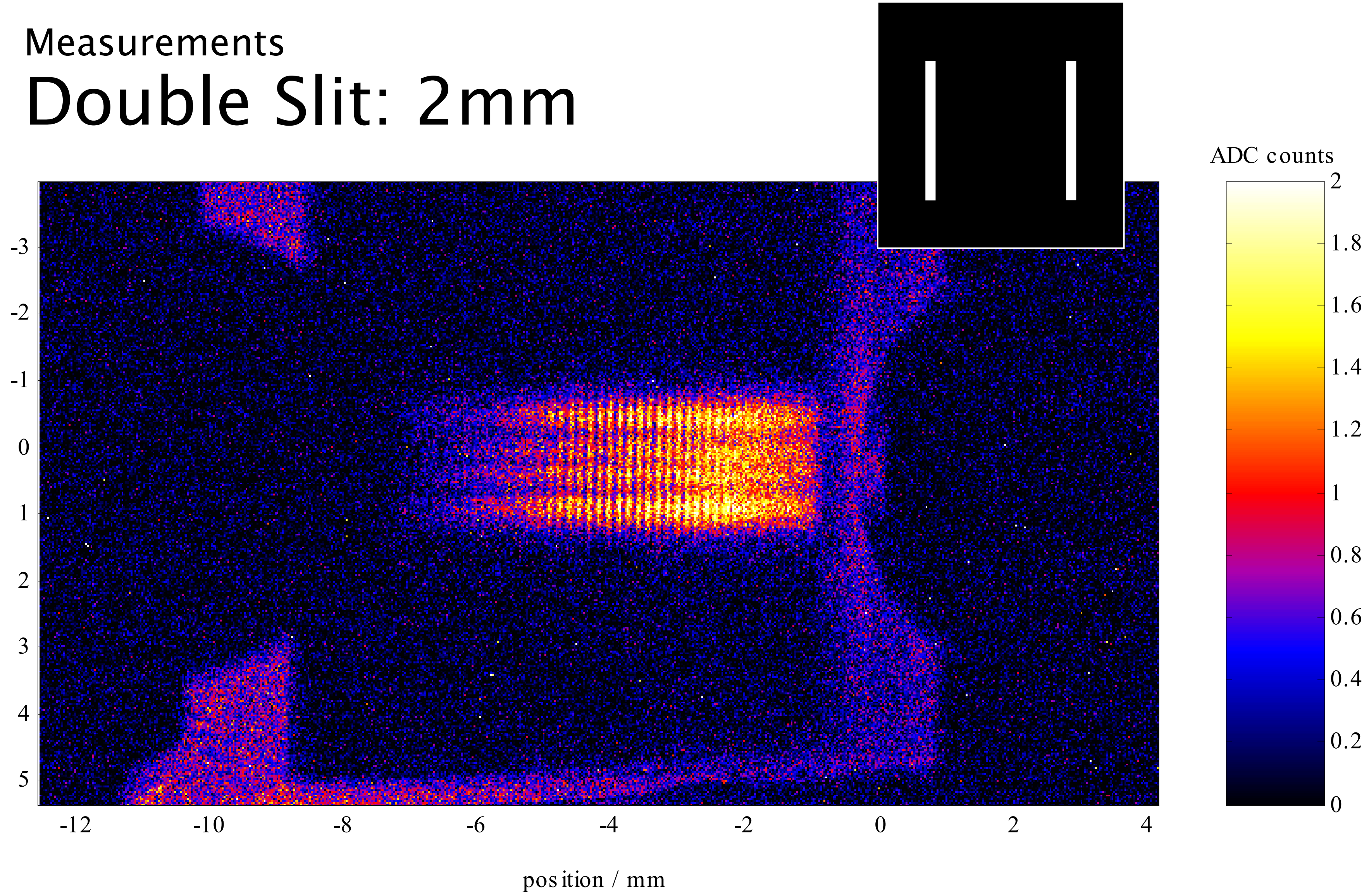
Double Slit: 1mm



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

Measurements

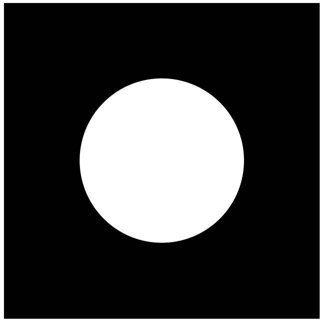
Double Slit: 2mm

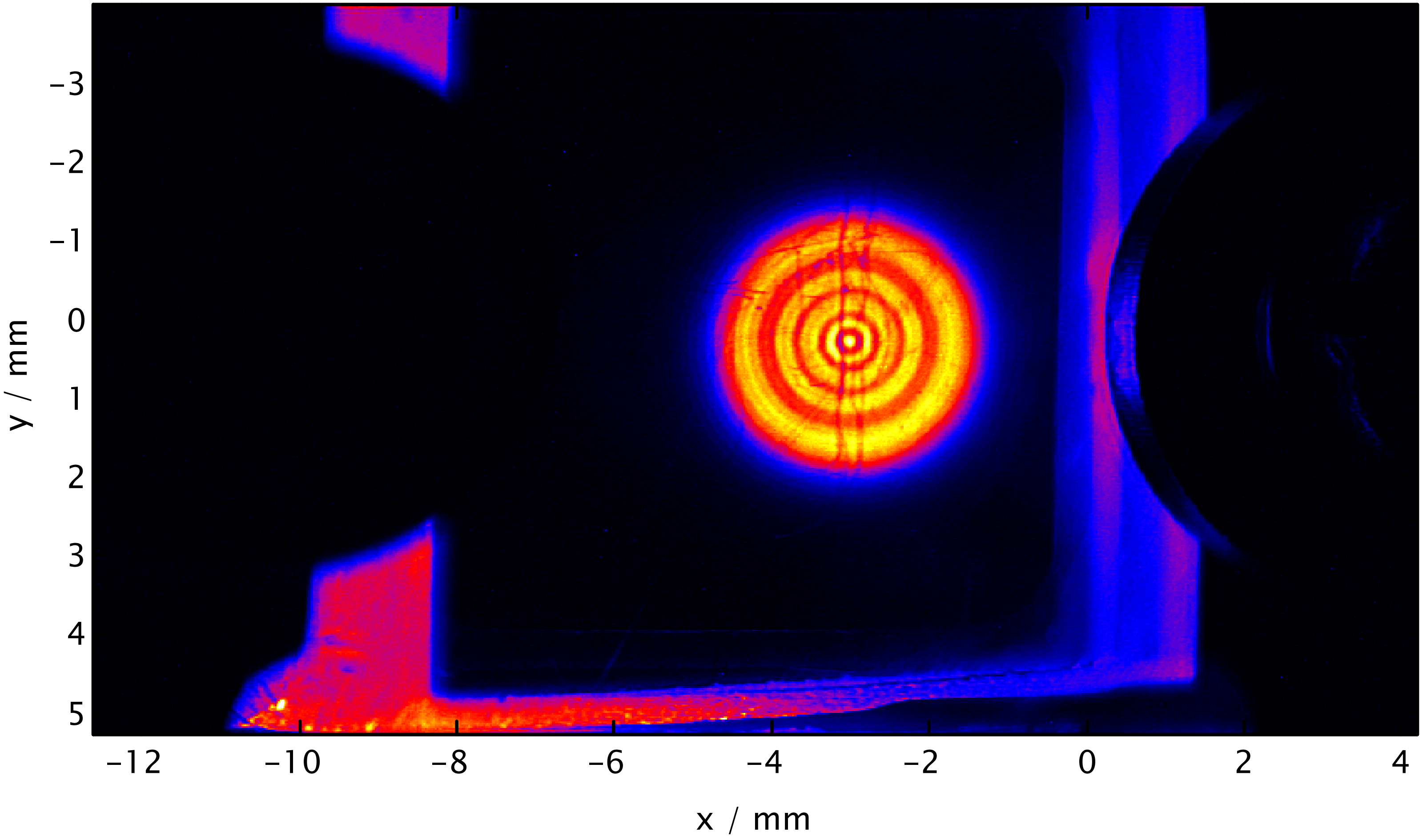


Vertical slits, 2 mm separation. Average of 99 images with 3 bunches each

Measurements

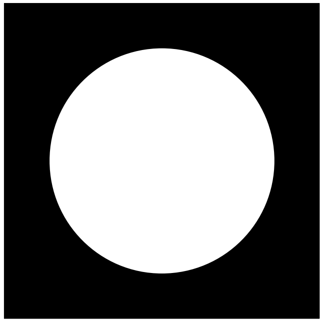
Circular Aperture: ∅ 3mm

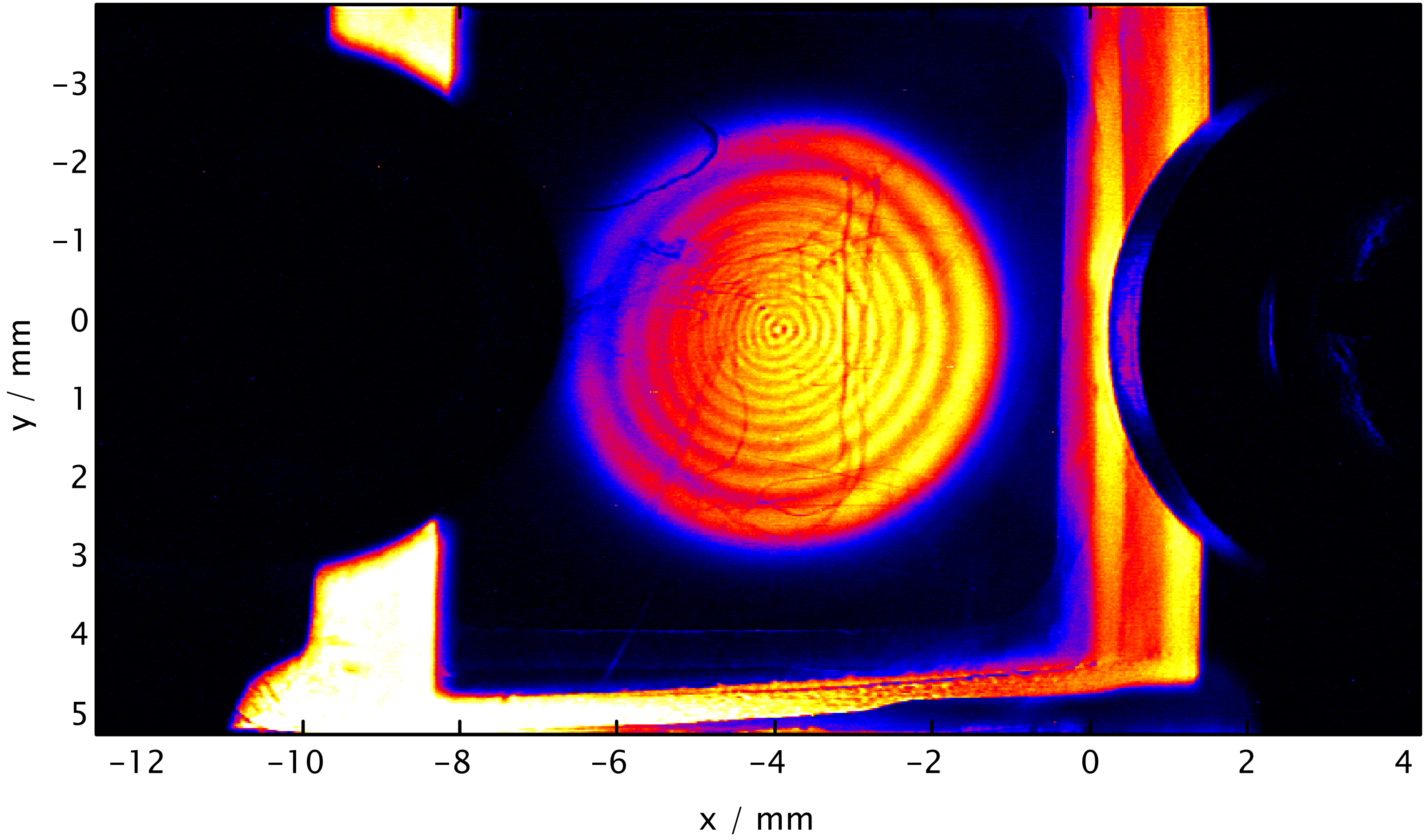




Measurements

Circular Aperture: ∅ 5mm





Measurements

Circular Apertures

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

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

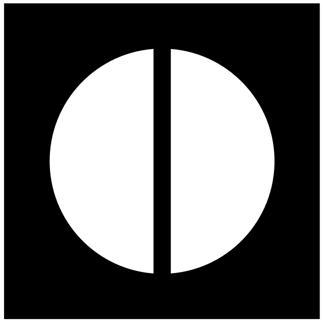
r: aperture radius, λ: wavelength, D: distance source—aperture,
L: distance aperture—screen

