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Sub-micrometer resolution transverse electron beam size measurement system based on optical transition radiation

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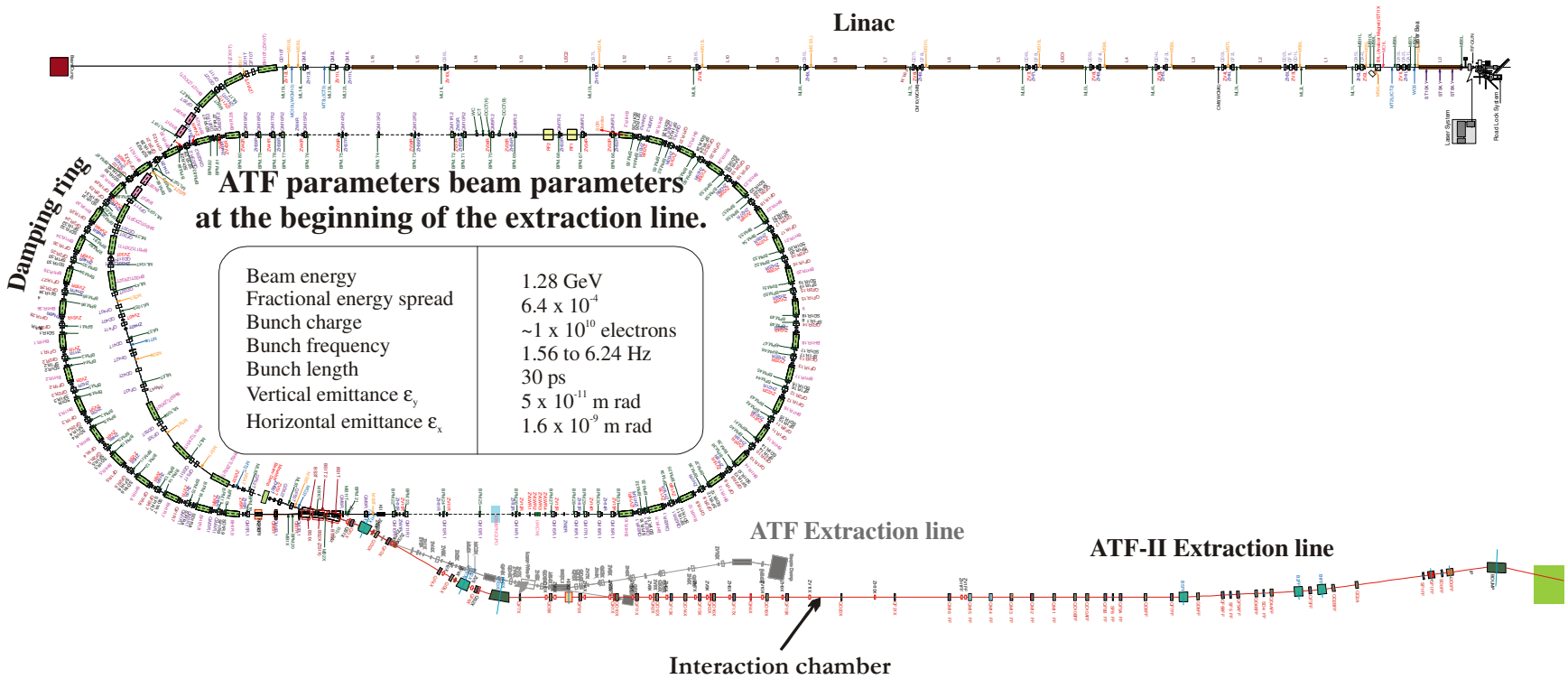
Introduction

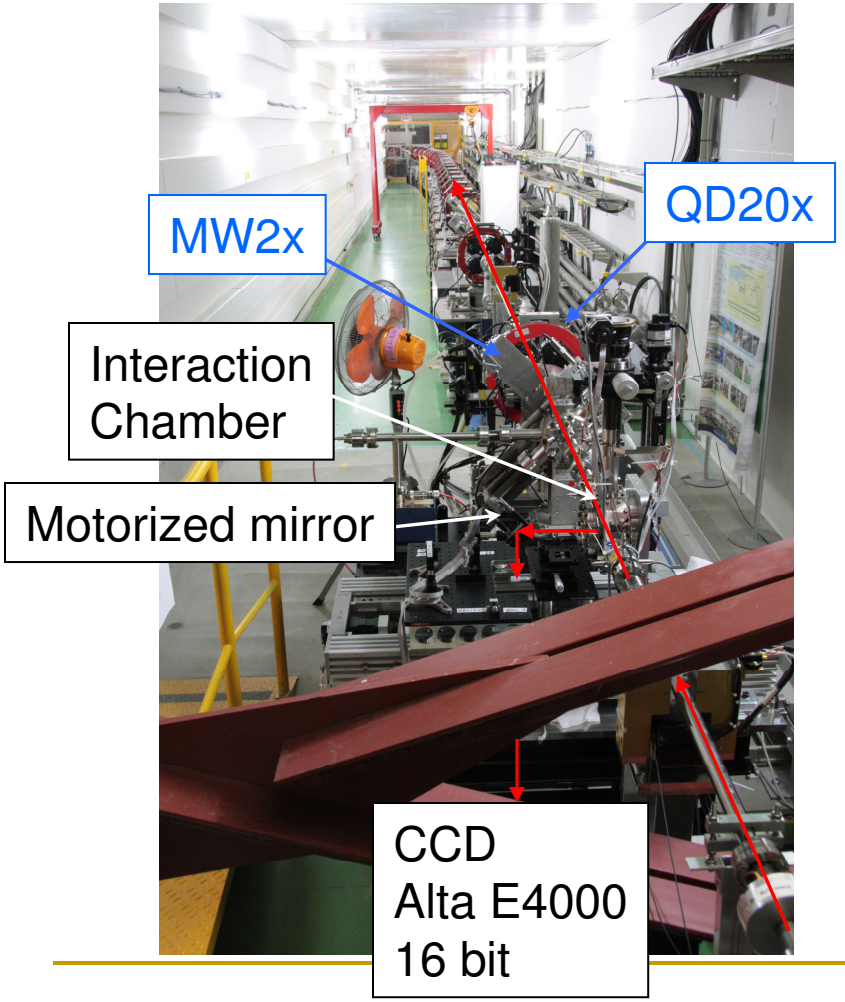
KEK ATF-II, beam parameters

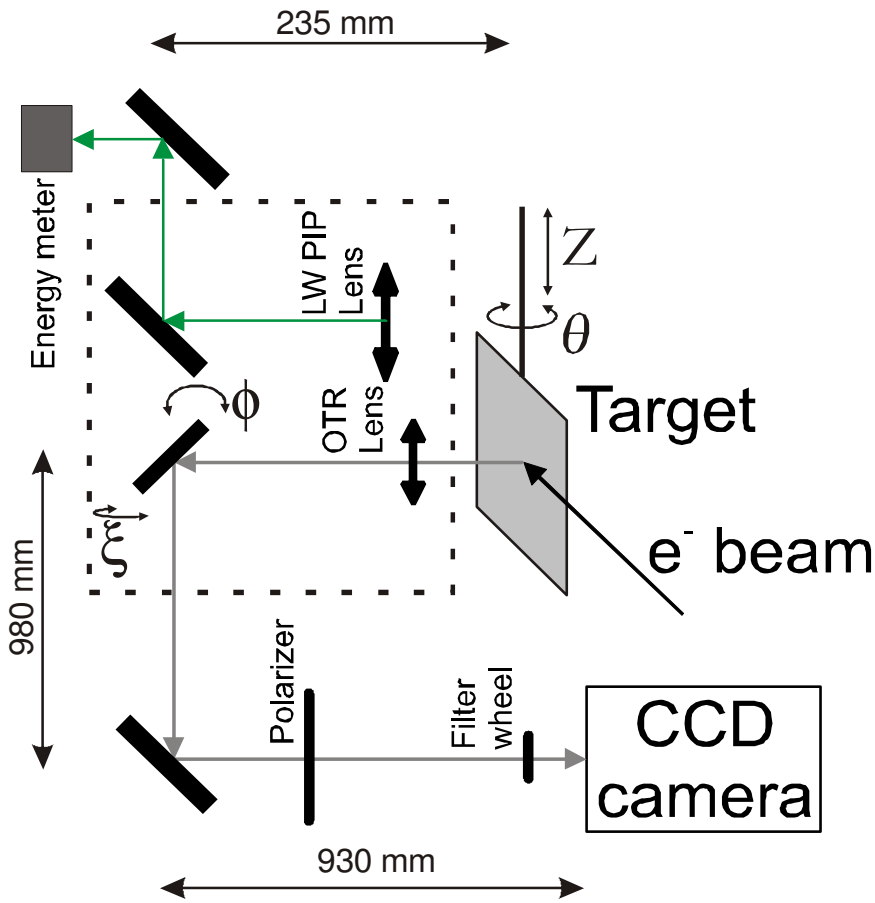


ATF parameters beam parameters at the beginning of the extraction line.

