Optical Diffraction Radiation for the Large Hadron Collider

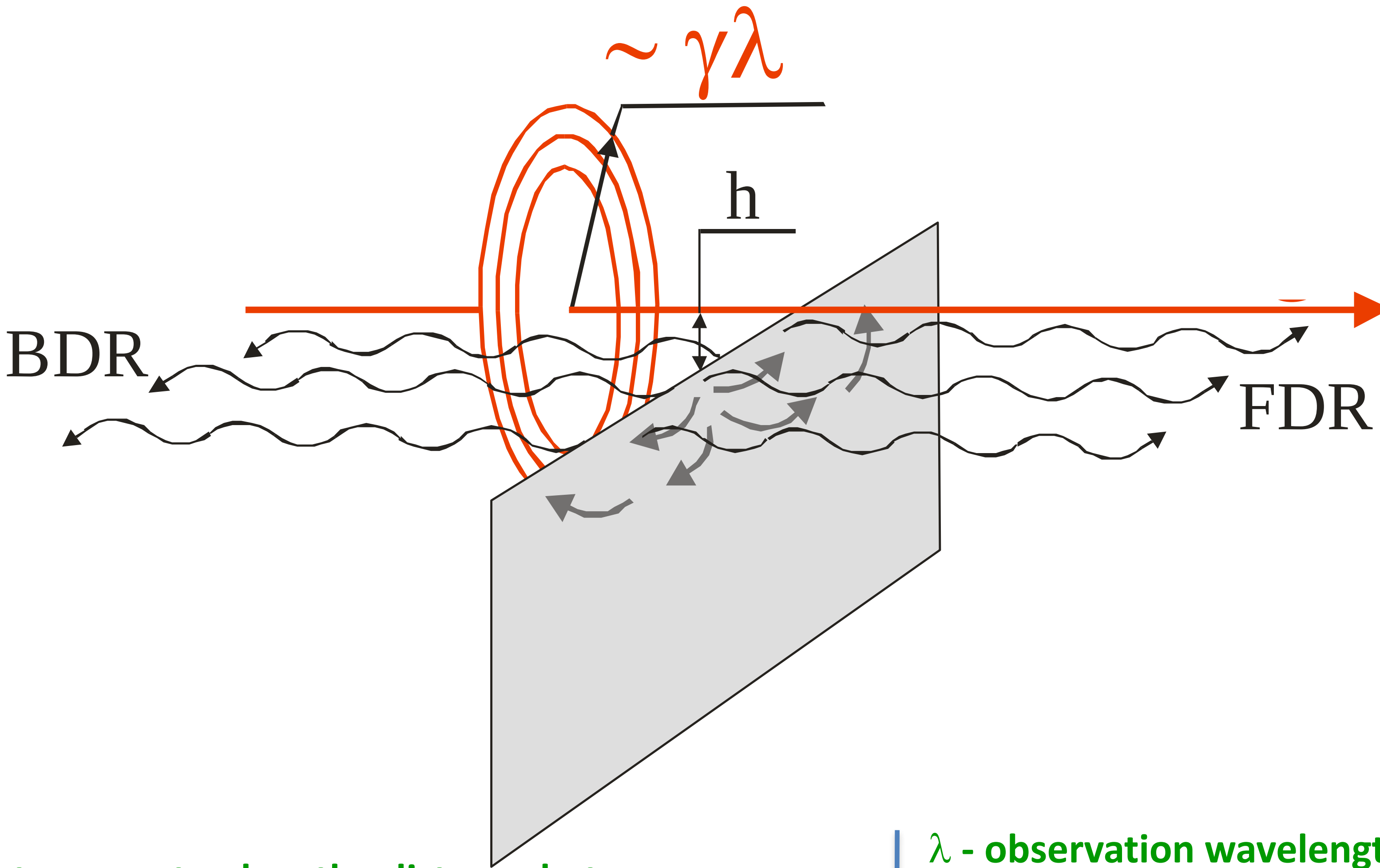
T. Aumeyr, M. Billing, L. Bobb, B. Bolzon, E. Bravin,
N. Chritin, P. Karataev, T. Lefevre *, S. Mazzoni

Outline

- Diffraction Radiation
  - Theory
  - Beam size monitoring
  - Data from past experiments
  - Already Known limitations
- Current Activities on DR
  - Simulation tools
  - Target developments
  - Experimental test on CESR ring @ Cornell
- Considerations for LHC

Diffraction Radiation

Diffraction radiation (DR) appears when a charged particle moves in the vicinity of a dielectric medium



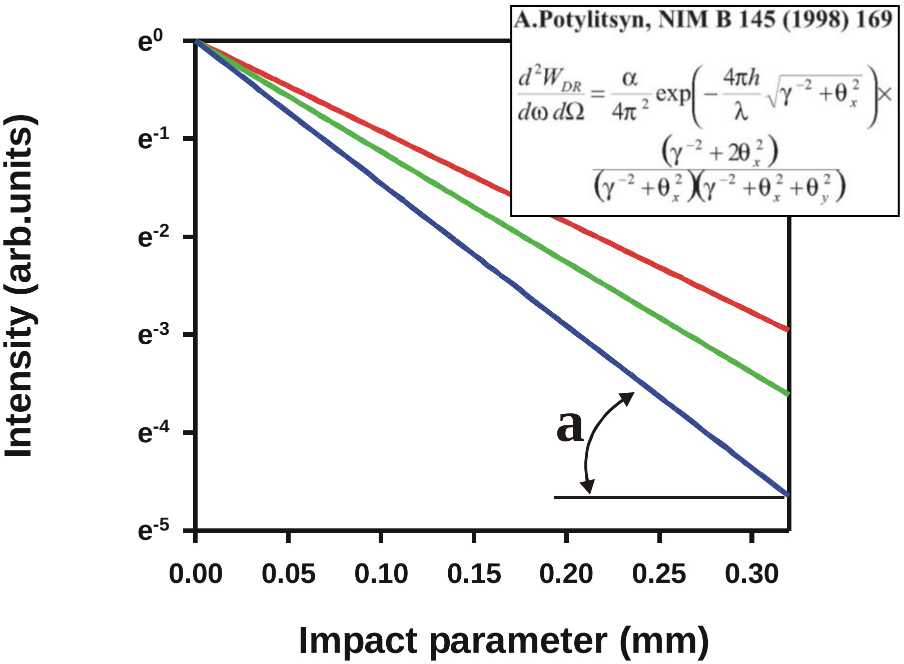
Impact parameter, h, – the distance between the target and the particle trajectory

λ - observation wavelength

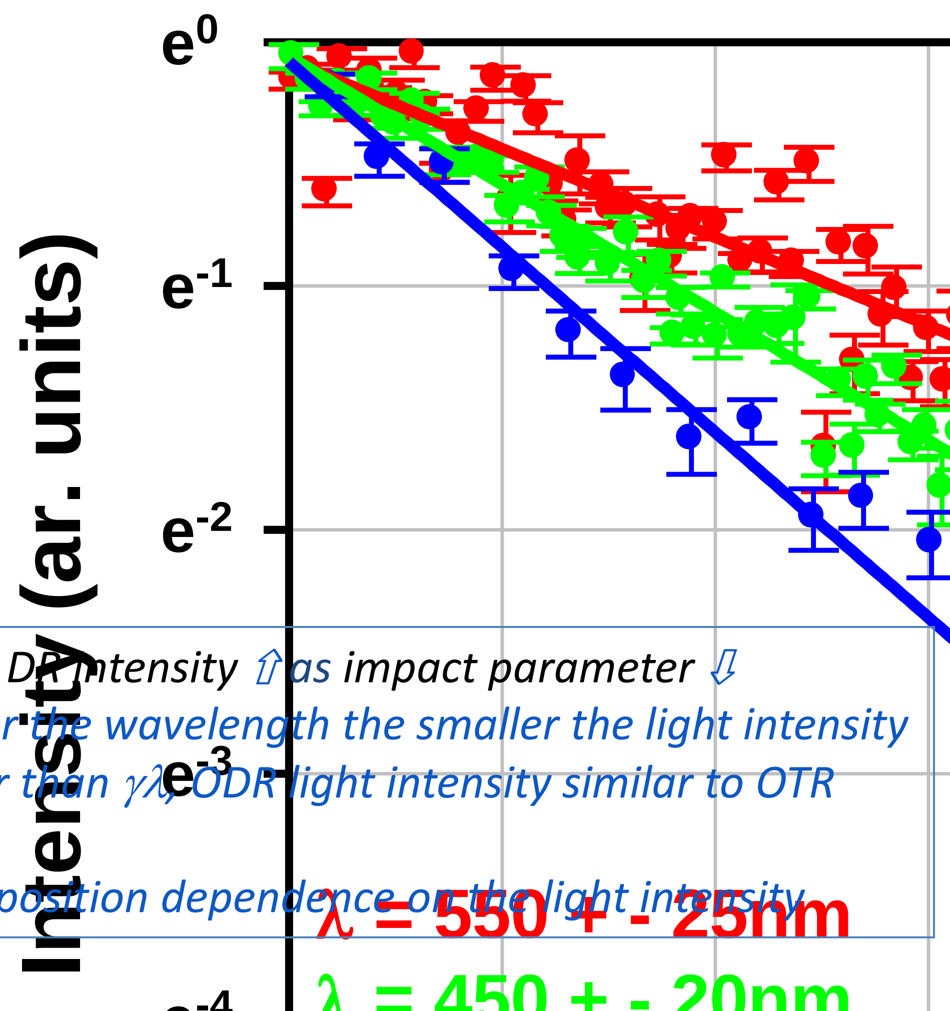
$\gamma = E/mc^2$ – Lorentz - factor

Diffraction Radiation

Light intensity as function of Impact parameter



Measured at ATF/KEK



λ	tan (a) theory	tan (a) experim.	Δtan (a) experim.
550nm	9.25	7.25	0.39
450nm	11.3	10.5	0.25
350nm	14.55	15.2	0.68

- *Generally: DR intensity ⇧ as impact parameter ⇩*
- *The shorter the wavelength the smaller the light intensity*
- *If h shorter than γλ, ODR light intensity similar to OTR*
- *There is a position dependence on the light intensity*

Beam size using DR

Most recent experiments using Optical Diffraction Radiation

- A.H. Lumpkin, W. J. Berg, N. S. Sereno, D. W. Rule and C. –Y. Yao, *“Near-field imaging of optical diffraction radiation generated by a 7-GeV electron beam”*, Phys. Rev. ST Accel. Beams 10, 022802 (2007).

- E. Chiadroni, M. Castellano, A. Cianchi, K. Honkavaara, G. Kube, V. Merlo and F. Stella, “Non-intercepting Electron Beam Transverse Diagnostics with Optical Diffraction Radiation at the DESY FLASH Facility”, Proc. of PAC07, Albuquerque, New Mexico, USA, FRPMN027.

- P. Karataev, S. Araki, R. Hamatsu, H. Hayano, T. Muto, G. Naumenko, A. Potylitsyn, N. Terunuma, J. Urakawa, *“Beam-size measurement with Optical Diffraction Radiation at KEK Accelerator Test Facility”*, Phys. Rev. Lett. 93, 244802 (2004).

σ_y = 14 μm measured
ATF2@KEK

Beam size using DR

Direct imaging on Diffraction Radiation from a single edge

A. Lumpkin et al, Measured at APS booster dump line

Images

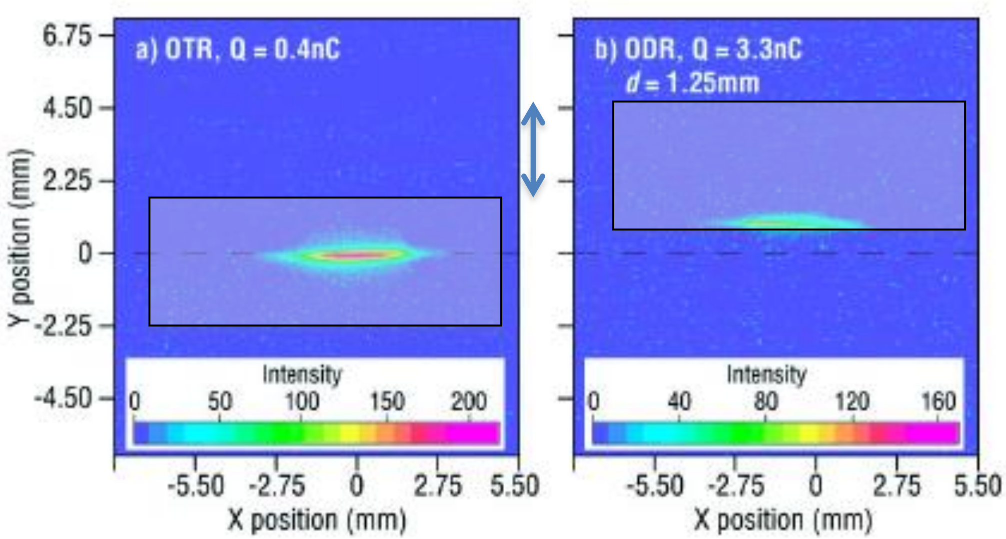


FIG. 4. (Color) Images produced by the 7-GeV beam: (a) OTR with $Q = 0.4$ nC and (b) ODR with $d = 1.25$ mm and $Q = 3.3$ nC. The dashed line is the beam centerline.

Vertical profiles

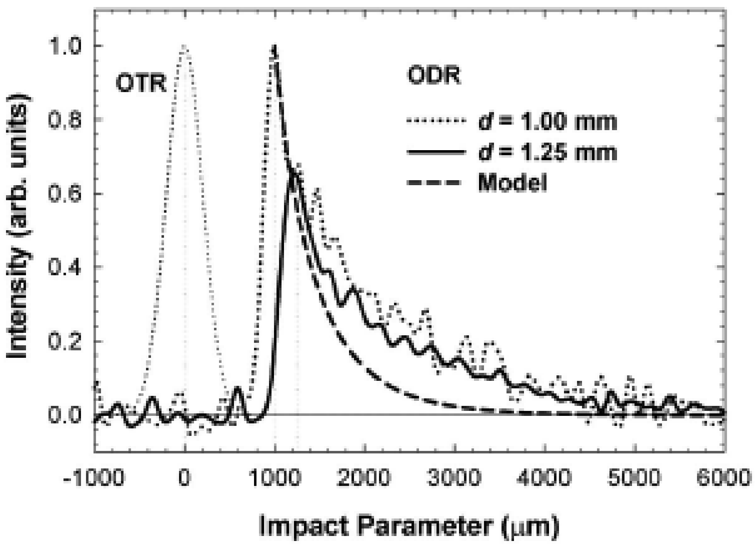


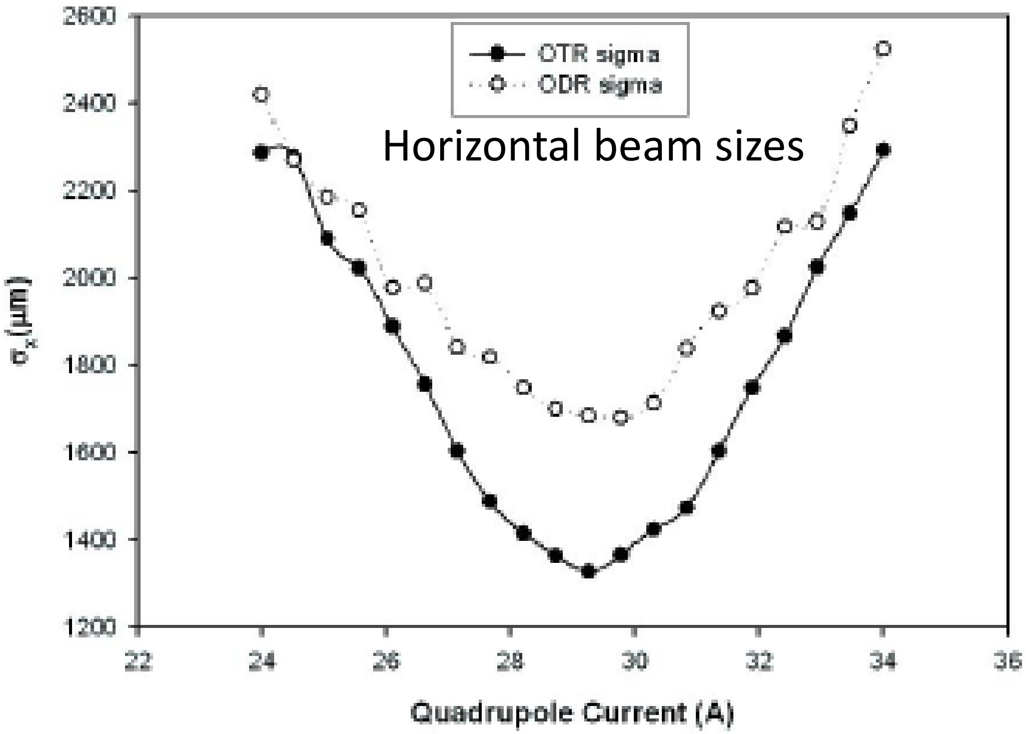
FIG. 7. Comparison plots of a Gaussian fit to the OTR beam distribution for $\sigma_y = 200$ μm centered at $d = 0$, the $d = 1000$ (dotted line) and 1250 μm (solid line) ODR image vertical profiles, and the Eq. (1) model result (dashed line) scaled to the vertical profile data.