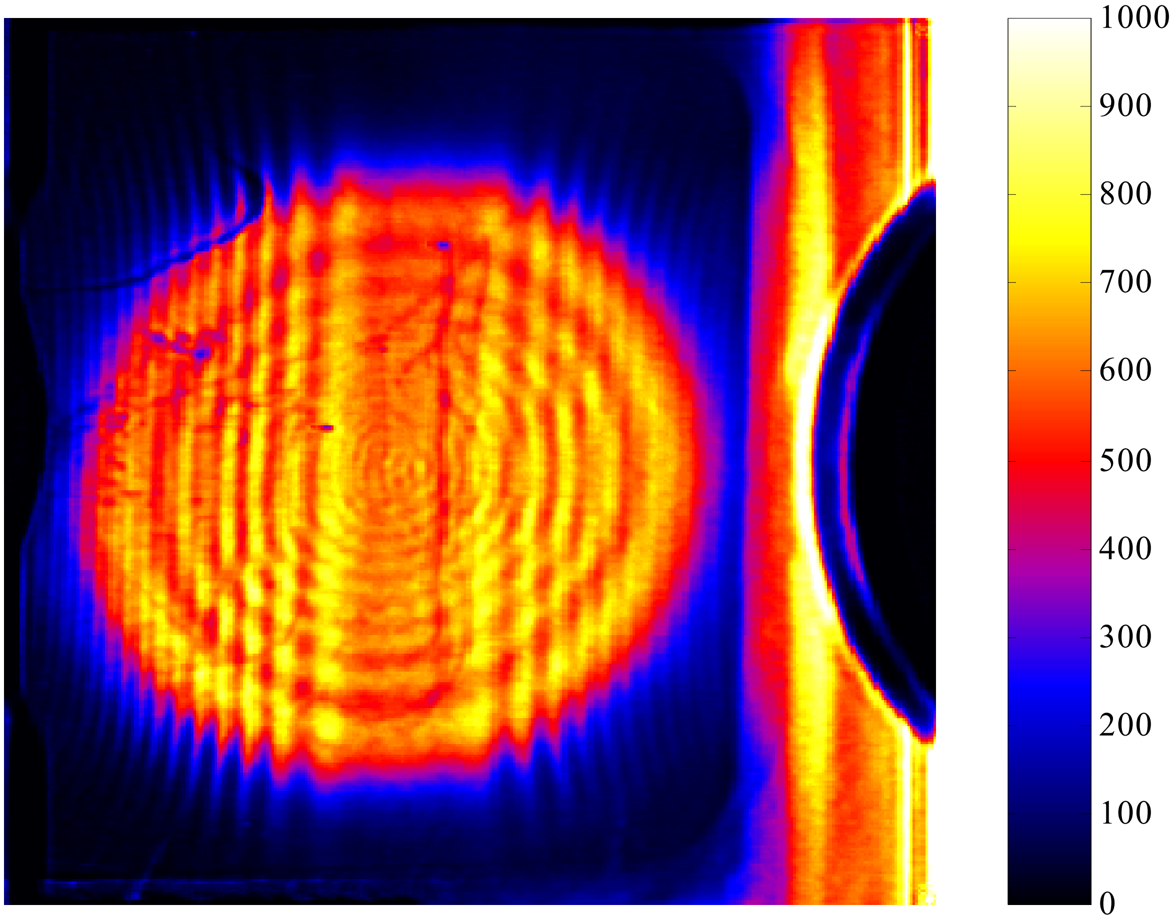
Here:

Aperture	predicted	observed
3 mm	9.2	9
5 mm	25.5	23

Measurements

Circular Aperture + Wire

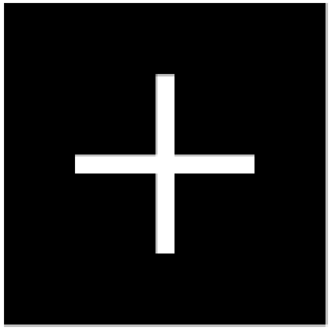




A wire in the beam path also creates diffraction

Measurements

Crossed Slits



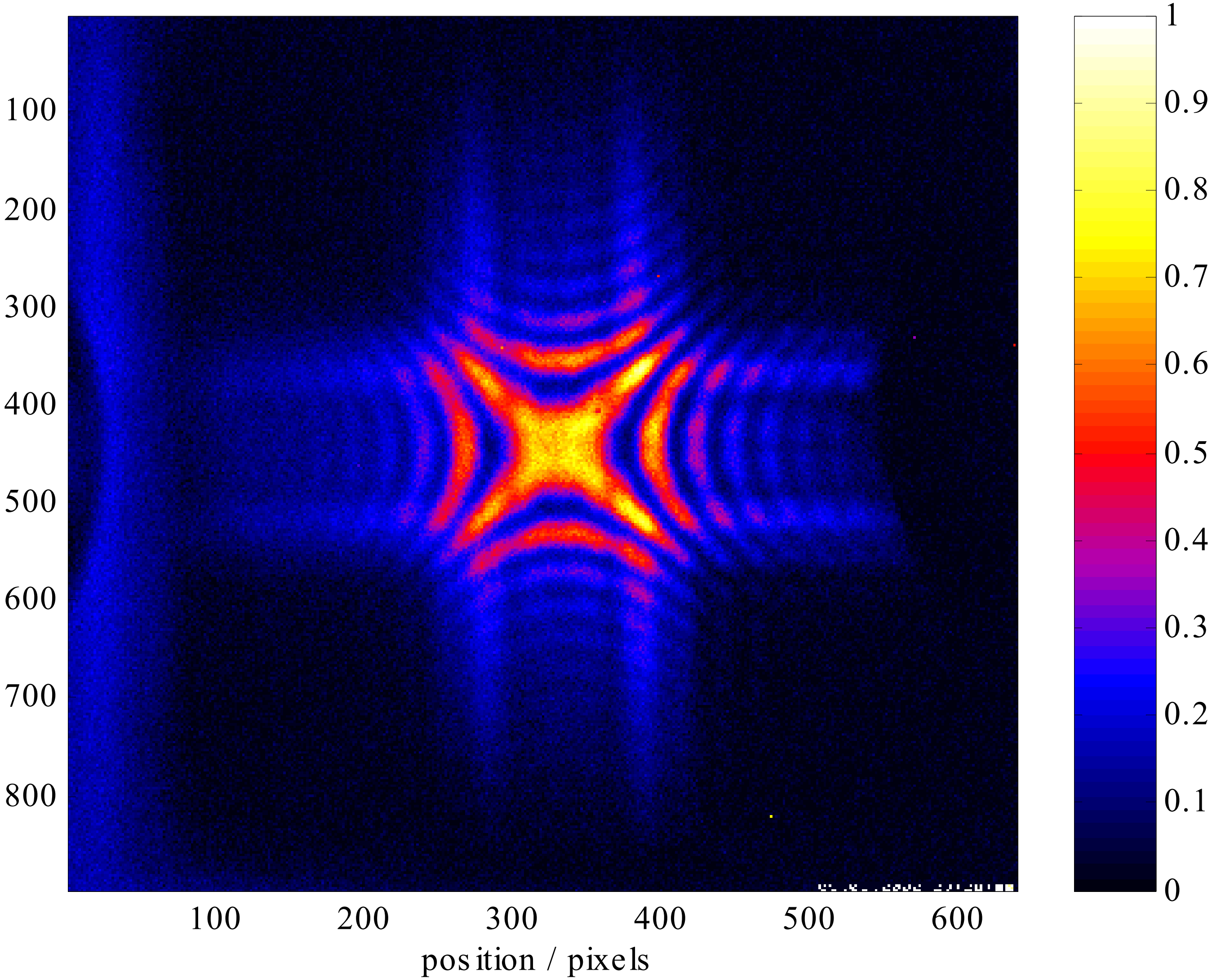


Image Processing

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:

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

Image Processing

Deconvolution of the Camera Resolution

⇒ Reduced contrast
  ⇒ apparently reduced FEL coherence

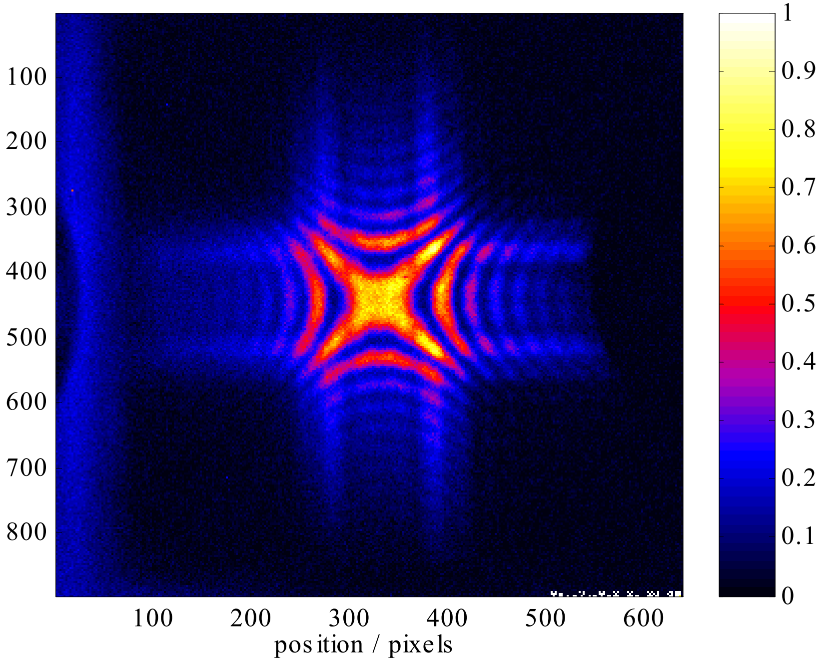
- If P is known, the system of equations can in principle be solved

➢ But: as a result of measurement errors (noise) in the measured image, negative values for the real intensities will appear!

