Cherenkov Diffraction Radiation from long dielectric materials: An Intense Source of Photons in the NIR-THz ?

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L. Bobb, Diamond light source

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 ?

- On-going Experimental tests
  - At Cornell Electron Storage Ring (CESR)
  - At CERN-CLIC Test Facility 3 on CALIFES beam line

Incoherent Diffraction Radiation

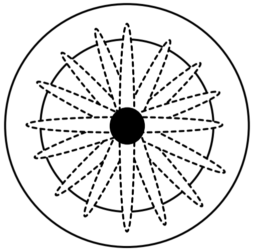
- Studying non-interceptive beam diagnostic using Diffraction Radiation for Linear Collider
  - ODR as transverse beam size monitor at CESR (Synchrotron ring - 2GeV e^-) and ATF2@KEK (extraction line- 1.2GeV e^-)
  - See previous Talk from R. Kieffer on 'OTR/ODR studies at ATF2'

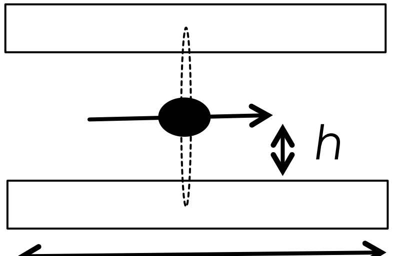
- From incoherent DR to incoherent Cherenkov DR
  - Investigation for possible use of such radiation processes for high energy hadrons and rings
  - Looking for highest possible light yield intensity using longer dielectric material rather than slit.
    - For $\gamma >>1$, $N_{oTR} \approx N_{oChR}$ 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

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

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





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

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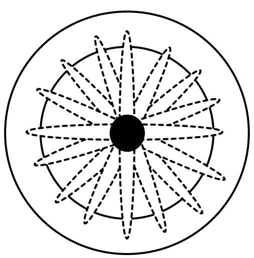

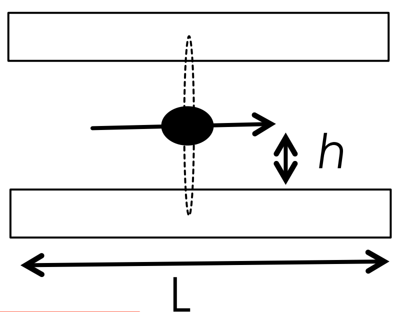

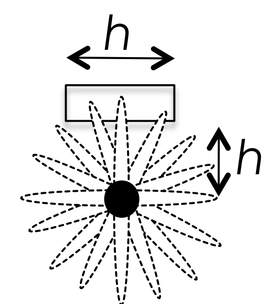

Additional reduction factor(x0.2) to take into account the smaller angular polarization field

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

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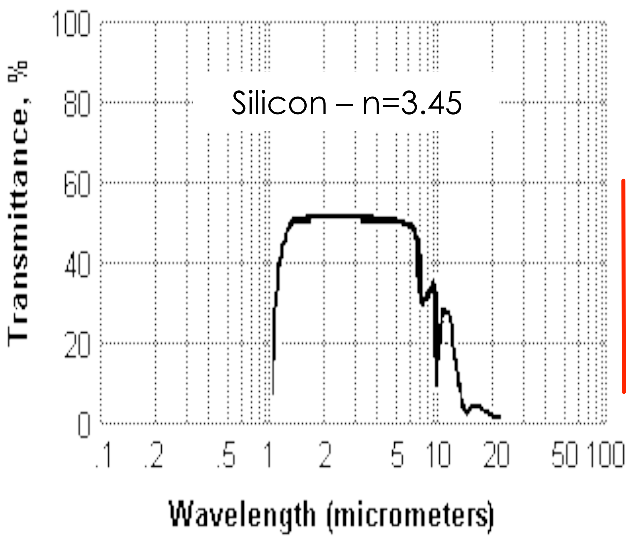
…Using beam parameters of LHC

