Detection of Cherenkov Diffraction Radiation on the Cornell Electron Storage Ring

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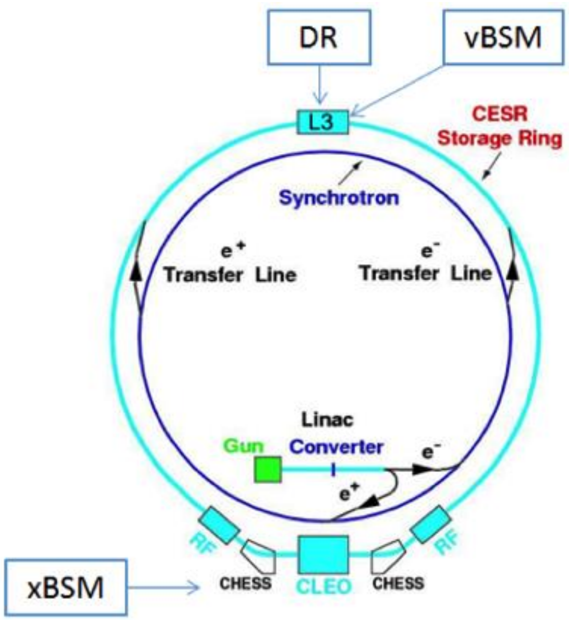
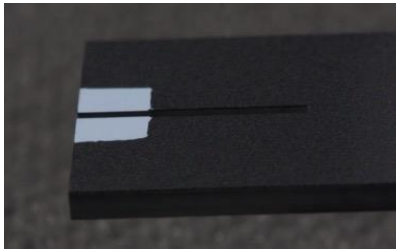
Outline

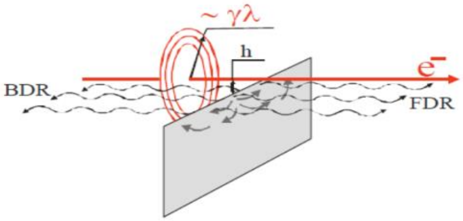
- Development of non-invasive beam size monitor for CLIC
  - From the emission of Diffraction radiation in Slits to Cherenkov Diffraction Radiation in longer dielectric
- Experimental set-up on CESR
- Experimental results obtained on CESR in 2017
- Perspectives and future work

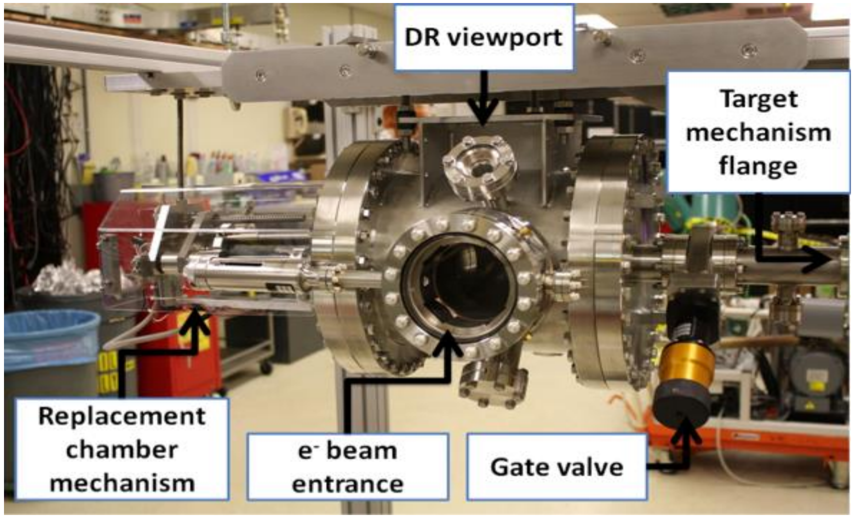
Incoherent Diffraction Radiation on CESR (1/6)

- Experimental program since 2011 at Cornell (electrons@2.1GeV) measuring DR for non-interceptive beam size monitoring using thin (0.5mm aperture) slits



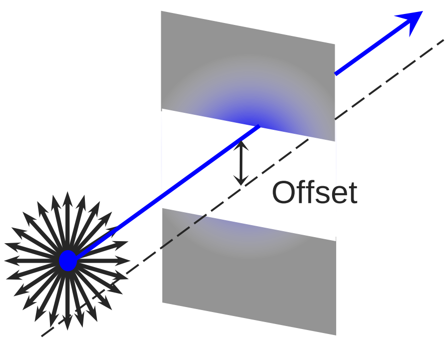




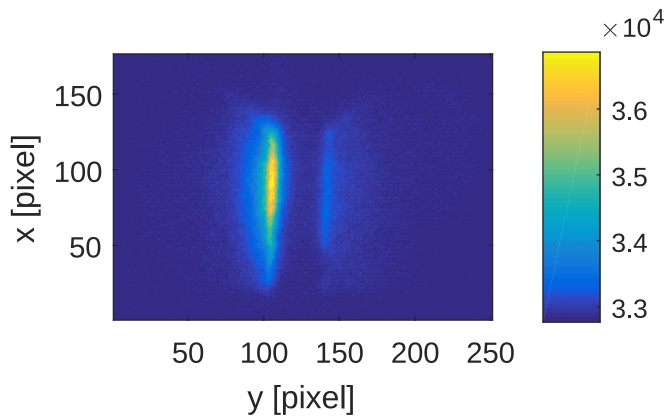


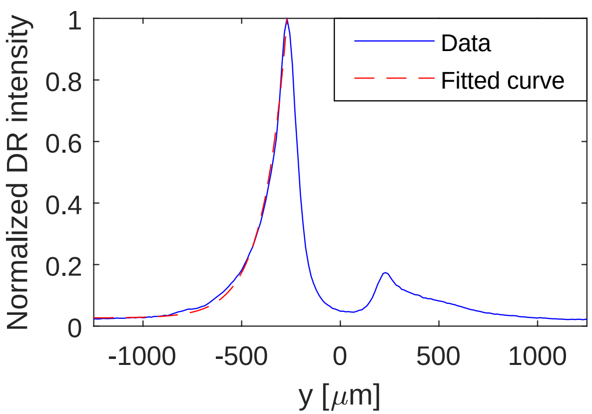
Incoherent Diffraction Radiation on CESR (2/6)

- Imaging the slits to measure the beam position / centering



Conditions: *wavelength 600 nm, beam size: 23.7 um, slit width 0.5mm*



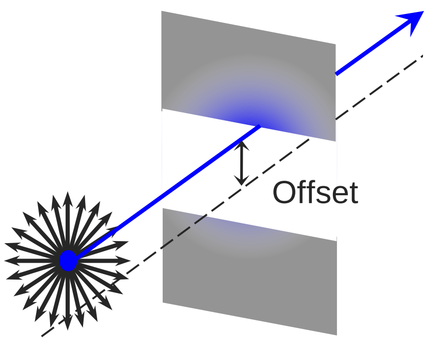


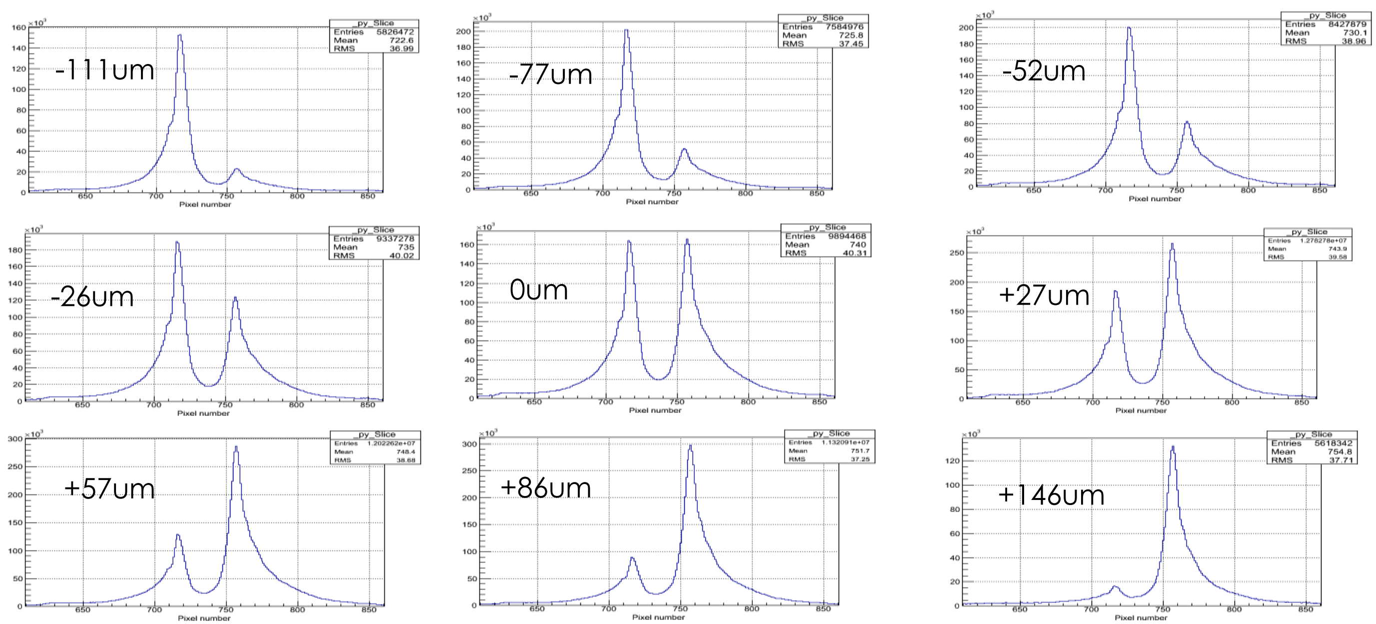
The light emitted by each edge of the slit changes depending on the beam centering

Incoherent Diffraction Radiation on CESR (3/6)

- Steering the beam through the slit

Conditions: *wavelength 600 nm, beam size: 23.7 um, slit width 0.5mm*

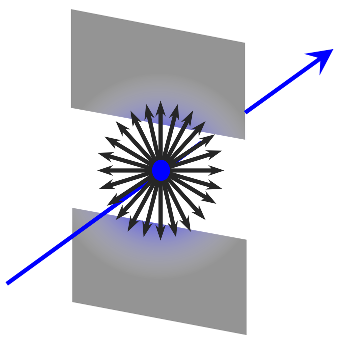


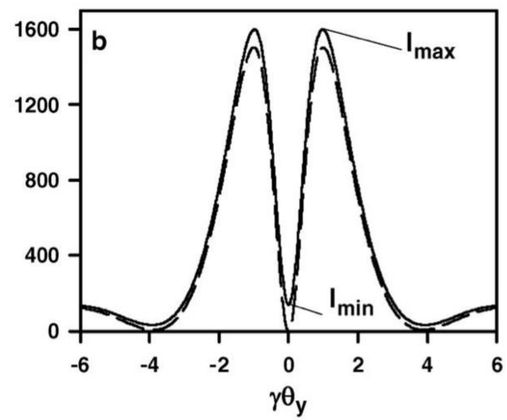


From the profile asymmetry we get **Optical Beam Position Monitor (BPM)** with a sensitivity: 1.52 %/um

Incoherent Diffraction Radiation on CESR (5/6)

- Measuring the **beam size** from the **visibility I_{min}/I_{max}** of the projected vertical polarization component of the ODR **angular distribution**

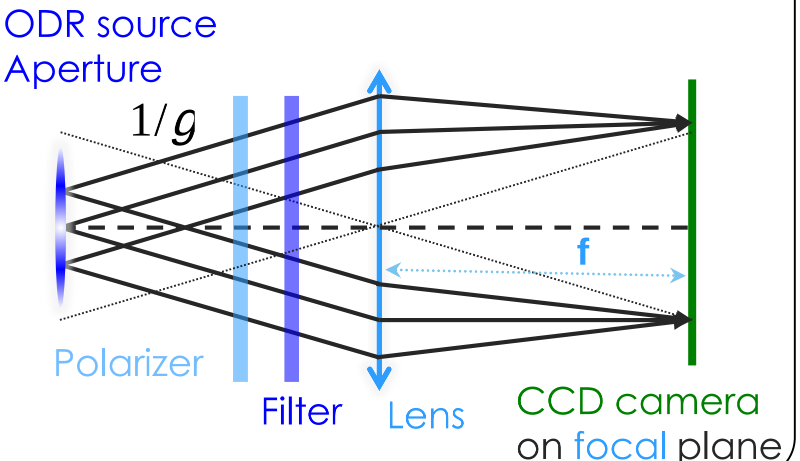




An **horizontal slit** is used to measure a **vertical beam size**.

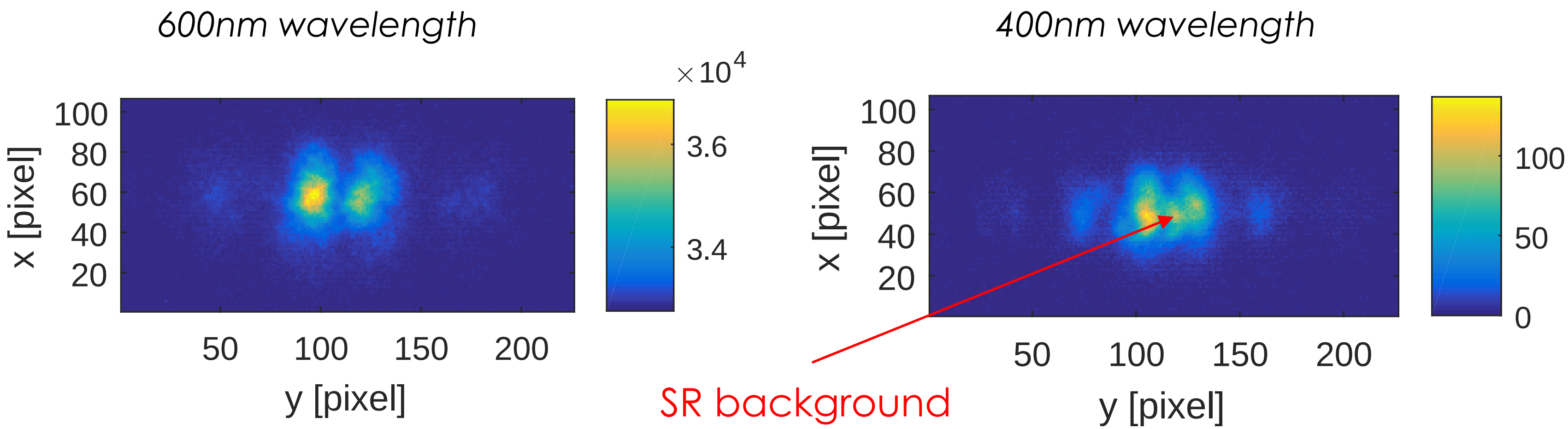
We use a polarizer to select only the **vertically polarized ODR photons** and 40nm BW **filters** to select the **wavelength**

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



Incoherent Diffraction Radiation on CESR (6/6)

- Main limitation is due to Synchrotron background, even using mask



- Slit aperture of 0.5mm is a serious aperture restriction to use ODR operationally (lifetime strongly affected due to scraping of beam tails on the slit)

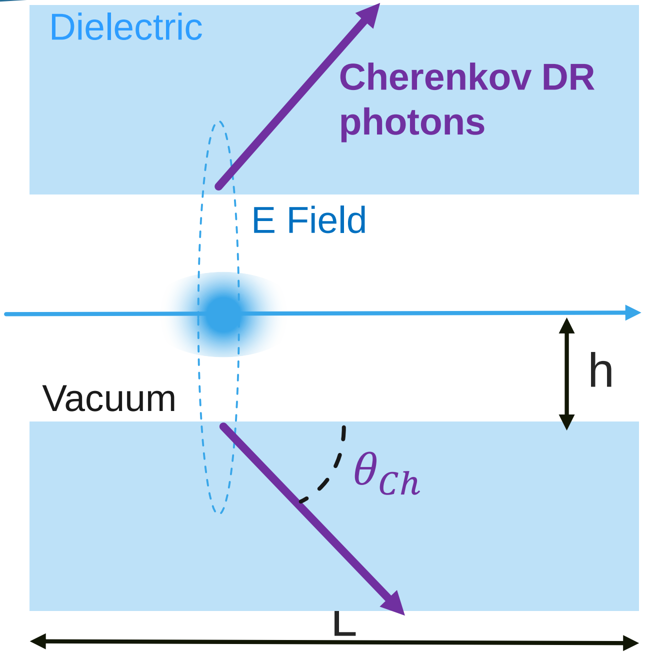
Motivation to develop Incoherent Cherenkov Diffraction Radiation

- Larger aperture slits
  - Difficult as DR will provide less photons
  - Looking for a physical process providing more photons

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

⇒ 'Generating Cherenkov diffraction radiation in longer dielectric'

Incoherent Cherenkov Diffraction Radiation



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

Exponential decay of the particle field

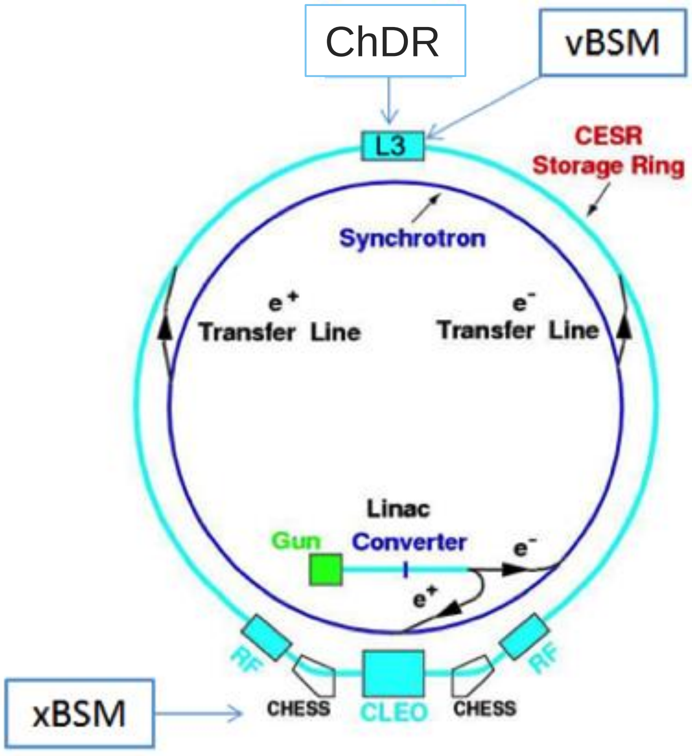
$$\frac{d^2 N_{Dcph}}{d\Omega d\lambda} = \frac{\alpha n}{\lambda}\left(\frac{L}{\lambda}\right)^2 \left(\frac{\sin\left(\frac{\pi L}{\beta\lambda}(1-\beta n\cos\theta)\right)}{\frac{\pi L}{\beta\lambda}(1-\beta n\cos\theta)}\right) sin^2\theta \,.\, e^{\left(-4\pi\frac{h}{\gamma\beta\lambda}\right)}$$