Using an Horizontal slit to measured the horizontal beam size using vertically polarized photons

Beam size using DR

Direct imaging on Diffraction Radiation from a single edge

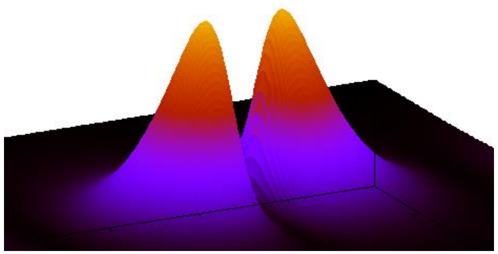
A. Lumpkin et al, Measured at APS booster dump line



- Observed 5 to 25% mismatch in beam sizes measured with OTR
- Contribution of OTR from halo particles to the ODR images ?
- No mask to suppress Sync light

Beam size using DR

Observing the interference pattern produced as the particles passes through a slit



DR Angular distribution

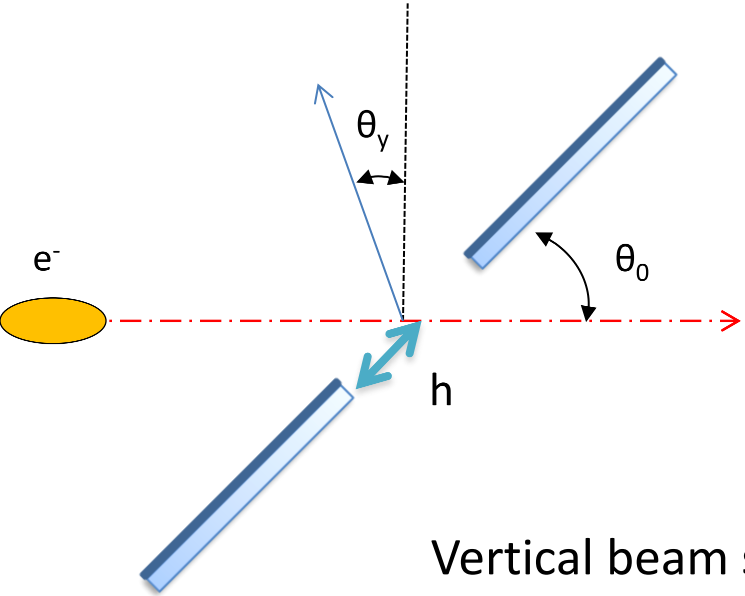
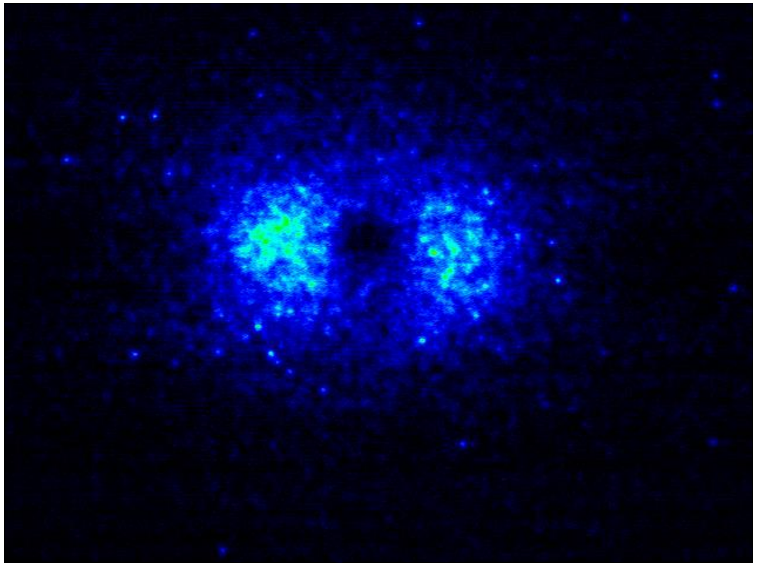


Image measured at ATF/KEK



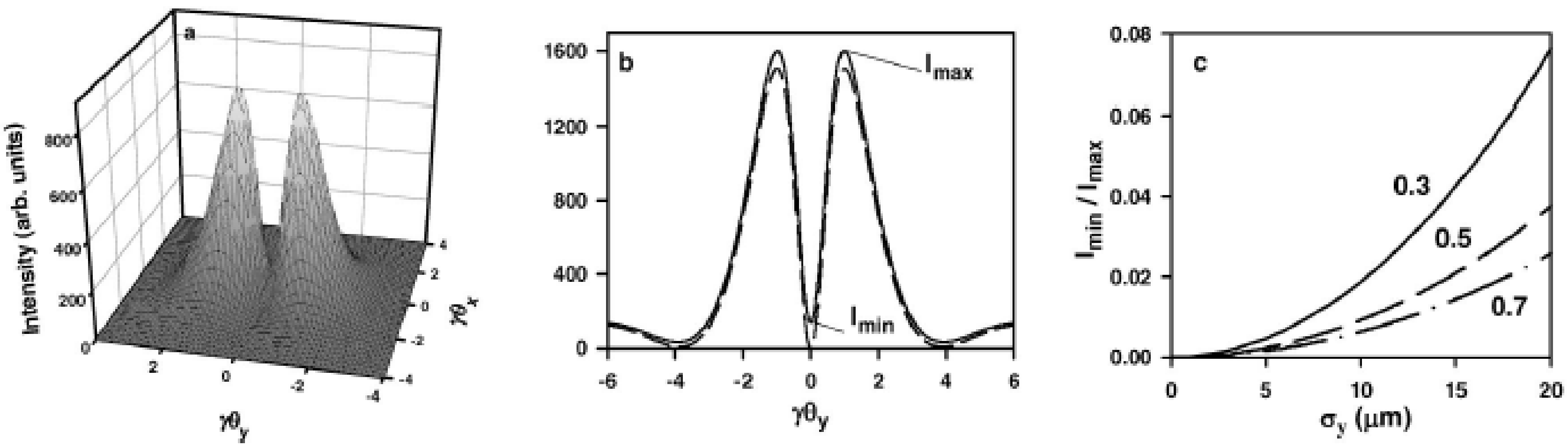
Vertical beam size measured from vertically polarized photons emitted by a horizontal slit

Beam size using DR

Vertical Beam Size Measurement using the Optical Diffraction Radiation (ODR) model + Projected Vertical Polarisation Component (PVPC)

P. Karataev et al.

PRL 93, 244802 (2004) PHYSICAL REVIEW LETTERS week ending 10 DECEMBER 2004



Vertical polarisation component of 3-dimensional (θ_x, θ_y, Intensity) DR angular distribution.

→

PVPC is obtained by integrating over θ_x to collect more photons.

→

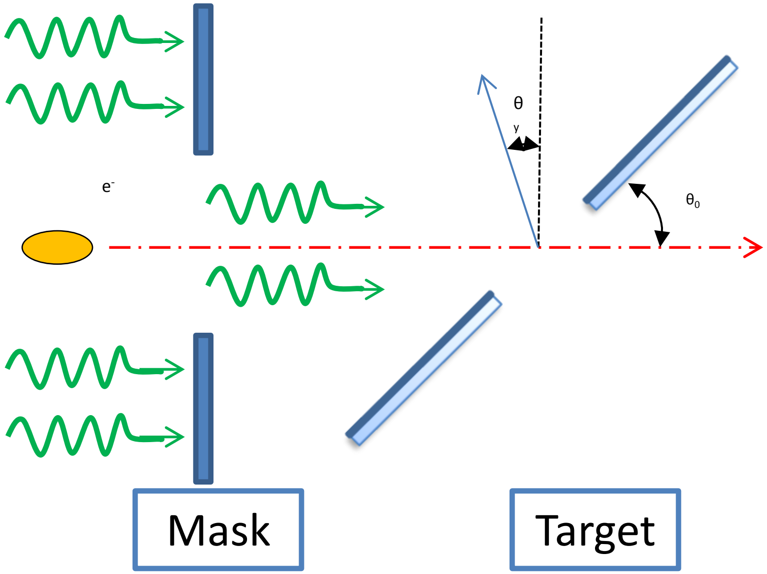
Visibility (I_{min}/I_{max}) of the PVPC is sensitive to vertical beam size σ_y.

Interference with SR

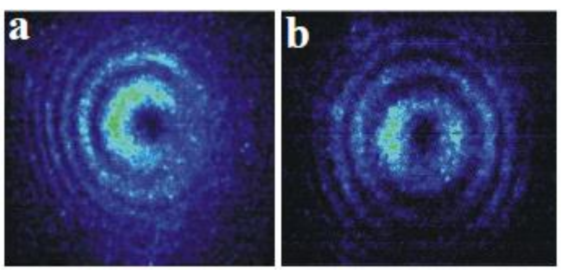
For ultra-relativistic beam, the formation length of the radiation becomes large and the SR photons emitted from neighboring magnet will interfere with DR

Source of background	Contribution
SR from beam-line optics	High
Camera noise	Low
Residual background	

Use a mask upstream of target to suppress SR contribution.

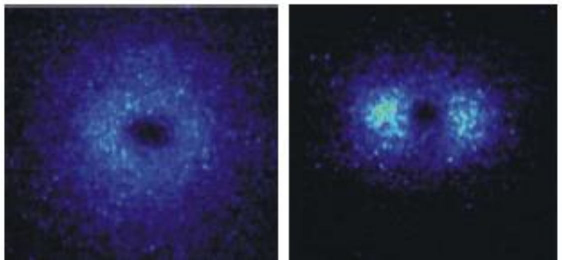


SR interference



OTR ODR

SR suppression



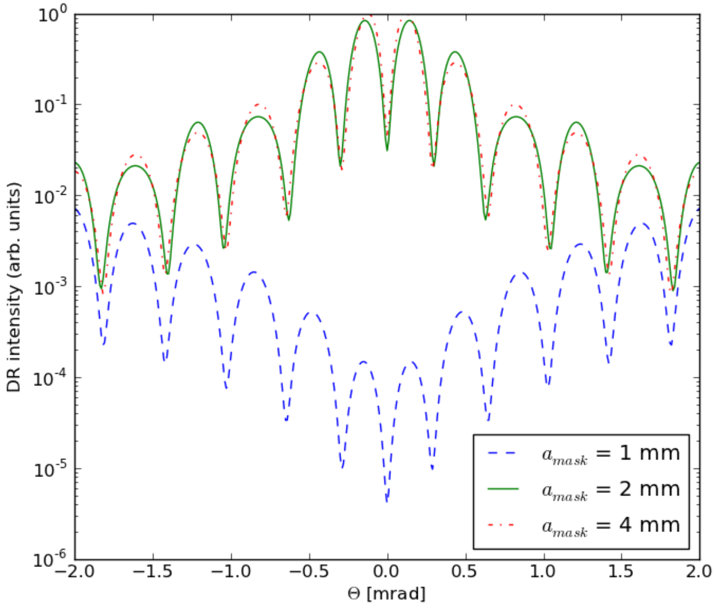
P. Karataev et al., Proc. of EPAC 2004, THPLT067

Interference with SR

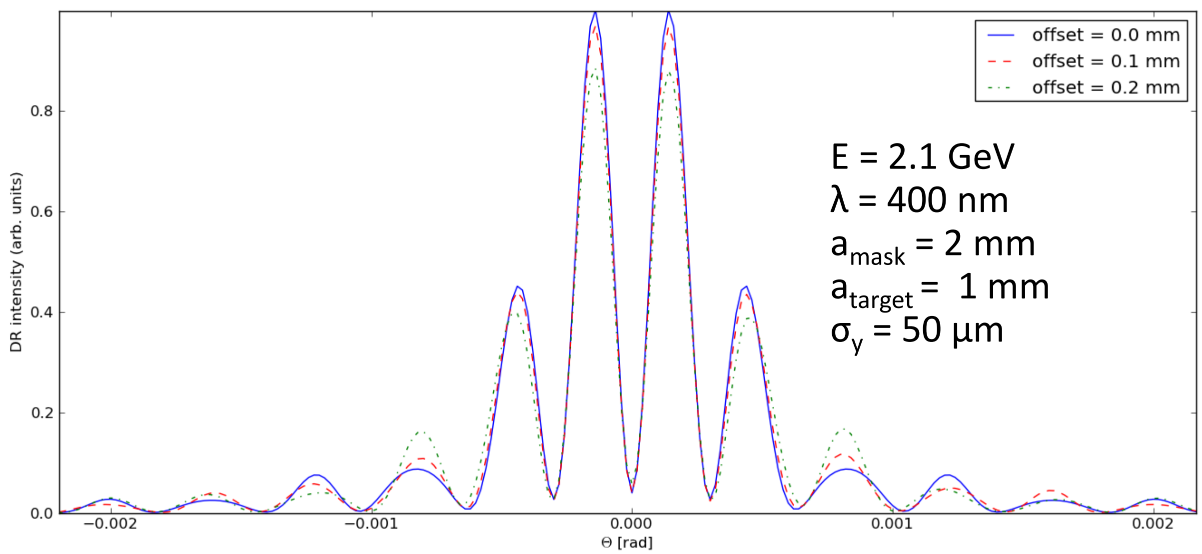
Optical Diffraction Radiation Interference

A. Cianchi et al., Phys. Rev. ST Accel. Beams 14 (10) 102803 (2011)

Aperture sizes	Interference
$a_{mask} = a_{target}$	Complete destructive interference of FDR + BDR (blue)
$a_{mask} \approx 2 \cdot a_{target}$	Measureable interference (green)
$a_{mask} \geq 4 \cdot a_{target}$	Negligible interference (red)

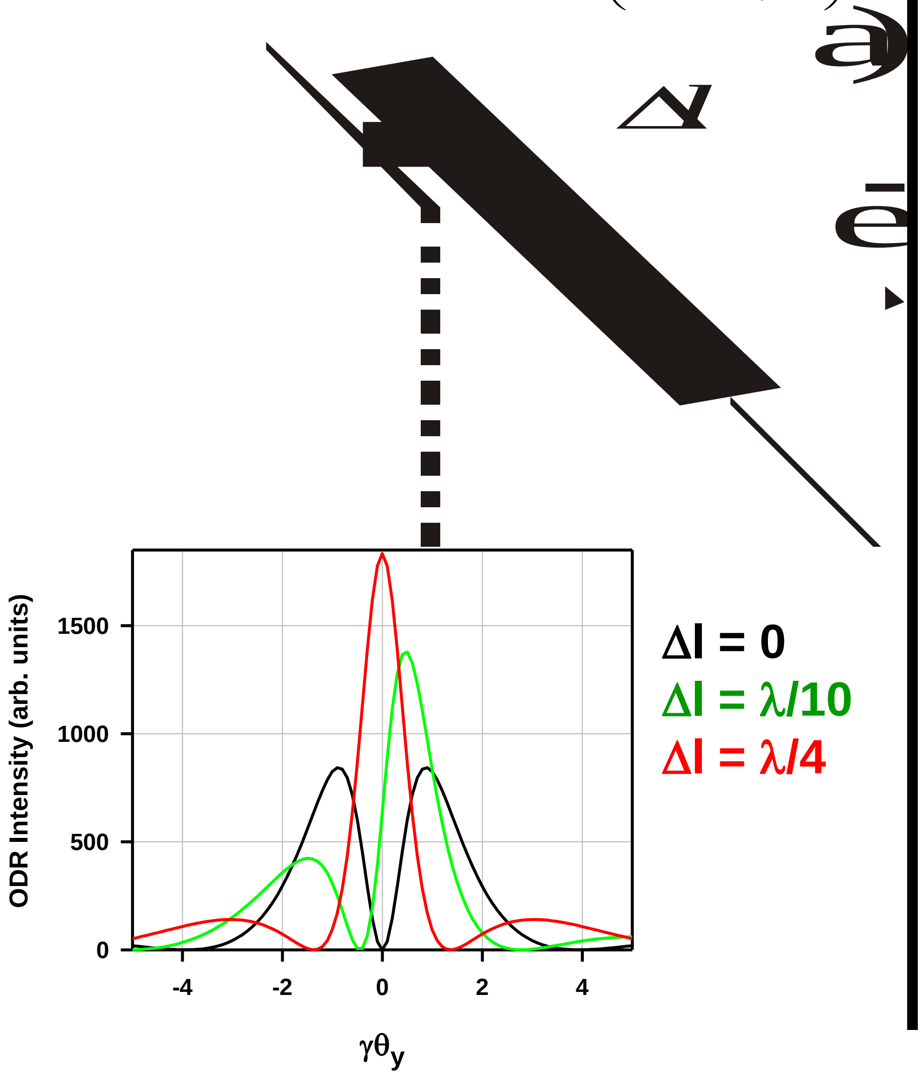


Using non-collinear slits (i.e. centres of mask + target do not coincide) allows measurement of beam size, beam offset from the target centre and angular divergence.

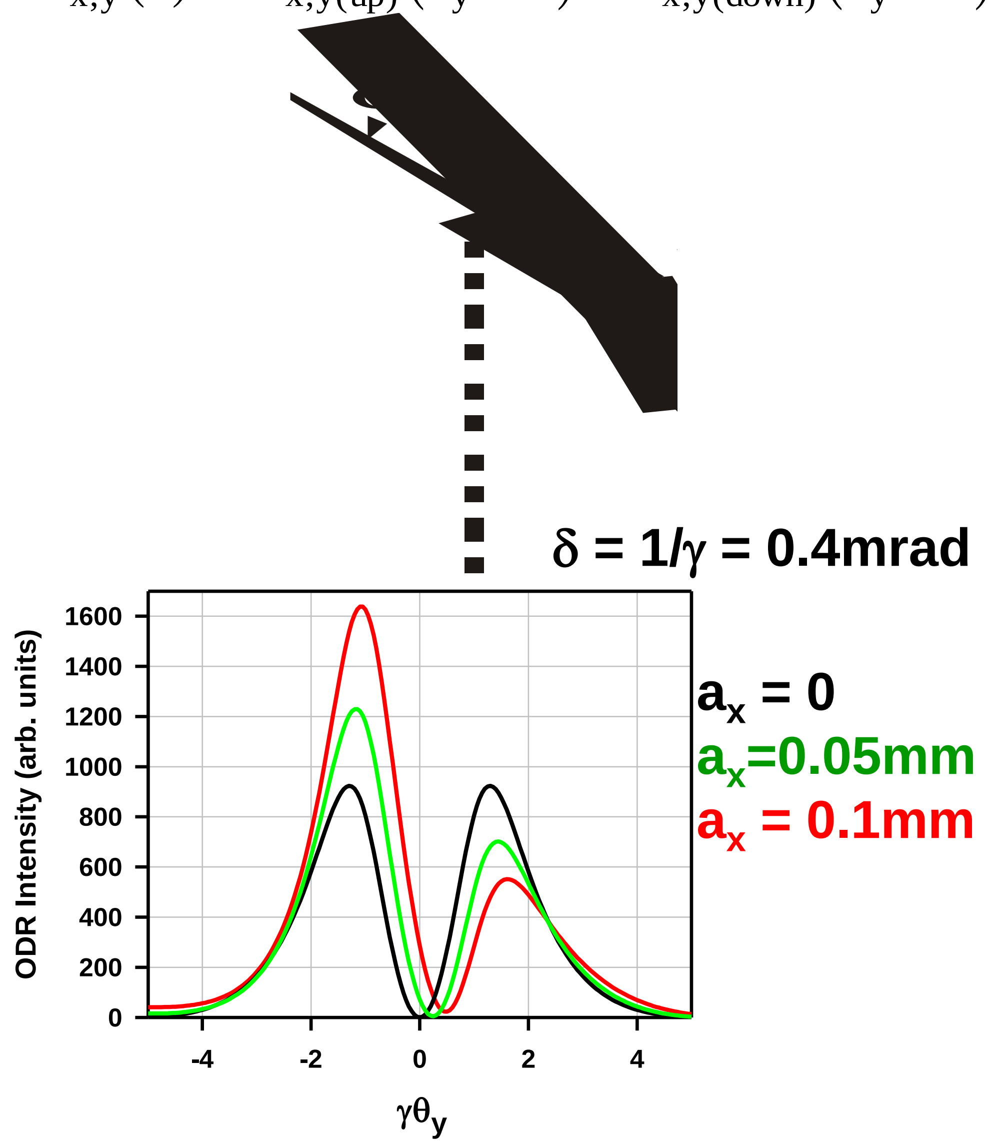


Requirements for the slit

$$E_{x,y}^{slit} = E_{x,y(up)} + E_{x,y(down)} \exp\left(-i\frac{4\pi\,\Delta l}{\lambda}\right)$$



$$E_{x,y}^{slit}(\delta) = E_{x,y(up)}(\theta_y+\delta) + E_{x,y(down)}(\theta_y-\delta)$$



Beam size using DR

Scaling laws for DR:

Assuming 1μm wavelength

Photon yield:

Optimal Sensitivity to beam size:

$$\sigma > 0.05\frac{\gamma\lambda}{2\pi}$$

• At high-energy, Pre-wave zone expands significantly

$$L > 10\frac{\gamma^2\lambda}{2\pi}$$

• To eliminate it, the camera must be placed in the back focal lane of a lens

Minimal Lens Diameter:

$$D > 20\frac{\gamma\lambda}{2\pi} + \frac{L}{\gamma}$$

Minimal Target Diameter:

$$T_D > 20\frac{\gamma\lambda}{2\pi}$$

	450GeV	7TeV
h <	70μm	1mm
σ >	4μm	50μm
L >	32cm	78m
D >	3.6mm	22mm
T_D >	1.5mm	22mm

Current Activities

- Simulation tools

- Target developments

- Experimental validation on CESR ring at Cornell

Optical Simulation with Zemax

• Using the DR field 2D distribution generated by single particle at the source position as an input file to Zemax (done using a user dll defining a 2D matrix)

•Running ZEMAX in the Physical Optic Propagation Mode which propagates the fields through the optical system using the Kirschoff's law of diffraction