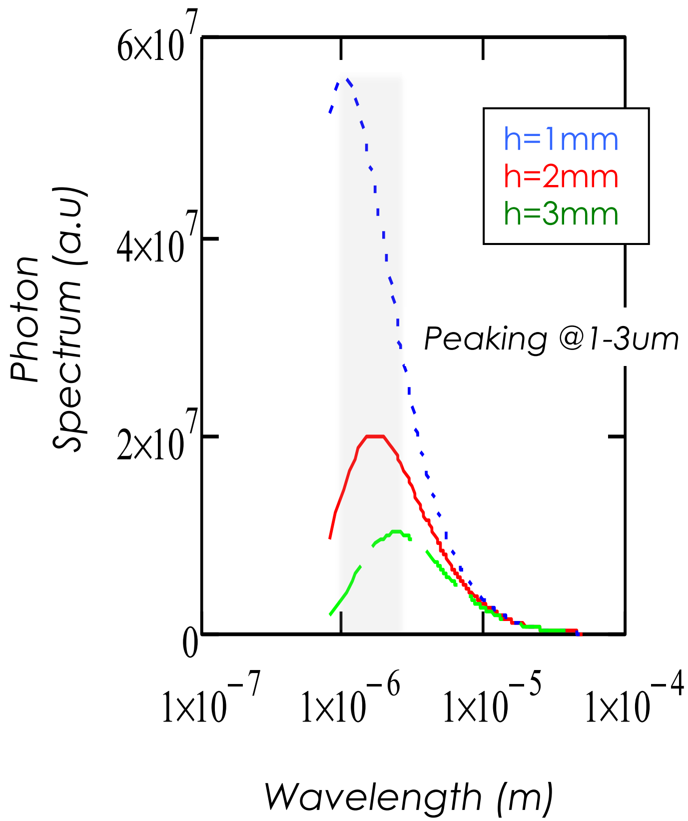
e.g. Cherenkov Diffraction Radiation

- 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



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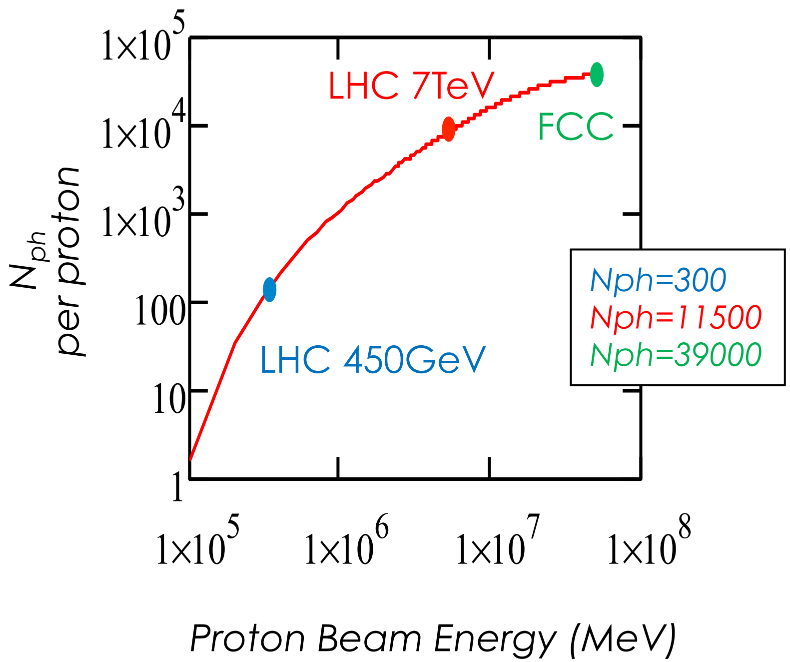
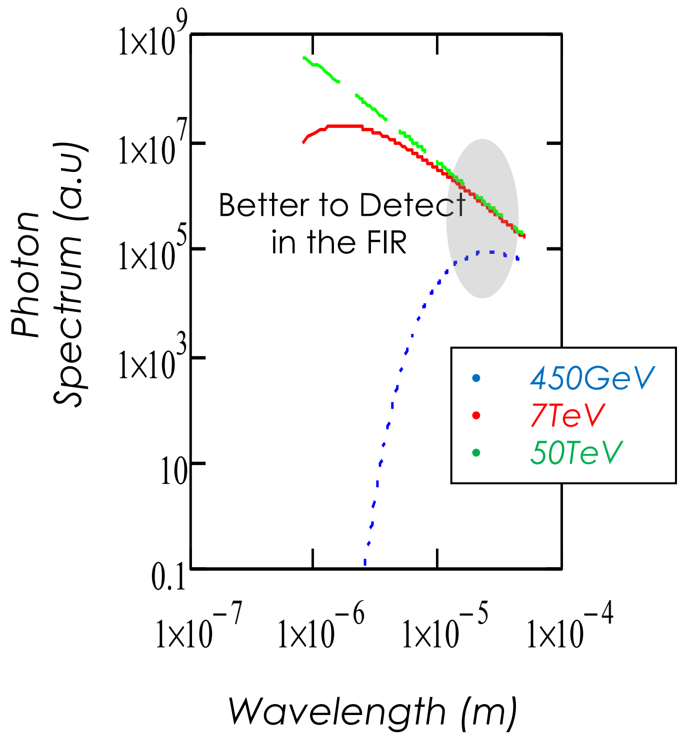
e.g. Cherenkov Diffraction Radiation

- 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

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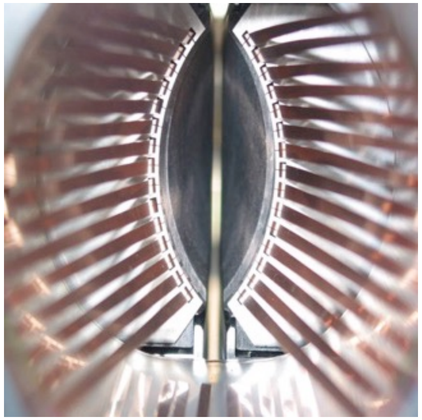
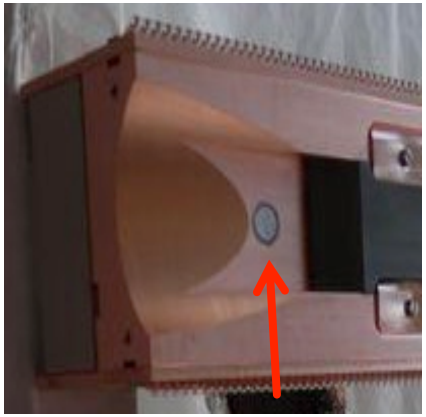
- LHC collimators are equipped with electrostatic BPM to allow their alignment with a resolution better than 10microns in10-20seconds at a distance of few mm from the beam