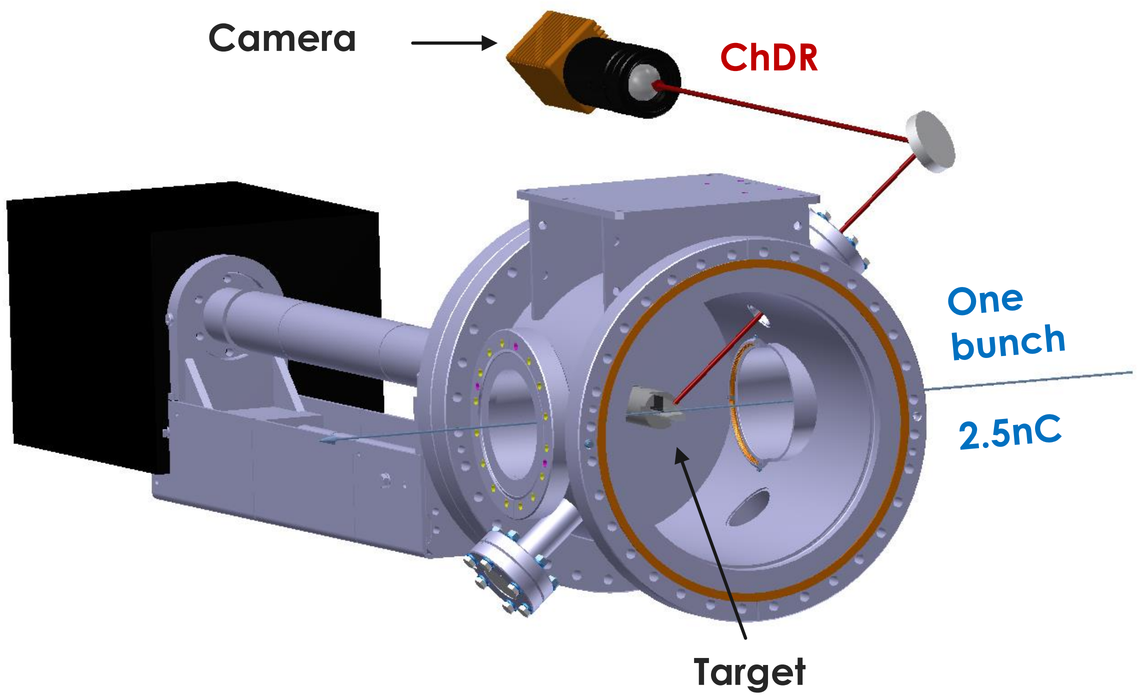
α, fine structure constant
β, normalised beam velocity
γ, beam relativistic factor
θ, angle of observation

T. Lefevre, LER 2018, CERN

Experimental set-up on CESR (1/3)

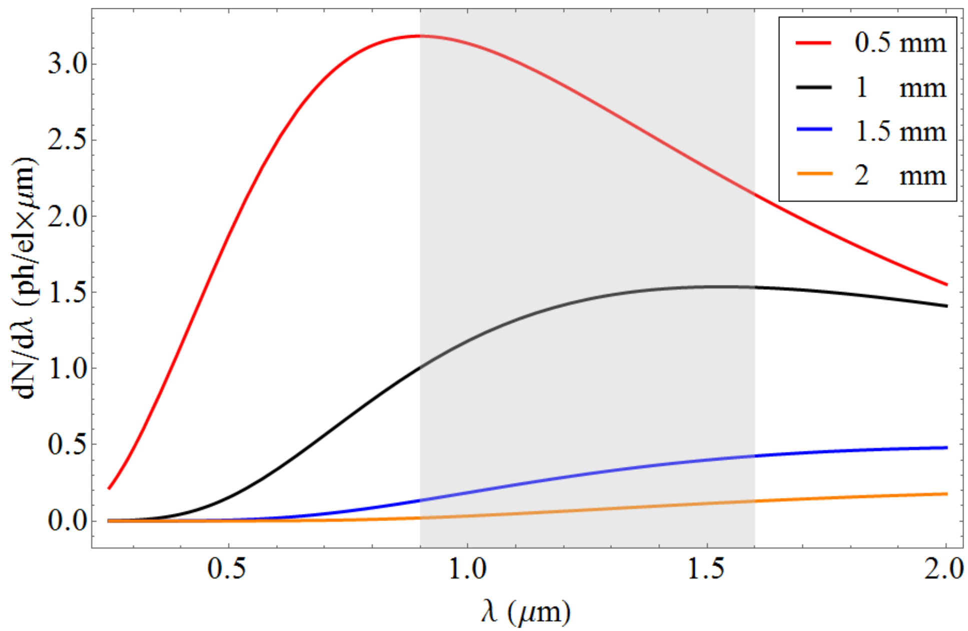
- Re-using the DR vacuum chamber and optical system





Experimental set-up on CESR (2/3)

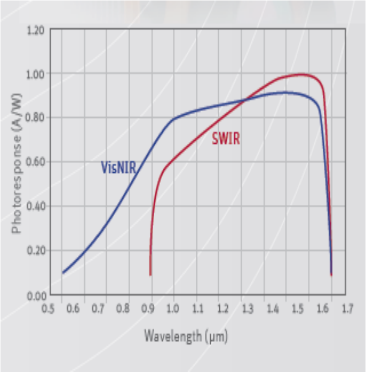
- Design a 2cm long SiO_2 (n=1.46) Cherenkov Diffraction Radiation target
  - Testing with 2.1GeV e^- and measuring in IR (0.9-1.7um) – April 2017



'The red curve as been scaled down by 1/3 for better presentation

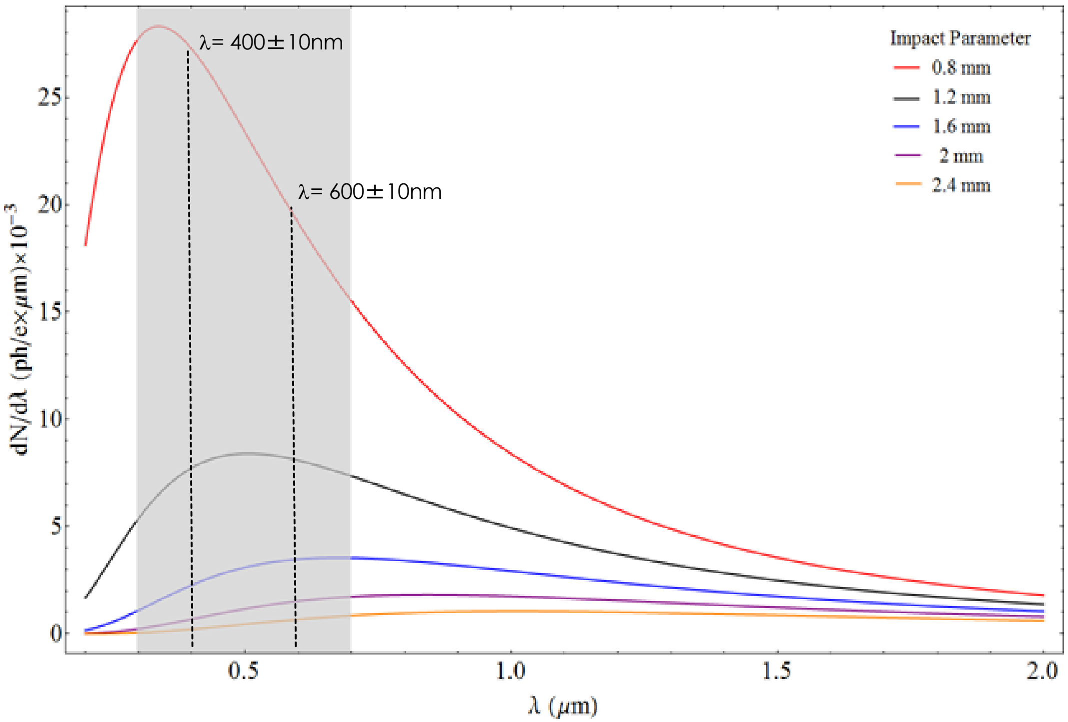
Xenics Bobcat 640 GigE

- Cooled InGaAs 640x512 pixels : 20um pixel pitch
- QE up to 80% at 1.6um
- 14bit ADC
- 1us-40ms integration window



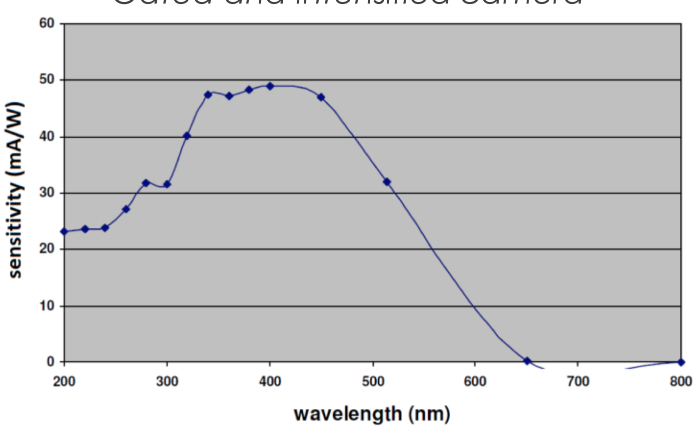
Experimental set-up on CESR (3/3)

- Design a 2cm long SiO_2 (n=1.46) Cherenkov Diffraction Radiation target
  - Testing with 5.3GeV e^- / e^+ and measuring in visible (0.3-0.7um) – October 2017



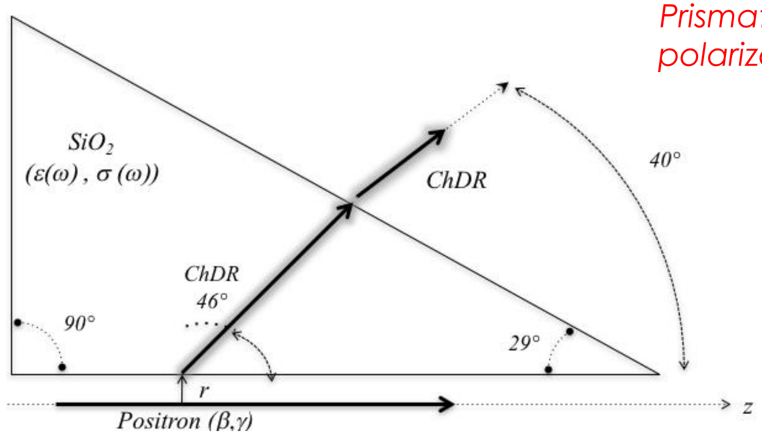
M.V. Shevelev and A.S. Konkov, JETP **118,** 501 (2014)

Gated and intensified camera

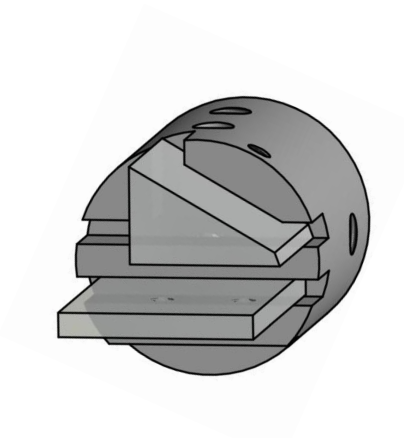


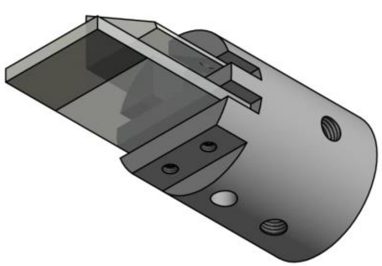
Cherenkov radiators (1/2)

- Two different geometries have been tested
  - **Prismatic radiator**

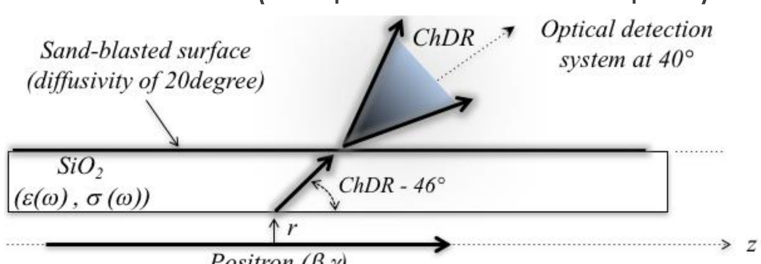


Prismatic target for polarization studies



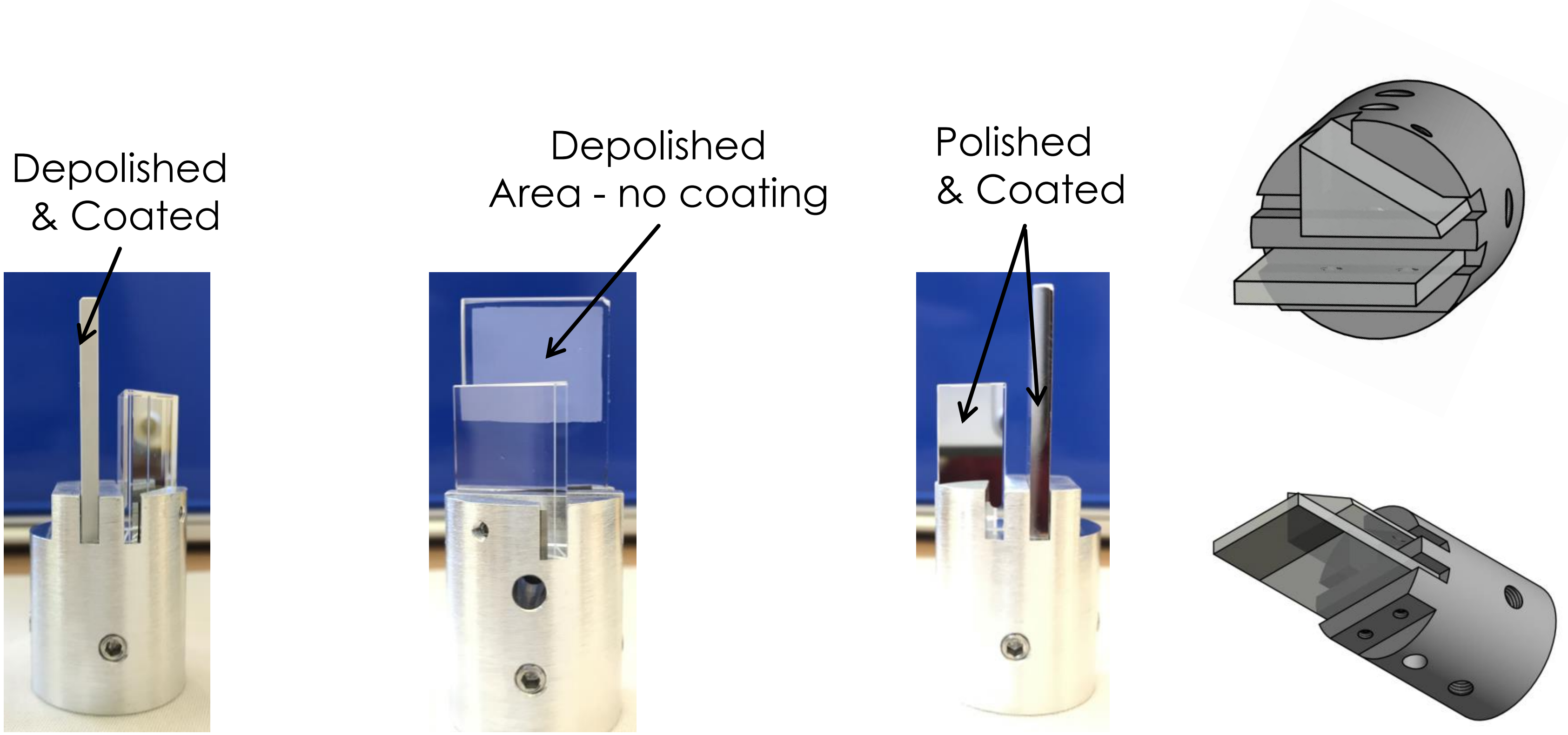


  - **Flat radiator** (simpler and cheaper)



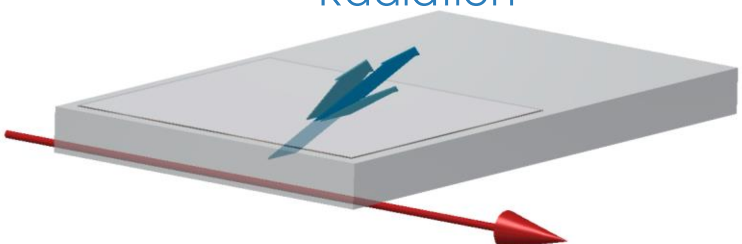
Cherenkov radiators (2/2)