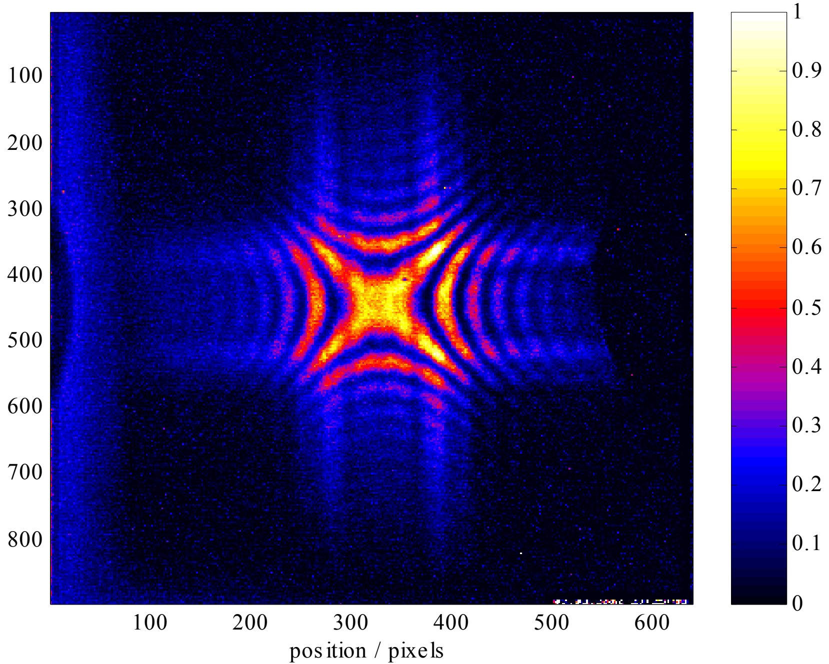
- The images can be reconstructed using the Lucy–Richardson algorithm
  - Maximize the likelihood of the measurement, with given boundary conditions
  - Widely used in image processing

Image Processing

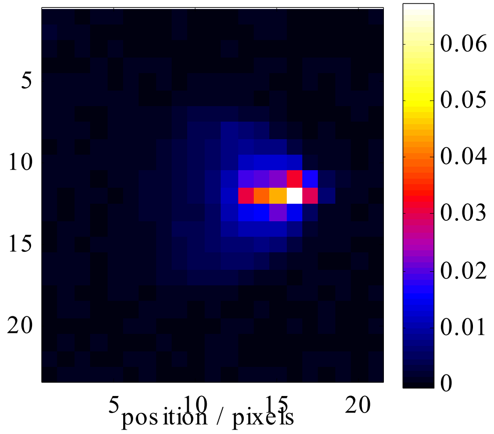
Deconvolution of the Camera Resolution



Measured distribution Φ



Reconstructed distribution Ψ

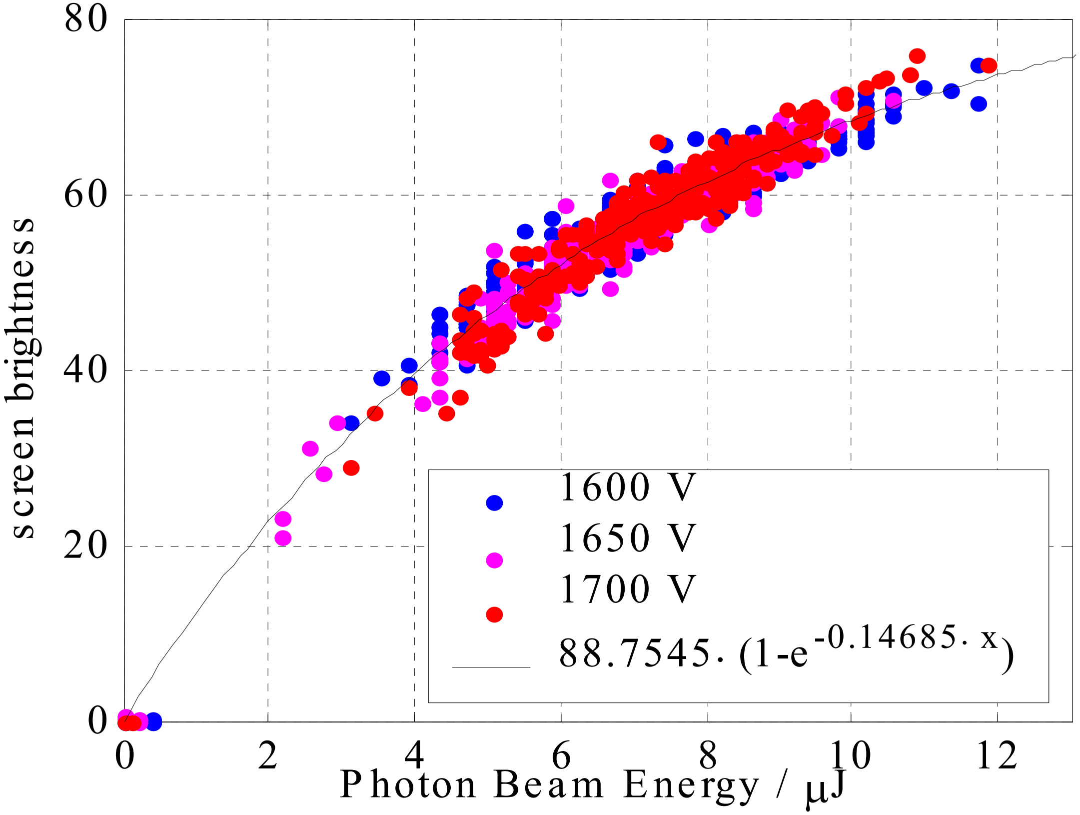


Point spread function P

Image Processing

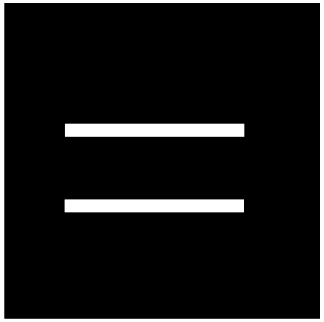
Correction for Non-Linear Response

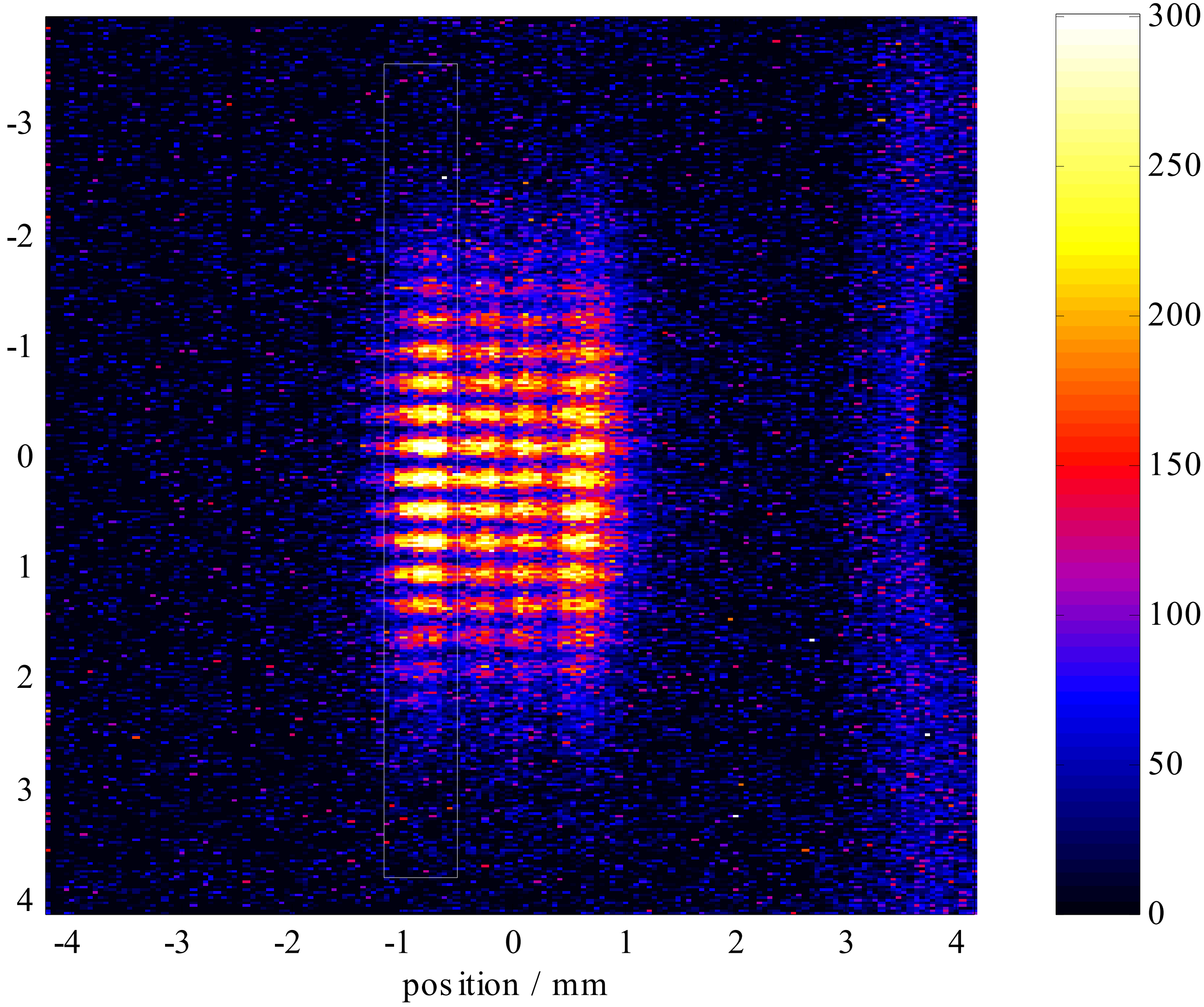
- Light emitted by the Ce:YAG crystal is not proportional to the incident energy
- Correction applied with the help of a calibrated multi-channel plate