LHC collimator aperture (≈1mm) at 7TeV



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

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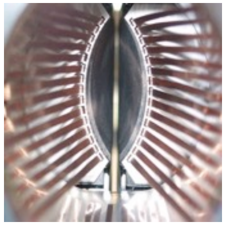
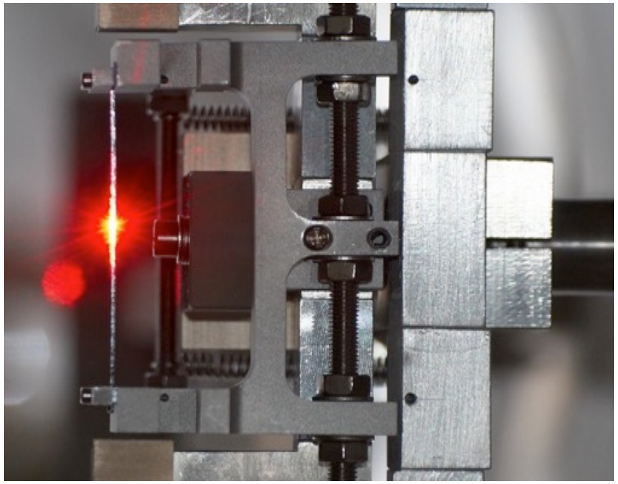
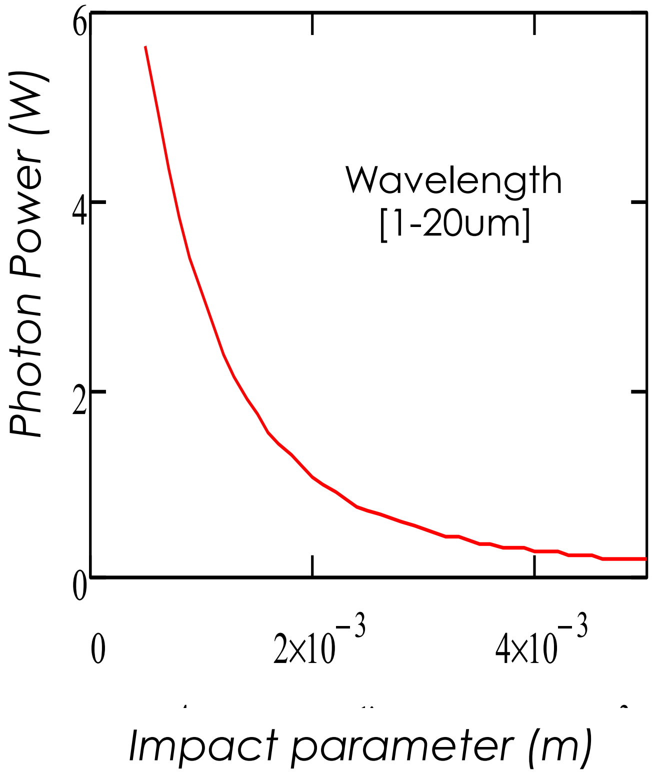


- Crystal collimators are now seriously considered as the future primary collimators in LHC and FCC
    - Investigating the use of Cherenkov Diffraction Radiation as way to measure the position of the crystal with respect to the beam



e.g. 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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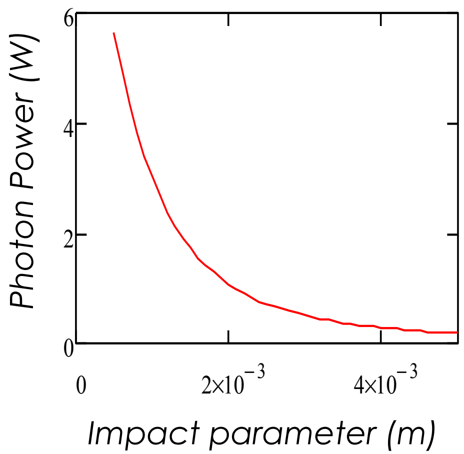
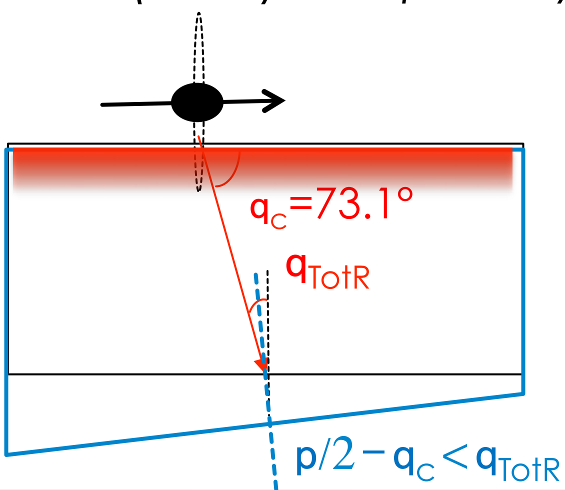


- *In current design (i.e. parallel crystal faces), a large fraction of the power would be totally reflected (16,9°) and possibly absorbed*

