Laserwire Scanner R&D and Ultra-high Resolution OTR Measurements

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Introduction

- Next generation LC (CLIC, ILC) and also X-Ray FELs require transverse beam size measurements with µm resolution:
- Laser-wire: laser beam scans through the electron beam
  - Non-invasive, can be used online or whenever needed
- OTR: charged particle crosses a boundary between two media with different dielectric properties
  - Widely used for transverse profile measurements
  - OTR monitors: simple, robust and give direct image of 2D beam profile
  - OTR PSF structure: extract beam size with sub-µm resolution
  - Invasive method: degrade beam properties or beam can destroy target → diagnose low intensity pilot beam

Laserwire

- Non-invasive method of measuring transverse size of electron beam:
  - High power laser beam focussed to small size and scanned across the electron beam.
  - Relativistic electron beam → photons are Compton-scattered to high energy and travel nearly parallel to electron beam.
  - Bend downstream separates Compton-scattered photons from the electrons and photons can be detected.
- Resolution of a laserwire limited by wavelength of laser (typically < 1 μm) → greater resolution than conventional wire-scanner (also no damage from electron beam).
- Imperative for measuring low emittance electron and positron beams with high charge densities (ILC, CLIC).

[1] L.J. Nevay et al., Phys. Rev. ST Accel. Beams 17, 072802 (2014)

LW@ATF2

- Located at ATF2 final focus section: strong, closely-spaced matching quadrupoles provide a vertical electron beam size of ~1 μm.
- Seeded Q-switched Nd:YAG laser with frequency-doubled output:
  - ~150 mJ
  - 532 nm
  - 3.25 Hz (Bunch repetition rate @1.3 GeV)
  - Laser: σ_τ = 77 ps (Electron bunches: σ_τ = 30 ps)
- Laser is located outside the accelerator enclosure and laser beam is transported to laserwire interaction point (LWIP) via series of mirrors.

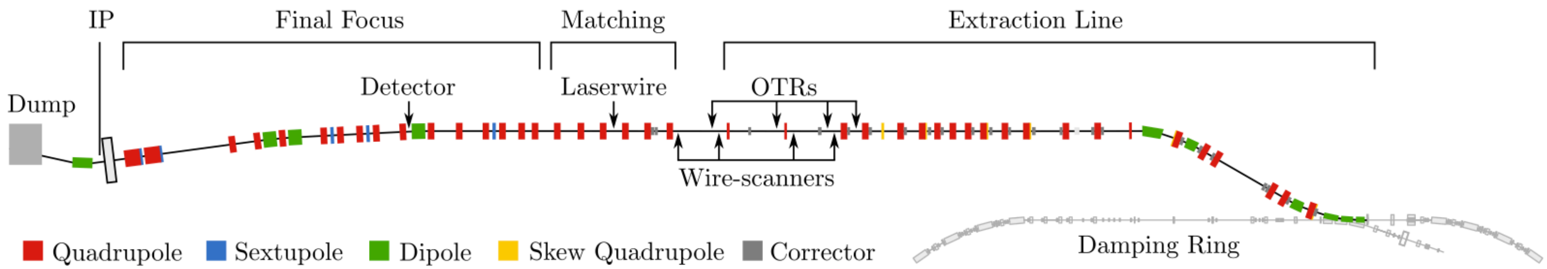


FIG. 1. Schematic of the ATF2 extraction line showing the location of the laserwire system as well as the detector located immediately behind the first dipole magnet after the laserwire interaction point. The wire scanners and OTR monitors are also shown at the end of the extraction line section. All quadrupoles and sextupoles in the matching and final focus sections are on individual three-axis mover systems.

LW@ATF2 (2)

- Compton-scattered photons detected ~10 m downstream immediately after dipole magnet.
  - Detector: 4 × 4 × 0.6 cm lead plate attached to aerogel scintillator of the same size and finally a shielded photo-multiplier tube.
  - DAQ: synchronously record data from the laserwire experiment, cavity BPM system and ATF2 diagnostics (EPICS).
- Performing scans: vacuum chamber moved on a two-axis mover system (LW lens mounted to chamber → laser focus moves with chamber).

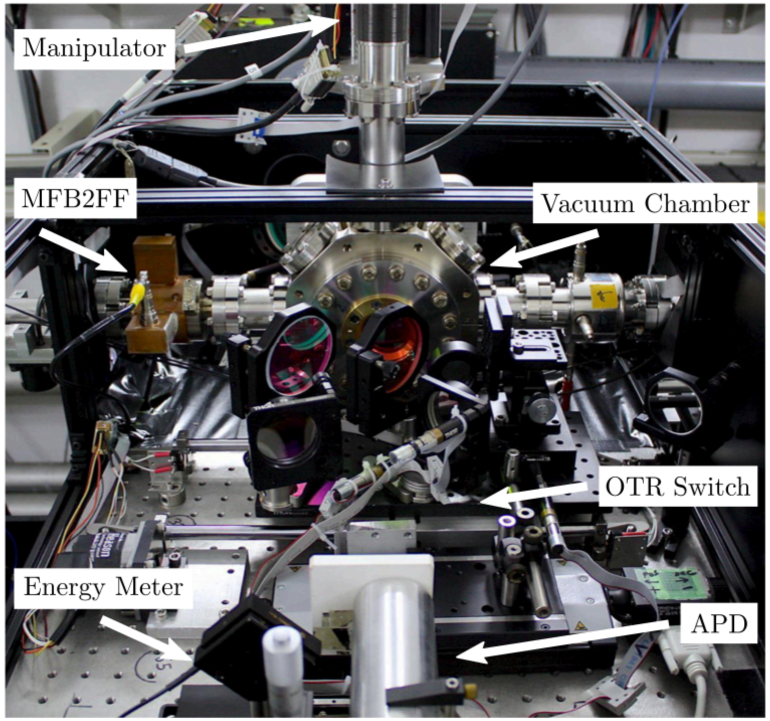


FIG. 2. Photograph of the laserwire installation in the ATF2 beam line. The electron beam travels from right to left and the laser beam enters behind the vacuum chamber and exits towards the reader. The manipulator for the OTR and alignment screen can be seen on top of the vacuum chamber. The avalanche photodiode (APD) used for timing and the laser pulse energy meter can be seen in the foreground. The high resolution CBPM MFB2FF is also shown attached to the laserwire vacuum chamber. The small optical breadboard (OTR switch) allows one to switch between the high power laser path for laserwire and the low intensity OTR path.

LW@ATF2 (3)

- Laser pulses and electron bunches were synchronised using OTR-screen on 4-axis manipulator arm inside the vacuum chamber
  - Screen is lowered into the electron beam with laser beam directed below it
  - OTR and attenuated laser light simultaneously detected in photodiode.
  - Timing of laser system adjusted with respect to the electron bunches until both overlap
  - Edge of OTR screen used to align laser focus spatially → moving the chamber (therefore focus and OTR screen together) away from referenced focus position until bremsstrahlung produced by OTR screen falls to half its maximum value.
  - Laser machined notch in OTR screen allows horizontal alignment by observing the minimum in bremsstrahlung as the electron beam passes through the notch.