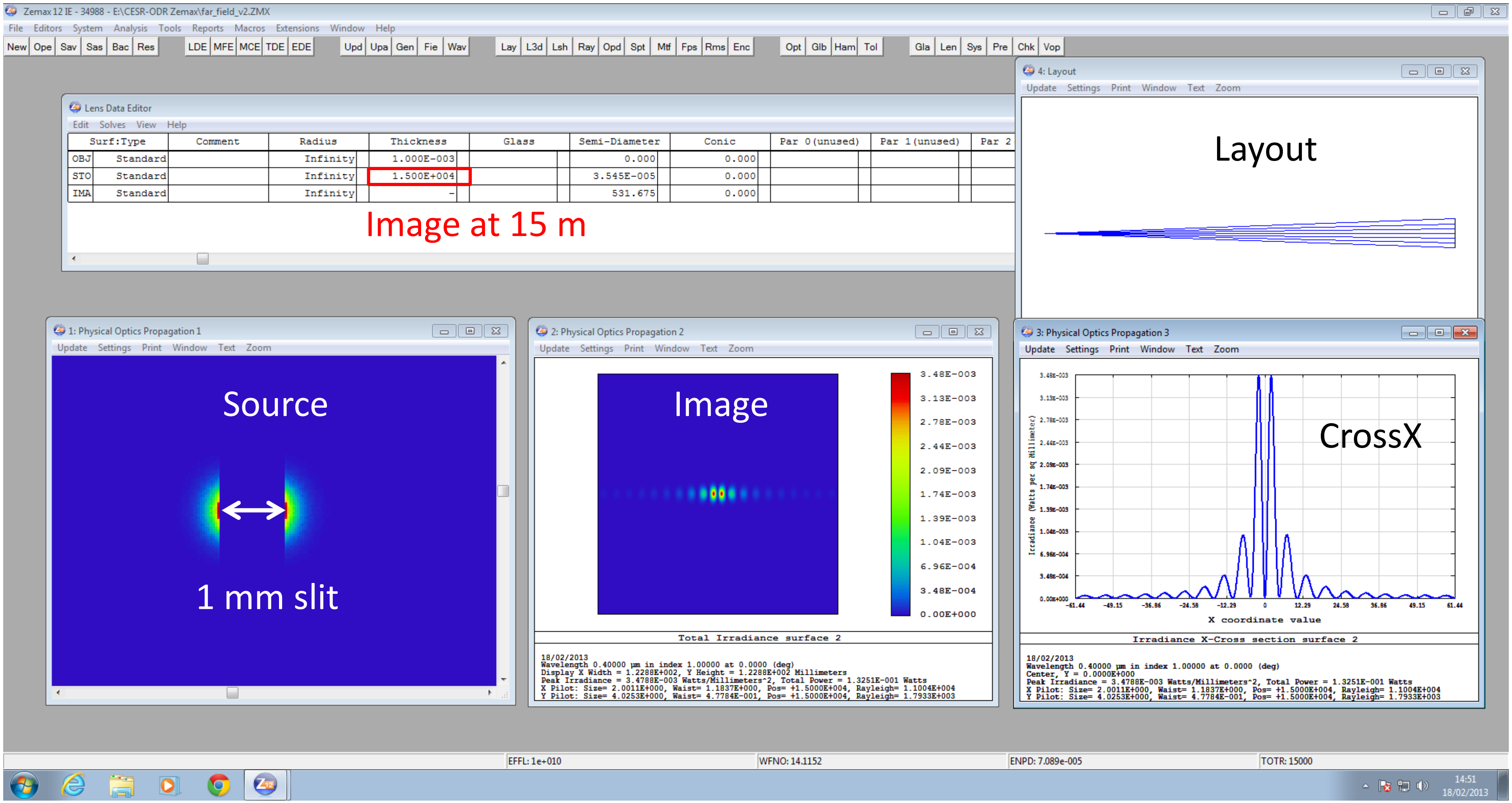
• Comparing Zemax simulations with an analytical model developed by P. Karataev in 2004

$$\frac{d^2W_y^{slit}}{d\omega d\Omega} = \frac{\alpha\left|R_y\right|^2}{4\pi^2}\frac{\exp\left(-\frac{2\pi a\sin\theta_0}{\lambda}\sqrt{\gamma^{-2}+\theta_x^2}\right)}{\gamma^{-2}+\theta_x^2+\theta_y^2}\times$$

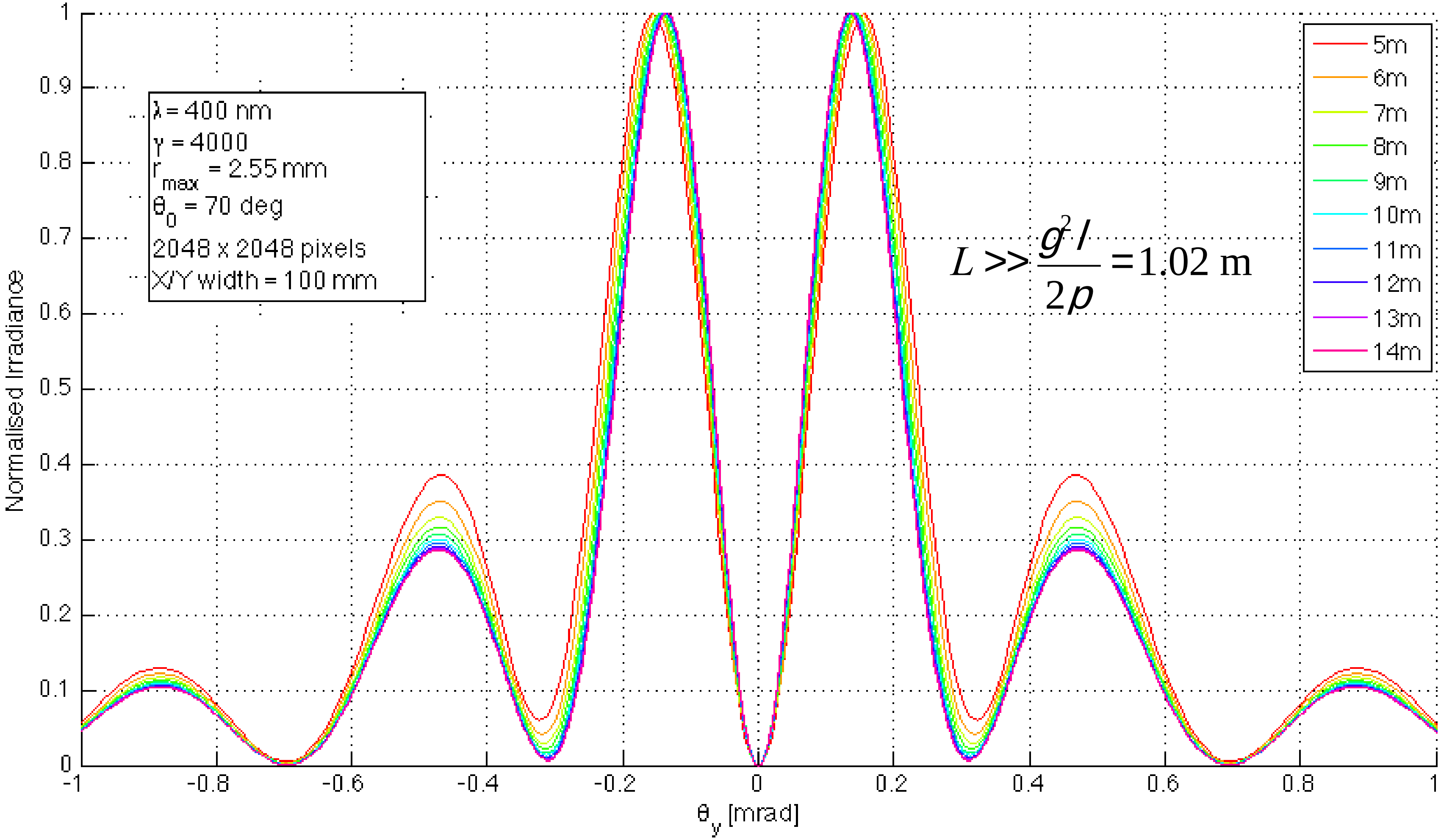
$$\left\{\exp\left[\frac{8\pi^2\sigma_y^2}{\lambda^2}\left(\gamma^{-2}+\theta_x^2\right)\right]\cosh\left[\frac{4\pi\overline{a}_x}{\lambda}\sqrt{\gamma^{-2}+\theta_x^2}\right]-\cos\left[\frac{2\pi a\sin\theta_0}{\lambda}\theta_y+2\psi\right]\right\}$$

with $\psi = \arctan\left(\frac{\theta_y}{\sqrt{\gamma^{-2}+\theta_x^2}}\right)$

Propagation in free space



Far-field conditions

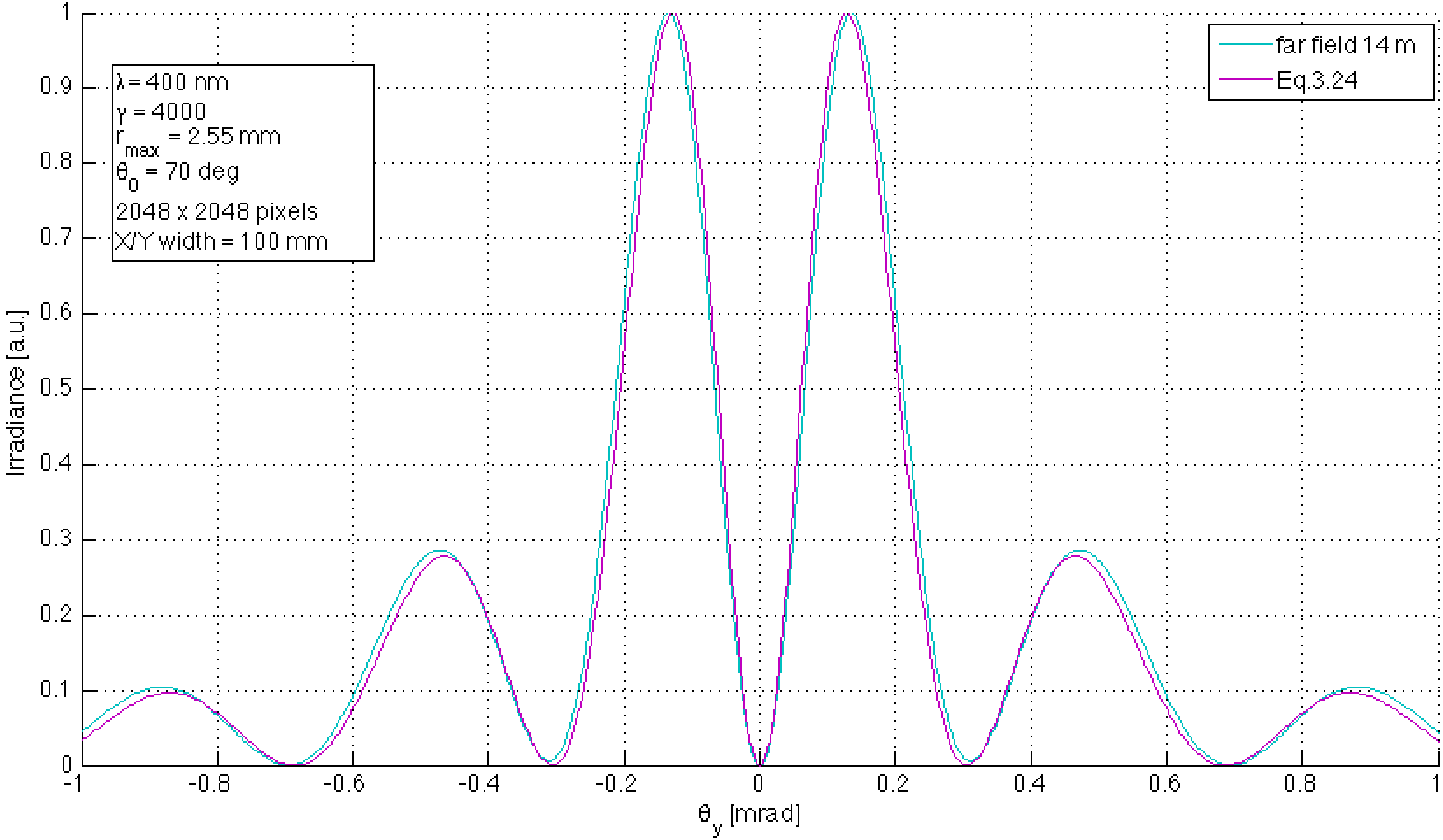


$$L >> \frac{g^2 l}{2p} = 1.02 \text{ m}$$

Angular distribution fully defined for distance > 10m

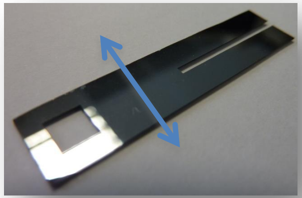
Far-field conditions

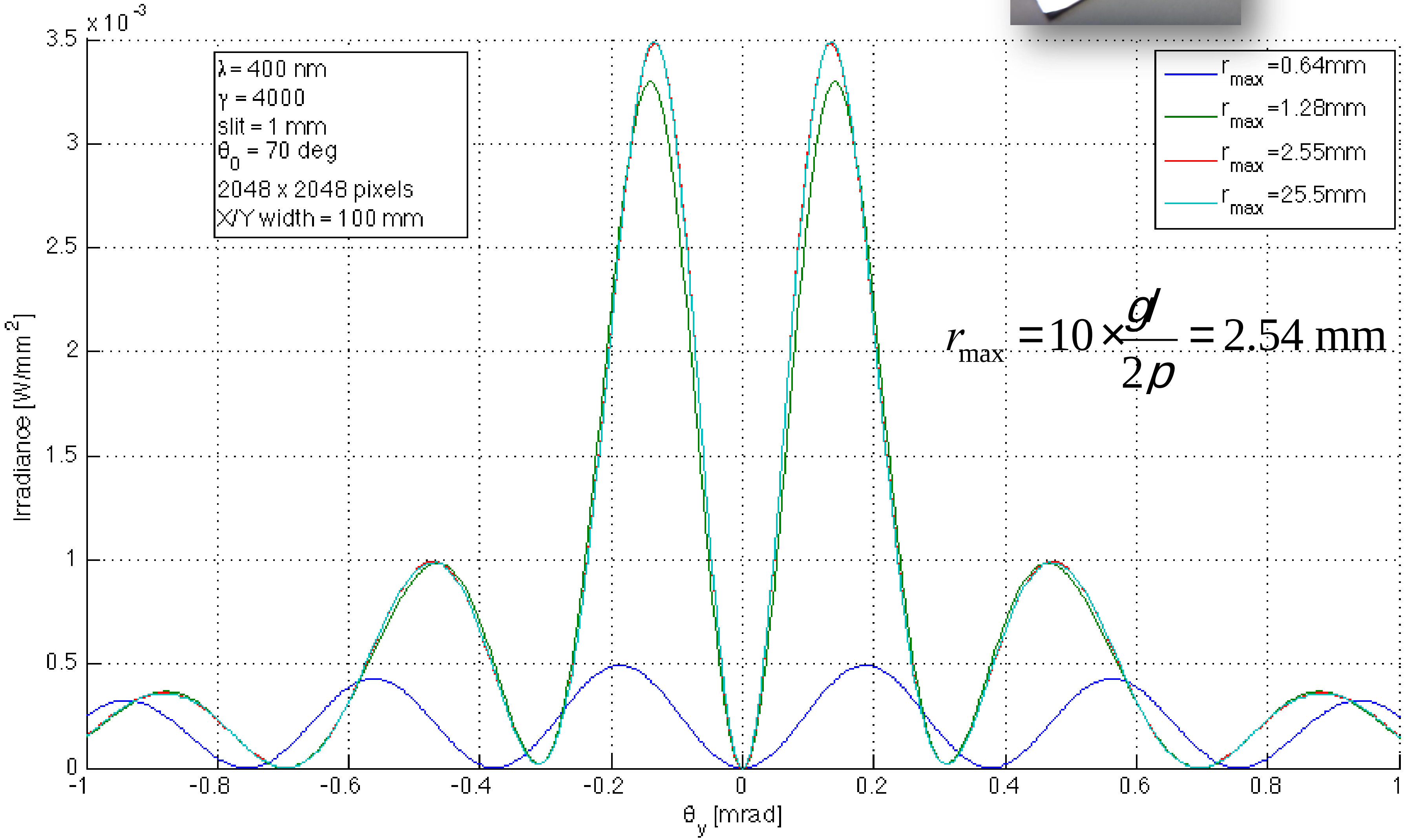
Good agreement with the analyical model



Radial size of the Target

How large must be the slit to capture the relevant field?