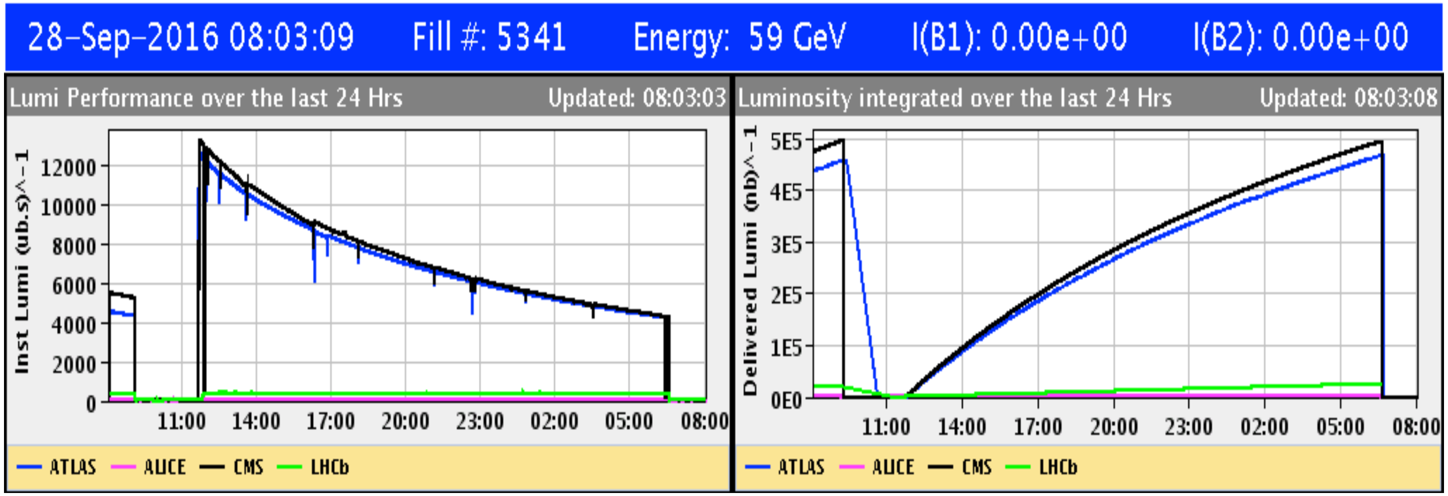


- *Crystal outer face built with different angle or with a high roughness to diffusive the light out*
- *Measuring infrared photons coupled in a optical fiber*

ChDR for Beam cooling ?

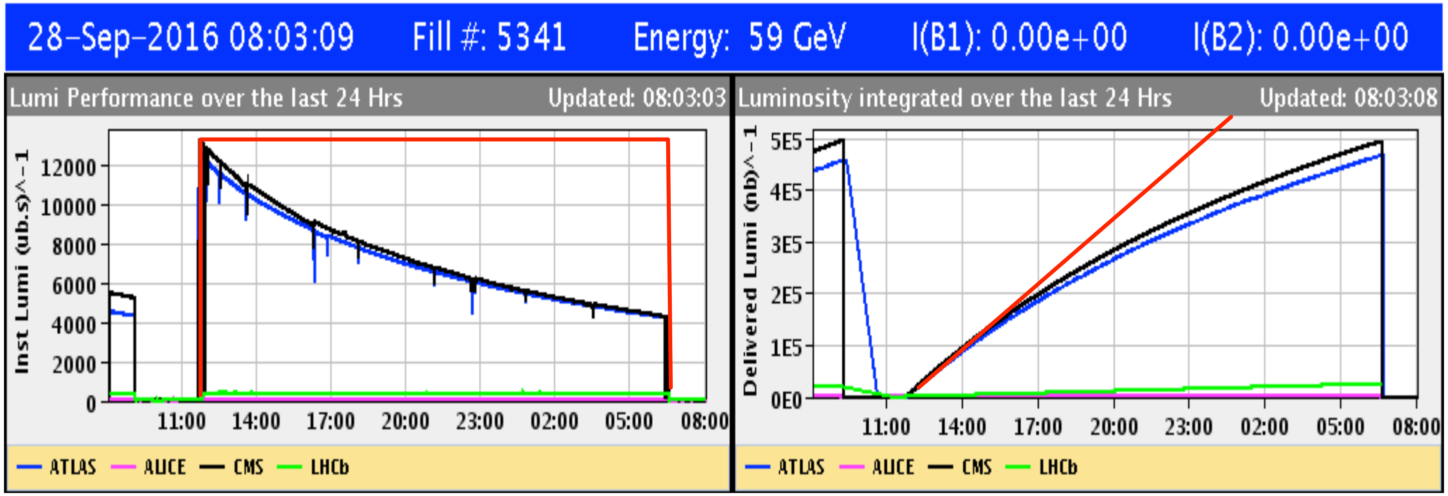
ChDR for Beam cooling ?