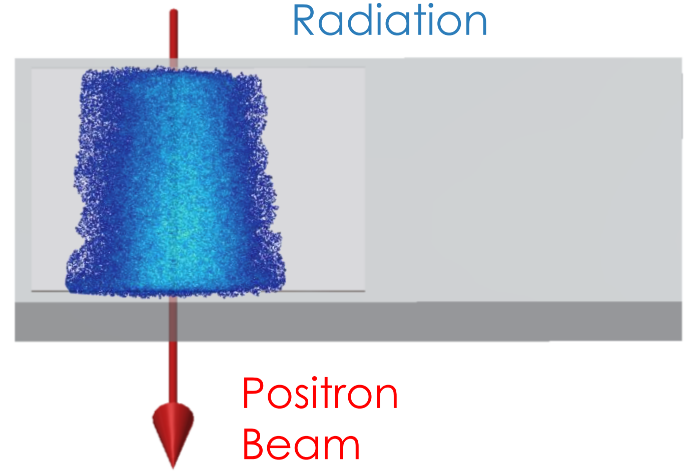
- Pictures of the radiators



Experimental data : Positron at 5.3GeV

- Imaging the Flat radiator (diffusive coating to extract the photons out of the target)



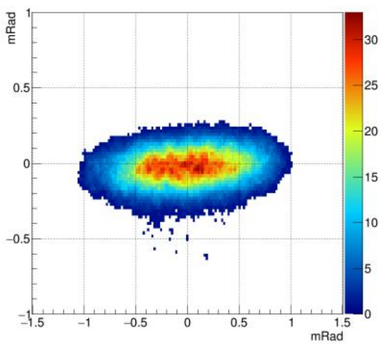


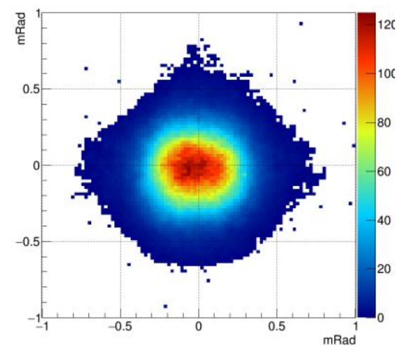
'Cherenkov photons emitted all along the target surface'

Experimental data : Positron at 5.3GeV

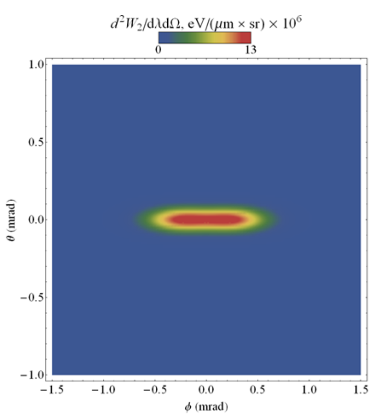
- Angular distributions with Prismatic radiator : Comparison with simulations

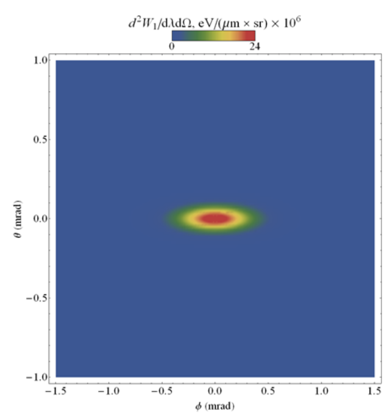
Horizontal polarization — *Vertical polarization*





Measurements



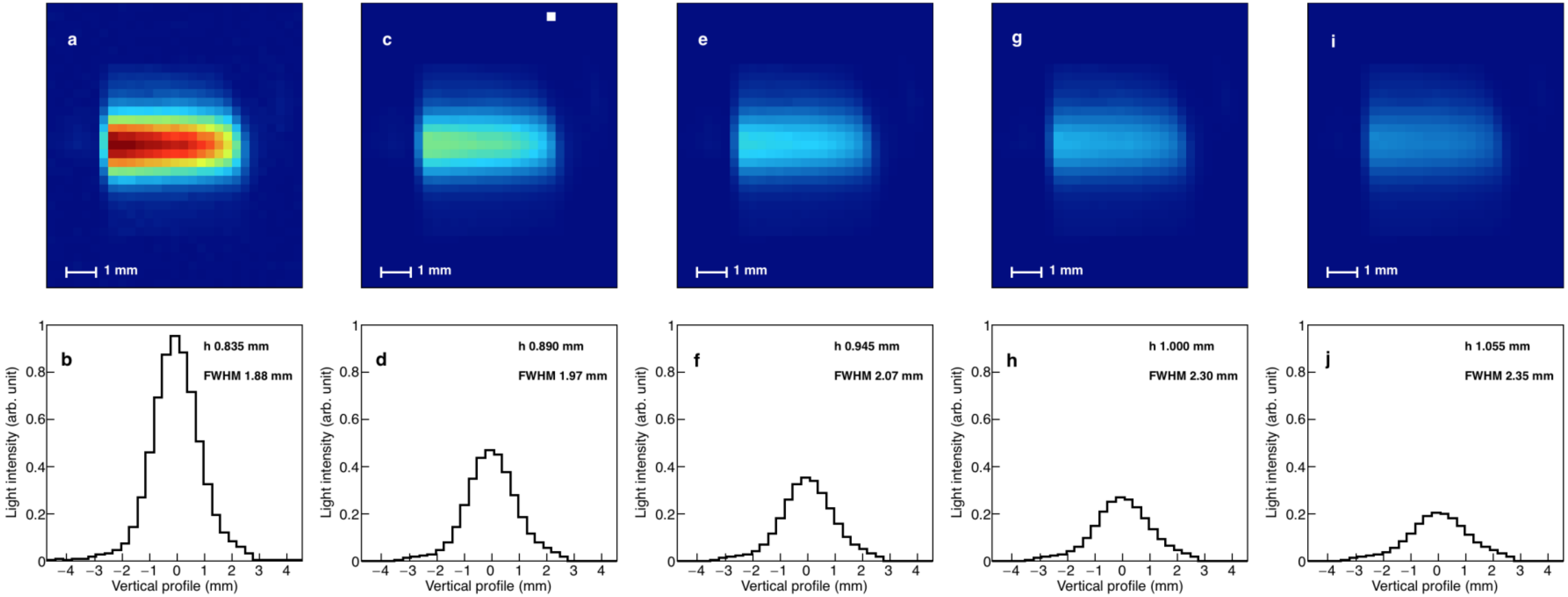


Simulations

T. Lefevre, LER 2018, CERN

Experimental data : Electron at 2.1GeV

- Steering the beam vertically
  - No wavelength filter – no polarizer



'Cherenkov photons yield increasing strongly for smaller impact parameter'

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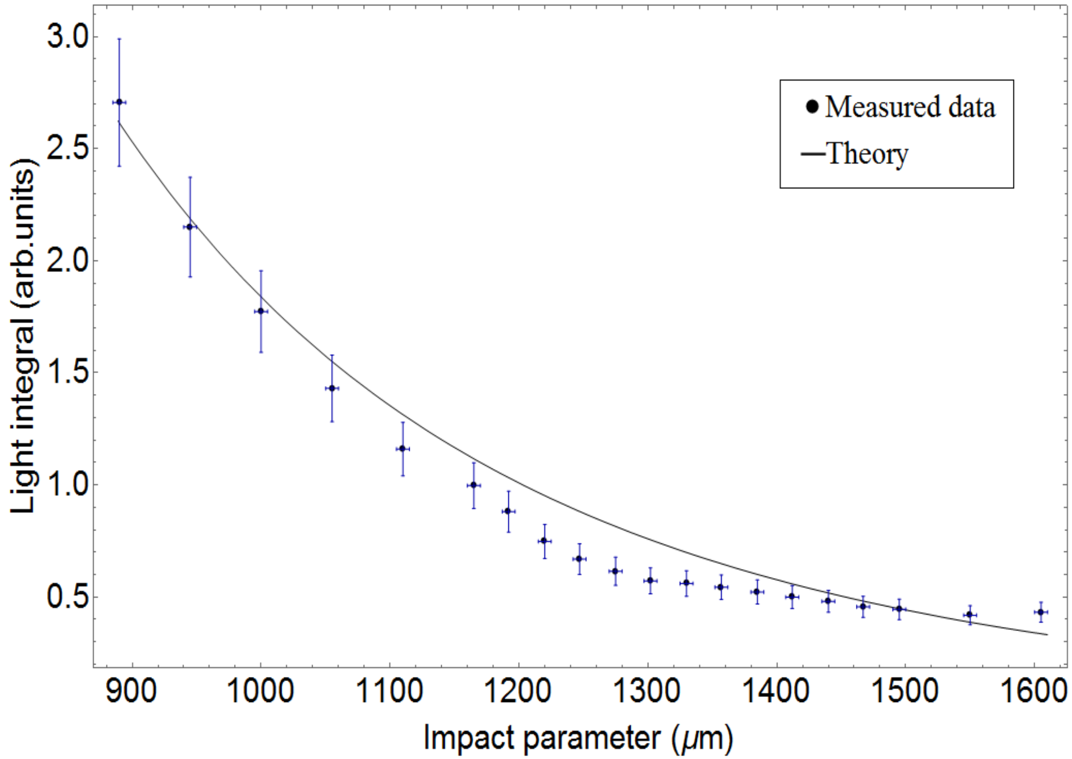
Experimental data : Electron at 2.1GeV

- Steering the beam vertically : comparison with simulations

No wavelength filter – No polarizer



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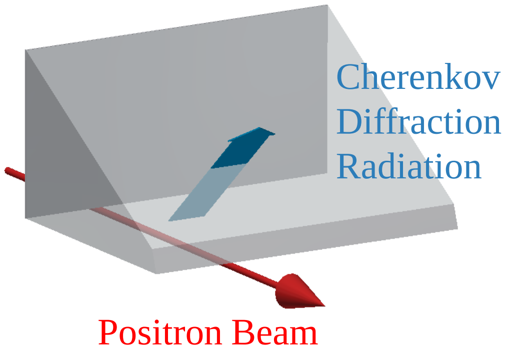
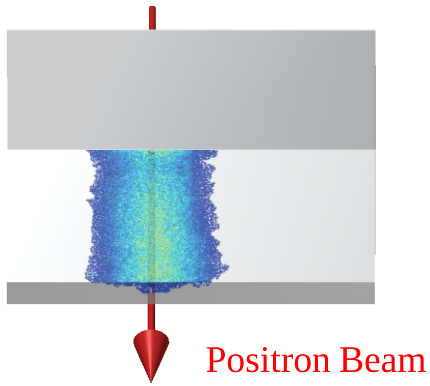
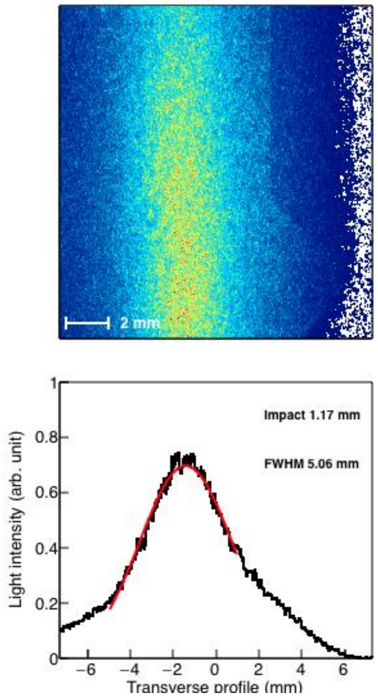
Experimental data : Positron at 5.3GeV

- Measuring the horizontal Beam size :

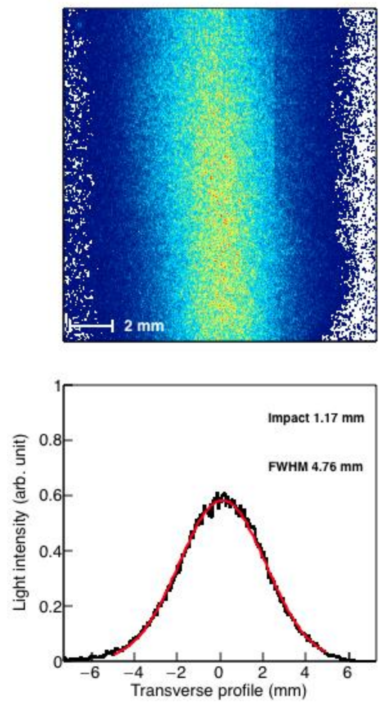




Horizontal polarization



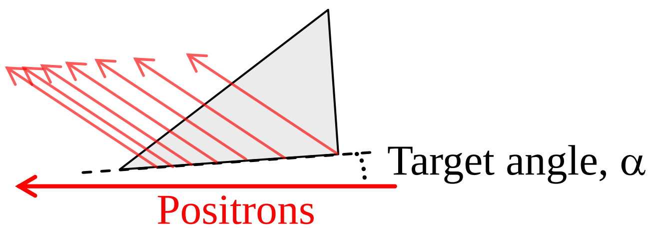
Vertical polarization

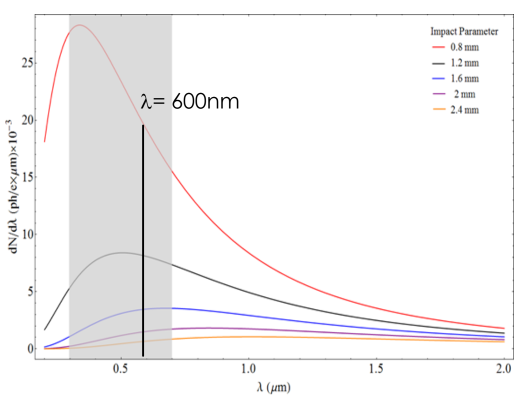


'Vertically polarized photons give the best spatial resolution (σ_y=2mm)'

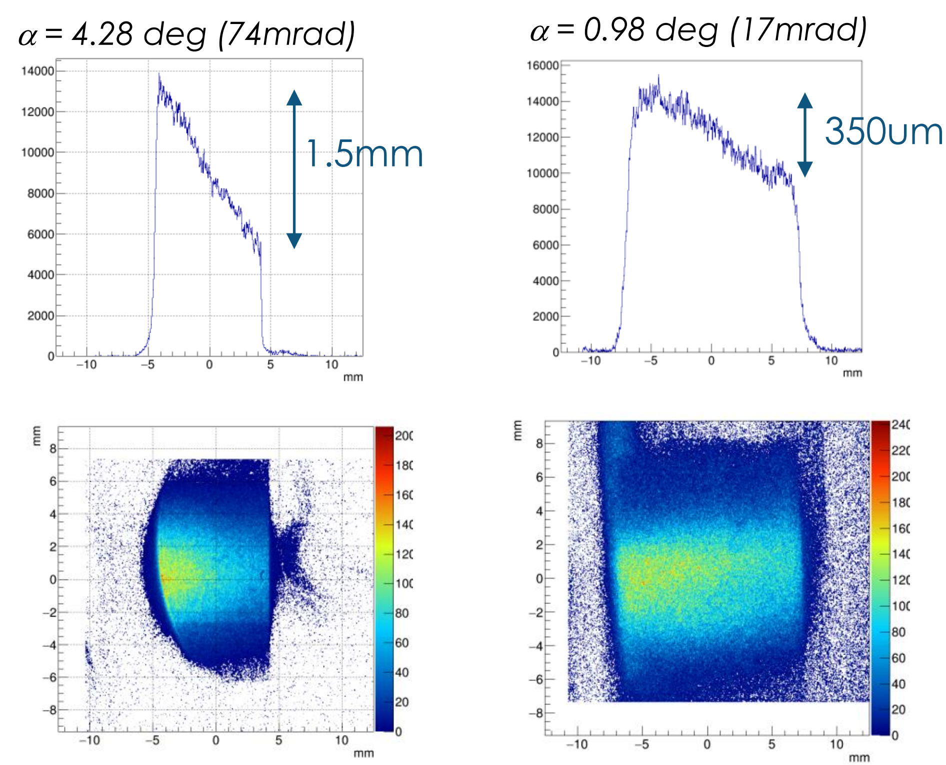
Experimental data : Positron at 5.3GeV

- Rotating the target :





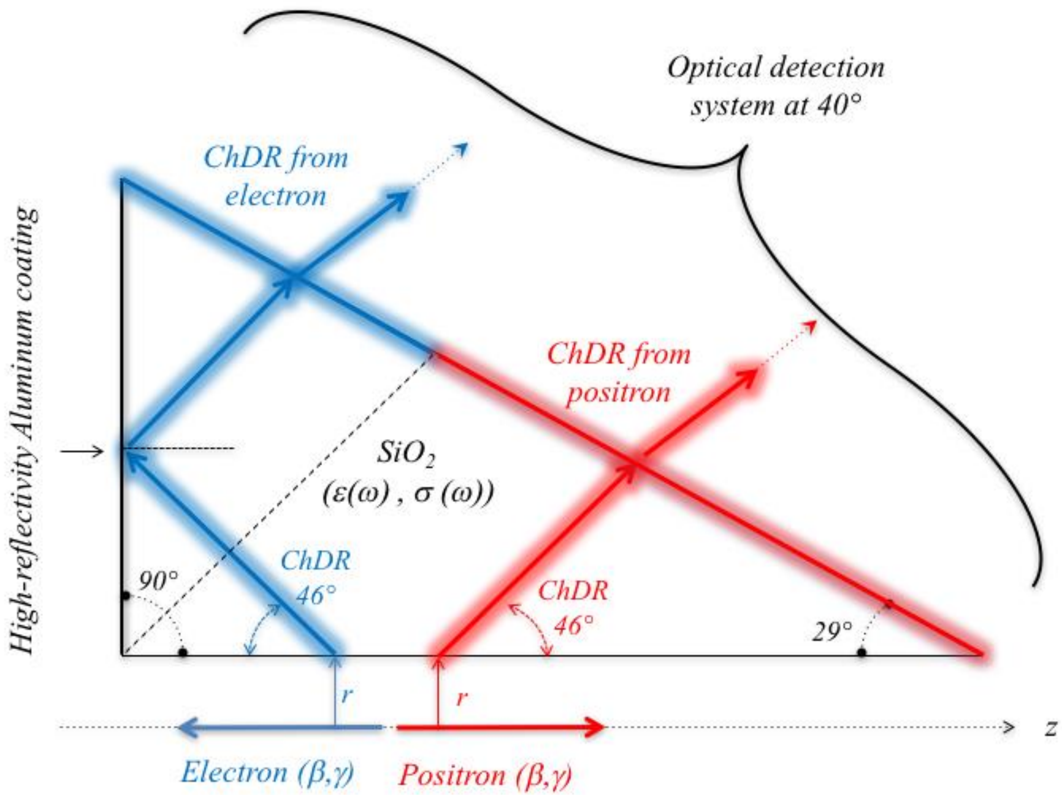
ChDR @600±10nm ; h_{mean} = 1.5mm



'Measuring the Beam tilt angle with respect to the surface of dielectric as the light intensity strongly depends on the impact parameter'