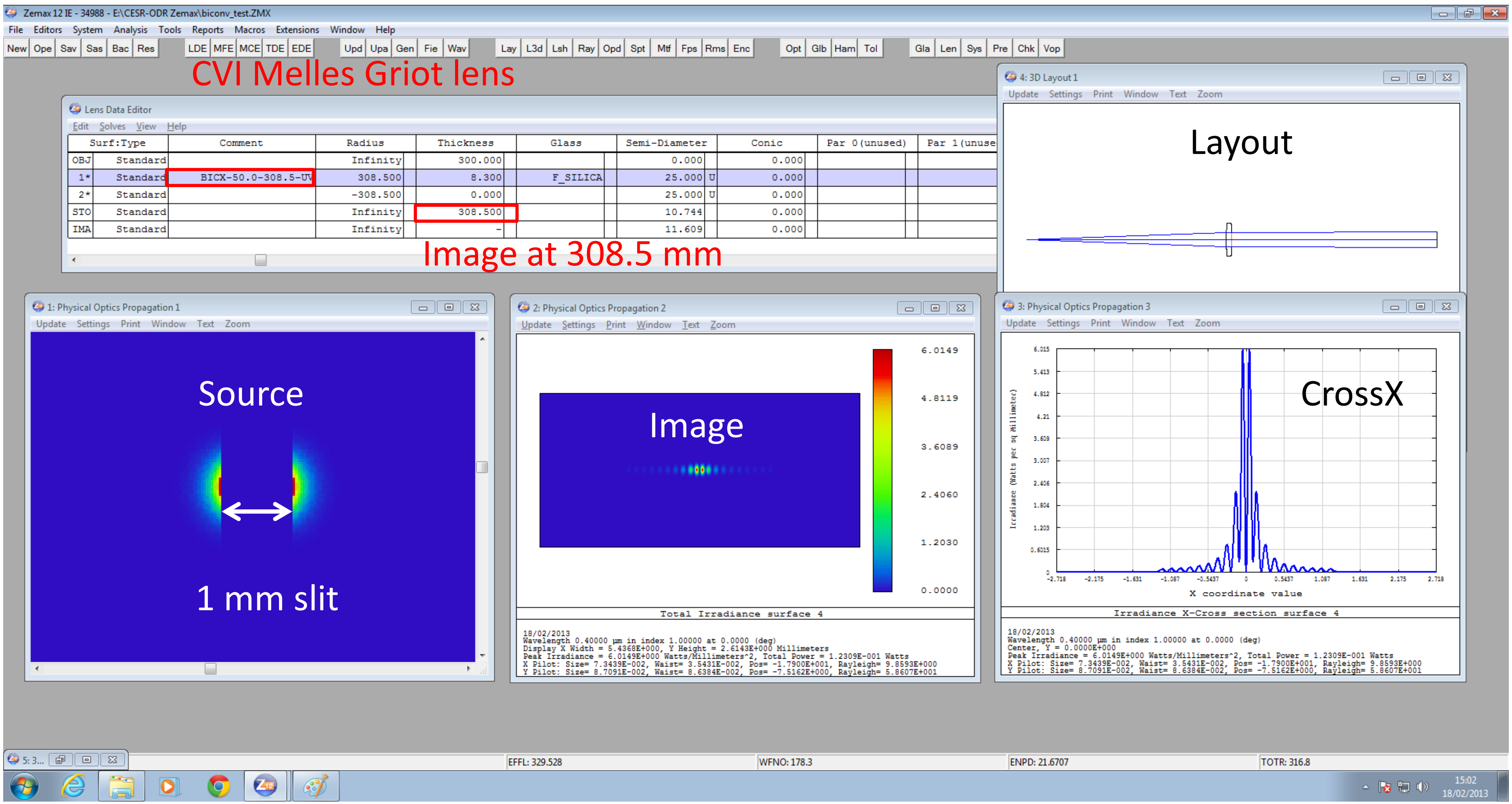




$$r_{max} = 10 \times \frac{\lambda}{2\pi} = 2.54 \text{ mm}$$

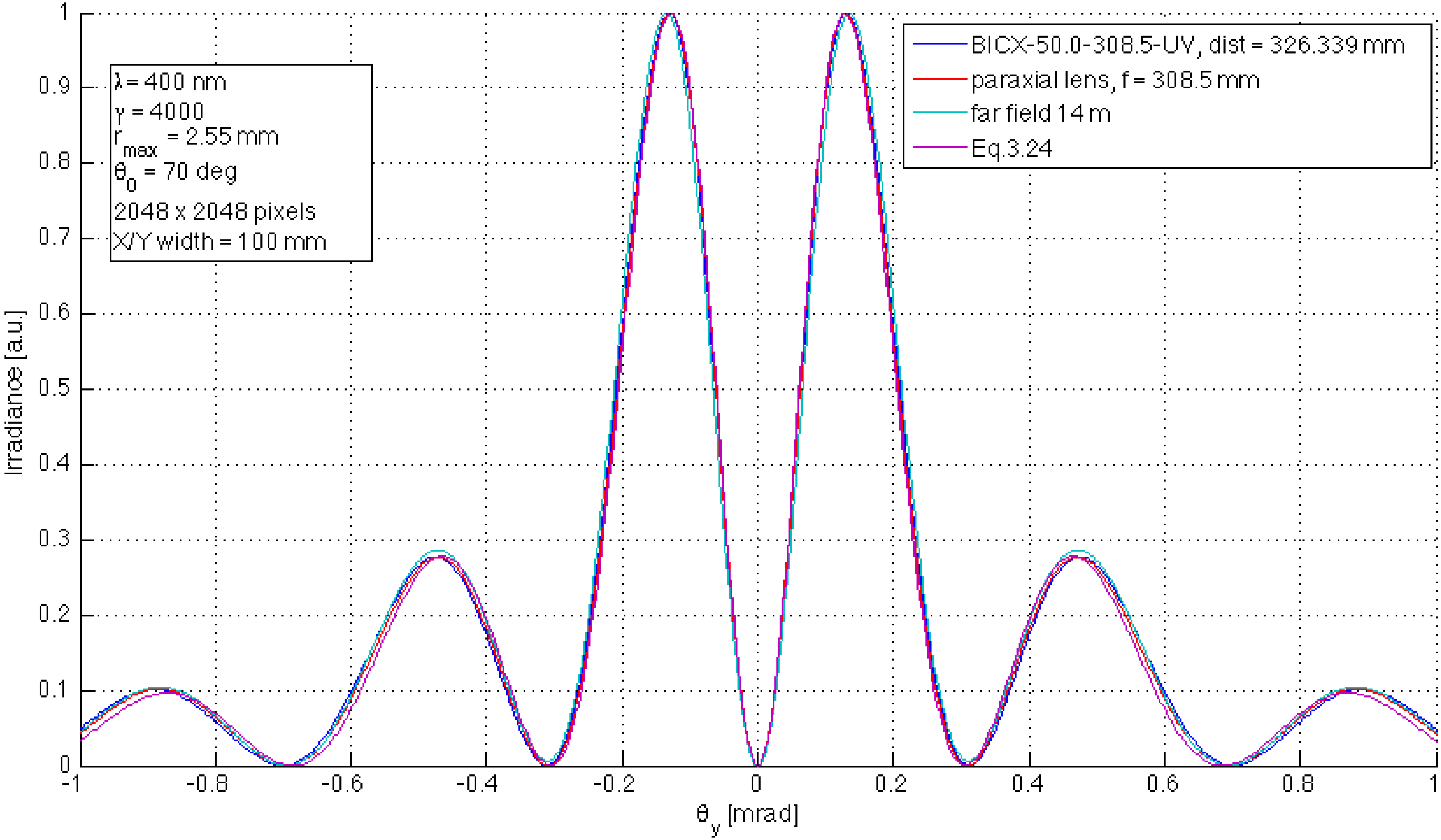
Biconvex lens

Using a Biconvex lens to extract the DR angular distribution in near field conditions

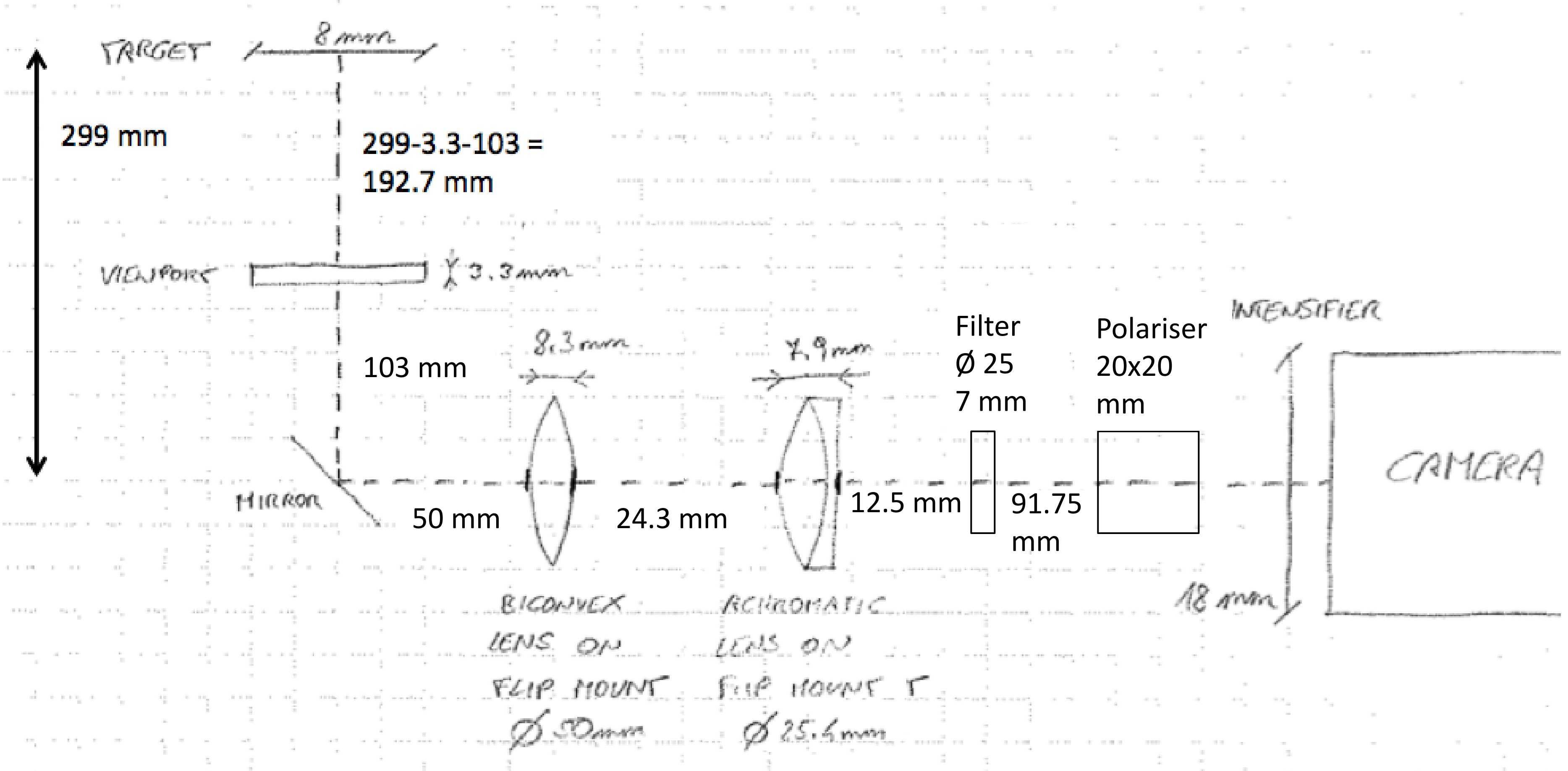


Biconvex lens

Angular distribution is retrieved as in Far-field case once the detector is positioned in the real back focal plane (changing for different wavelength)

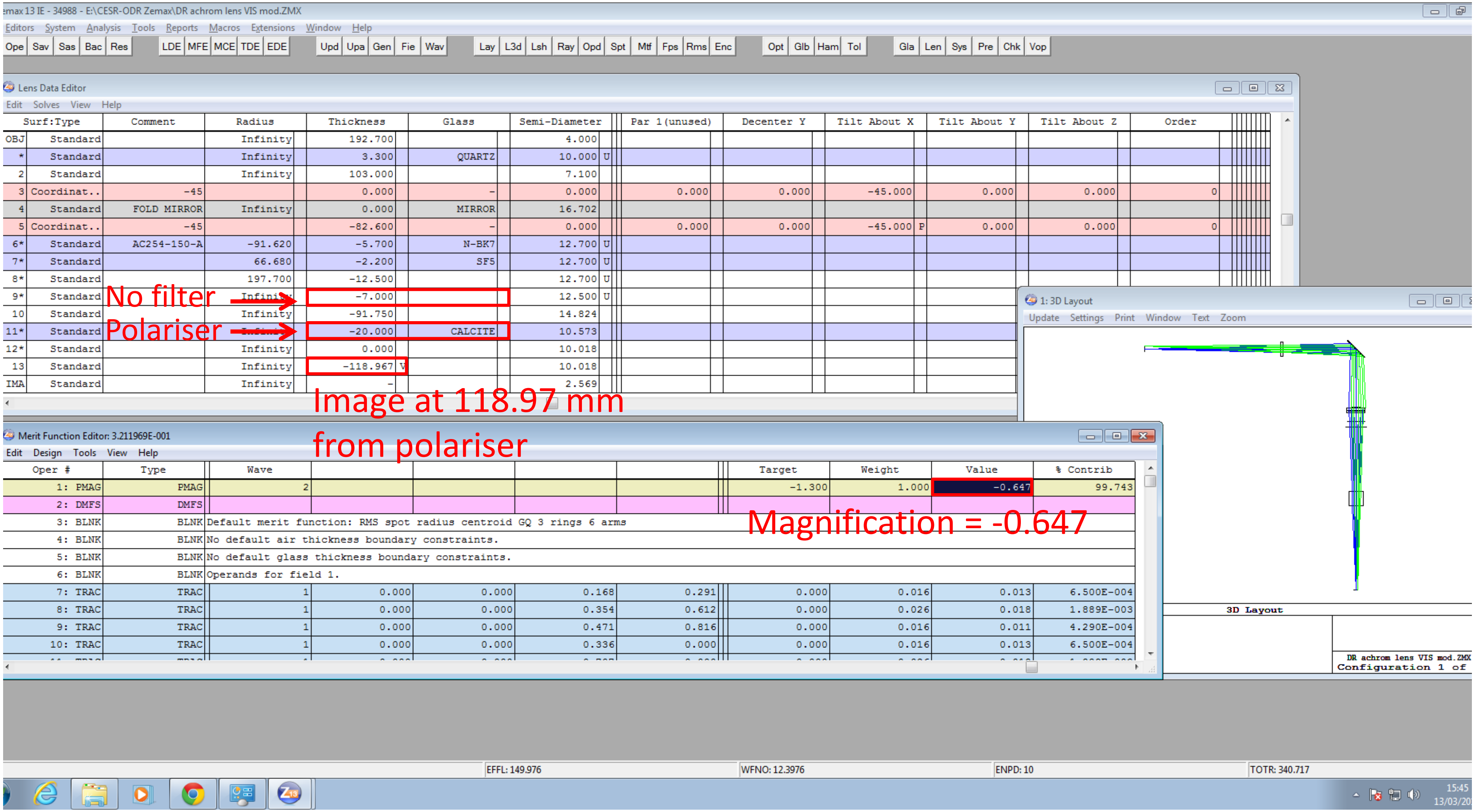


Full optical system



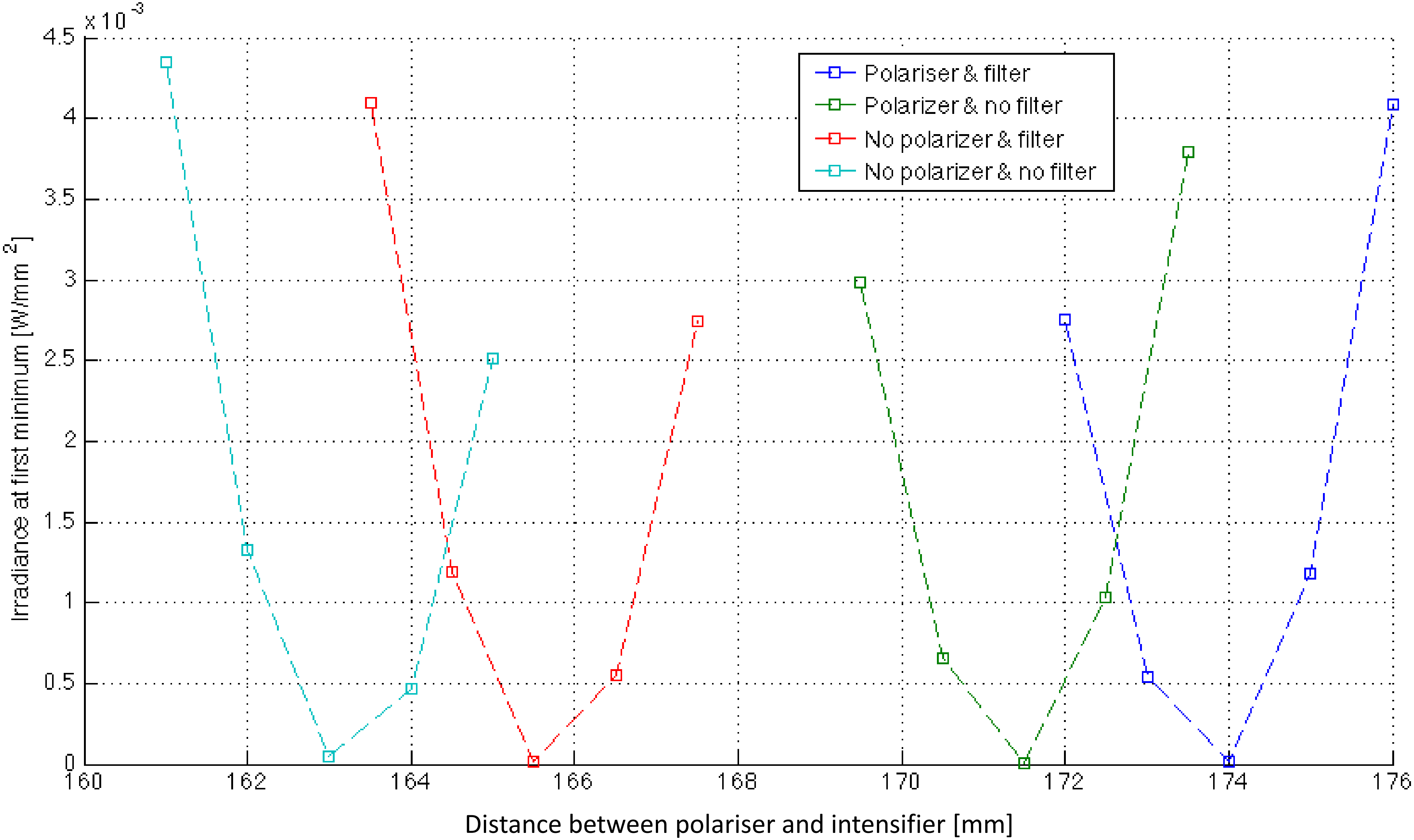
Full optical system

With Viewport, Mirror, Bandpass filter, Polariser, Lenses

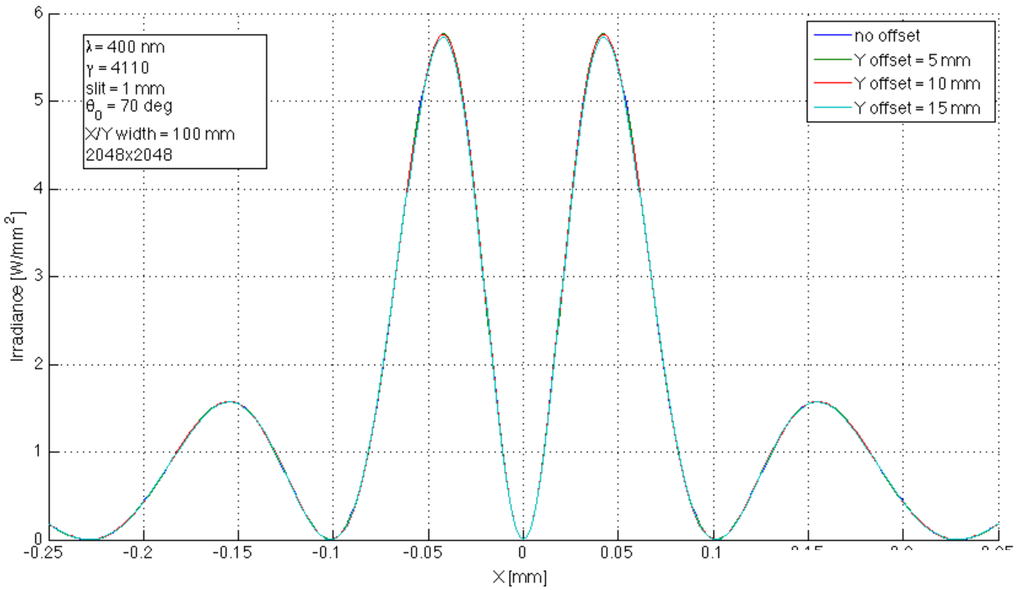


Full optical system

Simulating by how much the position of the image plane changes if using filter and polarizer

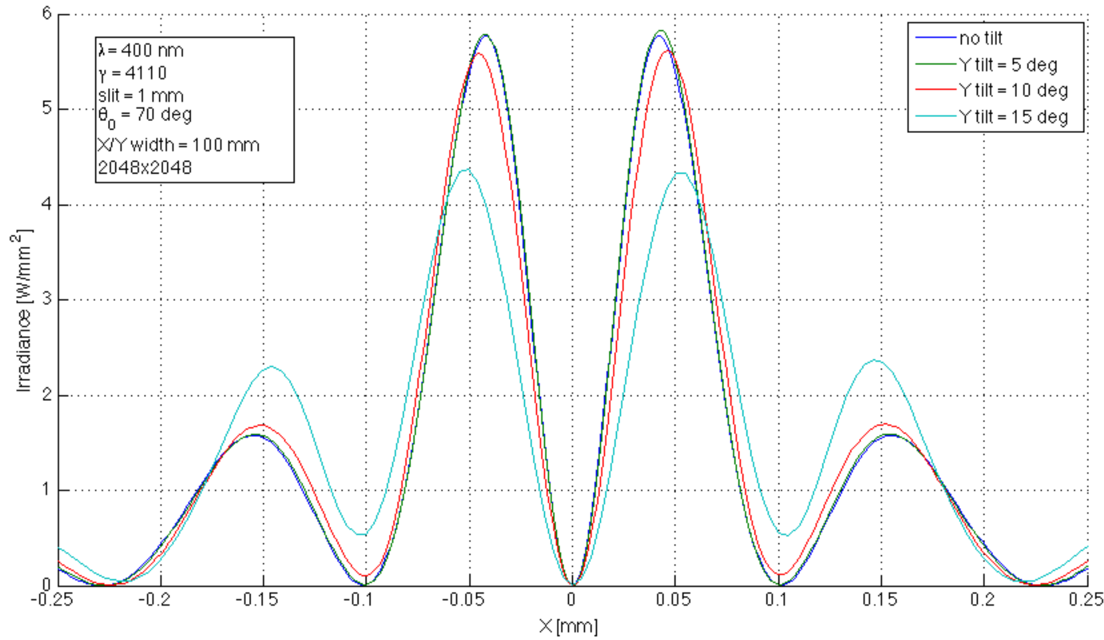


Full optical system



Simulating the offset of the lens

Simulating the tilt of the lens



Target developments

Requirements:

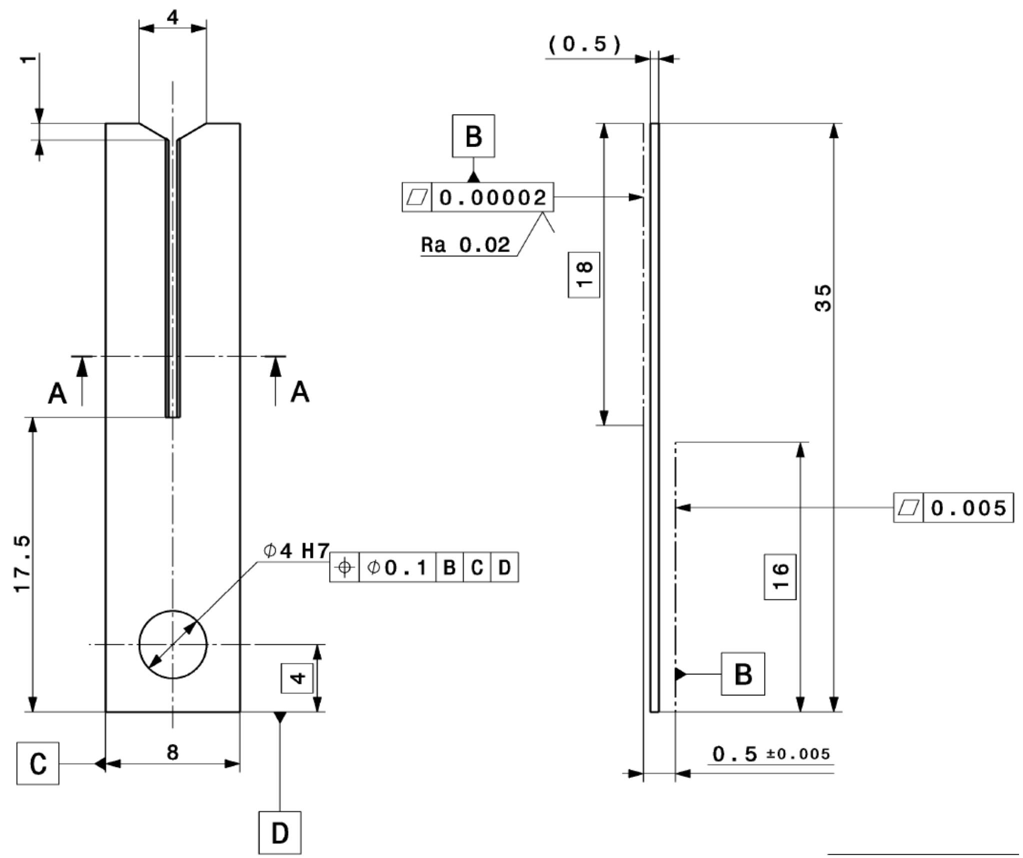
Silicon wafer 8mmx35mm

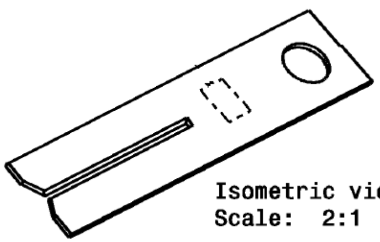
Aperture size of 0.5mm and 1mm

High precision slit size: +/-5μm

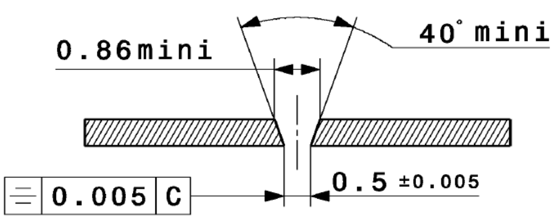
Coplanarity $\leq \lambda/10$ (~50nm)

Roughness better than $\lambda/100$





Isometric view
Scale: 2:1



Section view A-A
Scale: 10:1

- Chemically etched slit: 500μm thickness maximum
- Slits assembled by molecular adhesion: 1.5mm thick

Target developments

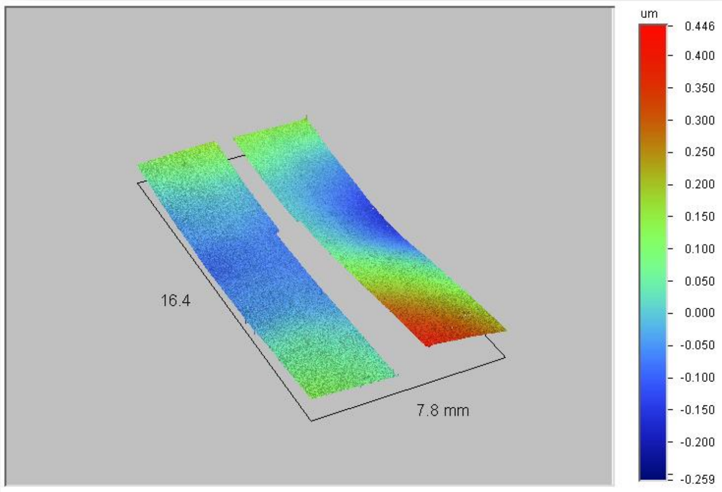
TARGET SUPPORT 0.5mm

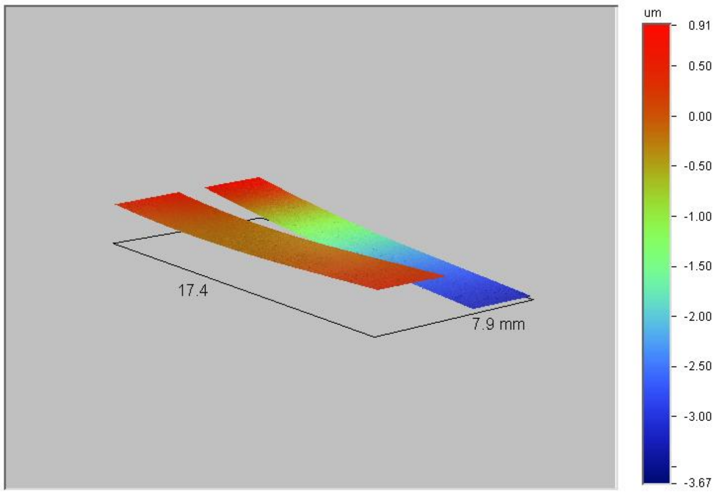
TARGET SUPPORT 1mm

- Target aperture ~ within specifications +/-7µm

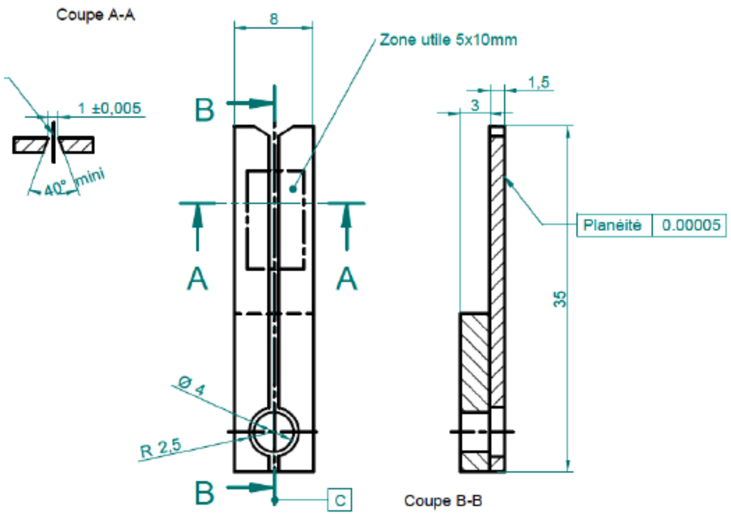
- Target Roughness good: mean value better than 2nm

- Target co-planarity: not reproducible: PV never better than 600nm: can be as bad as 10µm and possibly large tilt angles (up to 500µrad)



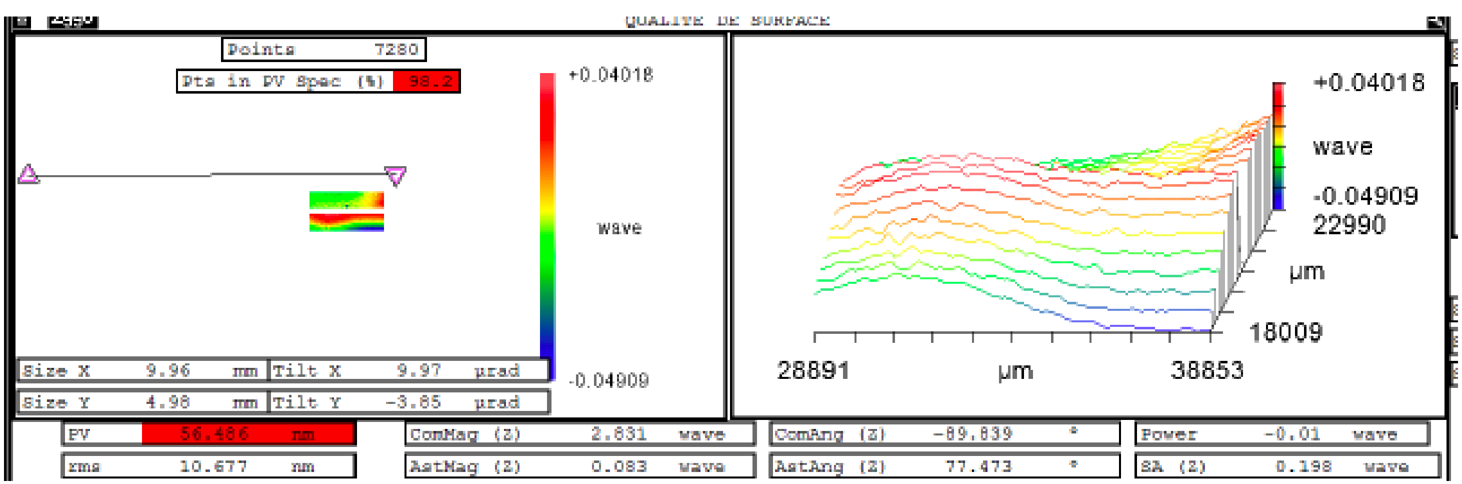


Target developments



Molecular adhesion Targets

- Target aperture within specifications +/-3μm
- Target Roughness good: mean value better than 2nm
- Target co-planarity reproducible with PV better than 70nm and an r.m.s value as good as 10nm



Molecular adhesion targets are fragile and sensitive to thermal effects

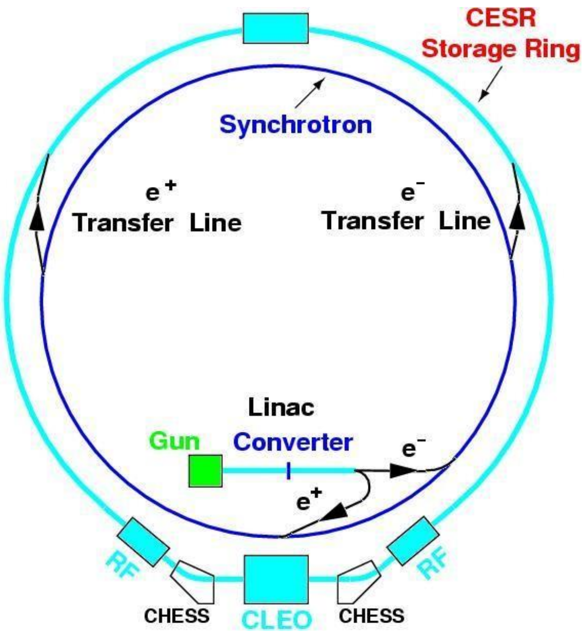
Experimental Validation

Project aim:

To design and test an instrument to measure on the micron-scale the transverse (vertical) beam size for the Compact Linear Collider (CLIC) using incoherent Diffraction Radiation (DR) at UV/soft X-ray wavelengths.

Cornell Electron Storage Ring Test Accelerator (CesrTA) beam parameters:

	E (GeV)	σ_H (μm)	σ_V (μm)
CesrTA	2.1	320	~9.2
	5.3	2500	~65



D. Rubin et al., "CesrTA Layout and Optics", Proc. of PAC2009, Vancouver, Canada, WE6PFP103, p. 2751.

http://www.cs.cornell.edu

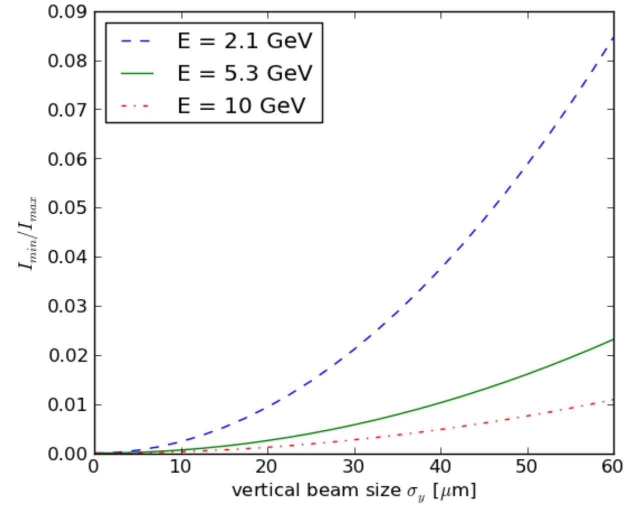
Experimental Validation

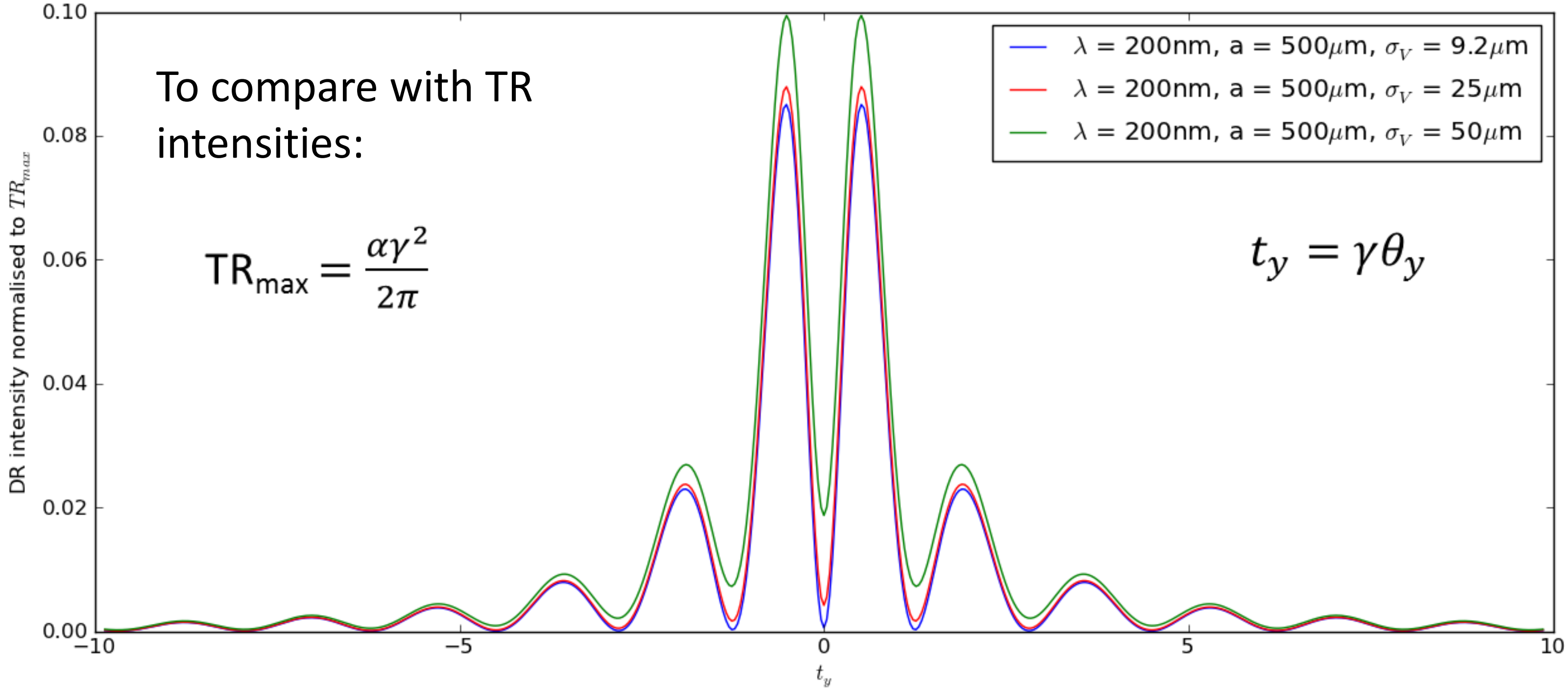
Measureable visibility for initial test at parameters:

λ = 200 - 400 nm

a = 0.5, 1 mm

σ_y = 50 µm





Experimental Validation

Beam lifetime and beam jitter

M. Billing, *"Introduction to Beam Diagnostics and Instrumentation for Circular Accelerators"*, AIP Conference Proc. 281, AIP 1993, pg.75 ff.

target slit size [mm]	vertical beam size [µm]	beam lifetime [min]
0.1	9.2	2.40
0.5	30	60 (max)
	50	2.22
1.0	50	60 (max)

$a_{target} \geq 5 \cdot \sigma_y$,
preferably $a_{target} = 7\text{-}10 \cdot \sigma_y$

↓

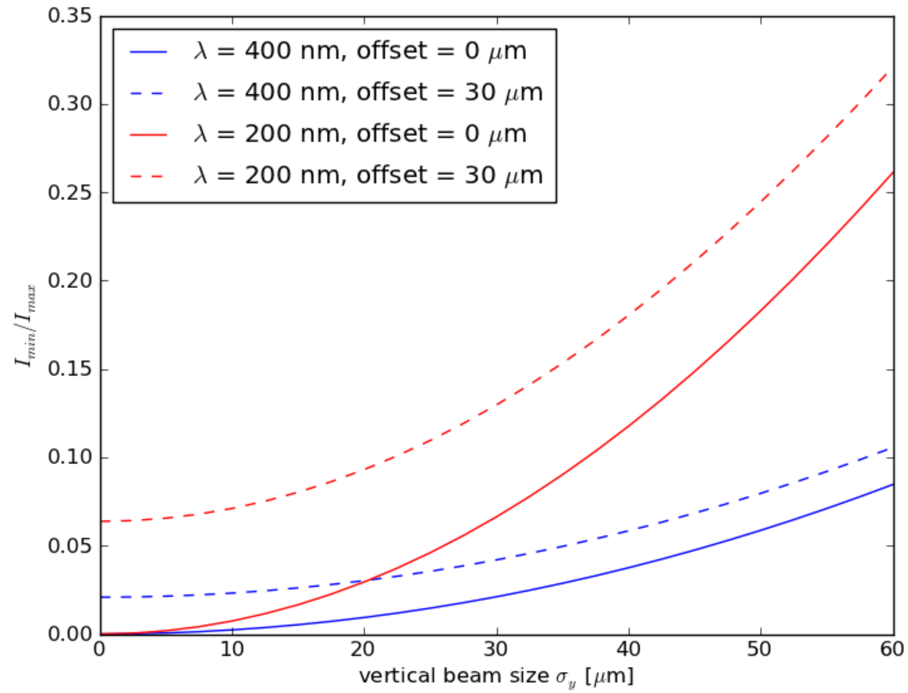
Large aperture = low DR intensity

↓

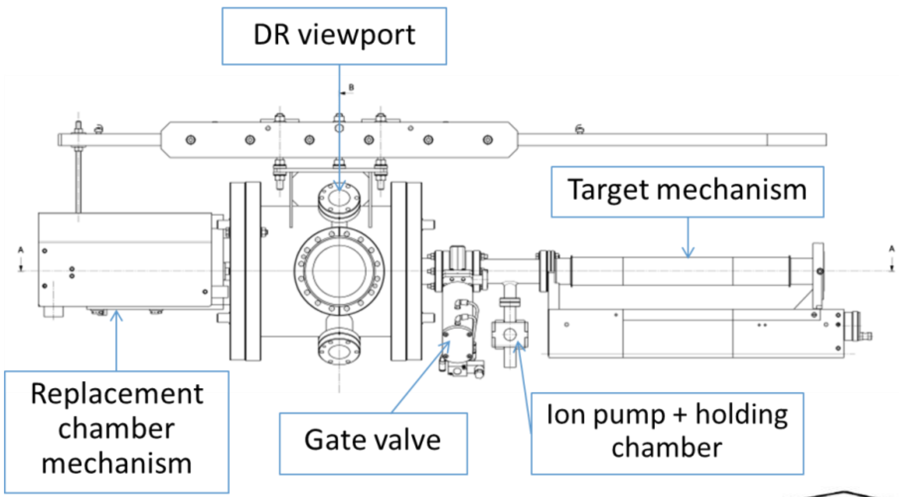
Multiple turns of a single bunch through the target aperture

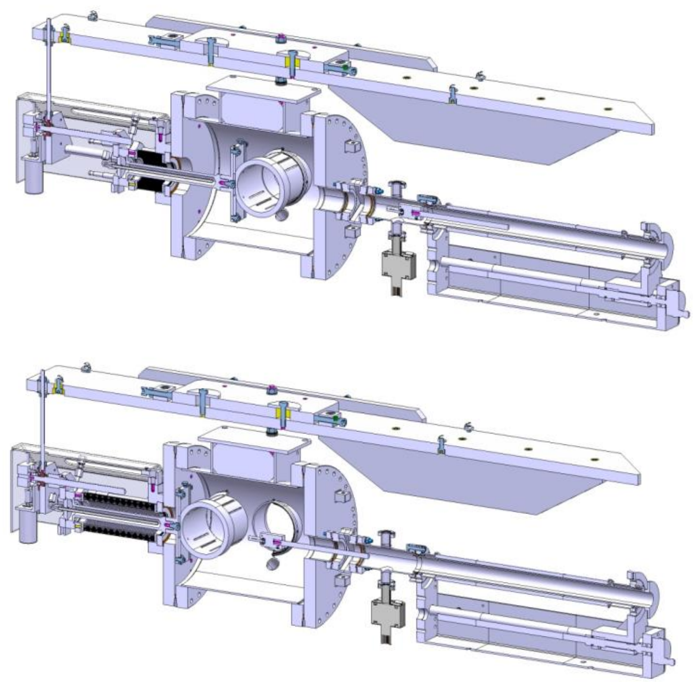
↓

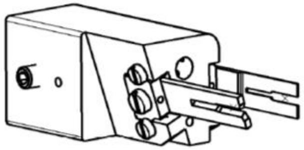
Errors due to beam jitter are reduced by including turn-by-turn vertical position measurements of the bunch in the target aperture.