- 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



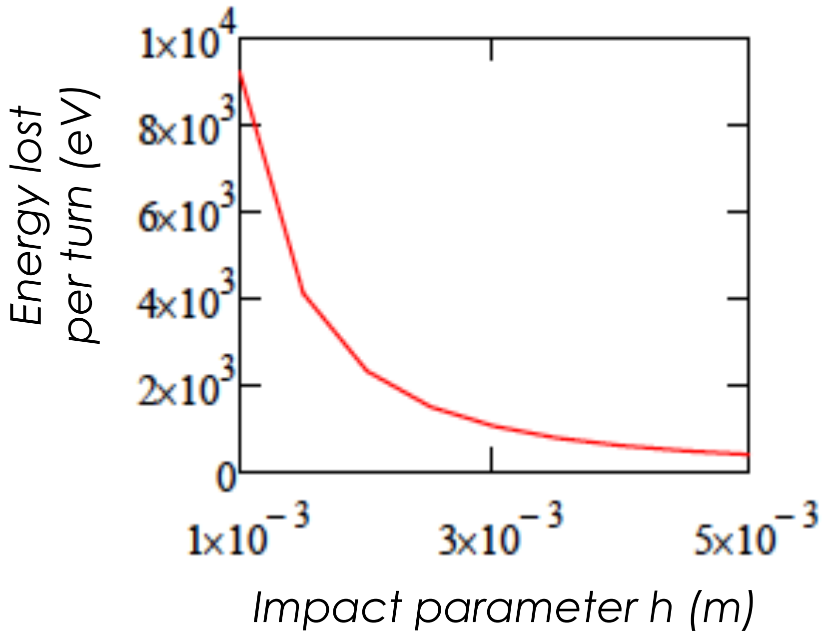
ChDR for Beam cooling ?

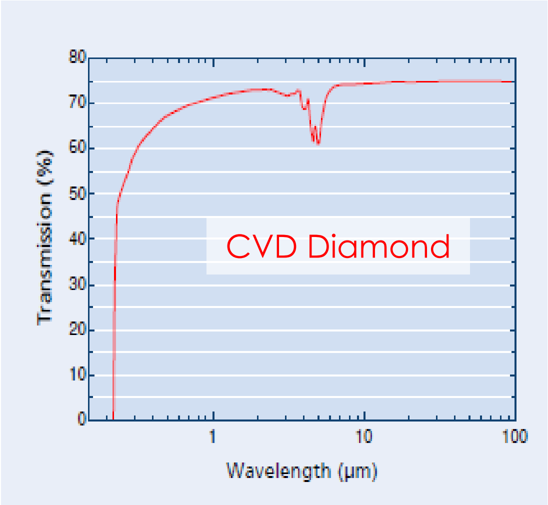
Cool the beam transversely in 4-5 hours to maintain the peak luminosity constant : Gain in integrated luminosity



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

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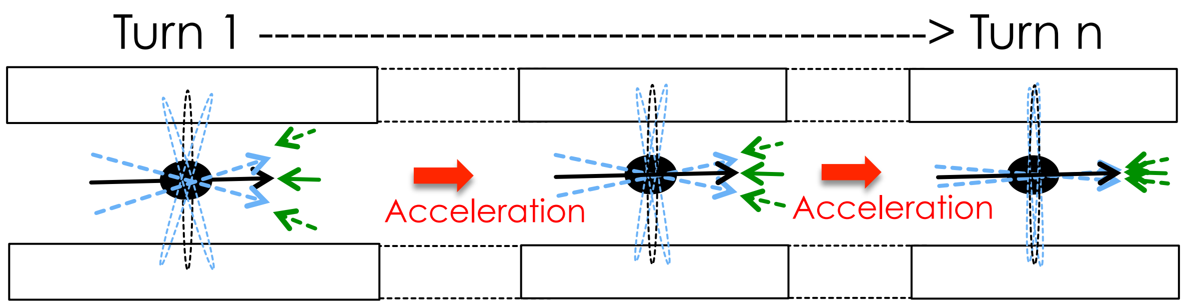
ChDR for Beam cooling ?

