UV/X-ray Diffraction Radiation for Non-intercepting Micron-scale Beam Size Measurement

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Contents

Most recent experiments using Optical Diffraction Radiation (ODR) for beam diagnostics

- 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.

- 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).

- 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).

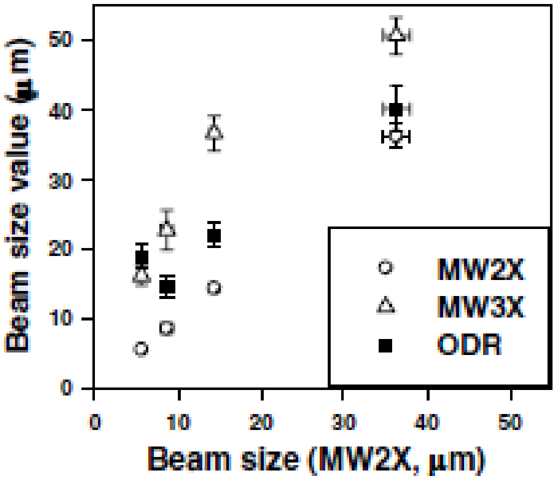


FIG. 7. The correlation between the beam size measured with ODR (black squares) and two wire scanners installed upstream (open circles) and downstream (open triangles) of the target.

σ_y = 14 µm measured ATF2@KEK

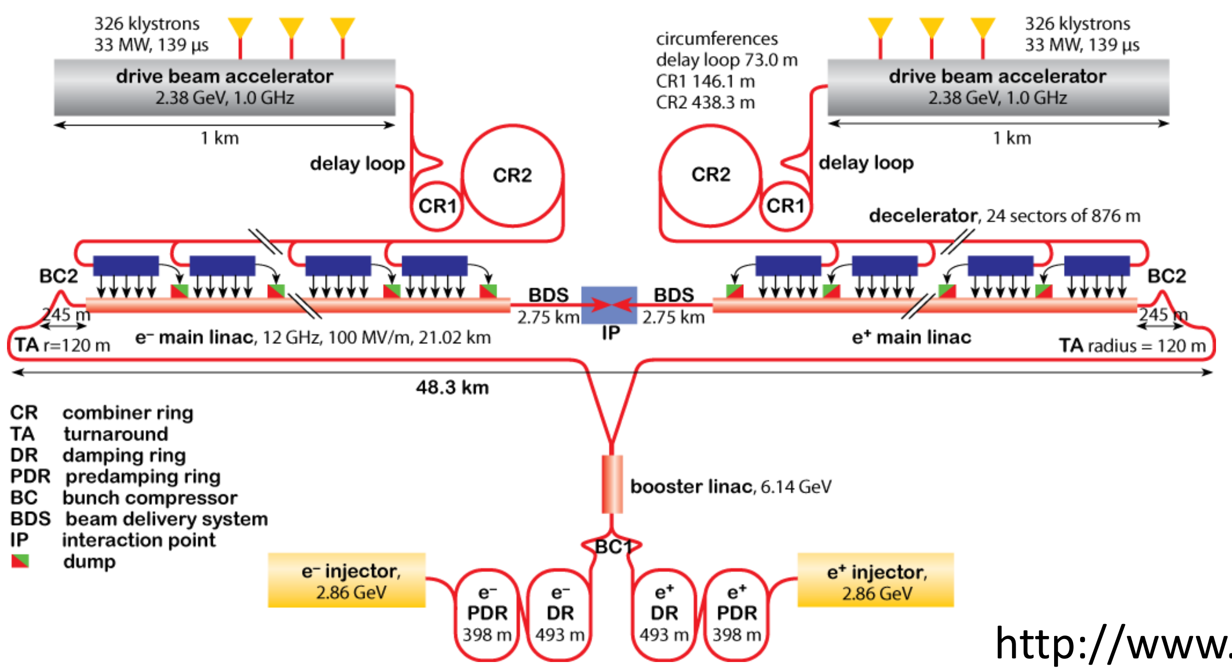
Motivation

Transverse beam size requirements for the Compact Linear Collider (*Table 5.62 CDR Volume 1, 2012*):

Section of machine	Beam Energy [GeV]	Beam size [µm]	Requirement
PDR (H/V)	2.86	50/10	Micron-scale resolution
DR (H/V)		10/1	
RTML (H/V)	2.86 - 9	10/1	
Drive Beam Accelerator	2.37	50 -100	Non-invasive measurement

Baseline high resolution non-interceptive beam profile monitor:
Laser Wire Scanners

S. T. Boogert et al., *"Micron-scale laser-wire scanner for the KEK Accelerator Test Facility extraction line"*, Phys. Rev. S. T. – Accel. and Beams 13, 122801 (2010)



http://www.clic-study.org/

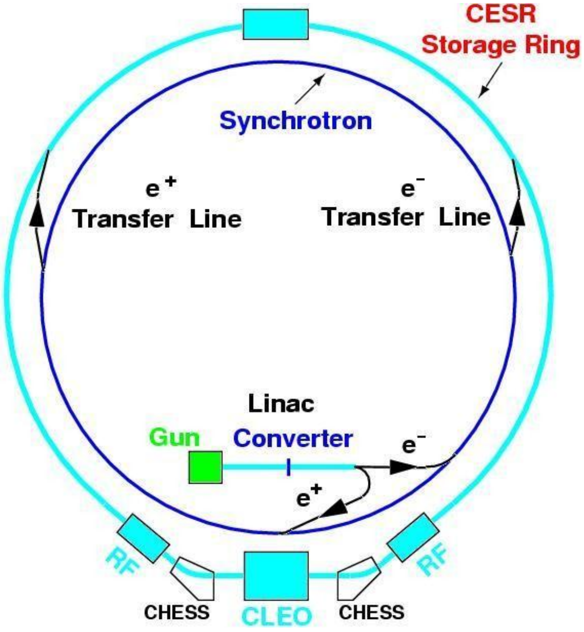
Our experiment

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:

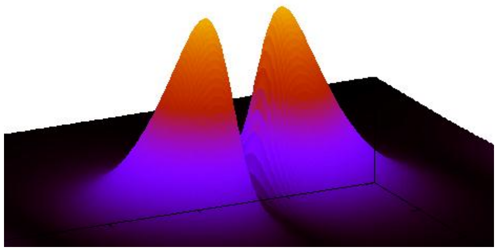
	E (GeV)	σ_H (μm)	σ_V (μm)
CesrTA	2.1	320	~9.2
	5.3	2500	~65



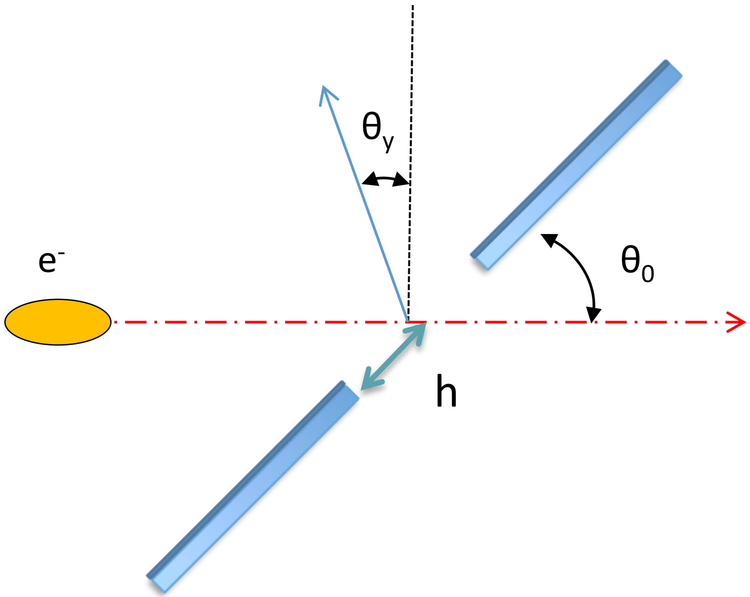
D. Rubin et al., "CesrTA Layout and Optics", Proc. of PAC2009, Vancouver, Canada, WE6PFP103, p. 2751.