Experimental Validation

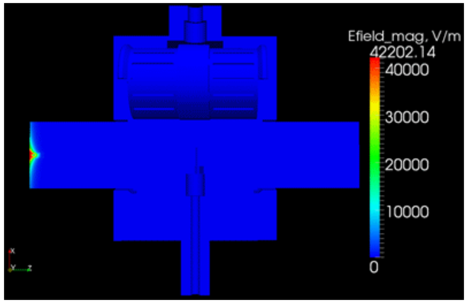


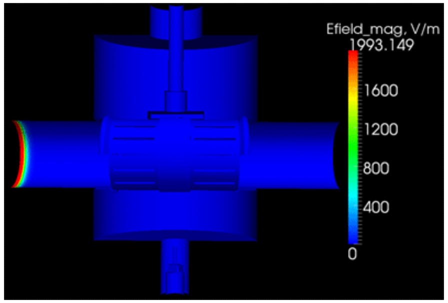




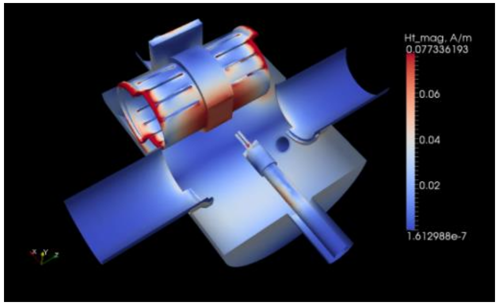
Technical drawings by N. Chritin
Simulations by A. Nosych

E-field magnitude of a single bunch pass in time domain (Gaussian bunch, length = [-4σ,4σ], σ = 10mm)





H-field surface tang complex magnitude (Loss map)
Mode Fr = 1.19 GHz, Q = 3309, Ploss = 0.075 W

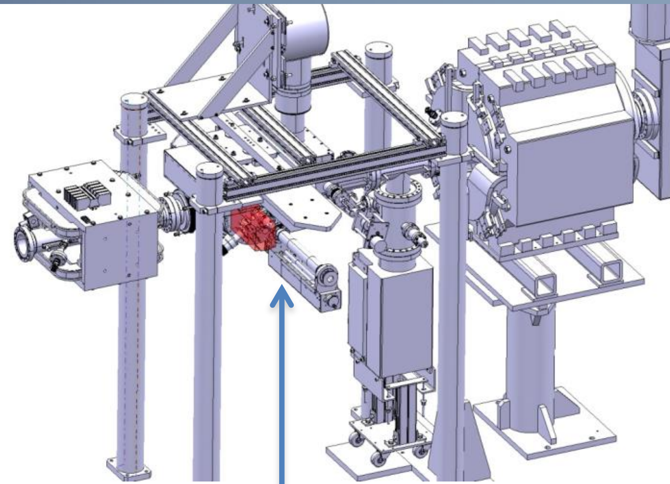


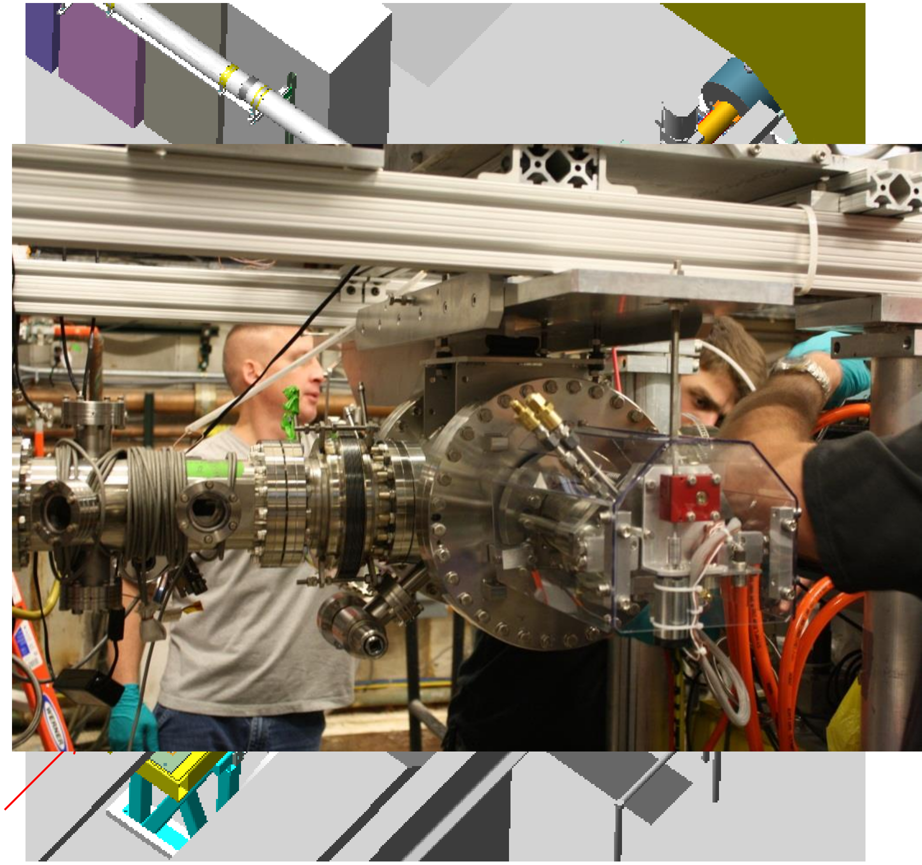
Total power loss for single bunch = 0.6 W

Experimental Validation

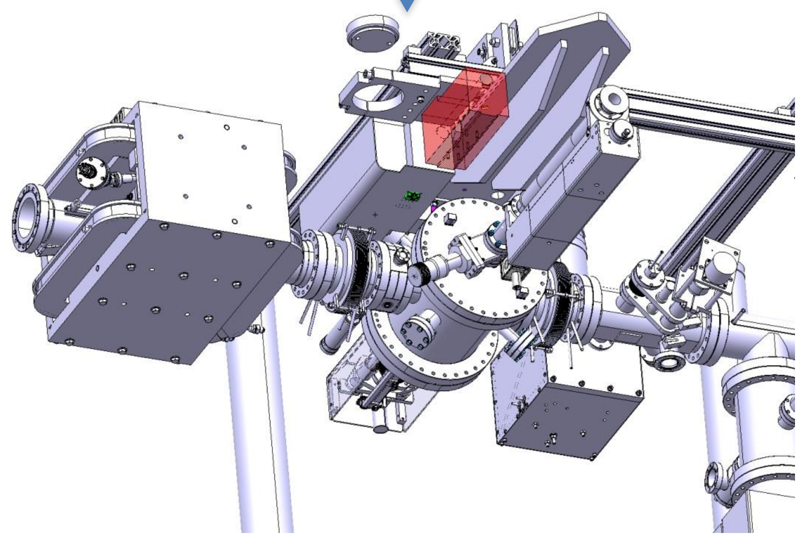
L3 layout @CesrTA

Electron beam direction





DR experiment



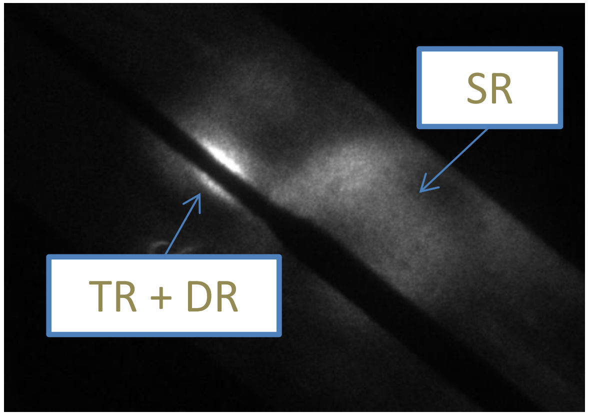
Experimental Validation

2 shifts for preliminary tests in December 2012

- Tested successfully all functionalities – Motors – Optical system – Beam loss monitors

- Beam lifetime much shorter than expected (approx. 2-3 mins instead of 60mins as expected) due to bad vacuum conditions

- First observation done using Dummy target – observing both DR&TR and SR



<u>Second test period with real slits starting next week-end</u>

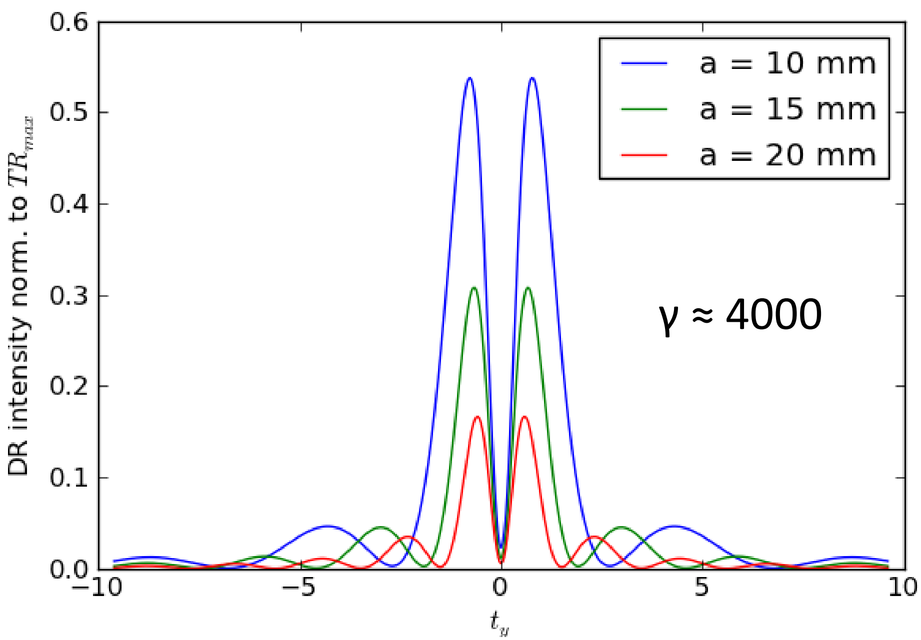
DR for LHC

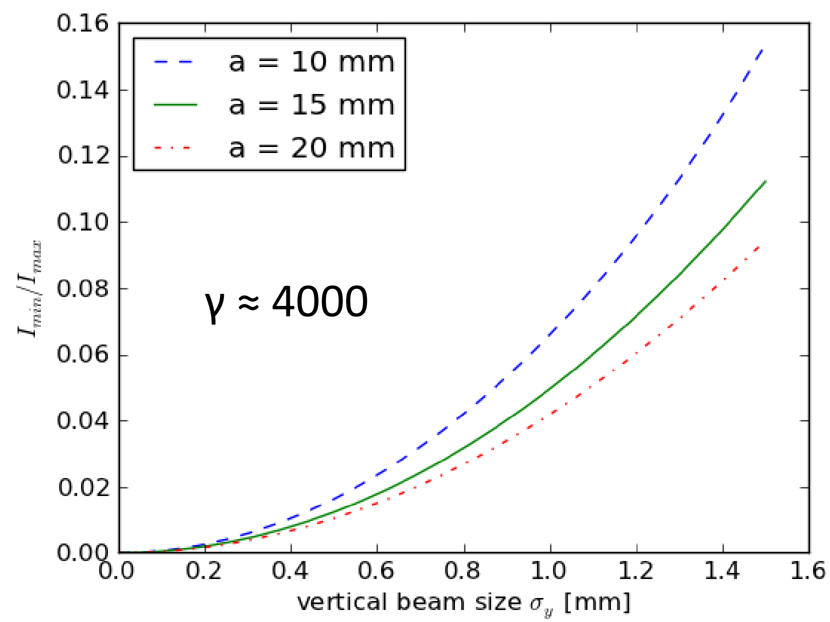
- Using proton beam:
  - LHC is relativistic enough..
  - Reduced SR background
  - Larger beam size (0.2um to 2mm)

- Wavelengths in the infrared spectral range (<10.3um)

Main requirement:
Non- invasive measurement

Must use target aperture as large as possible





To do list for DR@LHC

- DR light intensity is not a limitation even for large impact parameters (turn-by-turn, bunch-by-bunch measurement ?)
- Compared to Sync. Light monitor, no limitation from diffraction nor from having an extended source
- Imaging the slit might be enough to monitor the evolution of beam size through the cycle – Imaging in far infrared ?
- Sensitivity to beam size using slit interference to be checked carefully – Choice of wavelength – might be very different at injection and top energy
- Need a precise positioning of the target with respect to the beam (high precision BPM close to the Target)
- Impedance is an issue in LHC – Lessons from the LHC sync. light telescope – Adequate design of the slit holder and choice of slit material – Temperature effects might be a killer for interference scheme
- Do we need a SR mask in LHC ?
- Will OTR from halo particles degrade the measurements (How much of beam halo to be expected at distances of 10σ or higher) – Measuring OTR at shorter wavelength and compensating for that

Conclusions

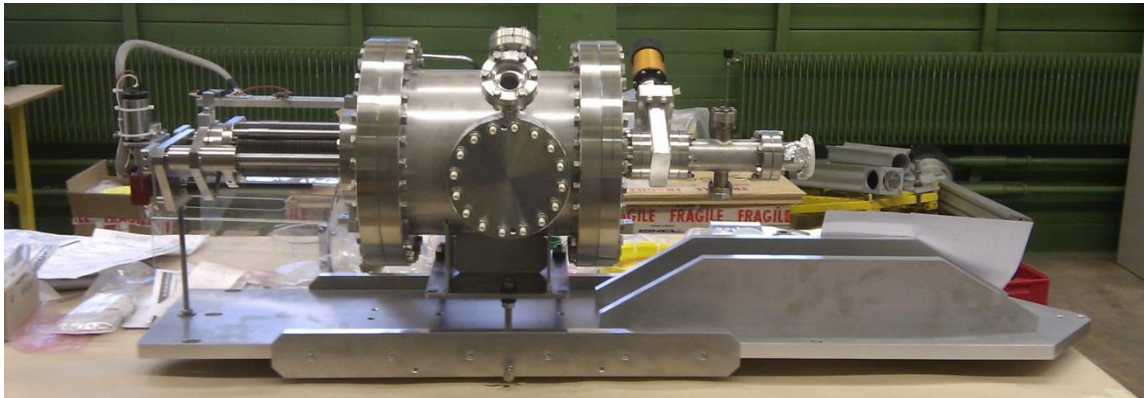
- DR has the potential to provide non-invasive beam size measurements for ultra-relativistic beams
- On-going R&D efforts in the framework of CLIC to study ring-type DR monitors
- Still a lot of open questions on how best we can use these devices on LHC – Time for simulations – We have all the tools for that..
- If successful, one would like to design and build a prototype to be tested on SPS, LHC or their transfer lines

Thanks for Lorraine and Tom for most of slides

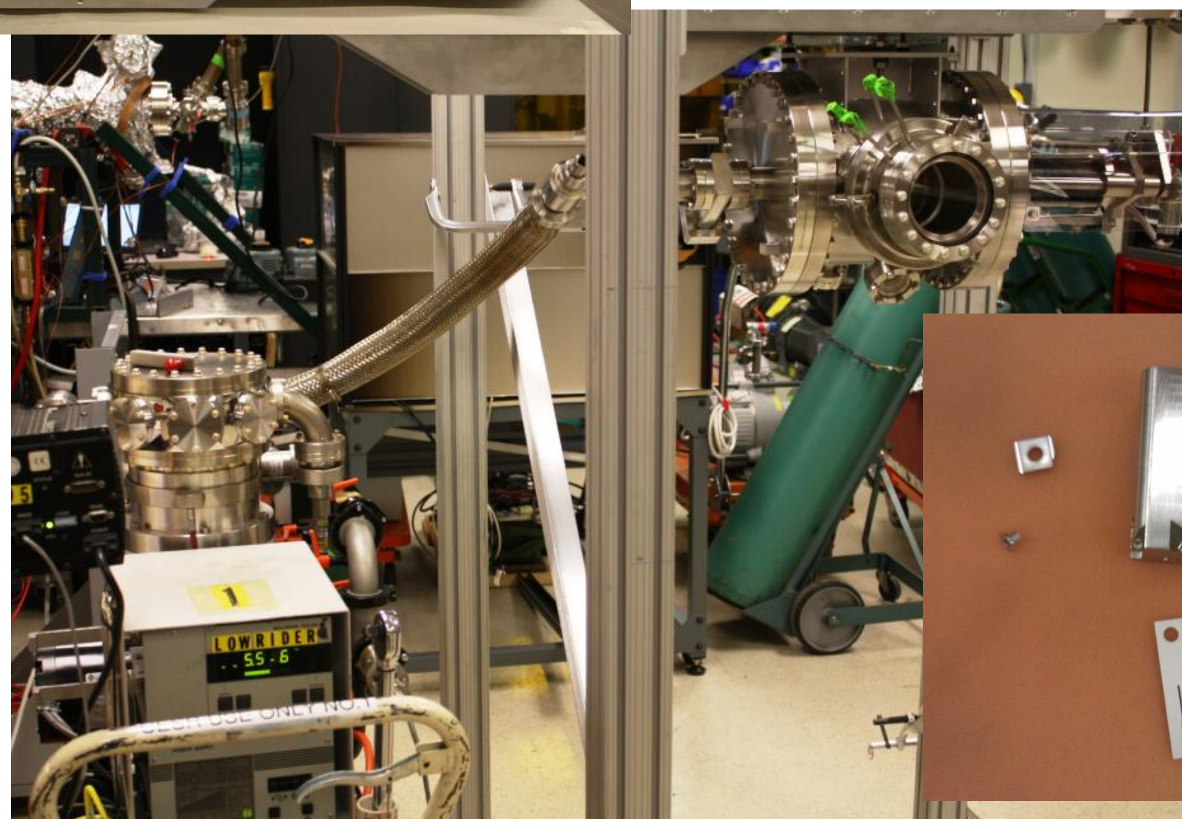
Thanks you for listenning

Experimental Validation

Vacuum chamber assembly cont'd



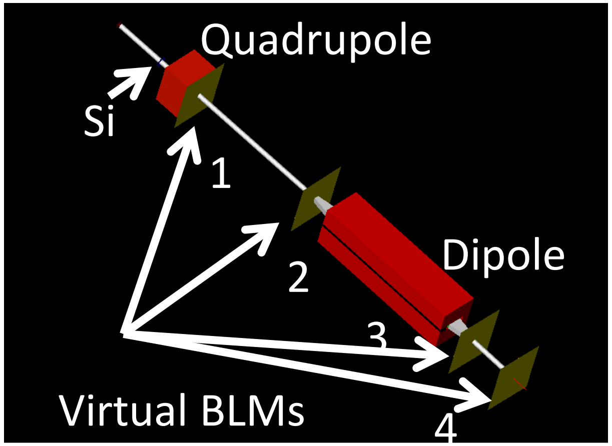
Images taken during assembly at CERN and current testing at Cornell.