Analysis

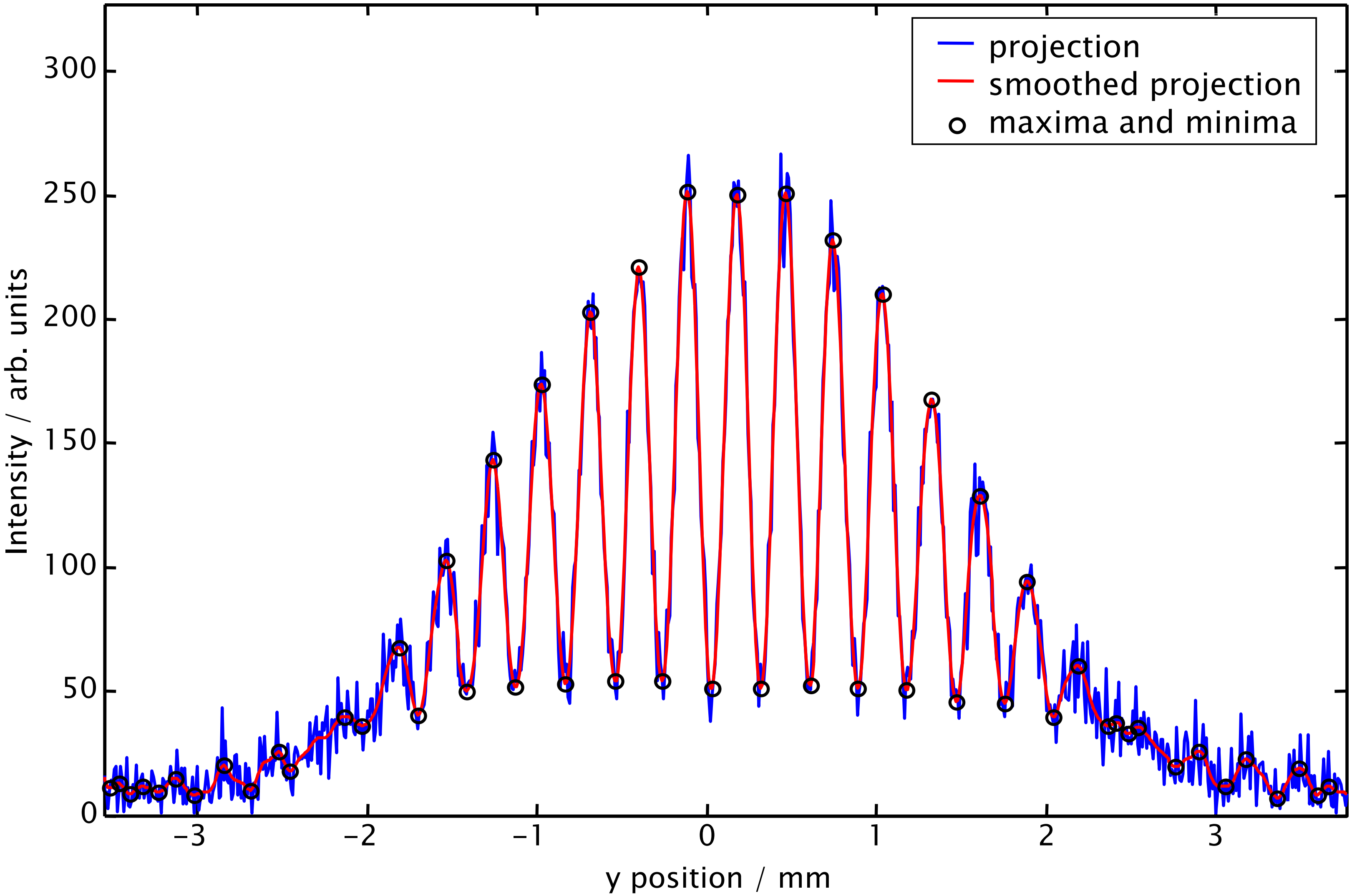
Measurement, 1mm double slit





Analysis of Experimental Data

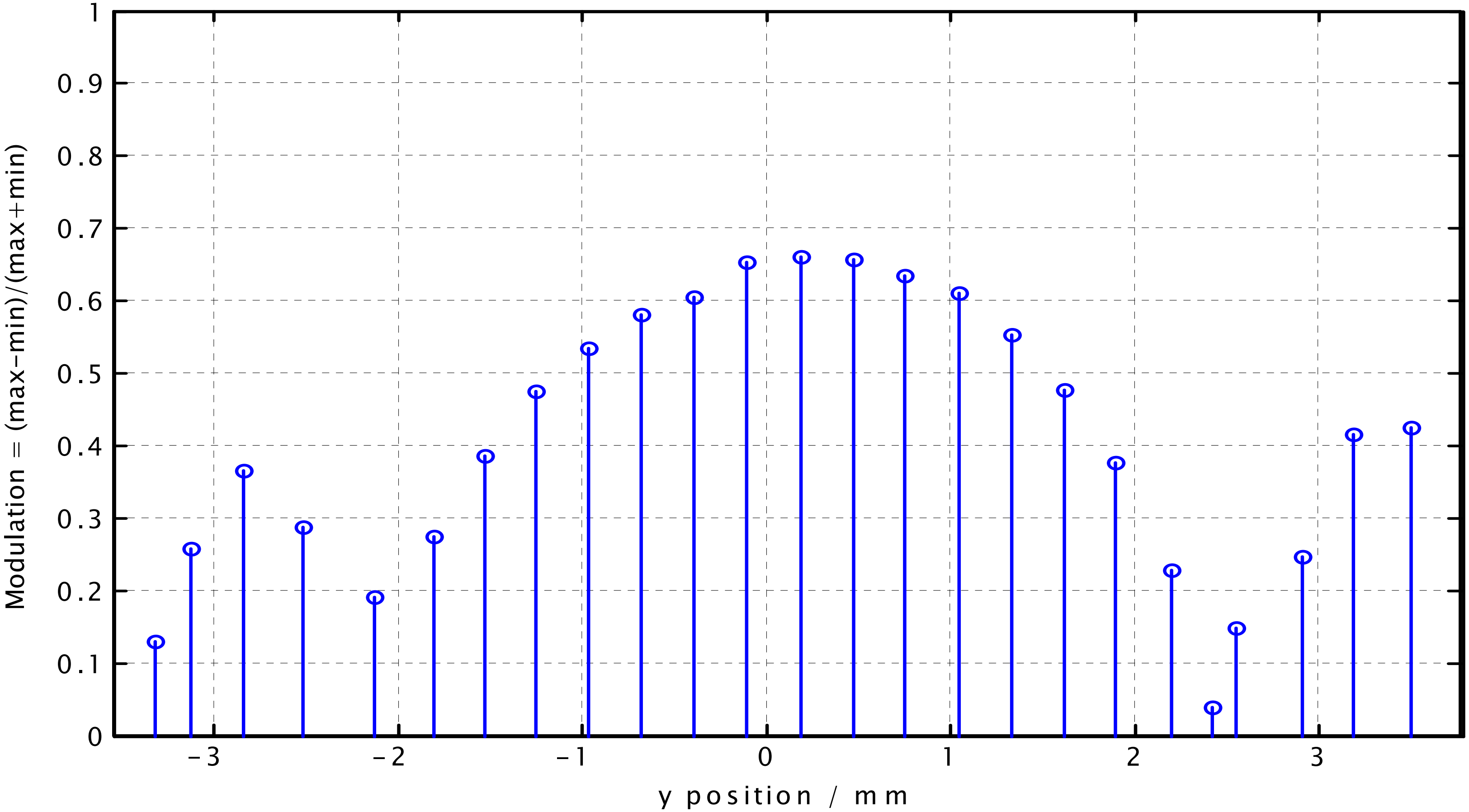
Projection of the Selected Area



Analysis of Experimental Data

Modulation Depth

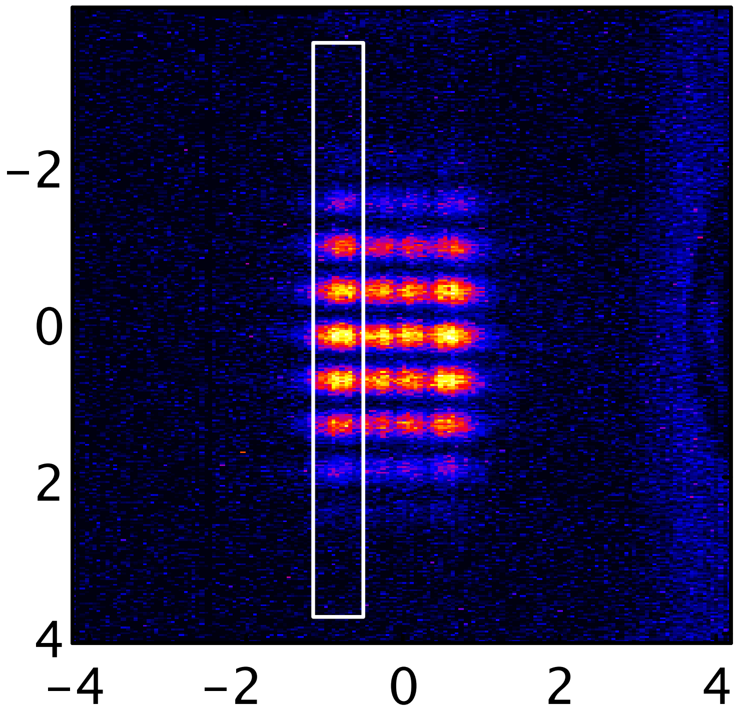
$$\text{modulation} = \frac{\text{max} - \text{min}}{\text{max} + \text{min}}$$



