Report on DR and ChDR studies at ATF2 during 2018

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ATF2 Project Meeting 2018, KEK, 20th November 2018

1. CERN European Organisation for Nuclear Research, Geneva, Switzerland
2. John Adams Institute at Royal Holloway, Egham, United Kingdom
3. KEK High Energy Accelerator Research Organization, Tsukuba, Japan
4. National Research Tomsk Polytechnic University, Russia

Outline

- Last results from Diffraction Radiation (DR) experiment during 2018 at ATF2
- Summary of DR Studies at ATF2
- Description of Cherenkov Diffraction Radiation (ChDr)
- ChDR experiment at ATF2 during 2018
- Summary and outlook of ChDR at ATF2

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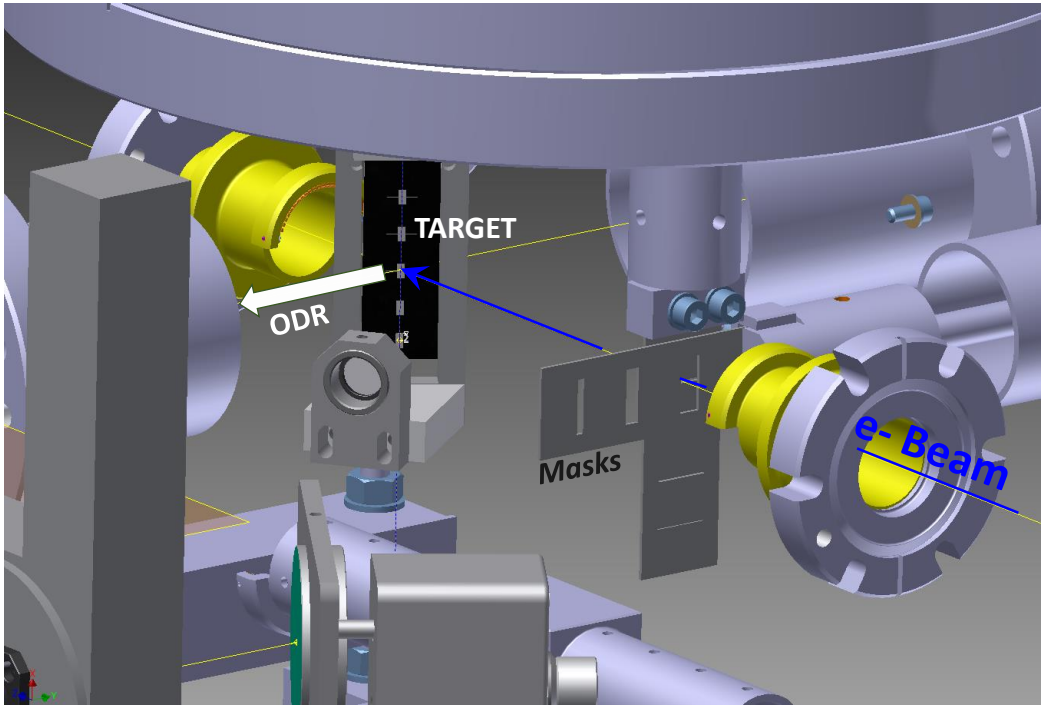
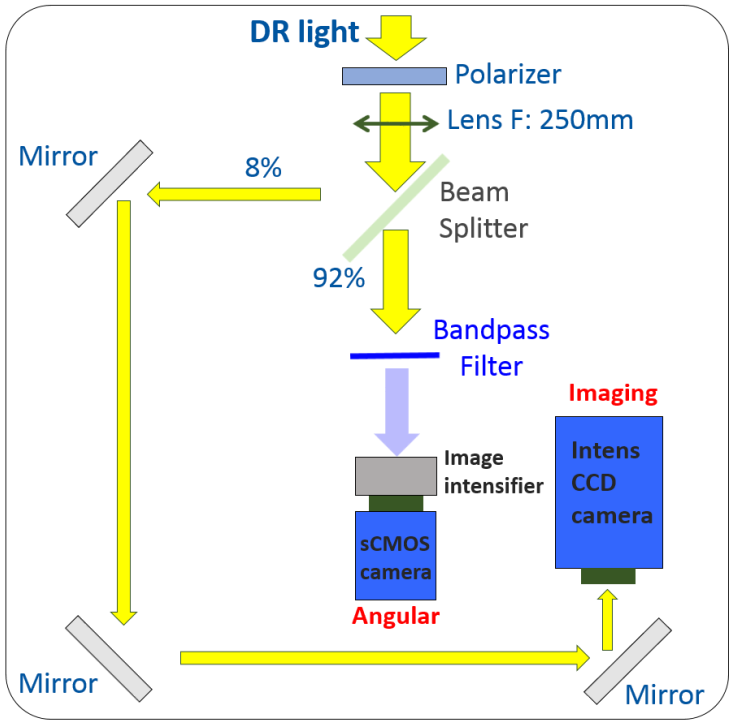
DR experiment at ATF2

- The **target** has **4 slits for DR (50 to 201 µm)**
- A couple of vertical and horizontal **mask slits** can be inserted 13 cm upstream the target

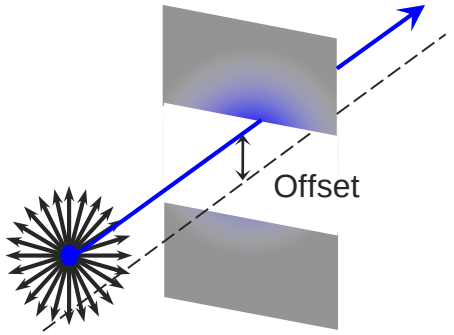


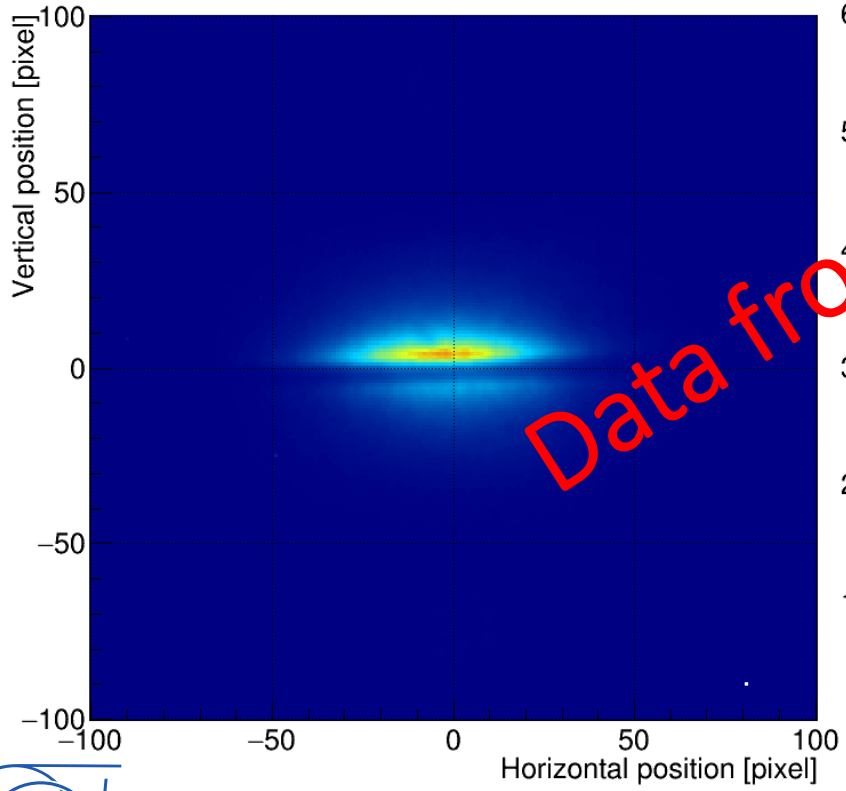


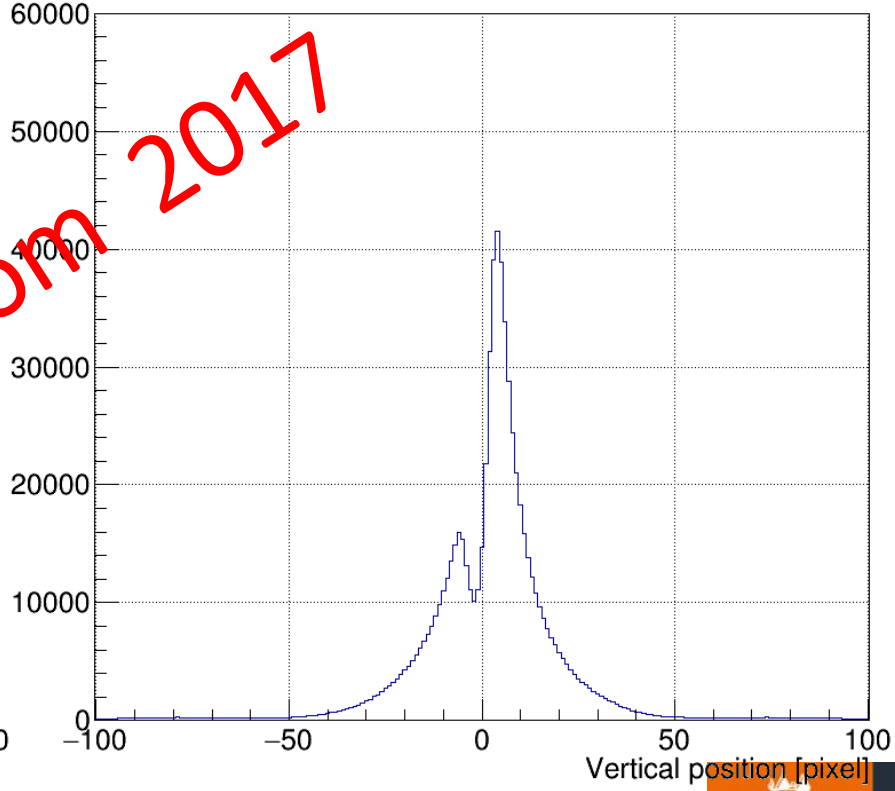
Synchronous Imaging and Angular acquisition for position filtering in angular

DR in imaging

There is **no visible beam size dependency** of the pattern in **imaging**.
But the **vertical position** into the slit changes the profile **asymmetry** => **Optical Beam Position Monitor (BPM)**

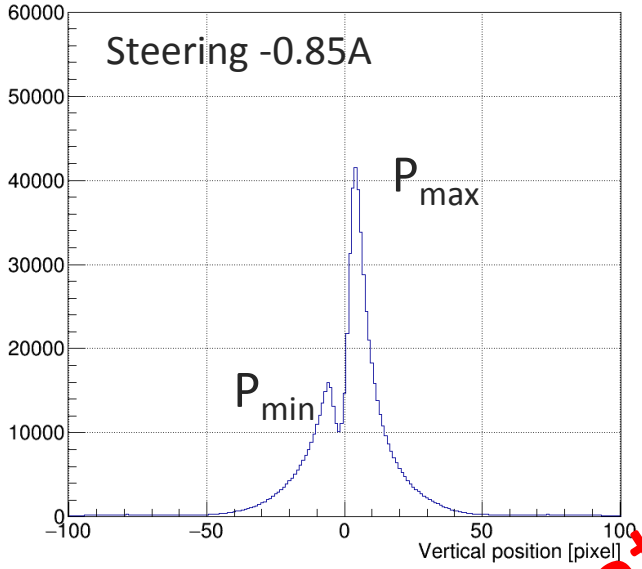






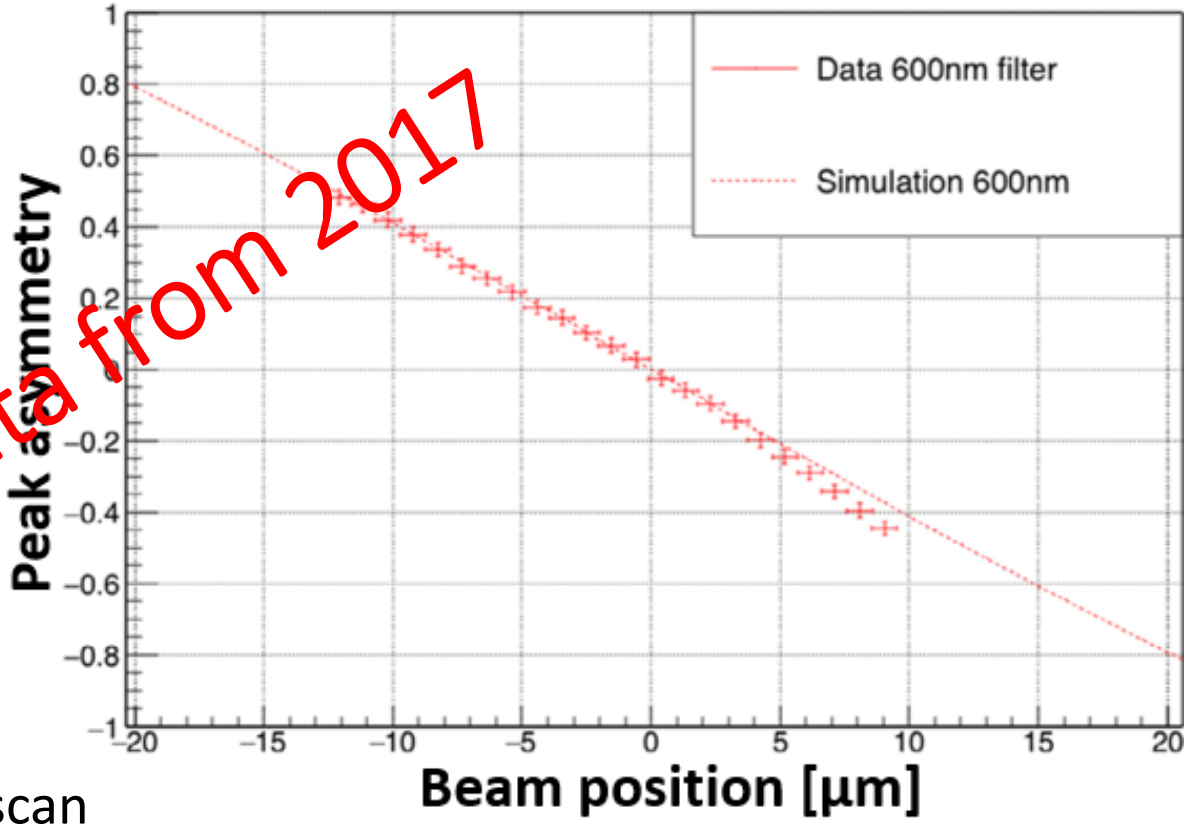
Data from 2017

DR imaging as an optical BPM



- Slit: **50 µm**
- Beam size: **1 µm**
- 30 shots statistics
- **Position resolution: about 1 µm**
- Steering magnet to scan the beam inside the slit

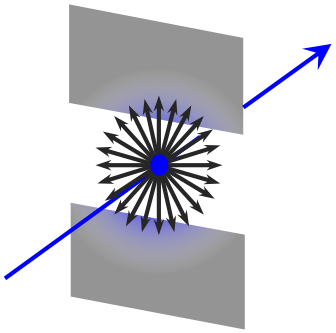
Asymmetry = $(P_{min}-P_{max})/(P_{max}+P_{min})$

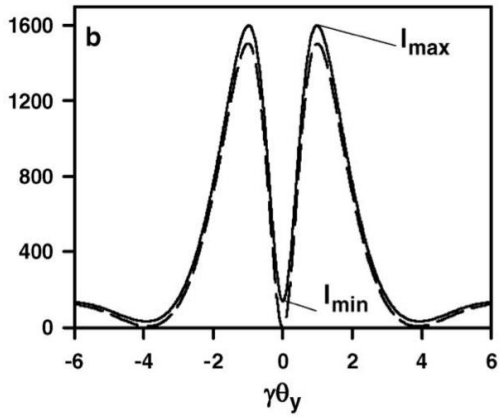


Data from 2017

ODR for beam size measurements

The **beam size** is extracted from the **visibility I_{min}/I_{max}** of the projected vertical component of the ODR **angular distribution**

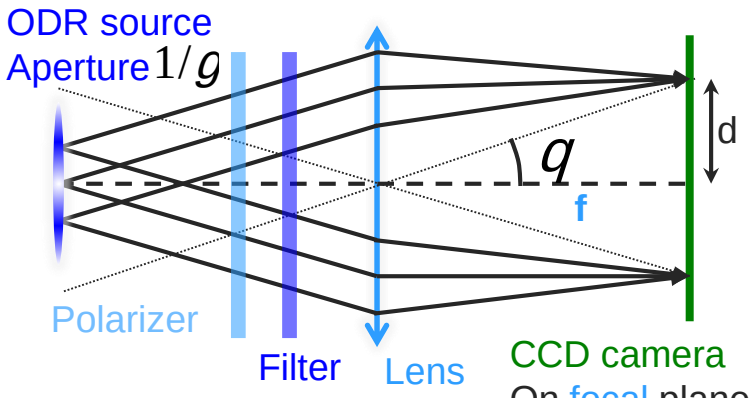




An **horizontal slit** is used to measure a **vertical beam size**.

We use a polarizer to select only the **vertically polarized ODR photons** and 40nm BW **filters** to select the **wavelength**

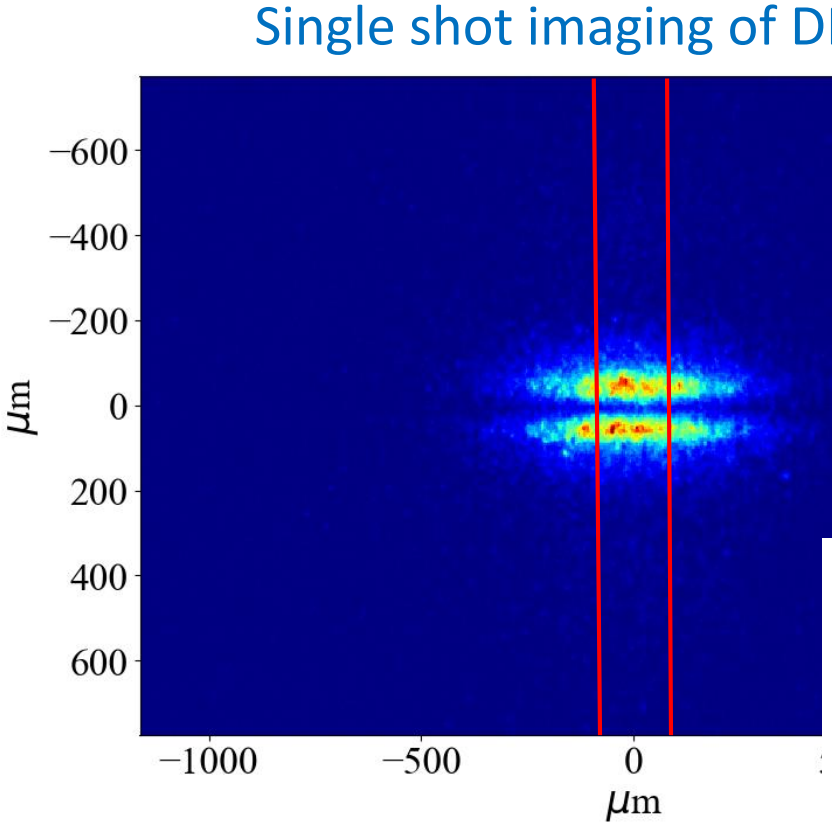
The **angular distribution** is obtained using a camera located at the back focal plane of an optical **lens** (effective infinity)

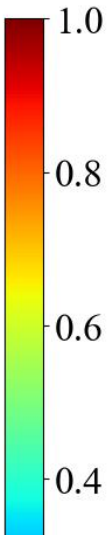


Angular magnification $q = \arctan(d/f)$

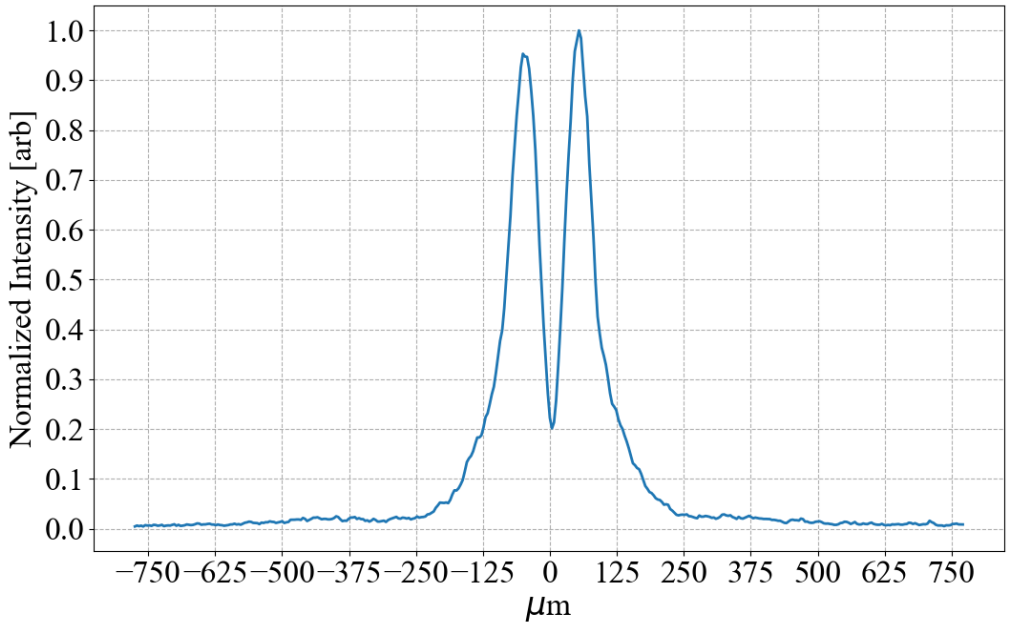
March 2018/November 2017 data

Single shot imaging of DR slit

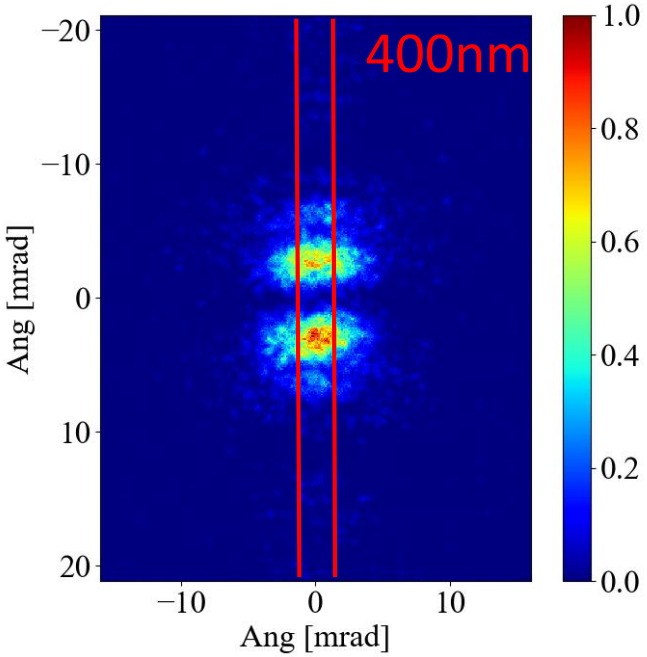


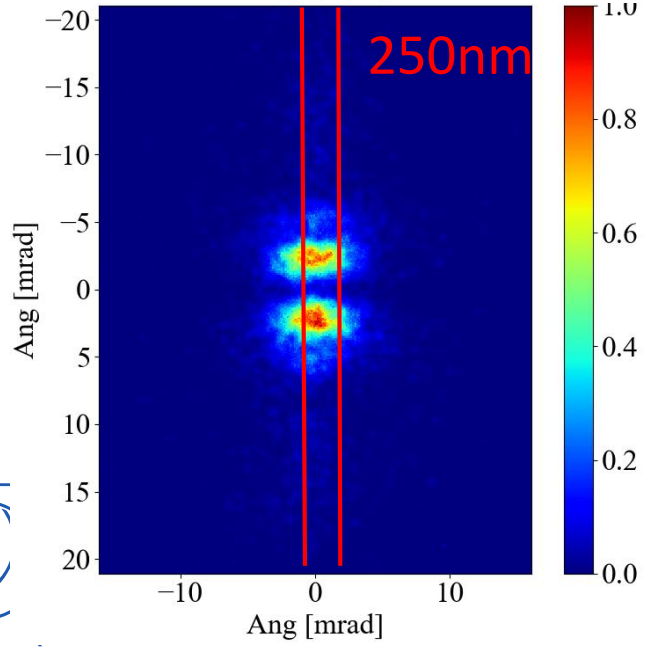


Single shot imaging profile of DR slit

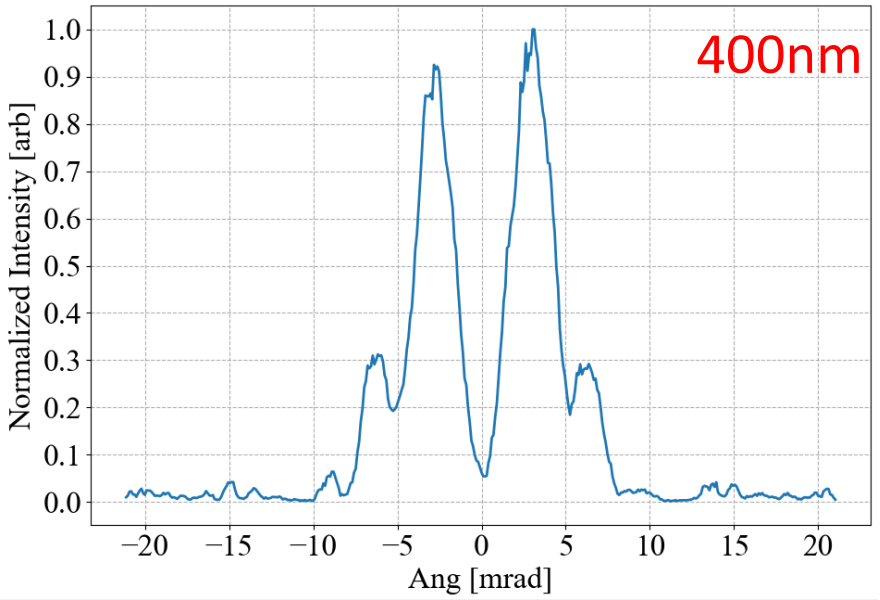


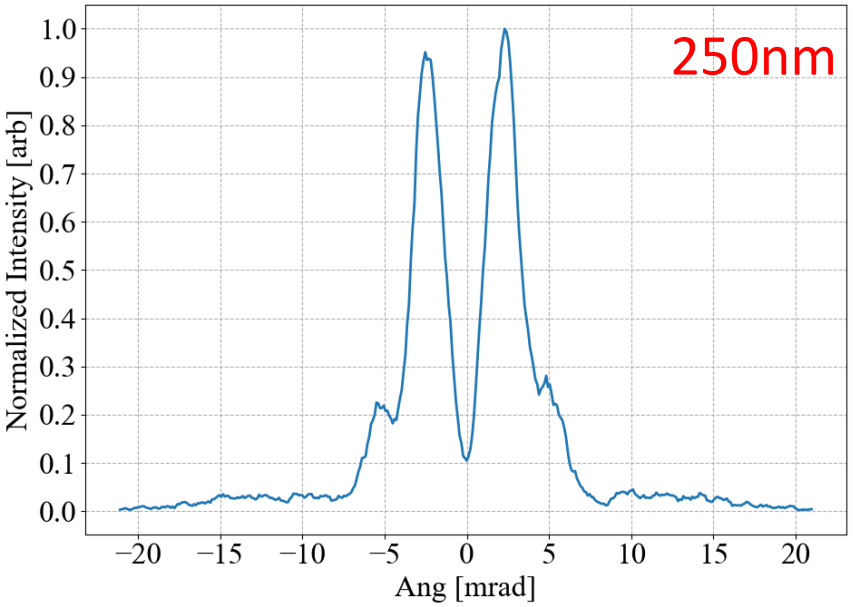
Single shot 2D angular distribution of DRI