Beam energy	1.28 GeV
Fractional energy spread	6.4×10^{-4}
Bunch charge	~1×10^{10} electrons
Bunch frequency	1.56 to 6.24 Hz
Bunch length	30 ps
Vertical emittance ε_y	5×10^{-11} m rad
Horizontal emittance ε_x	1.6×10^{-9} m rad

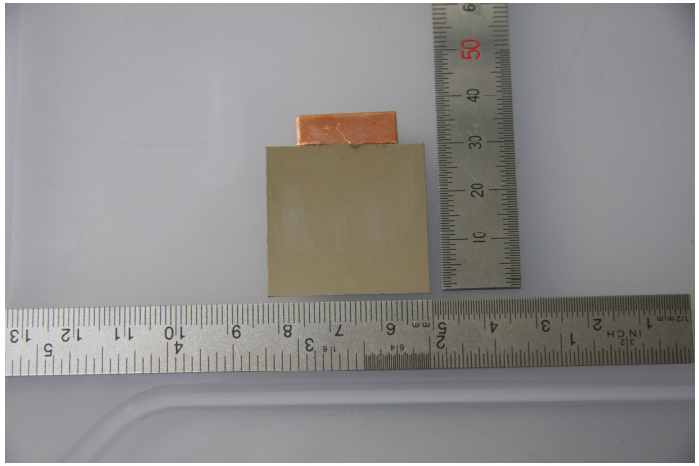
ATF-II beam line, OTR setup

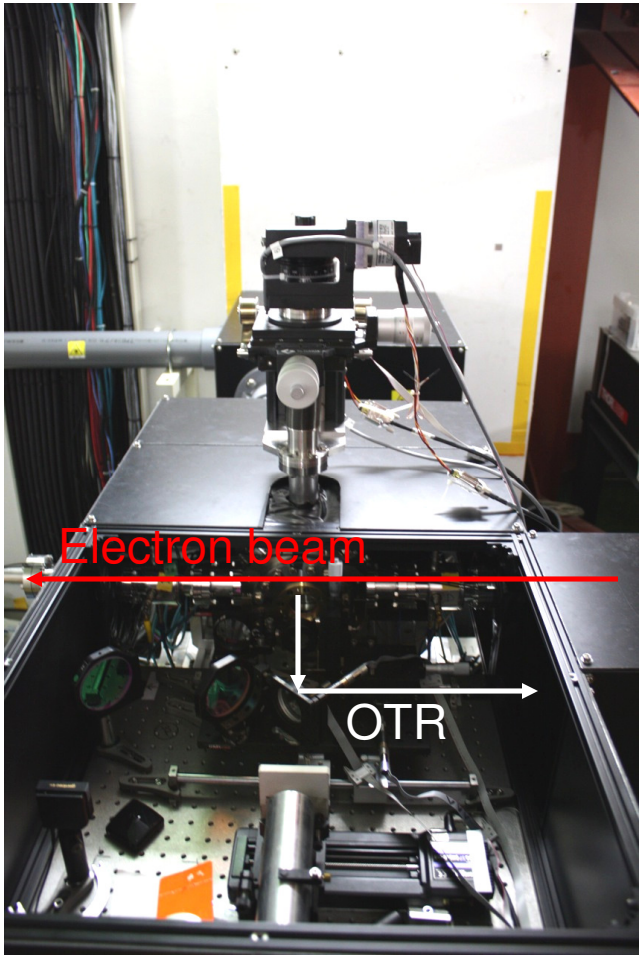




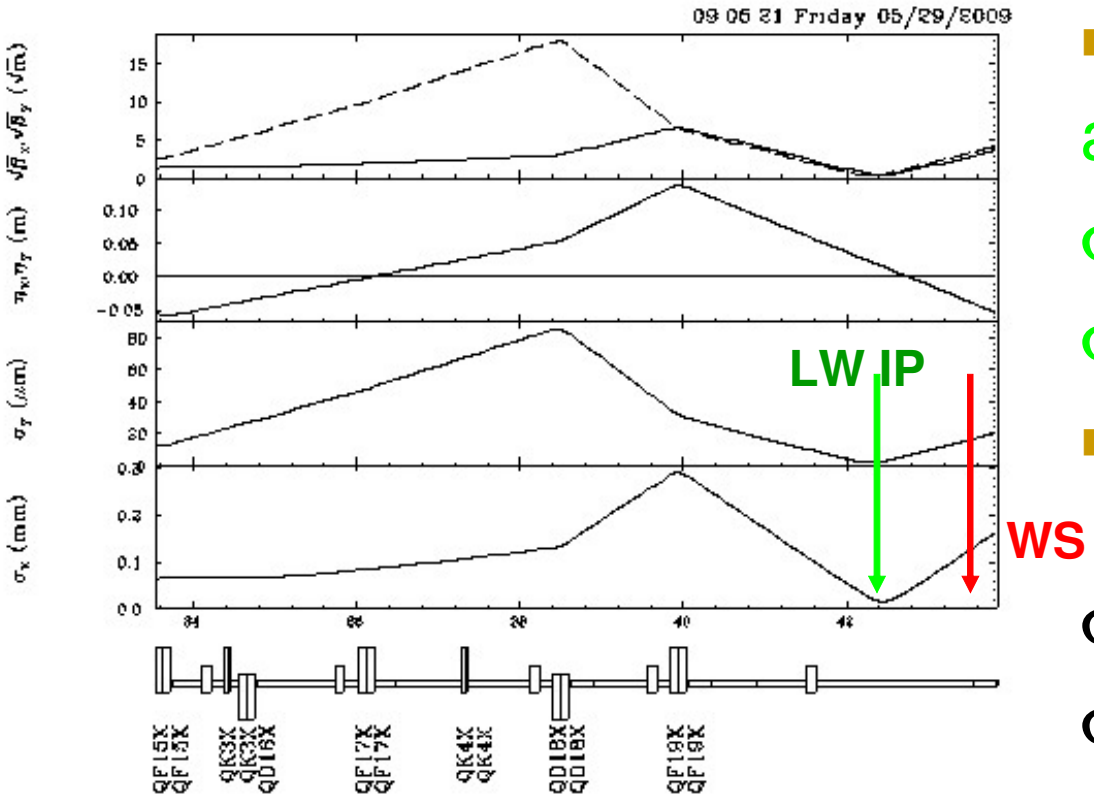
Interaction Chamber, OTR line

Si substrate coated with Al
30x30x0.3 mm





Electron beam optics



- Predictions:

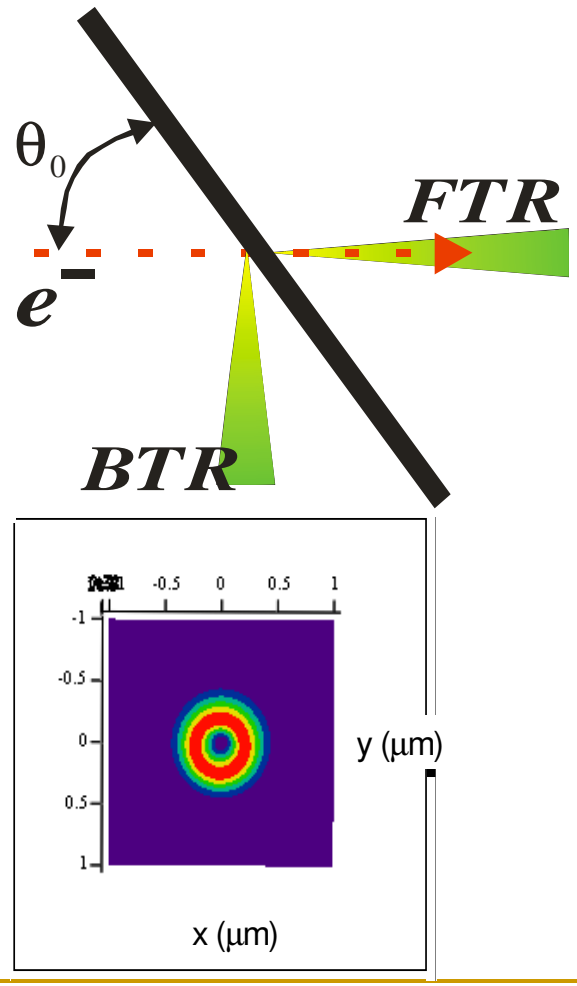
	at LW IP	at MW2X
σ_x =	20μm	20μm
σ_y =	1.7μm	2.3μm