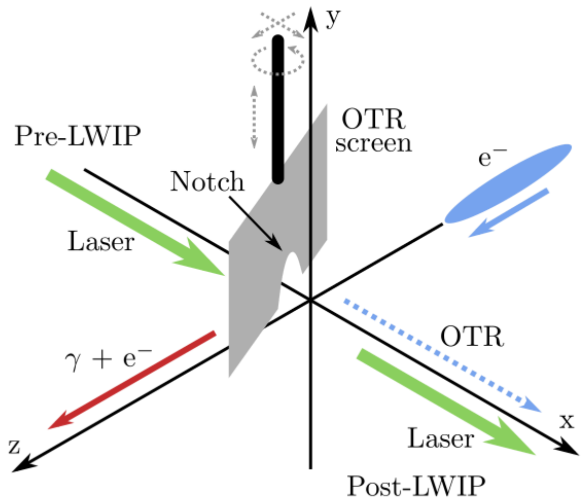


FIG. 6. Schematic of the beam geometry at the laserwire interaction point, including the OTR screen at 45° to the electron beam direction, incoming electron bunch, outgoing electron bunch, OTR path, laser beam path, and Compton-scattered photons (γ).

- With laser aligned to the electron beam → collisions are immediately detectable.
- Alignment subsequently optimised by performing successive horizontal, vertical and timing scans to maximise Compton signal.

Analysis

- LW scan: convolution of laser and electron beam distributions
- Knowing laser beam → LW scan can be de-convolved to get electron beam width.
- Difference between wire-scanner and LW: laser beam width varies throughout its focus.
- Rayleigh range: length scale over which laser changes significantly (distance from focus until the laser waist expands from its minimum at σ_0 by √2)

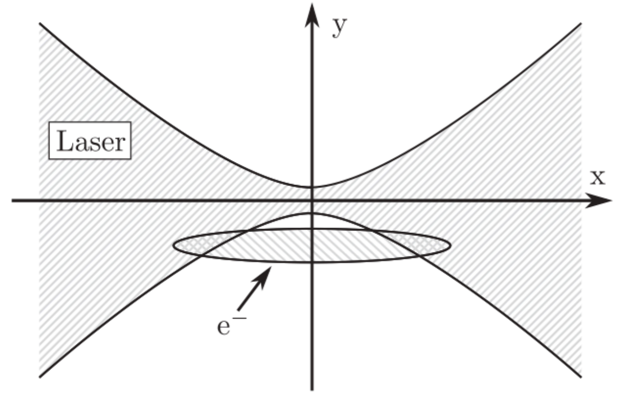


FIG. 5. Schematic of the laser focus showing its interaction with the high aspect ratio electron beam even when the laser focus is displaced from the electron beam. The vertical axis is expanded in scale compared to the horizontal axis to make the overlap clearer.

- If electron beam width is much less than Rayleigh range, laser beam width is effectively constant across the electron beam → vertical scan is the simple convolution of vertical laser photon and electron distributions - typically both Gaussian.
- BUT if the electron beam has high aspect ratio: even when laser focus is displaced from the electron beam, the divergent laser beam away from the focus continues to interact with the electron beam → non-Gaussian scan shape with wings away from centre.
- Laser propagation is measured and used with horizontal electron beam size to analyse vertical LW scans.

Laser propagation

- Precise measurement of µm-size focussed laser spot impossible with commercially available diagnostics
- Scaled focus generated at virtual LWIP: duplicate of the input laser beam to the LW lens but with sufficient space for laser diagnostics
- High resolution CCD laser beam profiler can then be used →asymmetrical laser propagation with two orthogonal axes of propagation rotated with respect to lab frame.
- M^2 model describes measured laser propagation in comparison to that of a laser beam with a perfect Gaussian transverse intensity distribution.

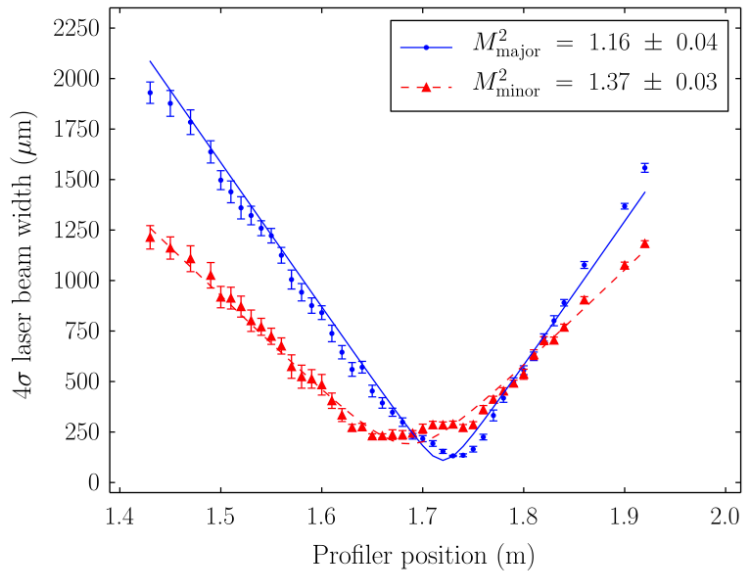


FIG. 10. Measured 4σ widths of the laser beam through the focus created with a $f = 1.677$ m lens. The M^2 model is shown for each intrinsic axis of the laser propagation, which were found to be rotated to the extrinsic lab axes by $-17.4°$.

- For given input laser beam size to a lens, the focussed spot size is factor M^2 bigger ($M^2 \geq 1$).

$$\sigma(x) = \sigma_o \sqrt{1 + \left(\frac{(x - \Delta_x - x_{\sigma o})\lambda M^2}{4\pi\sigma_o^2} \right)^2}$$

- The two laser propagation axes are combined to calculate the relevant vertical projection in the lab frame

$$\sigma_l = \sqrt{(\sigma_{horizontal}\ \sin\theta)^2 + (\sigma_{vertical}\ \cos\theta)^2}$$

Centering the beam

- For accurate de-convolution of vertical LW scans: horizontal size & horizontal offset of laser focus from the electron beam must be known
- To measure this, horizontal scan was performed in addition to vertical scan.
- Horizontal scan shape and size vary with vertical offset of laser focus to electron beam → small vertical scan with low sampling provides vertical centering before performing detailed horizontal scan.
- After this, laser focus was centred horizontally and detailed vertical LW scan performed.
- Gaussian model is used to fit initial scan: not accurate but sufficient to achieve desired centering

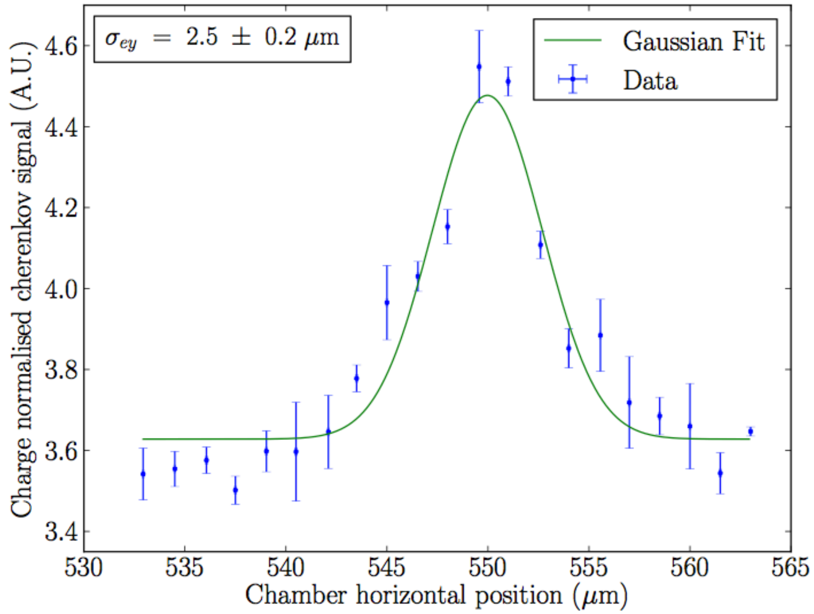


Figure 4: Initial vertical laserwire scan for centering purposes fitted to a Gaussian model.