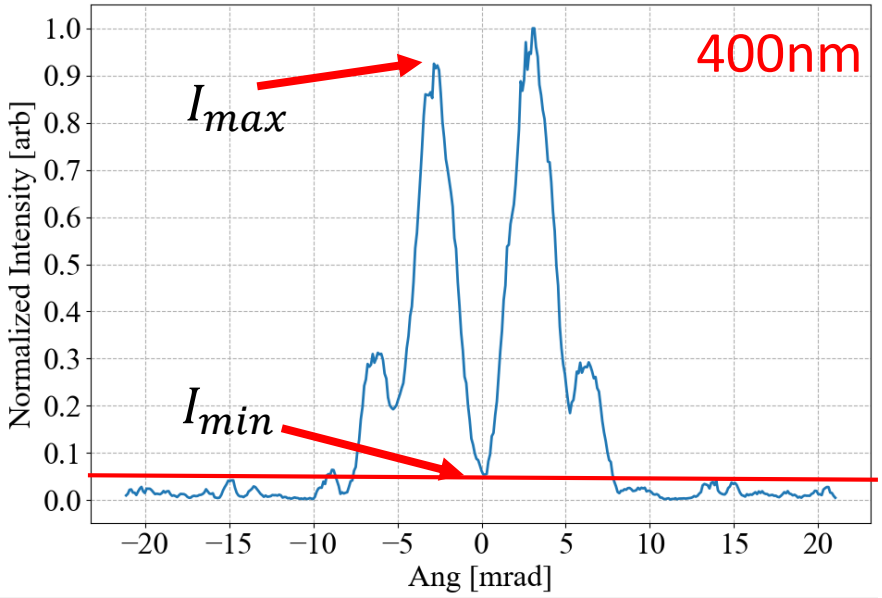


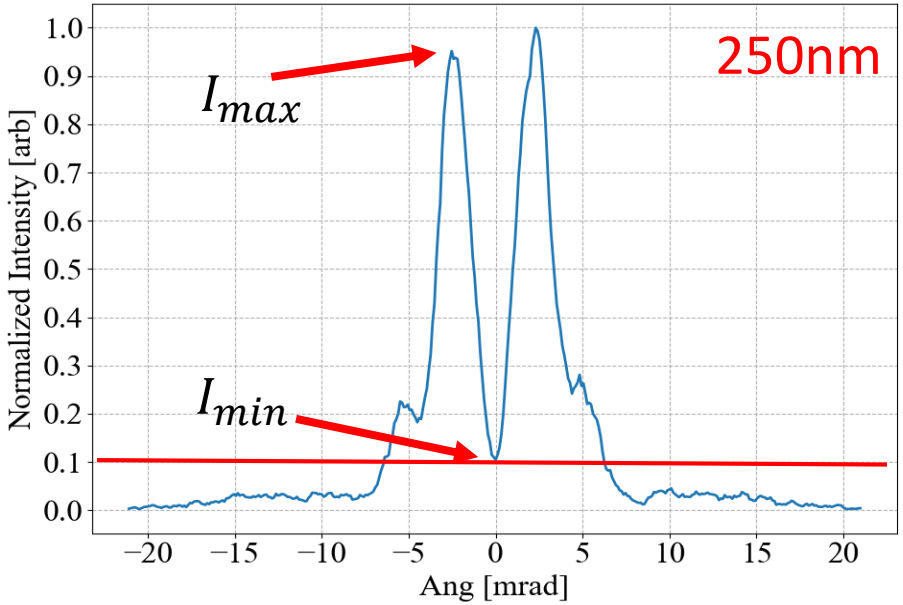
Single shot angular profile of DRI





Visibility of single image in DRI angular profile

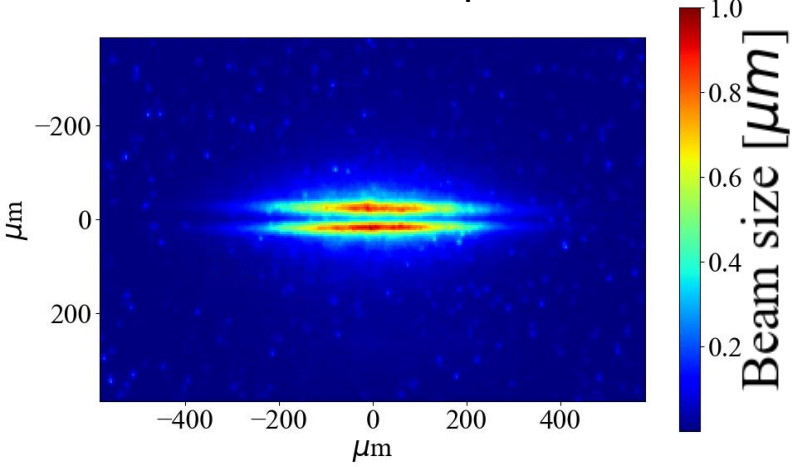




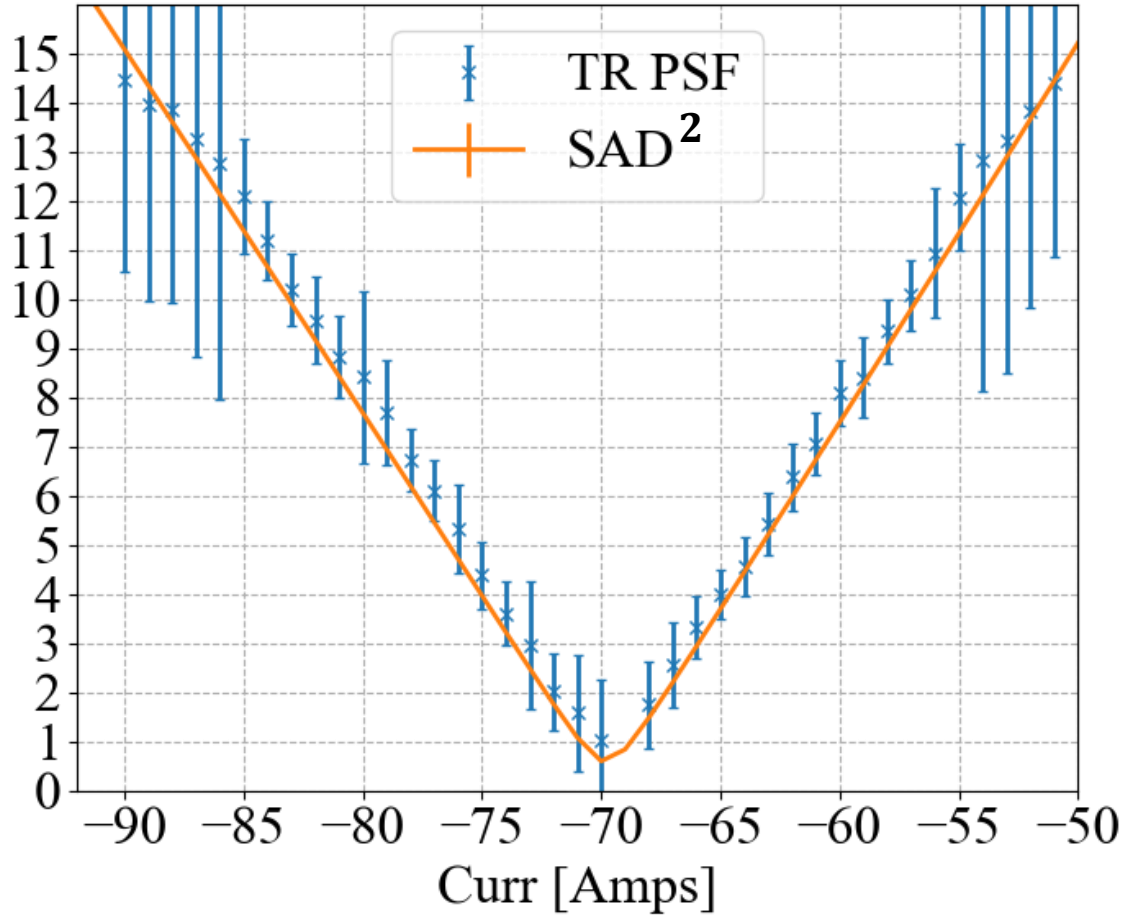
$$Visibility = I_{min}/I_{max}$$

OTR Beam size calibration

The side mirrors of the DR slit were used to record reference TR beam size measurement using PSF technique[1]



OTR PSF could be used in CLIC/ILC with single bunch. Then DR can be used for full beam charge.



1. Very high resolution optical transition radiation imaging system: Comparison between simulation and experiment, B. Bolzon et al., 2015, Physical Review Special Topics - Accelerators and Beams , 18

2. Simulation performed by **R. Yang**

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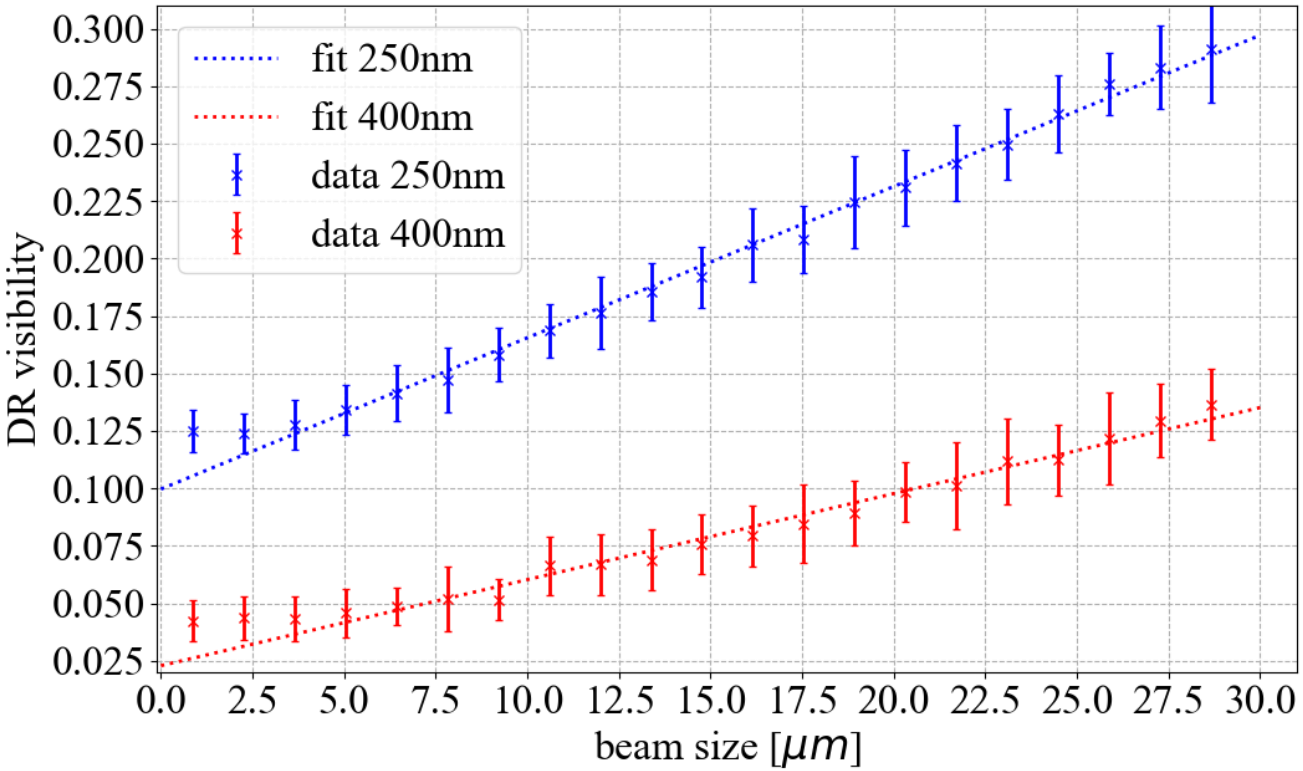
DR at ATF2 November 2017/March 2018

mask $= 100.0\ \mu m$, target $= 49.7\ \mu m$

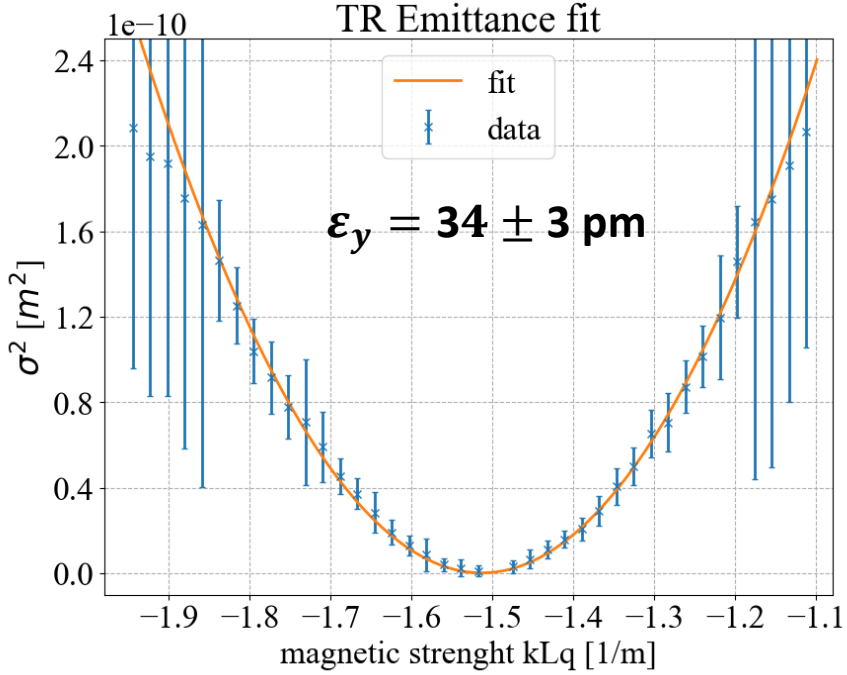


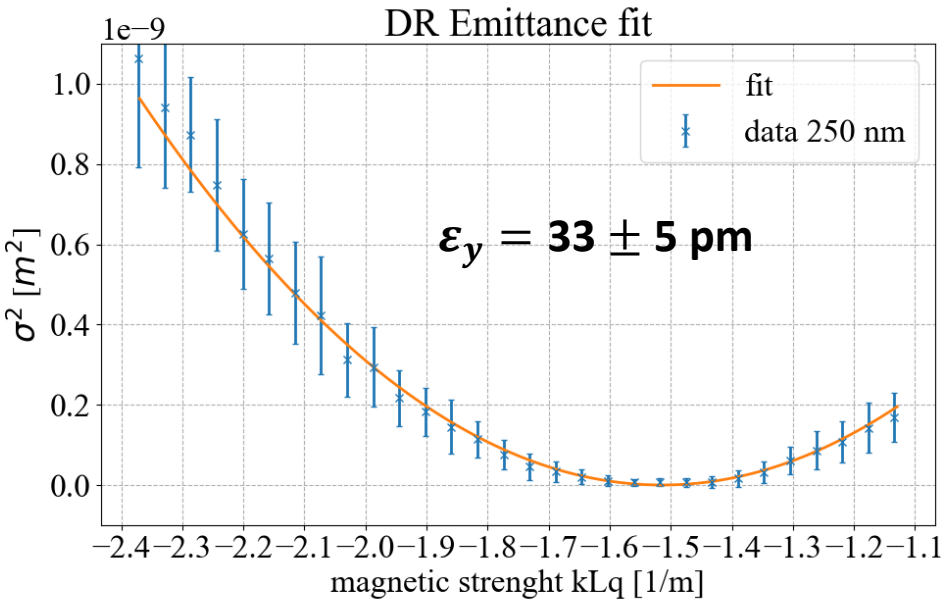
As expected sensitivity increase with decreasing wavelength, good sensitivity for UV down to 5 micrometers.

Previous measurements minimum was 14 μm^2

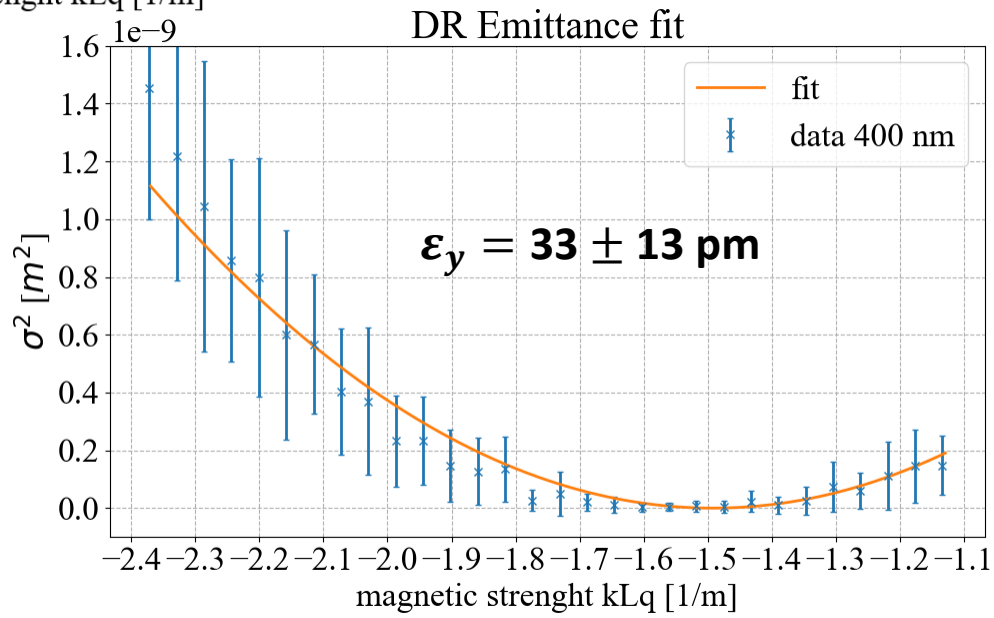
2. Beam-Size Measurement with Optical Diffraction Radiation at KEK Accelerator Test Facility, P. Karataev et al., 2004, Phys. Rev. Lett., 93

Verical Emittance measurement





Good agreement with simulated SAD emittance



Summary of DR studies at ATF2

2018 DR Achievements

- Imaging the DR source to monitor the position of the beam during angular data acquisition => beam in the slit centre
- Beam orbit optimisation needed to minimize SR contribution
- Mask contribution to block SR has been observed
- Data successfully collected also in the far UV (250 nm)

- Cross calibration and simulation needed
- Sensitivity to micrometer scale beam size has been demonstrated down to few µm (5 µm)
- Reproducibility of measurements studies, performed during November 2017 and March 2018 operations

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Motivation to develop Incoherent Cherenkov Diffraction Radiation (ChDR)

- Suppress Synchrotron radiation → cleaner signal
  - DR and SR are emitted at similar angles
  - Looking for a physical process emitted at larger angle

- Larger aperture compare to DR slits (> 500 μm)
  - Difficult as DR will provide less photons
  - Looking for a physical process providing more photons

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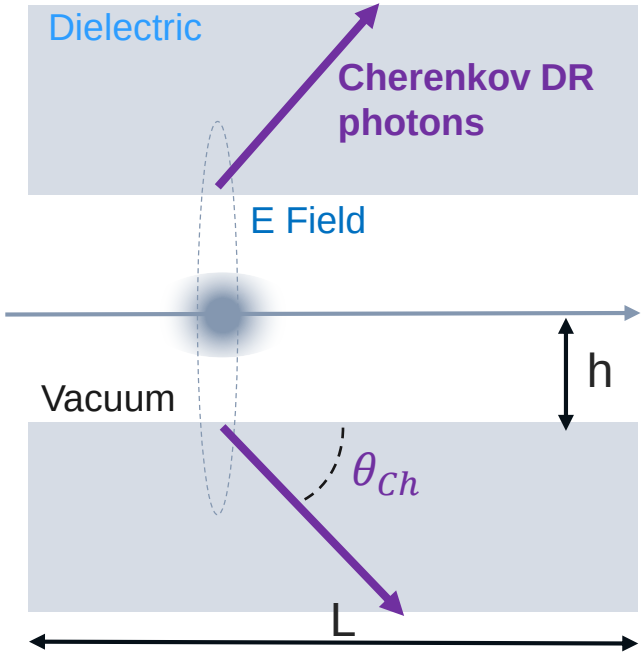
Incoherent Cherenkov Diffraction Radiation (ChDR)

The electric field of ultra-relativistic charged particles passing in the vicinity of a dielectric radiator produce photons by Cherenkov mechanism (polarization effect).

