THz Radiation using Cherenkov Diffraction Radiation

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L. Bobb, Diamond light source
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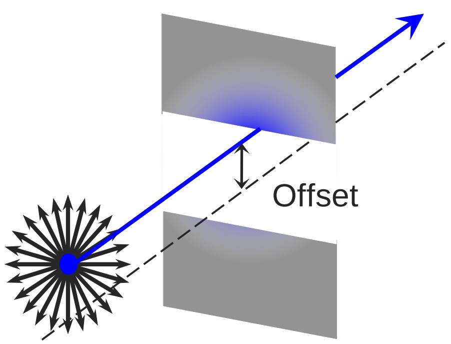
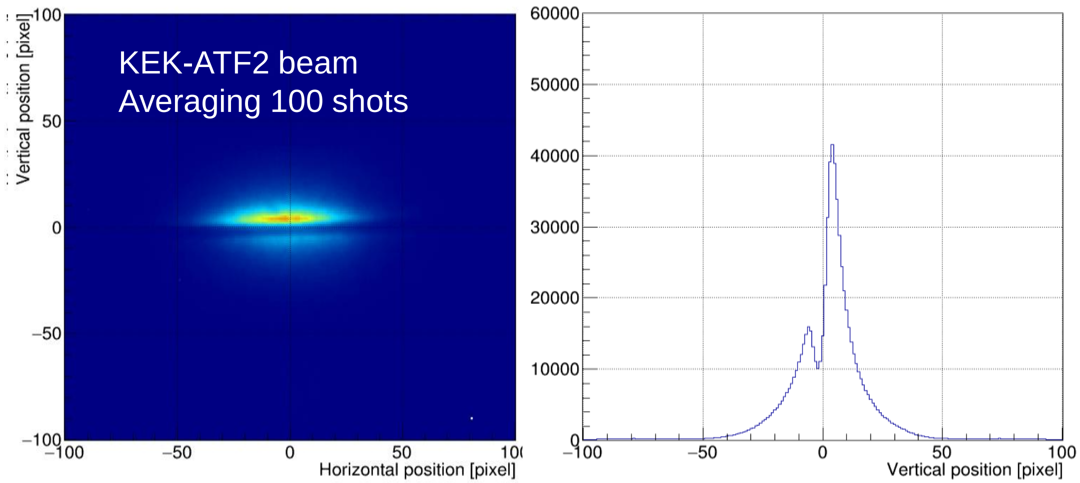
Outline

- Incoherent Diffraction Radiation Studies for beam instrumentation
- Motivation and possible applications of Incoherent Cherenkov Diffraction radiation
  - Beam diagnostic – for example for positioning bent Crystal collimators in LHC/FCC
  - Can Cherenkov Diffraction radiation be used as a beam Cooling mechanism for High energy Hadrons ?
  - Can it be used as an intense source of NIR/THz in Electron Synchrotron ring ?
- What can be tested on CALIFES ?

Incoherent Diffraction Radiation

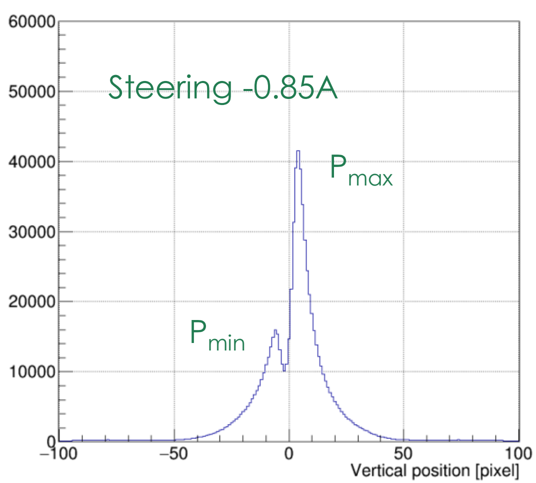
- Studying non-interceptive beam diagnostic using Diffraction Radiation for Linear Collider
  - ODR from small slit as transverse beam size monitor at CESR (Synchrotron ring - 2GeV e$^-$) and ATF2@KEK (extraction line- 1.2GeV e$^-$)



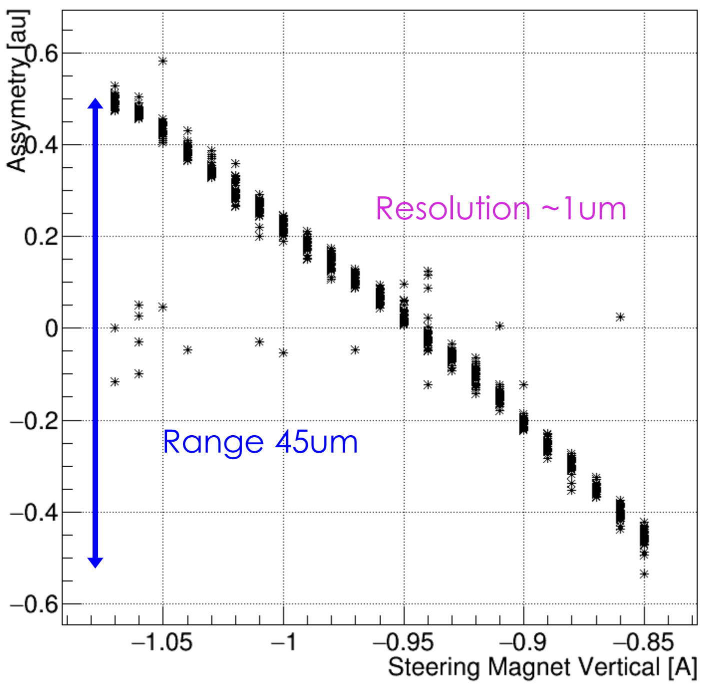


Incoherent Diffraction Radiation

- Optical Diffraction radiation as sensitive Beam Position Monitor
  - Slit: **56um**
  - Beam size: **1um**
  - 30 shots statistics
  - Steering magnet to scan the beam inside the slit.

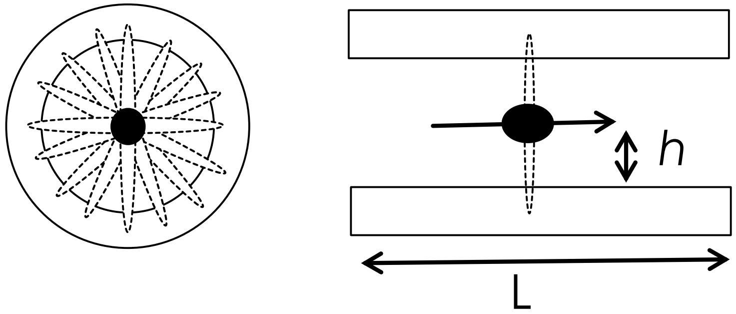


Asymmetry = $(P_{min}-P_{max})/(P_{max}+P_{min})$



Incoherent Diffraction Cherenkov Radiation

- Investigation for possible use of such radiation processes for high energy hadrons and rings with larger slit apertures
- Looking for higher possible light yield using longer dielectric material rather than slit.
  - For $\gamma \gg 1$, $N_{oTR} \approx N_{oChR}$ for 1micron long radiator
  - In Visible, IR, and THZ depending on material Fused silica (SiO2), Silicon (Si) or Diamond



- Motivated by the work of many groups present today
  - A. Potylitsyn *et al*, Journal of Physics: Conference Series 236 (2010) 012025
  - T. Takahashi *et al*, Physical Review E 62 (2000) 8606
  - M.V. Shevelev and A.S. Konkov, JETP 118 (2014) 501

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

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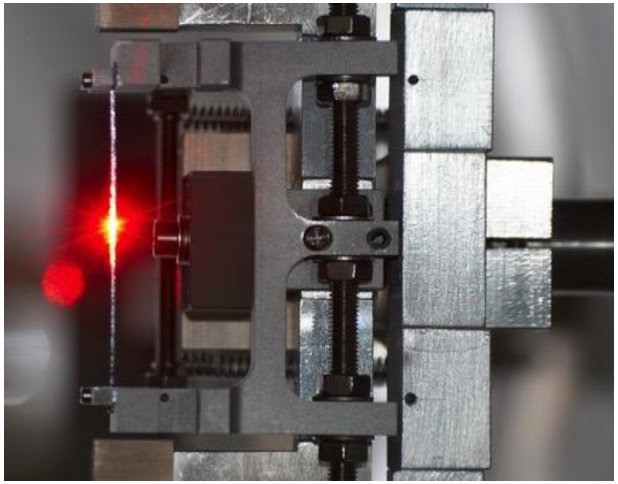
- LHC collimators are equipped with electrostatic BPM to allow their alignment with a resolution better than 10microns in10-20seconds at a distance of few mm from the beam


- 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
  - In a *3mm long Silicon Crystal siting at 1mm away from the beam, the LHC beam (7TeV* p^+*) will produce 5watts of radiation (1-10um wavelegnth)*



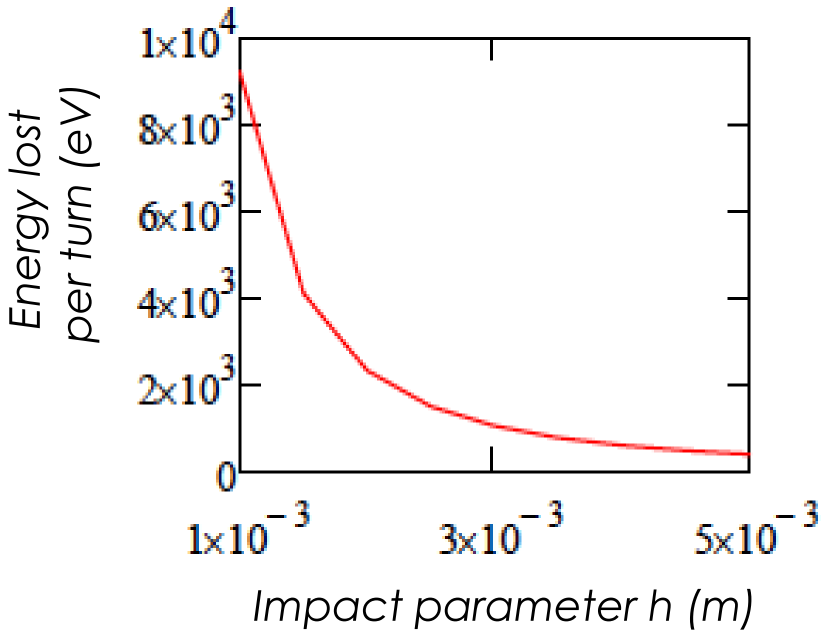
ChDR for Proton cooling ?