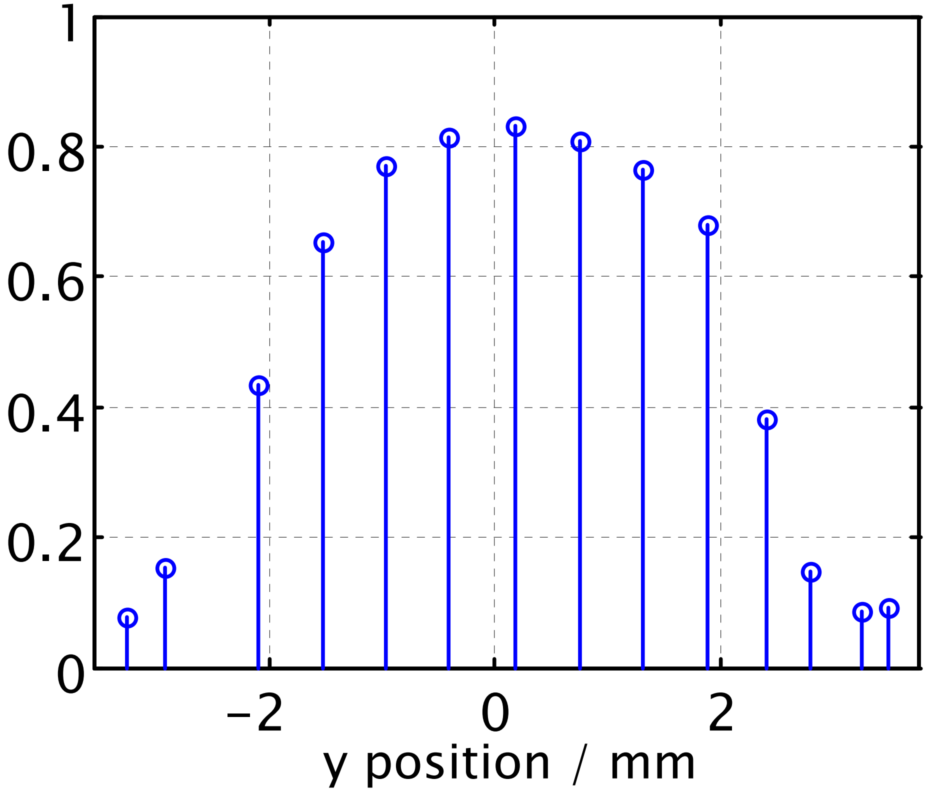
Analysis of Experimental Data

Double Slit — 0.5 mm separation

Reconstructed Image



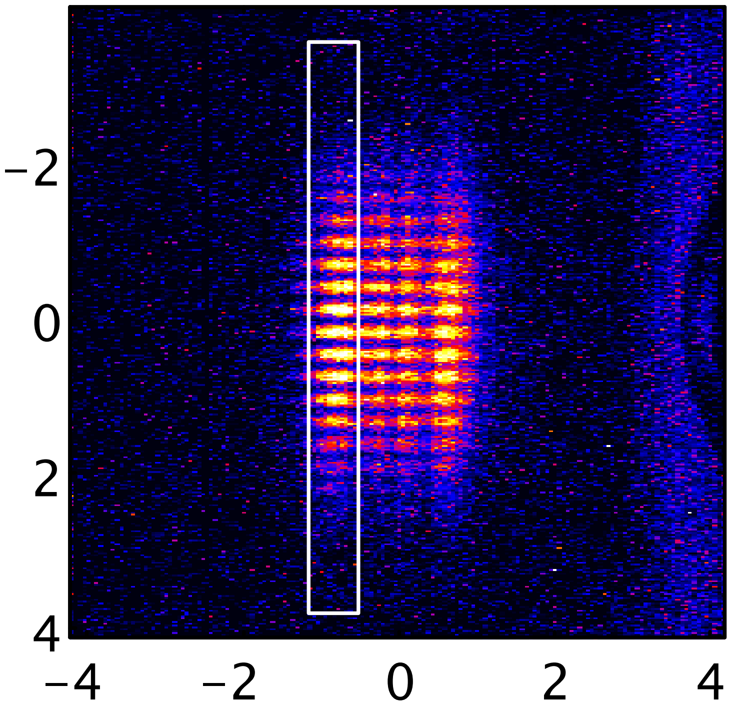
Modulation



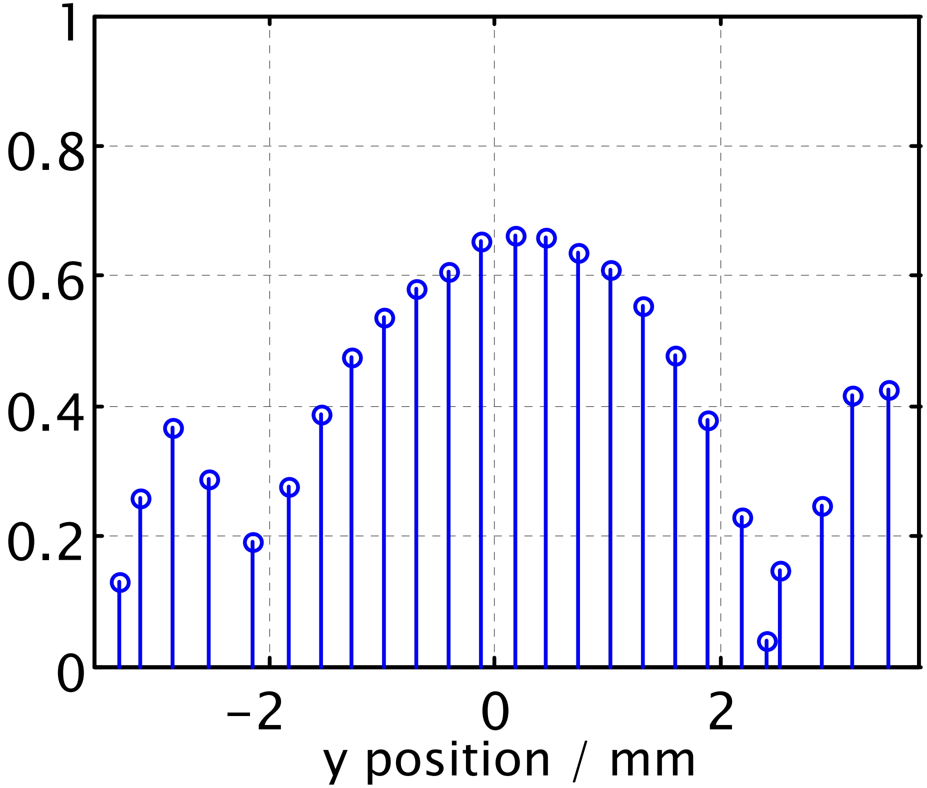
Analysis of Experimental Data

Double Slit — 1 mm separation

Reconstructed Image

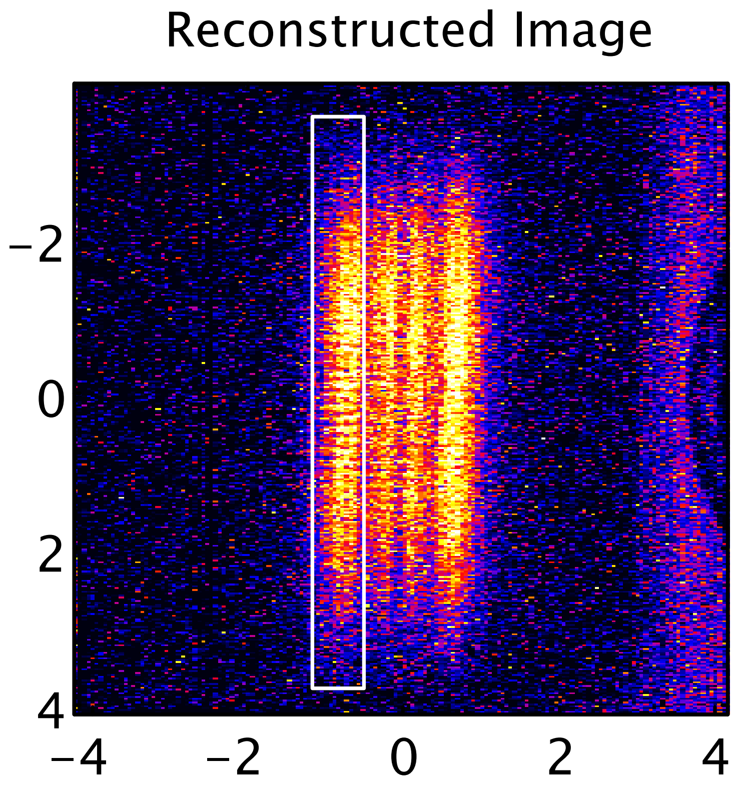


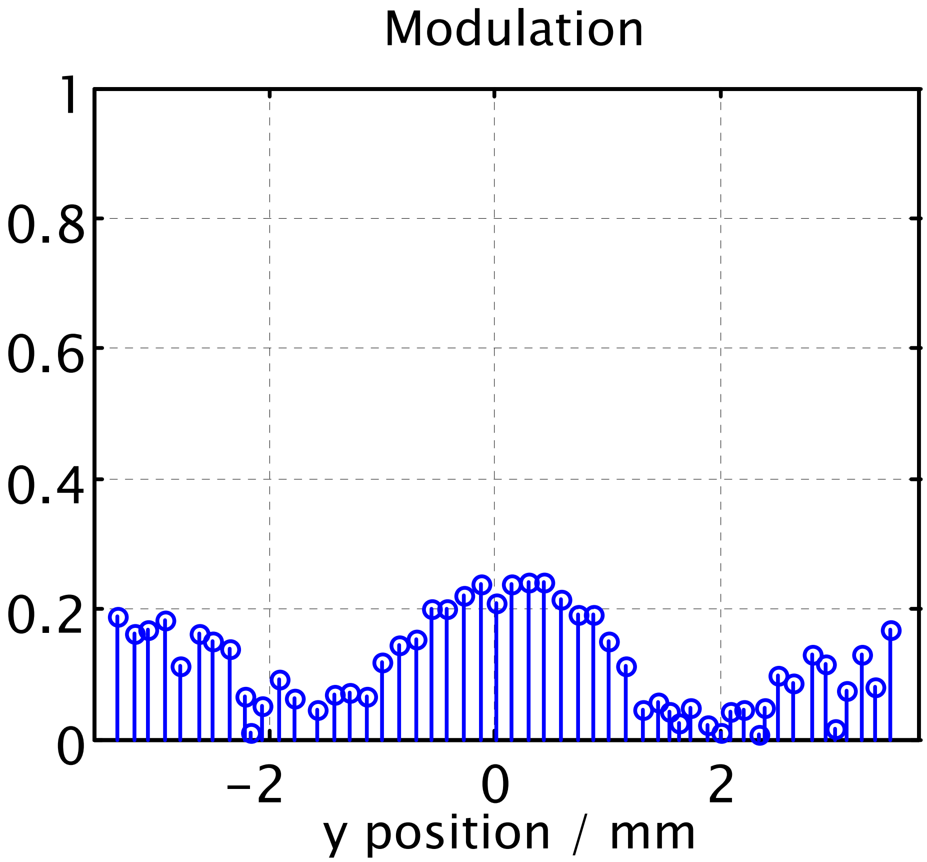
Modulation



Analysis of Experimental Data

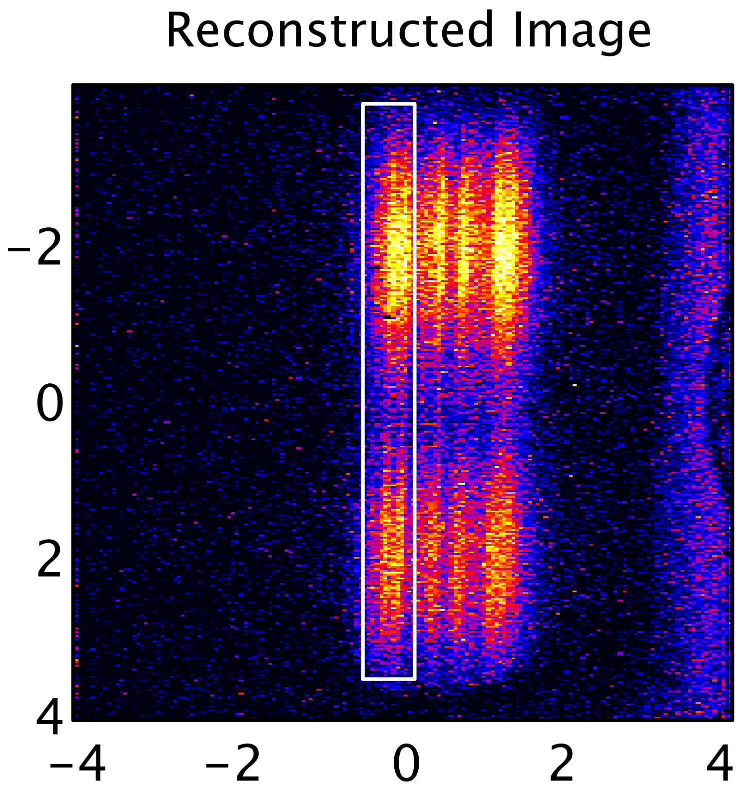
Double Slit — 2 mm separation

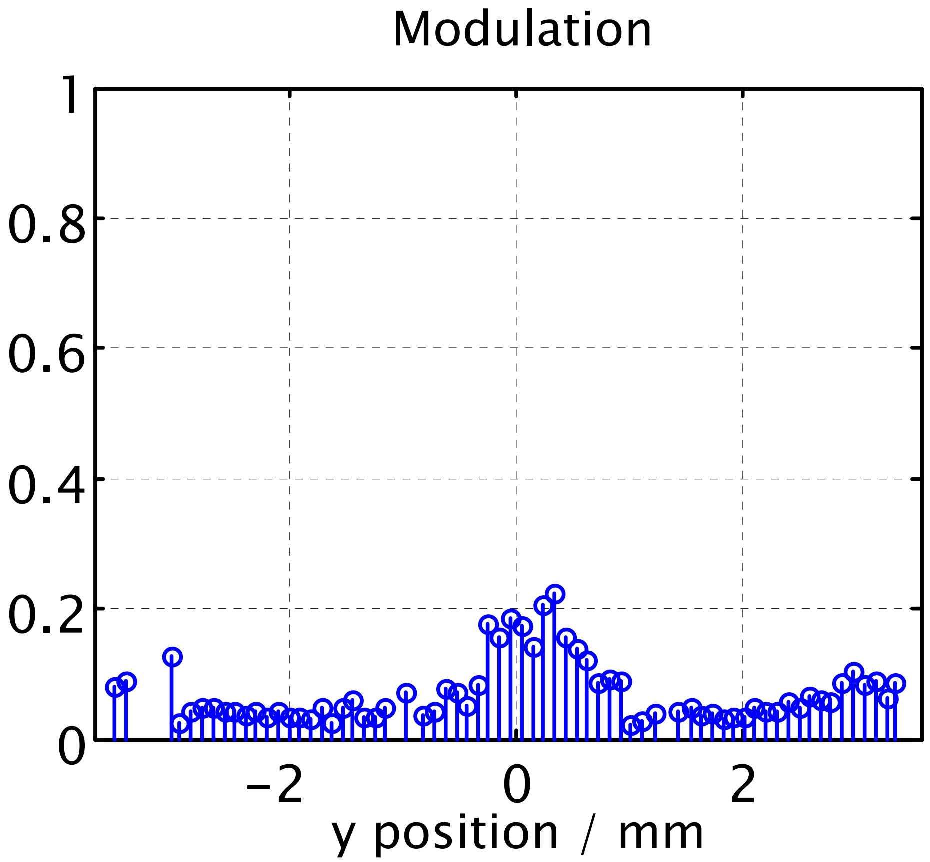