Radiating and Cooling

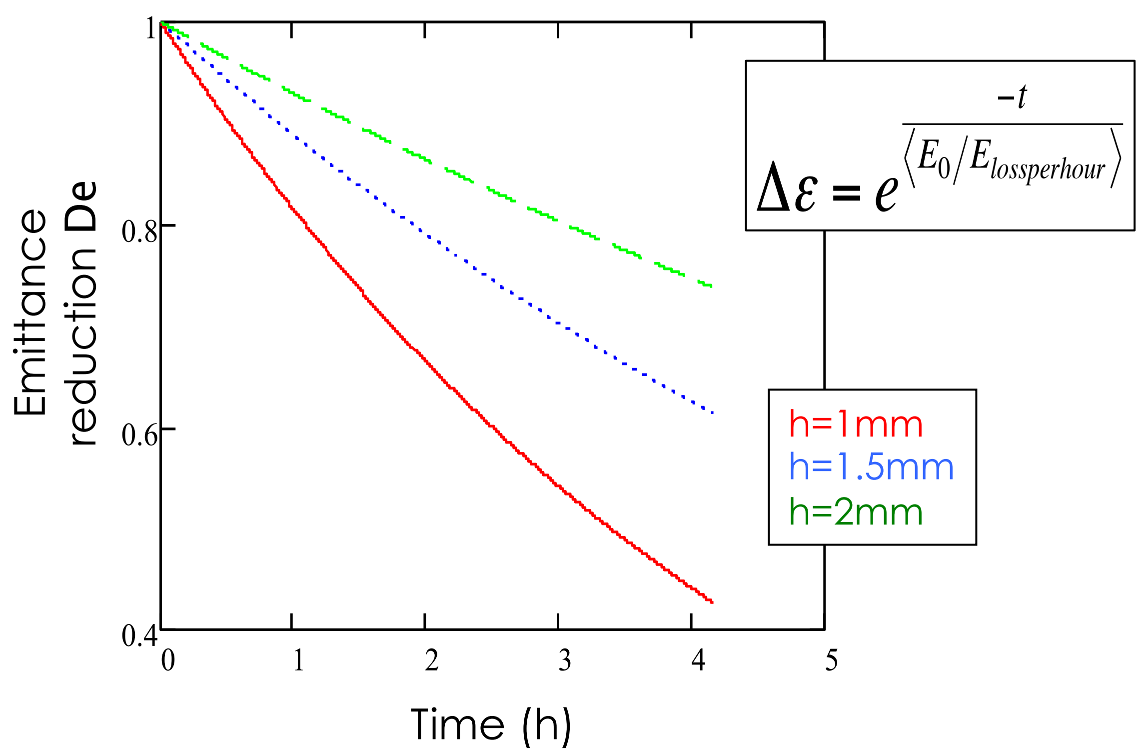


It requires that Particle recoils opposite to its direction of propagation

- 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 ?

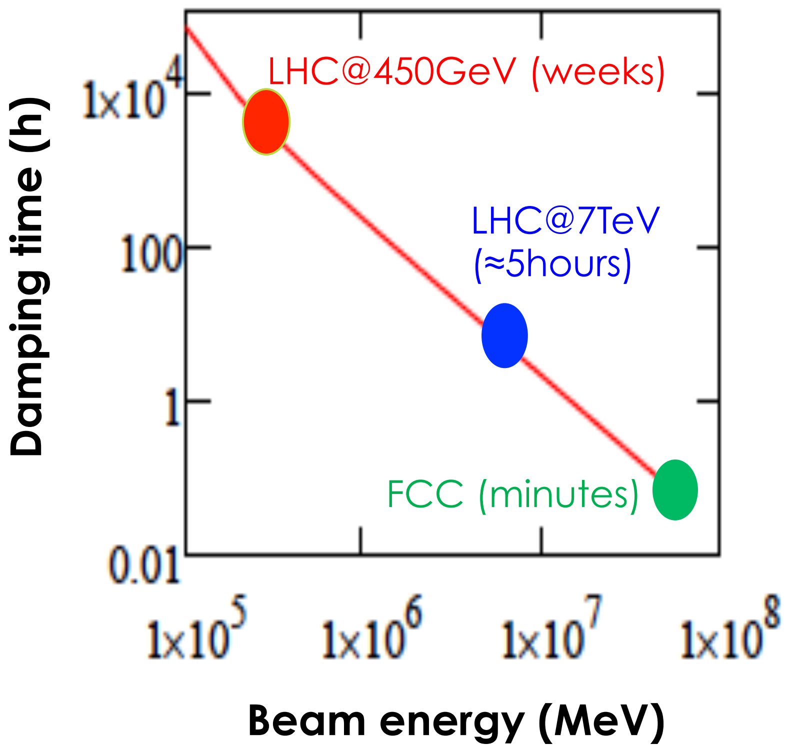
Time evolution of the LHC beam emittance at 7TeV for different impact parameter h



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 ?

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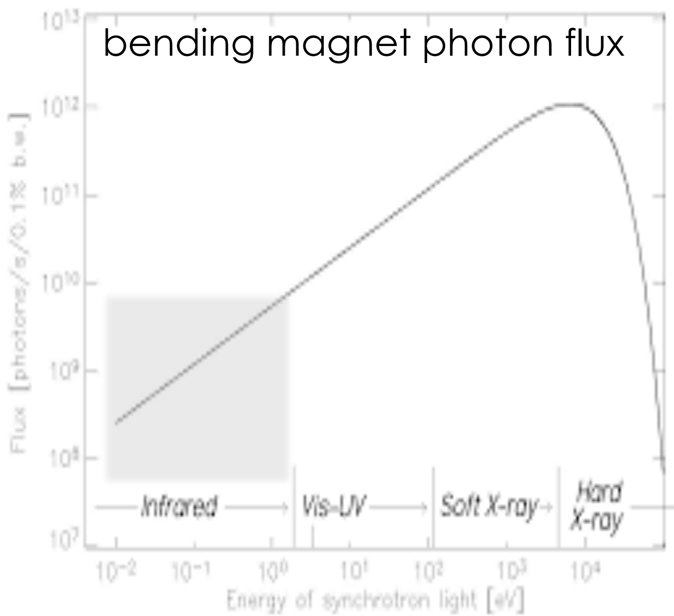
Beam energy	3 GeV
Beam current	200mA
Ring Circonference	220m



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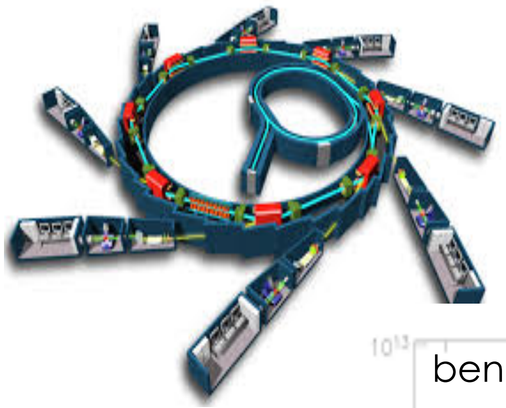