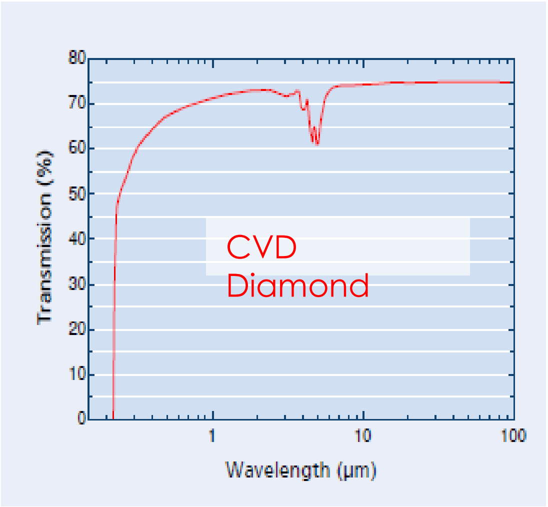
All started while discussing with S. Fartouhk

looking for possible ways to cool LHC proton beams

ChDR for Proton cooling ?

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

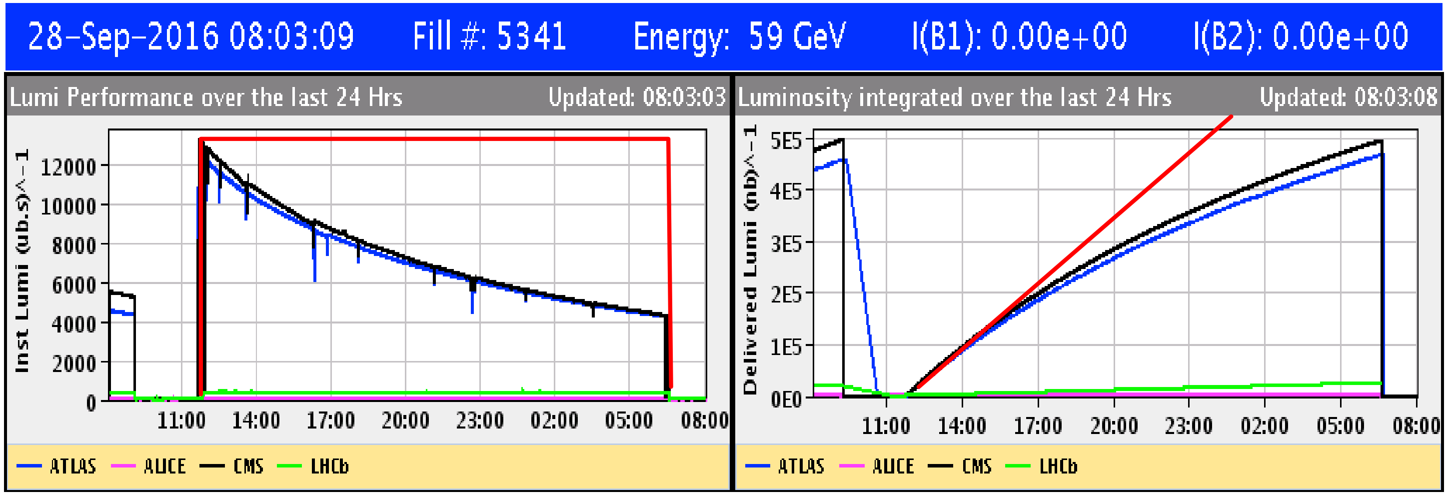




- To be compared to 7keV energy lost per turn by SR

ChDR for Proton cooling ?

Cool the beam transversely in 4-5 hours to maintain the peak luminosity constant : Gain in integrated luminosity Using long Cherenkov Diffraction Radiator (10m ?)



ChDR as source of Radiation ?

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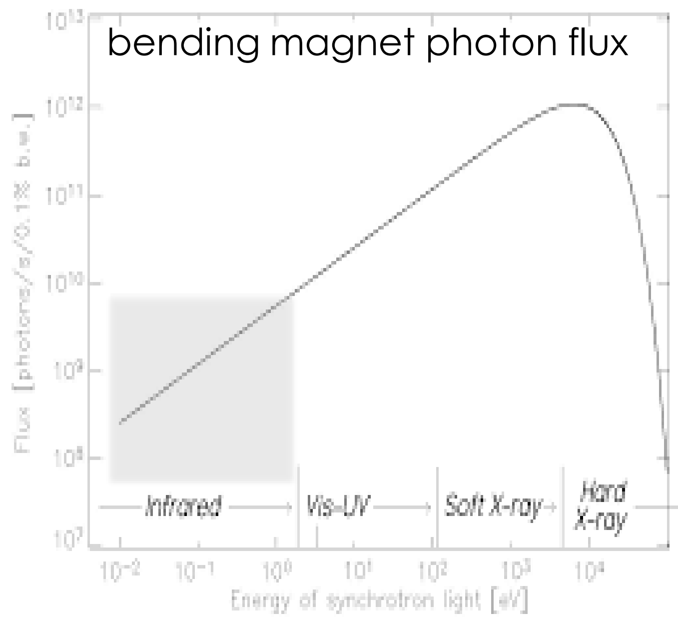
Beam energy	3 GeV
Beam current	200mA
Ring Circonference	220m



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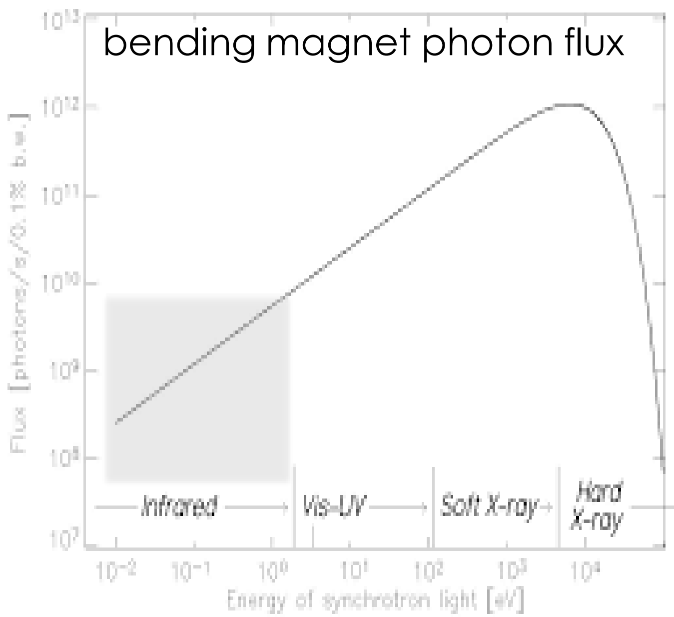
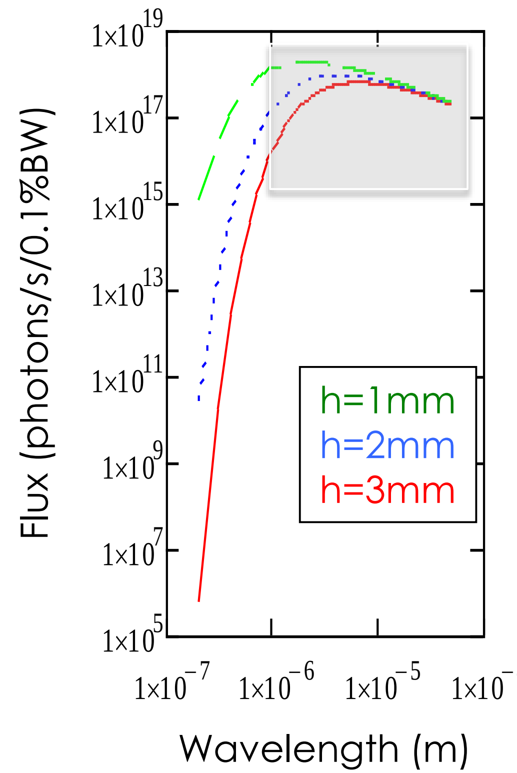
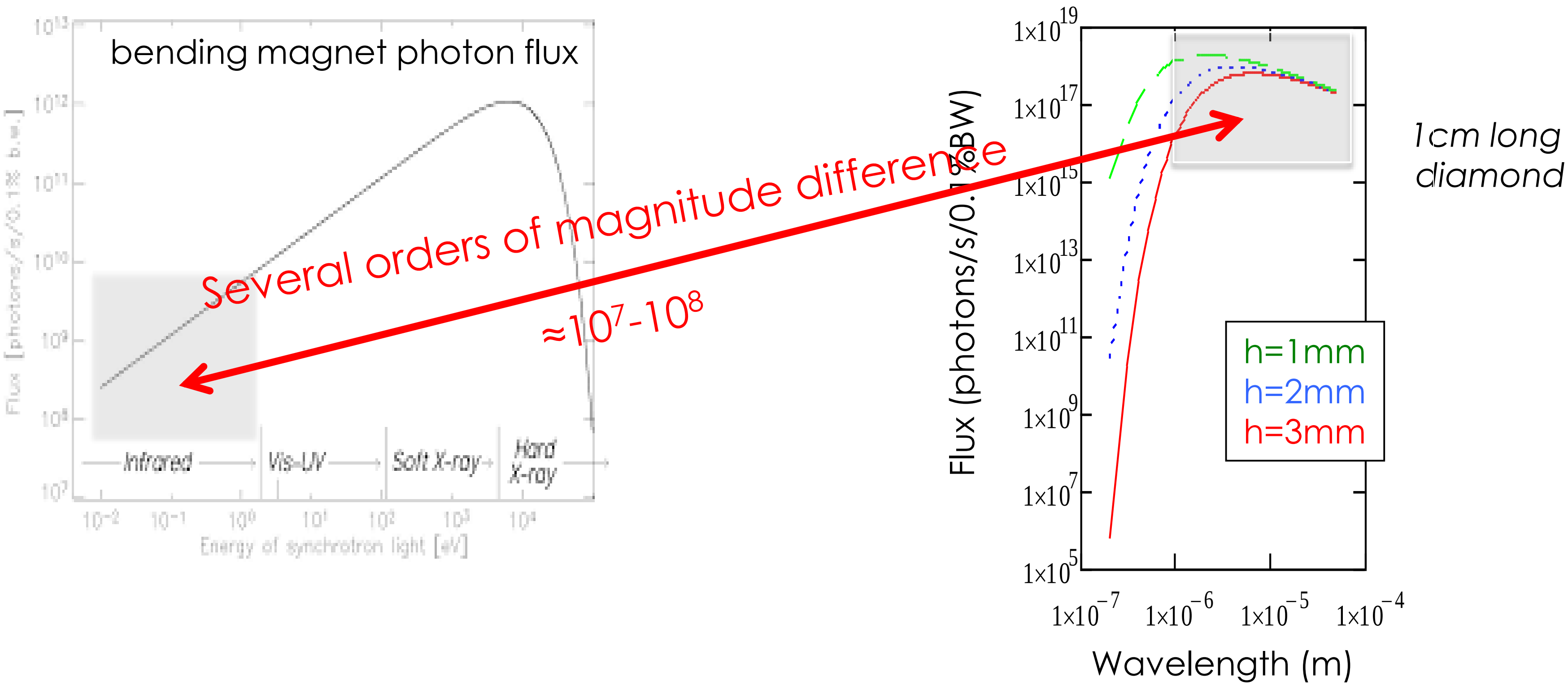


ChDR from a 1cm long diamond radiator



ChDR as source of Radiation ?