http://www.cs.cornell.edu

Diffraction Radiation



DR Angular distribution



Principle:

1. Electron bunch moves through a high precision co-planar slit in a conducting screen (Si + Al coating).
2. Electric field of the electron bunch polarizes atoms of the screen surface.
3. DR is emitted in two directions:
   - along the particle trajectory "Forward Diffraction Radiation" (FDR)
   - In the direction of specular reflection "Backward Diffraction Radiation" (BDR)

Impact parameter:

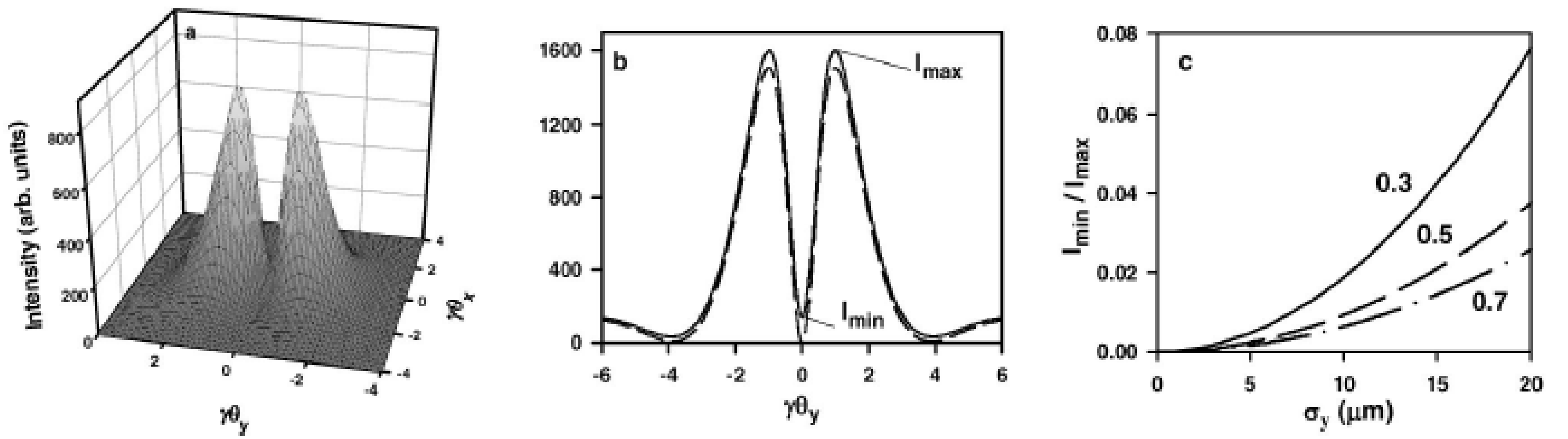
$$h \leq \frac{\gamma\lambda}{2\pi}$$

Generally:
DR intensity ⇧ as slit size ⇩

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



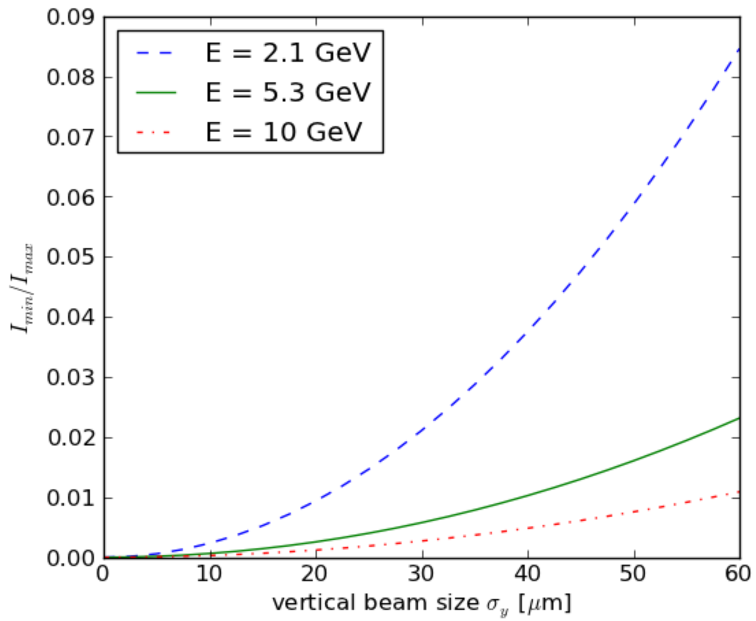
Vertical polarisation component of 3-dimensional (θ_x, θ_y, Intensity) DR angular distribution.

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.

Phase 1 Experiment Simulations for CesrTA

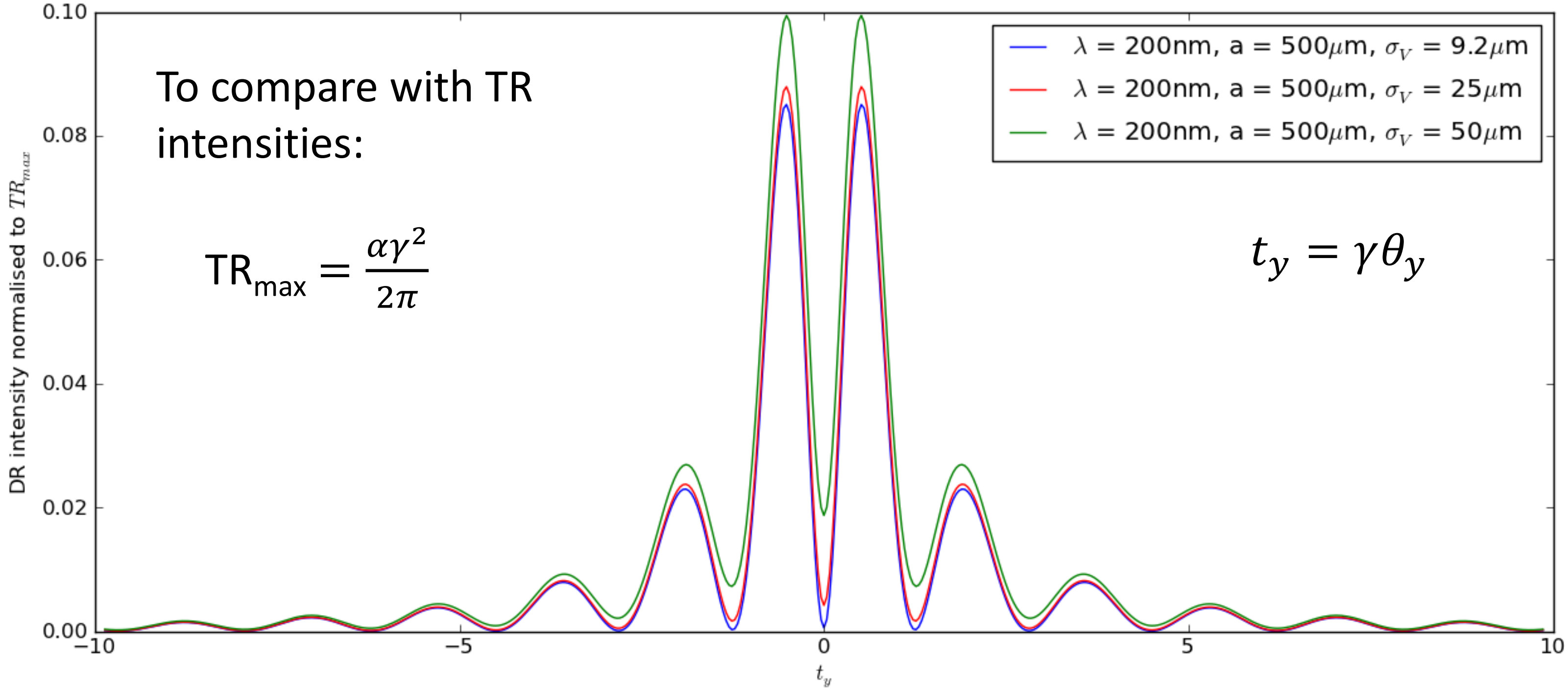
Measureable visibility for initial test at parameters:
λ = 200 - 400 nm
a = 0.5, 1 mm
σ_y = 50 µm