Combined analysis

- Divergent laser beam continues to interact with electron beam even when laser focus is displaced → vertical LW scans must cover scan range significantly greater than vertical size of the electron beam for accurate fitting.
- Necessary long range BUT central part of scan contains very narrow peak → sufficient sampling for precise scan → non-linear step sizes for accurate LW scans in minimum time possible.
- Previous LW operations: Gaussian model to fit the horizontal LW scans.

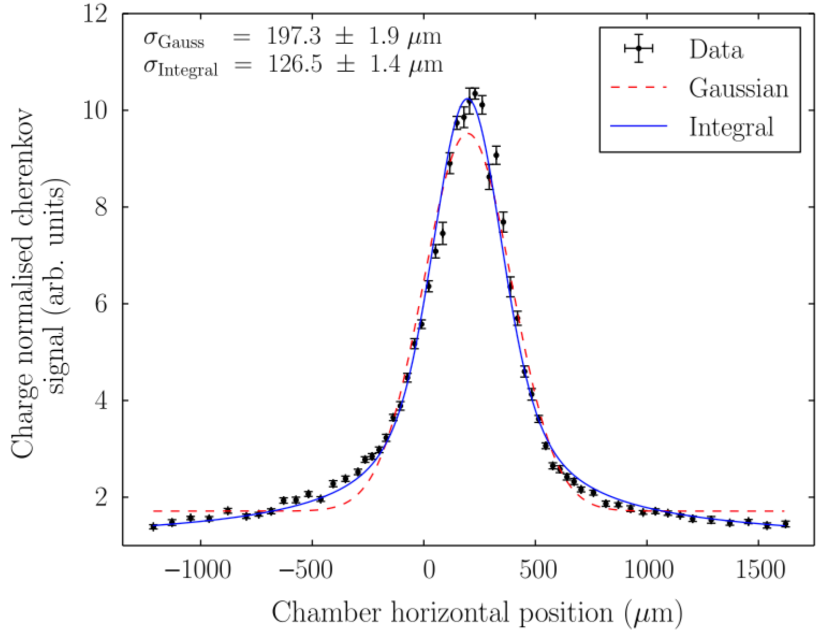


FIG. 18. Comparison of Gaussian and overlap integral models for the horizontal laserwire scan.

- Horizontal scan is convolution of laser intensity along its propagation axis with Gaussian electron distribution.
- Initial assumption: Rayleigh range is significantly less than electron beam width → convolution is dominated by Gaussian electron beam → fitted sigma will be accurate to < 2 %
- Gaussian model does not depend on the vertical electron beam size → simplifies de-convolution of vertical LW scans considerably.

Smallest vertical beam

- To de-convolve horizontal scan, vertical electron beam size must be known and vice versa → circular problem: scans were fitted iteratively together until convergence was reached.
- The measured horizontal electron beam size was 119.0 ± 2.4(stat) ± 0.01(sys) μm and the vertical beam size was 1.07 ± 0.06(stat) ± 0.01(sys) μm.

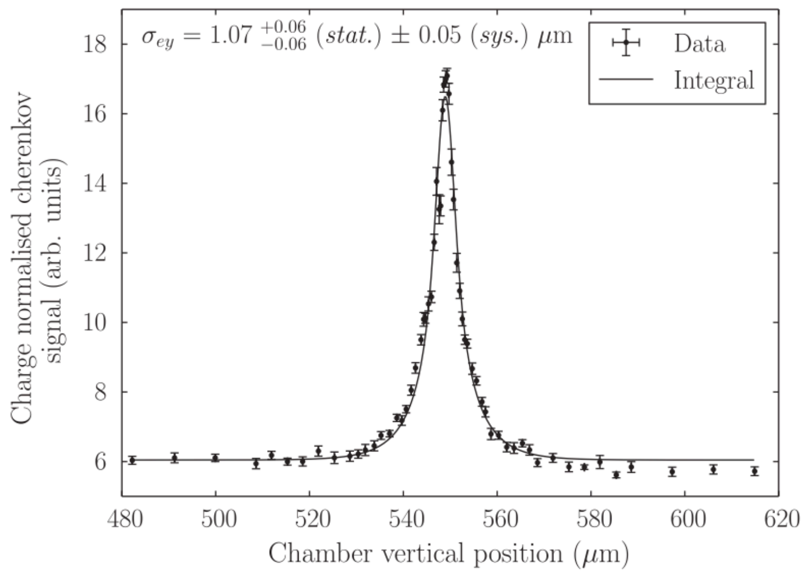


FIG. 19. Nonlinear step size laserwire scan with the smallest measured electron beam size.

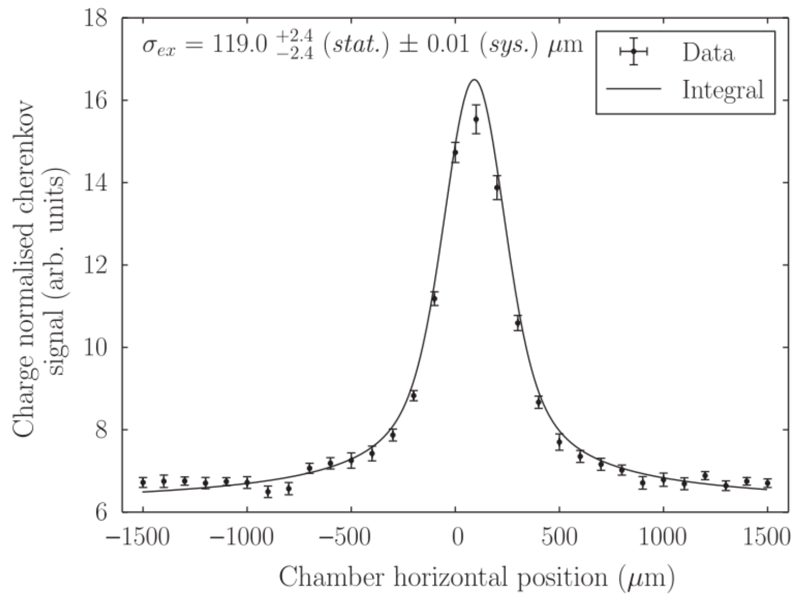
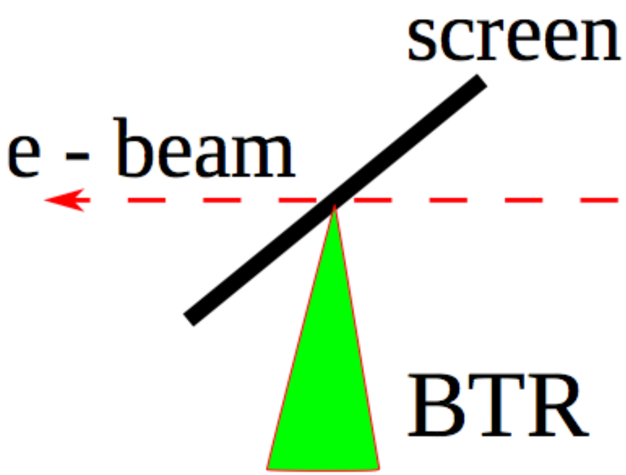
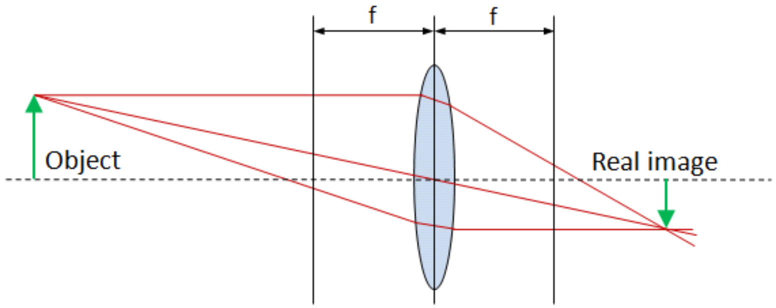


FIG. 20. The corresponding horizontal laserwire scan for the smallest vertical scan, which was required for the combined analysis.