Experimental data : Measuring counter-propagating beams

- Measuring counter-propagating beams using the prismatic target



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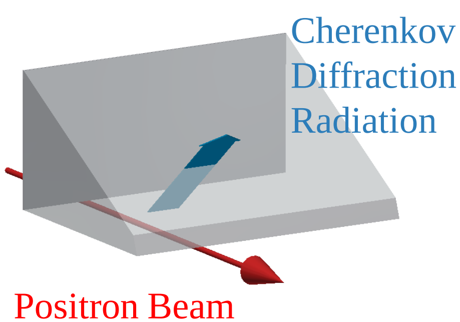
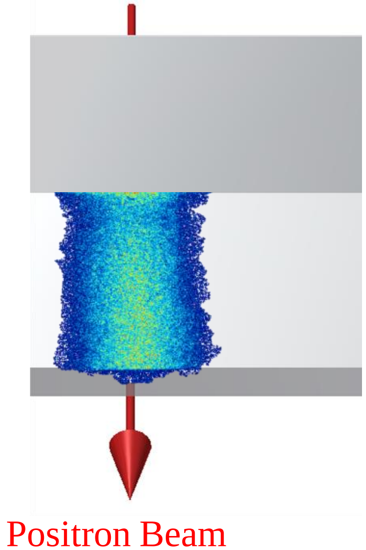
Experimental data : Measuring counter-propagating beams

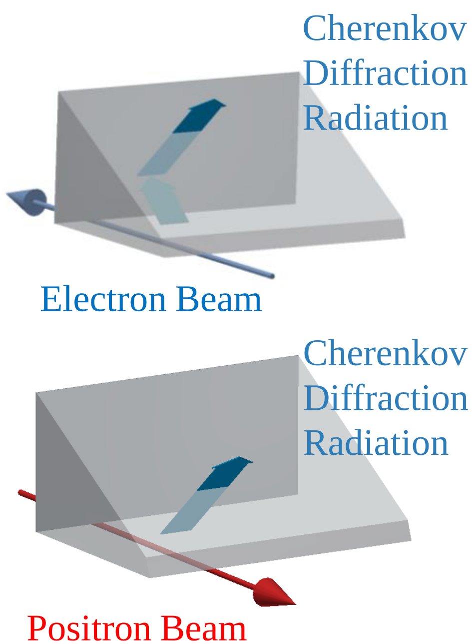
- Imaging both beams with the prismatic target

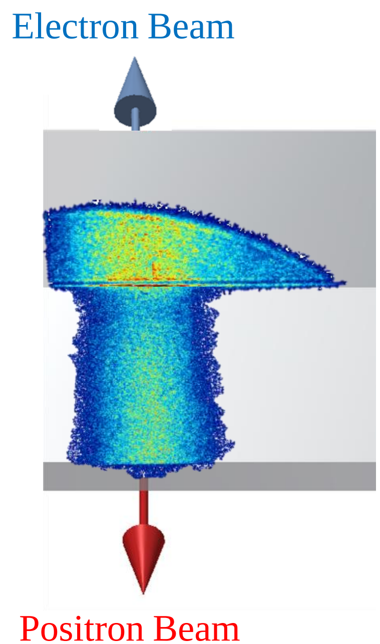




Experimental data : Measuring counter-propagating beams

- Imaging both beams with the prismatic target





Images from e^- is truncated due to the limited aperture of the current detection system

The photons produced by electrons and positrons appear on a different part of the target and give the possibility to high directivity beam measurements (measured more than 60dB)

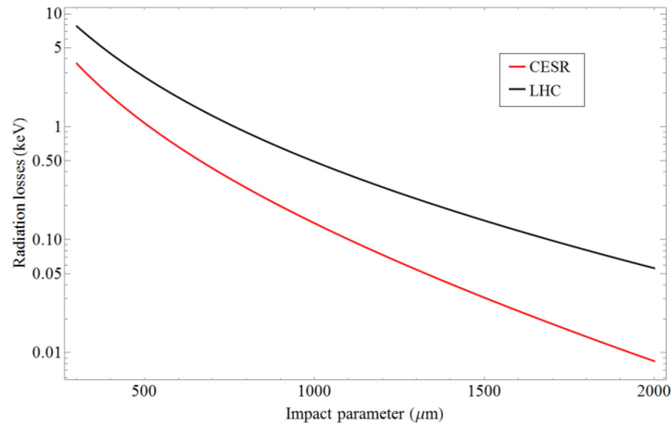
T. Lefevre, LER 2018, CERN

Summary of the measurements

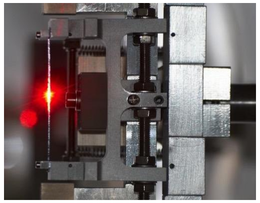
- Incoherent ChDR has been studied in IR and visible range for beams propagating at a distance of 1-3mm from the edge of the dielectric
- The light is polarized and emitted in a narrow cone angle providing excellent S/N ratio
- The number of photons scales linearly with the length of the radiator and exponentially with the impact parameter
  - e.g. for 5.3GeV and h=1.5mm, measured 10^{-3} photons/turn/particle
- Different target geometries have been successfully tested
- Still many things to learn to understand how to use this radiation at best

Perspectives for beam instrumentation

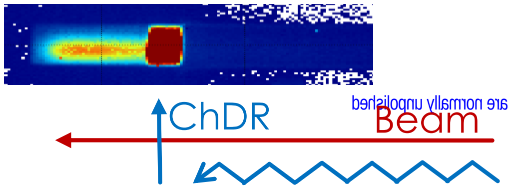
- Imaging system for relativistic beam
  - What is the the smallest beam size measurable ?
    - The Cherenkov diffraction PSF should be smaller than transition radiation PSF
      → possible tests in 2018 with micron beam sizes on ATF2



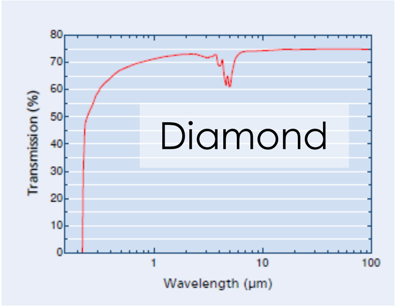
- What is the smallest the beam tilt angle measurable ?
  - A non linear response depending on wavelength, beam energy and impact parameter
- Measuring counter-propagating beams with very high directivity : BPM for FCC, HE-LHC, …
- A Beam Position Monitor for Crystal collimator on LHC

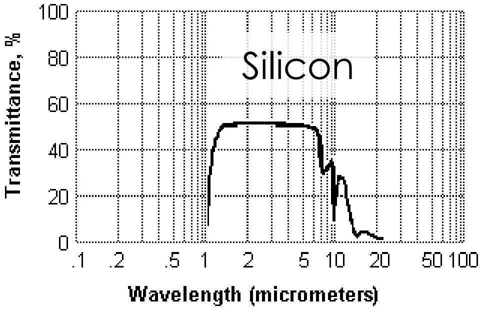


Perspectives on radiator's shapes and material



- Prismatic or flat targets ? Something else ?
  - BPM using flat target – possibly using long(er) target
  - Imaging system requiring to select the appropriate polarization
- How thick should a target be ? cm/mm/um ?
  - ChDR is mainly emitted within the first atomic layer of the dielectric since the beam field decreases as it penetrates inside the material.
- Testing different materials for different applications / wavelength





Conclusions

- Incoherent Cherenkov Diffraction Radiation looks promising for Beam diagnostic applications on both high-energy leptons and hadrons
- After CESR, several beam tests prepared at CERN/CLEAR and possibly at KEK/ATF2 and Diamond in order to continue the R&D
- Optimisation of the radiator geometry for a given application
  - Best shape/configuration for light extraction and polarization selection
- Motivation to study the Beam dynamic involved in the emission of ChDR
  - ChDR is the emission of wakefield in a dielectric materiel
  - Coherent and incoherent emissions should lead to very different beam dynamic effects
  - Some work on-going on the simulation/theoretical sides (Tomsk Univ.)
    - Simulations of coherent ChDR is being studied with codes such as Particle studio, Magic or Vsim for different applications (Dielectric acceleration and THz source)

Thanks for your attention

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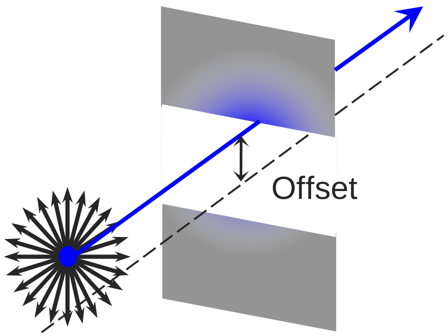
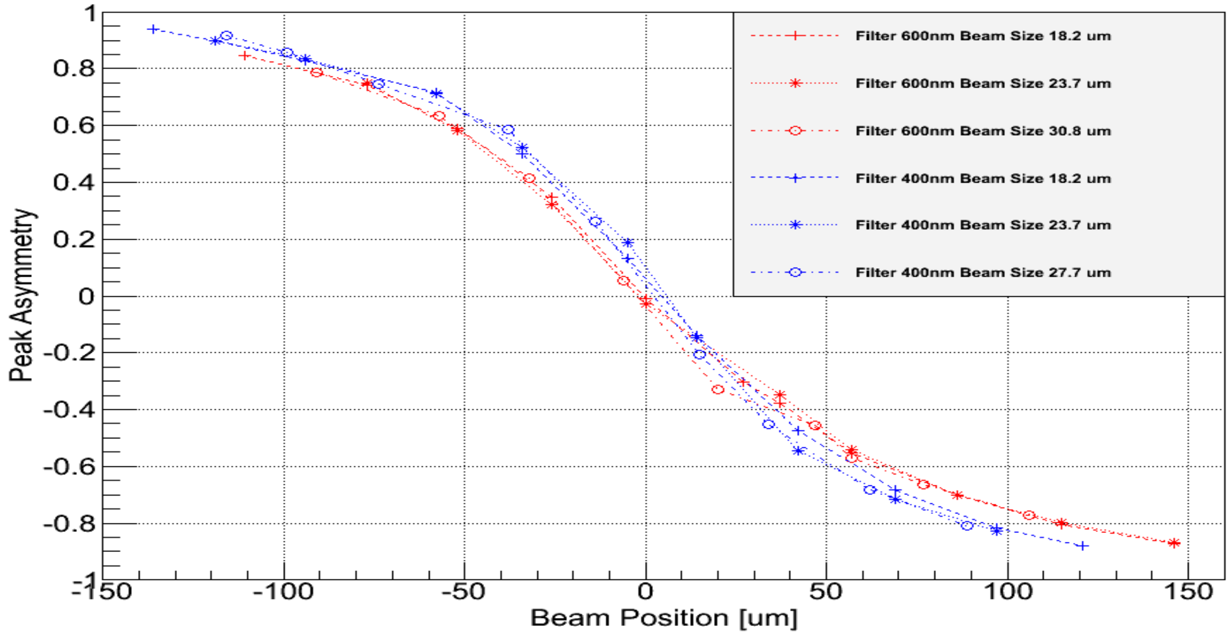
4. Diamond Light Source, Oxfordshire, United Kingdom
5. John Adams Institute at Royal Holloway, University of London, Egham, United Kingdom

Incoherent Diffraction Radiation on CESR (4/6)

- Steering the beam through the slit



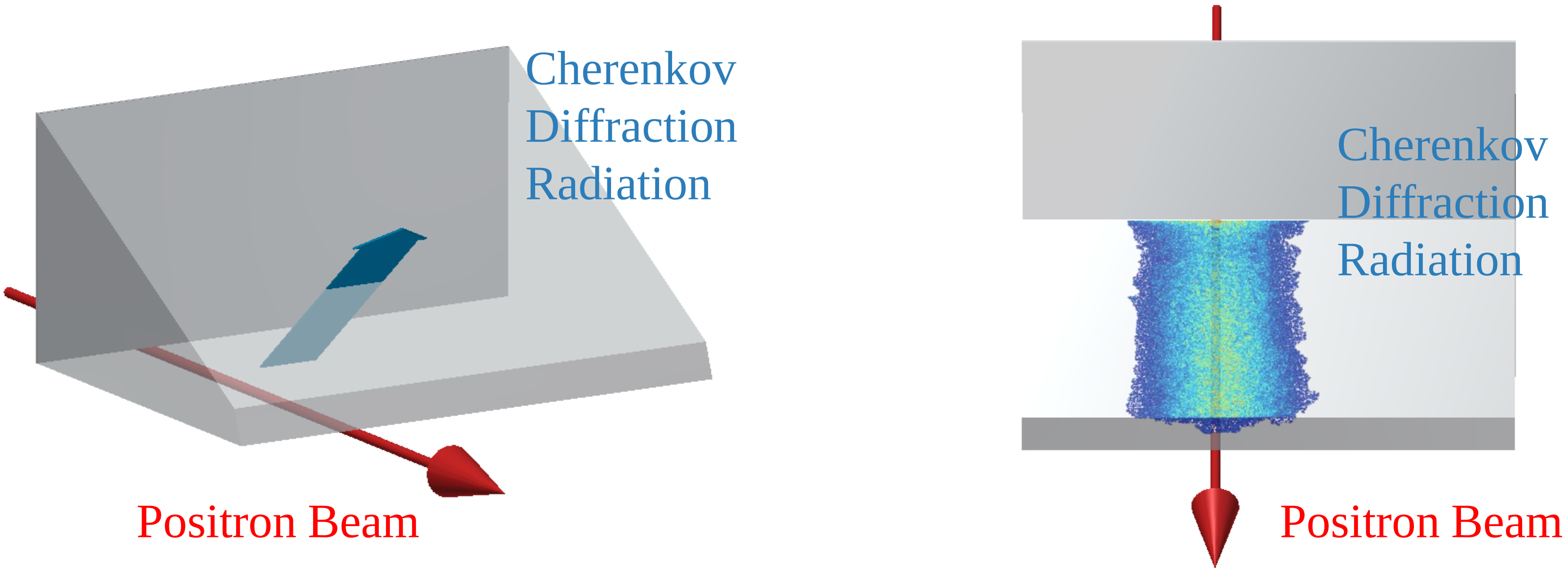
Conditions: *wavelength 400/600 nm, beam size: 16.2/23.7 um, slit width 0.5mm*



Different sensitivity depending on the wavelength

Experimental data : Positron at 5.3GeV

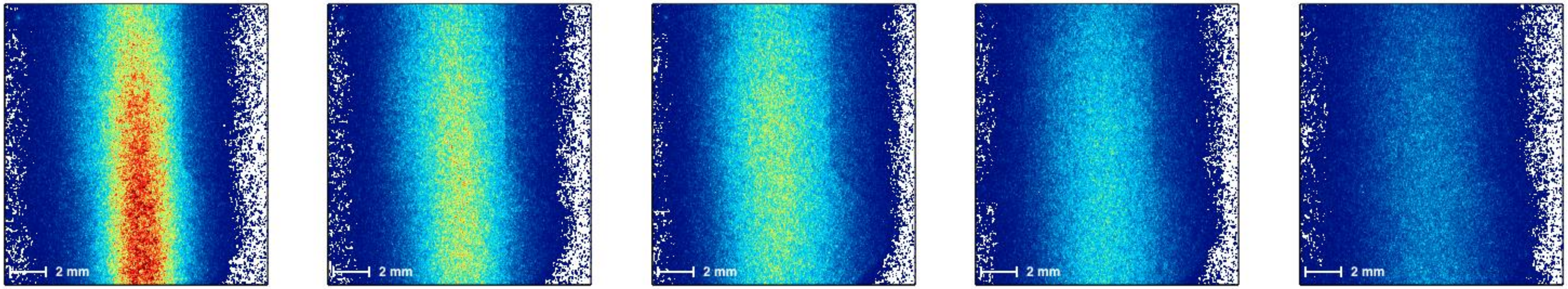
- Imaging the prismatic target at wavelength of 600±10nm