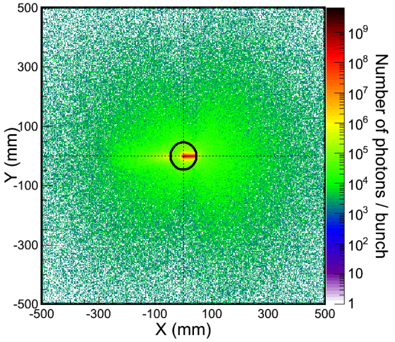


Experimental Validation

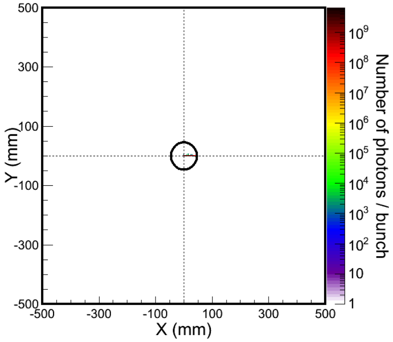
Method of Operation

1. Alignment of the electron beam with the target aperture:
   - BPMs for centering
   - Target imaging to look for OTR from beam halo
   - Correlate with BLMs:

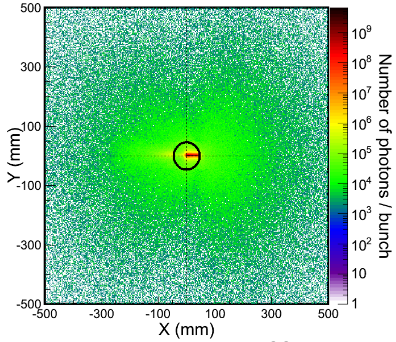




-400µm off



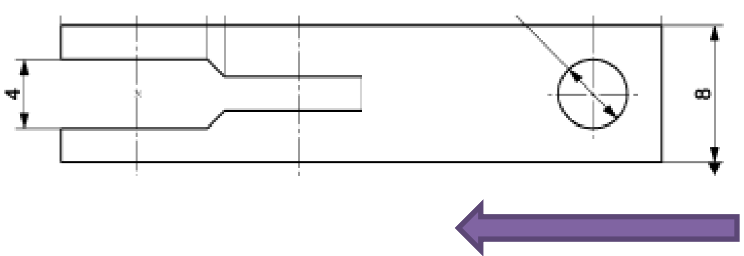
center



+400µm off

Virtual Detector 3

Single bunch of electrons



Gradually move target in

Summary + Conclusion

- Simulations have demonstrated the feasibility of vertical beam size measurements at CesrTA. The phase 1 experiment is planned for the end of December 2012 for which the design and vacuum assembly are close to completion.
- The design must account for the experiment location in a circular machine. This introduces some advantages and disadvantages not applicable for linacs.
- Preliminary simulations for the phase 2 test aiming for the soft x-ray spectral range have been presented.
- Feasibility of DR diagnostics on other accelerators has been considered such as simulations for transverse beam size measurements at the LHC.

Acknowledgements

I would like to thank J. Barley, J. Conway, J. Lanzoni, Y. Li, T. O'Connell, M. Palmer, D. Rice, D. Rubin, J. Sexton, C. Strohman and S. Wang (@Cornell) for all technical contributions and advice. In addition, O.R. Jones and H. Schmickler for organisation of the collaboration, A. Apyan, E. Bravin, A. Jeff, A. Nosych and S. Vulliez (@CERN) and T. Aumeyr (@RHUL).

Experimental achievements of ODR project

- **The first observation of Optical (incoherent) Diffraction Radiation from the target edge (PRL 90, p. 104801 , 2003)**
- **The first observation of the ODR interference produced from two edges (slit target) (PRL 93, p. 244802, 2004)**
- **Investigation of basic ODR characteristics from a "semi-plane" and slit targets (angular distribution, wavelength dependence, dependence on impact parameter, etc.) (NIM B 227, p. 158, 2005)**
- **The first observation of the pre-wave zone effect in Diffraction Radiation phenomenon (PR ST-AB 11, p. 032804, 2008)**
- **The first application of the Optical Diffraction Radiation for non-invasive transversal beam size measurement (PRL 93, p. 244802, 2004)**
- **Observation of focusing effect in OTR and ODR phenomena (PR ST-AB 12, p. 071001, 2009)**
- **Single-shot beam size measurement (paper preparation is in progress)**
- **Sub-micrometer resolution OTR monitor based on shape analysis of Point Spread Function (Journal of Physics: Conference Series, 236 (2010) 012008)**

Theoretical Considerations

- **Diffraction radiation from a particle moving through a rectangular hole in rectangular screen (NIM B 227 (2005) 198)**
- **Resonant polarization radiation from a particle moving trough a tilted grating (and (NIM B 201 (2003) 133))**
- **Resonant diffraction radiation from a particle moving trough a slit between two identical gratings (NIM B 201 (2003) 201)**
- **Diffraction radiation in the pre-wave zone (Phys. Lett. A 345 (2005) 428)**
- **Transition and diffraction radiation from a concave (convex) target (Phys. Lett. A 345 (2005) 428)**
- **Investigation of the transverse kick caused by an ODR target (NIM B 227 (2005) 170)**
- **Diffraction radiation from a particle moving trough a double screen system of targets (unpublished)**

EDMS N° 1274854

TARGET SUPPORTS

Project : CLIC
(ODR BEAM SIZE MEASUREMENT)

Presentation of the metrology results

Measurements on 4 items

Controler : Lilian REMANDET
lilian.remandet@cern.ch

Customer : Lorraine BOBB
lorraine.bobb@cern.ch

CONDITIONS OF MEASUREMENT

- *Roughness :* Measure on optical roughness tester (non-contact) :
  - Roughness tester VEECO – NT 3300
  - Optical zoom : x 20
  - Optical lens : x 1
  - Measurement unit : in µm
  - Estimation of uncertainty of measurement : 10 % of the parameter value
- *Flatness :* Measure on optical roughness tester (non-contact) :
  - Roughness tester VEECO – NT 3300
  - Optical zoom : x 2.5
  - Optical lens : x 0.5
  - Measurement unit : in µm
  - Estimation of uncertainty of measurement : 10 % of the parameter value
- *Distance :* Measure on Optical measuring system :
  - Optical measuring system MAHR Wegu OMS 600
  - Optical zoom : x 40
  - Measurement unit : in µm
  - Estimation of uncertainty of measurement : ± 2 µm
- *Temperature :* 20 ± 1° C
- *Notice :* none

DEFINITION OF ROUGHNESS PARAMETERS

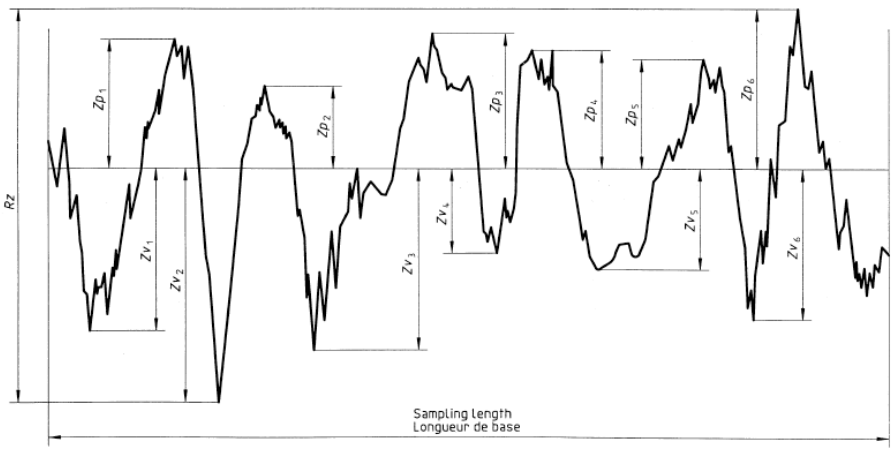


Figure 8 — Maximum height of profile (example of a roughness profile)
Figure 8 — Hauteur maximale du profil (exemple de profil de rugosité)

maximum profile peak height

Pp, *Rp*, *Wp*

largest profile peak height *Zp* within a sampling length

maximum profile valley depth

Pv, *Rv*, *Wv*

largest profile valley depth *Zv* within a sampling length

total height of profile

Pt, *Rt*, *Wt*

sum of the height of the largest profile peak height *Zp* and the largest profile valley depth *Zv* within the evaluation length

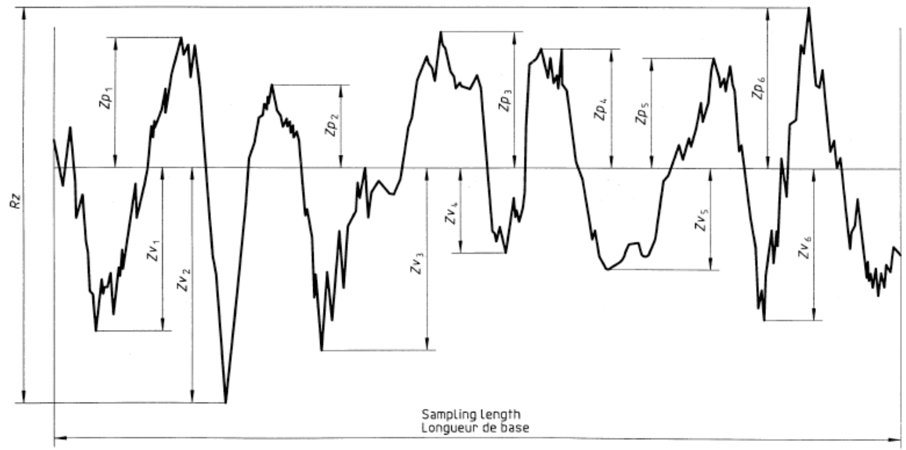


Figure 8 — Maximum height of profile (example of a roughness profile)
Figure 8 — Hauteur maximale du profil (exemple de profil de rugosité)

arithmetical mean deviation of the assessed profile

Pa, *Ra*, *Wa*

arithmetic mean of the absolute ordinate values $Z(x)$ within a sampling length

$$Pa, Ra, Wa = \frac{1}{l}\int_0^l |Z(x)|\,dx$$

with $l = lp$, lr or lw according to the case.

root mean square deviation of the assessed profile

Pq, *Rq*, *Wq*

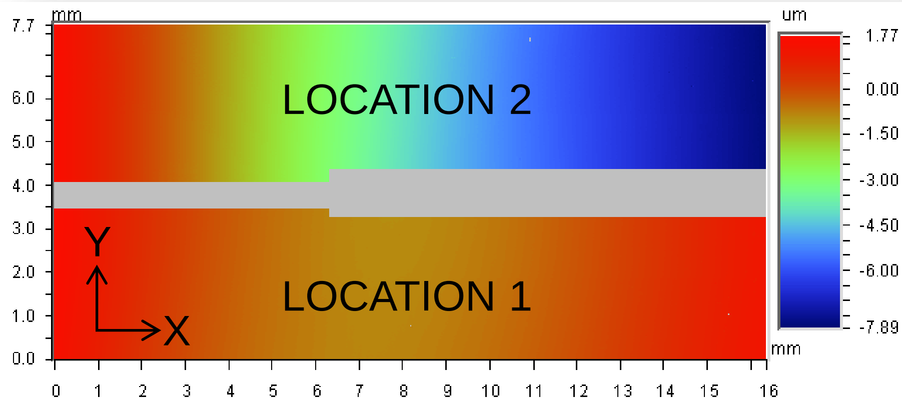
root mean square value of the ordinate values $Z(x)$ within a sampling length

$$Pq, Rq, Wq = \sqrt{\frac{1}{l}\int_0^l Z^2(x)\,dx}$$

with $l = lp$, lr or lw according to the case.

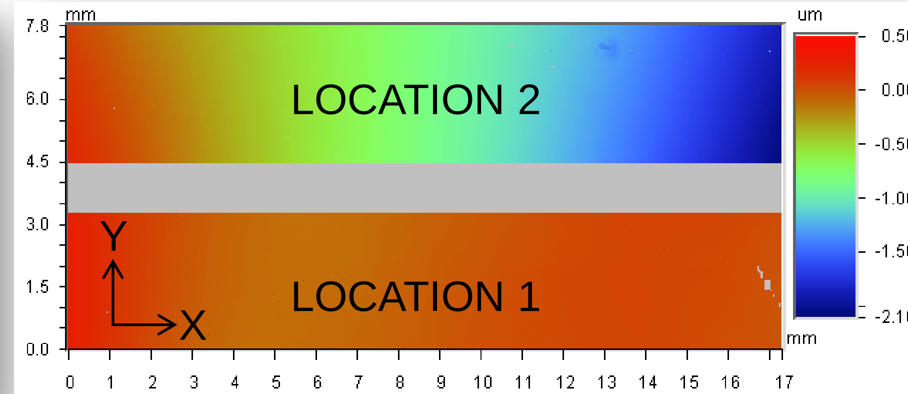
FLATNESS MEASUREMENT – 7V TARGET SUPPORT

TARGET SUPPORT 0.5mm



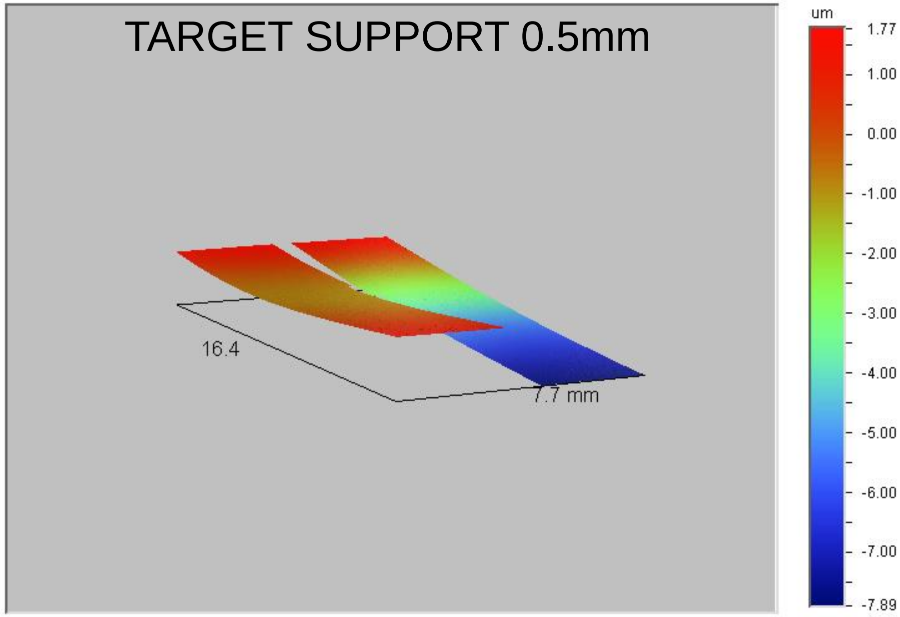
Specification	Location 1 (in µm or in µrad)	Location 2 (in µm or in µrad)
Maximum to minimum	2.74 µm	9.66 µm
Tilt in X direction	0 µrad	587.8 µrad
Tilt in Y direction	0 µrad	-8.9 µrad

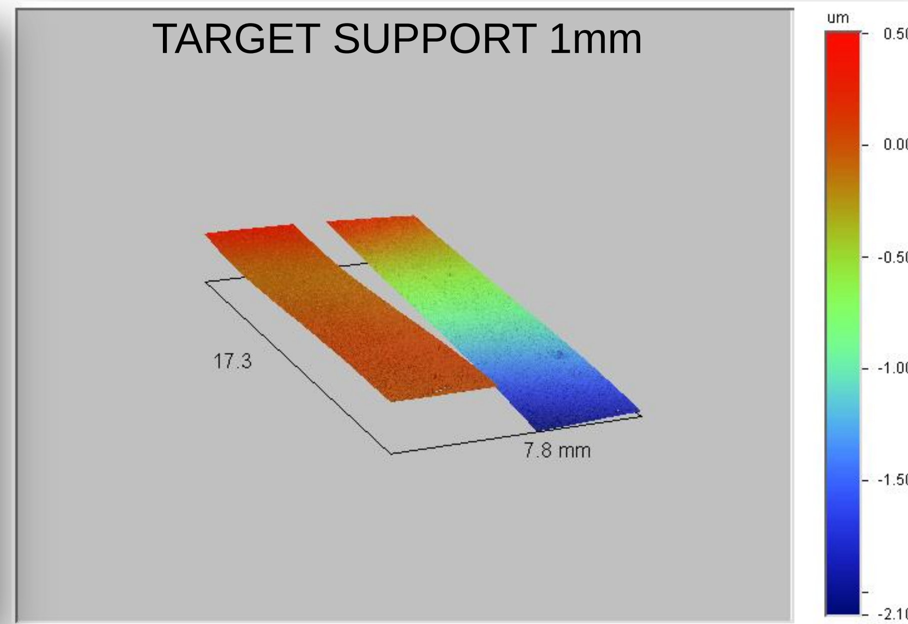
TARGET SUPPORT 1mm

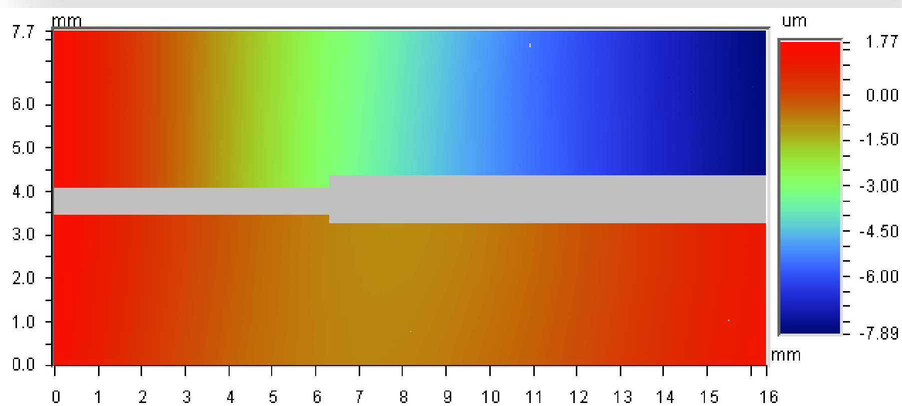


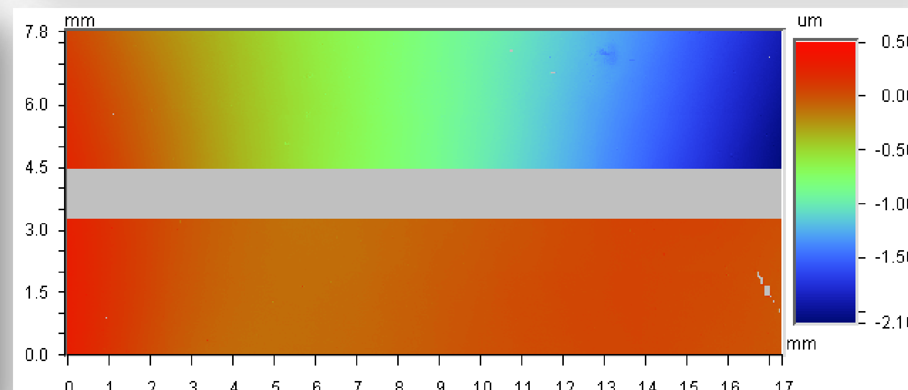
Specification	Location 1 (in µm or in µrad)	Location 2 (in µm or in µrad)
Maximum to minimum	0.90 µm	2.34 µm
Tilt in X direction	0 µrad	114.1 µrad
Tilt in Y direction	0 µrad	-6.2 µrad