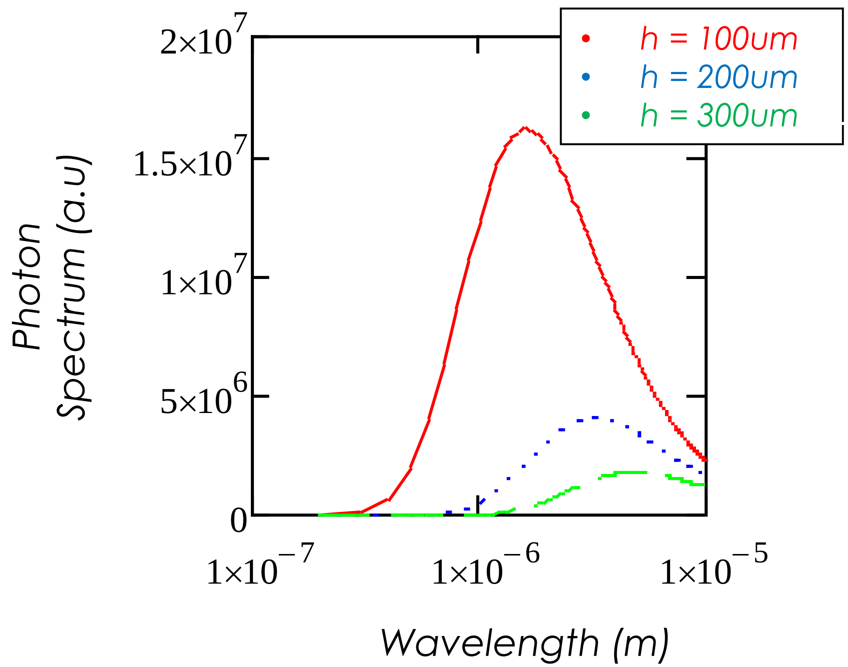


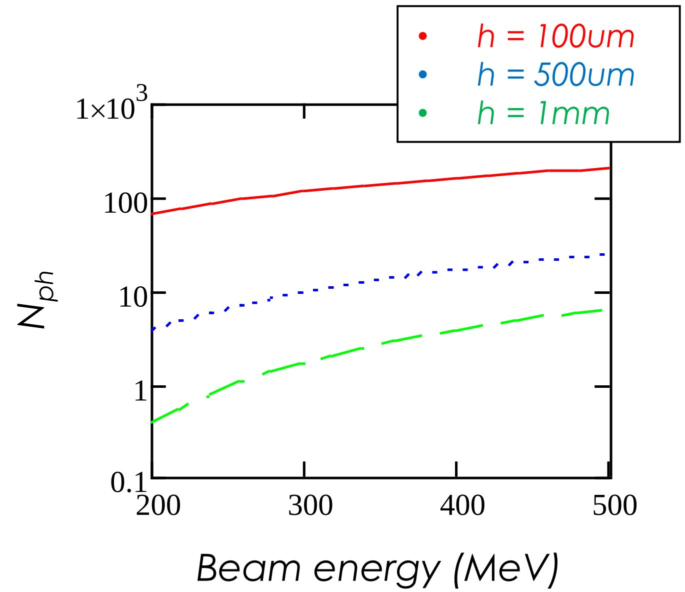
- Beware, this is the ChDR photon flux produced and not extracted ($\times10^{-3}$) !
- If interested in longer wavelength *(FIR/THz) – use larger impact parameter*

Experimental tests on CALIFES

Experimental tests on CALIFES

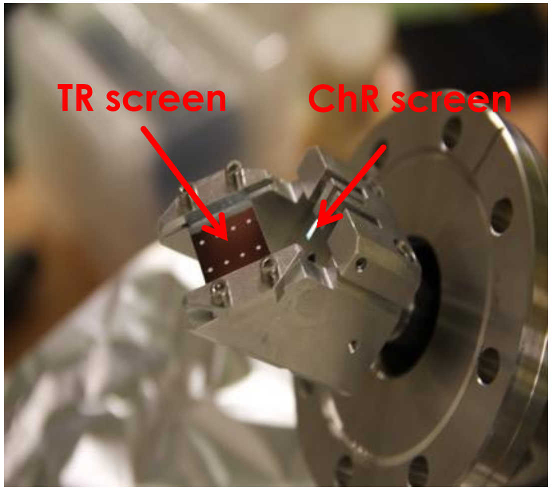
- CALIFES : 200MeV e⁻ - 1nc – using 1cm long diamond Crystal

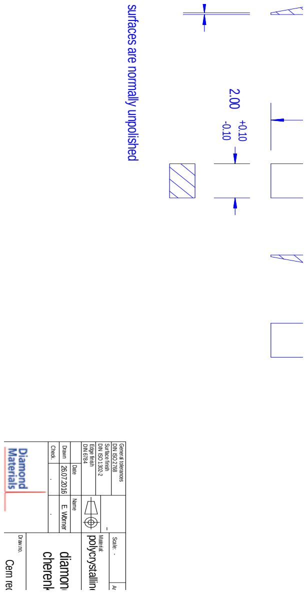


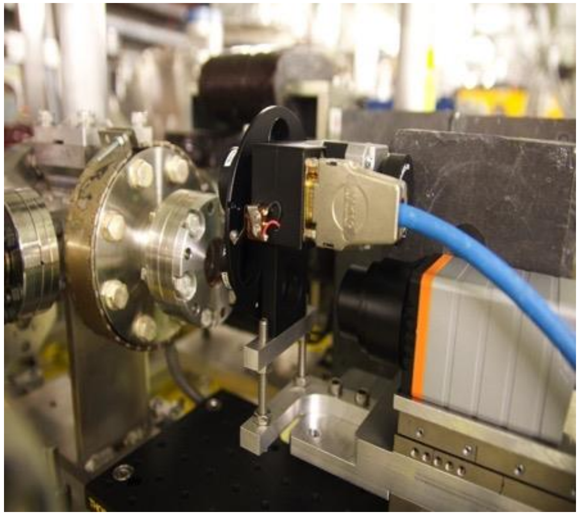


Experimental tests on CALIFES

- 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 MIR/FIR Camera
- Measuring and comparing Transition, Cherenkov and Cherenkov Diffraction radiation







Conclusions

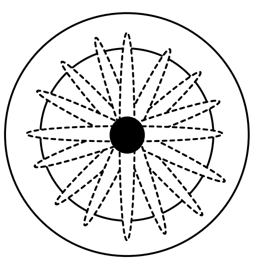
- Possible applications of Incoherent Cherenkov Diffraction Radiation for Beam diagnostic, Beam cooling or as Source of radiation are under investigation
- Collaboration with Tomsk Polytechnic University to understand the beam dynamic involved in polarisation radiation from long dielectric
  - How does particle recoil in a given geometry ? Is cooling via ChDR possible ?
    - What would be the equilibrium emittance in both planes ?
    - Does the beam halo cool faster ?
- Beam tests on CALIFES would allow
  - Measuring the properties of the emitted photons (power and spectrum)
  - Optimising the radiator geometry
    - How thick can the radiator be ? Microns to mm thicknesses ?
    - Best shape/configuration for light extraction/absorption ?

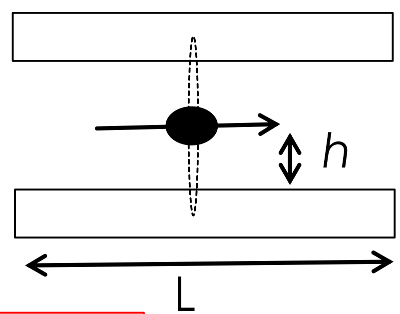
Thanks

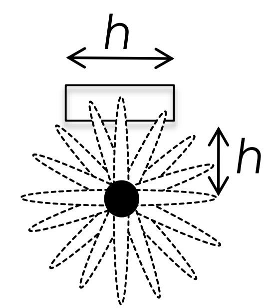
Estimation of incoherent Cherenkov Diffraction Radiation

- A simple model to estimate the radiation power spectrum and photon flux
- Combining Cherenkov angular spectrum as predicted by Tamm's theory by a weighting factor which accounts for the transverse exponential decay of the particle field

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







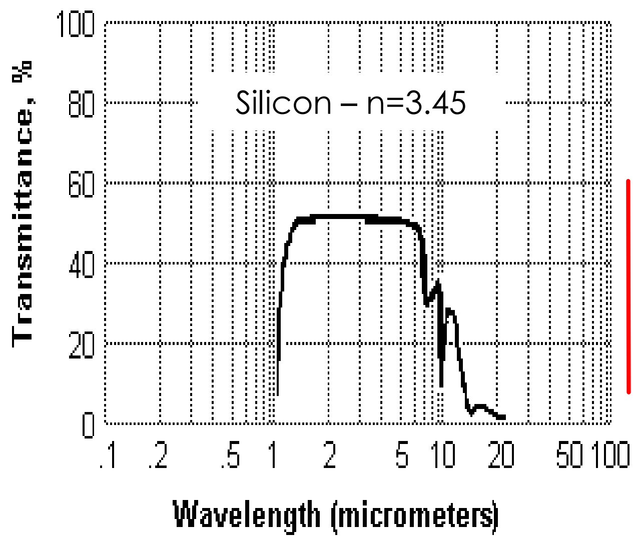
Additional reduction factor(x0.2) to take into account the smaller angular polarization field