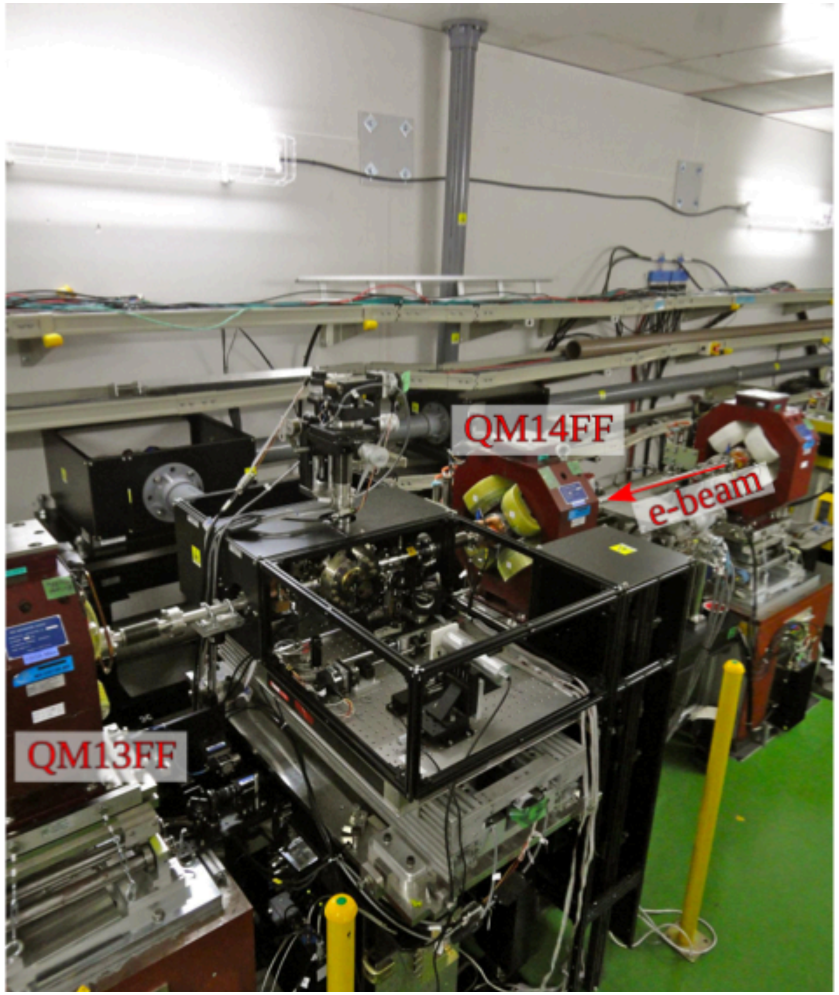
OTR: introduction



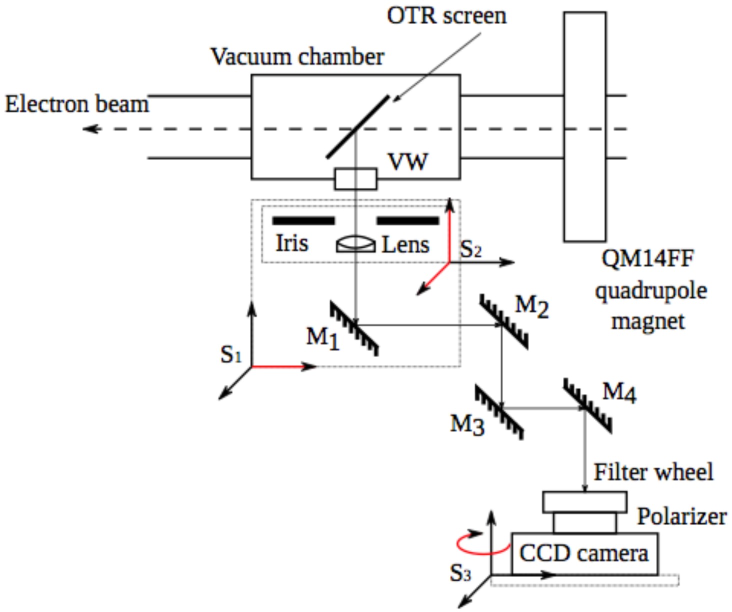


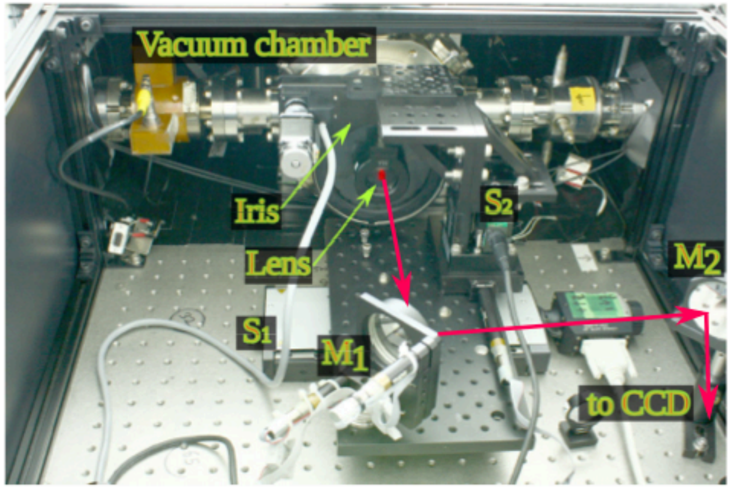
- Transition radiation (TR) appears when a charged particle crosses a boundary between two media with different dielectric constants.
- The resolution is determined by the source dimensions induced by a single particle plus distortion caused by the optical system (diffraction of OTR tails) → root-mean-square of the so-called point spread function (PSF).
- The OTR PSF has a structure itself which can be used to extract the beam size with sub-µm resolution resolution.
- To study the PSF, the simulated detector plane has to be in the image plane of a lens.

ATF2 Extraction Line



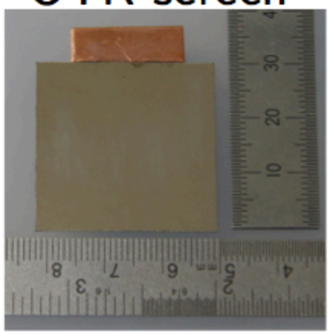
Experimental setup





- Lens - "CVI Laser Optics" cemented achromat, f=120mm, ø=30mm
- CCD Camera - SBIG-ST8300M with 5.4 μm pixel size, 3352×2532 pixel array and ~50% quantum efficiency

OTR screen



0.3×30×30 mm aluminized silicon

[2] K. Kruchinin et al., J. Phys.: Conf. Ser. 517, 012011 (2014)