- Measurements at MW2X

σ_x = 30μm

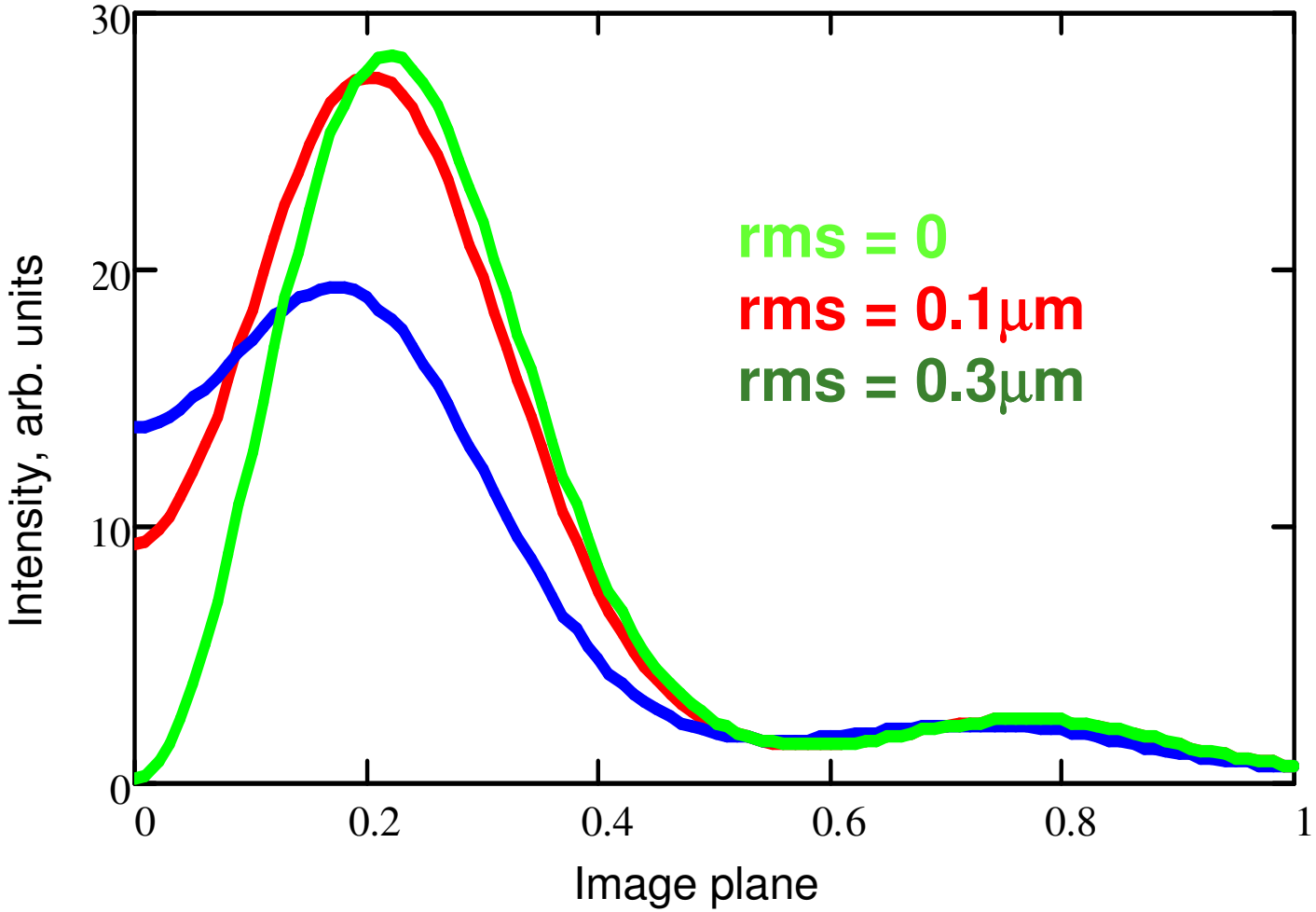
σ_y = 3.4μm

Optical Transition Radiation

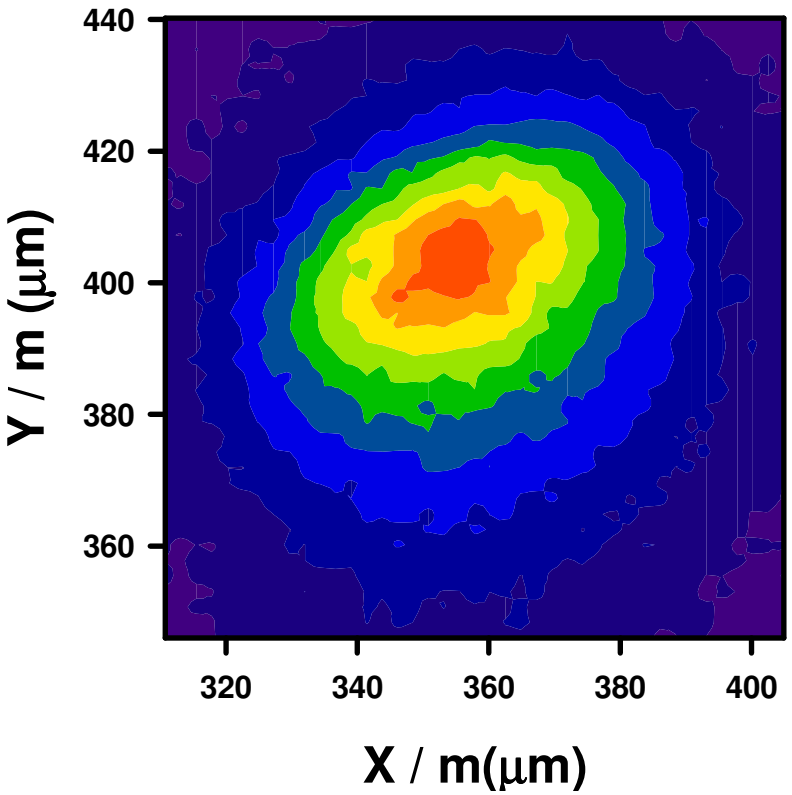


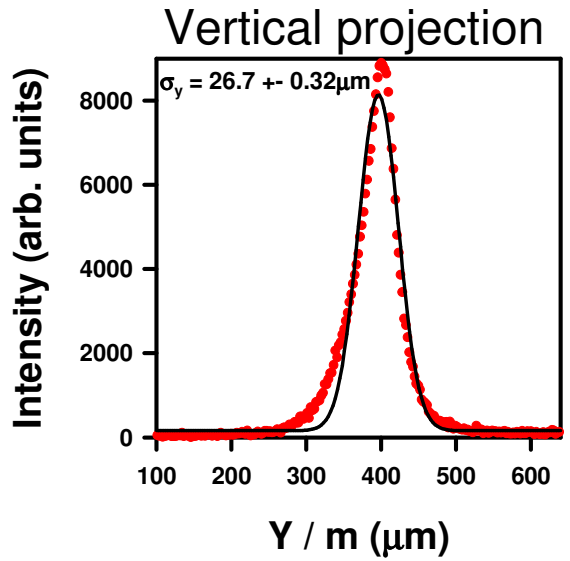
- Transition radiation (TR) appears when a charged particle crosses a boundary between two media with different dielectric constants.
- The resolution is determined by the source dimensions induced by a single particle plus distortion caused by the optical system (diffraction of OTR tails)