To compare with TR intensities:

$$\mathrm{TR_{max}} = \frac{\alpha\gamma^2}{2\pi}$$

$$t_y = \gamma\theta_y$$



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 $a_{target} = 7\text{-}10 \cdot \sigma_y$

↓

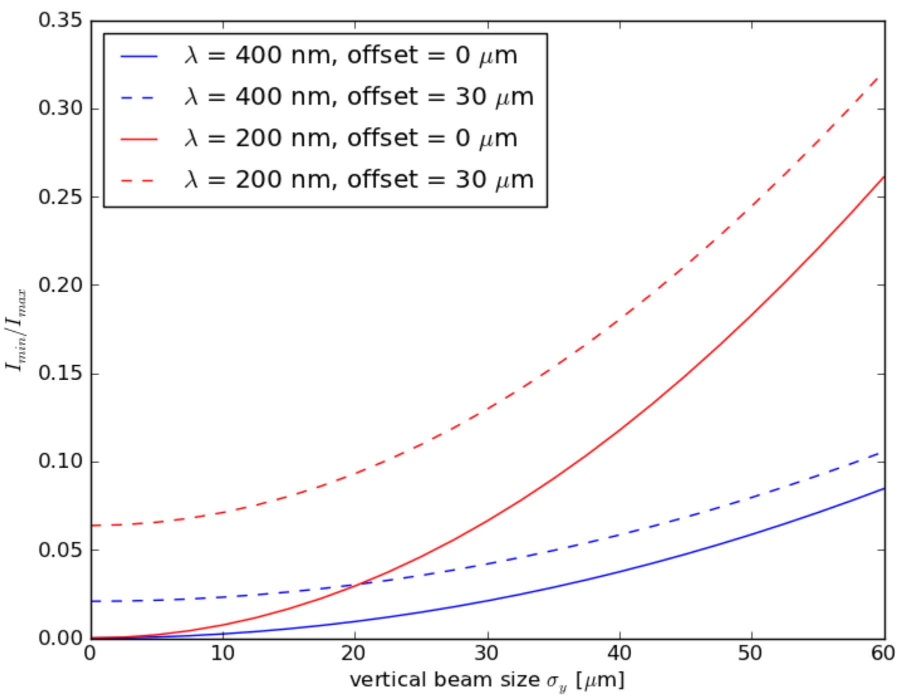
Large aperture = low DR intensity

↓

Multiple turns of a single bunch through the target aperture

↓

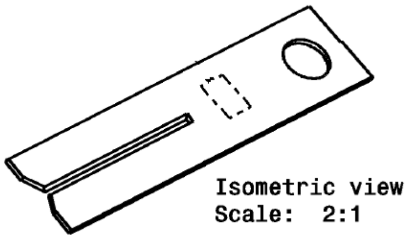
Errors due to beam jitter are reduced by including turn-by-turn vertical position measurements of the bunch in the target aperture.

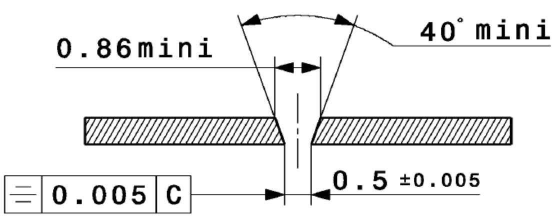


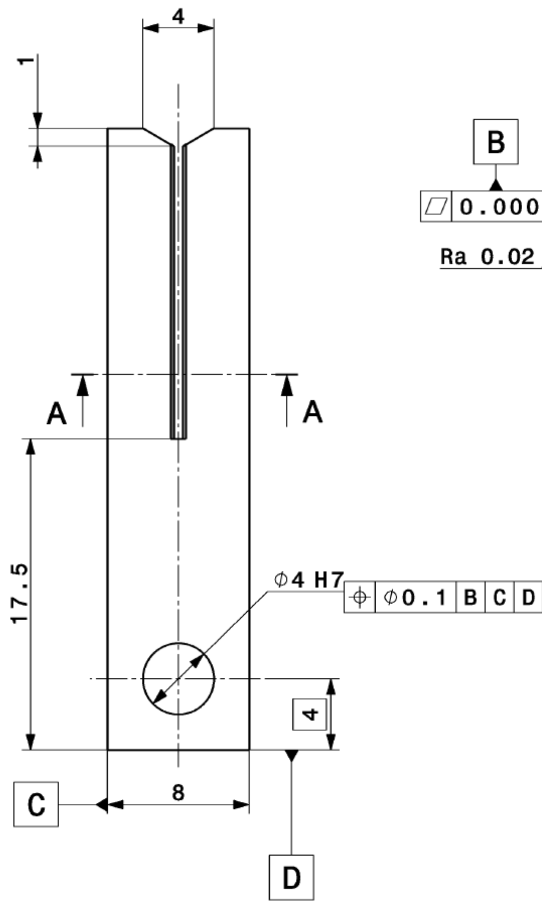
Target design

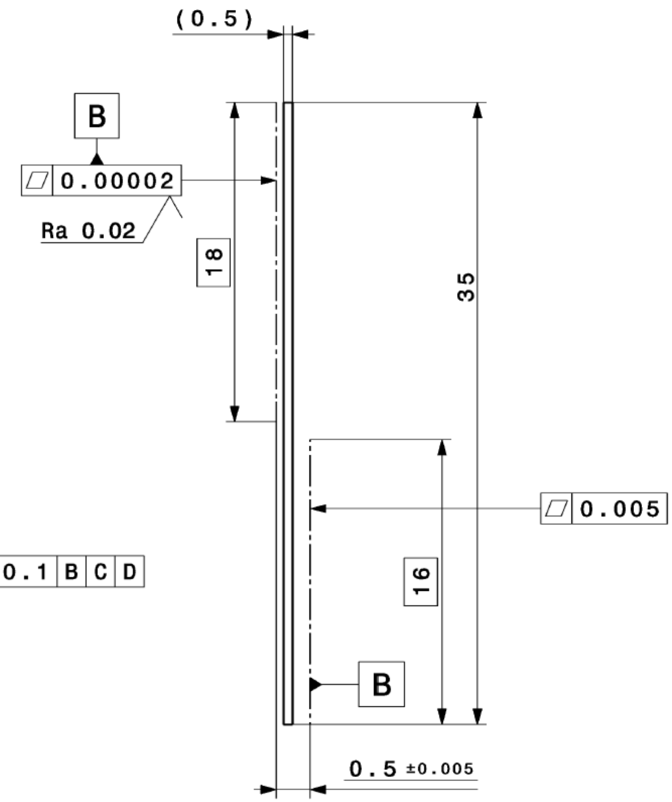
Requirements:
High precision slit size
Coplanarity ≤ 10% · λ
High reflectivity at λ