Experimental data : Positron at 5.3GeV

- Steering the beam vertically
  - Wavelength 600±10nm
  - Vertical Polarization component

h= 0.96mm 1.17mm 1.52mm 2.09mm 2.43mm

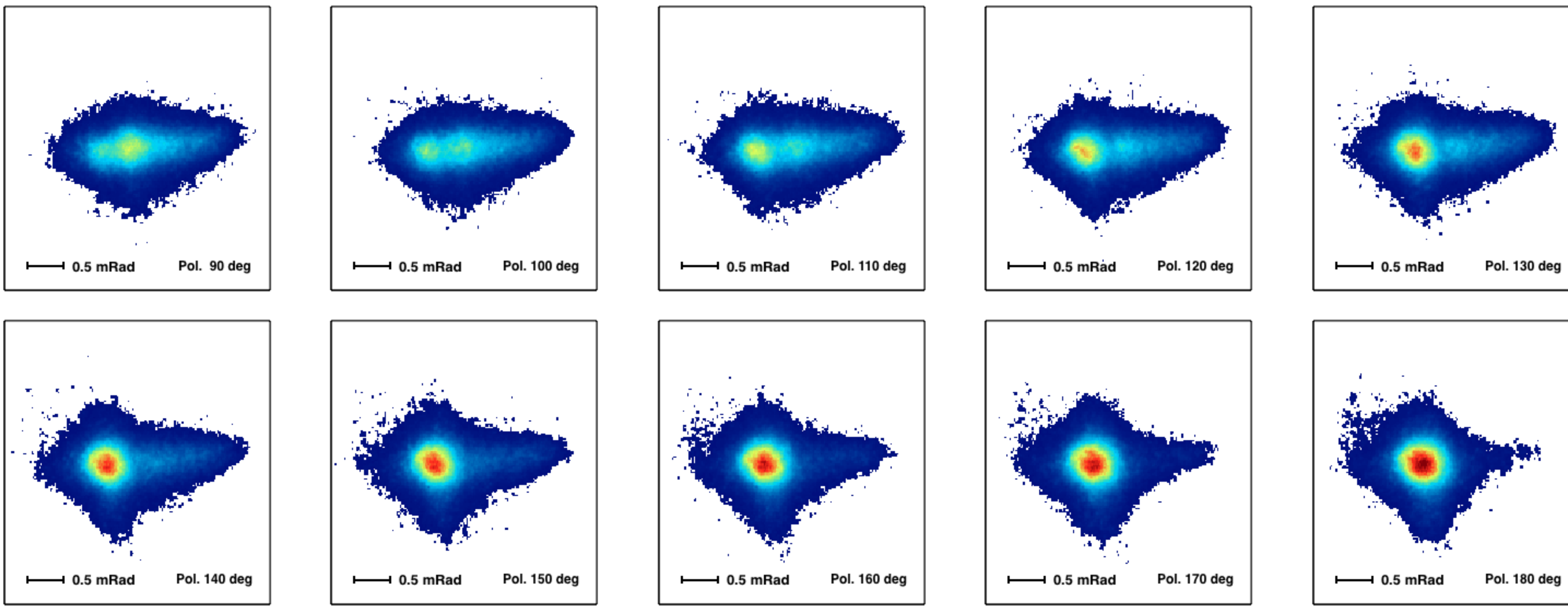


Cherenkov photons yield increasing strongly for smaller impact parameter

Experimental data : Positron at 5.3GeV

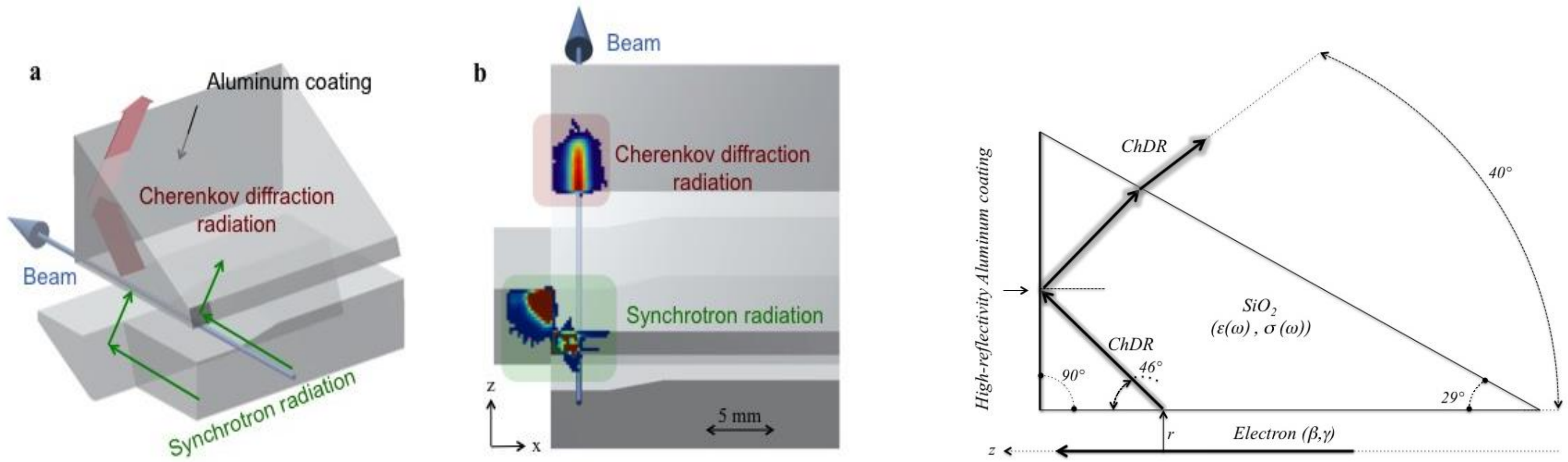
- Prismatic target : Angular distribution and polarization study

Impact parameter fixed , 600±10nm wavelength, Polarization Scan



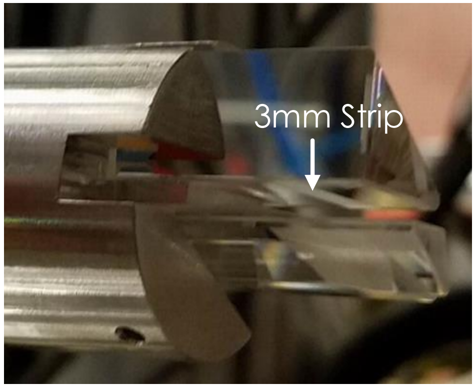
Experimental data : electron at 2.1GeV

- Prismatic target for the detection of electrons

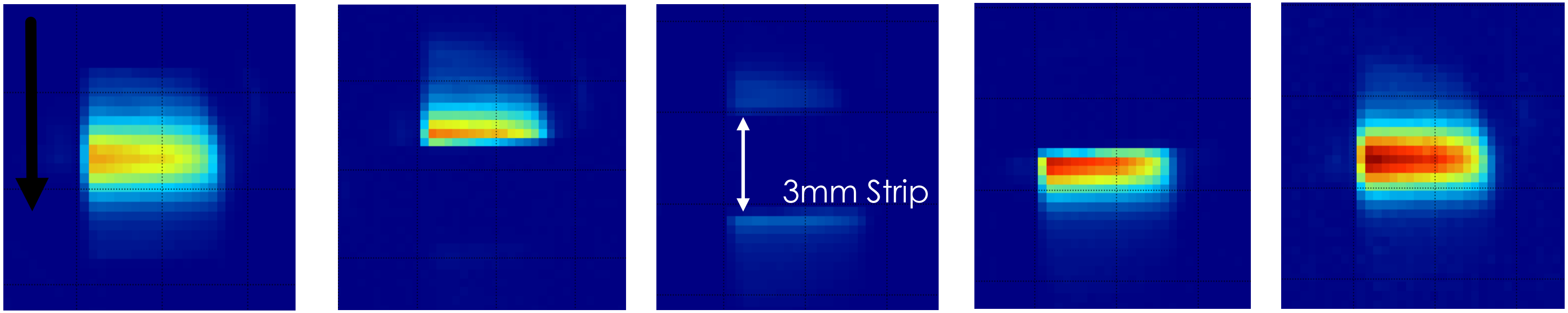


Experimental data : electron at 2.1GeV

- Optically polished ChDR target insertion passing over a 3mm de-polished strip on the surface.
- Diffusive surface =>We loose the highly directional ChDR emission.

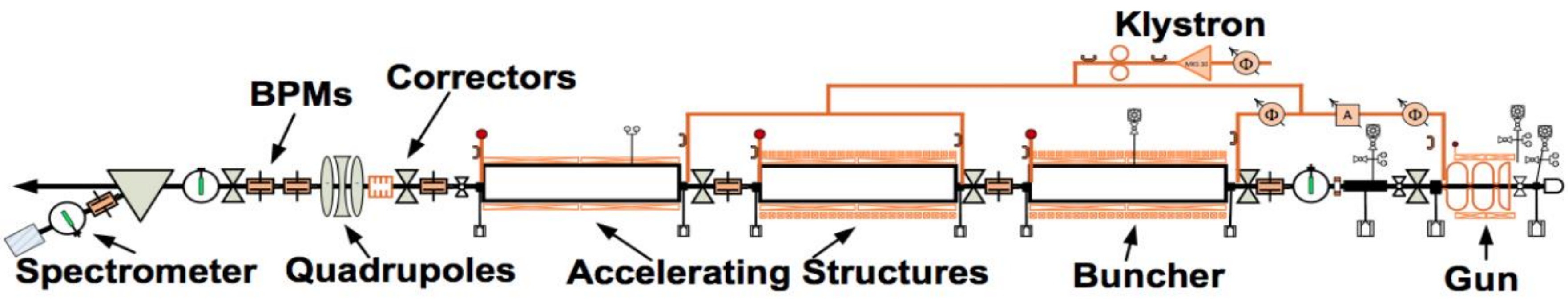


Target Movement



ChDR measurements at CERN

- Previously named CTF3-**CALIFES**, the new CERN electron beam test facility **CLEAR** is being commissioned at present.
- Beam: **130-220MeV** electrons
- **Up to 0.5nC per bunch**, trains available 1-100 bunches.
- CLEAR Proposal online: https://clear.web.cern.ch/sites/clear.web.cern.ch/files/documents/CLEAR_proposal.pdf

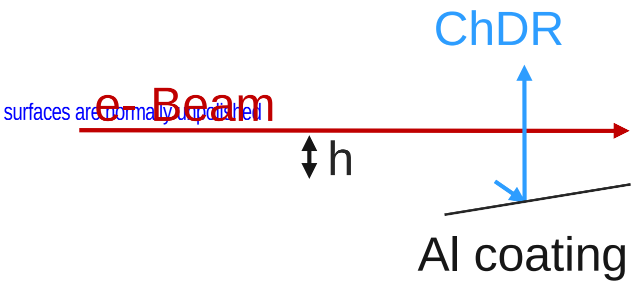


<u>End of 2017 two **ChDR** experiments foreseen, in the infrared range:</u>

1. Under vacuum, using **CVD diamond** radiator.
2. In-air, using crystalline **silicon** radiator.

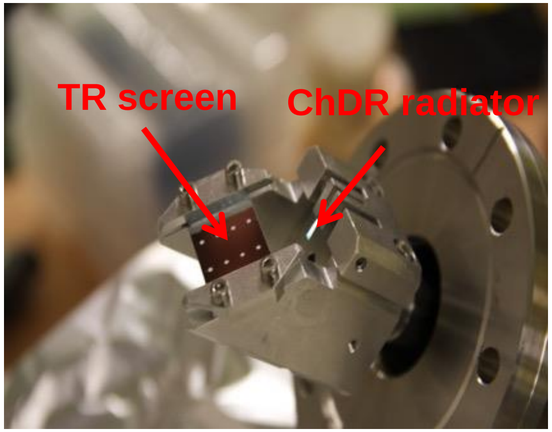
1. Diamond ChDR on CLEAR at CERN

CVD diamond radiator under vacuum.
<u>Goal:</u> Comparison between OTR, Cherenkov, and ChDR light emission.



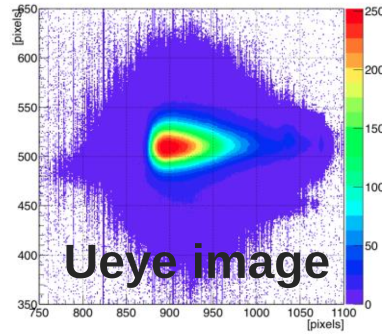
<u>Already tested cameras on that setup:</u>

- **Ueye** (visible range) =>*Nice images, but inappropriate wavelength for diffraction radiation studies at 200 MeV*
- **Onca-MWIR-InSb** (2-5um) =>Bad SNR
- **Gobi-LWIR**(8-15um) =>Bad SNR (bolometer)



<u>To be tested soon:</u>

- **Bobcat-SWIR**(0.8-1.6um) Might be the right one for this measurement.



Ueye

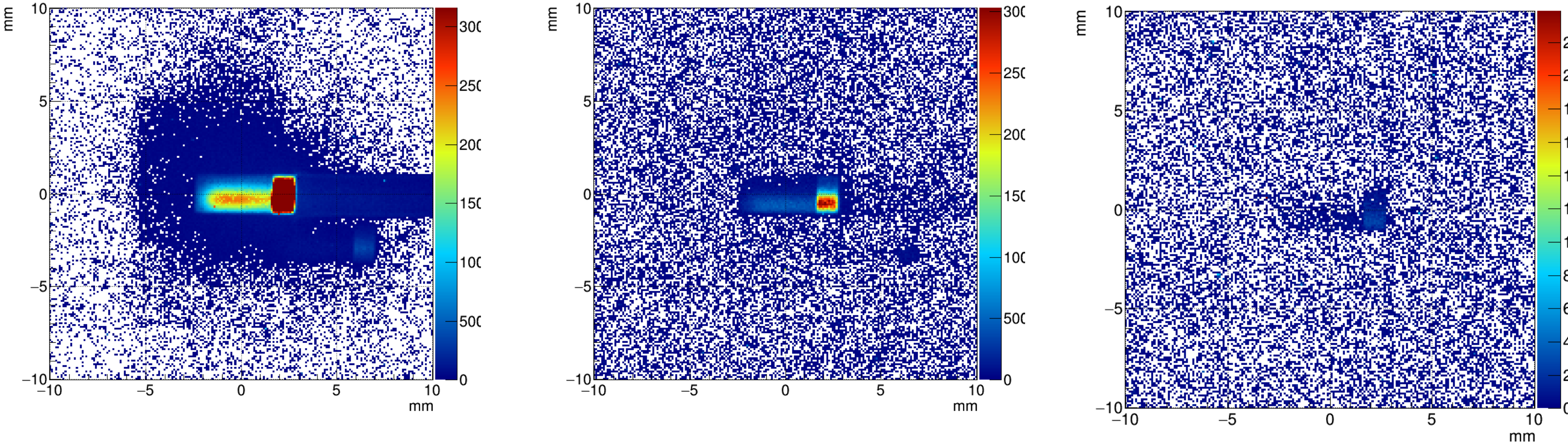
Onca

Gobi

Bobcat

Experimental set-up at Califes@CERN

- CALIFES : 200MeV electrons – up to 15nC per bunch train
- 15x2x1.2mm Diamond crystal with one face cut and Al Coated to reflect the ChDR photons on a FIR Camera (microbolometer, 16bit, 8-14um)
- Measuring and comparing Transition, Cherenkov and Cherenkov Diffraction radiation