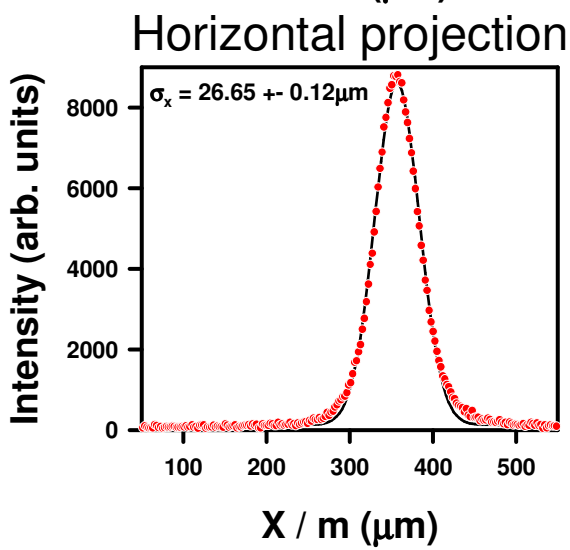
Beam size effect



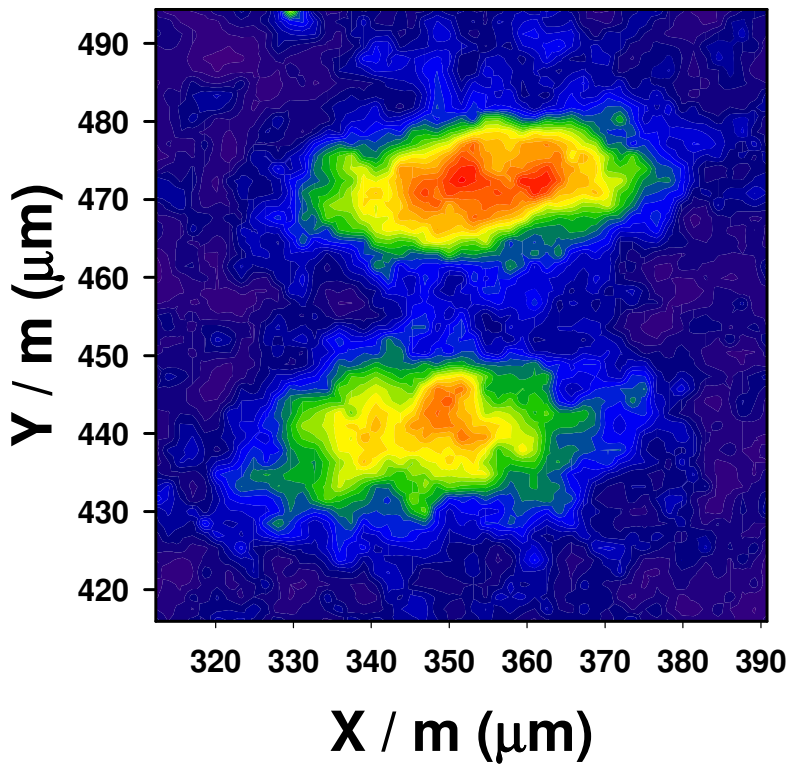
OTR image with NO filter and polarizer

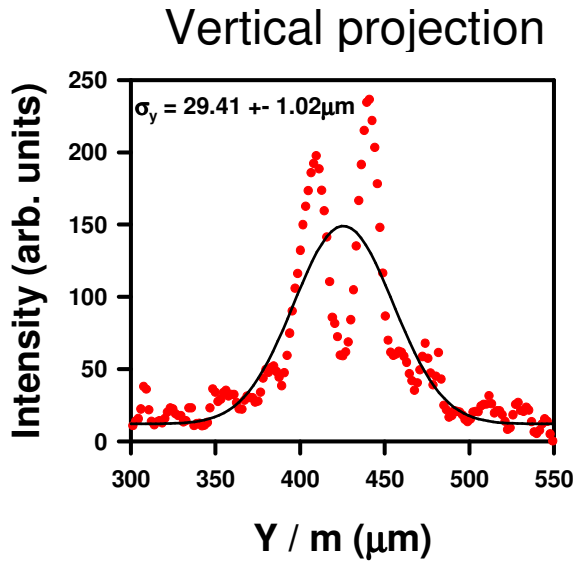


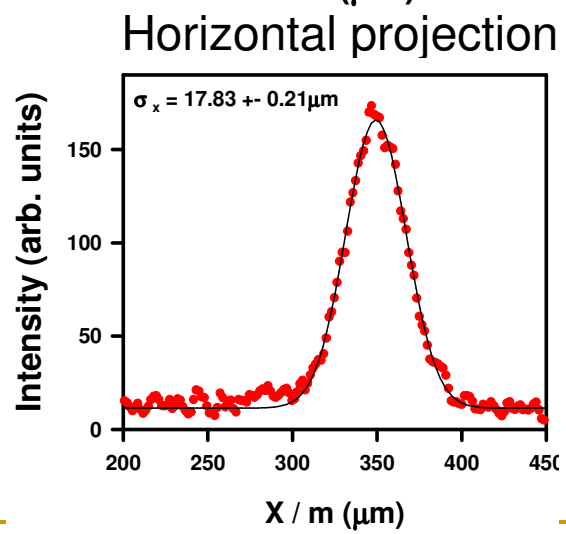




OTR image with polarizer and optical filter







P. Karataev, et al., The First Observation of the Point Spread Function of Optical Transition Radiation, submitted to Physical Review Letters.

Errors propagation

- CCDs are silicon semiconductor devices which use a reverse-biased p–n junction to absorb photons and produce charges representing sensed pixels. The accumulated electrons in each pixel get represented by a number in ADU (Analogue-to-Digital Unit).
- Inverse-Gain is this conversion factor in dimensionless units of e–/DN.
- Noise in photon counting is referred to as "Poisson" noise associated with counting statistics. For the Poisson distribution and taking into account Inverse-Gain, the standard deviation is

$$STD_{pixel} = \sqrt{gain \cdot N}$$

- , where N is the number of detected events [S. B. Howell, Handbook of CCD astronomy, Cambridge University Press, 2000].
- The next step in image processing is pixel-by-pixel background subtraction with correct error propagation:

$$STD_{pixel}^{sub} = \sqrt{STD_{pixel}^{image\,2} + STD_{pixel}^{background\,2}}$$

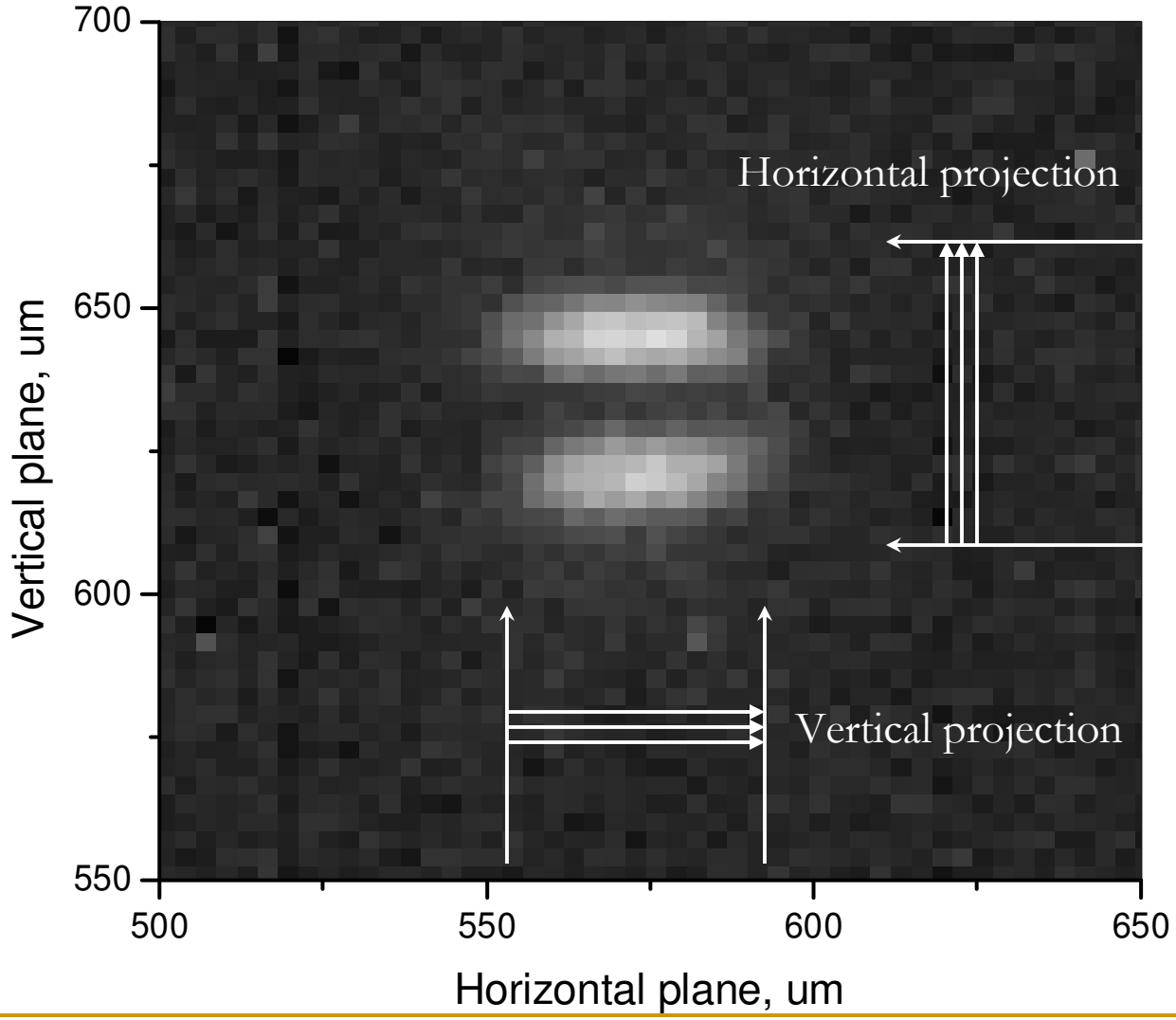
Image manipulation

- To deduct image noise and remove bad pixels the median window filter was used [A. Bovik, The essential guide to image processing, Elsevier, 2009].
- A portion of resulting image to produce horizontal or vertical projections summing rows or columns respectfully was extracted and pixel scale of the projection was converted into microns as follows:

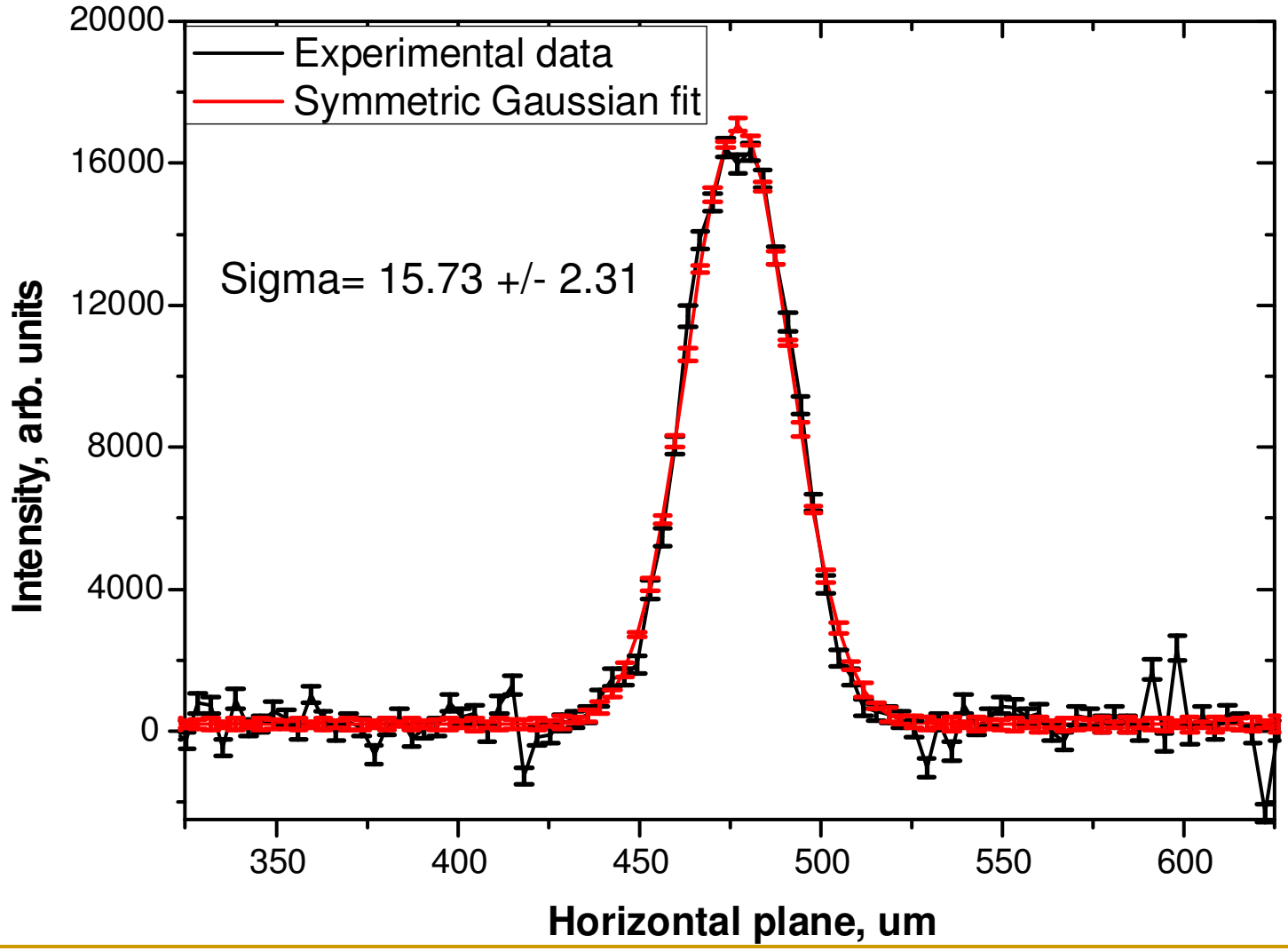
$$X_i^{um} = \frac{X_i^{pixel} \cdot binning \cdot pixel\ size}{magnification\ factor}$$

- The magnification factor for the data set under analysis was 10.69, [A. Aryshev, et. al., IPAC'10, June 2008, Kyoto, Japan, MOPEA053]

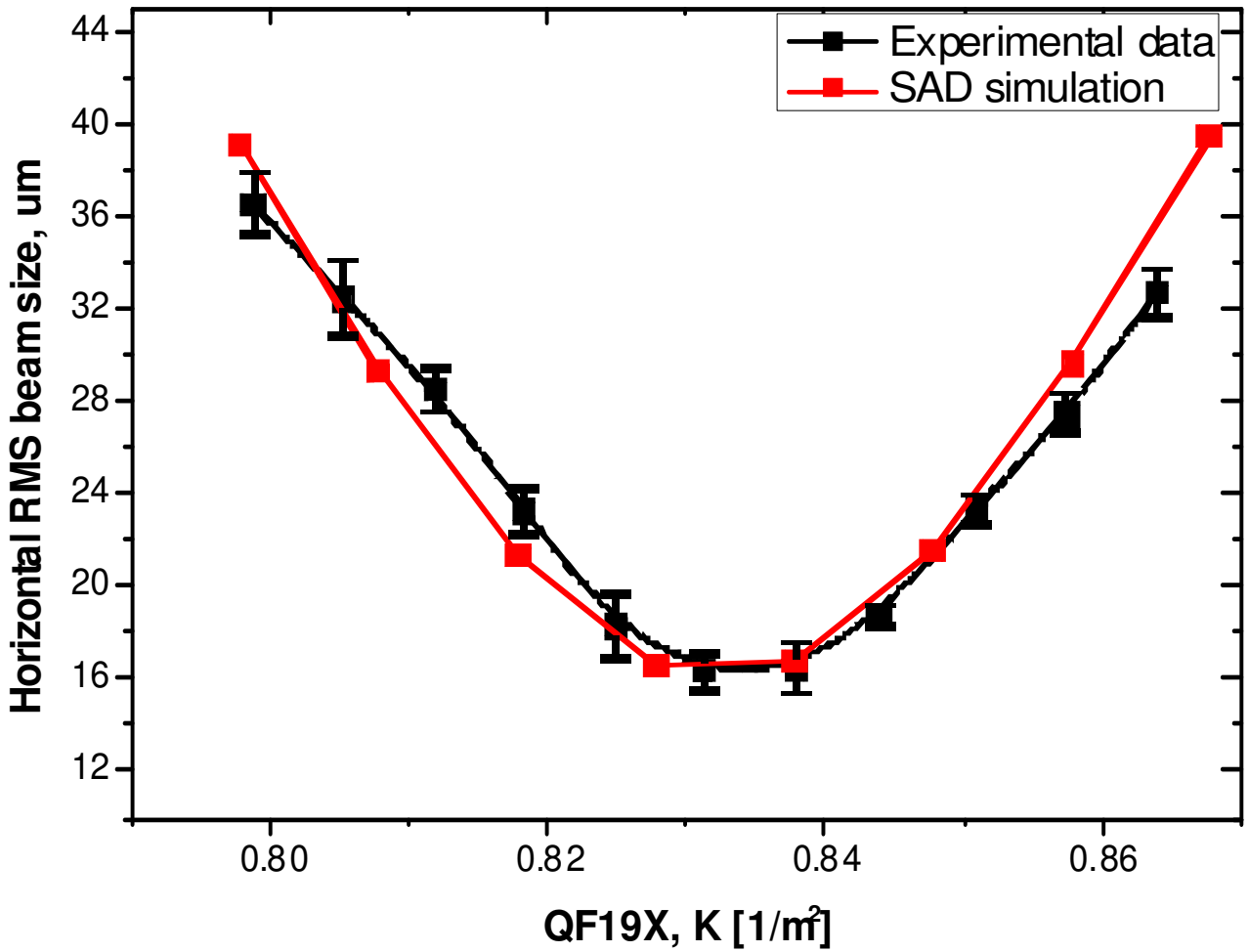
OTR image


700
650
600
550
500
550
600
650
Vertical plane, um
Horizontal plane, um
Horizontal projection
Vertical projection

Horizontal projection



Quadrupole scan, horizontal projection

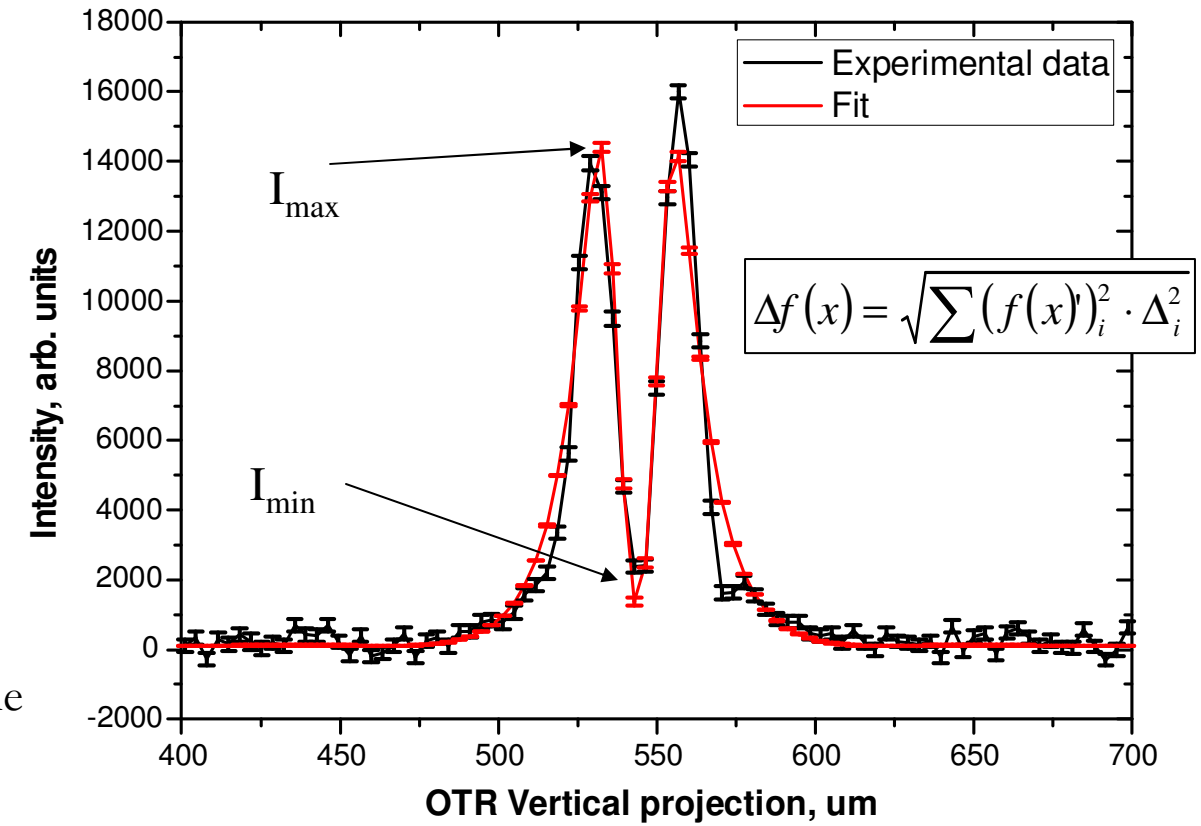


OTR PSF-like Fit function

$$f(x) = a + \frac{b}{1+[c(x-\Delta x)]^4}\left[1 - e^{-2c^2\sigma^2}\cos[c(x-\Delta x)]\right]$$

a	143.034	+/- 80.2691
b	60440.8	+/- 175.643
c	0.0807	+/- 0.00165
Δx	543.838	+/- 0.18656
σ	2.36213	+/- 0.59153