- Large emission angle: $\cos(\theta_{Ch}) = \frac{1}{\beta n}$
- Photons emitted along the target



For a cylindrical geometry

Cherenkov emission

$$\frac{d^2N_{Dcph}}{d\Omega d\lambda} = \frac{\alpha n}{\lambda}\left(\frac{L}{\lambda}\right)^2 \left(\frac{\sin\left(\frac{\pi L}{\beta\lambda}(1-\beta n\cos\theta)\right)}{\frac{\pi L}{\beta\lambda}(1-\beta n\cos\theta)} \right) sin^2\theta \; . \; e^{\left(-4\pi\frac{h}{\gamma\beta\lambda}\right)}$$

Exponential decay of the particle field

α, fine structure constant
β, normalised beam velocity
γ, beam relativistic factor
λ, wavelength
θ, angle of observation
n, refractive index

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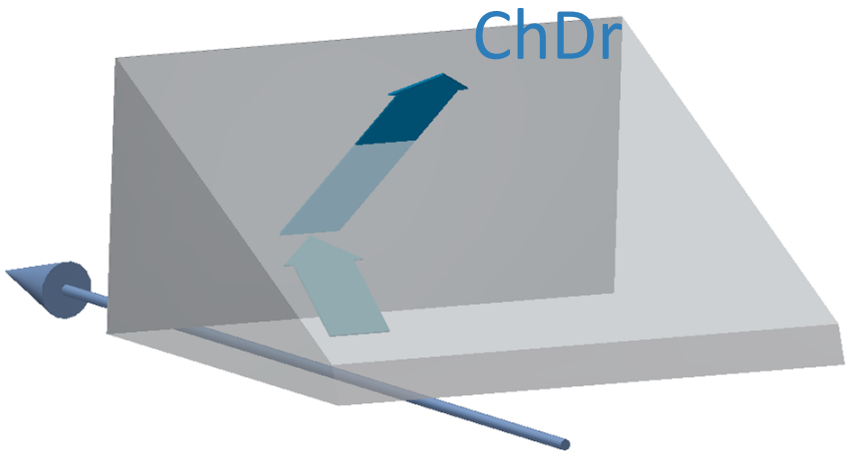
ChDR at ATF2

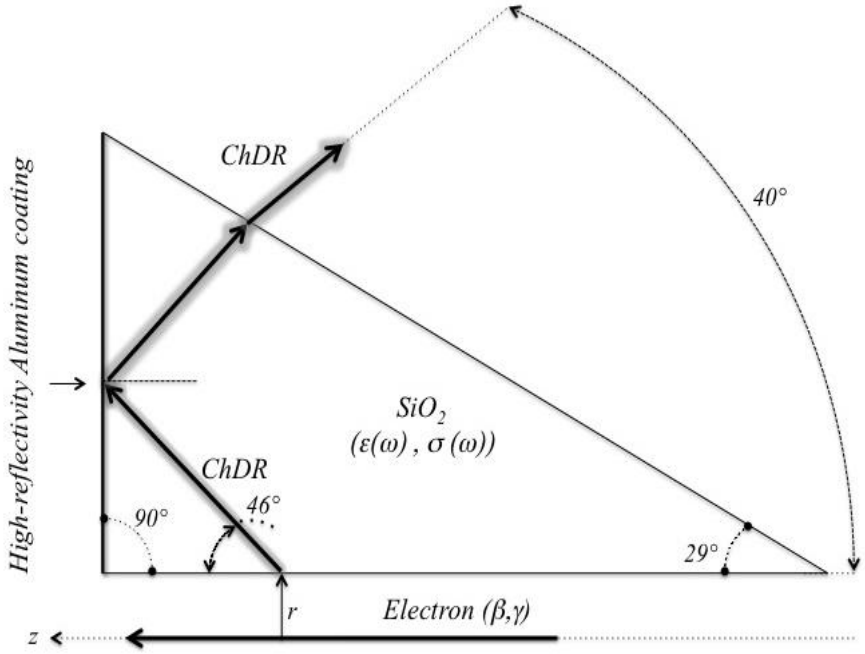
- **Recent studies showed the possibility to built imaging system for relativistic beams based on ChDR[1]**

- What is the the smallest beam size measurable ?
  - The Cherenkov diffraction PSF should be smaller than transition radiation PSF
- At ATF2:
  - energy 1.2 GeV allows to perform test in visible range
  - possibility to test with micron beam sizes
  - test after Quadrupole QM14FF and QM15FF allows to explore different beam size and impact parameter (depending on σ_x and σ_y)

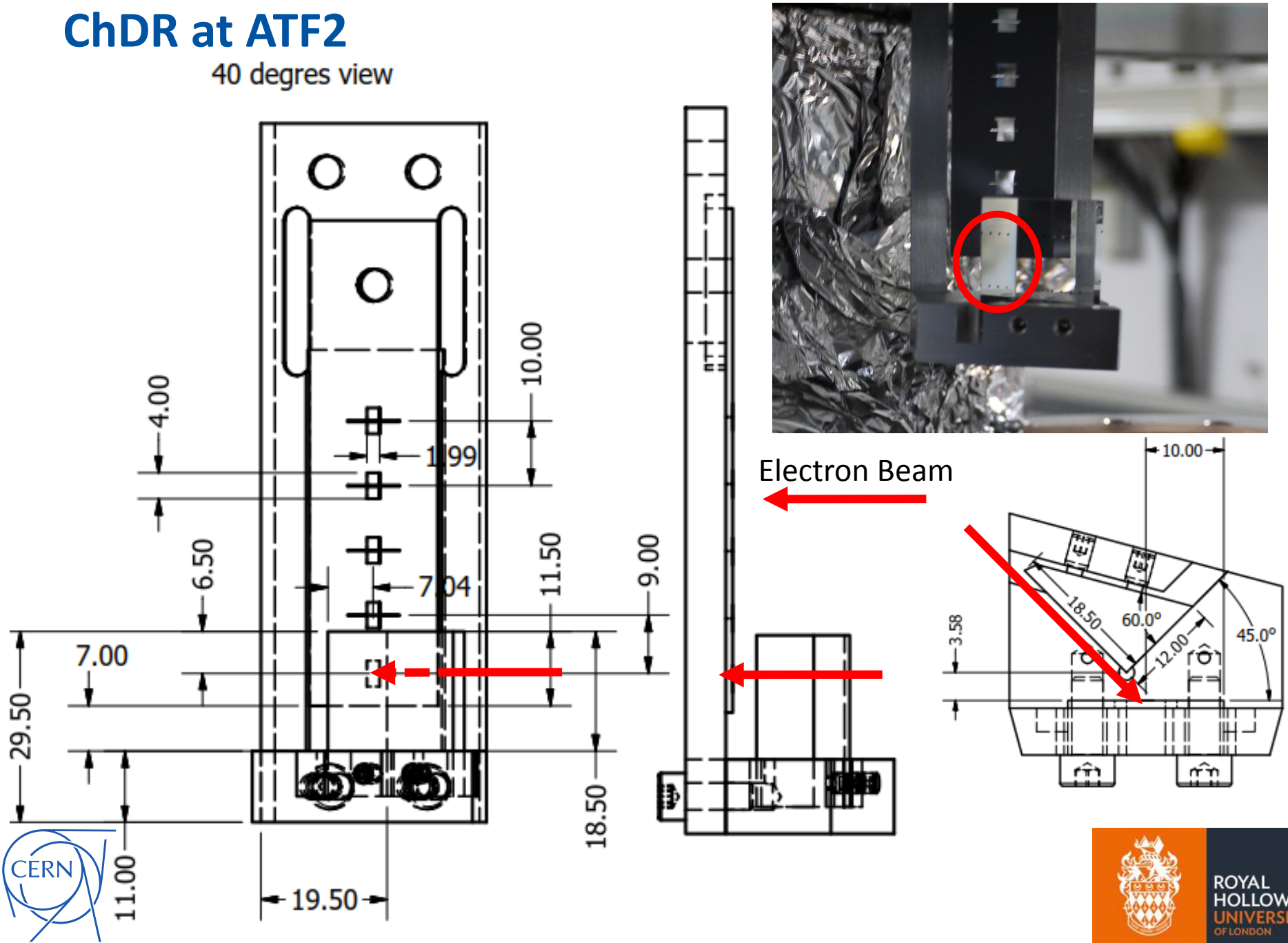
1. Direct Observation of Incoherent Cherenkov Diffraction Radiation in the Visible Range, R. Kieffer et al., 2018, Phys. Rev. Lett., 121

ChDR at ATF2

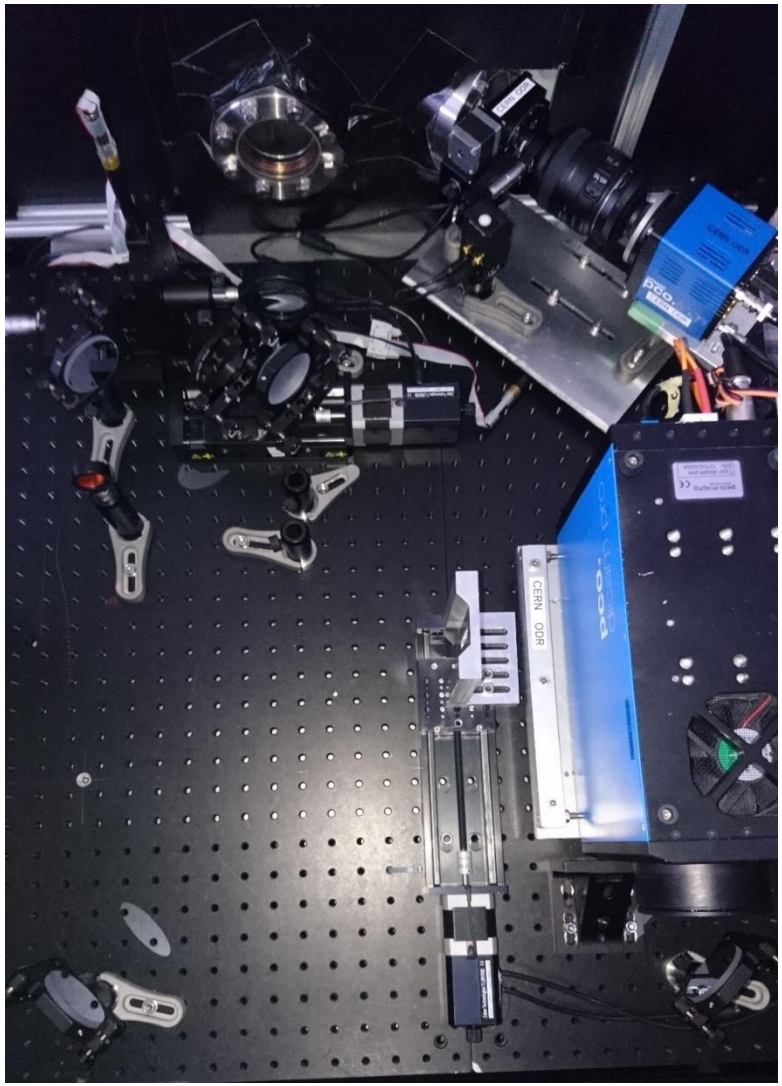

ChDr
Electron
Beam

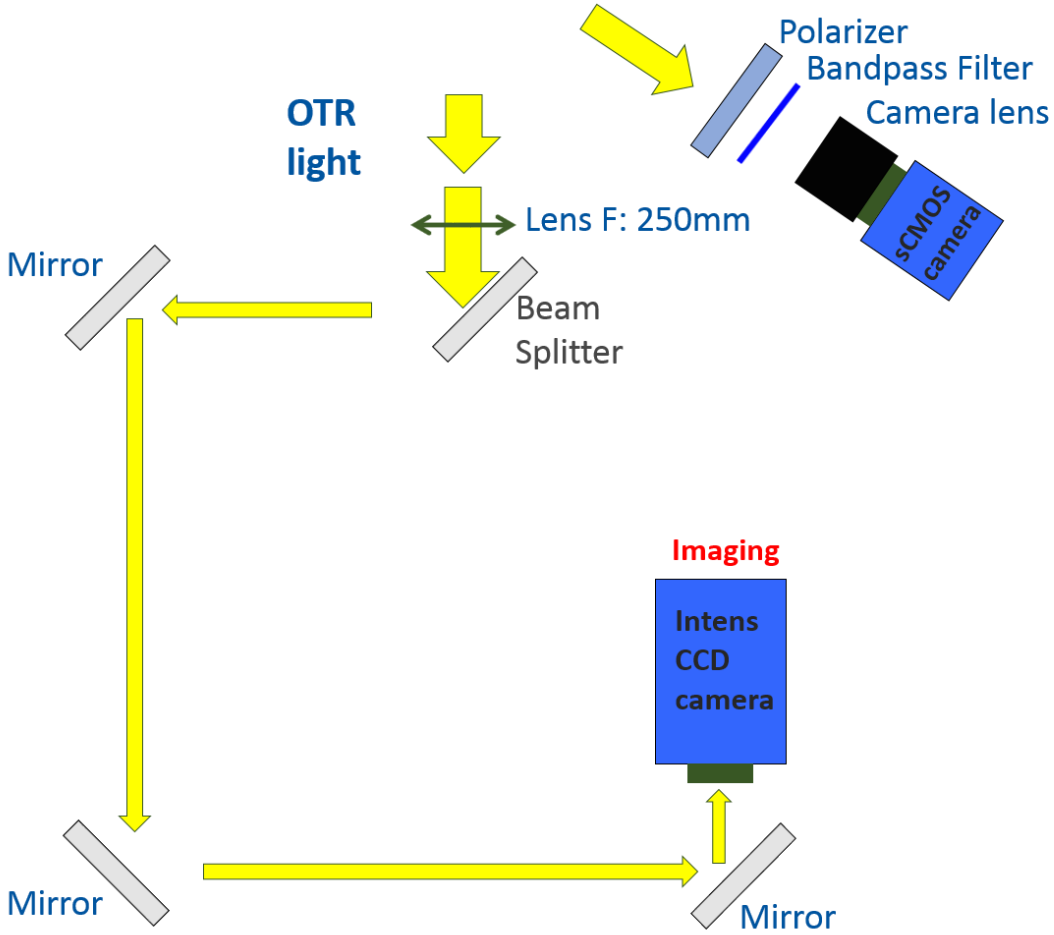

ChDR
40°
High-reflectivity Aluminum coating
SiO2
(ε(ω) , σ (ω))
ChDR
46°
90°
29°
r
Electron (β,γ)
z

ChDR at ATF2


40 degres view
4.00
10.00
1.99
6.50
7.04
11.50
9.00
7.00
29.50
18.50
11.00
19.50
Electron Beam
10.00
3.58
18.50
60.0°
12.00
45.0°

ChDR at ATF2

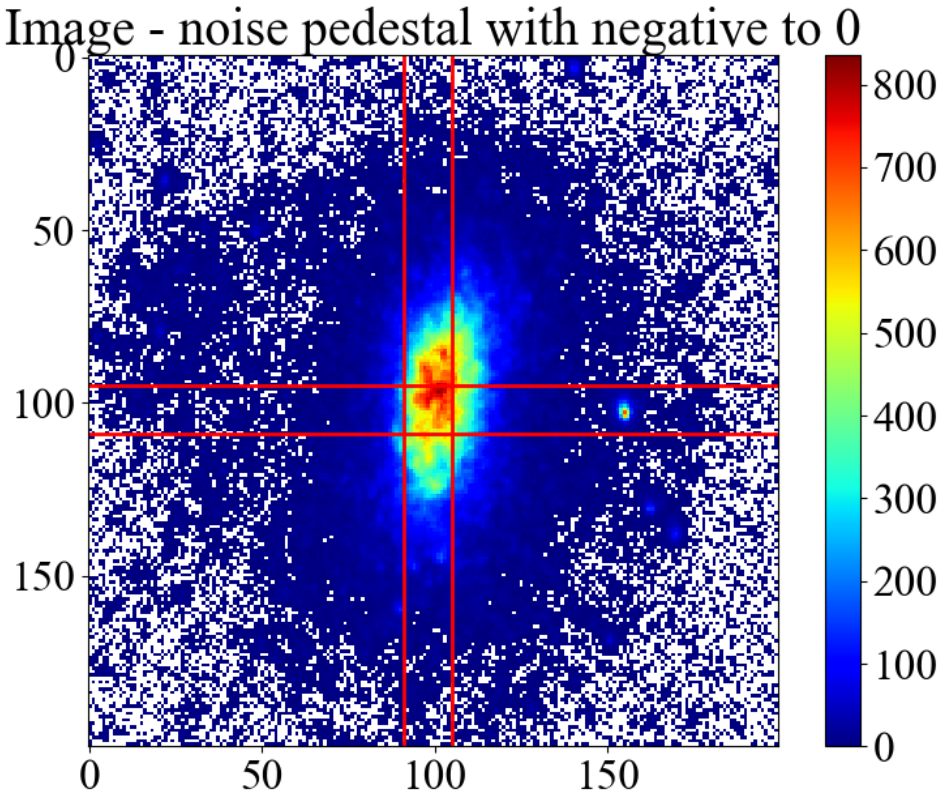




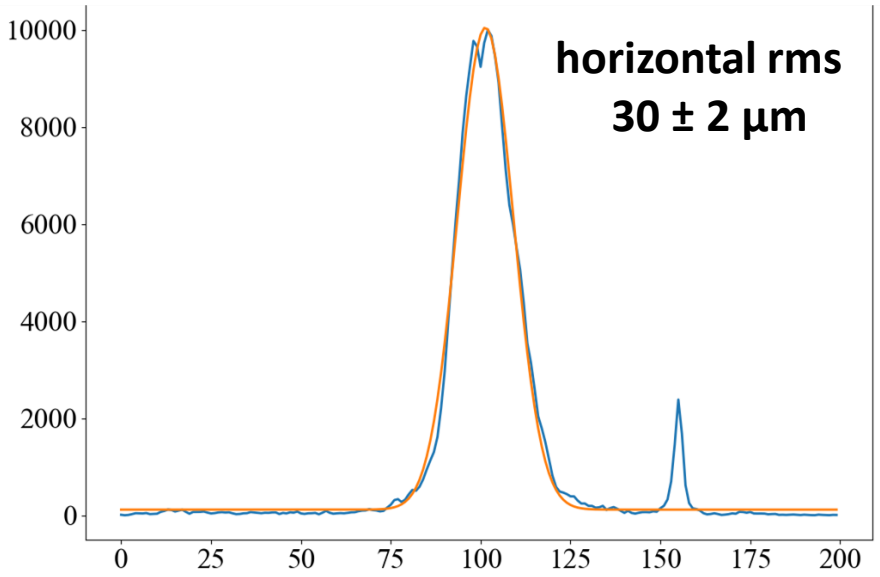
ChDR optical line magnification M≈2

TR measurement

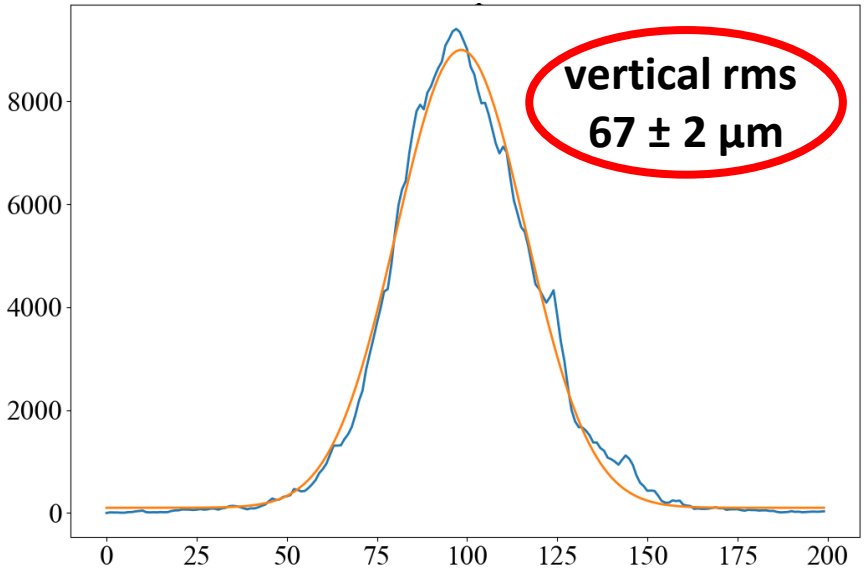
Profiles



Horizontal Profile

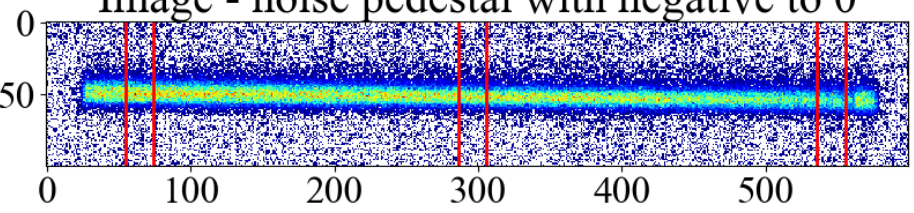


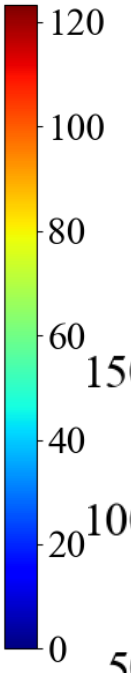
Vertical Profile



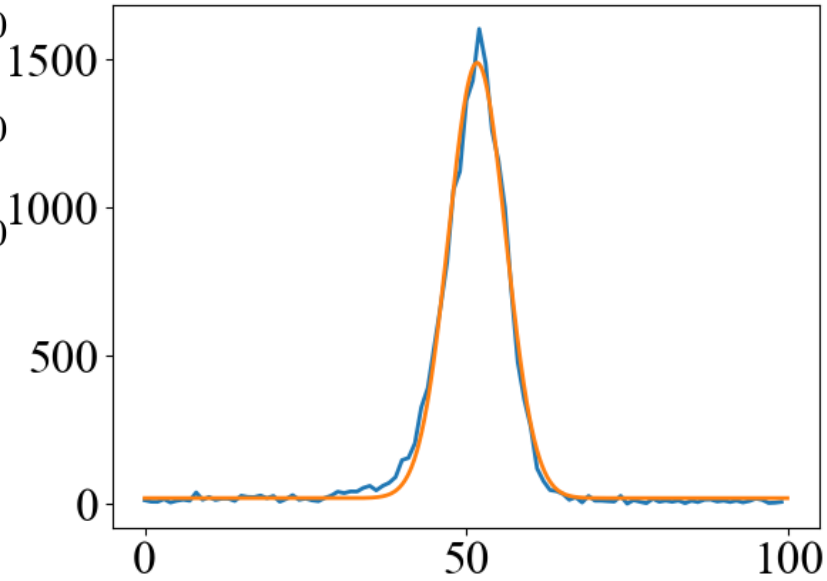
ChDR at ATF2

Horizontal Polarization



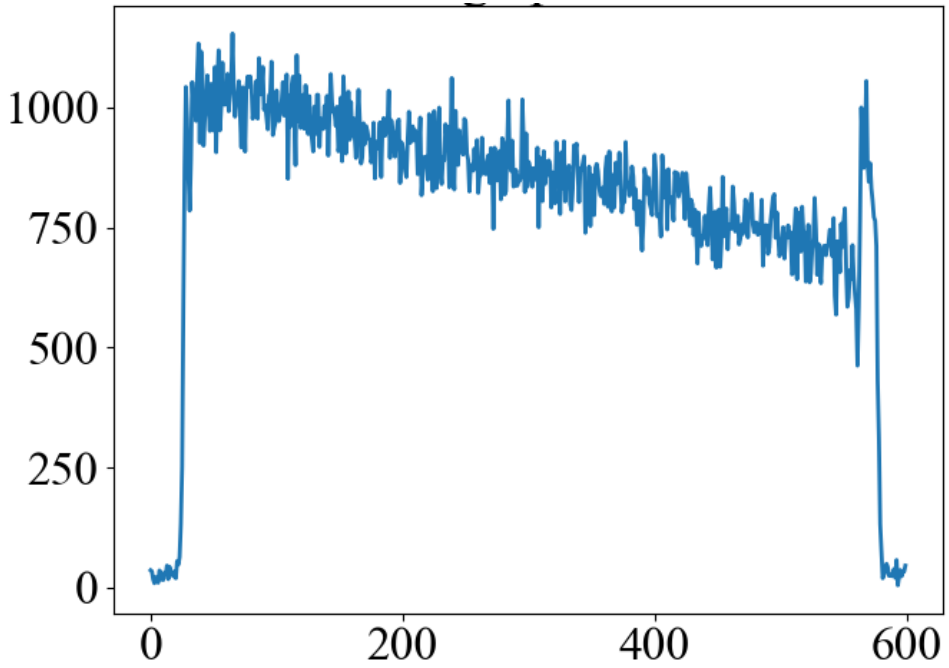


Vertical Profile in the center of the DrCh



Vertical rms 63±2 µm

Horizontal Profile



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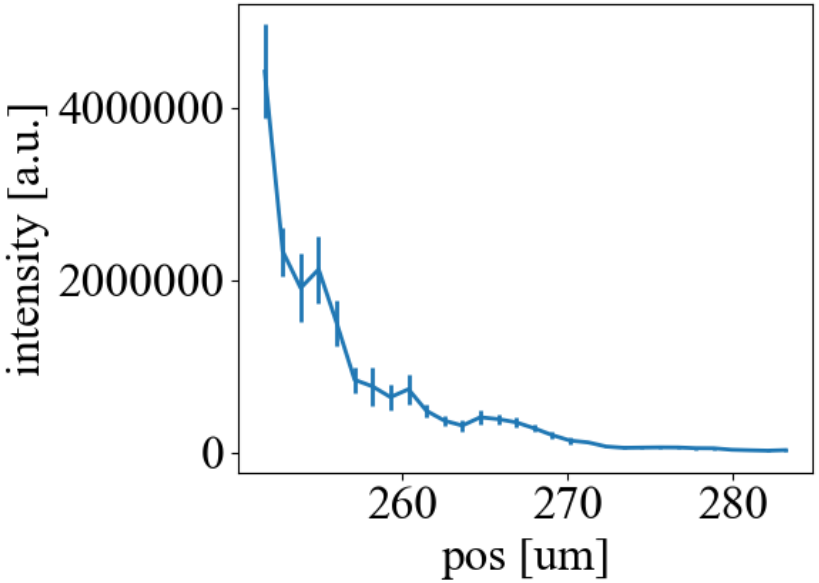
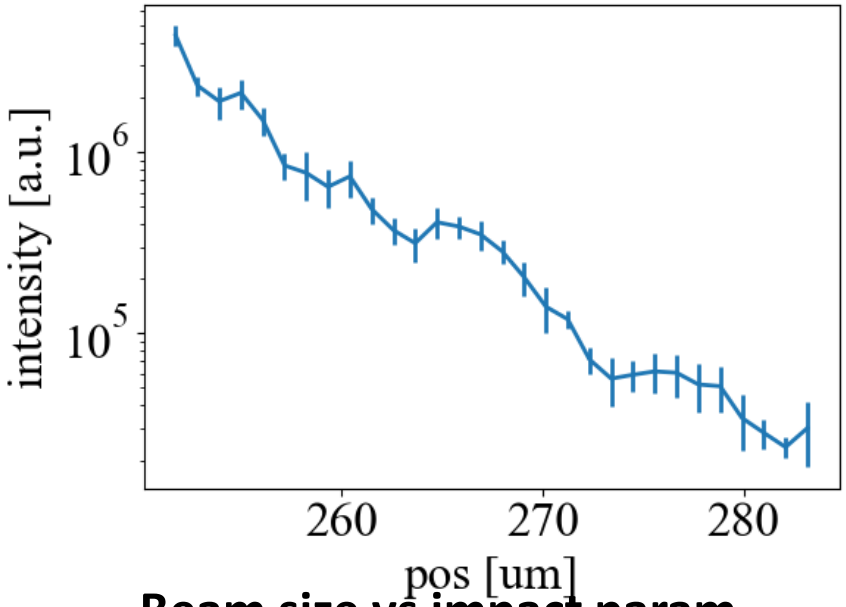
ChDR at ATF2