- *Assuming beam has no physical size*
- *Assuming beam is perfectly centered*

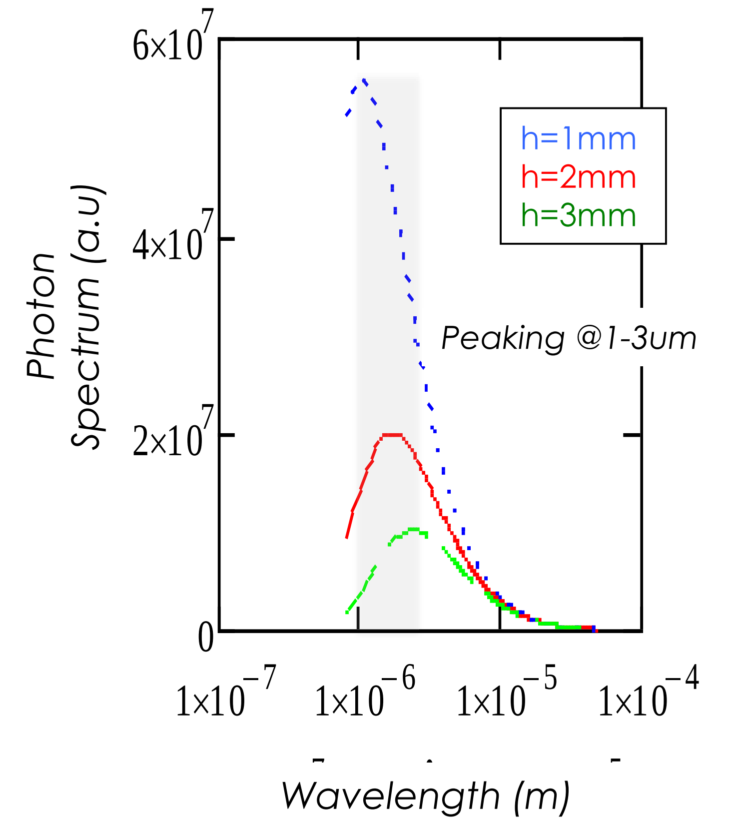
e.g. Cherenkov Diffraction Radiation

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

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



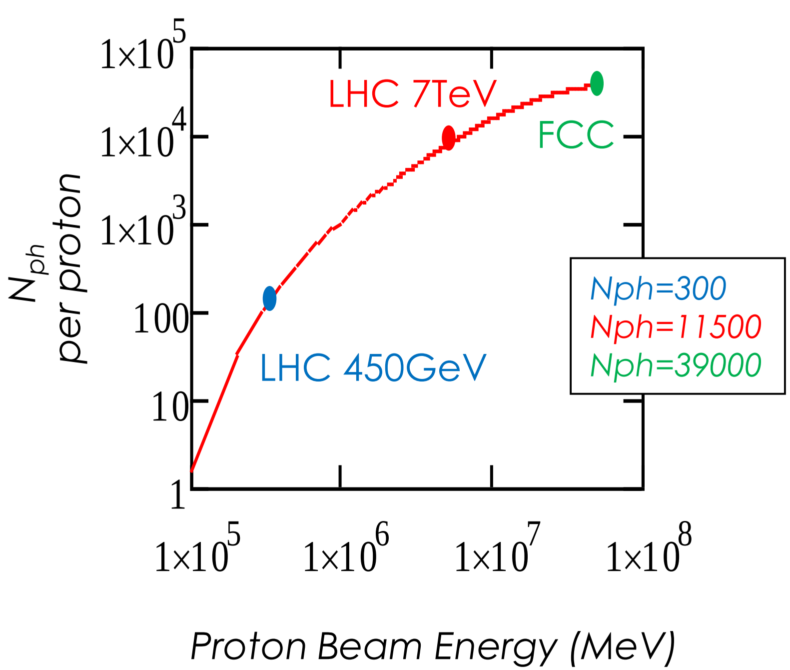
Photon spectrum only calculated over the transmission bandwidth of corresponding material

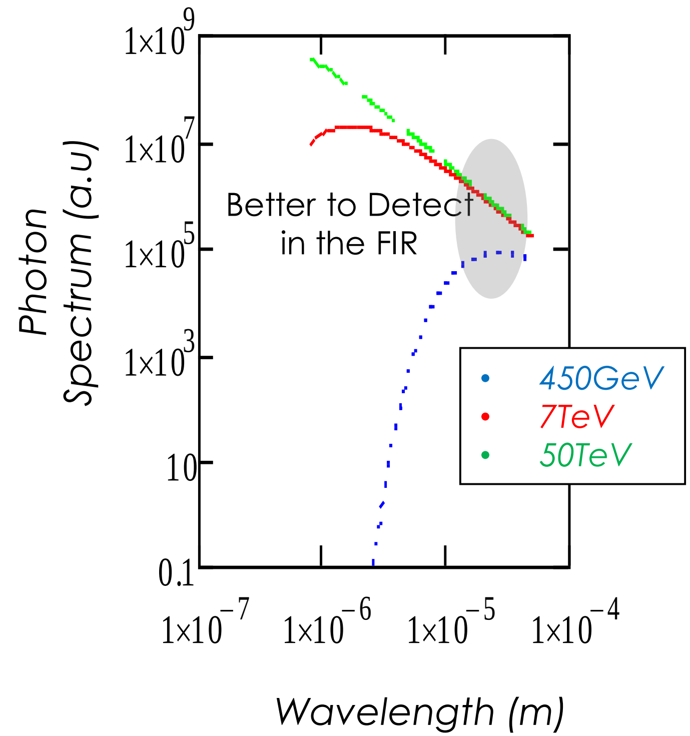


T. Lefevre, 7th Channeling Conference, Sirmione, 2016

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





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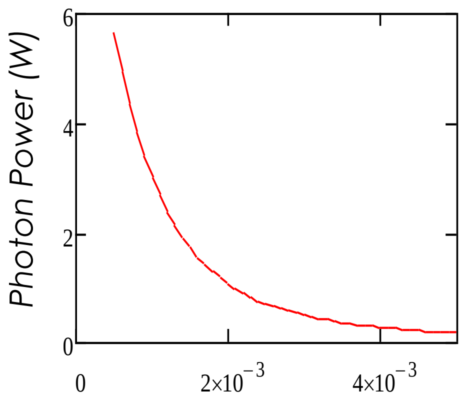
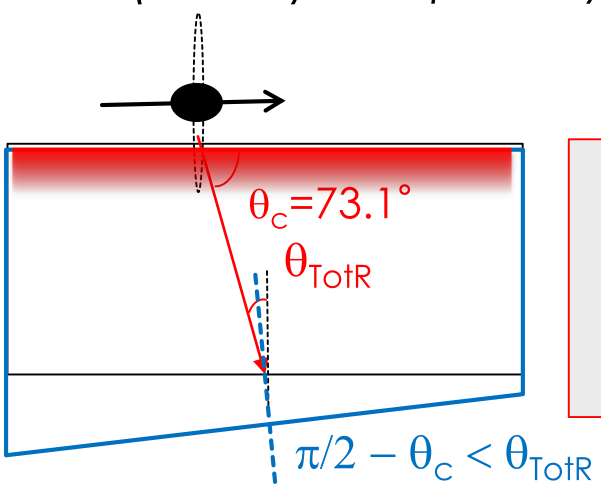
e.g. Positioning of Crystal collimator in LHC or FCC

- *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)



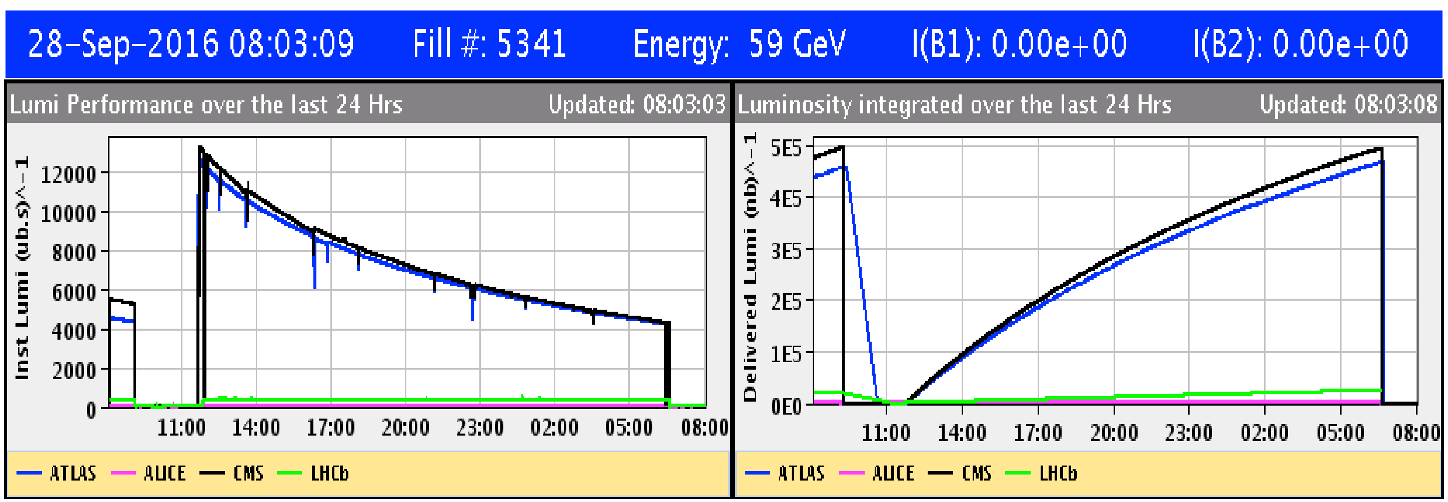
- *In current design (i.e. parallel crystal faces), a large fraction of the power would be totally reflected (16,9°) and possibly absorbed*



- *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*

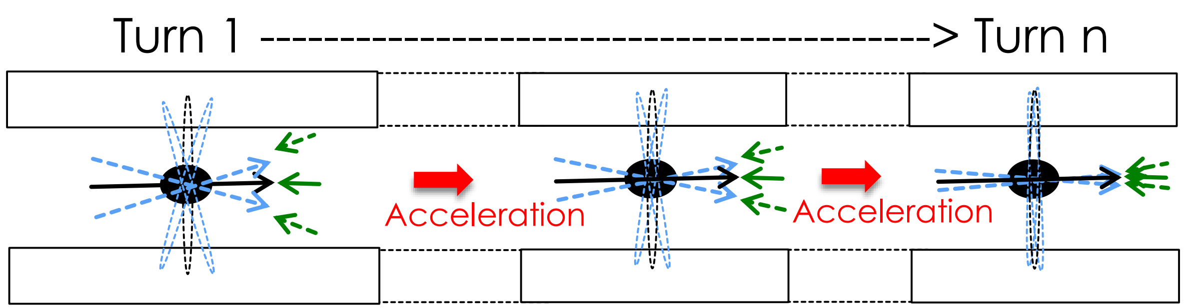
ChDR for Proton cooling ?