Here *a*, *b*, c, σ, and Δx are free parameters of the fit function;
- *a* is the vertical offset of the distribution with respect to zero.
- *b* is responsible for the amplitude of the distribution;
- c is responsible for the distribution width;
- σ is the smoothing parameter dominantly defined by the beam size;
- Δx is the horizontal offset of the distribution with respect to zero.



Self-Calibration procedure

- In the whole data set find a file with smallest $I_{\min} / I_{\max}$
- Calculate error of the ratio

$$\Delta_{I_{\min}/I_{\max}} = \sqrt{\sum \left({}_{I_{\min}/I_{\max}}' \right)_i^2 \cdot \Delta I_i^2} = \sqrt{\frac{\Delta I_{\min}{}^2}{I_{\max}{}^2} + \frac{I_{\min}{}^2 \cdot \Delta I_{\max}{}^2}{I_{\max}{}^4}}$$

- Re-generate fit curve *f(x)* with errors *Δf(x)* for the calibration file substituting zeros for horizontal and vertical offsets *(a,c)* and σ.

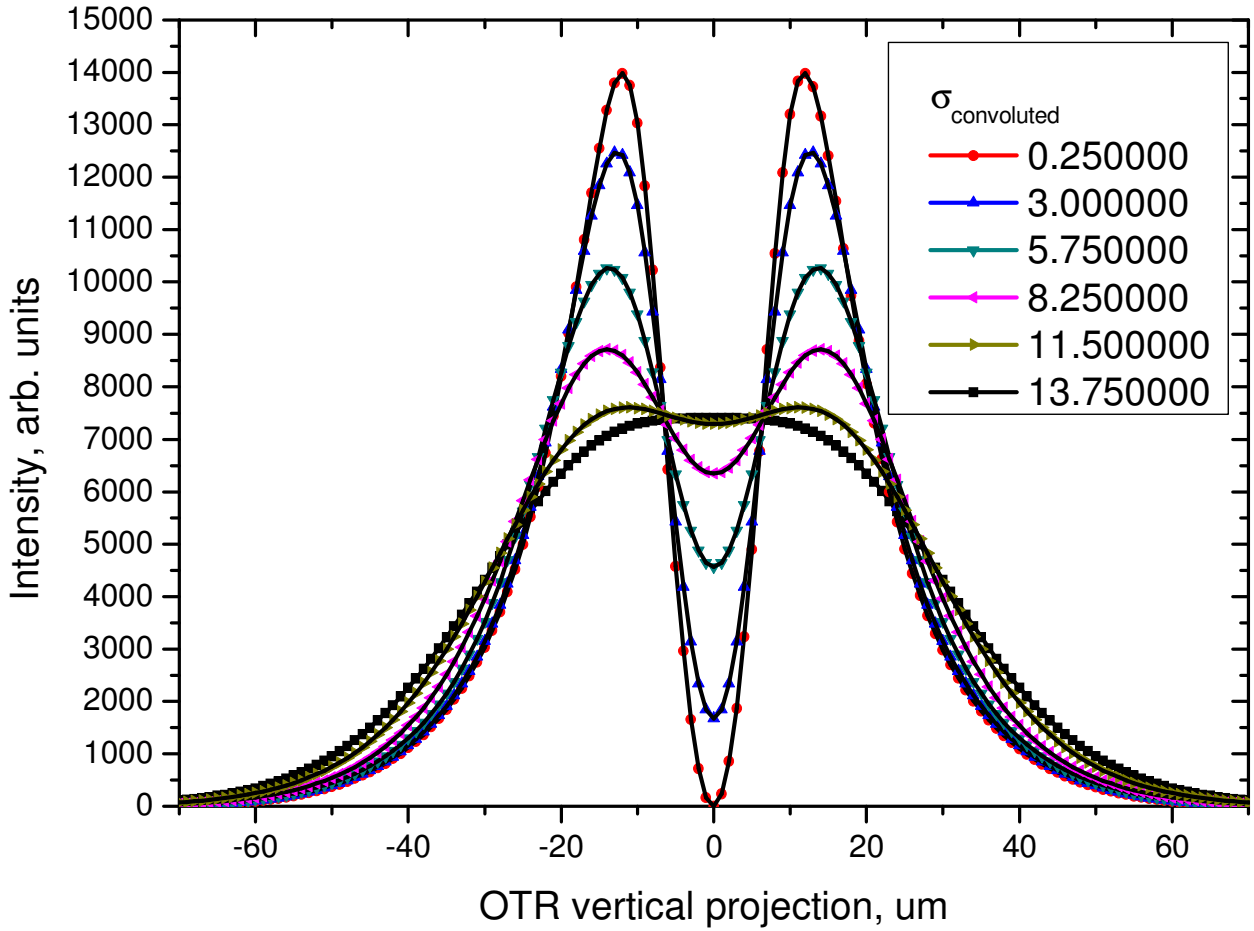
Self-Calibration procedure

- Convolute it with Gaussian as follows:

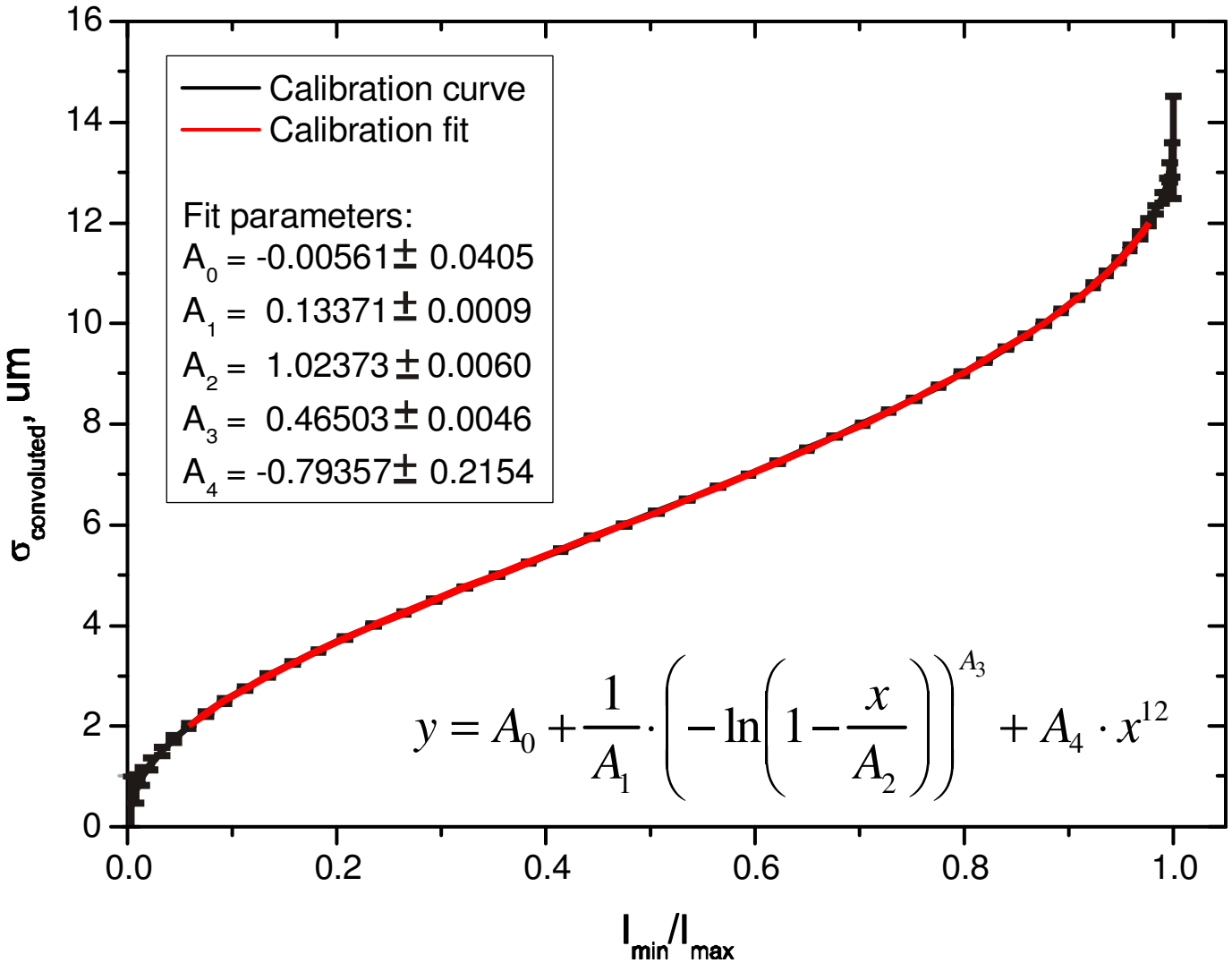
$$F_j^{Convolution} = \frac{\sum_{i=1}^{N} f_i(x_i) \cdot \exp\left(\frac{-(x-x_i)^2}{2\sigma_{conv}^{\ 2}}\right)}{\sum_{i=1}^{N} \exp\left(\frac{-(x-x_i)^2}{2\sigma_{conv}^{\ 2}}\right)}$$

- Propagate errors *Δf(x)* through convolution, repeat convolution *N* times varying σ_{conv} from *0* to *M* with a fine step.
- For each iteration, find $I_{\min} / I_{\max}$ and calculate its errors resulting in calibration curve.