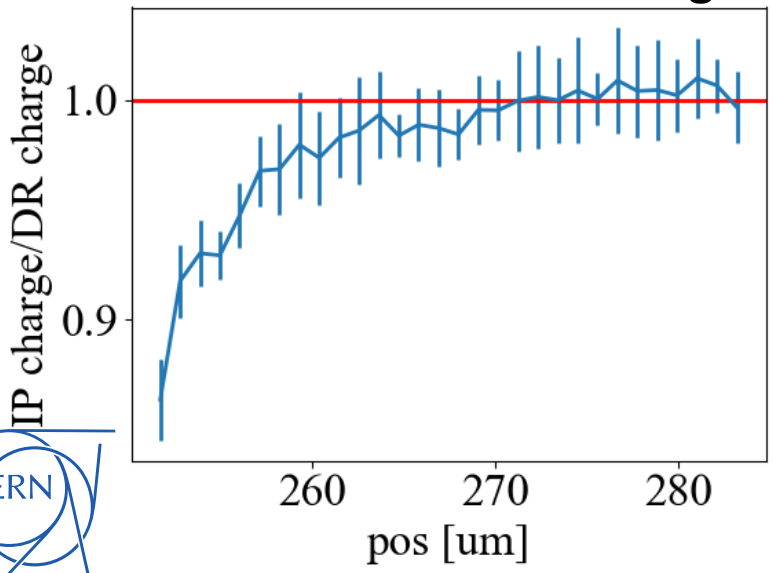
Total intensity linear scale



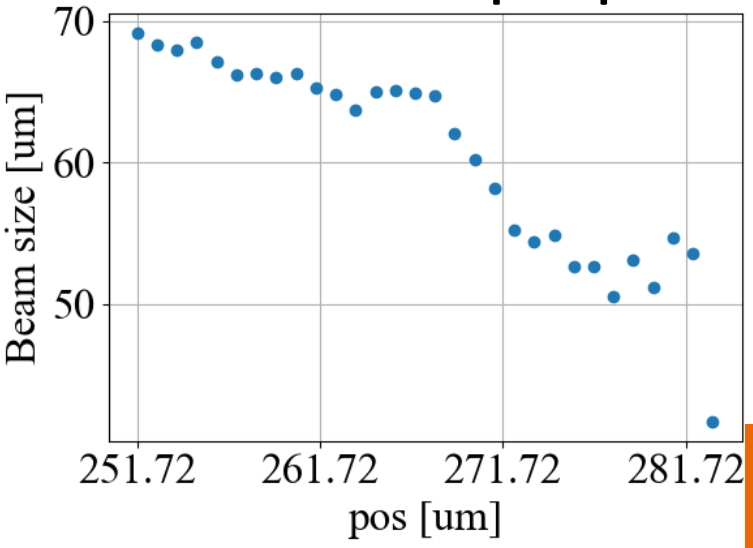
Total intensity log scale



Beam transmission over target



Beam size vs impact param



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Summary of DR studies at ATF2

2018 ChDr achievements

- Non-interceptive measurement
- Successfully measured 60 µm beam

ChDr future plan

- Increase the magnification of our system to understand the limitation of this technique (from M≈2 to M ≈7)
- Studies more in details the PSF of ChDr for both polarization (vertical and horizontal)
- Install a new optical system on at the end of next week, we plan to arrive at ATF on Friday 30th November
- 3 measurement shifts from 3 to 7 December

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Thank you for your attention!

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Back-up slides

Diffraction Radiation studies Overview

Motivation:

- Measurement for small beam size: non-invasive transverse profile station for CLIC/ILC beams with micron resolution

Goals:

- DR in the visible and UV, to optimize sensitivity to smallest beam sizes
- Cross-calibration with OTR PSF for micron size beam
- Reproducibility of measurements studies, performed during November and March operations

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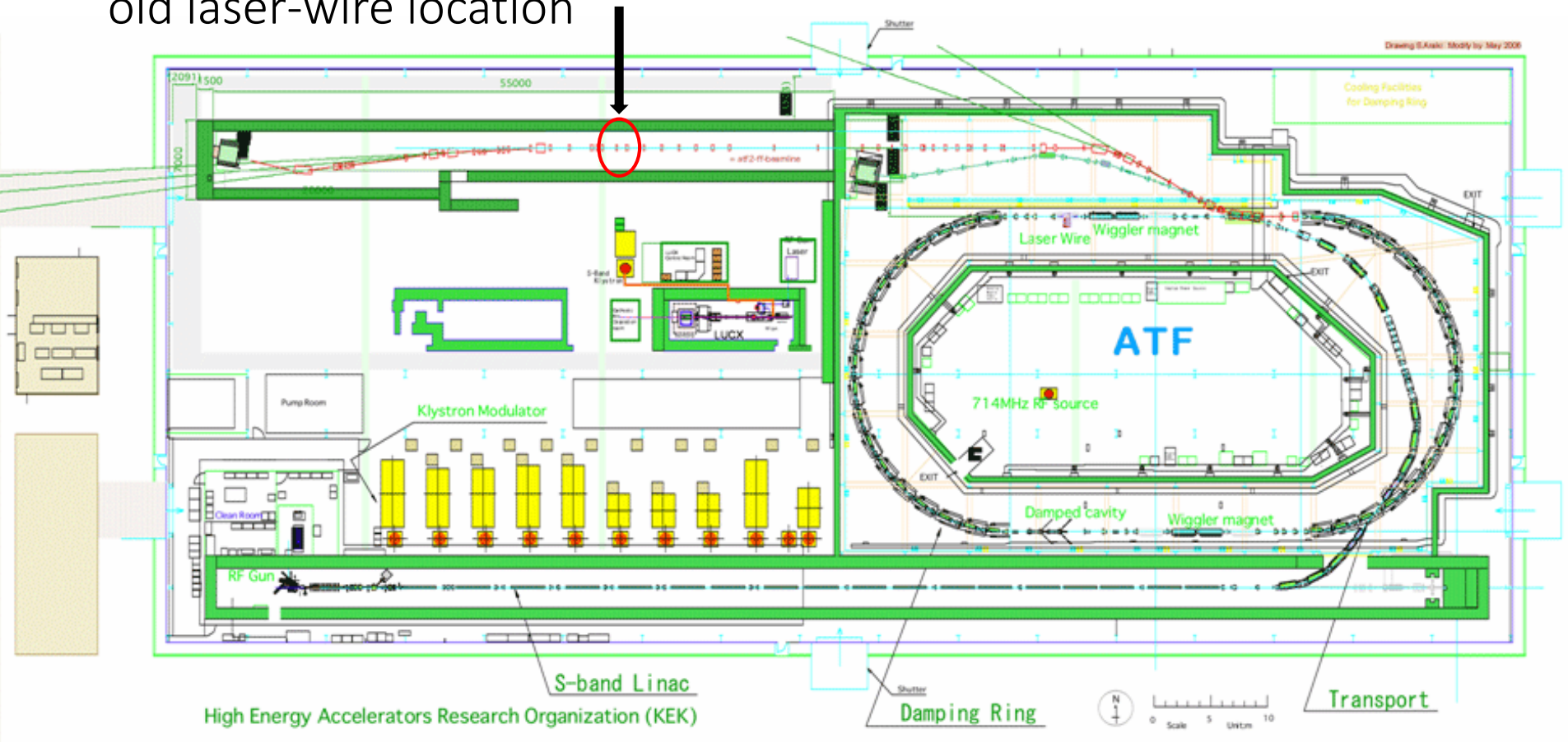
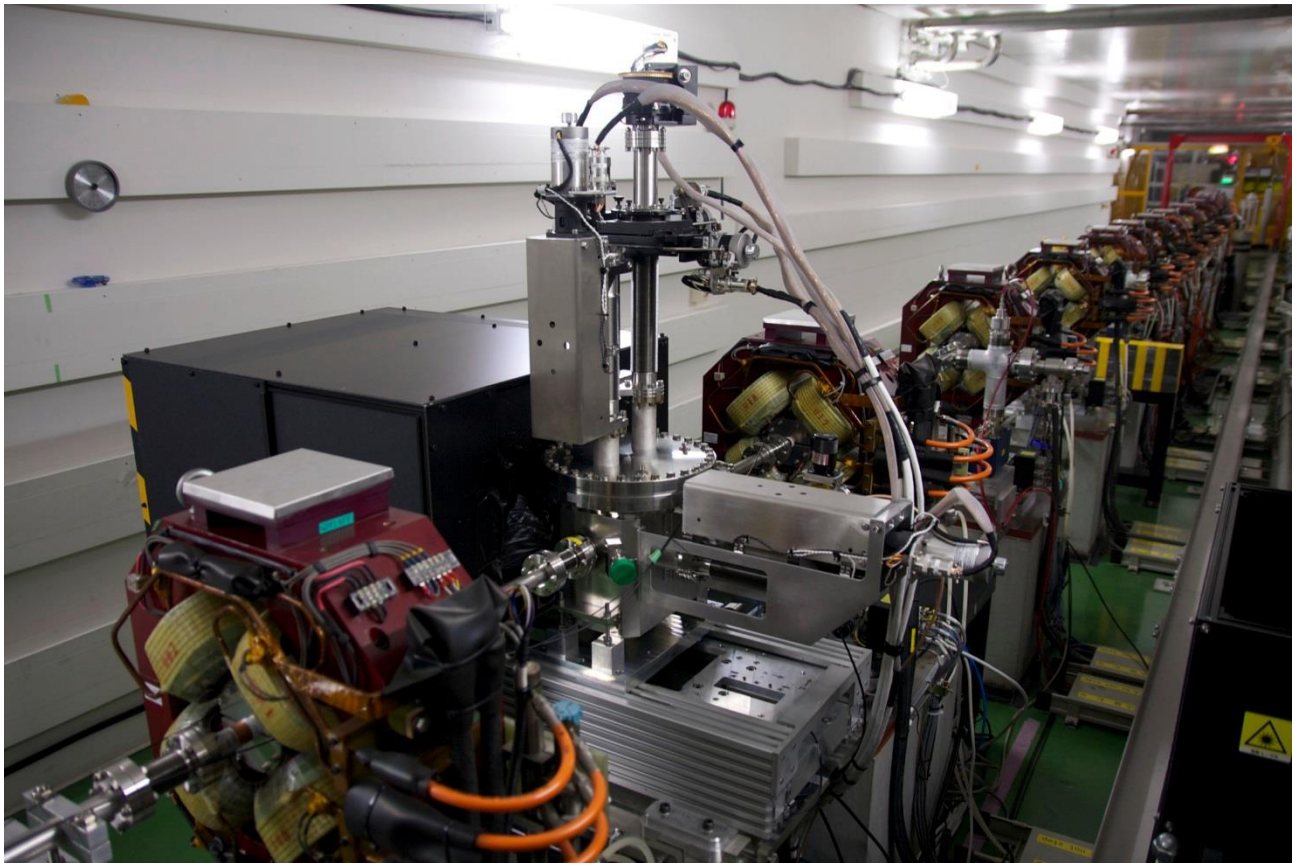
ODRI experiment at KEK ATF2

ODRI experiment location between QM14FF and QM13FF
old laser-wire location



ODRI experiment at KEK ATF2

Experiment installed at ATF2 in February 2016, in the laser-wire previous location where vertical beam can be focused to < 1um



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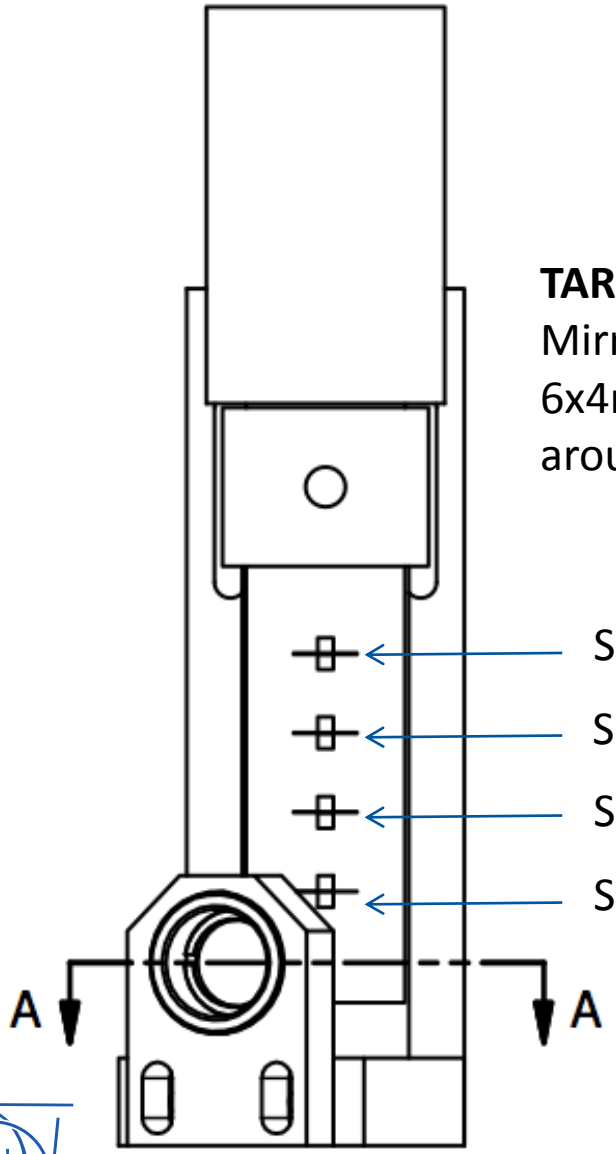
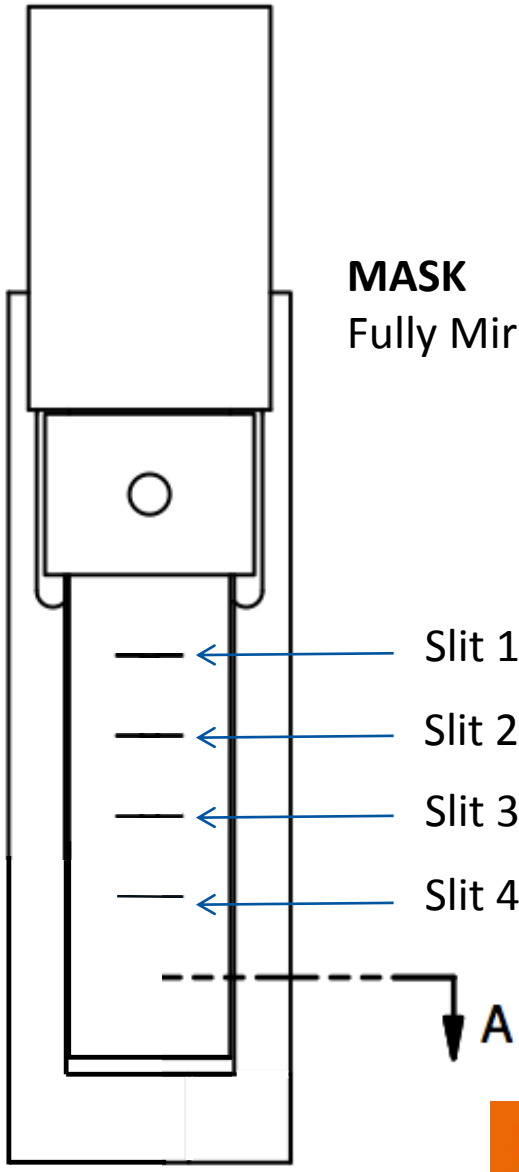
ODRI experiment at ATF2



TARGET
Mirrored areas
6x4mm^2
around slits

Slit 1 201.7um
Slit 2 100.6um
Slit 3 77.2um
Slit 4 49.57um



MASK
Fully Mirrored

Slit 1 399um
Slit 2 198.9um
Slit 3 149.2um
Slit 4 100um

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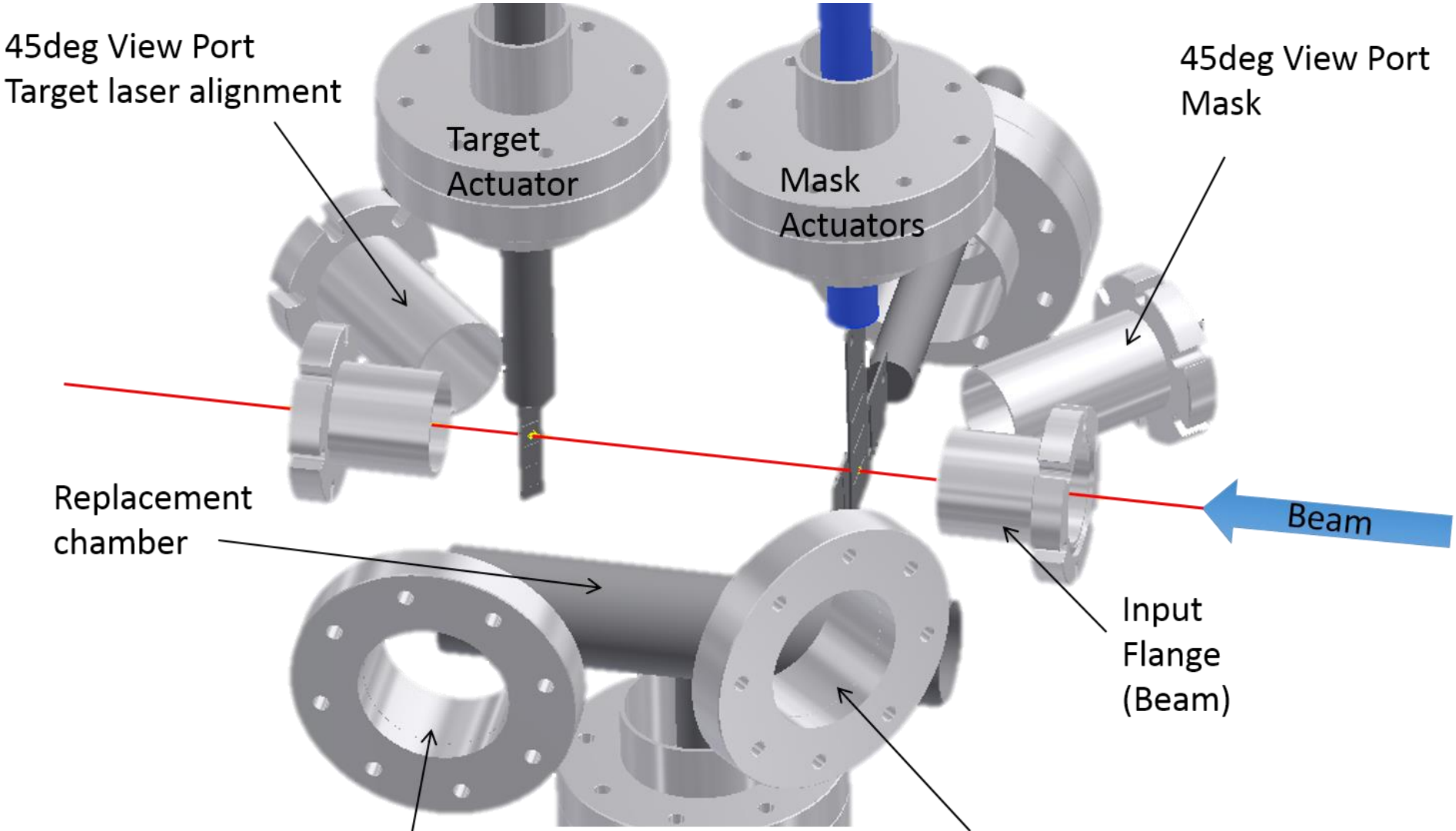
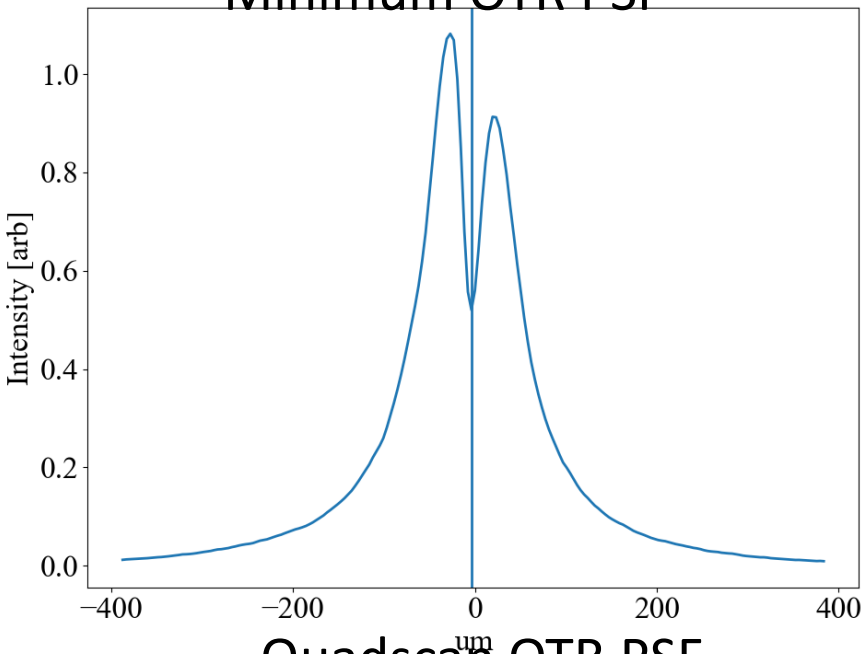
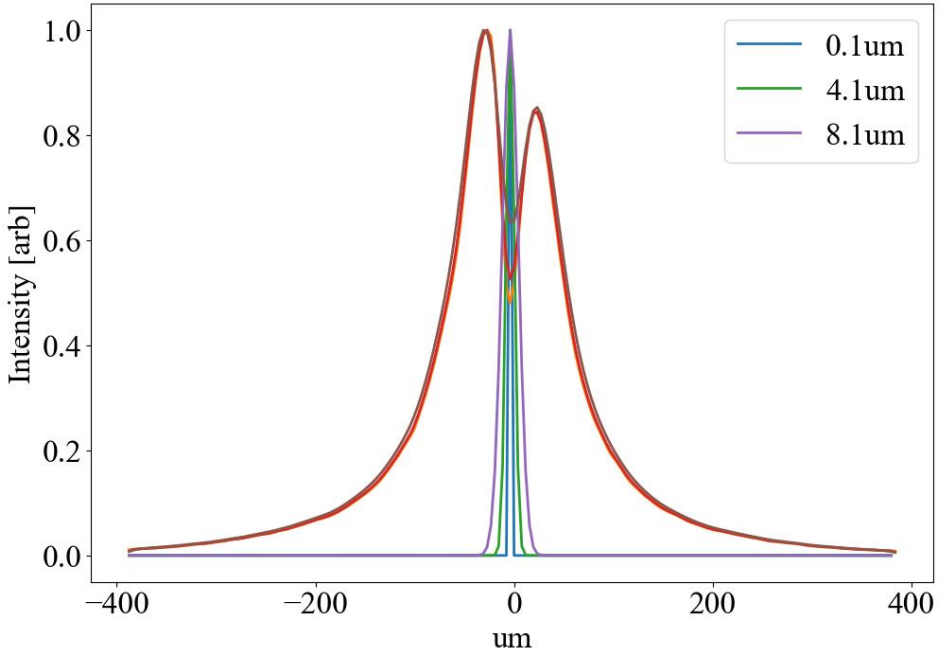
ODRI experiment at KEK ATF2