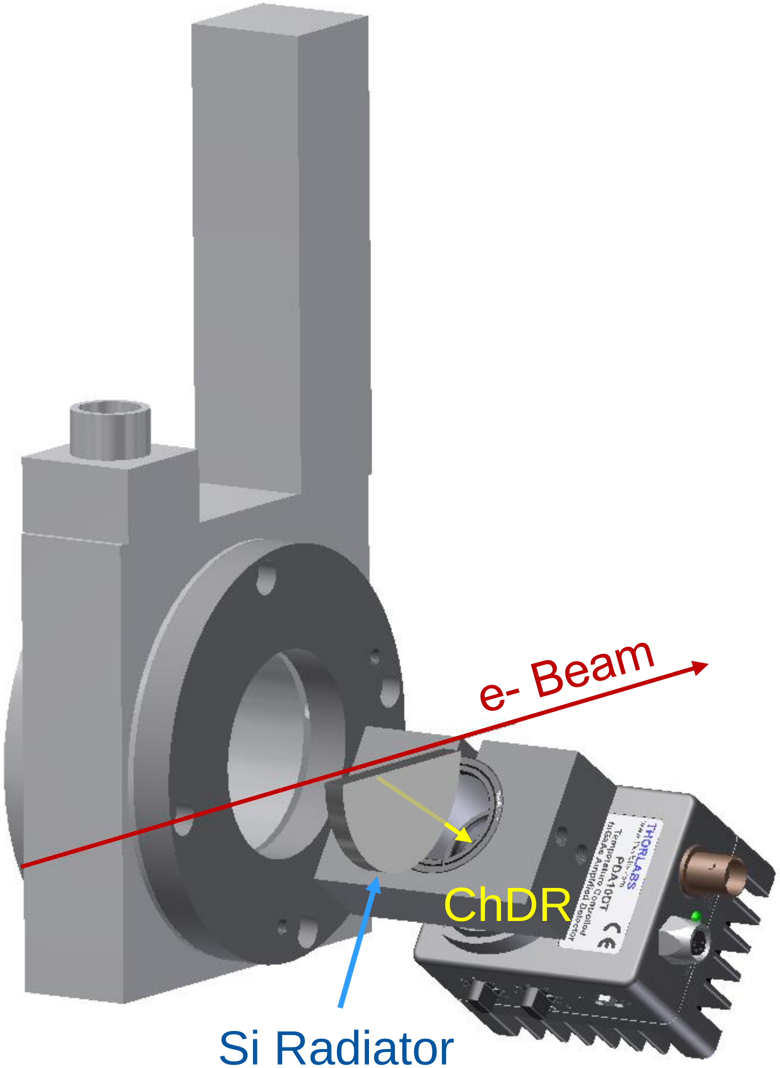


2. Silicon ChDR on CLEAR at CERN

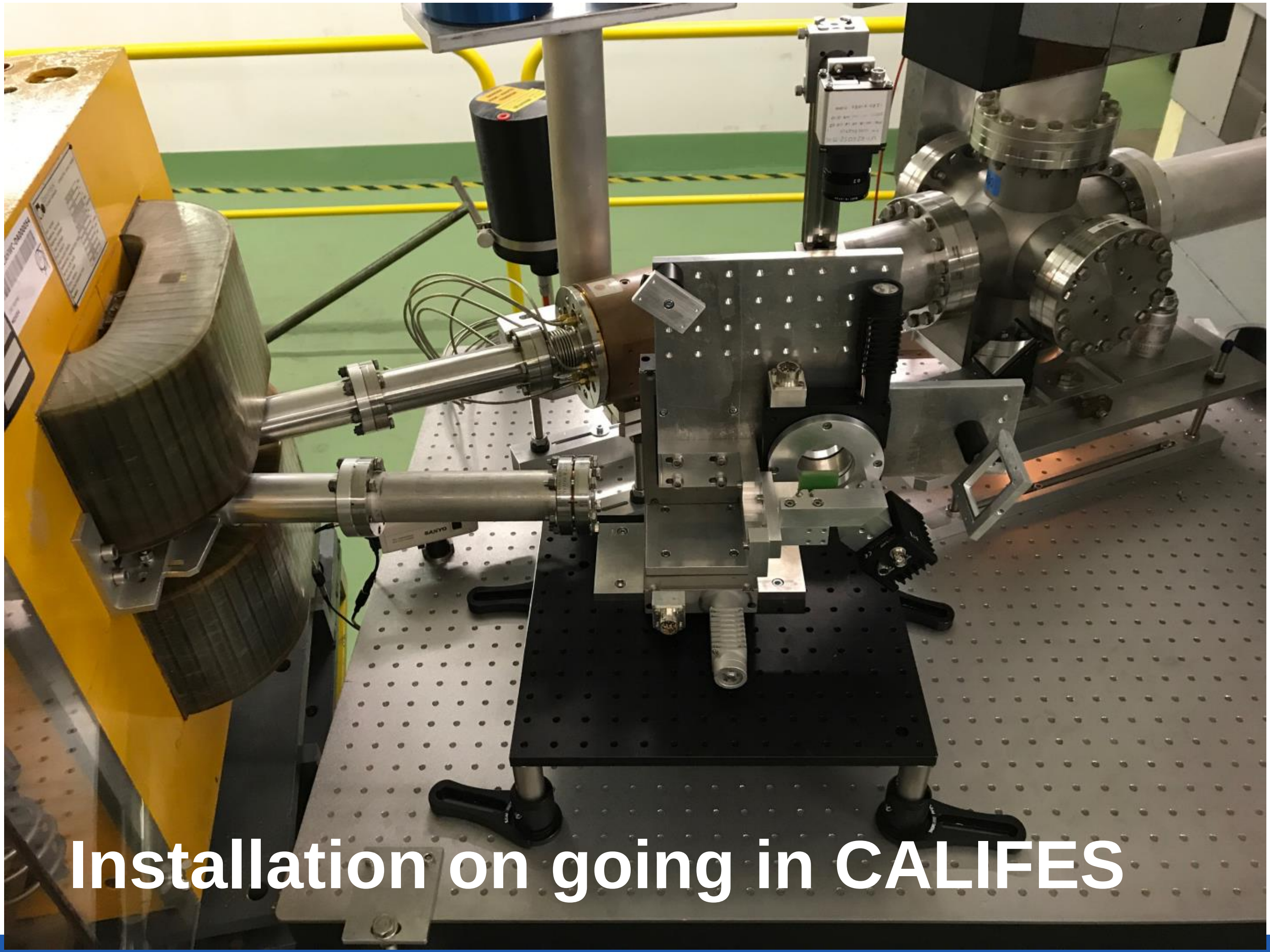
In-air spectral-angular measurement of ChDR in an half silicon wafer radiator.

Detector: PDA10 InGaAs (0.9-2.6um) single pixel photodiode mounted on a motorized Goniometer.

Set of bandpass filters used to select wavelength (BW 30nm).



2. Silicon ChDR on CLEAR at CERN

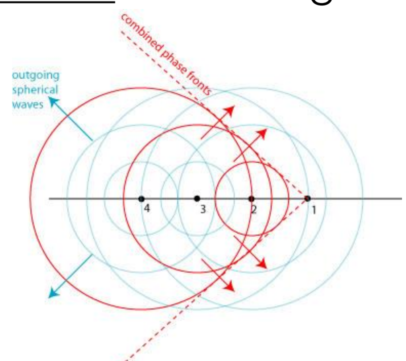


Cherenkov radiation (1/2)

‘Equivalent to the supersonic boom but for photons’

Threshold process: Particles go faster than light $\beta > 1/n$

- n is the index of refraction
- β is the relative particle velocity



- θ_c is the Cherenkov light emission angle

$$\cos(\theta_c) = \frac{1}{\beta n}$$

- d the length of the cherenkov radiator

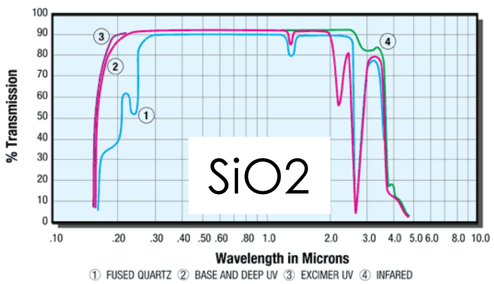
- The total number of photons proportional to the thickness of the Cherenkov radiator

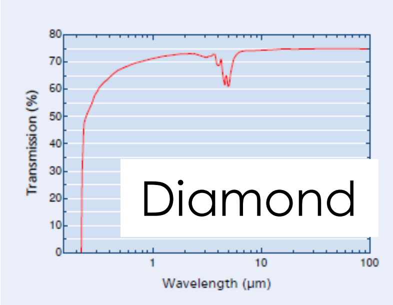
$$N_{ph} = 2\pi\alpha \cdot d \cdot \left(\frac{1}{\lambda_a} - \frac{1}{\lambda_b}\right)\left(1 - \frac{1}{(\beta n)^2}\right)$$

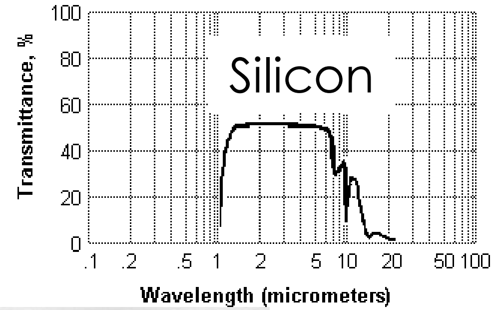
- Almost no dependency on beam energy

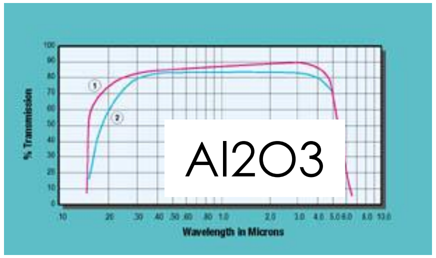
Cherenkov radiation (2/2)

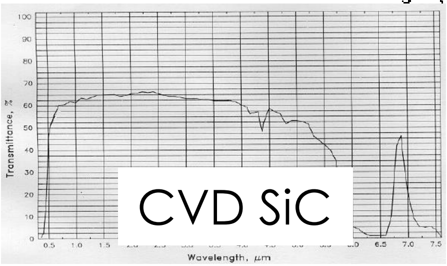
- Emitted (measurable) power spectrum depends on the materiel transparency ($Tr(\lambda)$)









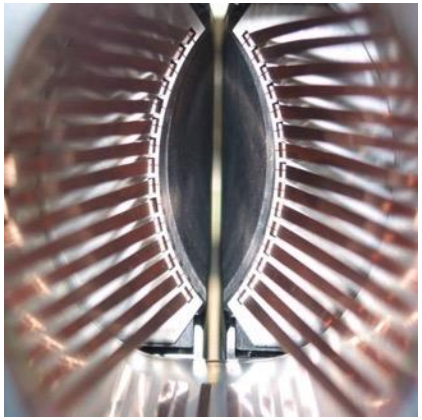


…Using beam parameters of LHC

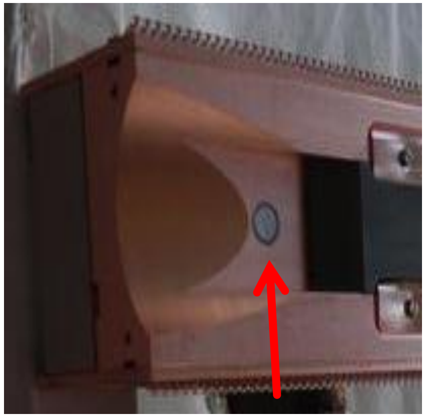
e.g. Positioning of Crystal collimator in LHC or FCC

e.g. Positioning of Crystal collimator in LHC or FCC

- LHC collimators are equipped with electrostatic BPM to allow their alignment with a resolution better than 10microns in10-20seconds at a distance of few mm from the beam



LHC collimator aperture (≈1mm) at 7TeV

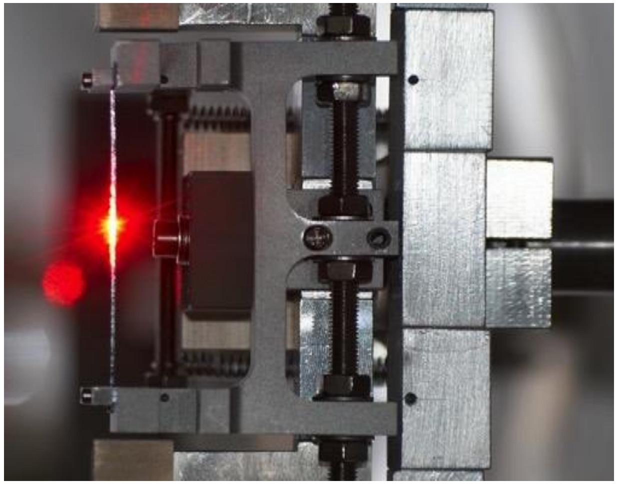


Equipped with BPM button on both end of the jaw (1m long)

e.g. Positioning of Crystal collimator in LHC or FCC

- LHC collimators are equipped with electrostatic BPM to allow their alignment with a resolution better than 10microns in10-20seconds at a distance of few mm from the beam

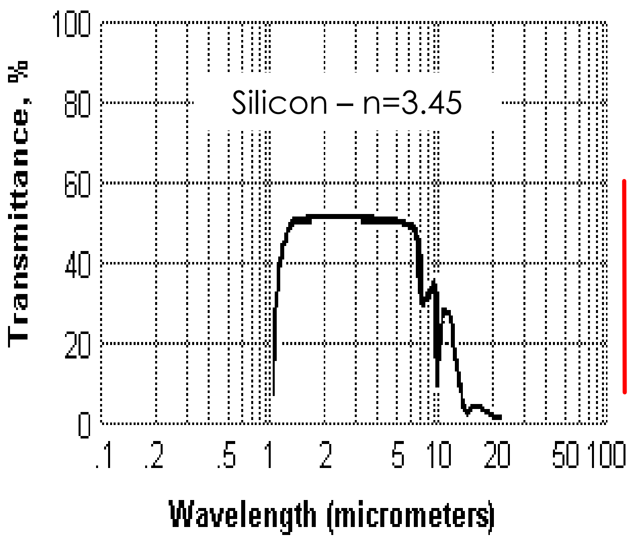

- Crystal collimators are now seriously considered as the future primary collimators in LHC and FCC
  - Investigating the use of Cherenkov Diffraction Radiation as way to measure the position of the crystal with respect to the beam



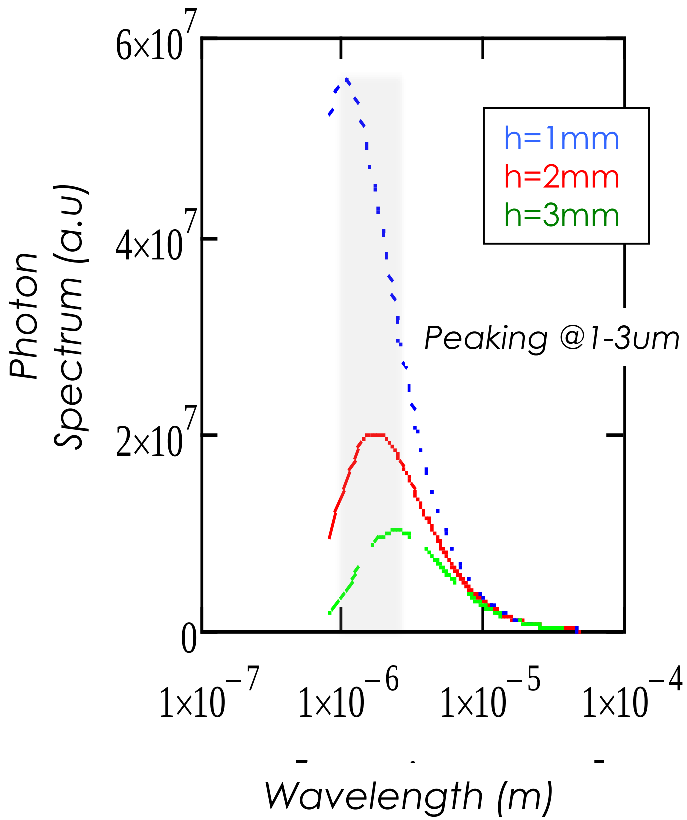
e.g. Cherenkov Diffraction Radiation

- ChDR Photons spectrum in Silicon for LHC (7TeV protons) and different impact parameters

$$\frac{dP}{d\lambda} = \frac{2\pi\alpha \cdot L \cdot Tr(\lambda)}{\lambda^2} e^{\frac{-4\pi \cdot h}{\gamma\beta\lambda}} \left(1 - \frac{1}{(\beta n)^2}\right)$$

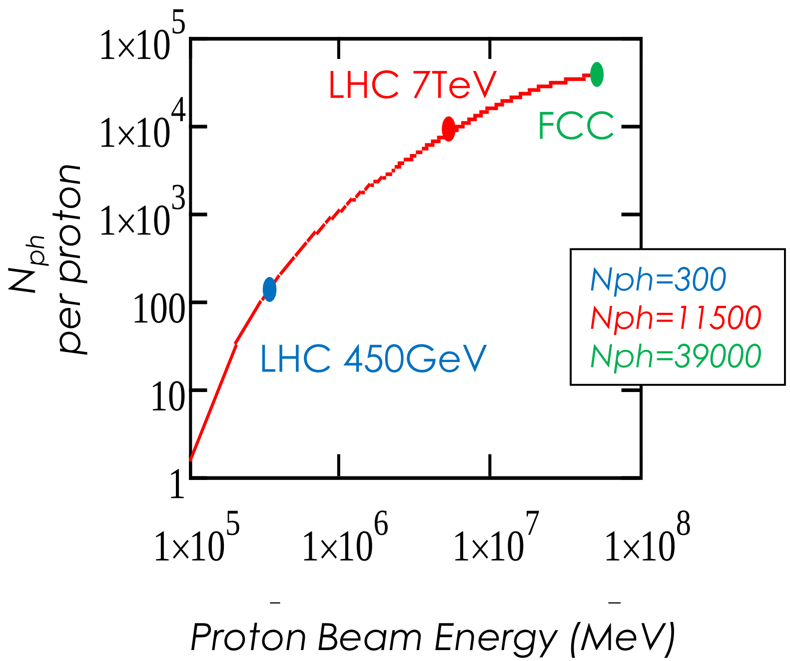


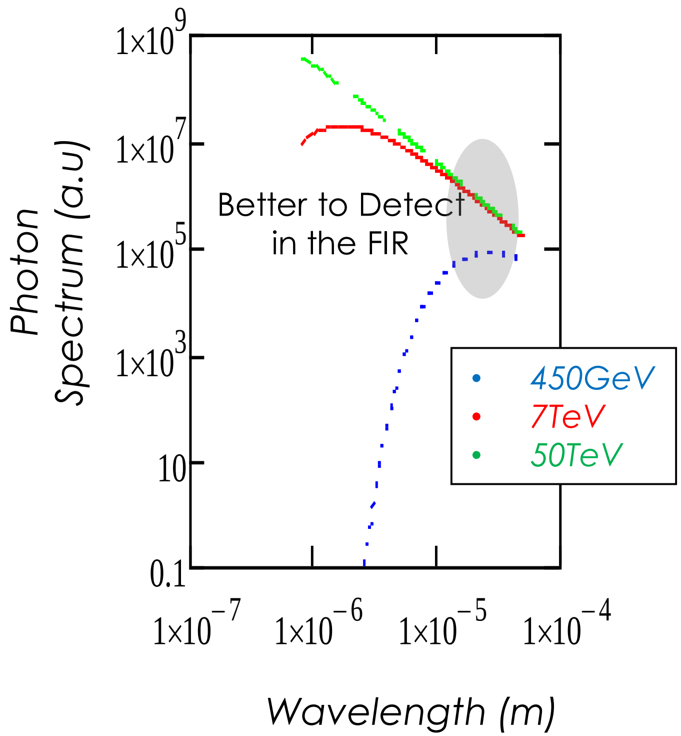
Photon spectrum only calculated over the transmission bandwidth of corresponding material



e.g. Cherenkov Diffraction Radiation

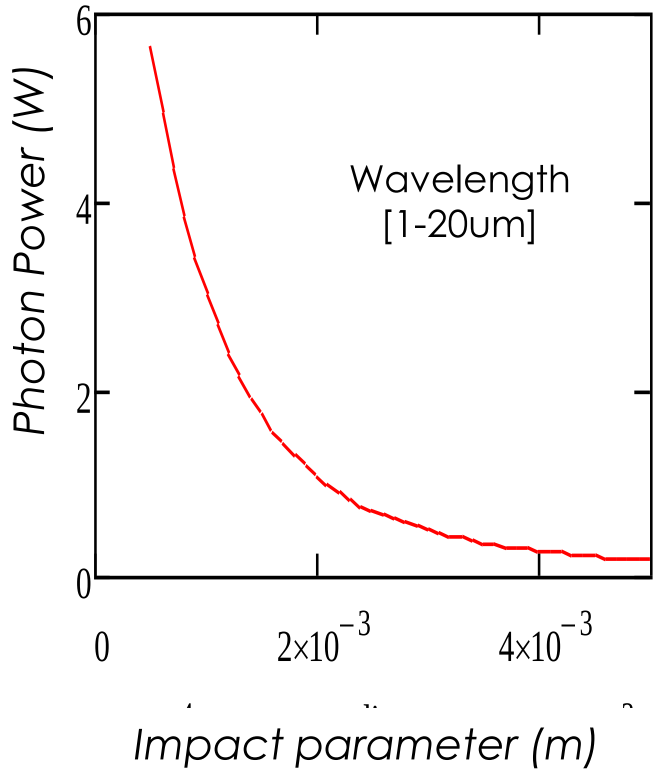
- Number of ChDR photons and ChDR power spectrum as function of beam Energy (LHC-FCC)
  - 1m Si crystal and impact parameter h = 2mm





e.g. Positioning of Crystal collimator in LHC or FCC

- *3mm long Silicon Crystal and 7TeV protons*
- *Emitted Photon power for h=1mm (typical for primary collimators) ≈ 5watts for full LHC beam 2808 nominal bunches (1.1E11 protons)*