- 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 Proton cooling ?

Radiating and Cooling

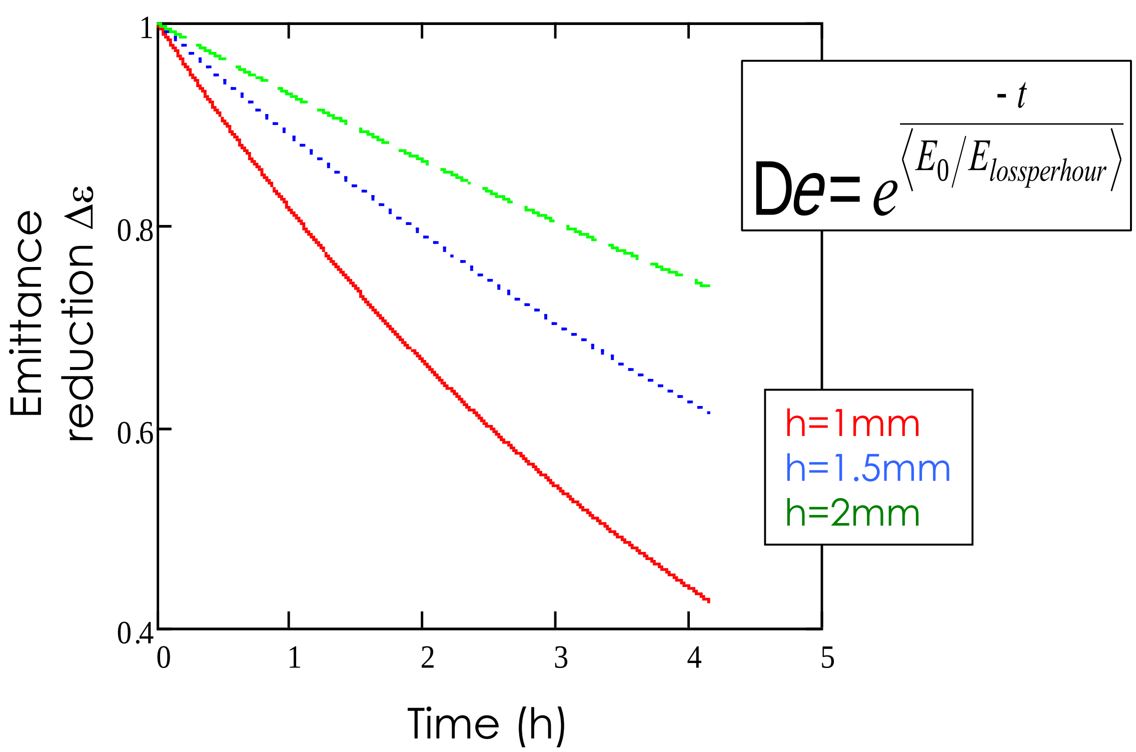


It requires that Particle recoils opposite to its direction of propagation

- 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**

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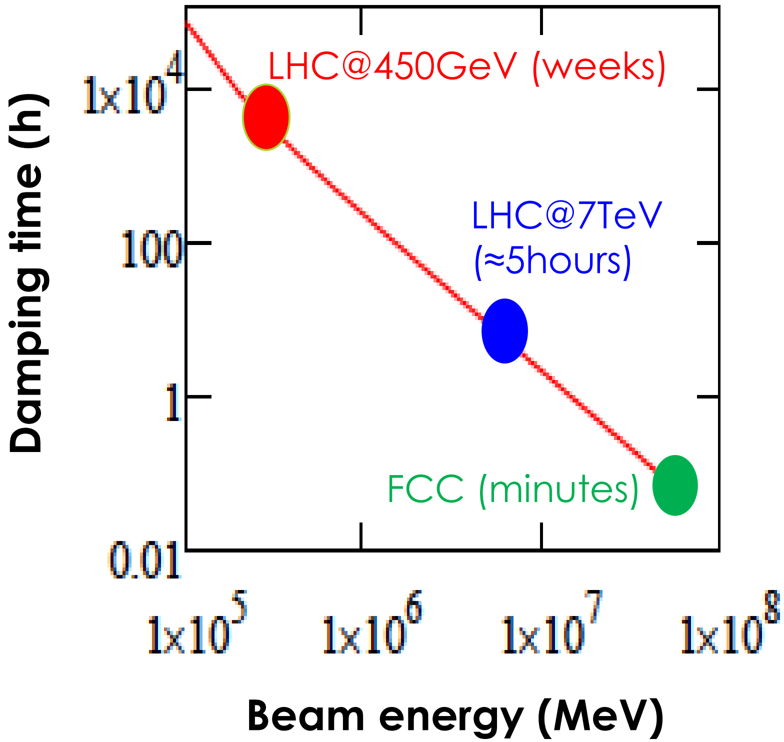
ChDR for Beam cooling ?

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

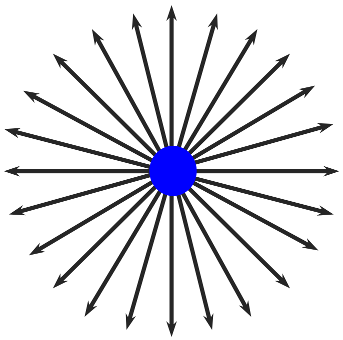


Damping time = the time it would take particle to lose half of its energy

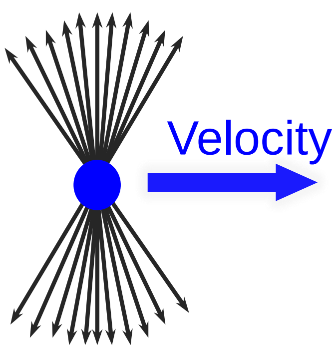
Assuming **10x 1m long Diamond radiators**

EM field of a charged Particle (from Jackson)

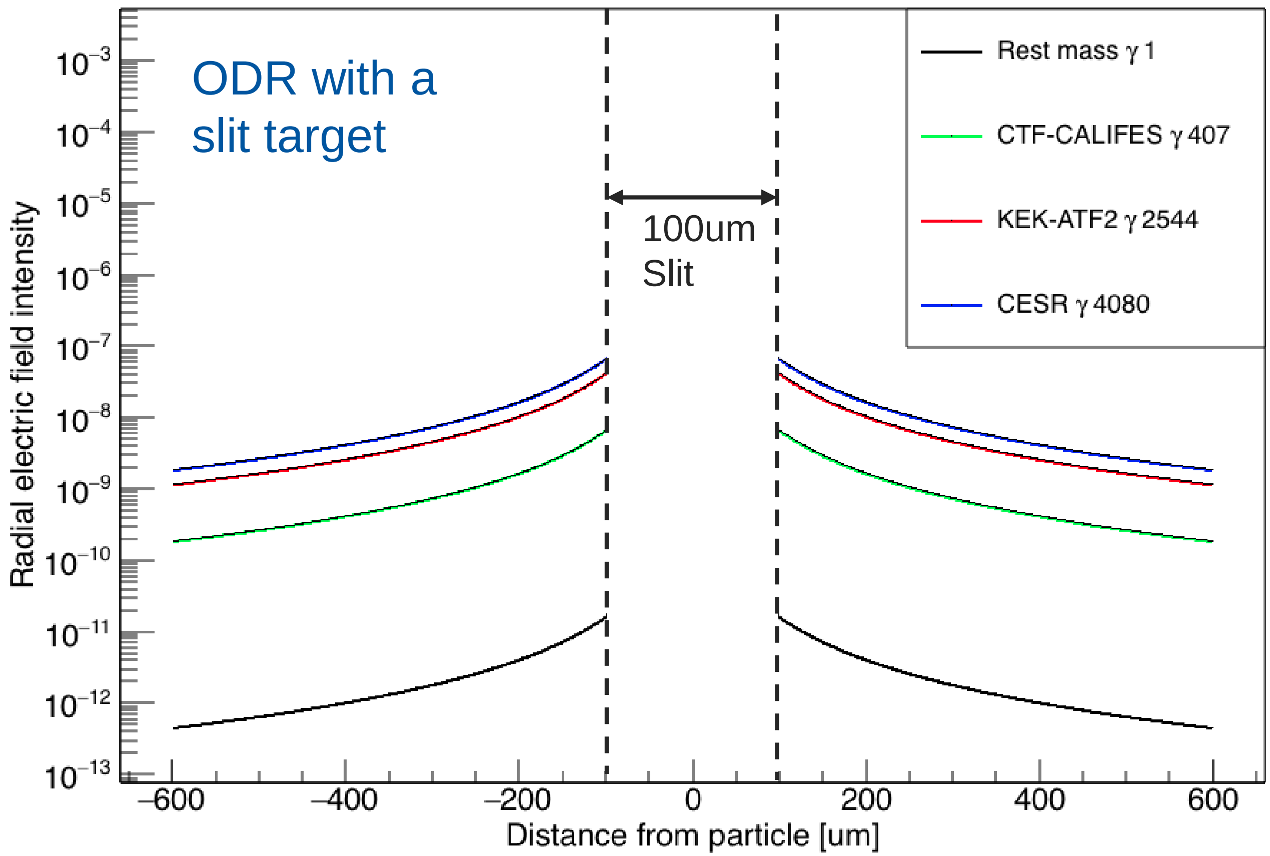
The transverse component of the electric field intensity scales linearly with the Lorenz factor γ.



Rest mass electron electric field map.



Relativistic electron electric field map.