Analysis of Experimental Data

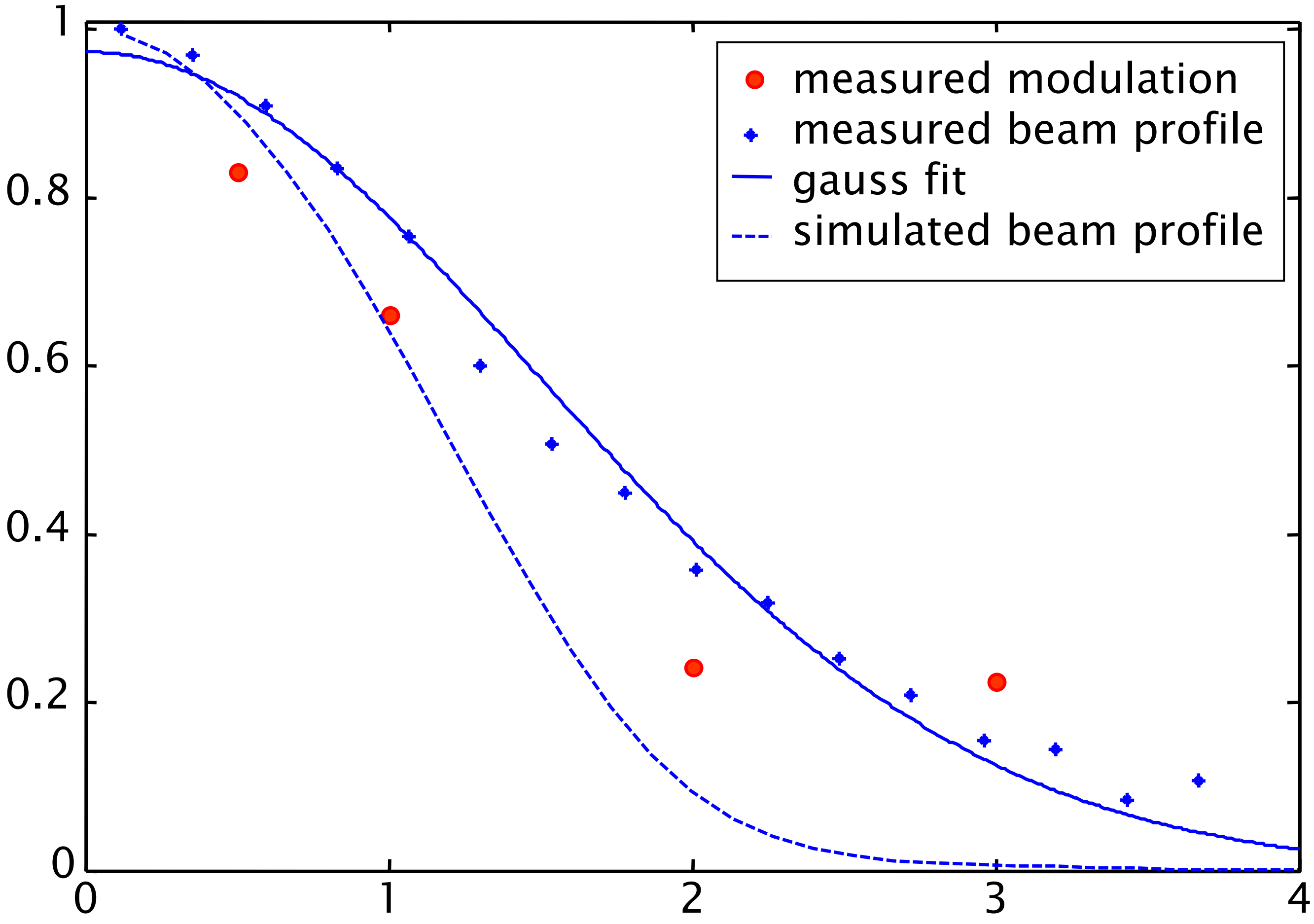
Double Slit — 3 mm separation





Analysis of Experimental Data

Slit Separation → Modulation



Simulations

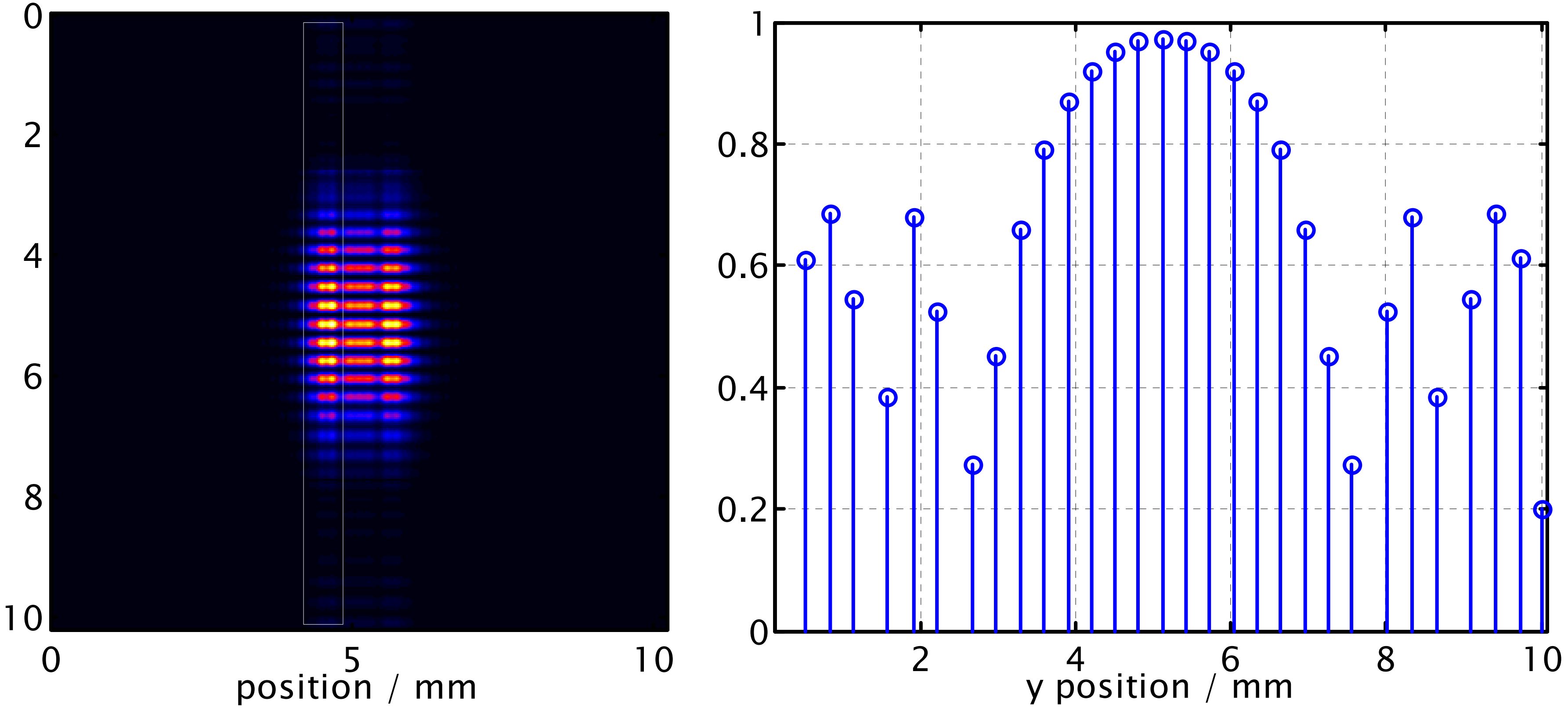
GLAD

- “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)

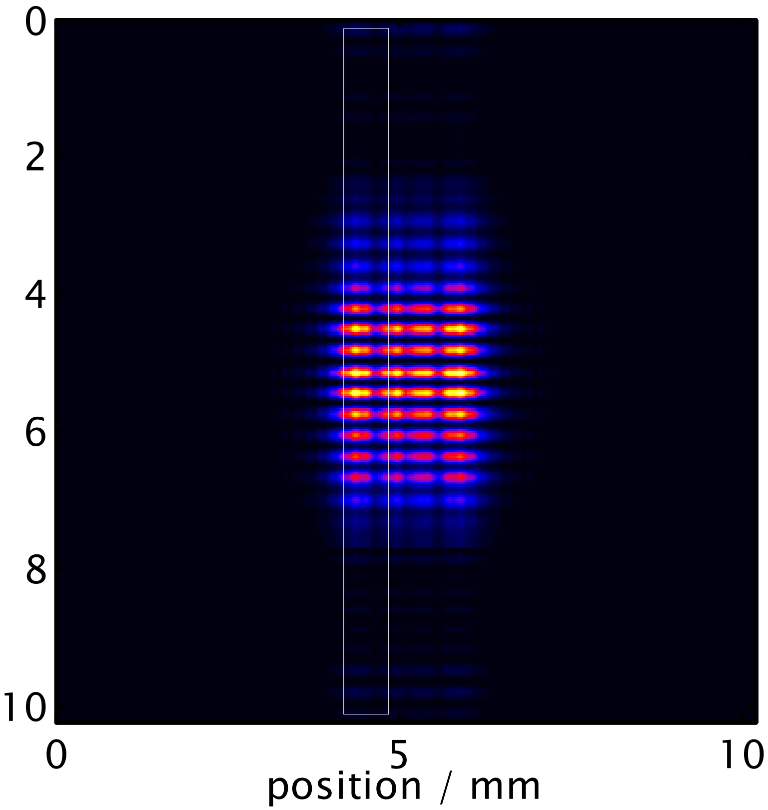
Simulations

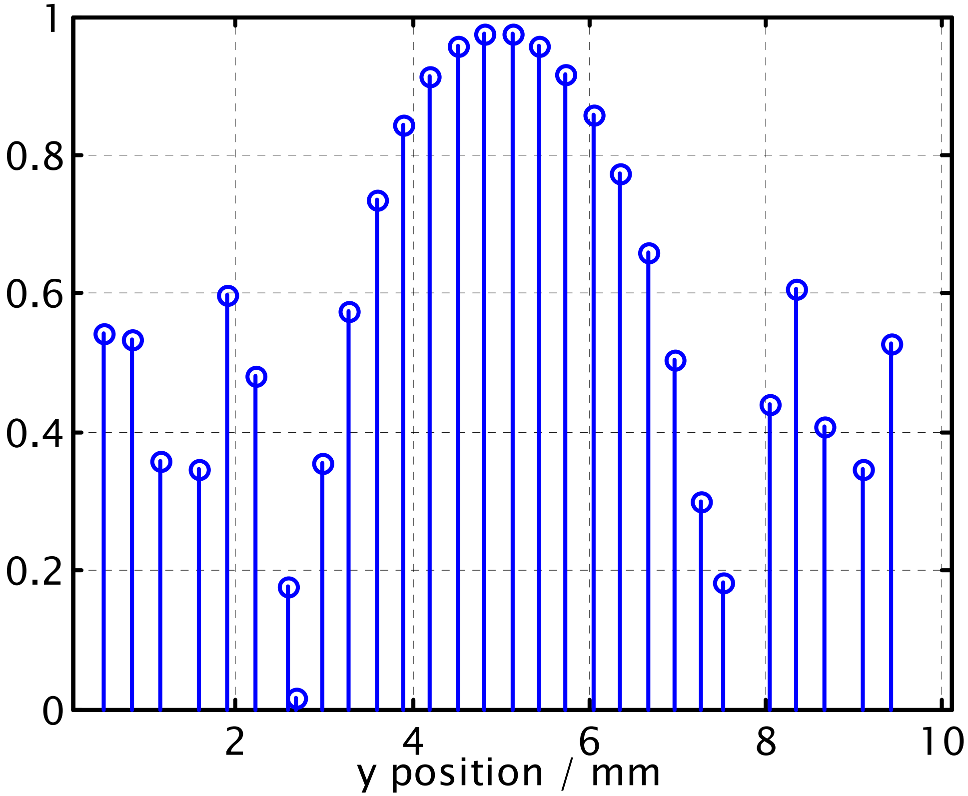
Plane Wave Input



Simulations

Gaussian Beam Input





Coherence Measurements

Comparison with other Methods

- For any beam, we have at the waist:

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

where σ_r is the beam diameter, σ_θ the angular divergence

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

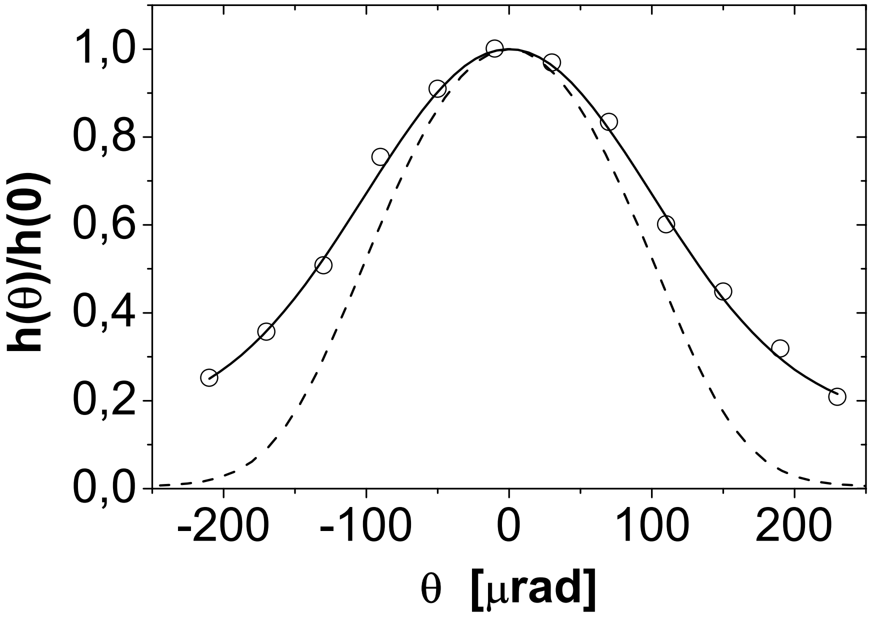
$$\sigma_r \sigma_\theta = \lambda/4\pi$$

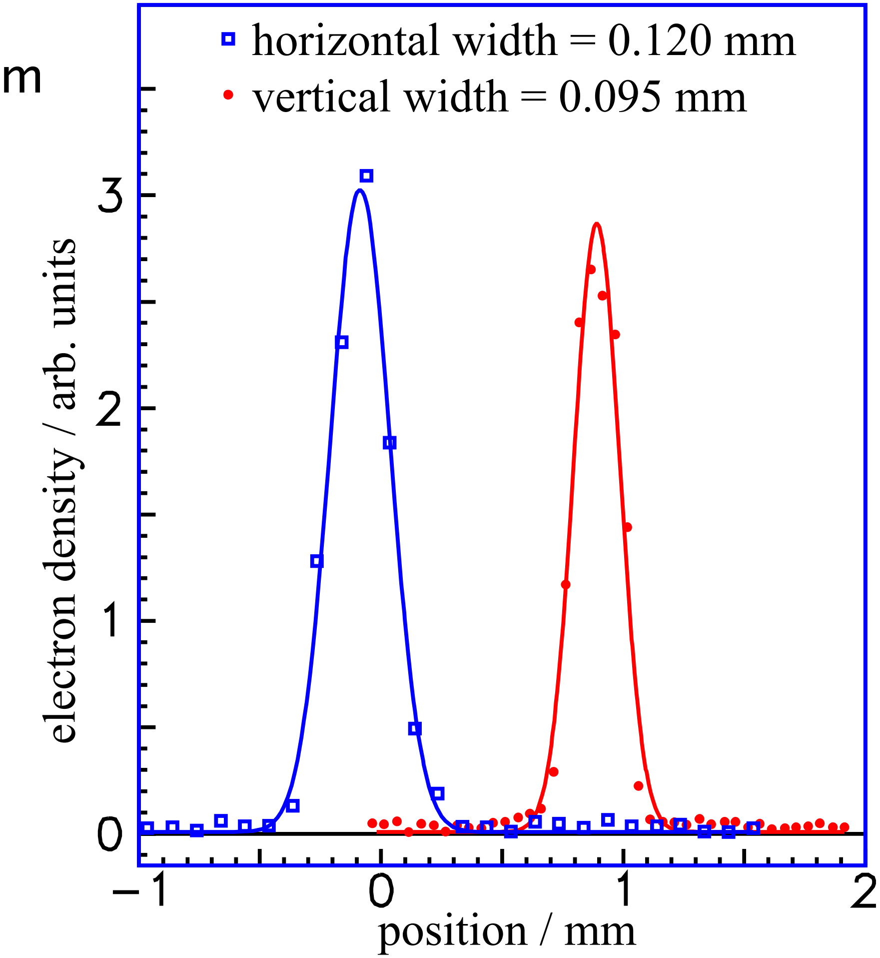
Coherence Measurements

Comparison with other Methods

- Here: σ_r = 100 … 150 µm

σ_θ = 120 µrad





⇒ $\sigma_r \, \sigma_\theta$ = 15 nm ≈ 8 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

Coherence Measurements

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

Coherence Measurements

Comparison with other Methods

- The coherence can be expressed in terms of the correlation function

$$\gamma_1(\vec{r}_\perp, \vec{r}'_\perp, z, t) = \frac{\langle \tilde{E}(\vec{r}_\perp, z, t)\tilde{E}(\vec{r}'_\perp, z, t)\rangle}{\left[\langle|\tilde{E}(\vec{r}_\perp, z, t)|^2\rangle\langle|\tilde{E}(\vec{r}'_\perp, z, t)|^2\rangle\right]^{1/2}}$$

- This is related to the normalized angular spectrum $h(\vec{k}_\perp, z)$:

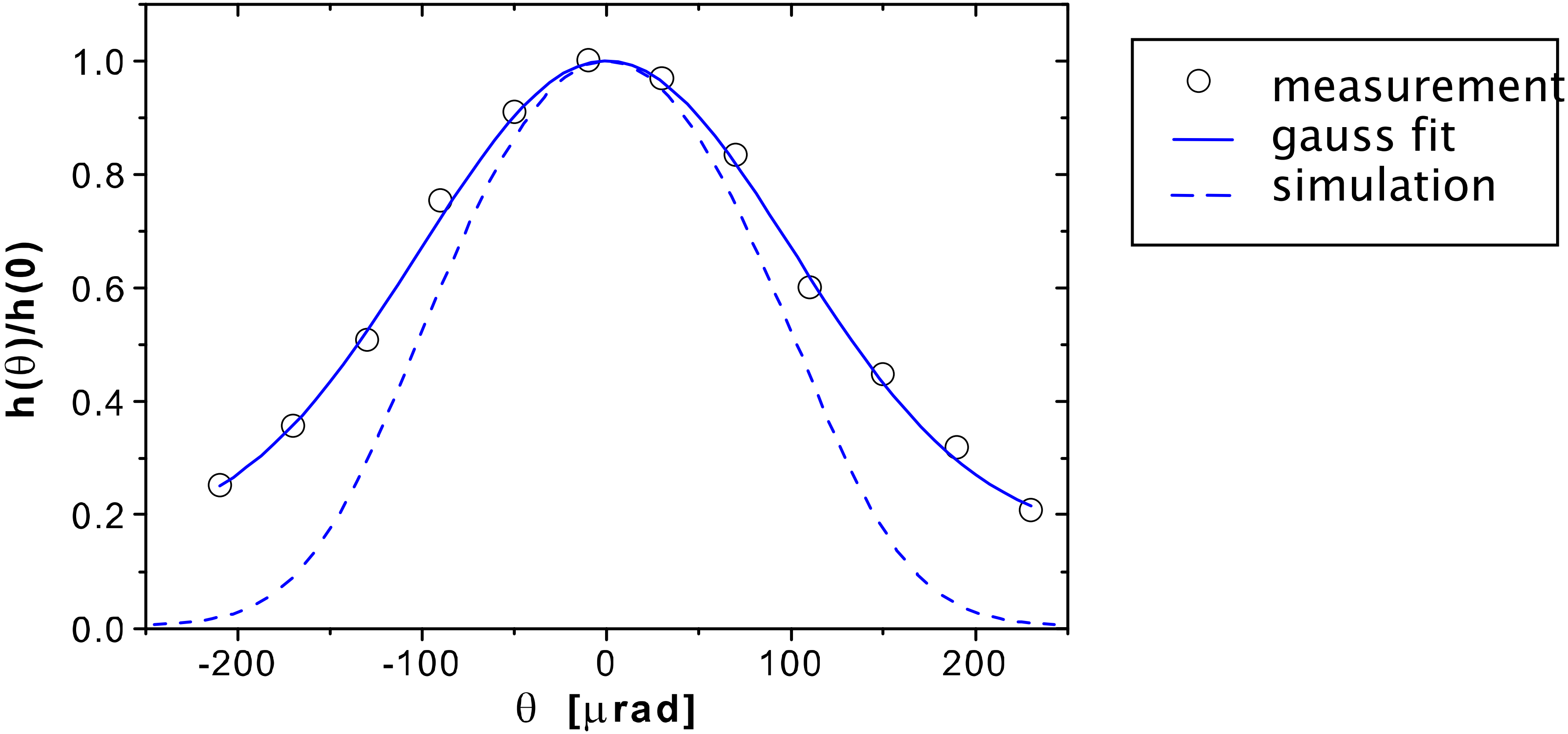
$$h(\vec{k}_\perp, z) = \frac{1}{(2\pi)^2}\int \gamma_1^{(eff)}(\vec{\rho}, z)e^{-i\vec{k}_\perp\cdot\vec{\rho}}\mathrm{d}\vec{\rho}$$