OTR image

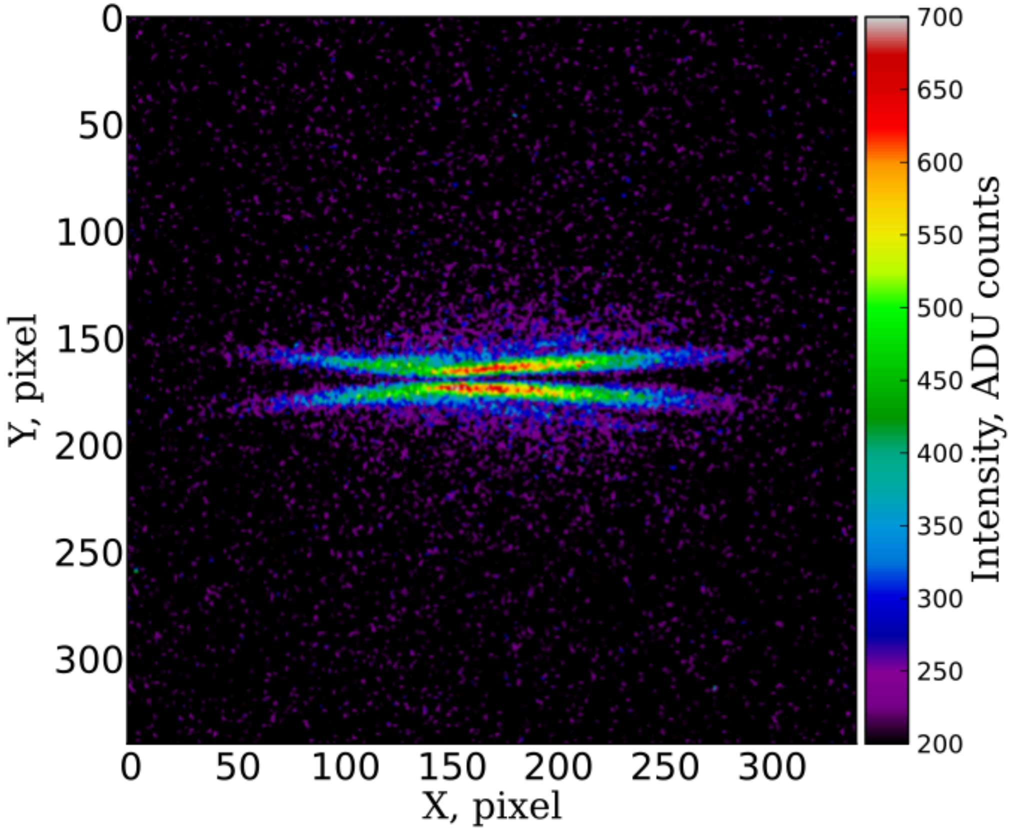
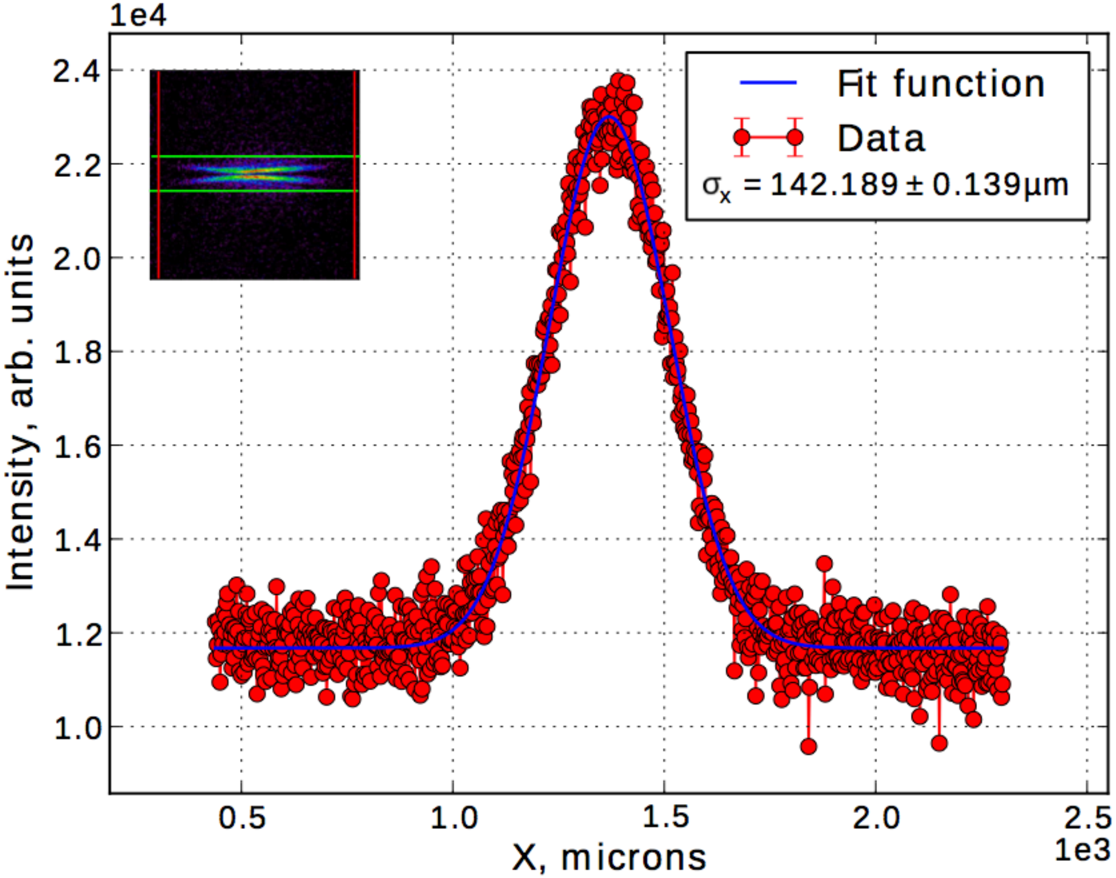
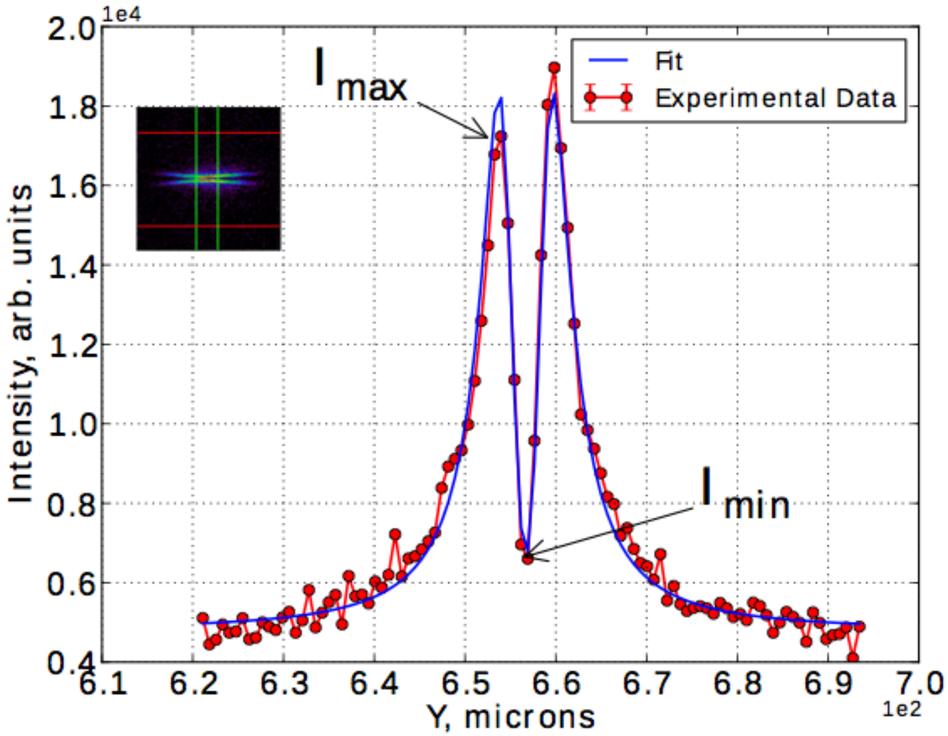