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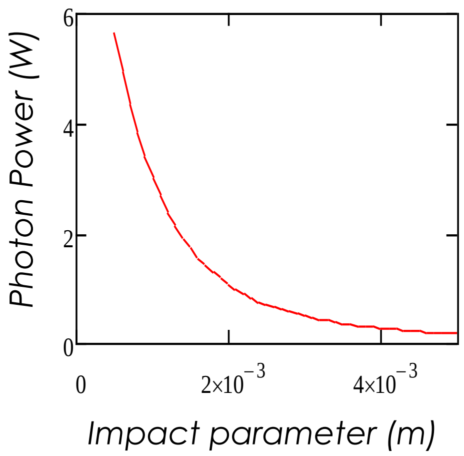
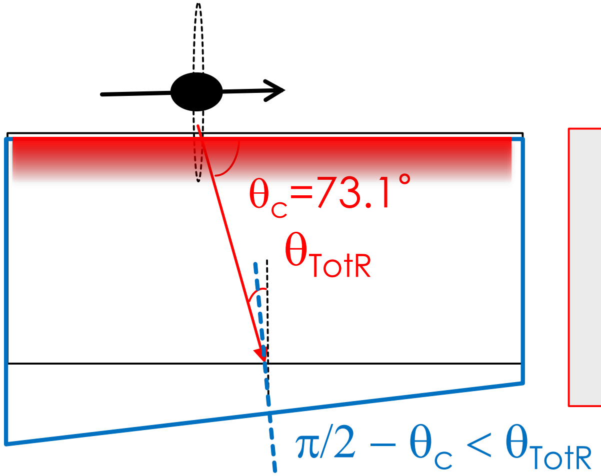


- *In current design (i.e. parallel crystal faces), a large fraction of the power would be totally reflected (16,9°) and possibly absorbed*

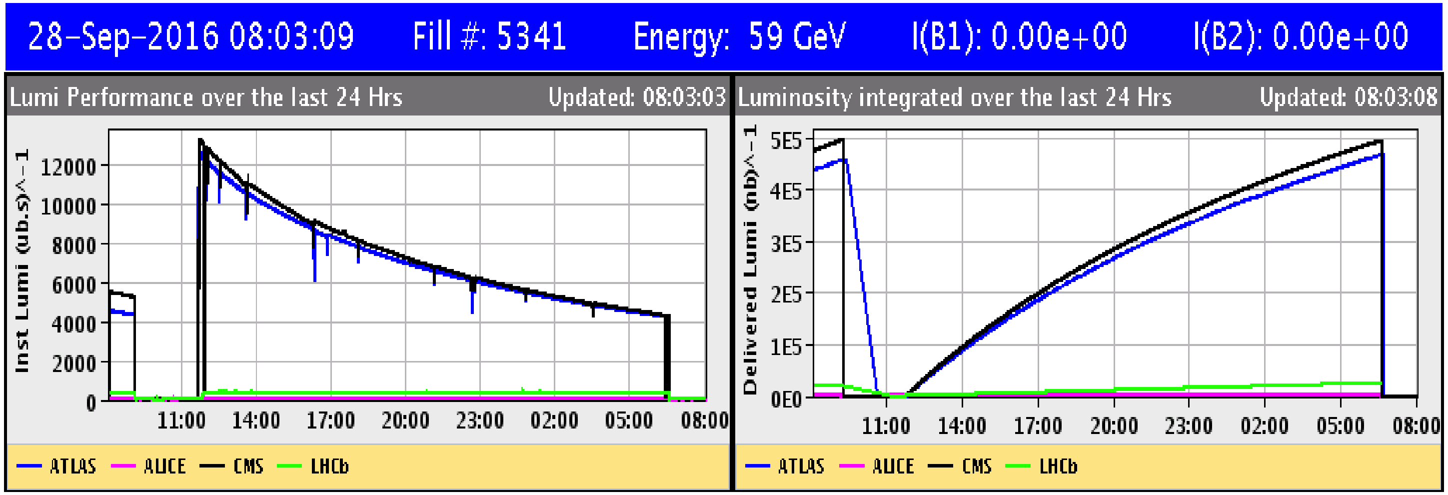


- *Crystal outer face built with different angle or with a high roughness to diffusive the light out*
- *Measuring infrared photons coupled in a optical fiber*

ChDR for Beam cooling ?

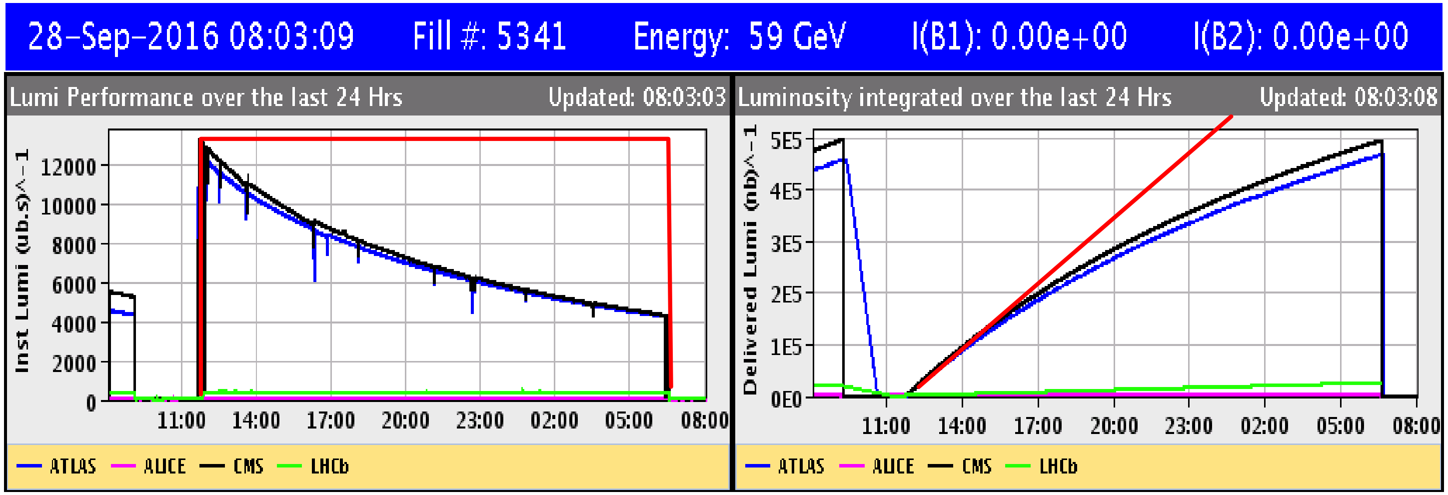
ChDR for Beam cooling ?

- During normal operation, LHC luminosity drops over a fill due to beam losses
- Synchrotron Radiation cooling time is 21hours
  - Particle energy lost by SR is approximately 7keV per turn (80MeV.s^{-1}) with a critical energy at 42eV
  - Effect of SR Transverse beam cooling is not visible on the peak luminosity



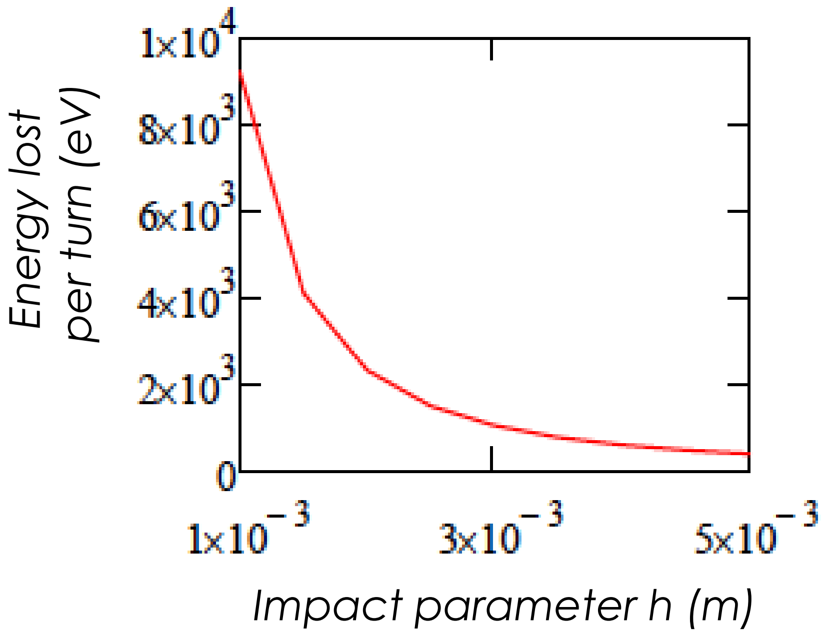
ChDR for Beam cooling ?

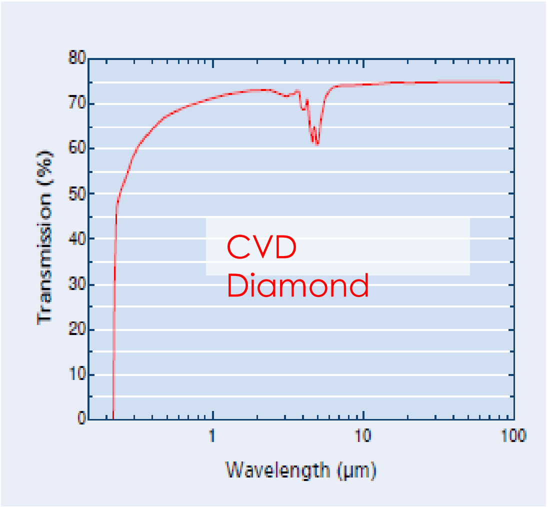
Cool the beam transversely in 4-5 hours to maintain the peak luminosity constant : Gain in integrated luminosity



ChDR for Beam cooling ?

- Assuming a ***ring shaped radiator***, the energy lost by one proton in a 1m long Diamond radiator as function of impact parameter h

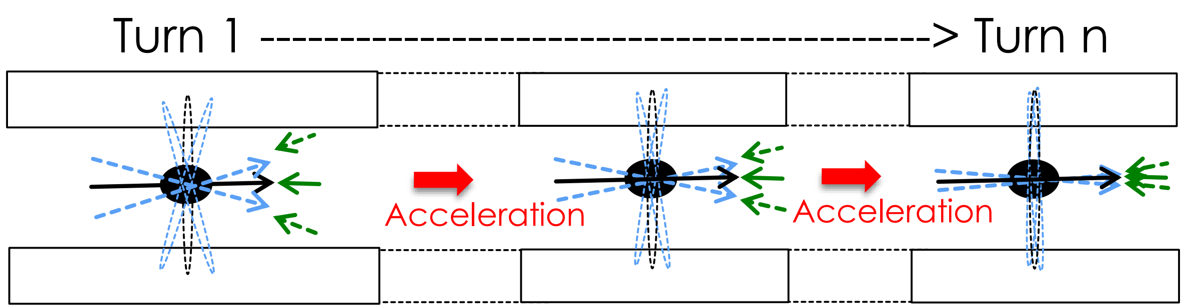




- To be compared to 7keV energy lost per turn by SR

ChDR for Beam cooling ?

Radiating and Cooling

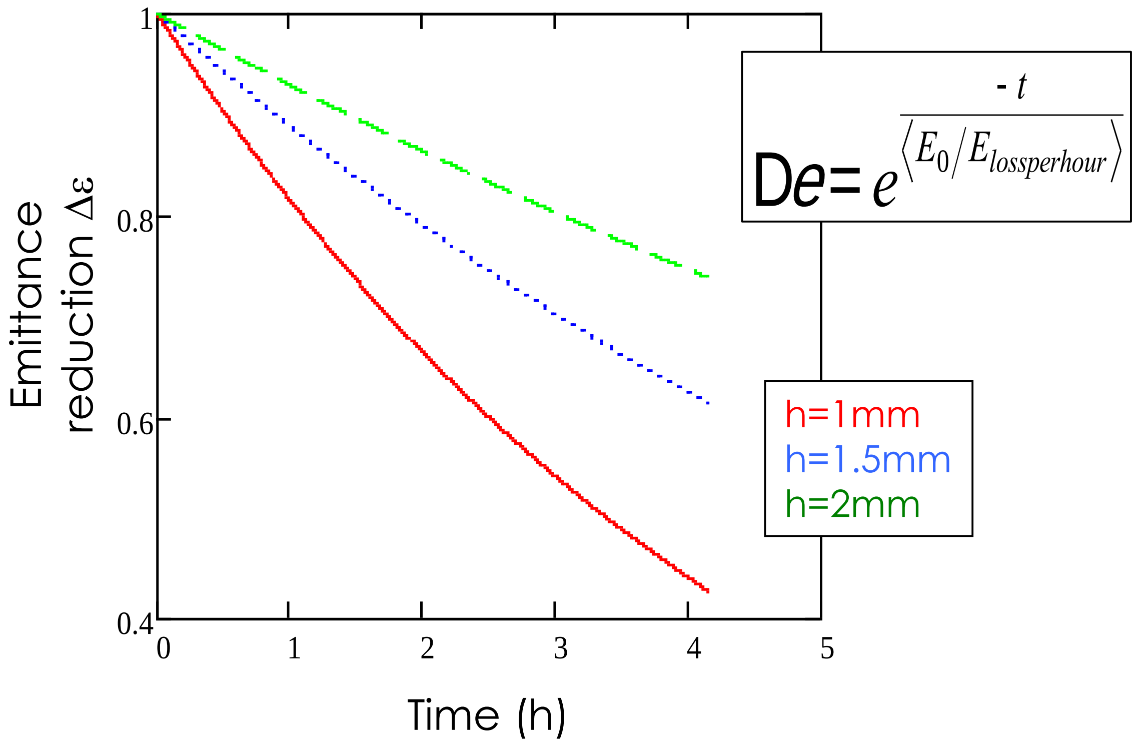


It requires that Particle recoils opposite to its direction of propagation

- Assuming this is true (or partially true), the emittance of the beam would then decrease down to an equilibirum emittance – What would that be ?
- Assumed that radiator is thin enough so that there is no coherent emission

ChDR for Beam cooling ?

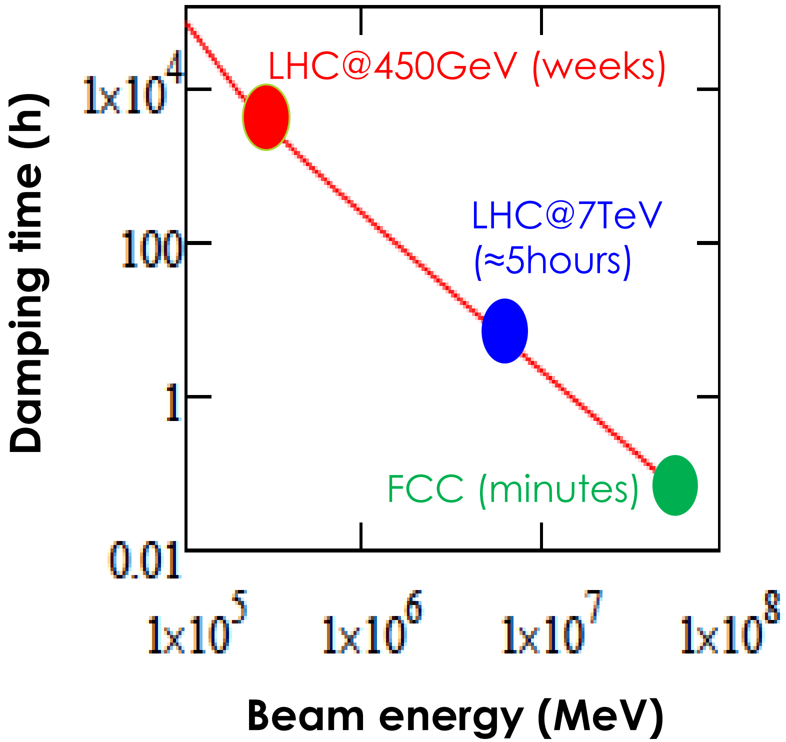
Time evolution of the LHC beam emittance at 7TeV for different impact parameter h



Assuming **10x 1m long Diamond radiators**

ChDR for Beam cooling ?

Damping time as function of beam energy (h=1.5mm)



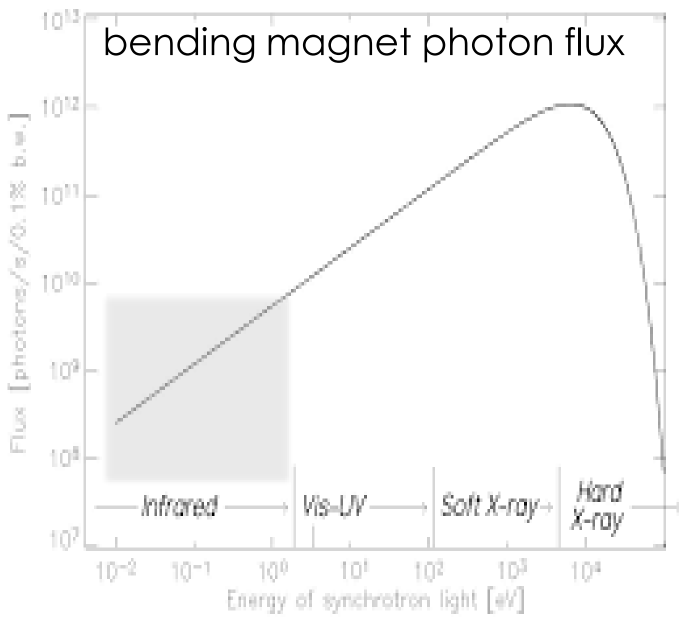
Damping time = the time it would take particle to lose half of its energy

Assuming **10x 1m long Diamond radiators**

ChDR as source of Radiation ?