Classical electrodynamics, John David Jackson

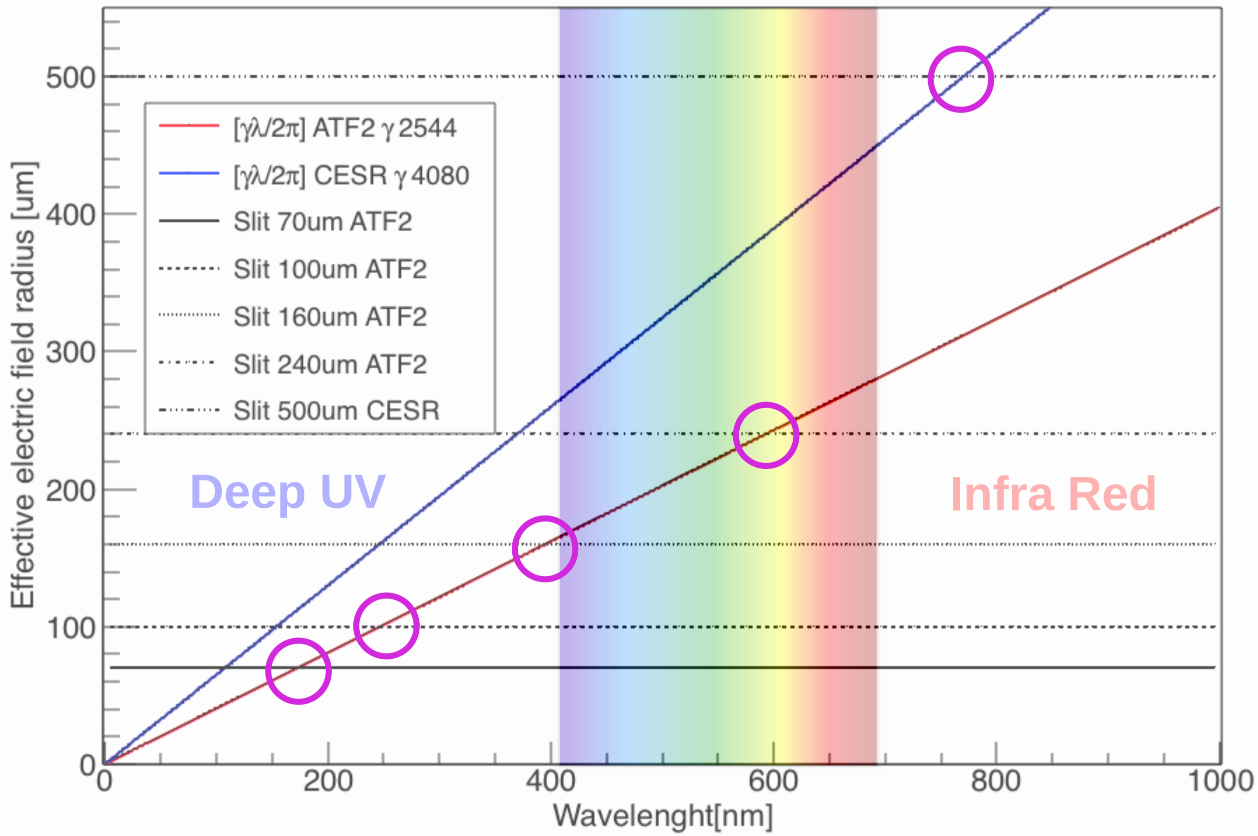
Optical Diffraction Radiation

The **ODR** photons yield is strongly dependent on the **effective electric field radius** and the **slit aperture a** (impact parameter) .

$a \ll \frac{\gamma\lambda}{2\pi}$ OTR

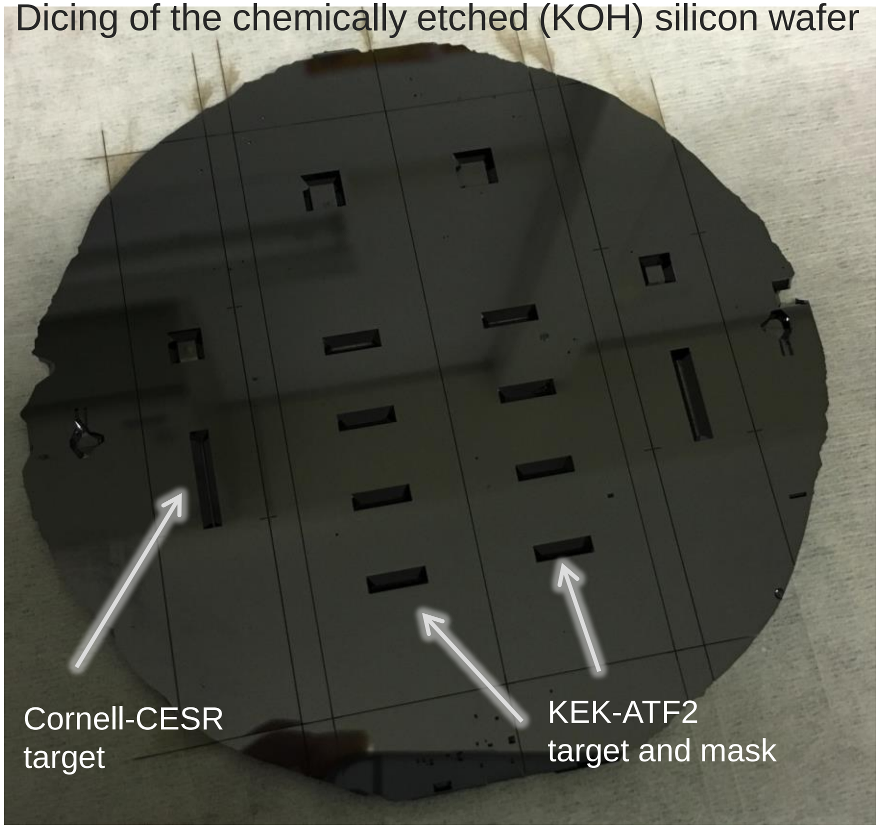
$a \gg \frac{\gamma\lambda}{2\pi}$ No radiation

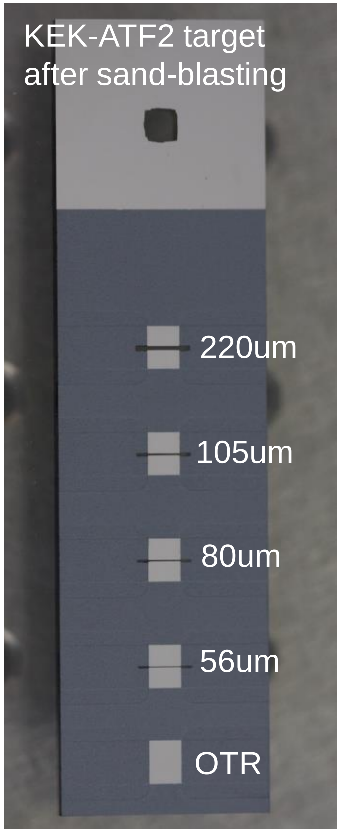
$a \approx \frac{\gamma\lambda}{2\pi}$ **ODR**



ODR target development

The targets were produced in Lausanne at the Center of MicroNano Technology CMI EPFL.

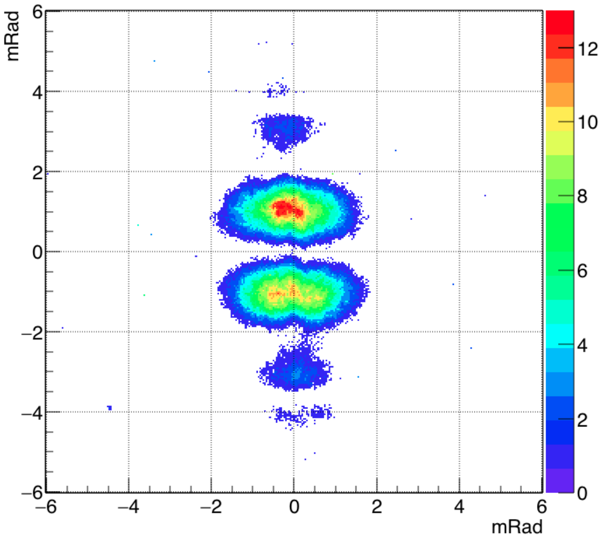




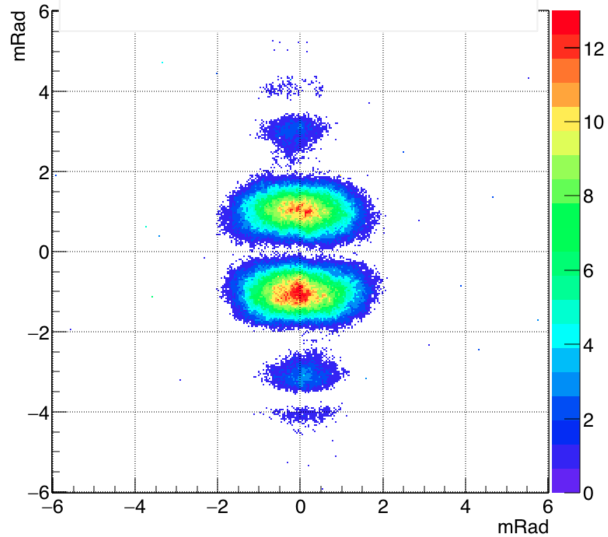
ODR Angular Distribution in ATF2

Filter:450nm Slit:105um Mask:202um Electron beam @ 1.3GeV ,1.2nC

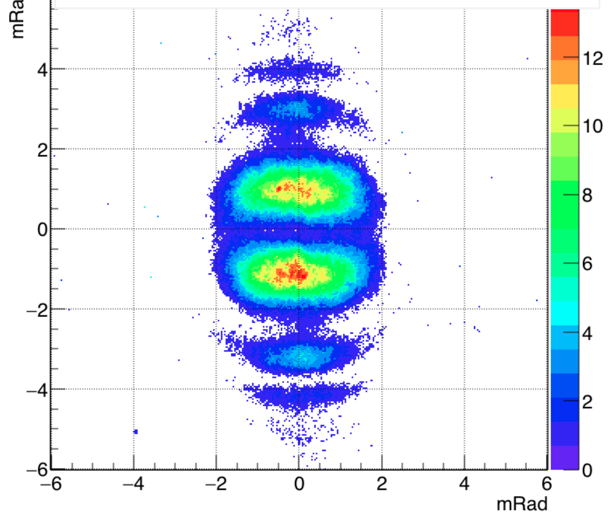
Beam 1um (100images)