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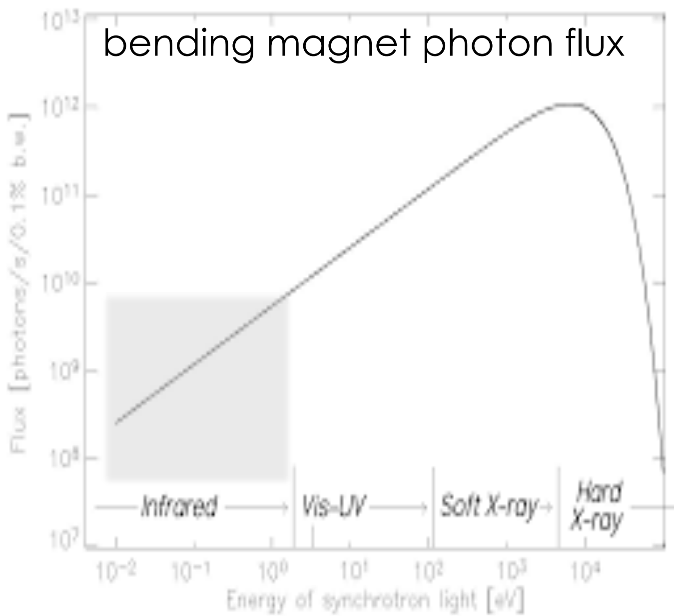
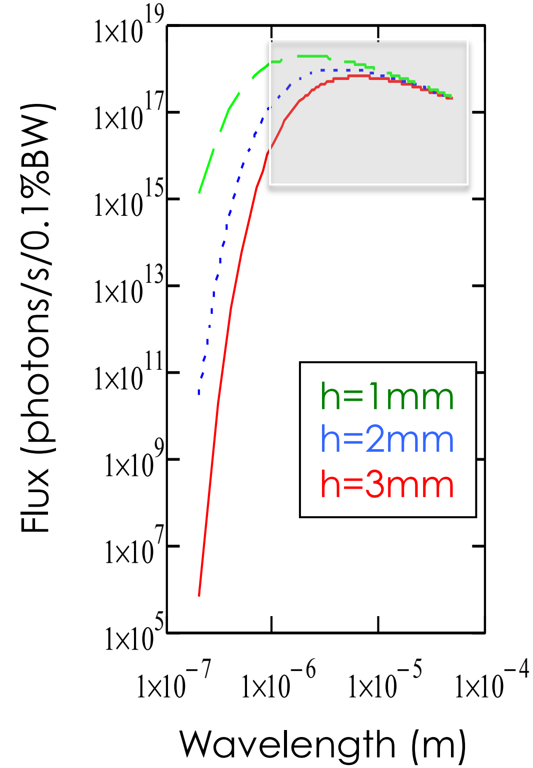


ChDR from a 1cm long diamond radiator



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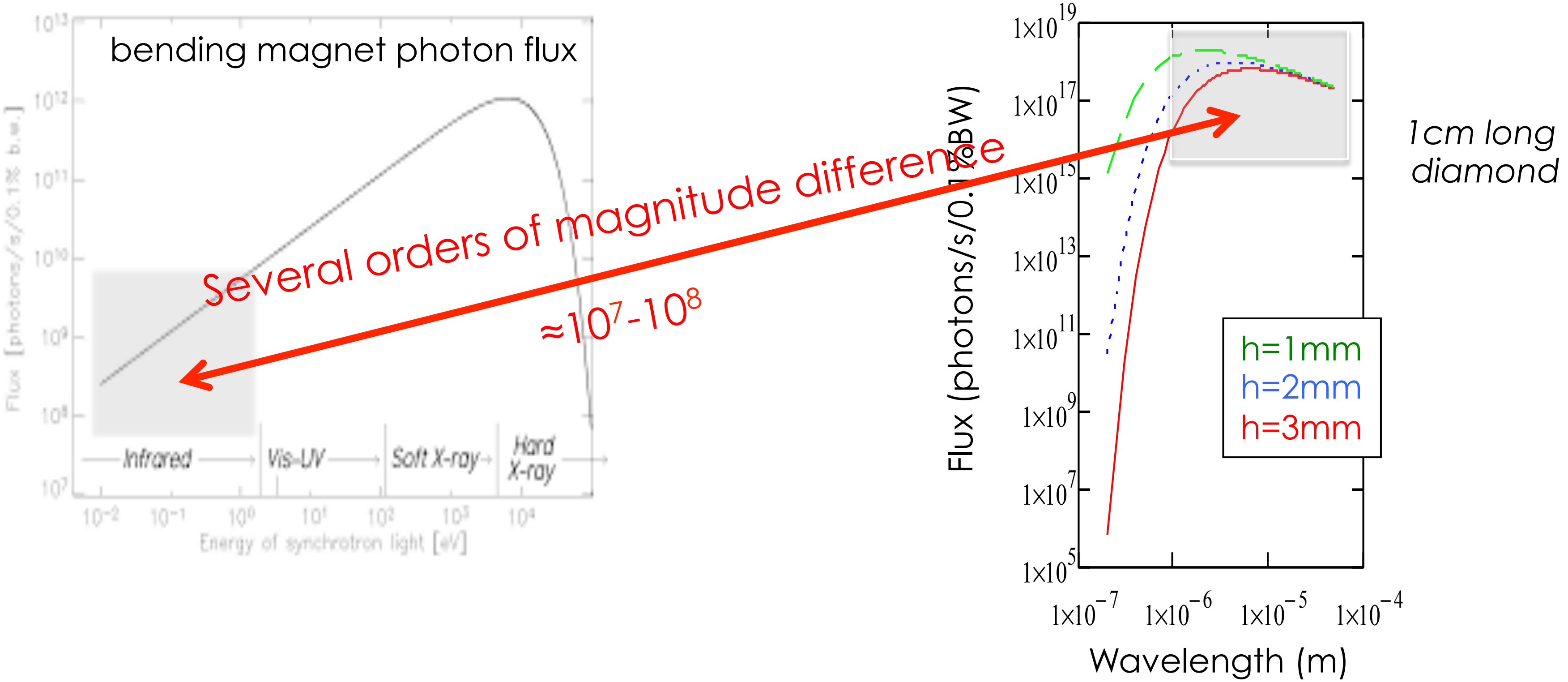
ChDR as source of Radiation ?