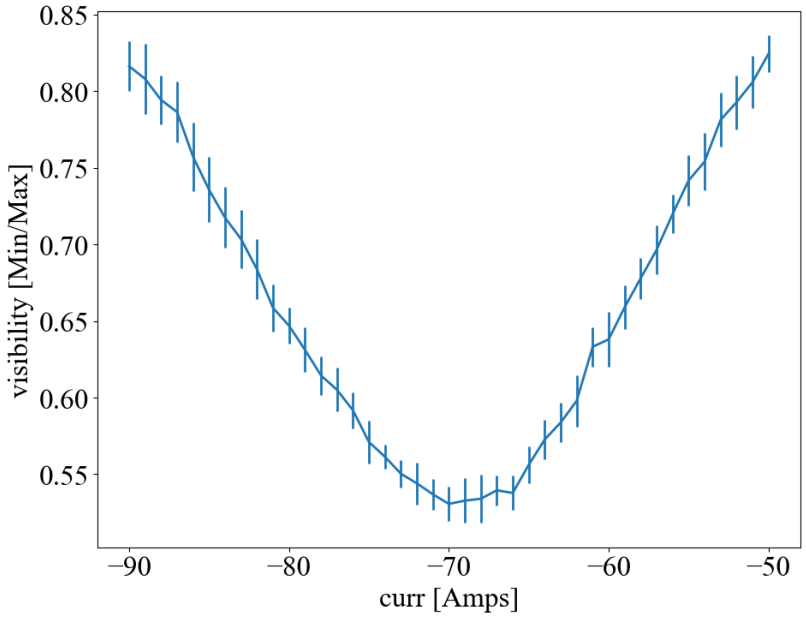
Minimum OTR PSF



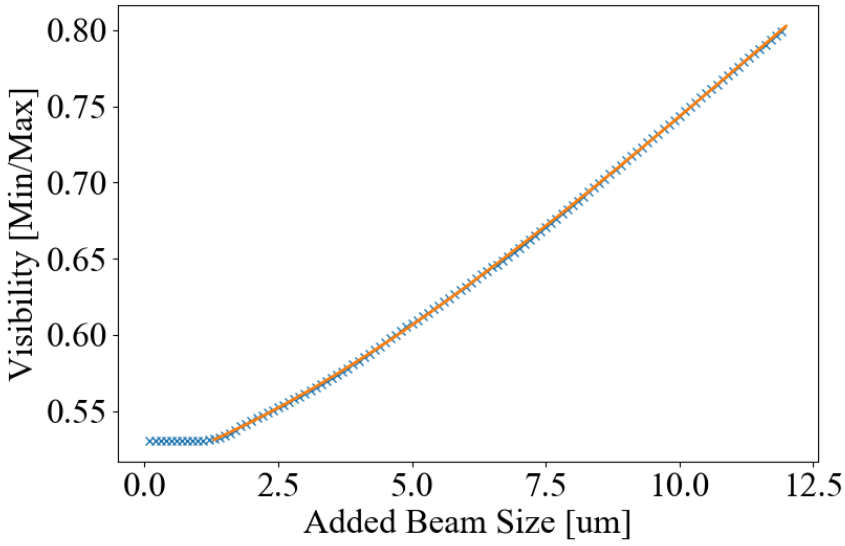
Convolution with gauss beam

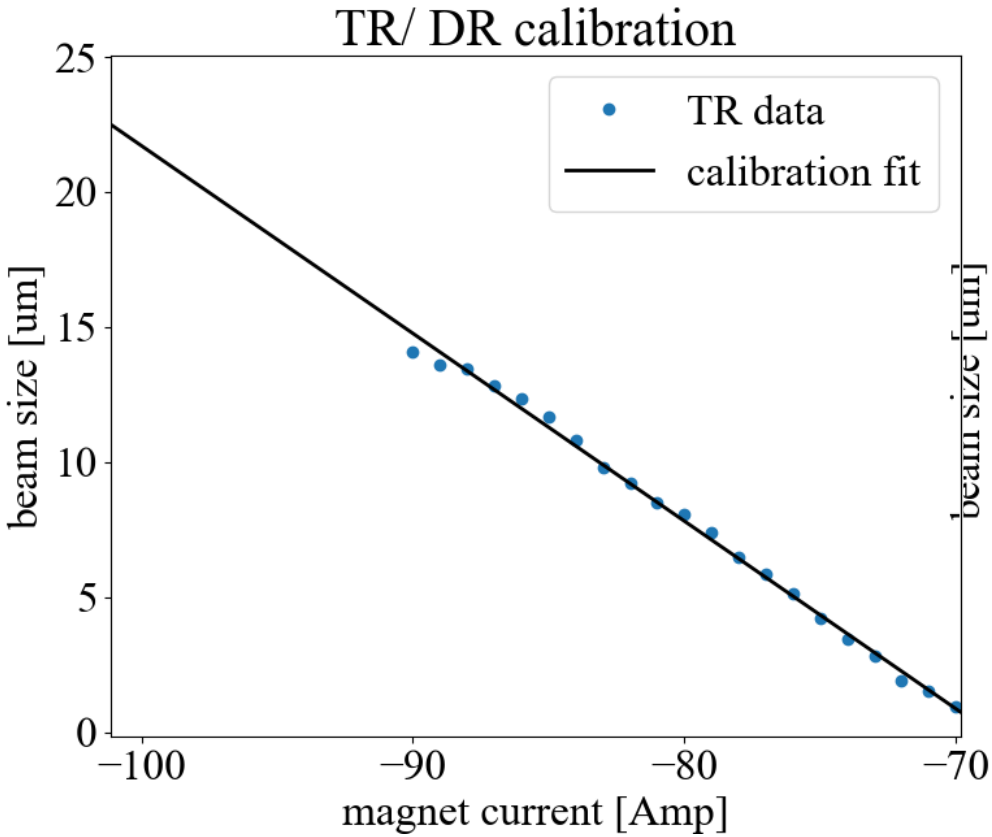


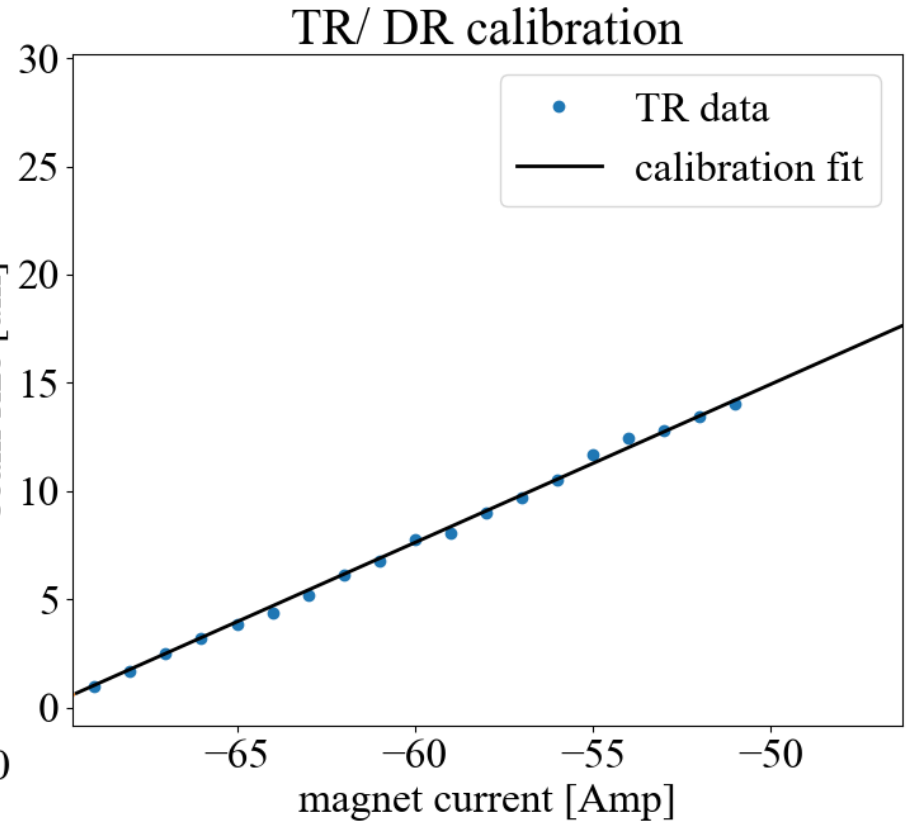
Quadscan OTR PSF



Calibration March shift

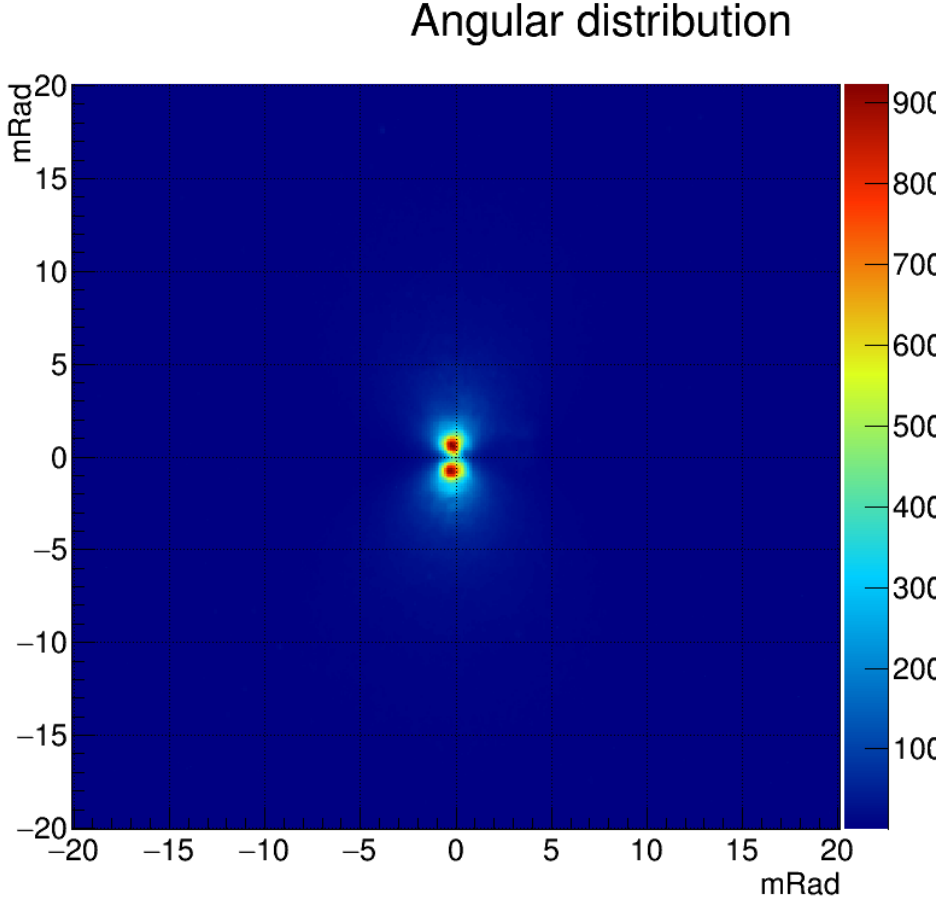


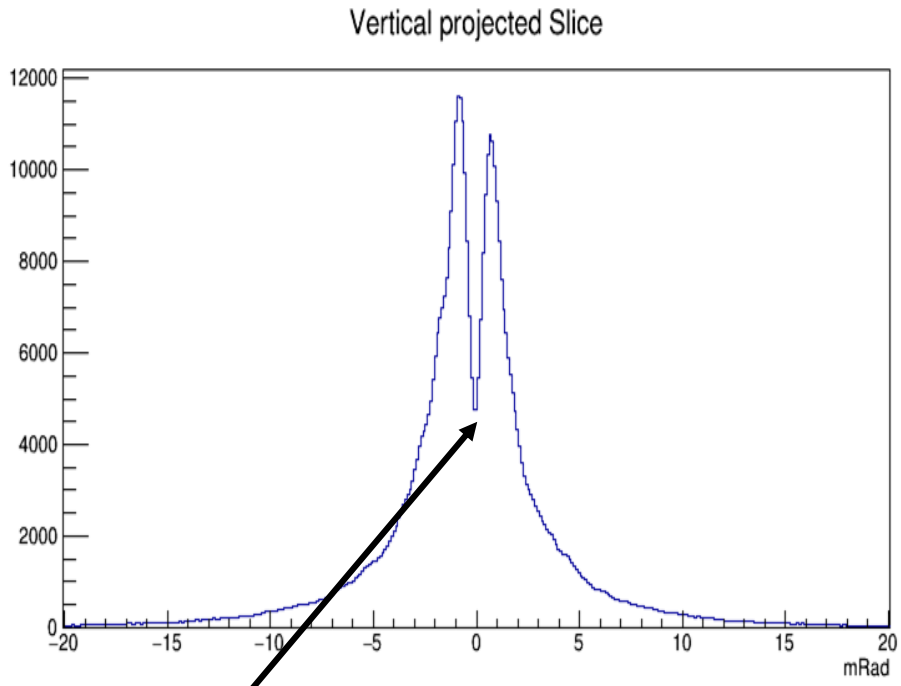

TR/ DR calibration
TR data
calibration fit
beam size [um]
magnet current [Amp]
25
20
15
10
5
0
−100
−90
−80
−70


TR/ DR calibration
TR data
calibration fit
beam size [um]
magnet current [Amp]
30
25
20
15
10
5
0
−65
−60
−55
−50

Synchrotron Radiation Contribution at ATF2

Observation of the angular pattern with target in the OTR position with mask inserted to evaluate Synchrotron Radiation Contribution



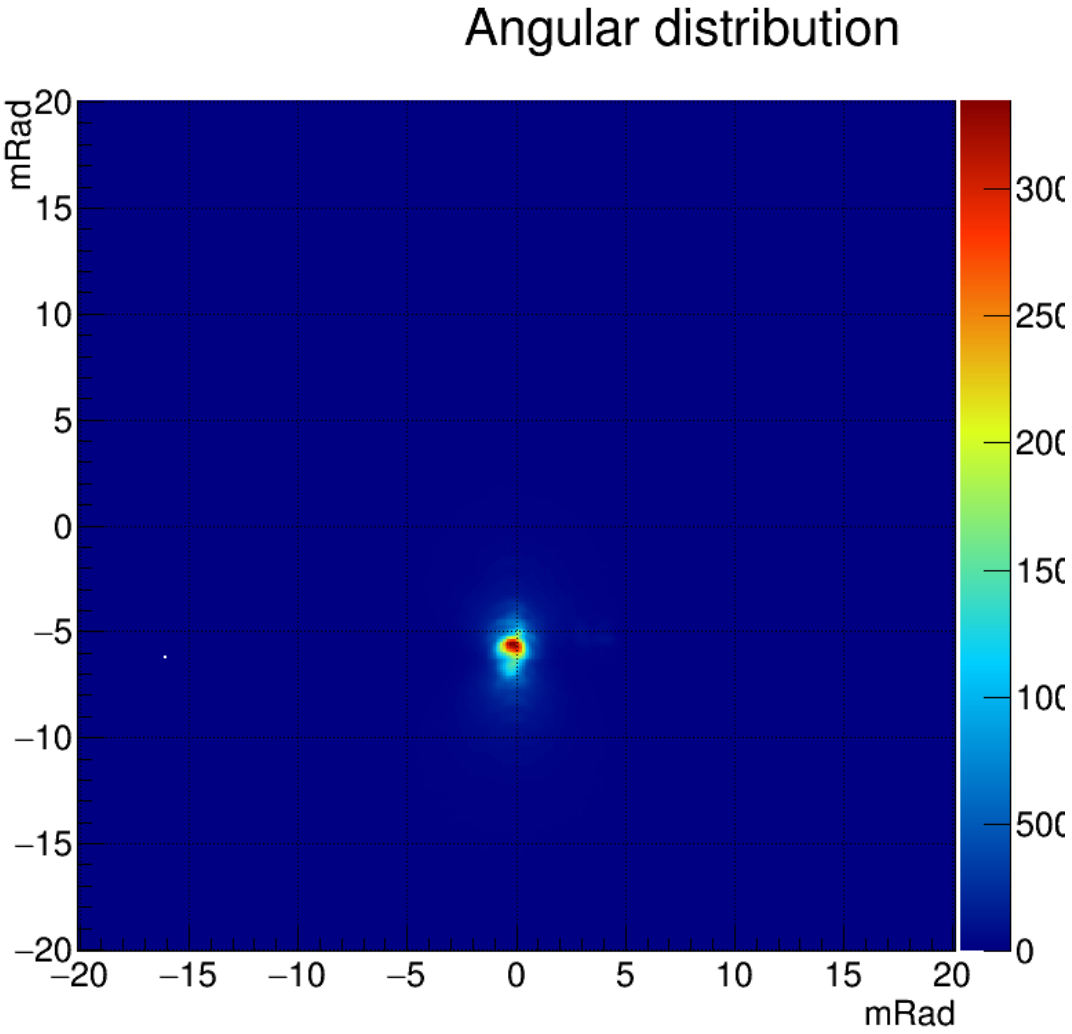


Minimum too high = high SR Contribution

Synchrotron Radiation Contribution at ATF2

OTR Angular pattern with steering magnet off and without mask

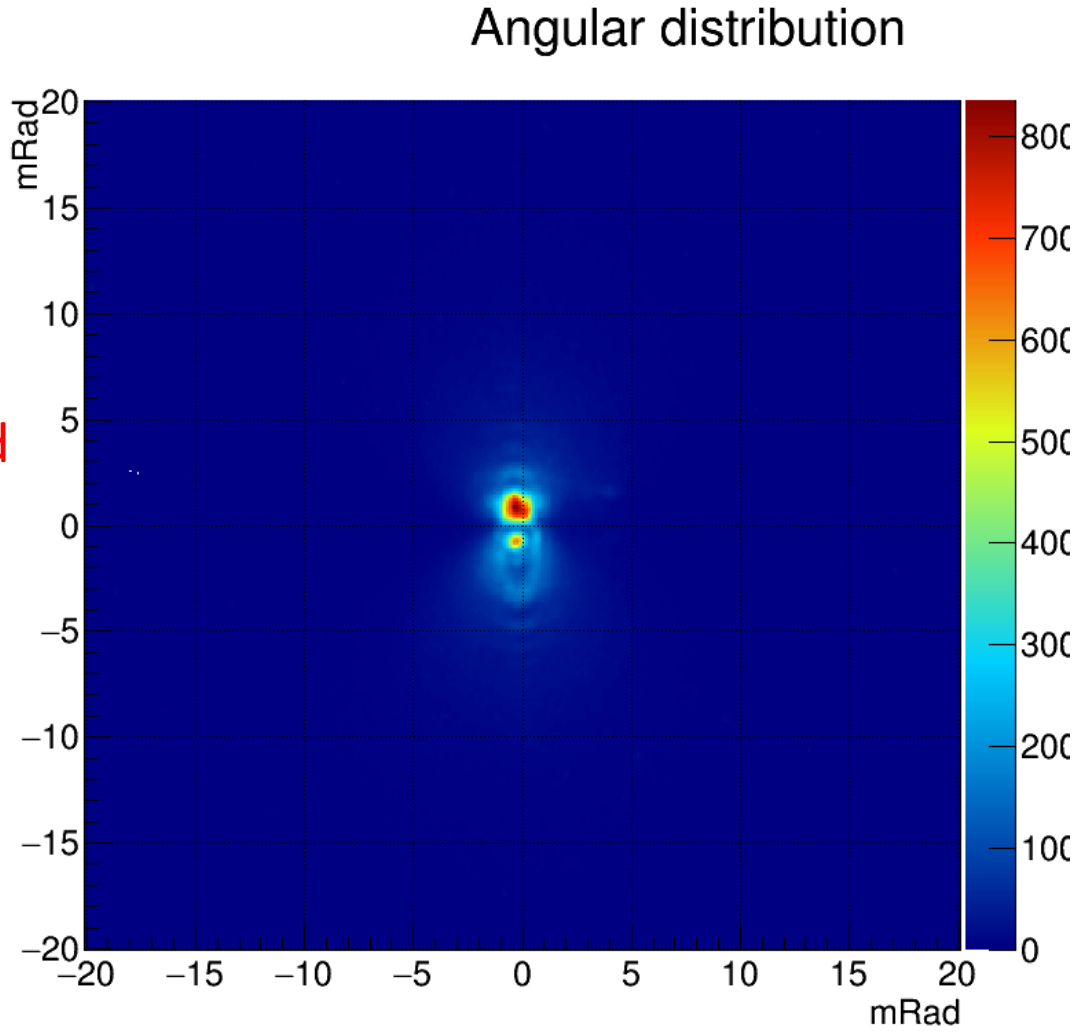
Strong Contribution, impossible to evaluate the TR angular pattern



Synchrotron Radiation Contribution at ATF2

Insertion of the mask (582 µm aperture)

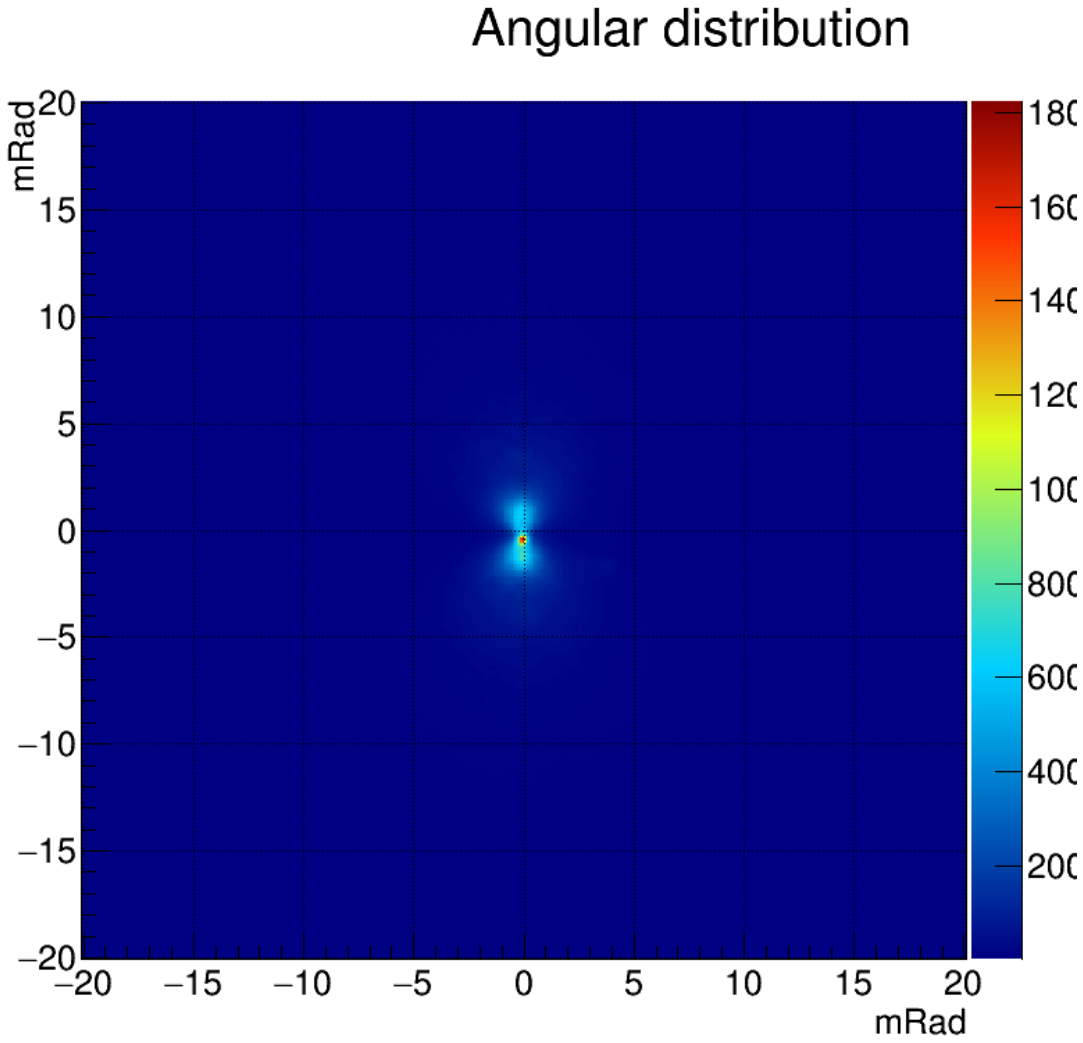
Although mask is inserted there is a strong Interference between Synchrotron Radiation and Transition Radiation because beam is not centered in the quadrupole (QM14FF) before the target.