Aperture sizes a:
0.5 mm, 1 mm
Material: Si





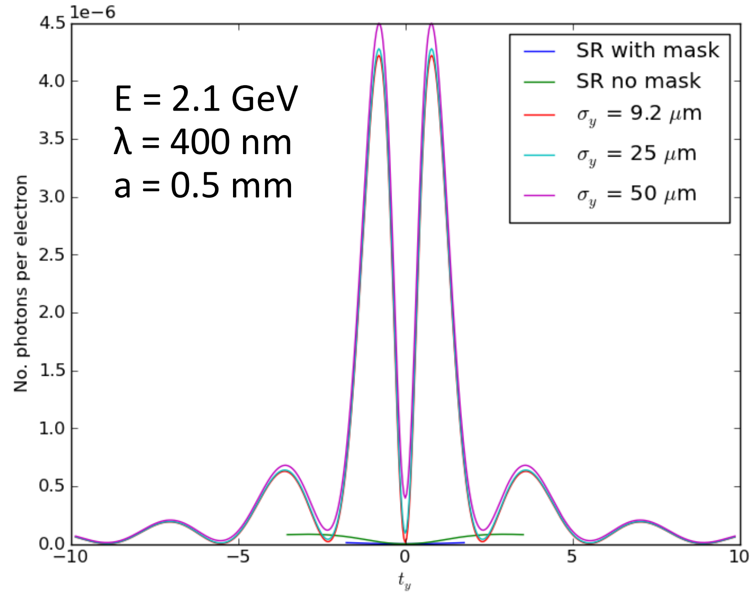




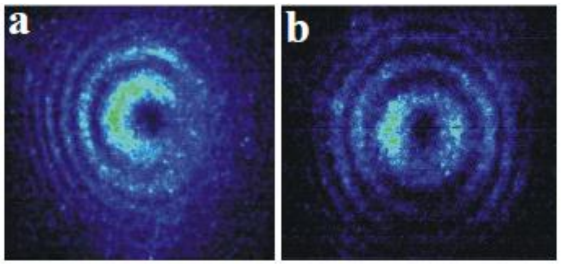
Technical drawings by N. Chritin

Synchrotron Radiation (SR)

Source of background	Contribution
SR from beamline optics	High
Camera noise	Low
Residual background	

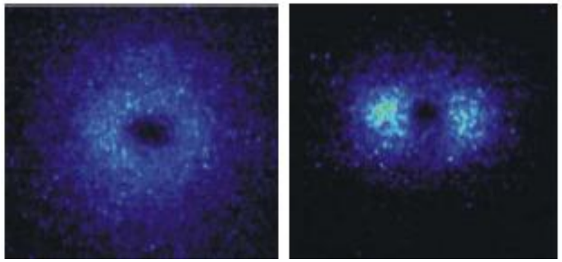


SR + DR interference



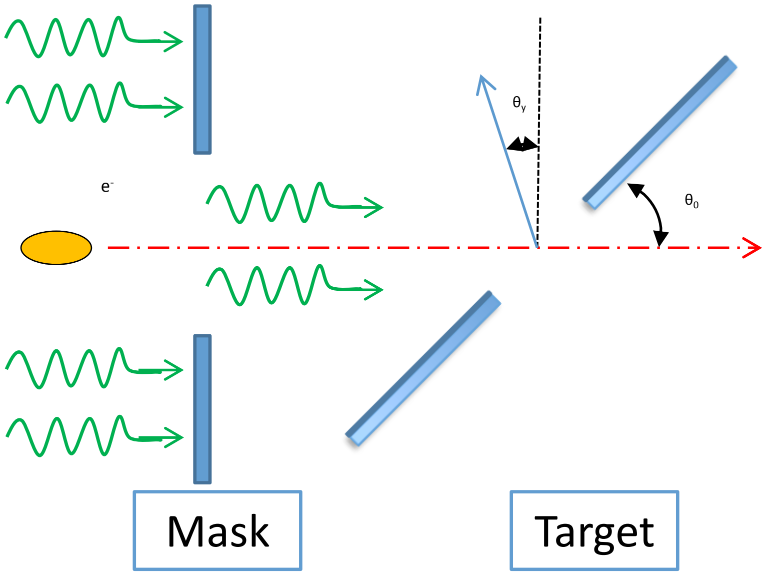
OTR ODR

SR suppression



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

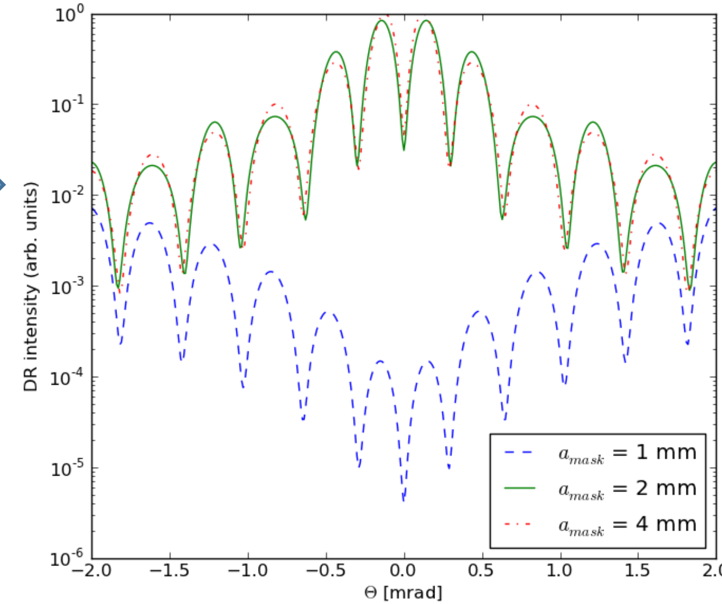
Use a mask upstream of target to suppress SR contribution.



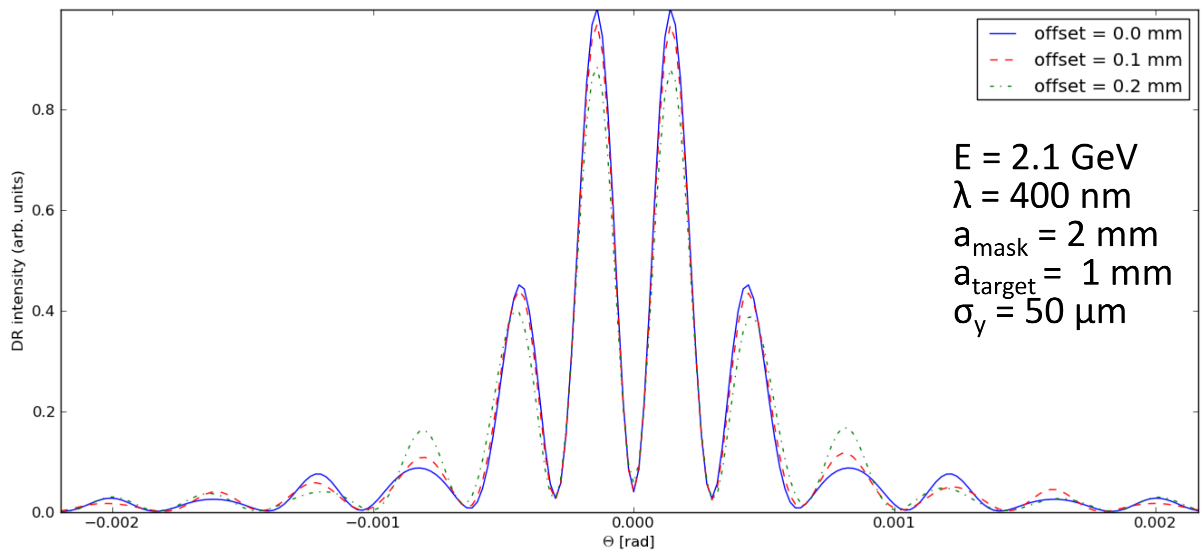
Optical Diffraction Radiation Interference (ODRI)

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)