Self-Calibration procedure



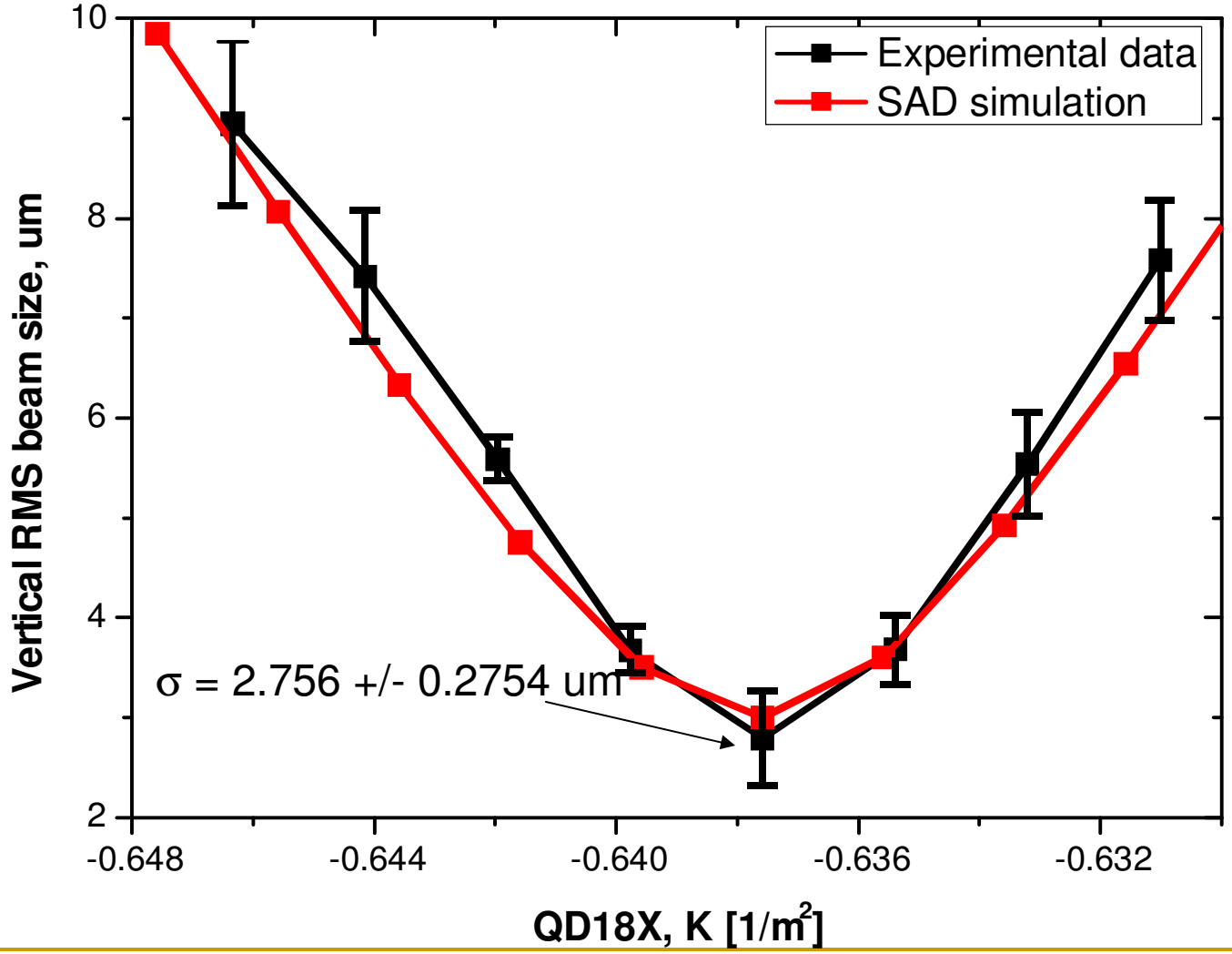
Calibration curve



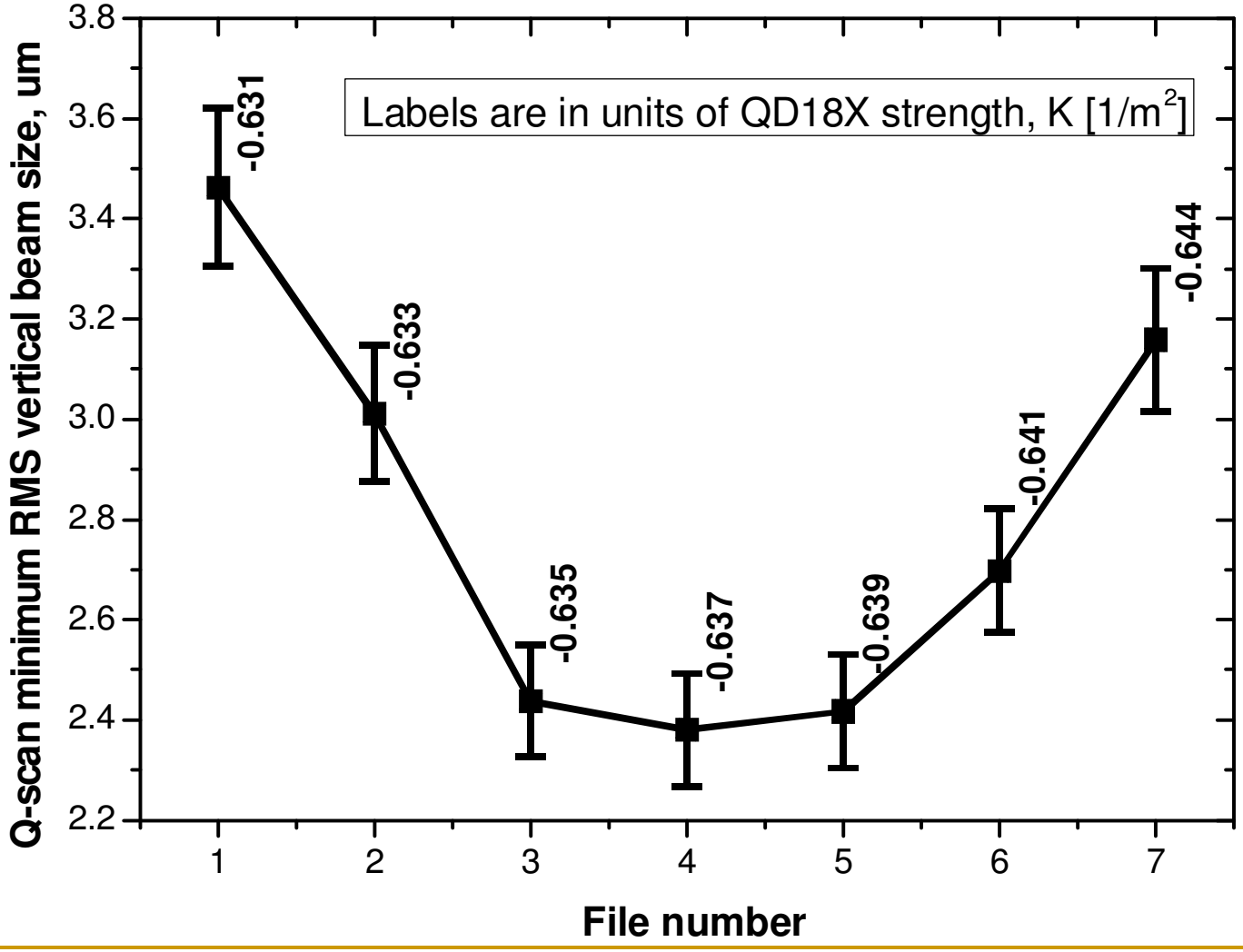
Self-Calibration procedure

- Propagate errors through calibration fit.
- Analyze all files in a data set, extracting $I_{\min} / I_{\max}$ and $\Delta_{I_{\min} / I_{\max}}$ for each file and convert it to real vertical RMS beam sizes using calibration fit parameters and its standard deviations.