Synchrotron Radiation Contribution at ATF2

No mask present, Alignment of the quadrupole magnet present before the target (QM14FF)

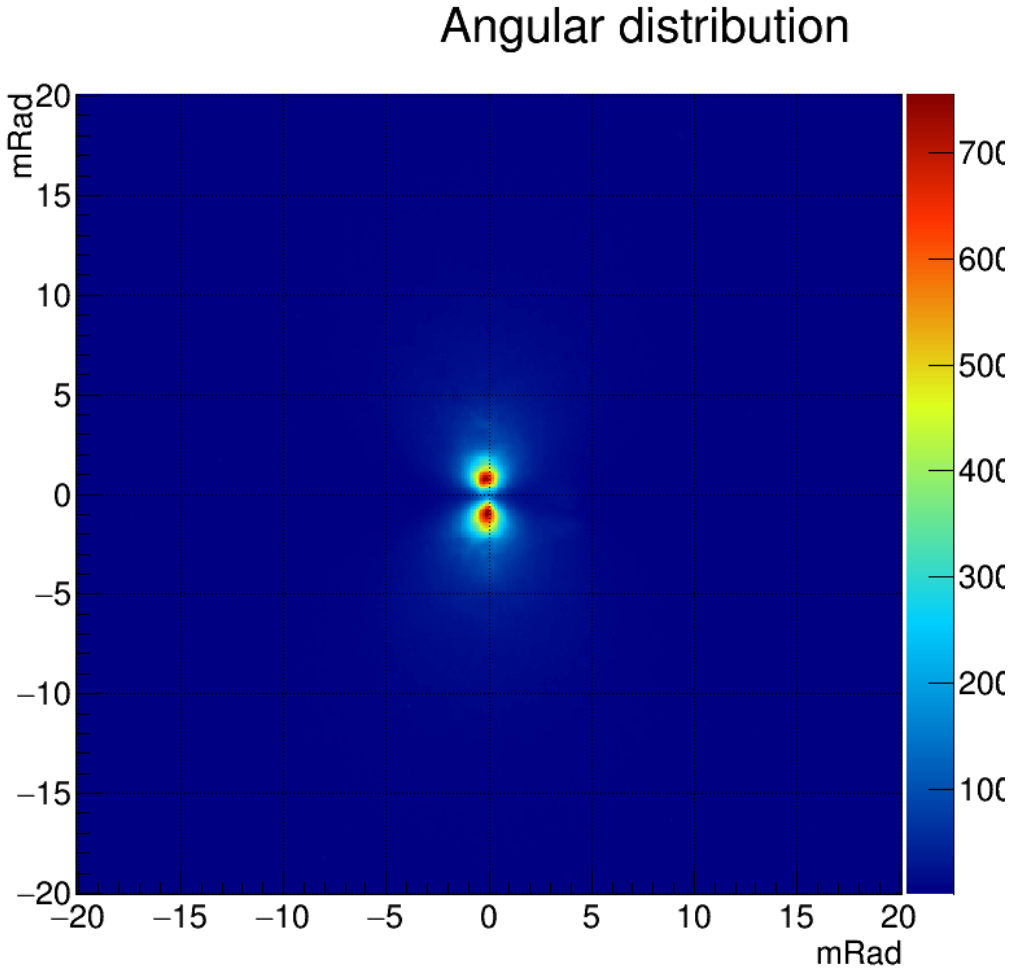
Better profile but peak present in the middle of the pattern due to Synchrotron Radiation generated upstream in the beam-line



Synchrotron Radiation Contribution at ATF2

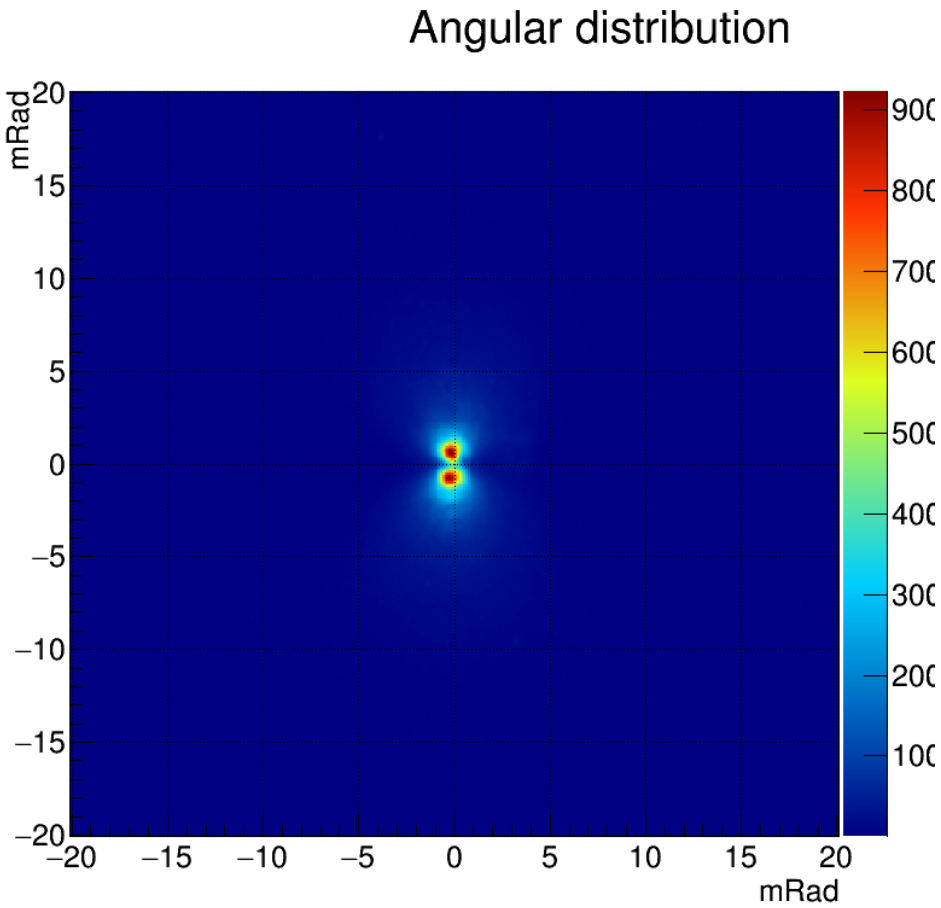
Re insertion of the mask (582 µm)

Maximum reduction of the Synchrotron Radiation Contribution

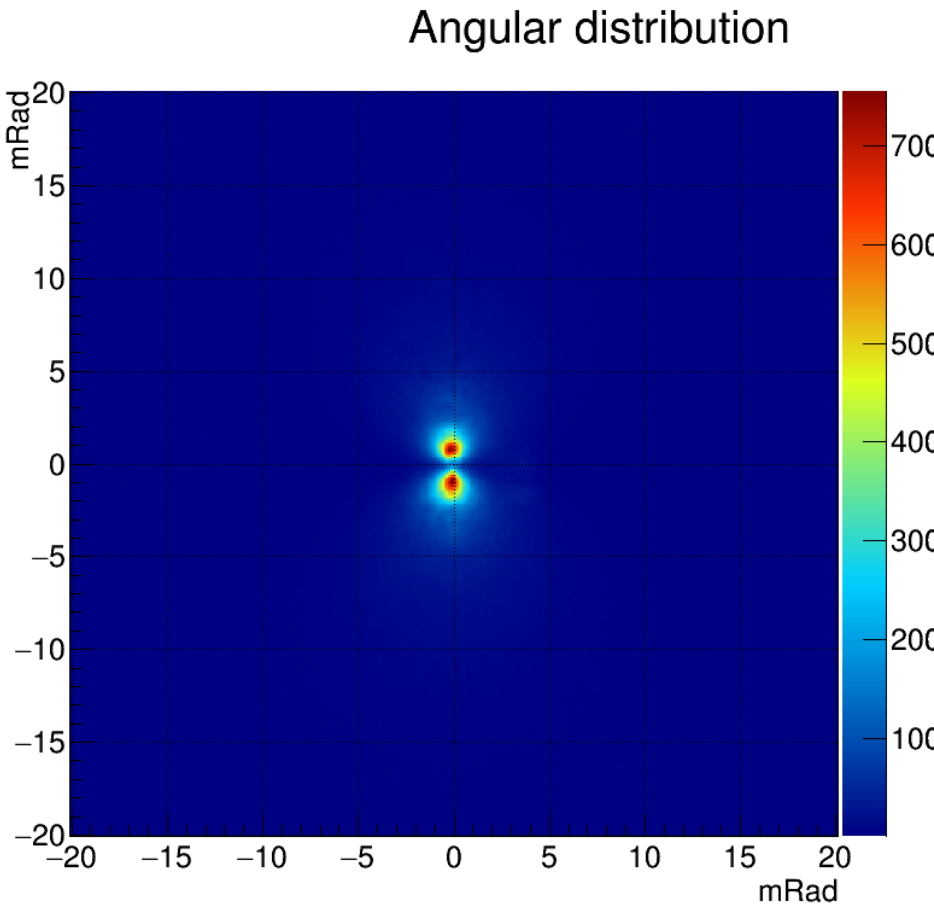


Synchrotron Radiation Contribution at ATF2

Before beam line optimization



After beam line optimization



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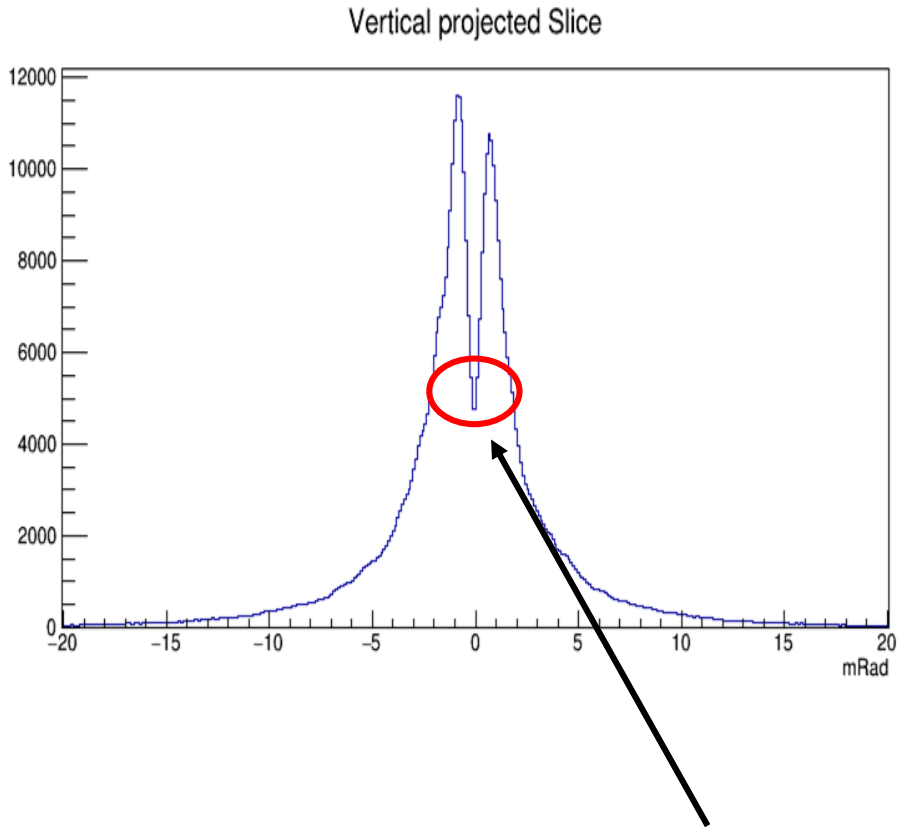
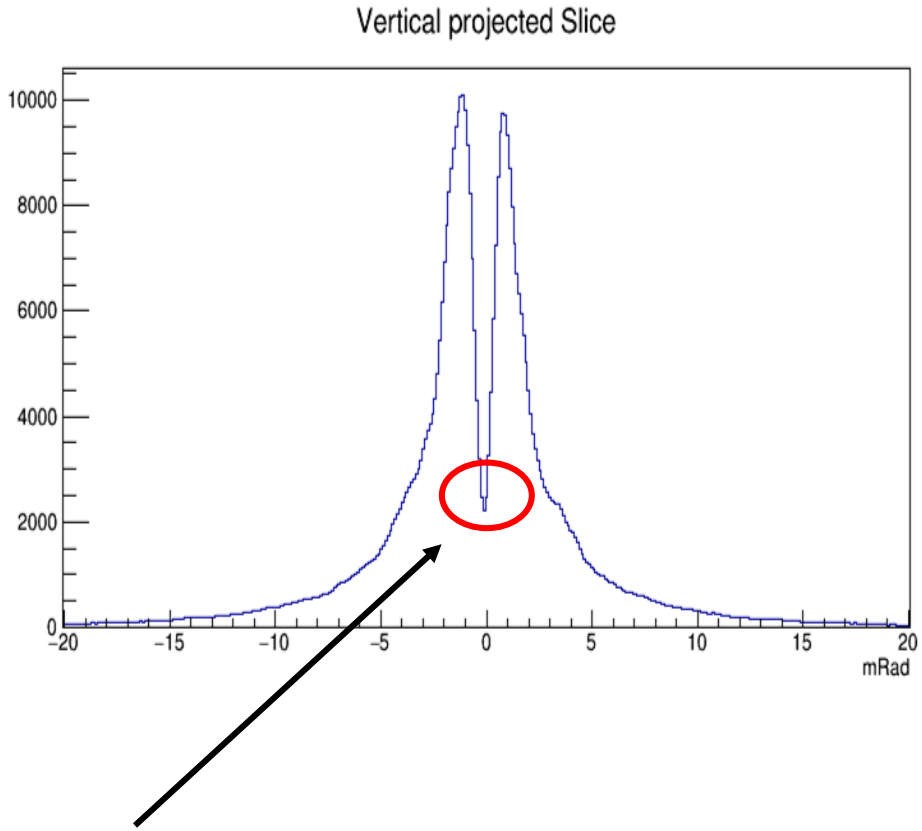
Synchrotron Radiation Contribution at ATF2

Before beam line optimization



After beam line optimization

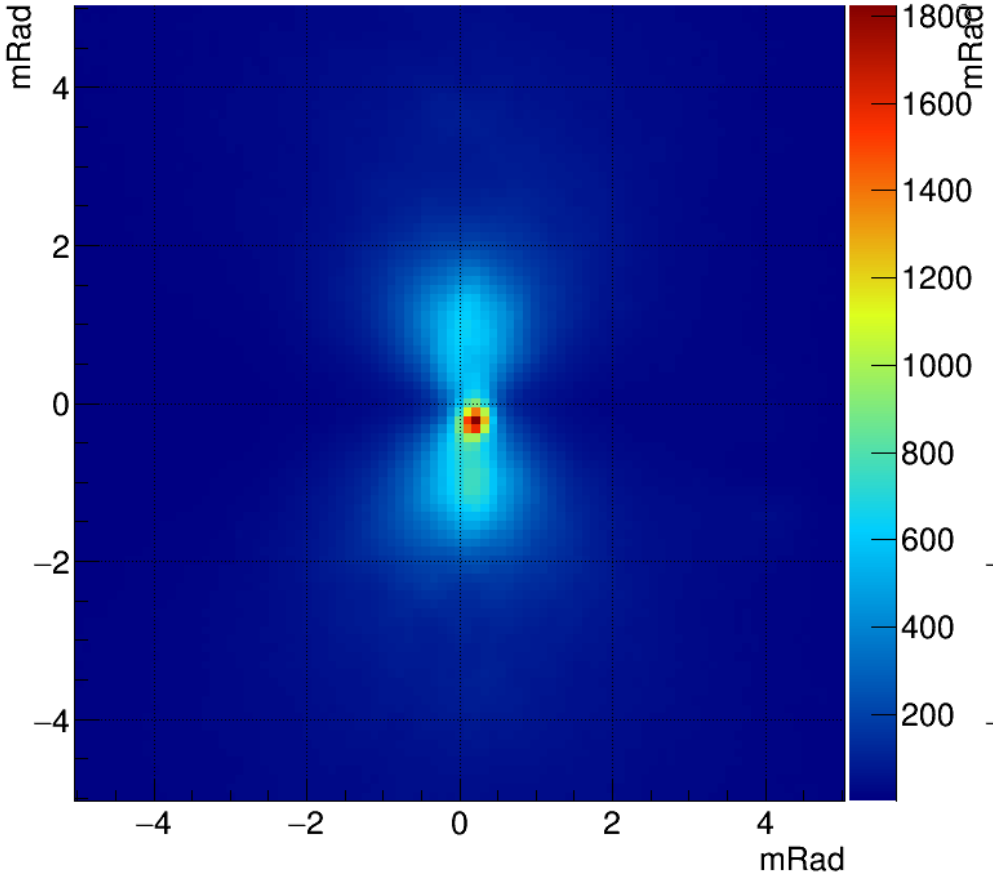


Lower minimum = lower SR Contribution

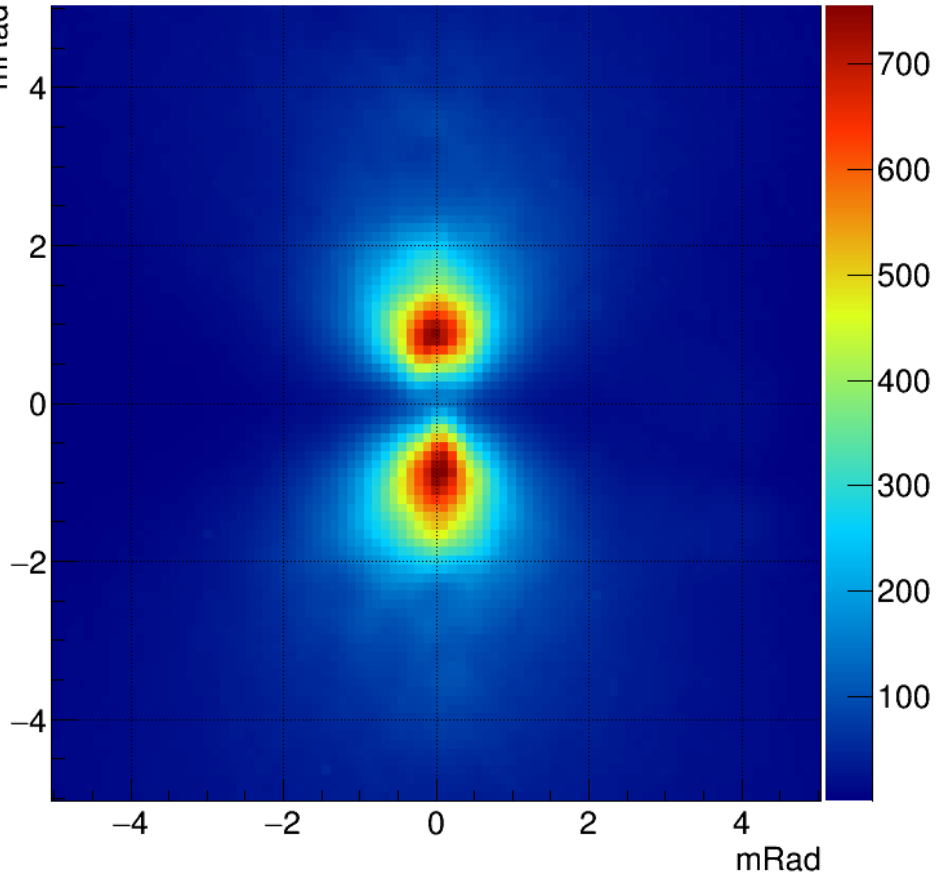
Binning limit the minima => bigger angular magnification needed

Synchrotron Radiation Contribution at ATF2

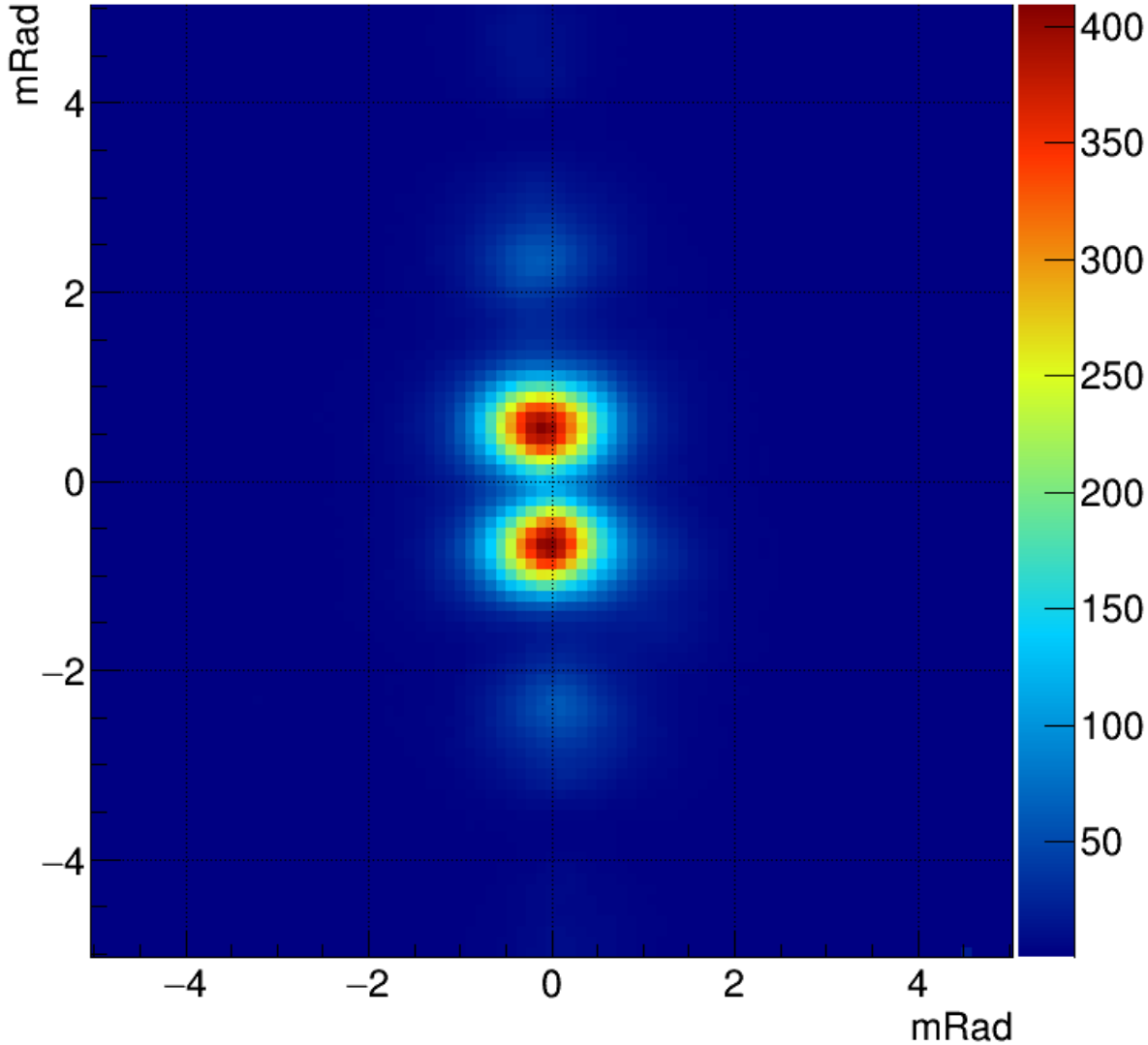
TR 2D profile without mask



TR 2D profile with mask



ODRI 2D angular intensity



$\lambda = 450\ nm$, beam size = 15.0 μm,
mask $= 582.0\ \mu m$, target $= 201.7\ \mu m$

ODRI simulation

$$E_{y,i} = \left\{ \frac{e^{-[(a_1/2)+z_1](f-ik_y)}}{f-ik_y} - \frac{e^{-[(a_1/2)-z_1](f+ik_y)}}{f+ik_y} \right\} -$$

$$-e^{i\Phi_0} \left\{ \frac{e^{-[(a_2/2)+z_2](f-ik_y)}}{f-ik_y} - \frac{e^{-[(a_2/2)-z_2](f+ik_y)}}{f+ik_y} \right\} \text{[1]}$$

With a_1 mask slit aperture, a_2 target slit aperture , z_1 and z_2 particle position at mask and slit, γ relativistic factor, λ observation wavelength, β ratio between the particle velocity and the speed of light, $k = (2\pi/\lambda)$, $\eta = (k/\beta\lambda)$, $\mathrm{f} = \sqrt{k_x^2 + \eta^2}$, $k_x = k \sin\theta \cos\phi$, $k_y = k \sin\theta \sin\phi$, $\Phi_0 = \eta d(1 - \beta \cos\theta)$, θ and ϕ angular coordinates in the observation plane.