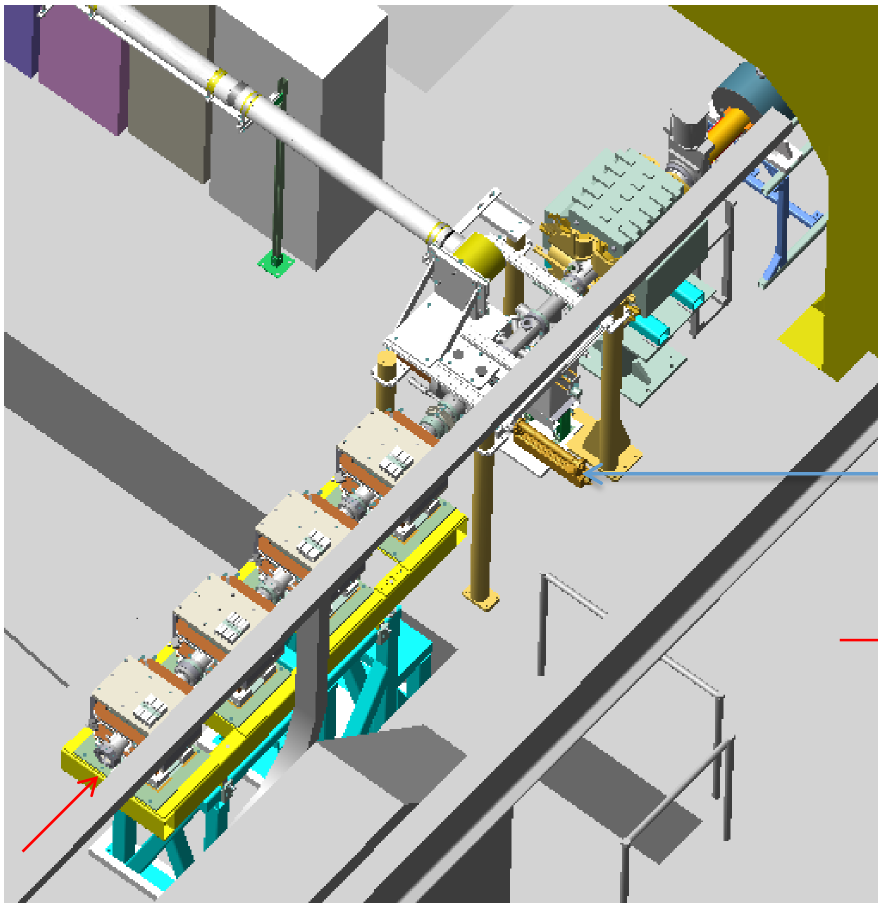


Using non-collinear slits (i.e. centres of mask + target do not coincide) allows measurement of beam size, beam offset from the target centre and angular divergence.