Image of the OTR spot taken with a linear polariser and an 550±20 nm optical filter

Horizontal projection



Vertical projection



PSF-like fit function:

$$f(x) = a_0 + \frac{a_1\left(a_4 + (x - a_3)^2\right)}{1 + (a_2 (x - a_3))^4}$$

Fit parameters:

- a_0 is the vertical offset of the distribution with respect to zero
- a_1 is the amplitude of the distribution
- a_2 is the smoothing parameter
- a_3 is the horizontal offset of the distribution with respect to zero
- a_4 is the distribution width

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Analytical calculation of:

- Minimum to maximum ratio
- Distance between peaks
- Simpler expressions for error calculation

$$I_{min}/I_{max} = \frac{2a_2^2 a_4}{a_2^2 a_4 + \sqrt{1 + a_2^4 a_2^2}}$$

$$\frac{2\sqrt{-a_2^2 a_4 + \sqrt{1 + a_2^4 a_2^2}}}{a_2}$$

Self-calibration procedure

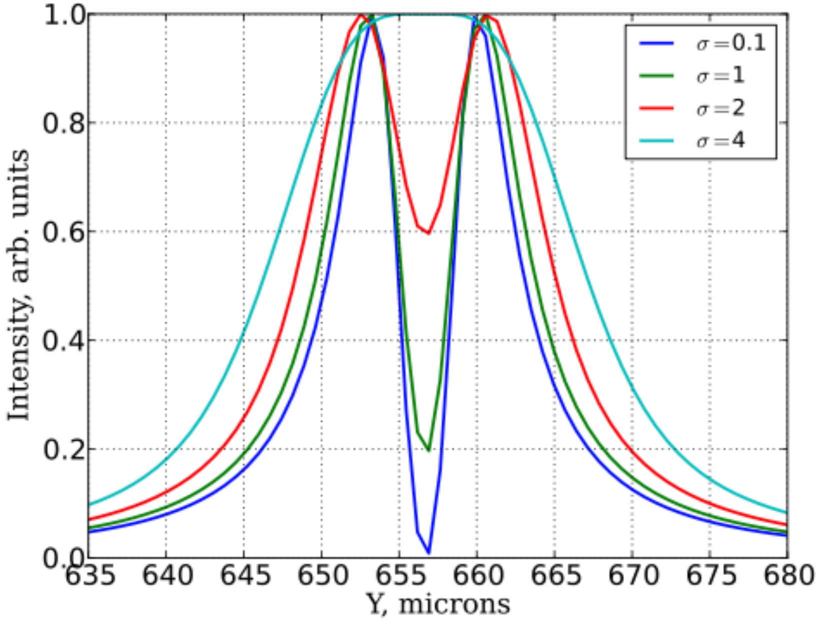
- In whole data set find file with smallest I_{min}/I_{max}
- Generate fit curve *f(x)* with errors for the calibration file, substituting zeros for vertical offset a_0 and smoothing parameter a_4
- Convolute fit with Gaussian distribution as follows:

$$F(x_j) = \frac{\sum_{i=1}^{N} f(x_i) \exp\left(-\frac{(x_j - x_i)^2}{2\sigma^2}\right)}{\sum_{i=1}^{N} \exp\left(-\frac{(x_j - x_i)^2}{2\sigma^2}\right)}$$

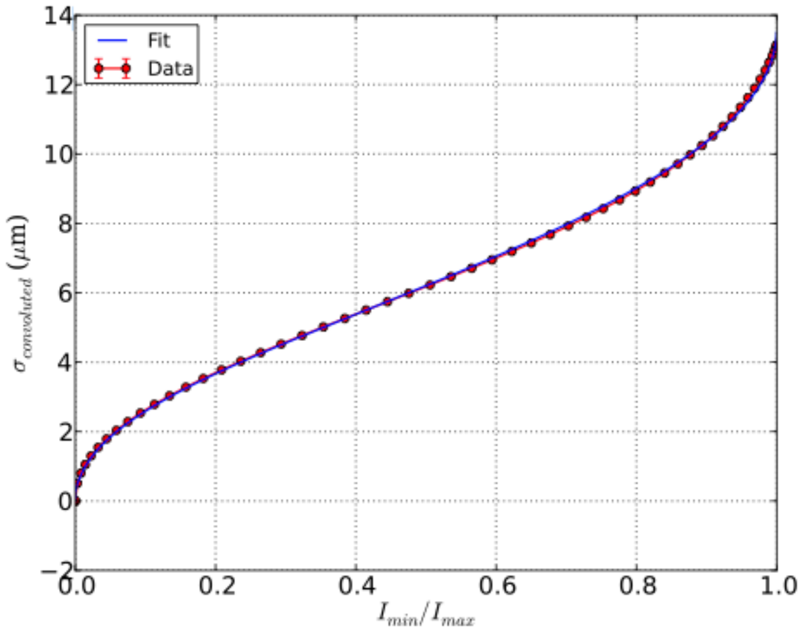
- Propagate errors into convolution.
- Repeat convolution N times varying σ from 0 to σ_m with a fine step.
- For each iteration, compute I_{min}/I_{max} and calculate its errors resulting in calibration curve

Self-calibration procedure (2)

Beam size effect



Calibration curve

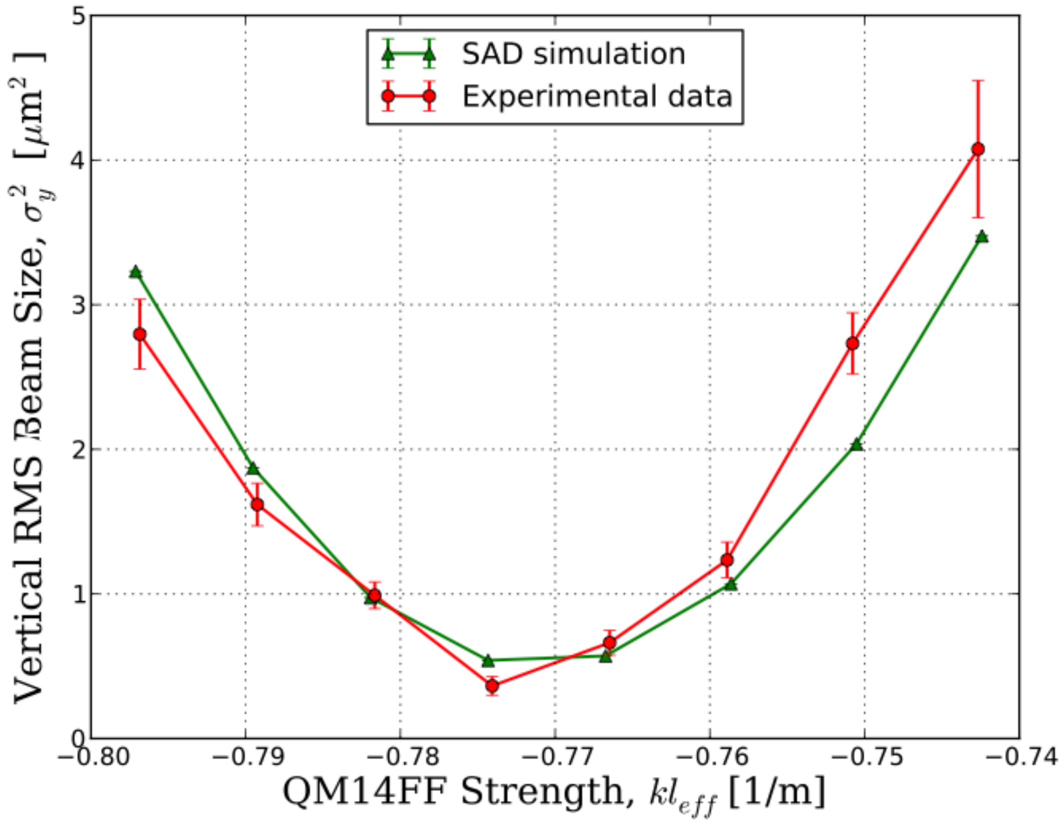


Fit function:

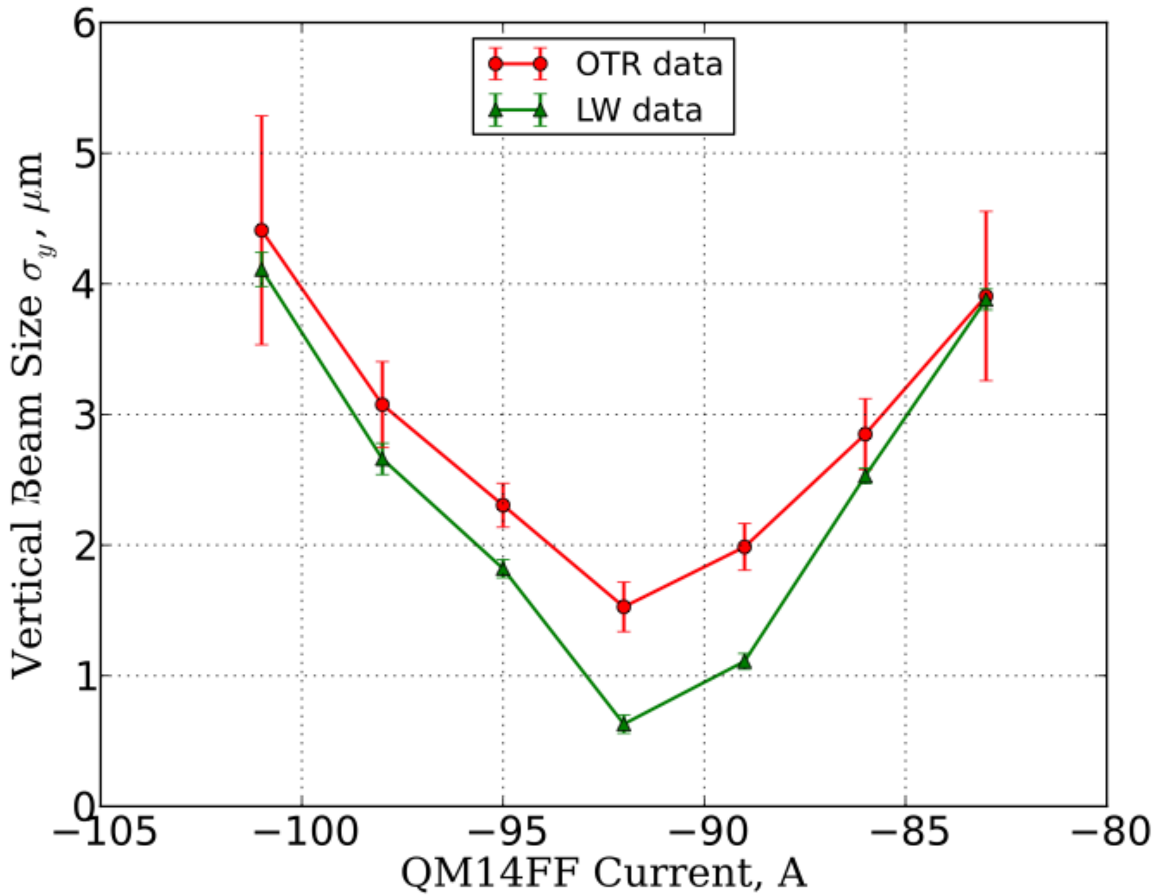
$$f(x) = a_0 + \frac{1}{a_1}\left(-\ln\left(1-\frac{x}{a_2}\right)\right)^{a_3} + a_4 x^{12}$$