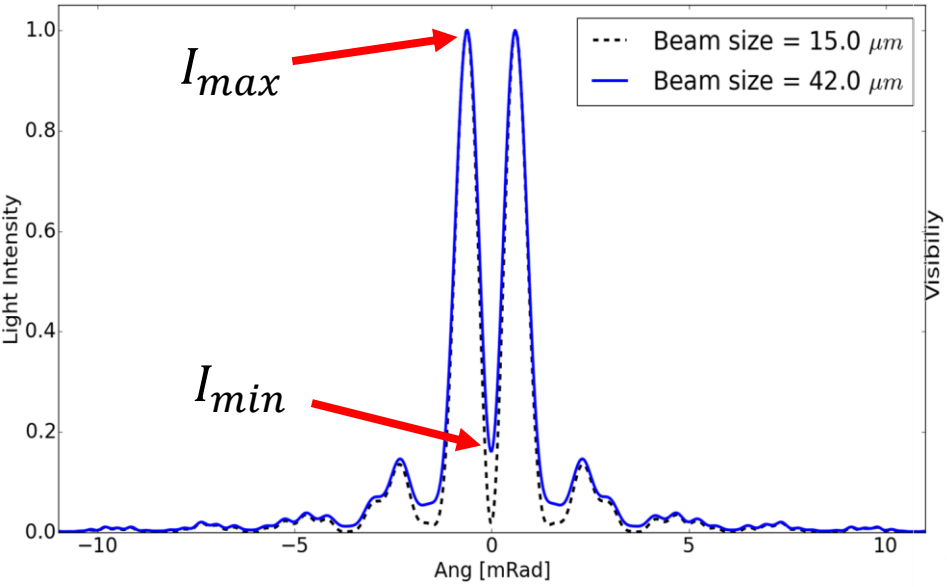
[1] A. Cianchi et al., *Non-intercepting electron beam size monitor using optical diffraction radiation interference*, Phys. Rev. ST Accel. Beams 14,102803 (2011)

ODRI simulation

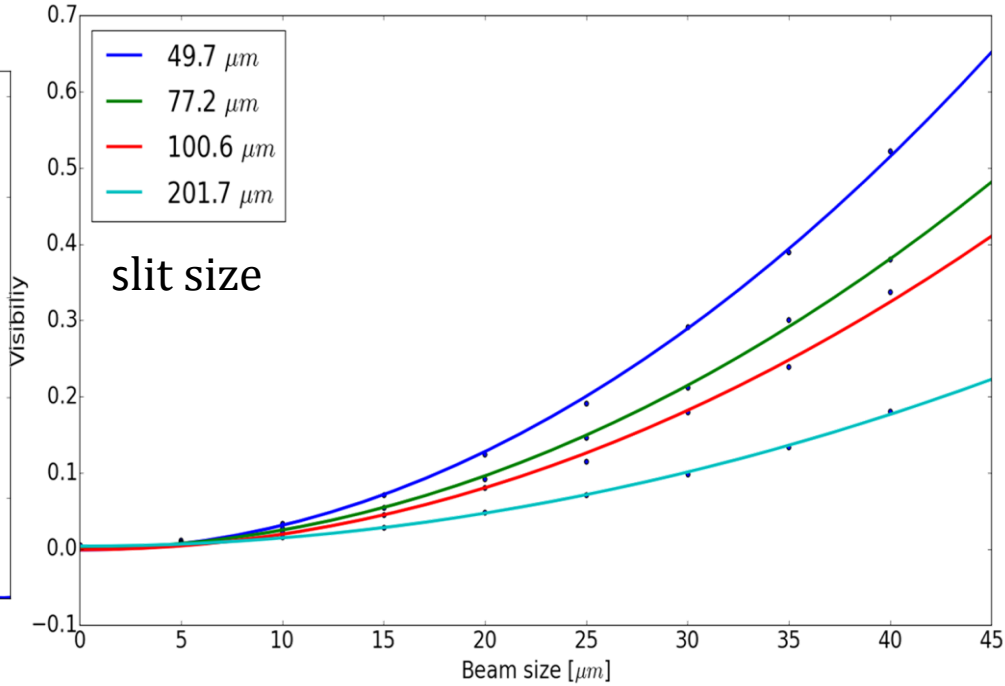
$$I = \sum_i^n E_{y,i}^2$$

$$n = 5000$$
$$d = 130\ mm$$

Projected Vertical Polarization Component (PVPC) [2] of DR angular Intensity for 2 beam sizes



Simulated Visibility vs Gaussian beam size for different target slit sizes



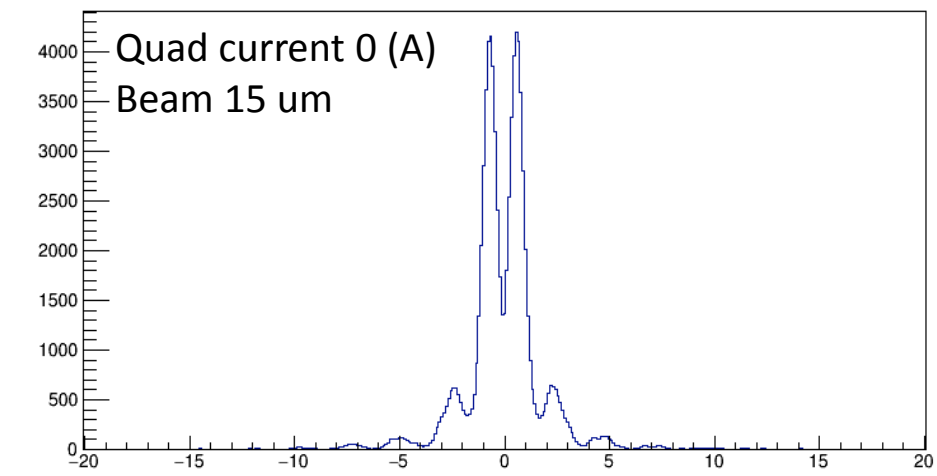
$\lambda = 450\ nm$, mask $= 582.0\ \mu m$, target $= 201.7\ \mu m$

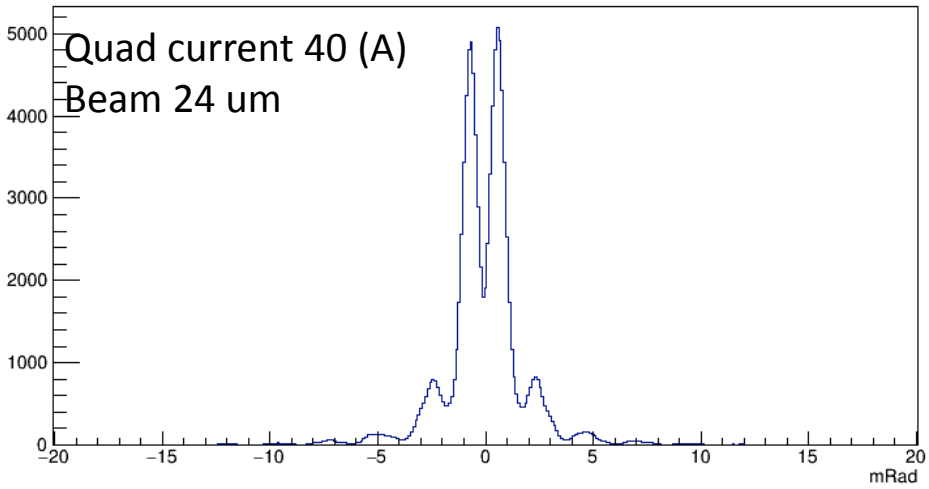
$$Visibility = I_{min}/I_{max}$$

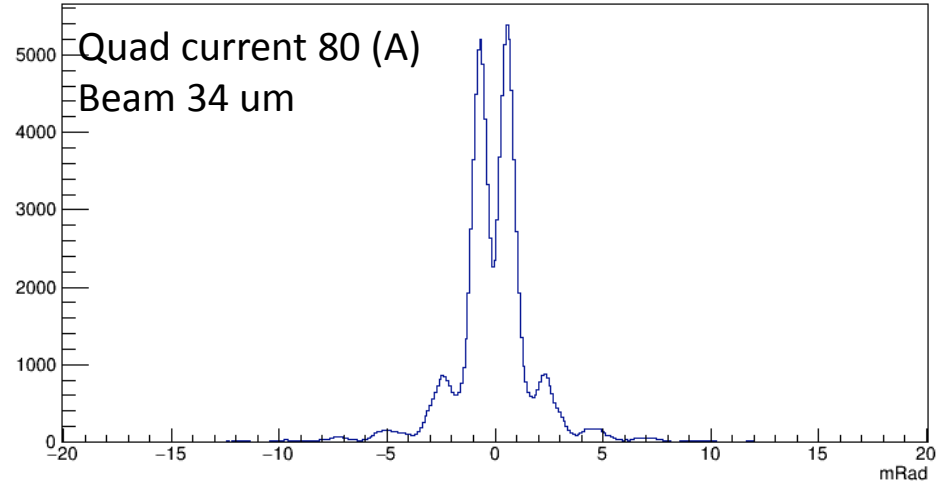
[2] P. Karataev, et al, *Beam Size Measurements with Optical Diffraction Radiation at KEK Accelerator Test Facility,* Phys. Rev. Lett. 93, 244802 (2004)

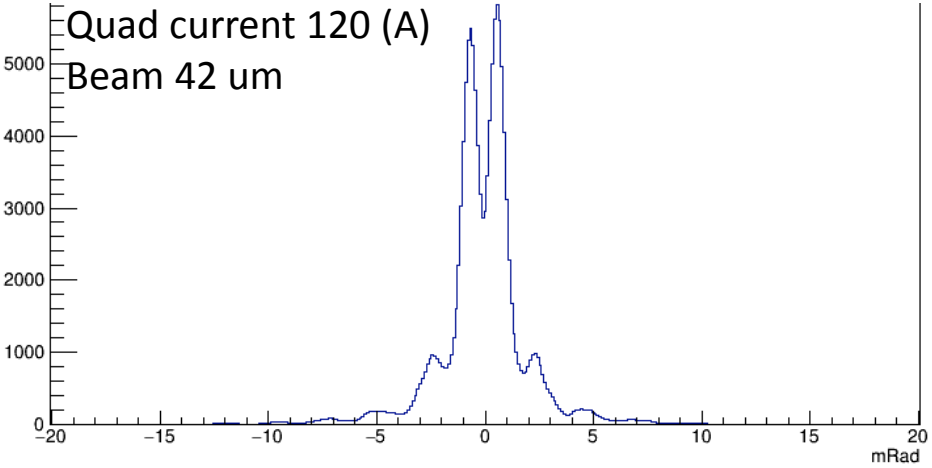
ODRI visibility Quad Scan

PVPC of DR angular intensity for different beam sizes





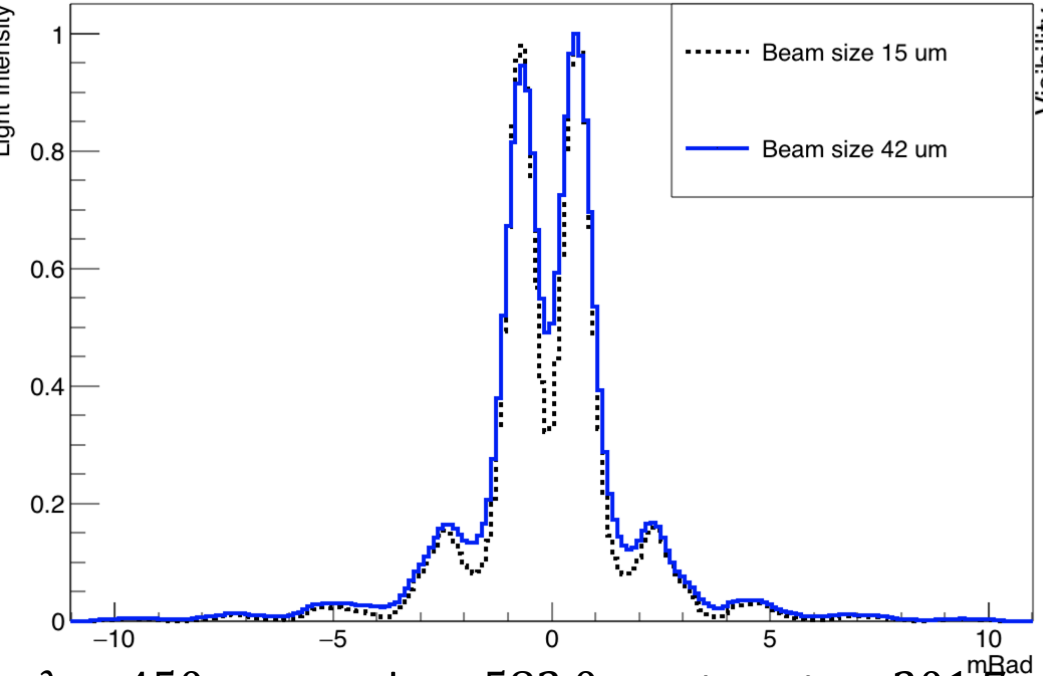




Filter:450nm Slit:201.7 µm Mask: 582 µm

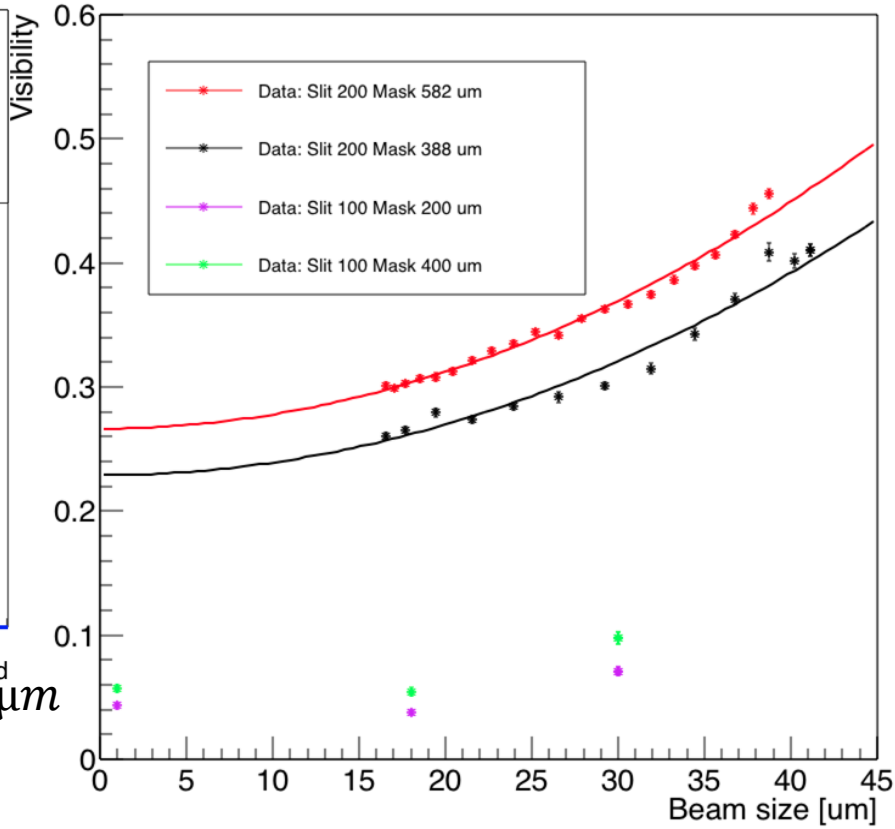
ODRI angular intensity

PVPC of DR angular intensity for 2 beam sizes



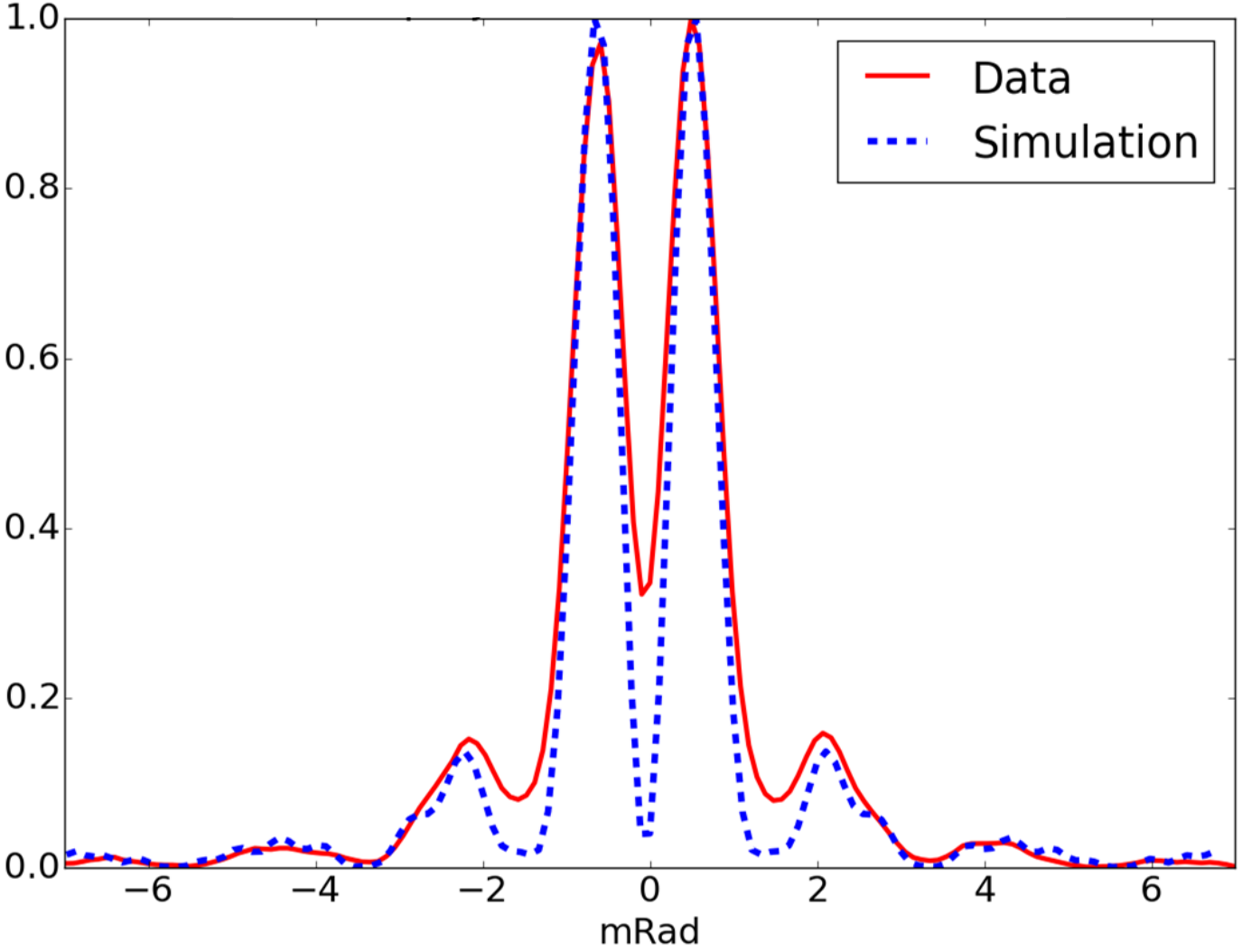
$\lambda = 450\ nm$, mask $= 582.0\ \mu m$, target $= 201.7\ \mu m$

Measured Visibility for different beam sizes and mask/target combination



ODR angular data vs simulation

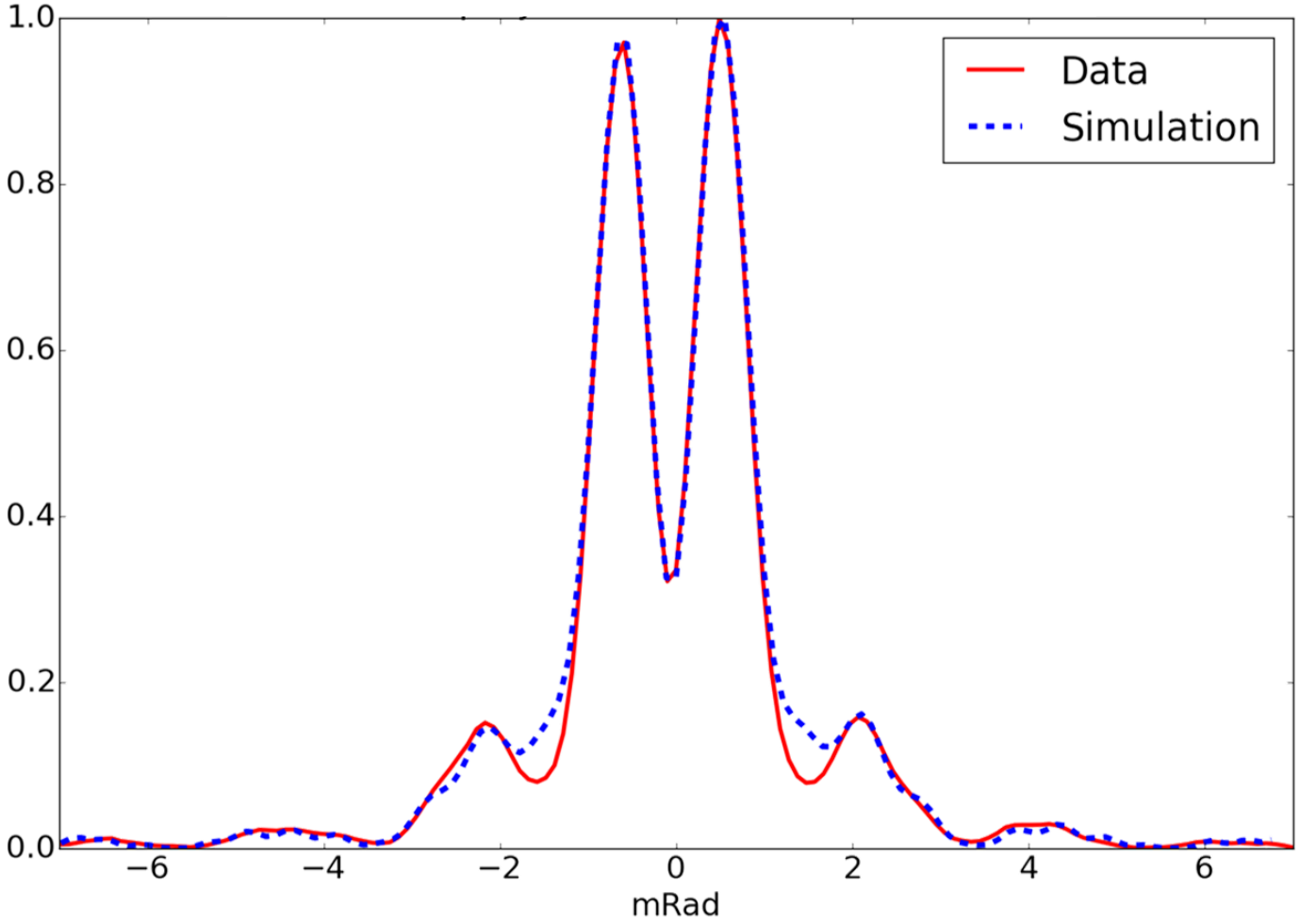
$\sigma = 15\ \mu m, \lambda = 450\ nm$, mask $= 582.0\ \mu m$, target $= 201.7\ \mu m$