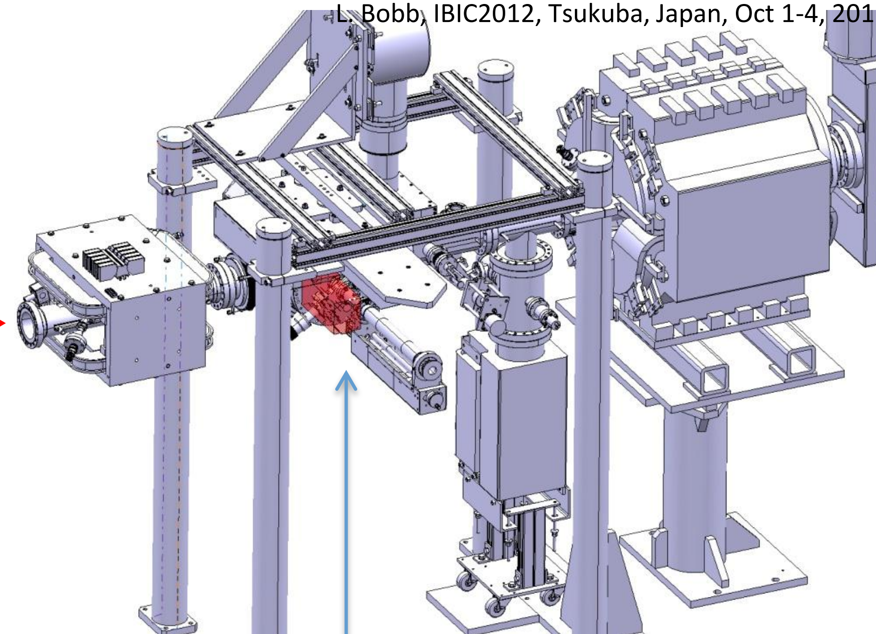


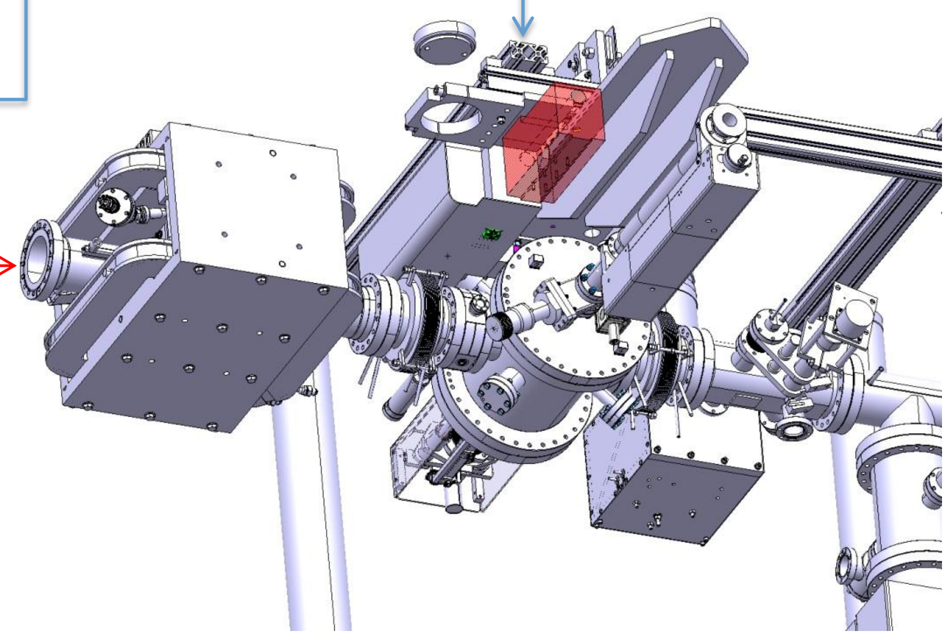
L3 layout @CesrTA

Electron beam direction



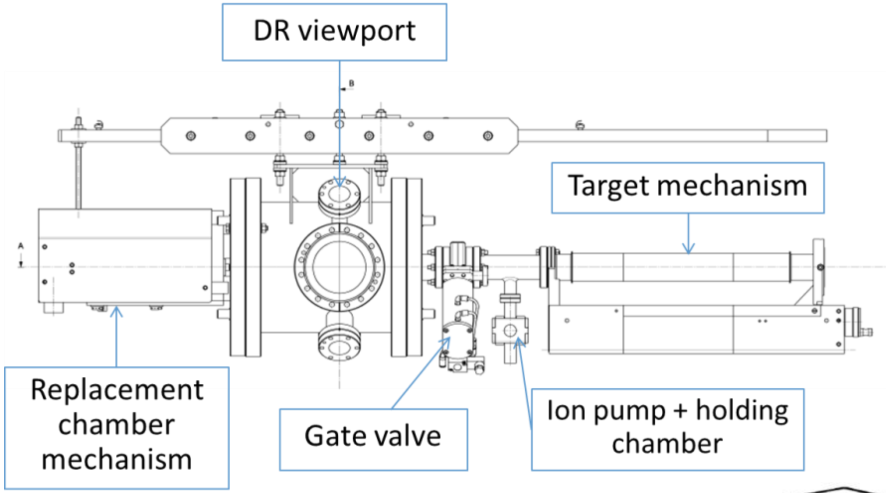
DR experiment

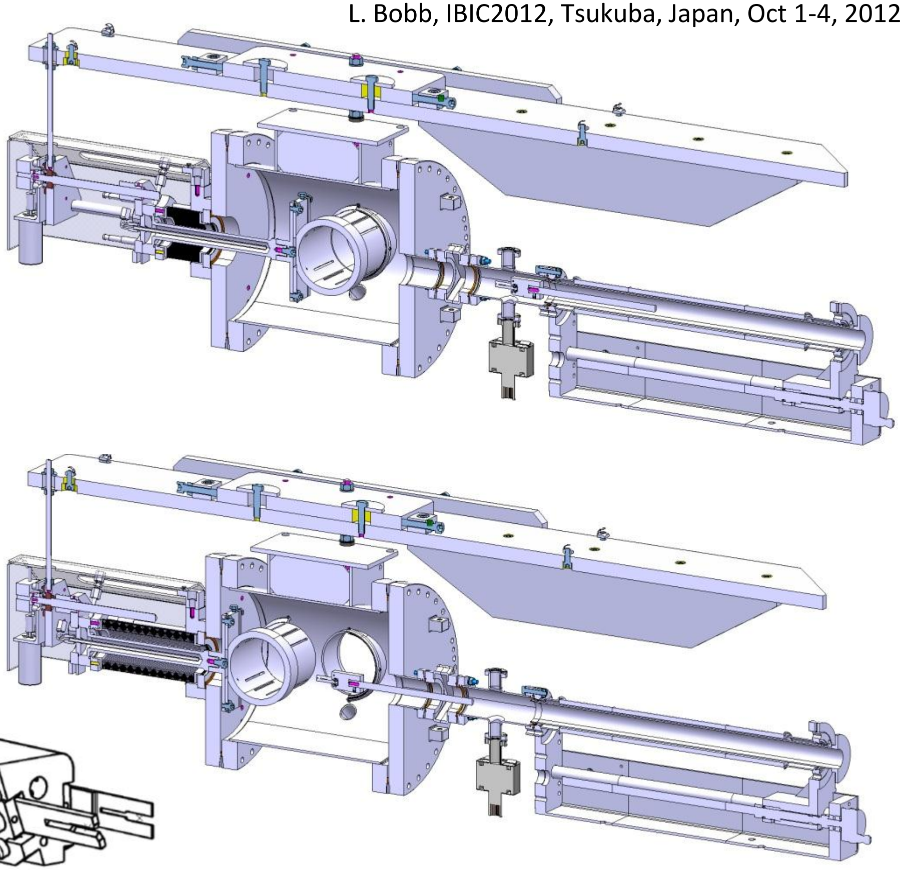


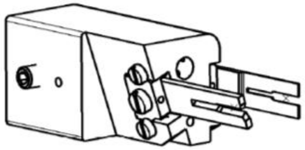


Technical drawings by N. Chritin

Vacuum chamber assembly

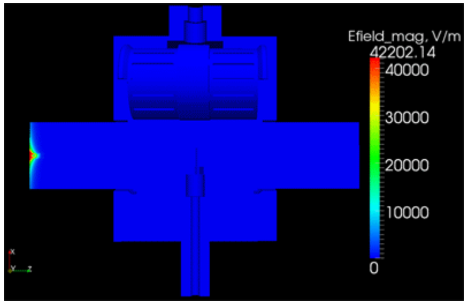


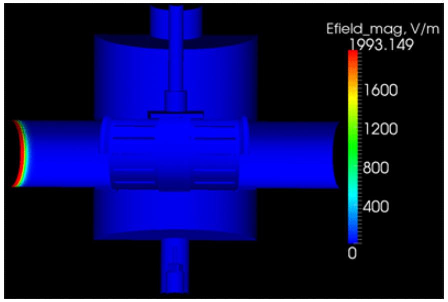




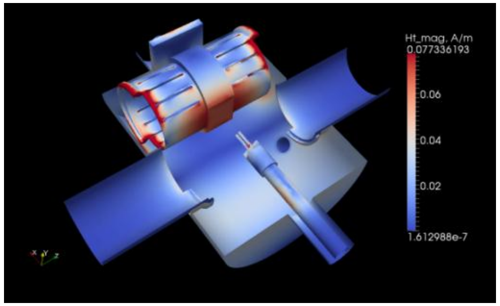
Technical drawings by N. Chritin
Simulations by A. Nosych

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



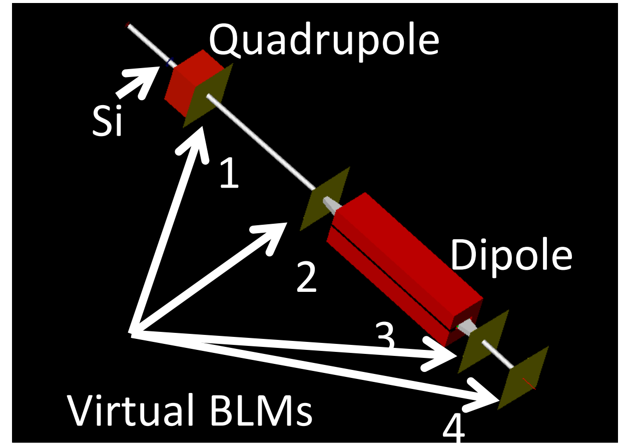


H-field surface tang complex magnitude (Loss map)
Mode Fr = 1.19 GHz, Q = 3309, Ploss = 0.075 W

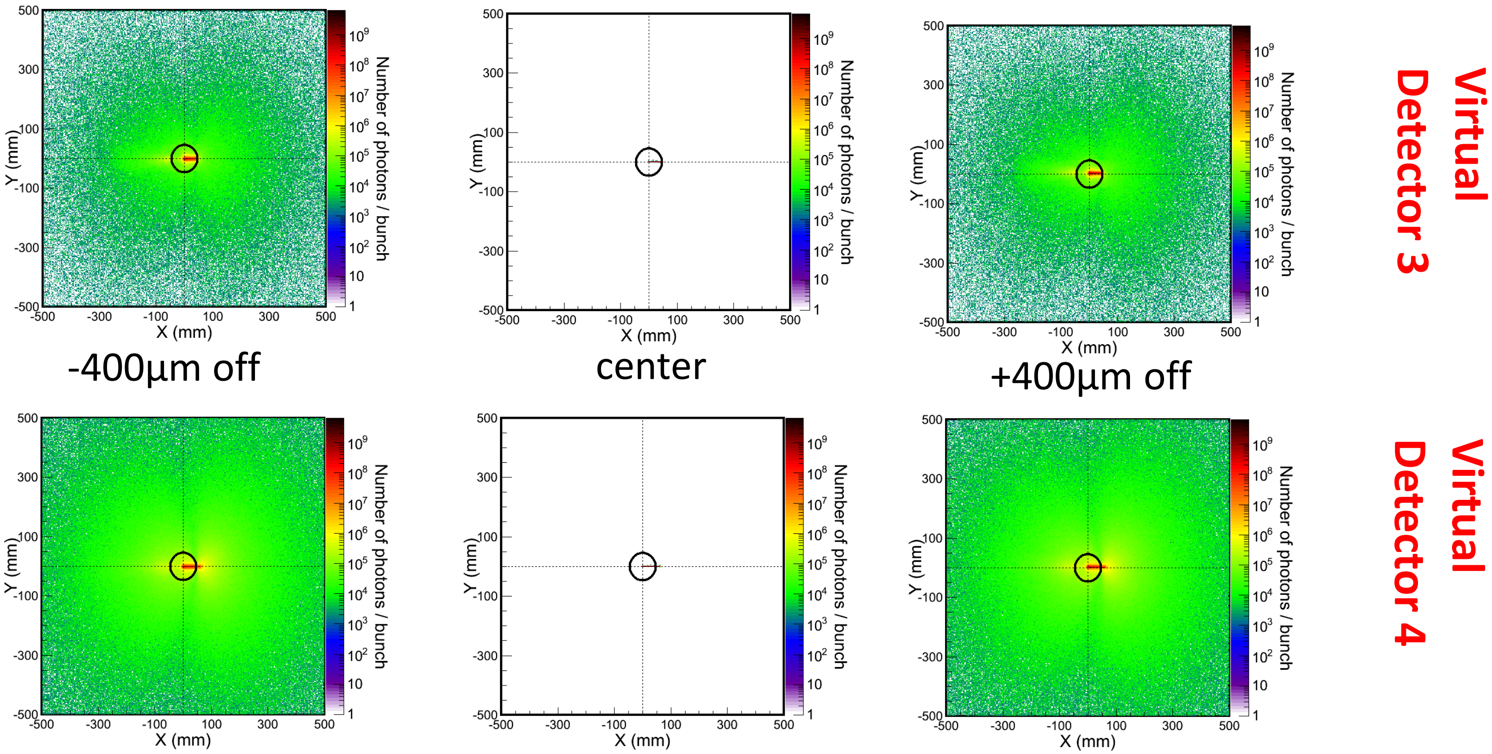


Total power loss for single bunch = 0.6 W

Method of Operation



1. Alignment of the electron beam with the target aperture:
   - BPMs for centering (~10 microns resolution)
   - Target imaging to look for OTR from beam halo
   - Correlate with BLMs:



2. DR vertical beam size measurement

Simulations by A. Apyan

Optical System

Far-field Condition:

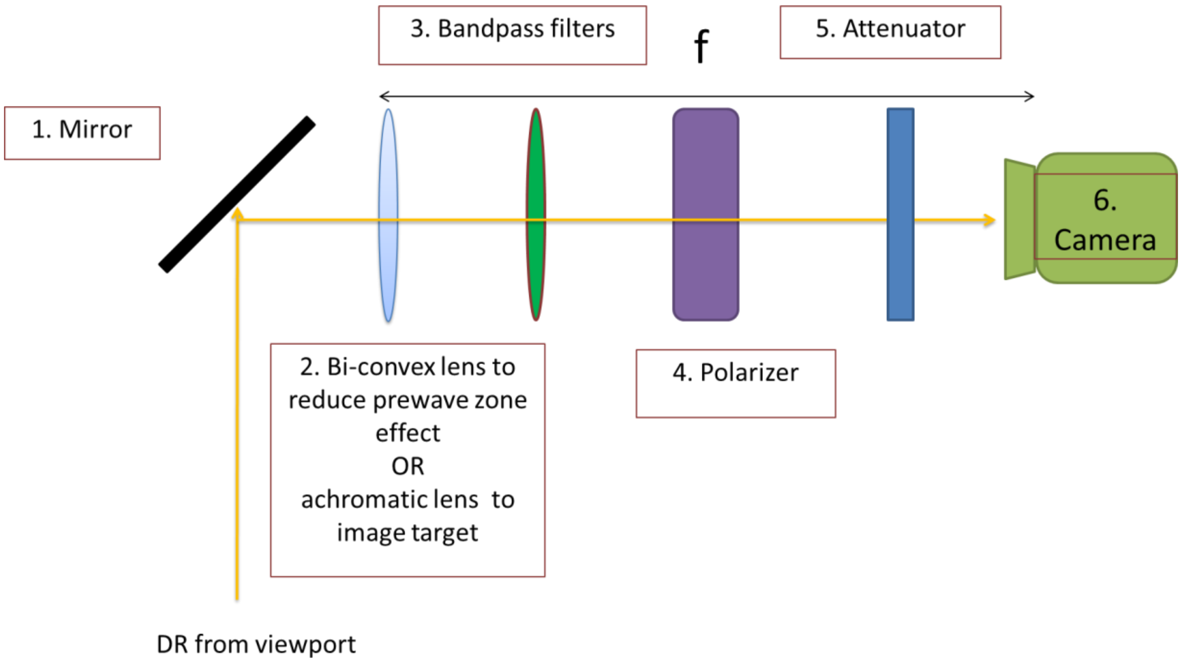
$$L \gg \frac{\gamma^2 \lambda}{2\pi}$$

- L = distance from source of DR to detector.
- Compact optical system is in the prewave zone

(*Pre-wave zone effect in transition and diffraction radiation: Problems and Solutions* -P. V. Karataev).

$\frac{\gamma^2 \lambda}{2\pi}$ given γ and λ:

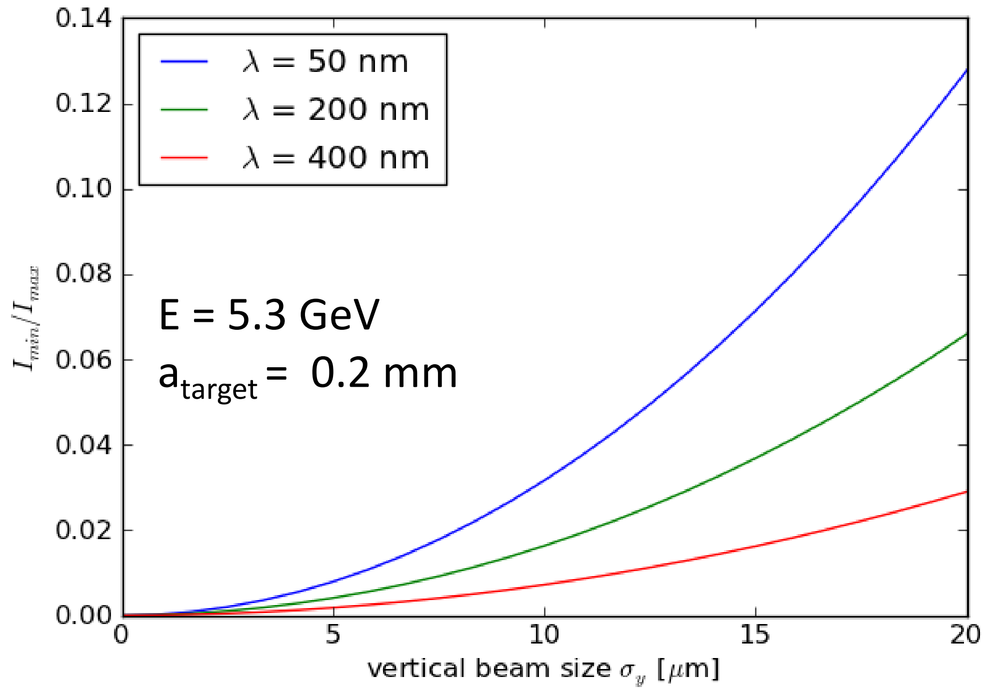
	2.1 GeV	5 GeV
200 nm	0.54 m	3.18 m
400 nm	1.08m	6.37 m



Compact optical system (distance to detector L ≤ $\frac{\gamma^2 \lambda}{2\pi}$)	Long-range optical system (distance to detector L >> $\frac{\gamma^2 \lambda}{2\pi}$)
Bi-convex lens required with camera in back focal plane.	Far-field zone
Dual purpose: 1. Image target 2. Image DR angular distribution	
DR observation wavelengths: λ = 200 nm, 400 nm	
In footprint of target mechanism (< 1m)	Determined by L and spatial constraints.

Phase 2: Micron-scale resolution

- DR at soft X-ray wavelengths:
    - More complex optical system.
    - Grazing target tilt angle
- Aperture size determined by impact parameter for given wavelength