Best quadrupole scan

Minimum measured beam size was: 0.754±0.034 μm

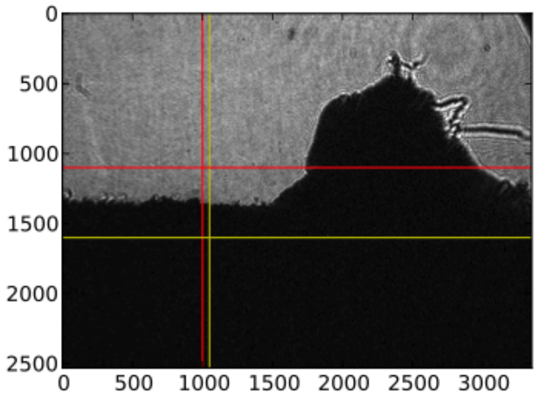


LW and OTR Comparison

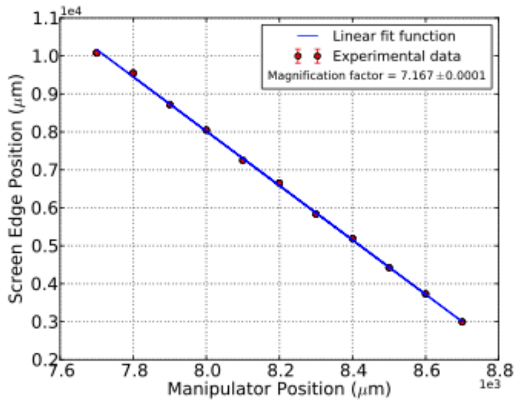


Calibration of the optical system

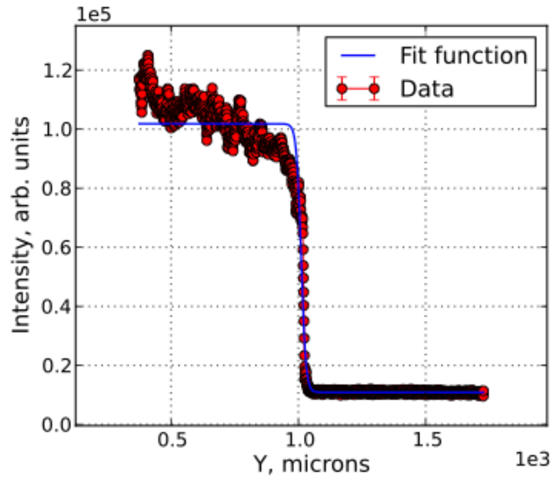
Image of the OTR screen



Calibration curve



Vertical projection

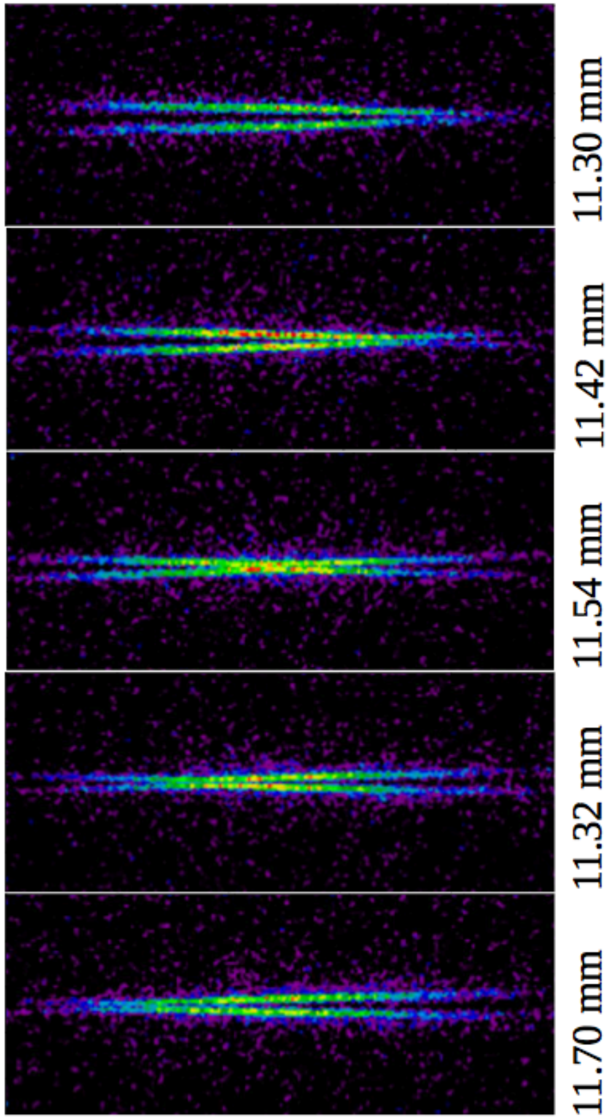


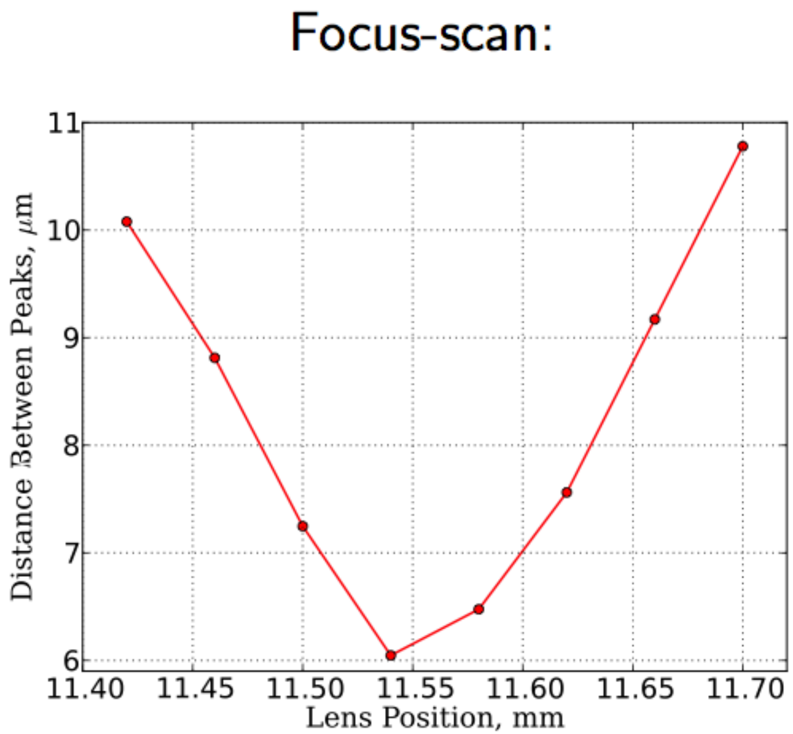
Fit function:

$$f(x) = a_0 + \frac{a_1}{1 + \exp\left(\frac{x - a_3}{a_2}\right)}$$

Measured magnification factor of the system: 7.17

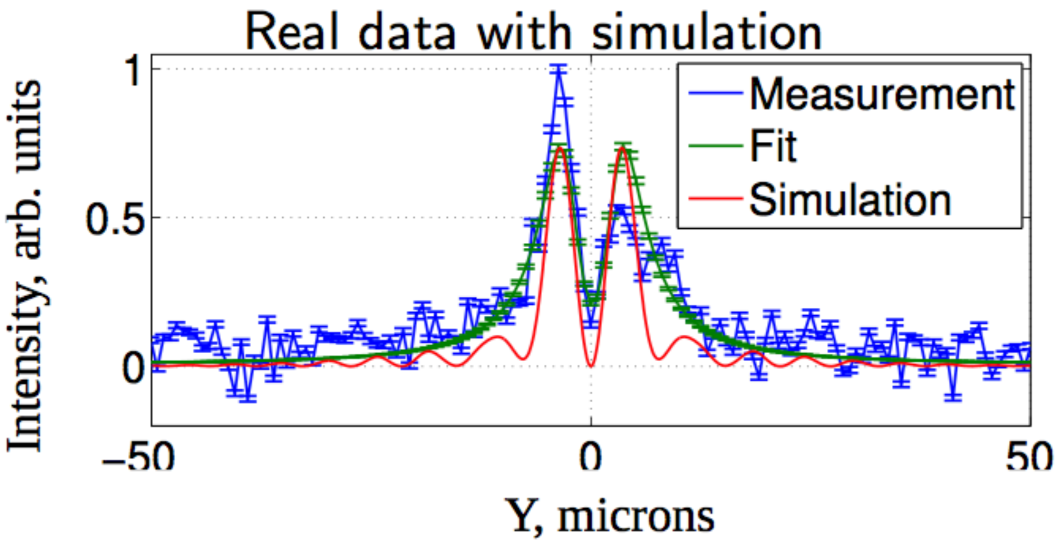
Focusing


11.30 mm
11.42 mm
11.54 mm
11.32 mm
11.70 mm

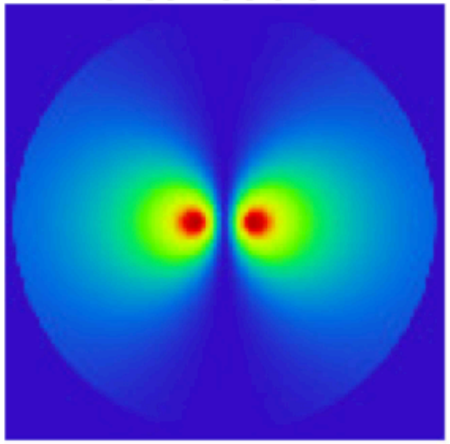

Focus-scan:
Distance Between Peaks, μm
Lens Position, mm
11
10
9
8
7
6
11.40
11.45
11.50
11.55
11.60
11.65
11.70

Zemax simulations

- Zemax "Physical Optics Propagation" simulations: Propagation of the OTR source using diffraction laws (near field conditions) through real commercial lenses
- PSF simulation: Propagation of vertically polarized electric field for a single electron



Simulated 3D OTR distribution



[3] T. Aumeyr et al., PR-STAB, accepted to be published
[4] B. Bolzon et al., PR-STAB, currently under revision

Future improvements

- Using simulation tools such as ZEMAX in order to better understand the PSF behavior and optimize the optical system
- Apply multi-element or reflective optics in order to reduce the resolution even further
- Upgrade experimental hardware (CCD camera, DAQ)
- Efforts towards automation (shot by shot beam size measurements)

Summary

- Simultaneous fitting of the data from the horizontal and vertical LW scans using the overlap integral model
- LW was successfully operated with a low electron bunch population of 0.2×10^{10} e^- and will easily scale to 2×10^{10} e^-
- Collected data shows a good progress in optimisation of PSF-like OTR monitor system
- Optimisation of the optical system and beam size studies have been performed for the OTR monitor
- Work on analysis and simulations shows good agreement with experimental data.

Thank you for your attention!

Any questions?