ChDR as source of Radiation ?

Beam energy	3 GeV
Beam current	200mA
Ring Circonference	220m



ChDR as source of Radiation ?

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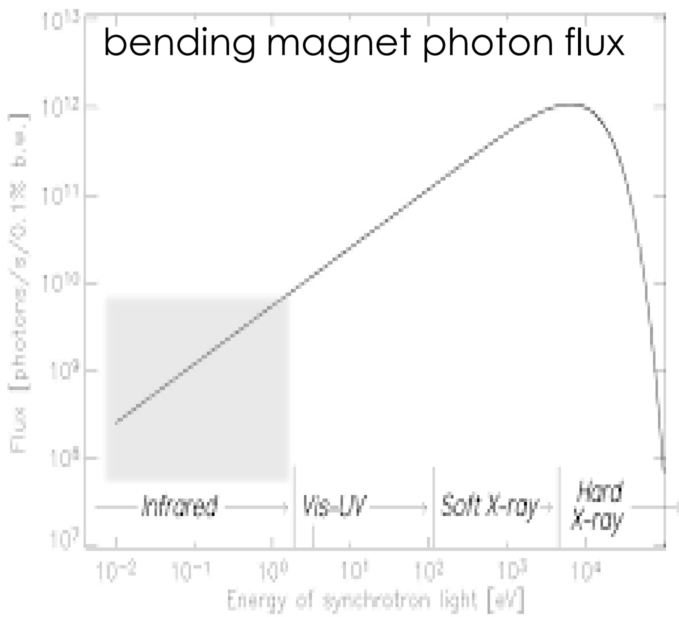
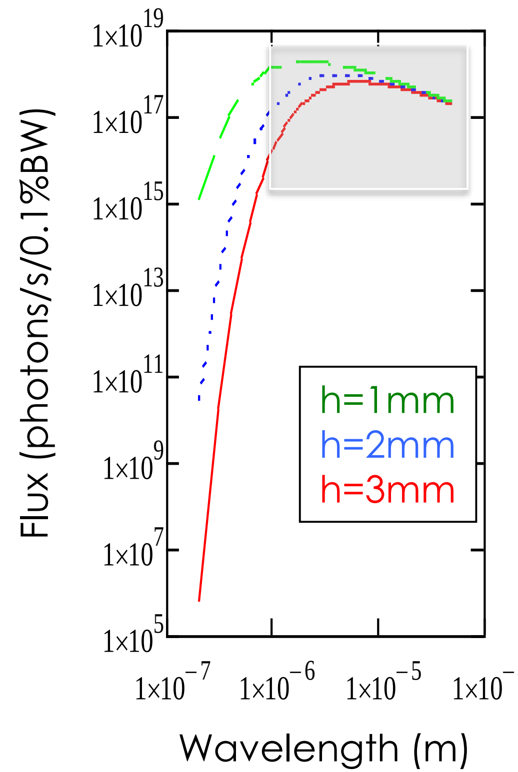
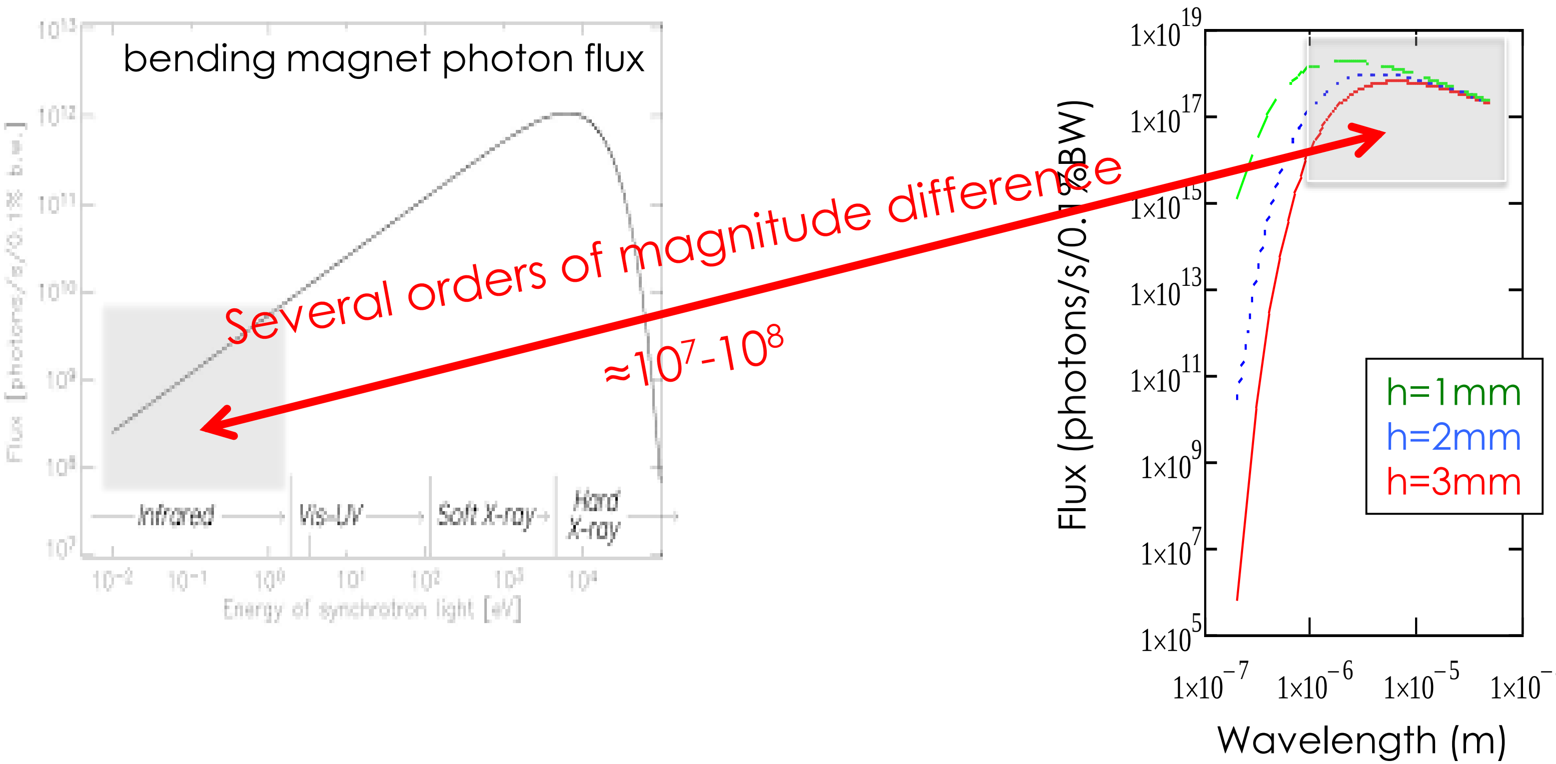


ChDR from a 1cm long diamond radiator



ChDR as source of Radiation ?

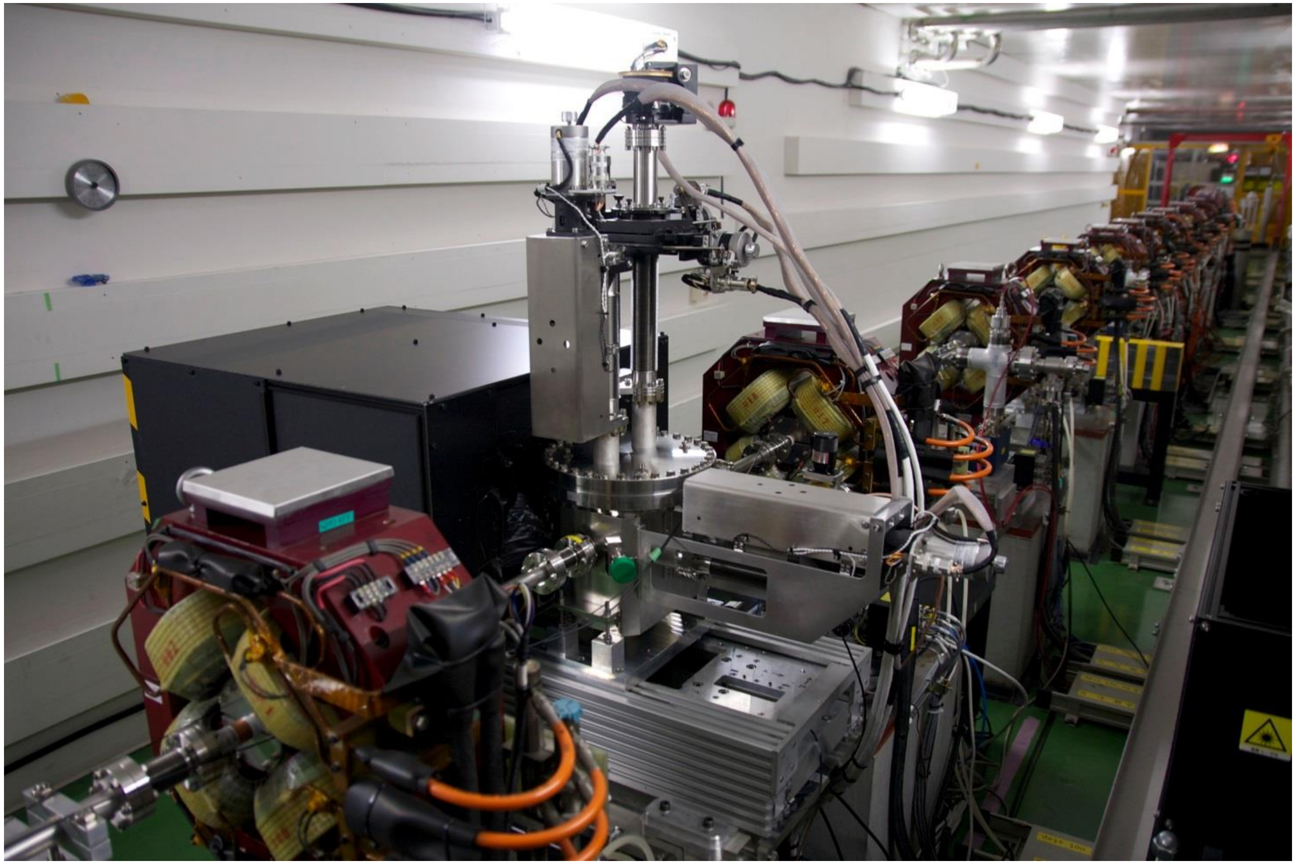


1cm long diamond

- Beware, this is the ChDR photon flux produced and not extracted ($x10^{-3}$) !
- If interested in longer wavelength *(FIR/THz) – use larger impact parameter*

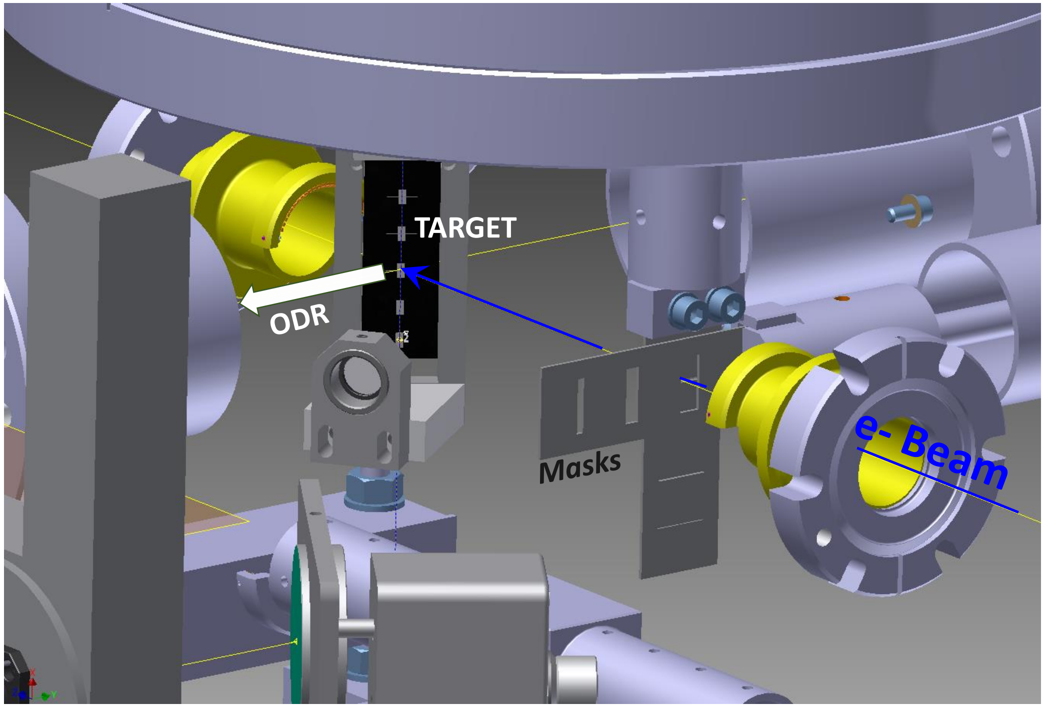
ODRI experiment at KEK ATF2

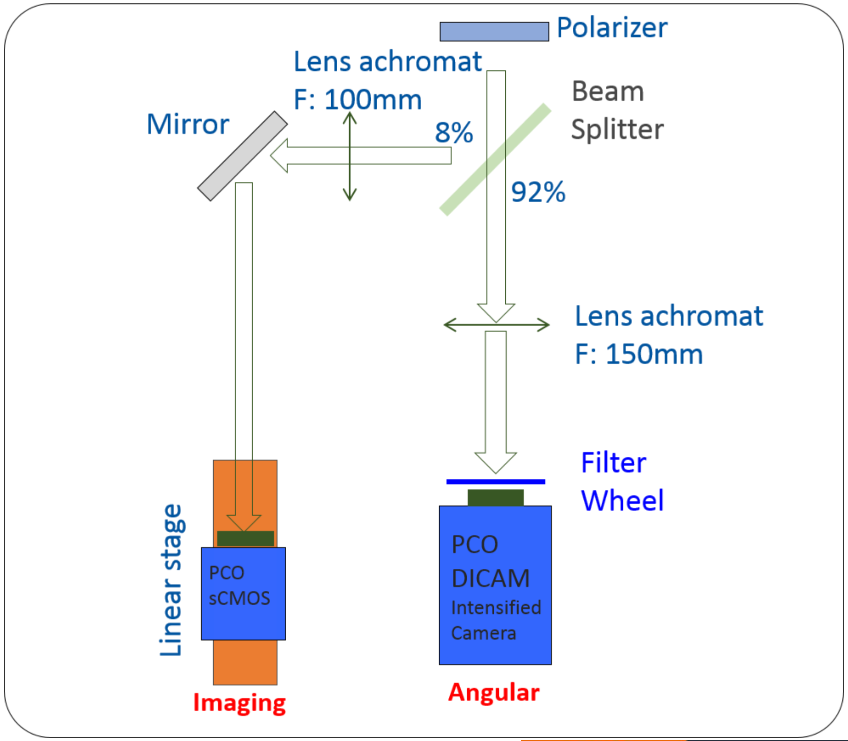
Experiment installed at ATF2 in February 2016, in the laser-wire previous location where vertical beam can be focused to < 1um



ODRI experiment at ATF2

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

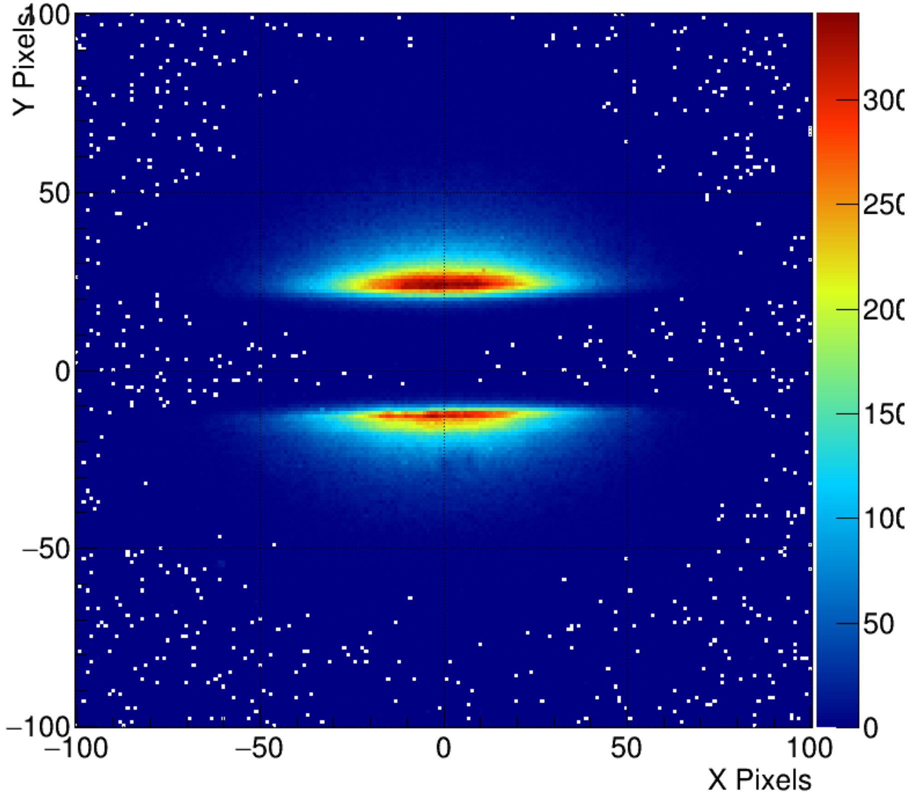




Synchronous Imaging and Angular acquisition for position filtering in angular

ODRI at ATF2

Direct Image of the ODRI



2D Angular distribution of the ODRI