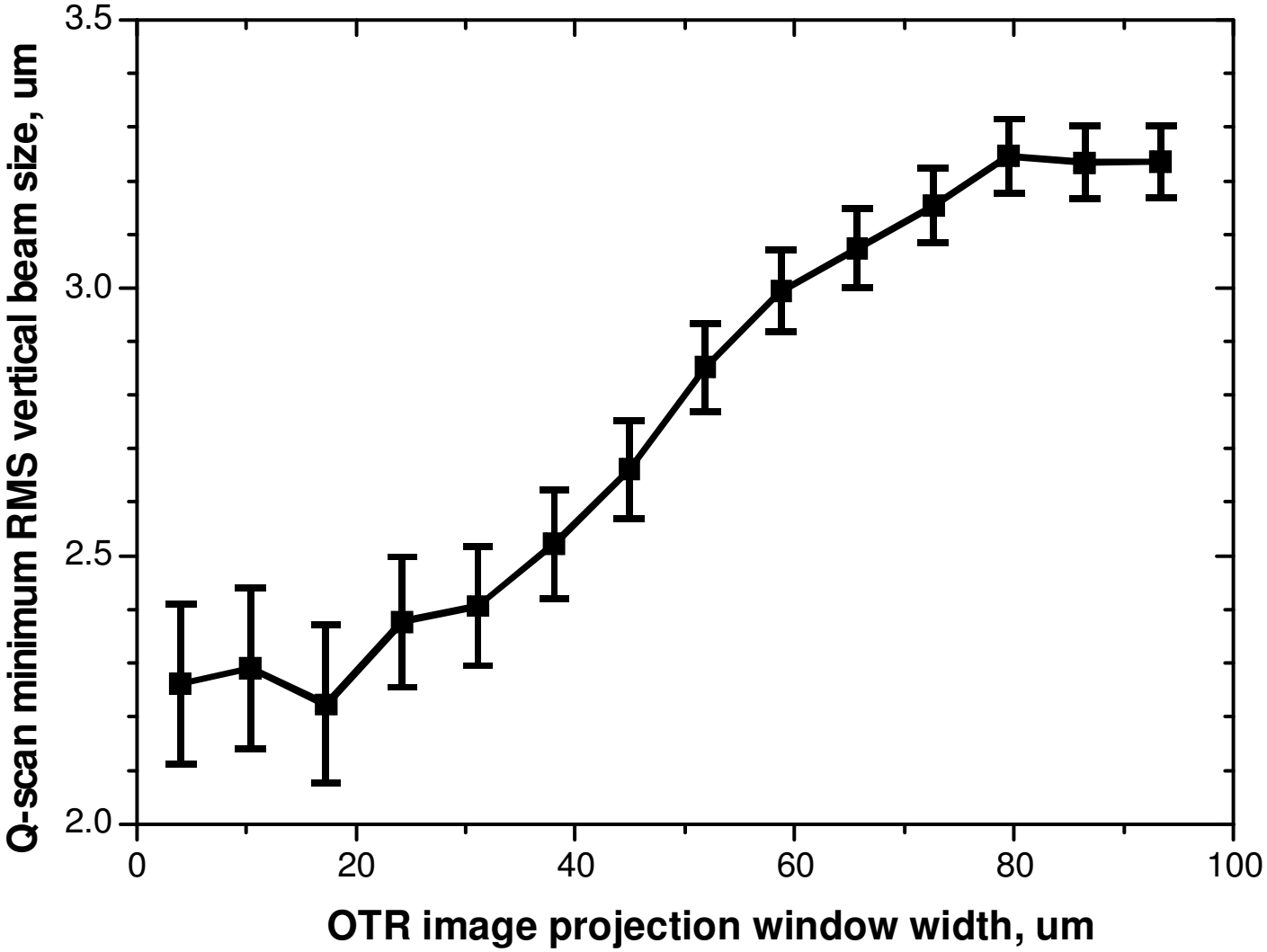
Reconstructed Q-scan



Calibration file variation



Cursors gap variation



Summary

- Results clearly demonstrate that the method based on the analysis of the PSF structure visibility gives an opportunity to measure the beam size with a sub-micrometer resolution.
- In order to improve the beam size measurement technique additional efforts toward the optimization of the optical system, and better understanding of the beam size effect has been taken.
- To be able to demonstrate better resolution achromat lens (to minimize the chromatic aberrations in the optical system) was employed.

Summary

- Also a few more optical filters covering the wavelength range from 350 to 800nm with 50nm step was used to investigate the spectral characteristics of the OTR PSF in details.
- The results will be represented in a successive paper.

Acknowledgements

We would like to thank the ATF extraction line Laser-Wire collaboration for giving us an opportunity to conduct the experiment.

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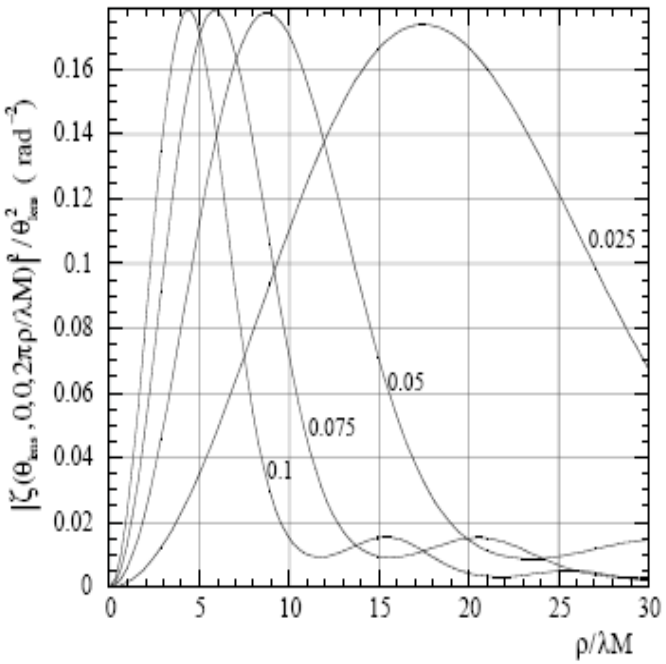
Phenomena leading to PSF distortion

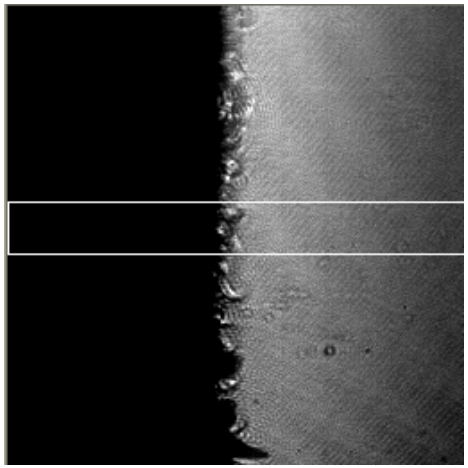
- Diffraction of OTR tails
- Chromatic aberrations
- Spherical aberrations

for instance, M. Castellano and V.A. Verzilov, Phys.Rev. ST-AB 1, 062801 (1998)

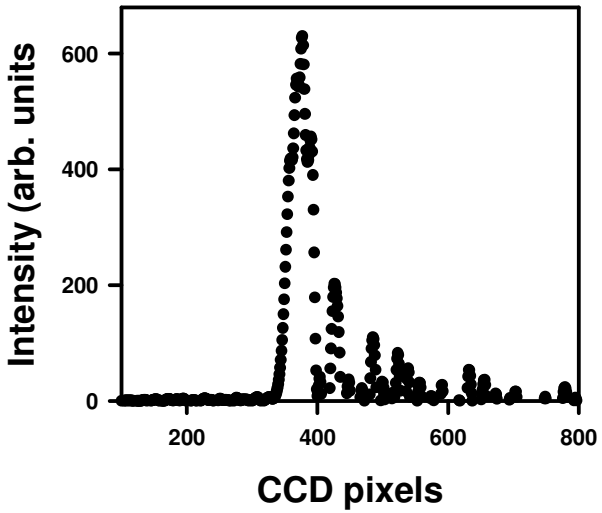


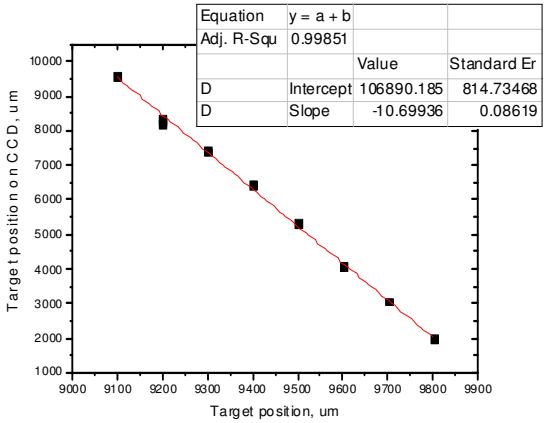
Calibration of the optical system

CCD Image of the target edge



Differentiated slope





Magnification factor of an optical System 10.69

Calibration fit, residual