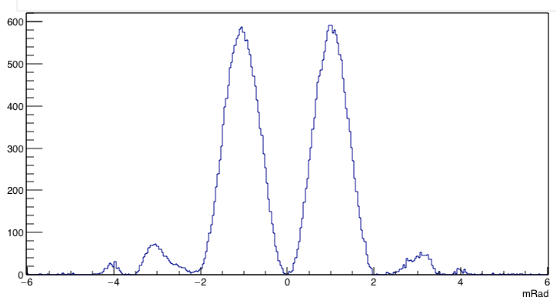
Beam 18um (100images)



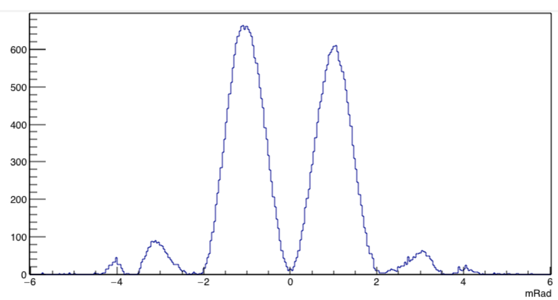
Beam 30um (100images)



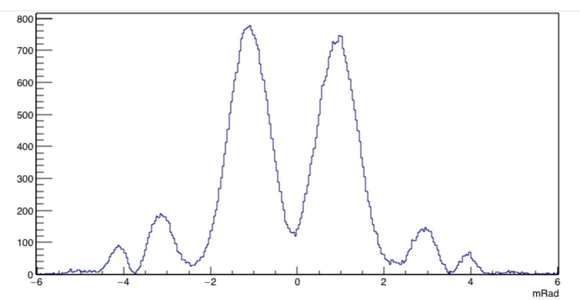
Beam 1um



Beam 18um



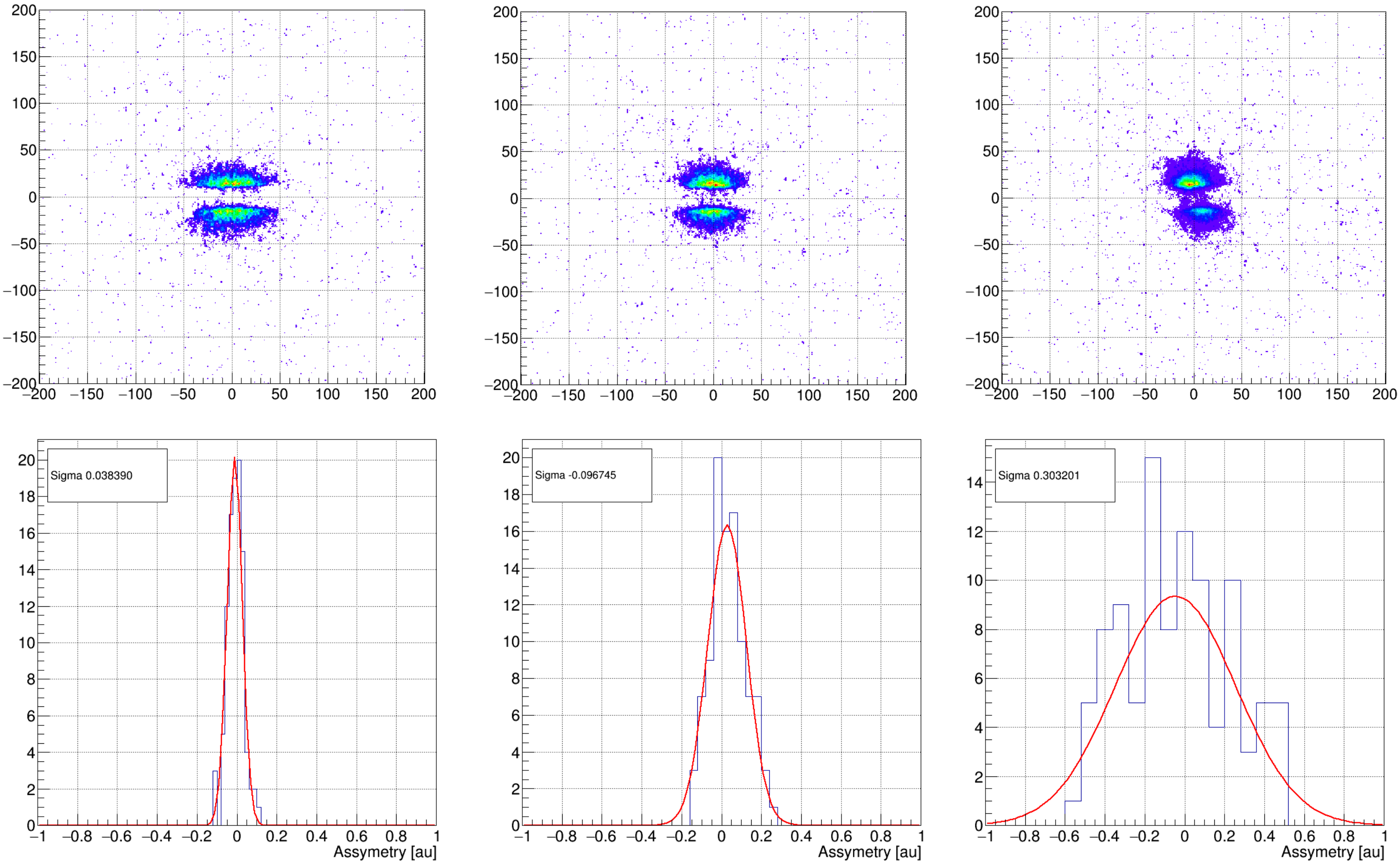
Beam 30um



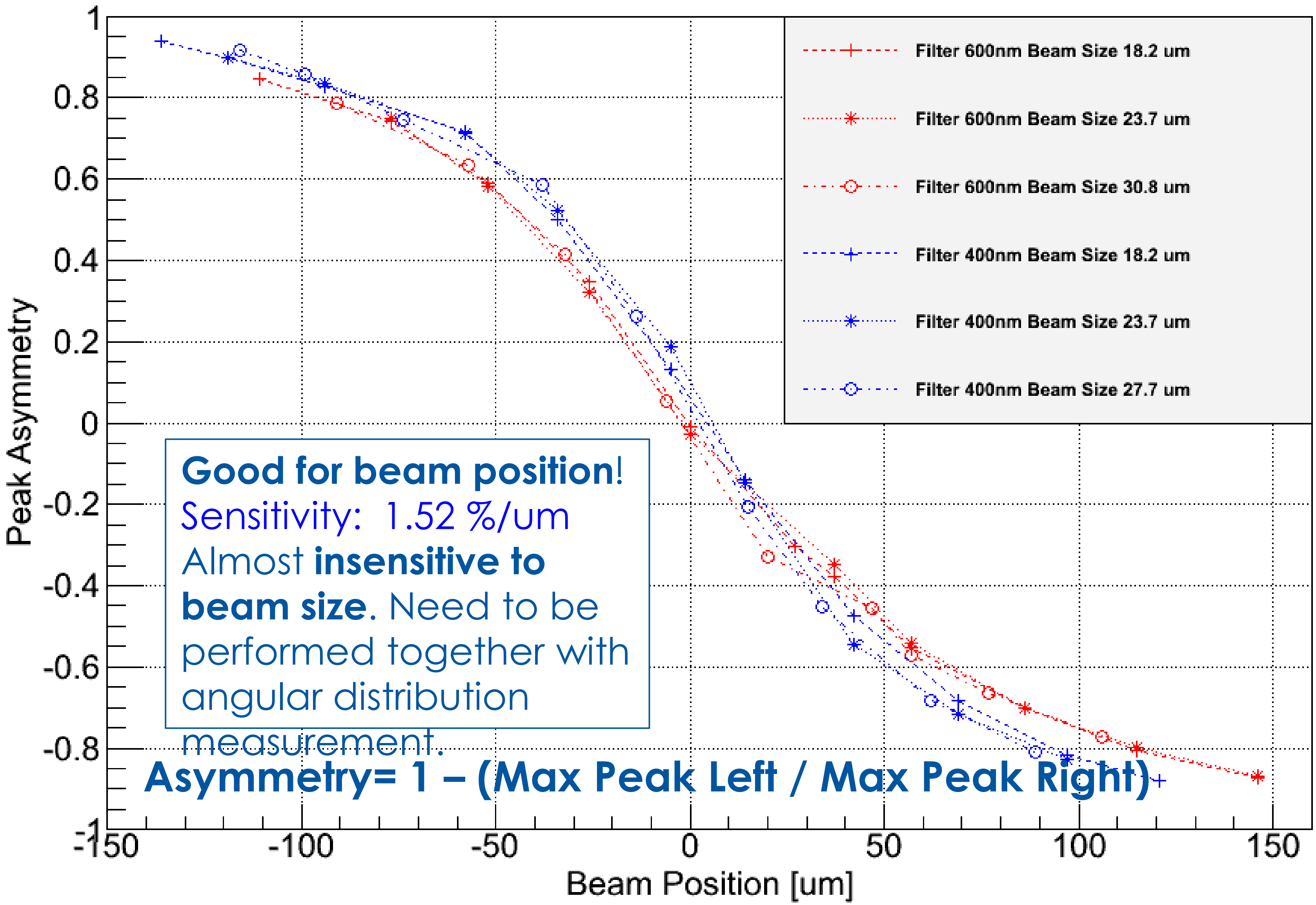
Jitter for different beam sizes

Filter:450nm Slit:220um NoMask

Vertical Beam Size **1um** | Vertical Beam Size **18um** | Vertical Beam Size **30um**



Imaging ODR profile Asymmetry after global BPM offset adjustment

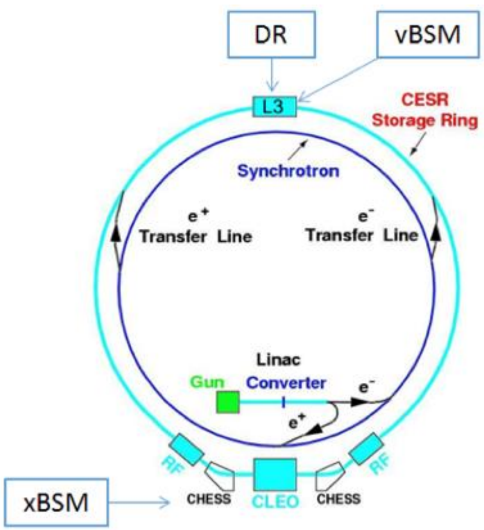


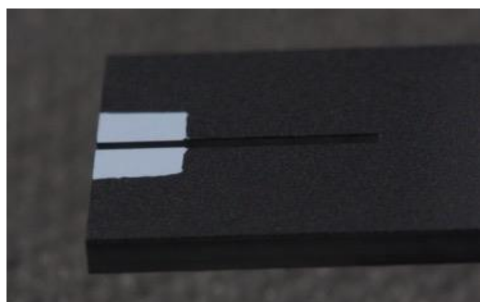
Good for beam position!
Sensitivity: 1.52 %/um
Almost **insensitive to beam size**. Need to be performed together with angular distribution measurement.