Main requirement:
Micron-scale resolution

Must use shorter wavelengths

Sensitivity @50 nm ≈ 2x sensitivity @200 nm

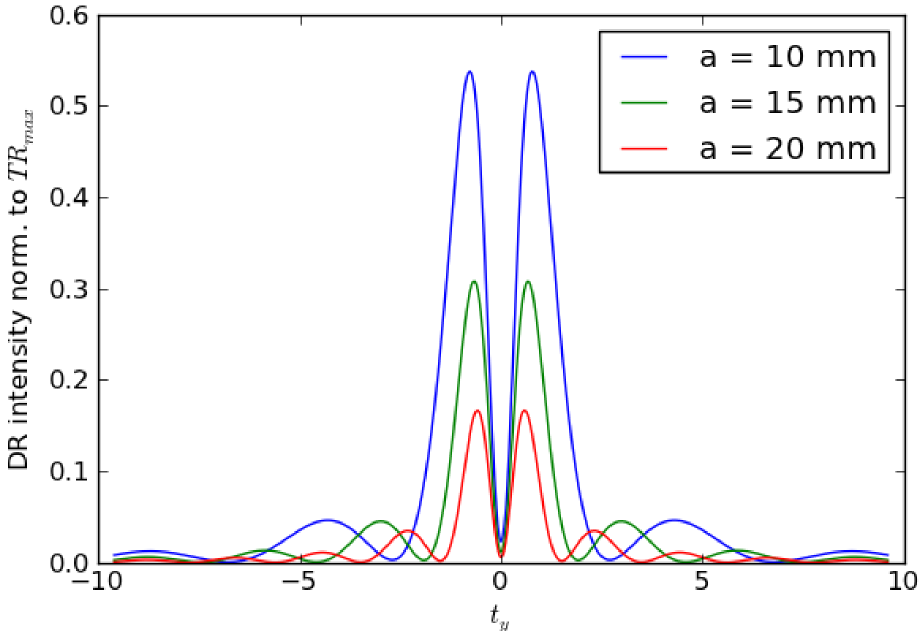
Feasibility of a ring beam size monitor

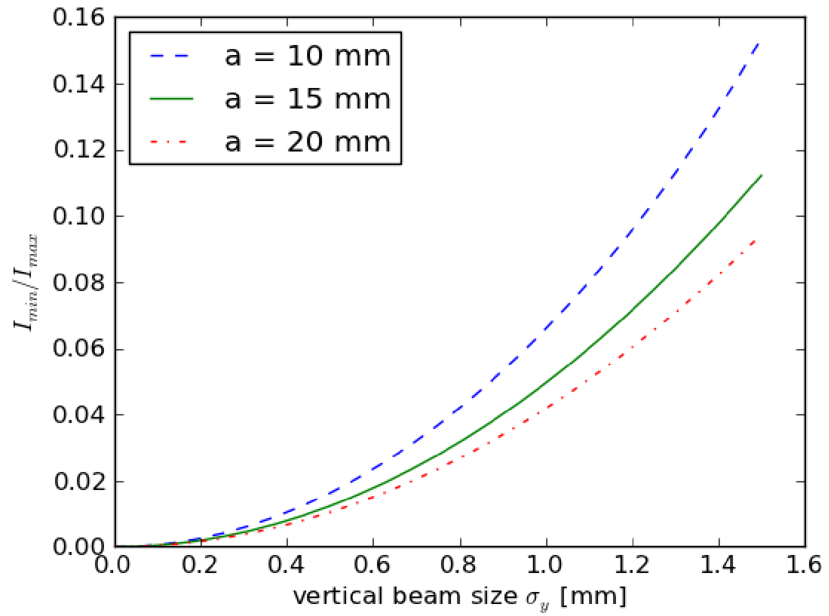
- LHC also has γ ≈ 4000 (@ E = 4000 GeV)
- Using proton beam:
  - Reduced SR background
  - Larger beam size
- Wavelengths in the infrared spectral range

Main requirement:
Non- invasive measurement

↓

Must use large target aperture





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).

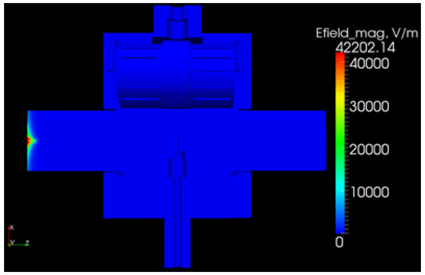
Thank you for your attention

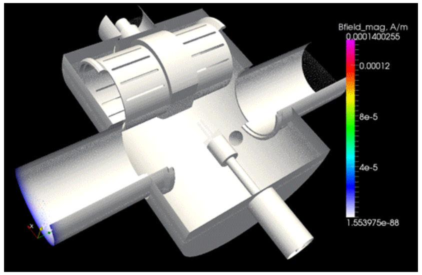
Questions?

Extra slides

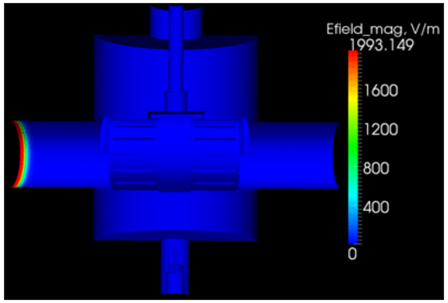
Higher Order Modes (HOMs)

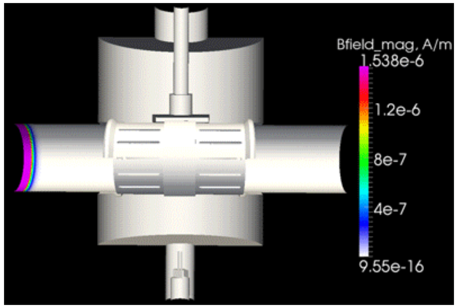
E-field + B-field magnitude of a single bunch pass in time domain (Gaussian bunch, length = [-4σ,4σ], σ = 10mm)

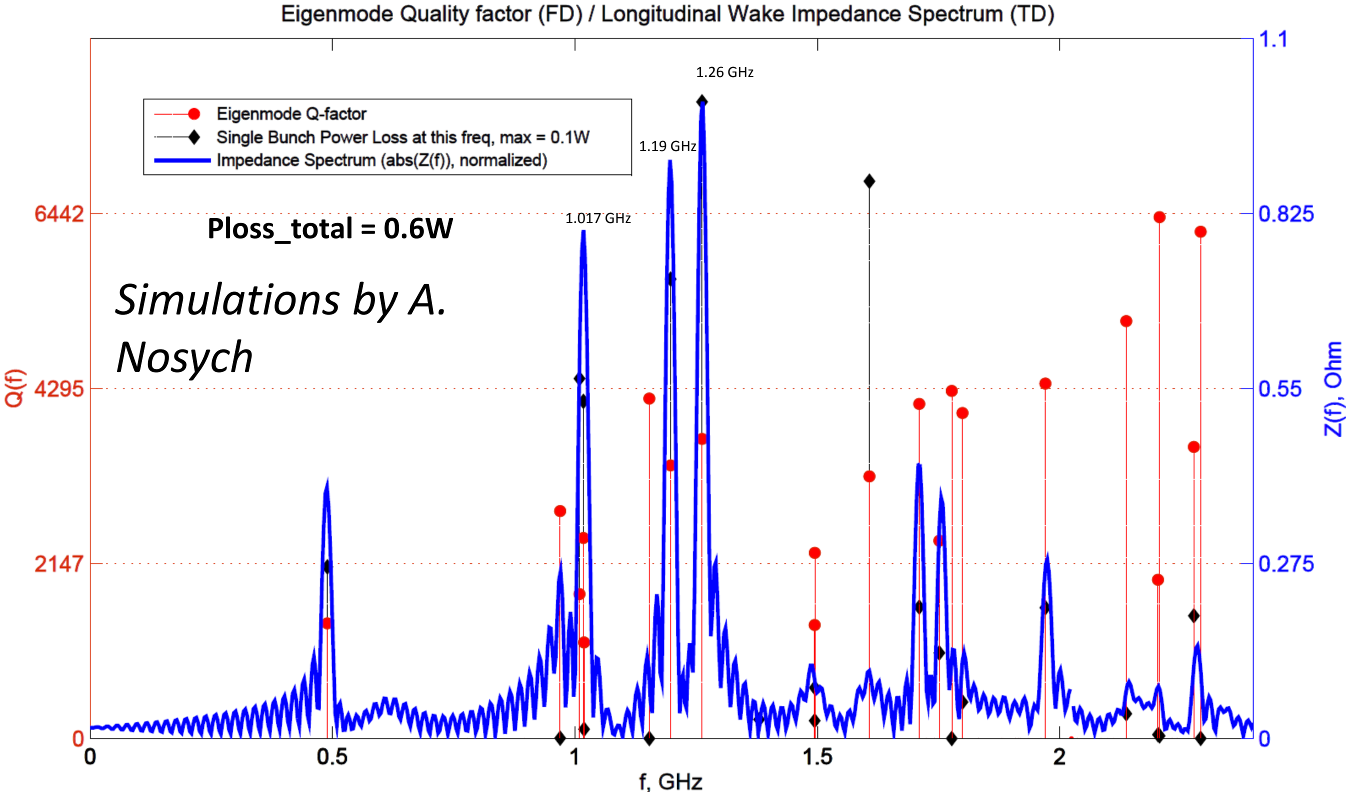




Fork OUT, Chamber IN







Ploss_total = 0.6W

Simulations by A. Nosych

H-field surface tang complex magnitude (Loss map)