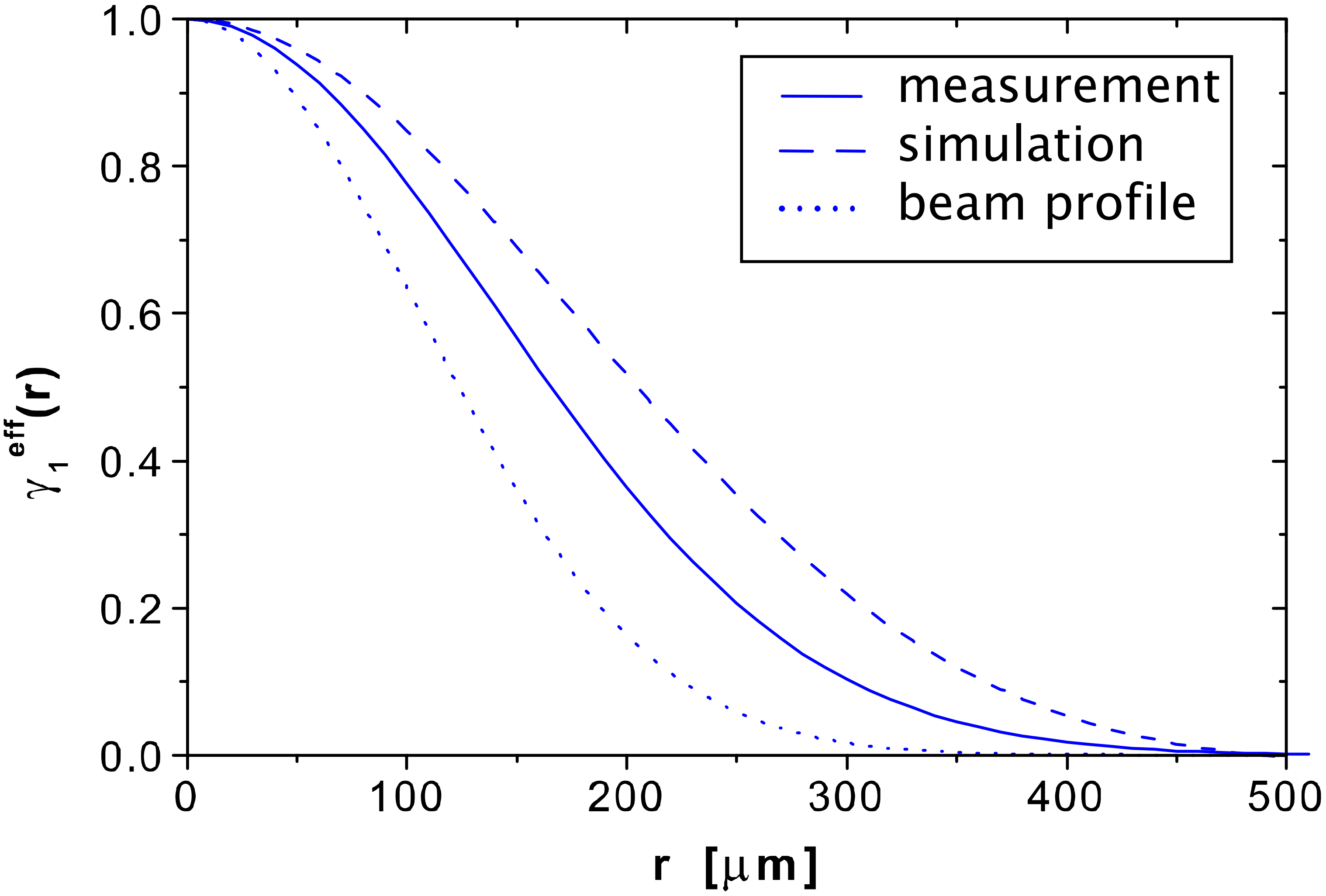
The latter is easy to measure: it is given by the intensity distribution in the far field.

Coherence Measurements

Comparison with other Methods

- Statistical fluctuations of the radiation power also depend on the coherence
- 80 % transverse coherence


h(θ)/h(0)
1.0
0.8
0.6
0.4
0.2
0.0
-200
-100
0
100
200
θ [μrad]
measurement
gauss fit
simulation


1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300
400
500
$\gamma_1^{eff}(r)$
r [μm]
measurement
simulation
beam profile

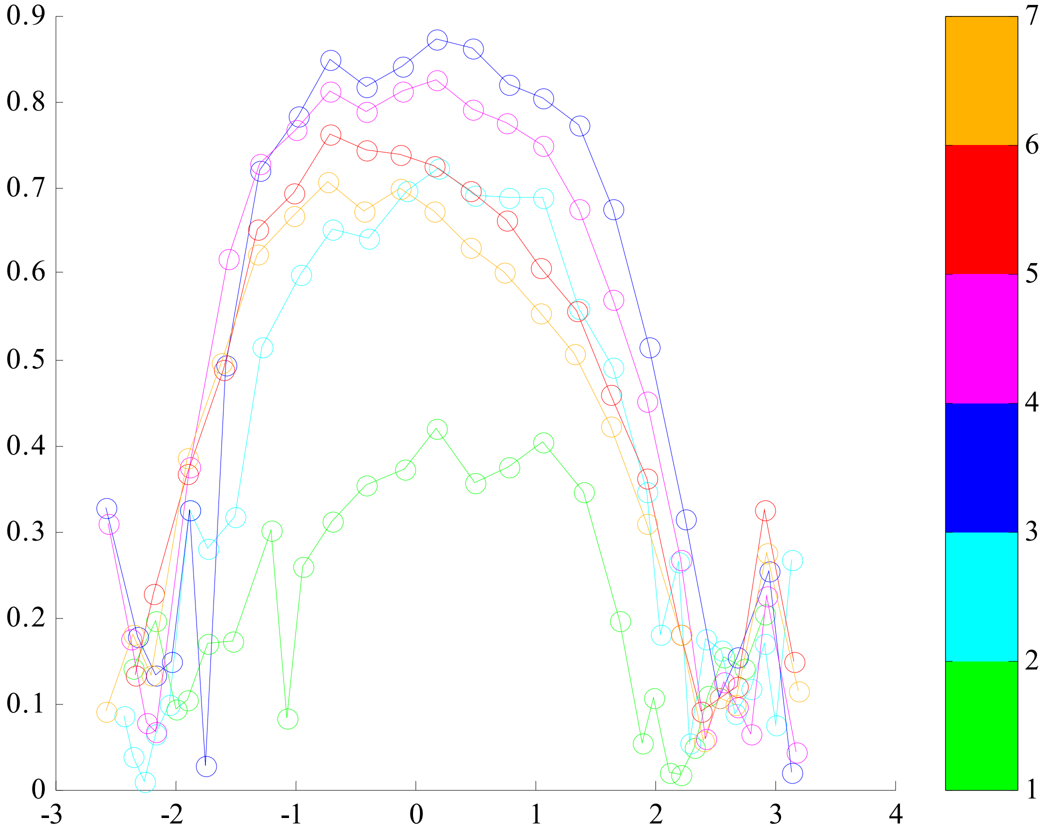
update: 14. March 2002, webmaster

Summary of the parameters of the VUV and Soft X-Ray FEL (TTF) and the X-ray FEL (TESLA)

	TTF-FEL Phase I (design)	TTF-FEL Phase I (actual)	TTF-FEL Phase II	X-ray FEL (1.0 nm)	X-ray FEL (0.1 nm)
Electron Beam					
Energy (GeV):	0.25	0.24	1.0	23	25
Normalized emittance (π mm mrad):	4	6	2	1.6	1.6
Emittance (π nm rad):	8.0	12	1.0	0.04	0.03
Bunch charge (nC):	1	2.8	1	1	1
RMS bunch length (µm):	240	30*	48	25	25
RMS bunch width (µm):	68	110	67	23	38
Bunches per second:	18000	up to 70	72000	57500	57500
Photon beam					
Energy (eV):	12	12	192.8	1231	12311
Wavelength (nm):	100	100	6.4	1	0.1
Peak power (GW):	0.5	1.0	2.3	185	37
Photons per bunch:	2.1 E14	2-5 E13	3.9 E13	1 E13	1.8 E12
Average brilliance**	1.0 E21	1.0 E17	1.0 E23	5.2 E24	4.9 E25
Peak brilliance**	4.3 E28	2-4 E28	2.2 E30	9.3 E32	8.7 E33
FWHM spectral bandwidth (%):	0.64	1.0	0.46	0.4	0.08

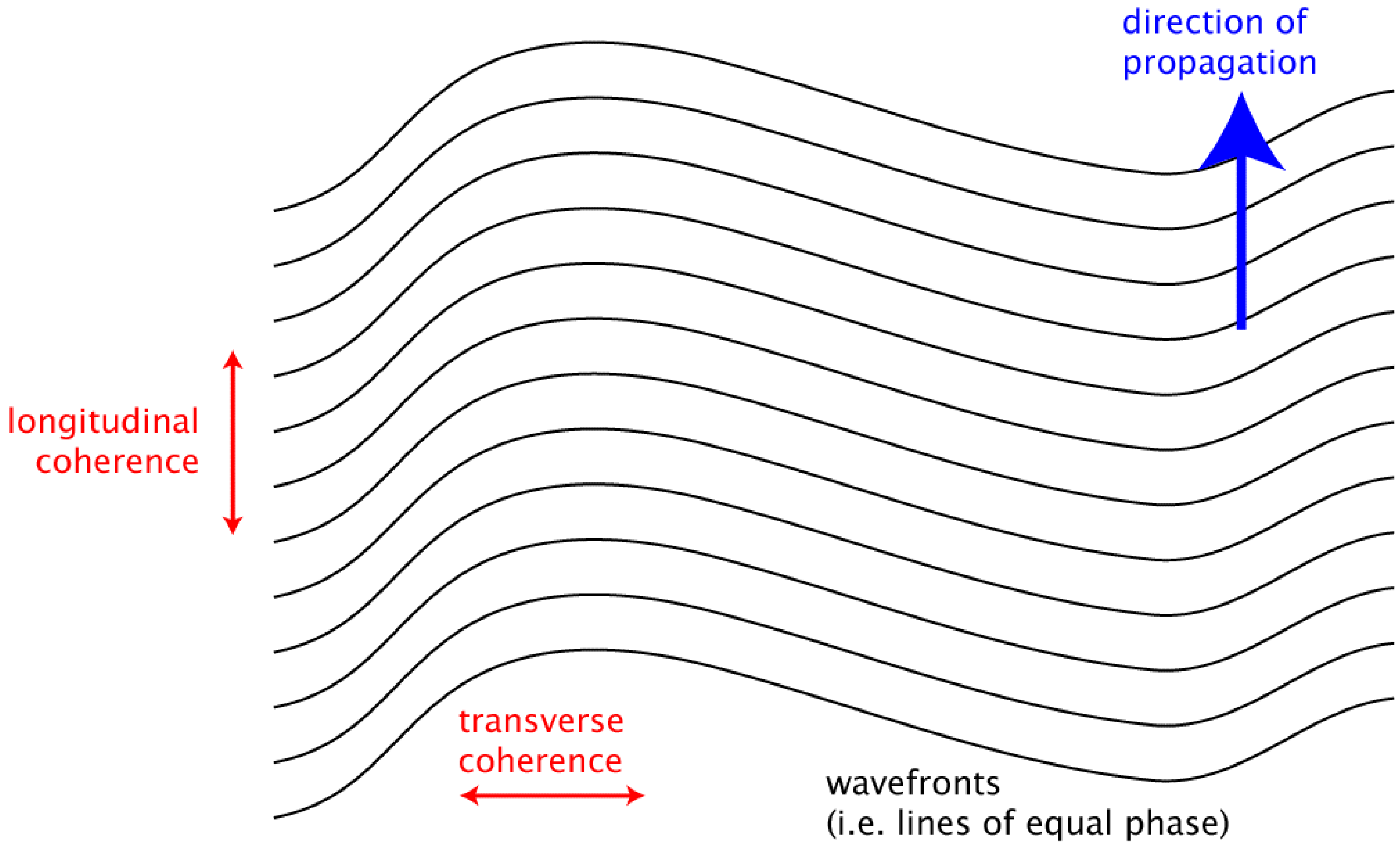
* "lasing" part of the bunch

**(photons/ sec/ mm^2/ mrad^2/ 0.1%)


0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-3
-2
-1
0
1
2
3
4
7
6
5
4
3
2
1

Simulations

Definitions



Simulations

Definitions