FLATNESS MEASUREMENT – 7V TARGET SUPPORT

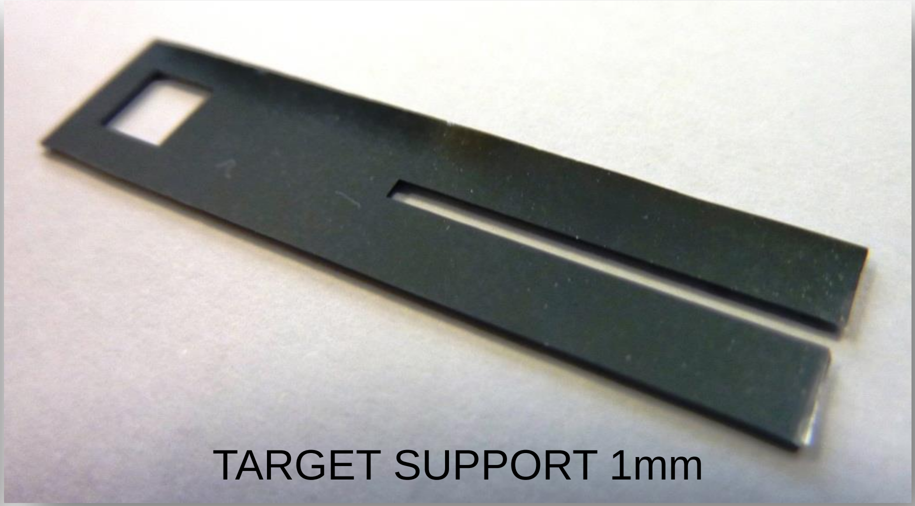








ROUGHNESS MEASUREMENT – 7V TARGET SUPPORT



TARGET SUPPORT 0.5mm

	Mean:	Std Dev:
Rq:	4.412 nm	1.334 nm
Ra:	2.353 nm	0.439 nm
Rt:	60.493 nm	23.023 nm
Rp:	39.524 nm	20.573 nm
Rv:	-20.969 nm	8.660 nm

TARGET SUPPORT 1mm

	Mean:	Std Dev:
Rq:	1.797 nm	0.594 nm
Ra:	1.217 nm	0.190 nm
Rt:	19.790 nm	13.166 nm
Rp:	8.804 nm	7.706 nm
Rv:	-10.986 nm	9.020 nm

Conditions of measurement

Long C/O: 80.000 um

Short C/O: 2.500 um

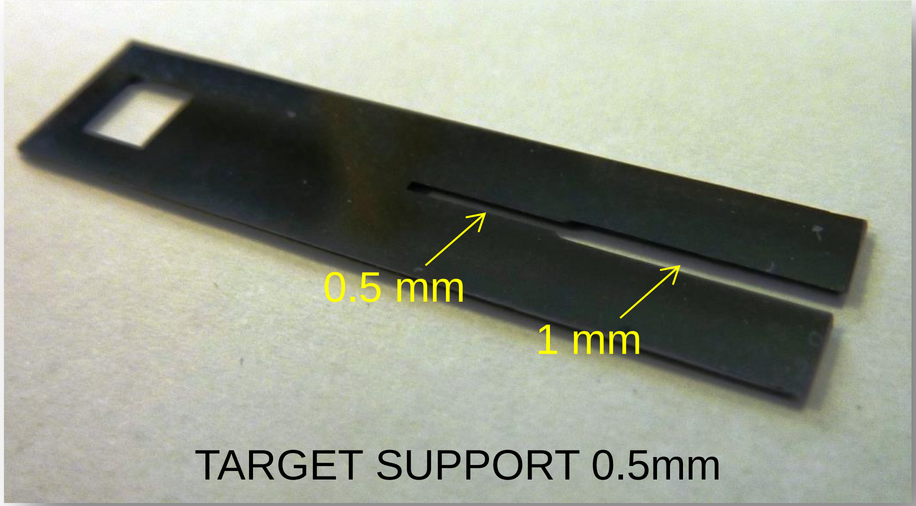
Pc Height: Ra

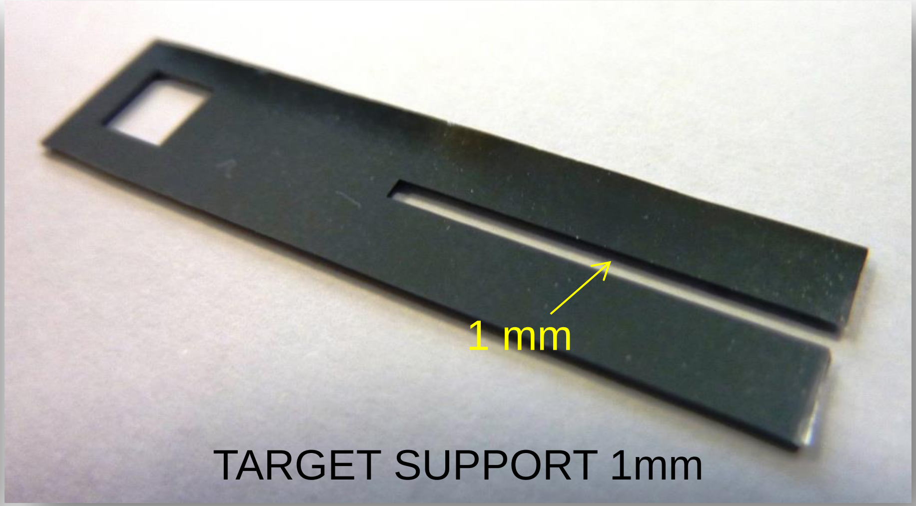
Sample Lengths: 5

X Asmnt: 398.747 um

X Lines Used: 500

DISTANCE MEASUREMENT – 7V TARGET SUPPORT



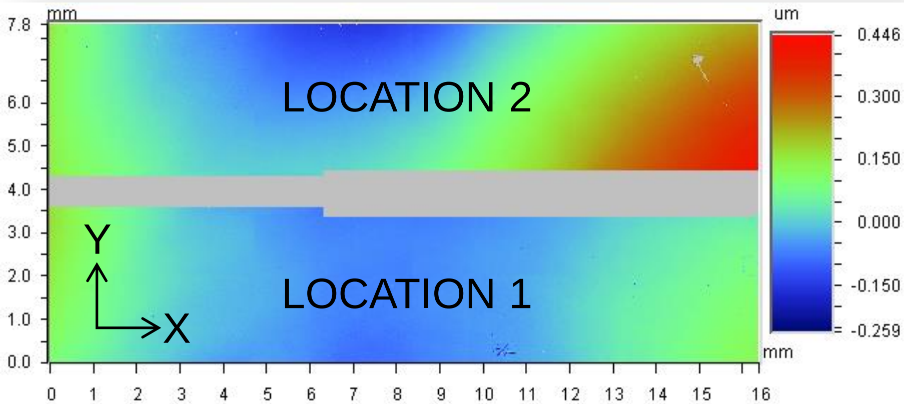


Specification	Average value (in µm)	σ value (in µm)	Number of values
1 mm	1003,7	8.5	9
0.5 mm	501.9	7.0	5

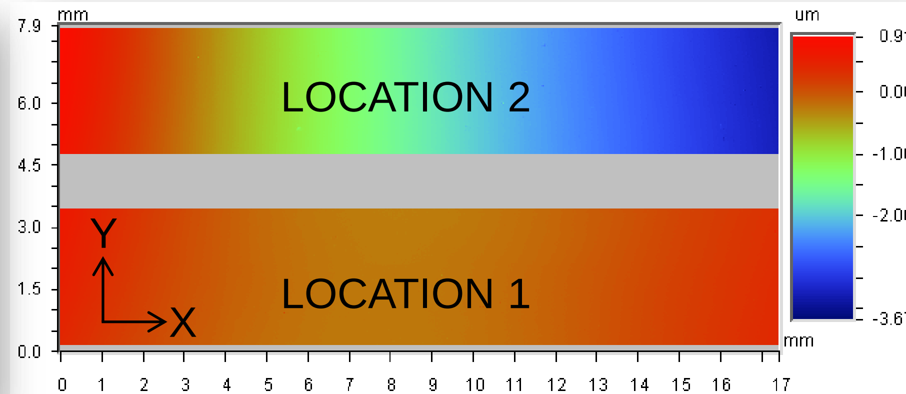
Specification	Average value (in µm)	σ value (in µm)	Number of values
1 mm	1002.7	6.7	16

FLATNESS MEASUREMENT – 2V TARGET SUPPORT

TARGET SUPPORT 0.5mm



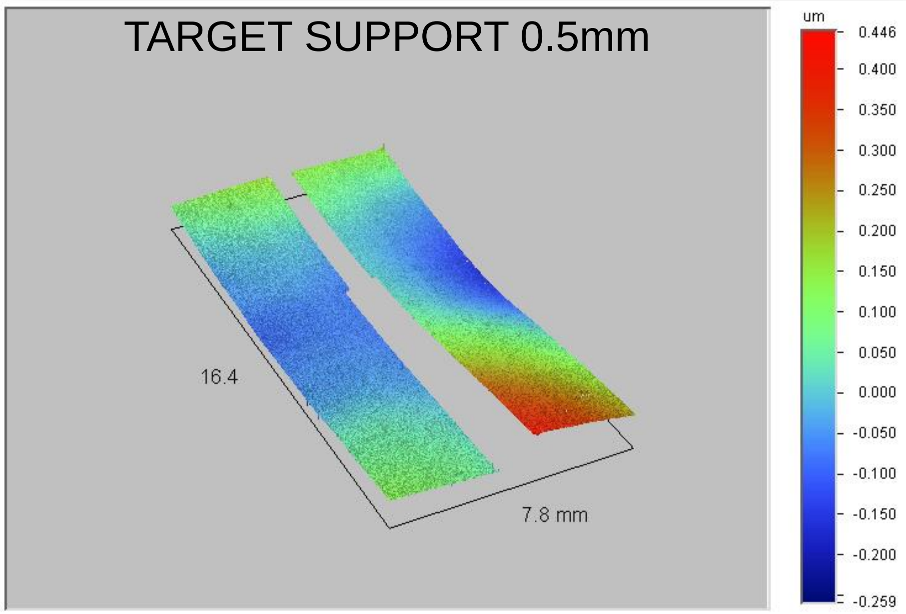
TARGET SUPPORT 1mm

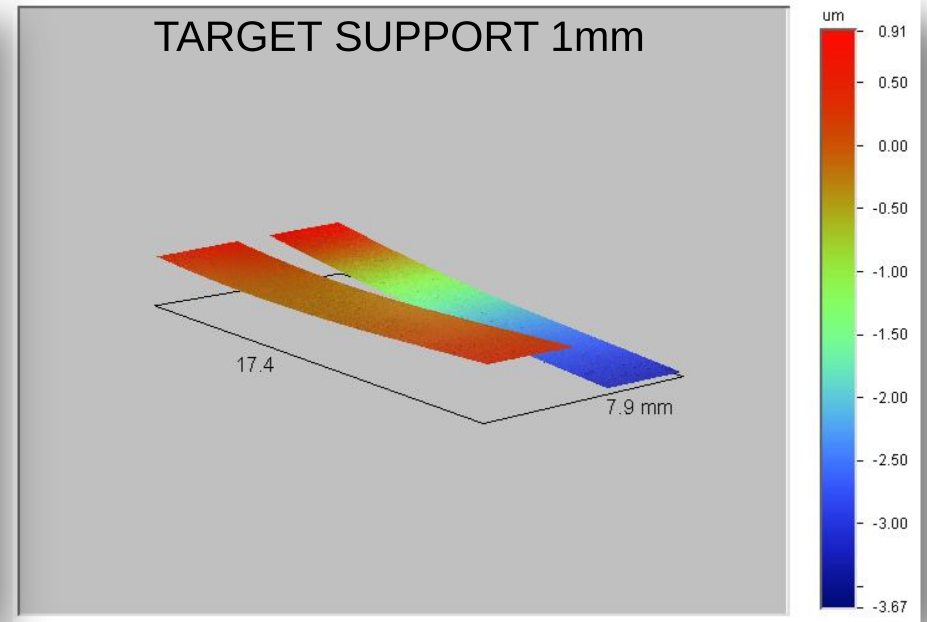


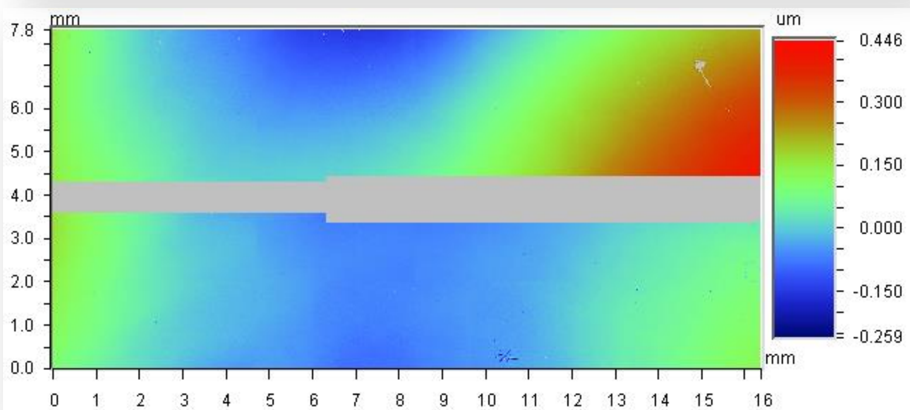
Specification	Location 1 (in µm or in µrad)	Location 2 (in µm or in µrad)
Maximum to minimum	0.64 µm	0.62 µm
Tilt in X direction	0 µrad	-17.6 µrad
Tilt in Y direction	0 µrad	37.9 µrad

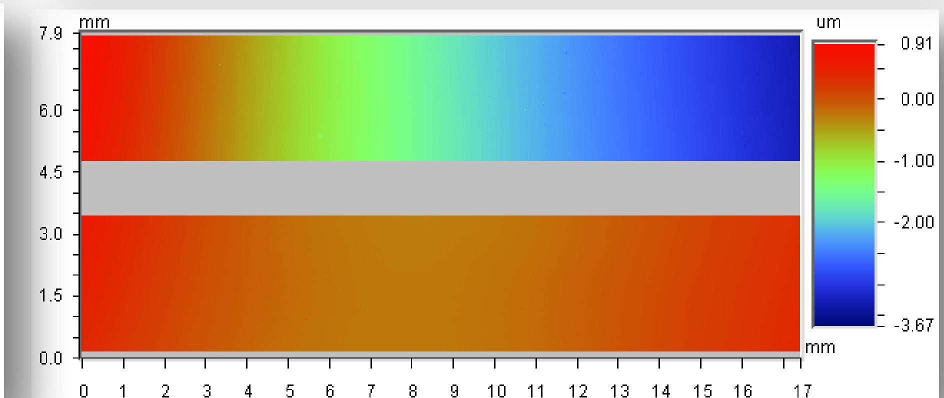
Specification	Location 1 (in µm or in µrad)	Location 2 (in µm or in µrad)
Maximum to minimum	1.12 µm	4.58 µm
Tilt in X direction	0 µrad	229.1 µrad
Tilt in Y direction	0 µrad	-2.7 µrad

FLATNESS MEASUREMENT – 2V TARGET SUPPORT

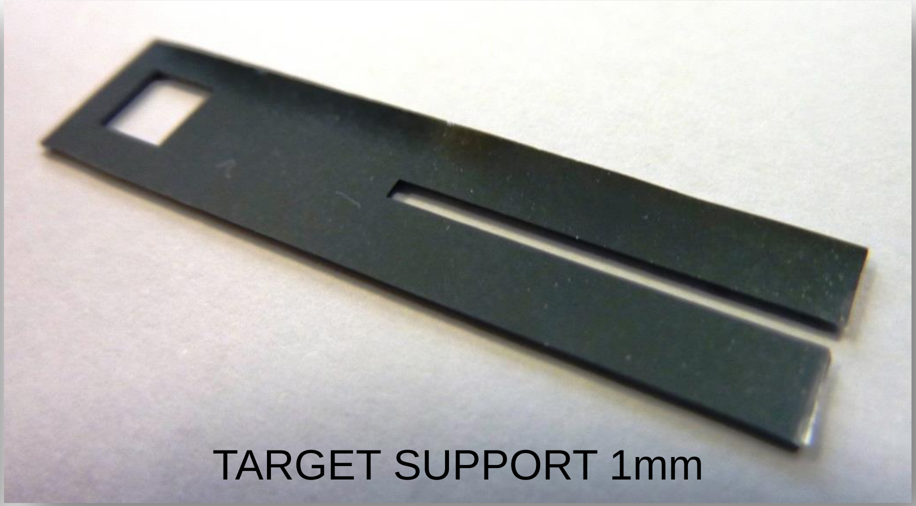








ROUGHNESS MEASUREMENT – 2V TARGET SUPPORT



Target support 0.5mm

	Mean:	Std Dev:
Rq:	3.571 nm	1.737 nm
Ra:	1.917 nm	0.448 nm
Rt:	49.328 nm	32.167 nm
Rp:	33.038 nm	29.166 nm
Rv:	-16.290 nm	6.587 nm

Target support 1mm

	Mean:	Std Dev:
Rq:	3.331 nm	1.161 nm
Ra:	1.801 nm	0.343 nm
Rt:	47.253 nm	21.663 nm
Rp:	28.946 nm	17.863 nm
Rv:	-18.306 nm	8.375 nm

Conditions of measurement

Long C/O: 80.000 um

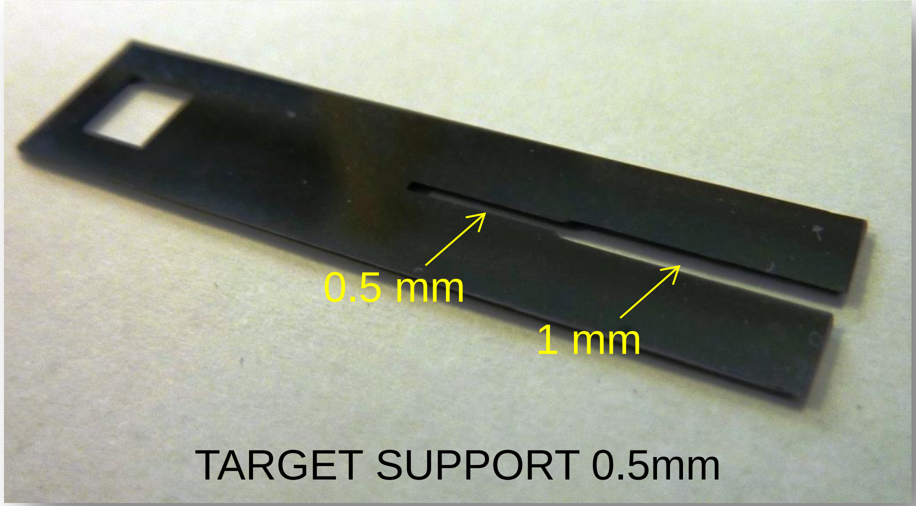
Short C/O: 2.500 um

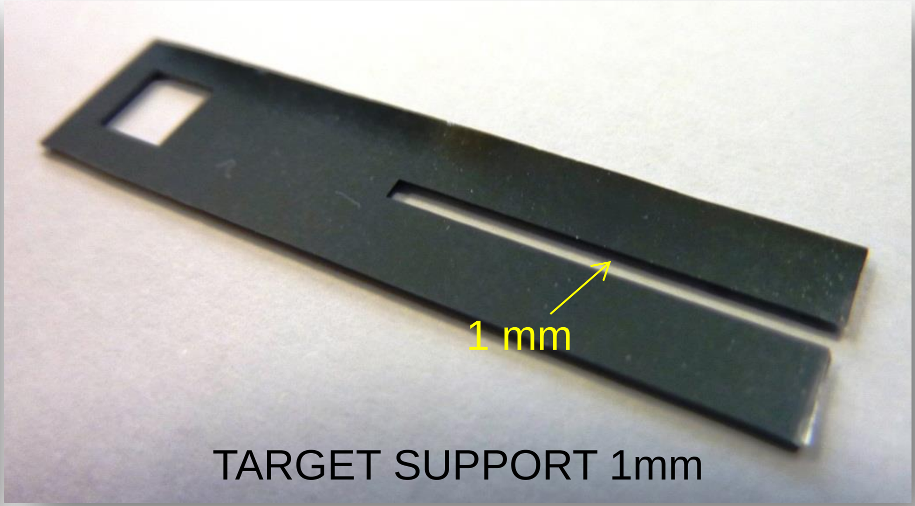
Pc Height: Ra

Sample Lengths: 5

X Asmnt: 398.747 um

X Lines Used: 500





Specification	Average value (in µm)	σ value (in µm)	Number of values
1 mm	997.7	7.6	9
0.5 mm	498.9	7.3	5

Specification	Average value (in µm)	σ value (in µm)	Number of values
1 mm	993.5	7.7	16