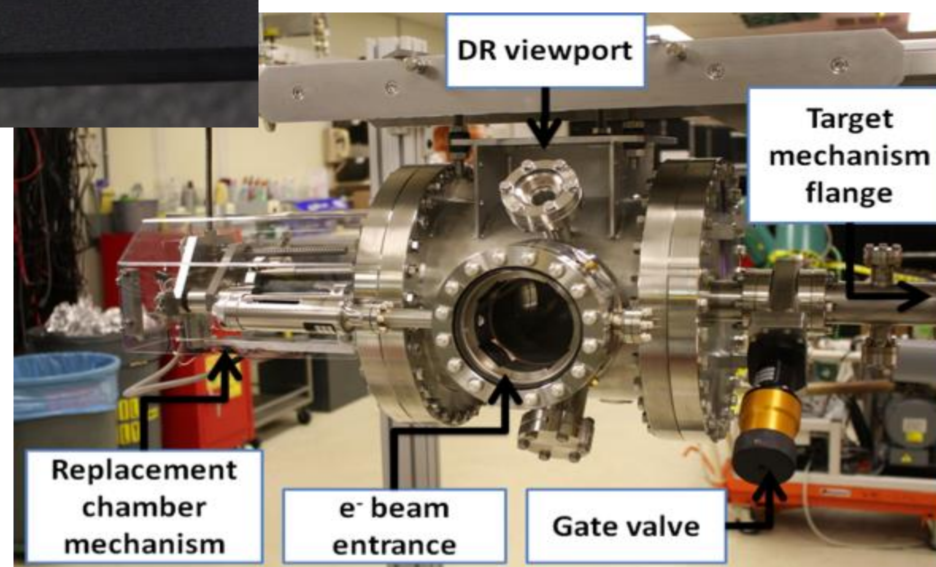
Asymmetry= 1 – (Max Peak Left / Max Peak Right)

Test at Cornell Electron Storage Ring

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







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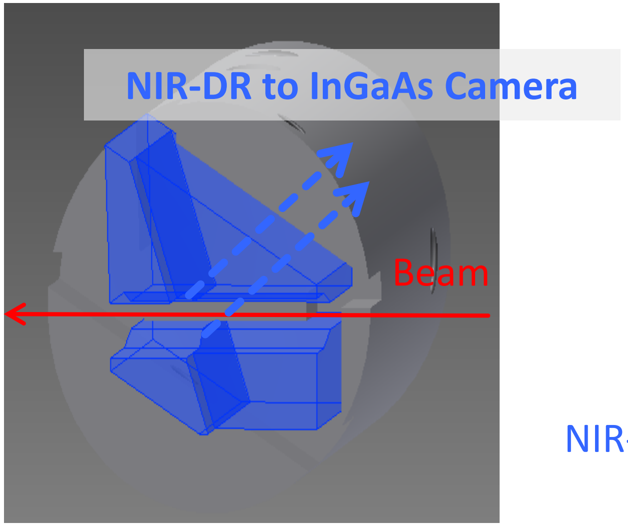
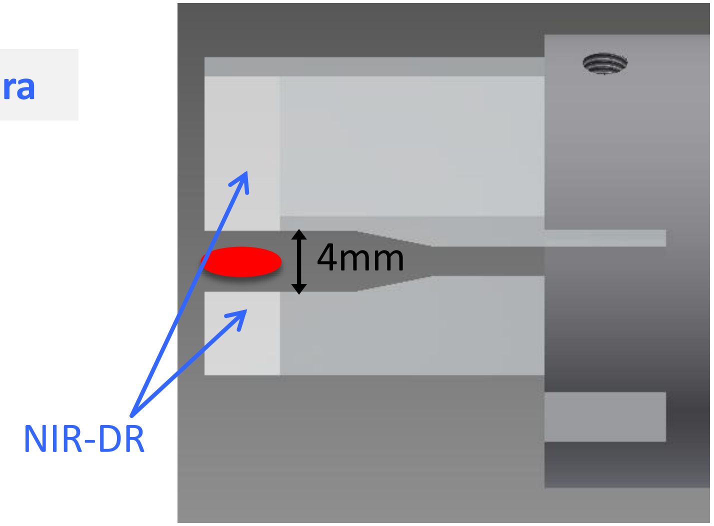
Test at Cornell Electron Storage Ring

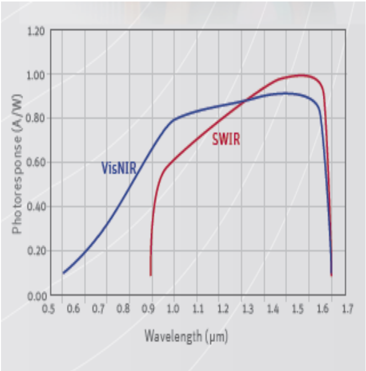
- Design a 1cm long SiO_2 Diffraction and Cherenkov Diffraction target in IR (0.9-1.7um)
  - **4mm 20° angle tilted DR slit for imaging purpose to help centering the beam in the slit**





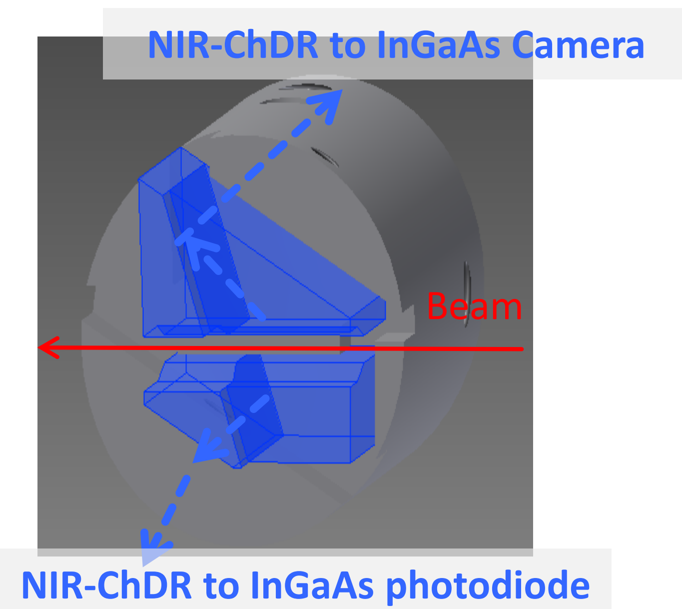
Xenics Bobcat 640 GigE

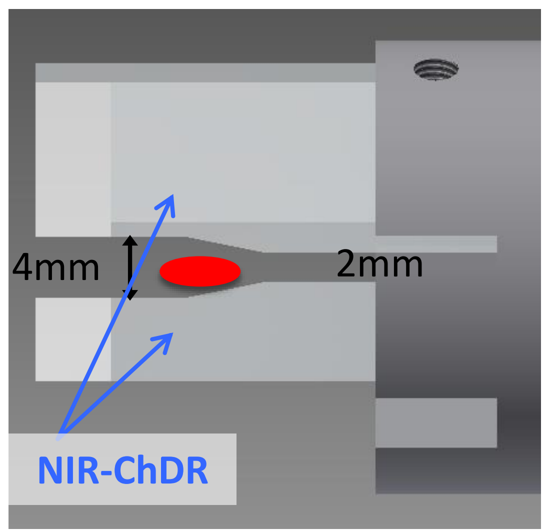
- Cooled InGaAs 640x512 pixels : 20um pixel pitch
- QE up to 80% at 1.6um
- 14bit ADC
- 1us-40ms integration window



Test at Cornell Electron Storage Ring

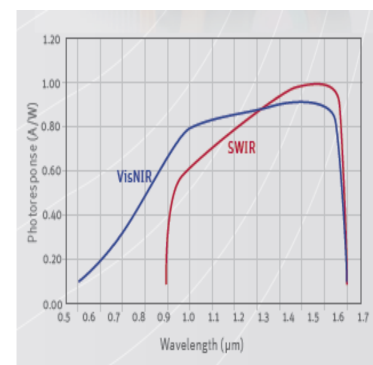
- Design a 1cm long SiO_2 Diffraction and Cherenkov Diffraction target in IR (0.9-1.7um)
  - 4mm 20° angle tilted DR slit for imaging purpose to help centering the beam in the slit
  - **4mm and 2mm aperture Cherenkov diffraction radiation slit target**





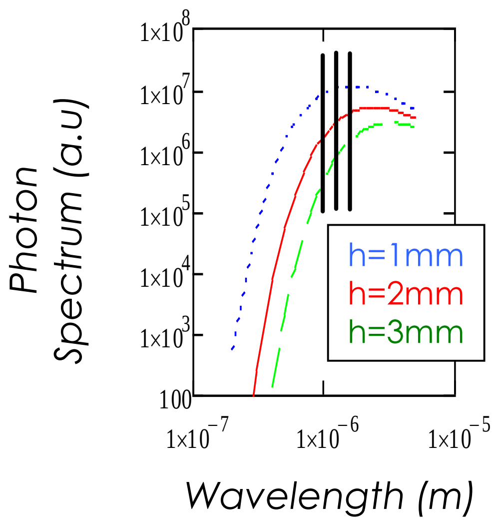
Xenics Bobcat 640 GigE

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



Test at Cornell Electron Storage Ring

- **Measure the Cherenkov DR photon spectrum and intensity** as function of beam position (Dec2016)
  - 1000nm, 40nm and 10nm bandwidth
  - 1300nm, 10nm bandwidth
  - 1550nm, 10nm Bandwidth



- **Test with positron and check the light directivity**

- **Measure any possible effects on the beam**
  - CESR lifetime is around 30minutes (limited by Touschek scattering)
  - Typical SR damping time of 50ms and emittance 20pm (vert) and 3nm (hor)
    - To be compared with 2 minutes damping time for 2mm slit aperture 1cm long radiator