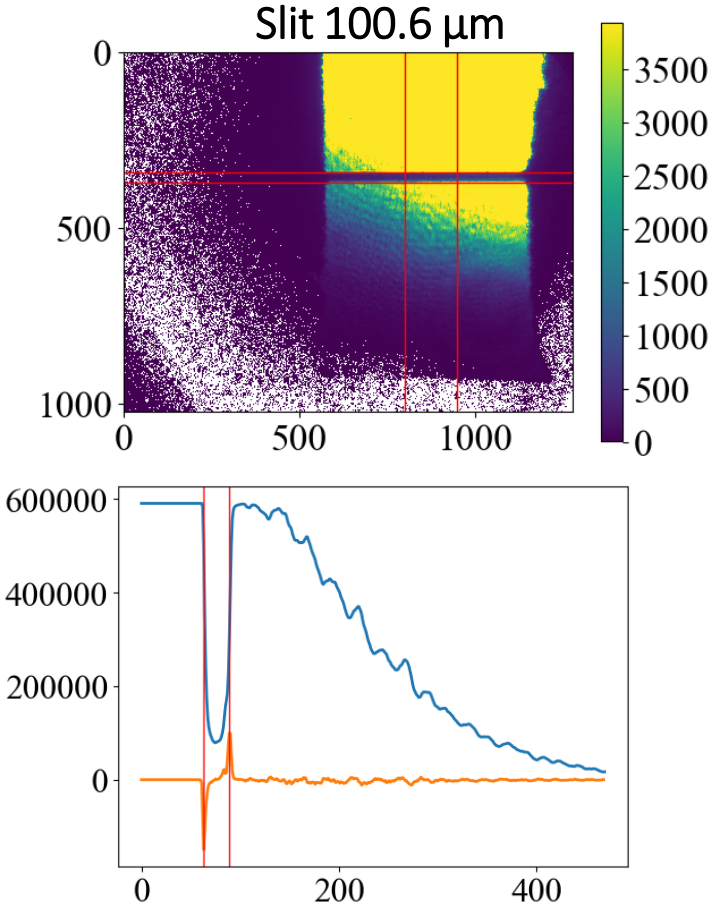
ODR angular data vs simulation

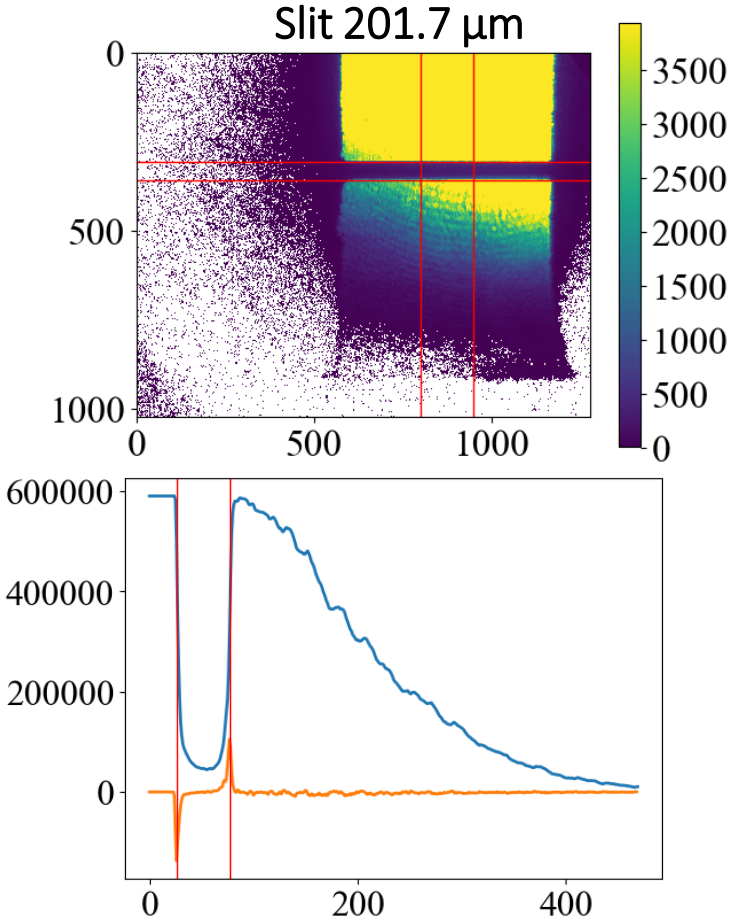
Synchrotron background Gaussian + 6 µm offset in the vertical alignment between slit and mask

$\sigma = 15\ \mu m, \lambda = 450\ nm$, mask $= 582.0\ \mu m$, target $= 201.7\ \mu m$

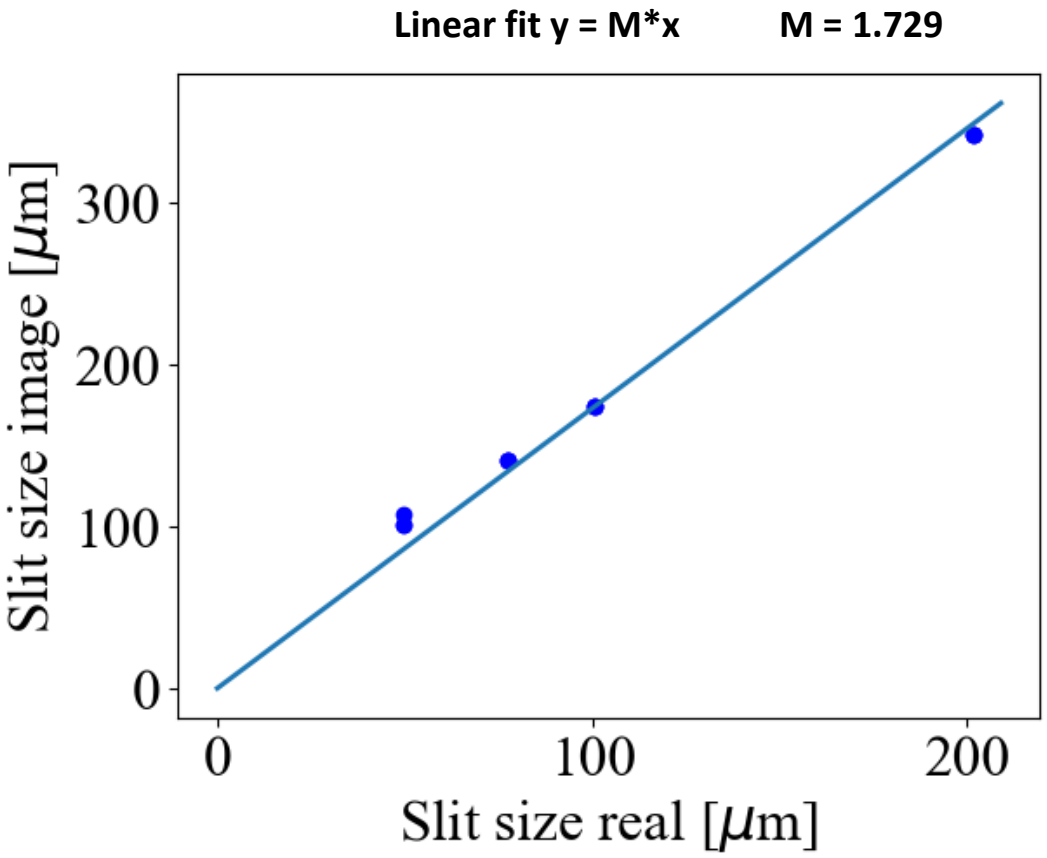


Single image with laser (632 nm) without filter



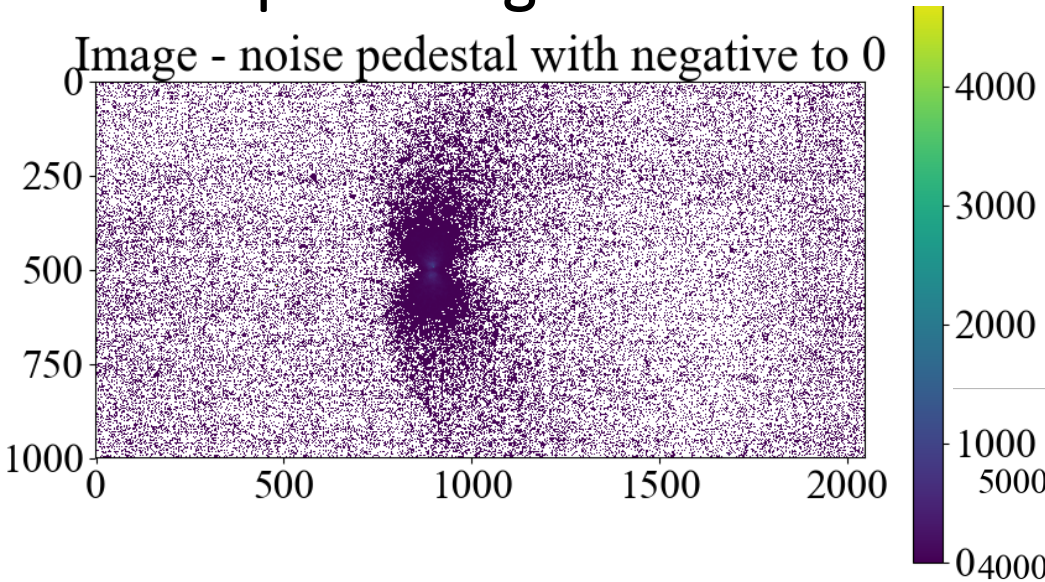


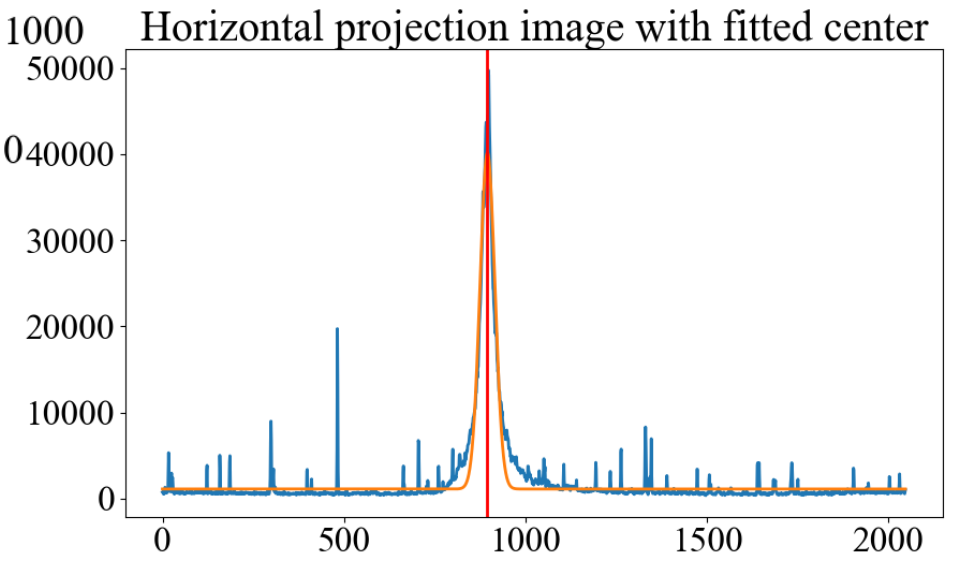
Final imaging calibration with laser



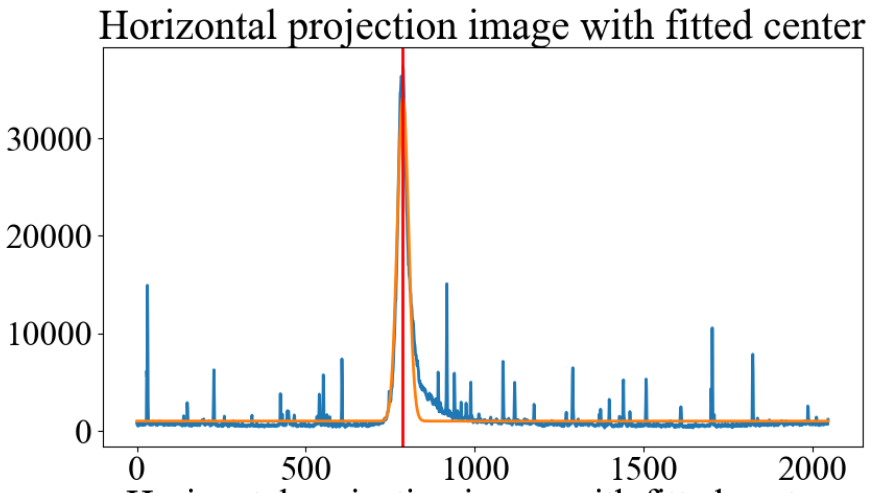
Calibration without filter
Magnification = 1.729
1 pixel = 3.874 µm

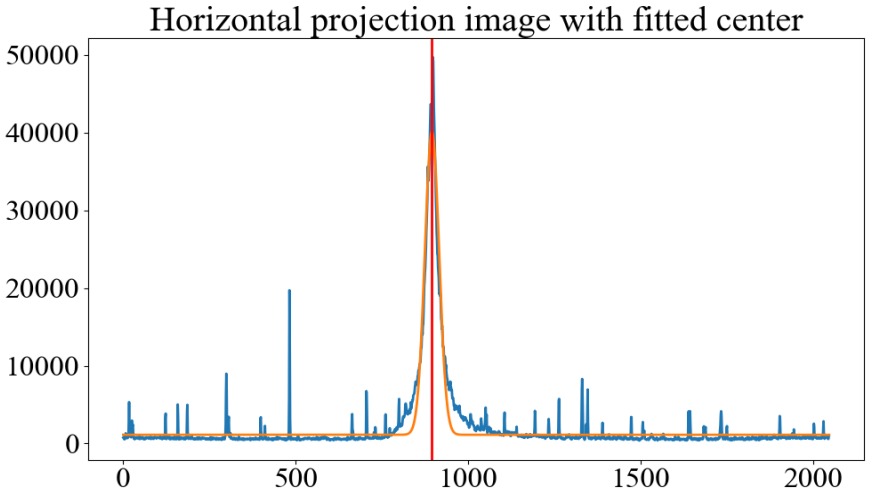
Example of angular calibration analysis (400nm)

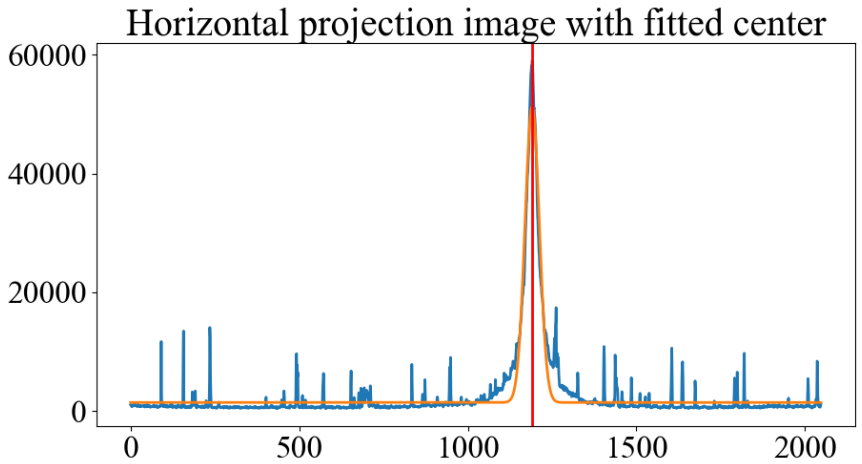


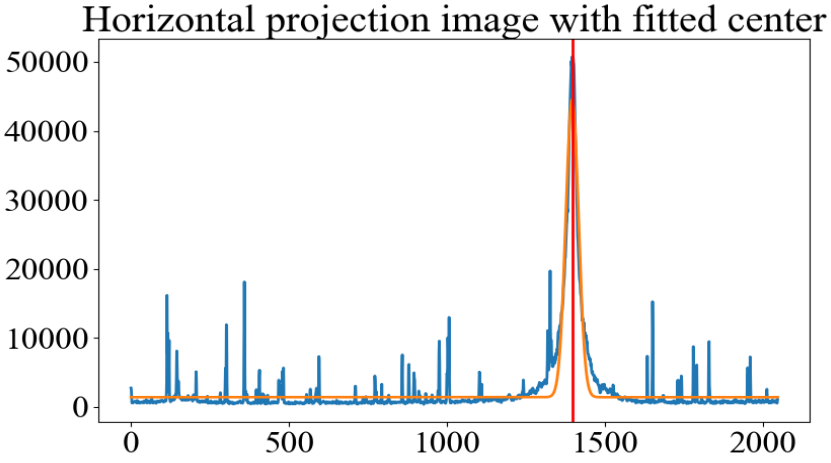


Rotate target registering step and encoder position









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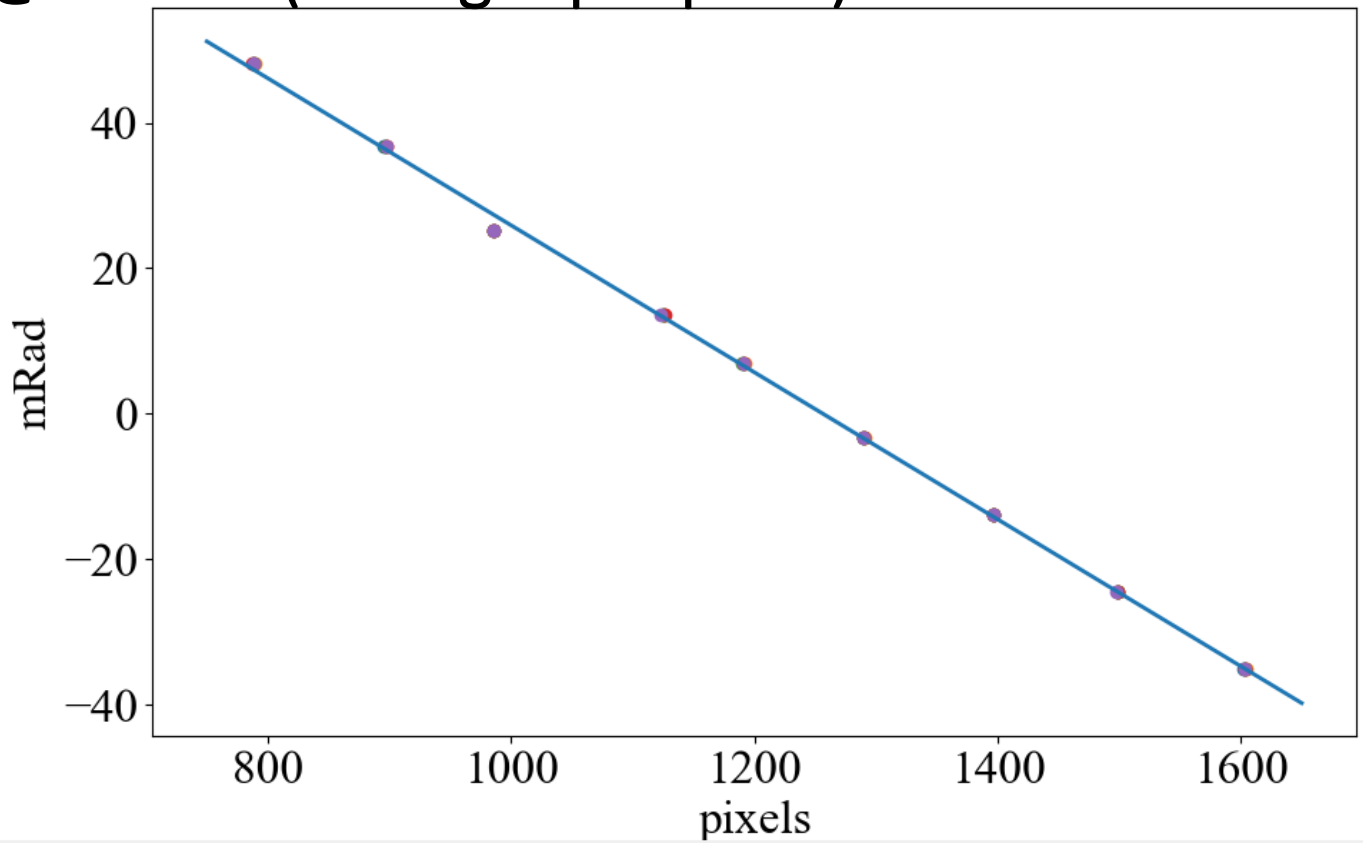
Final angular calibration taking into account mrad/encoder position @ 400nm (5 images per point)



Calibration @ 400nm
1 pixel = 0.0511 mrad

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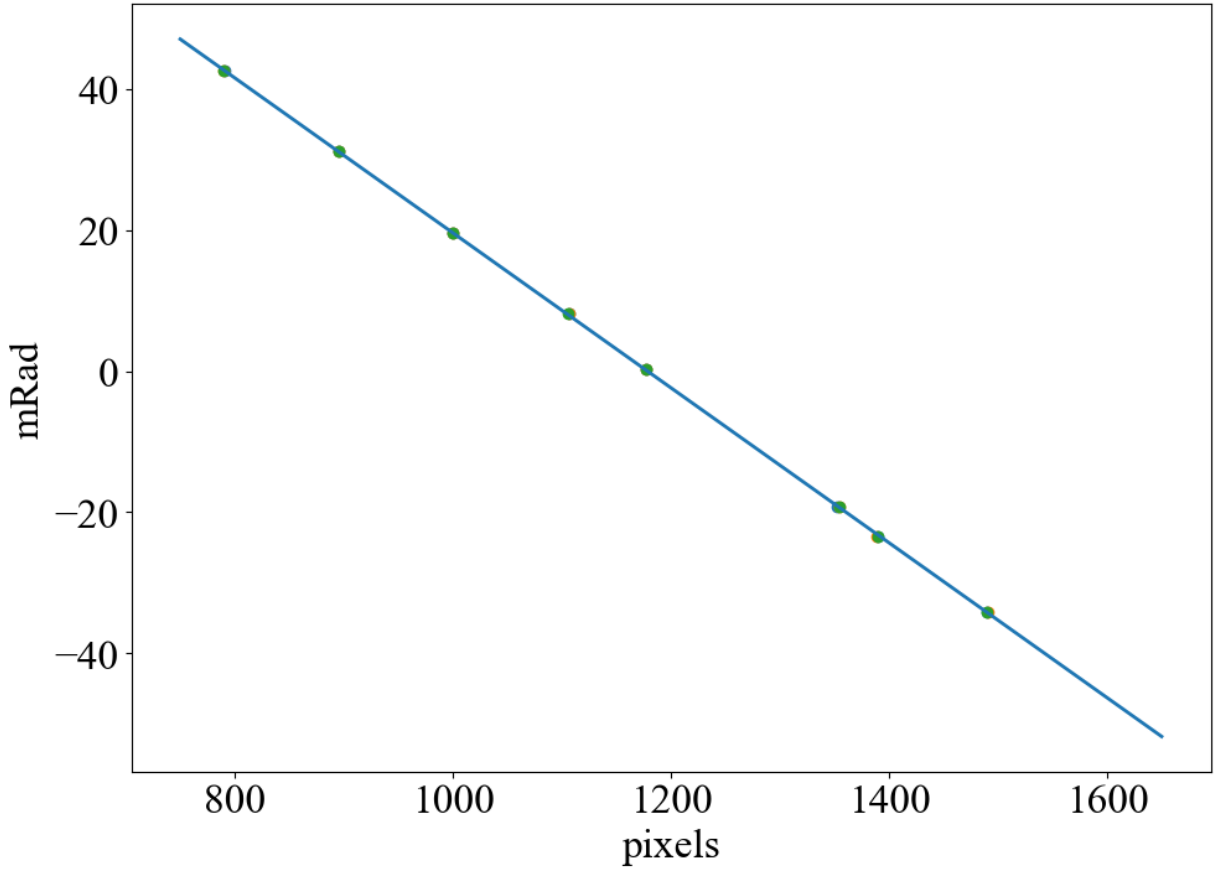
Final angular calibration @ 250nm (3 images per point)



Calibration @ 250nm
1 pixel = 0.0555 mrad

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