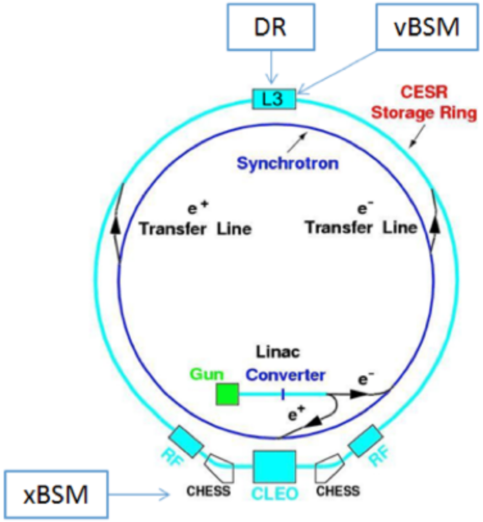


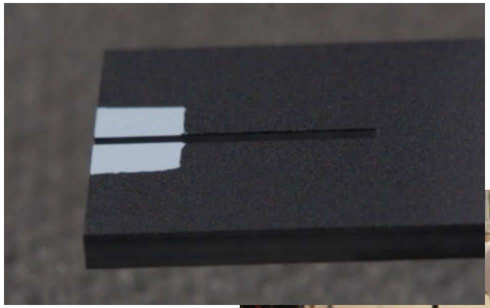
- Beware, this is the ChDR photon flux produced and not extracted (x10^{-3}) !
- If interested in longer wavelength *(FIR/THz) – use larger impact parameter*

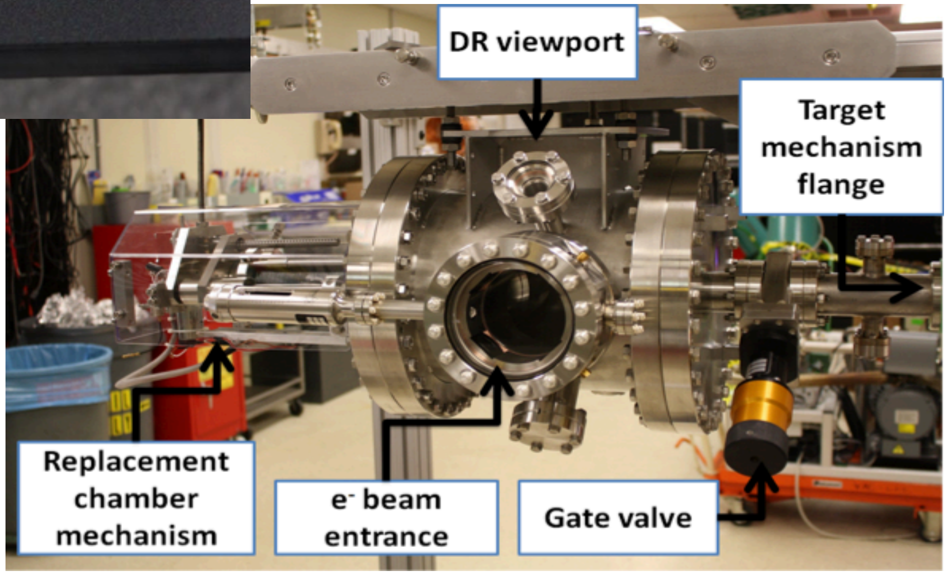
Experimental tests

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

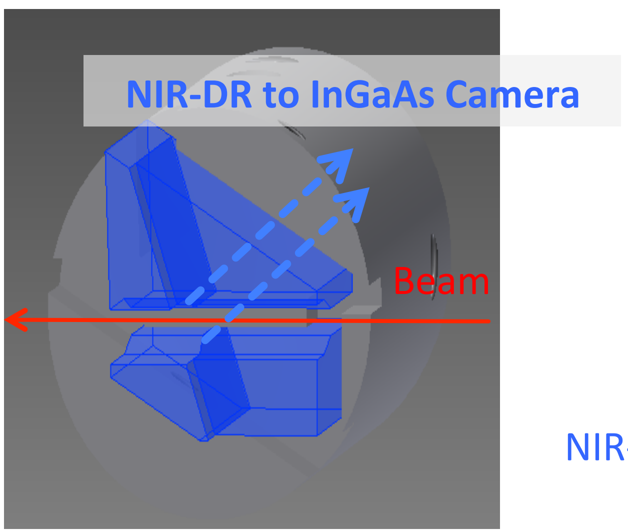


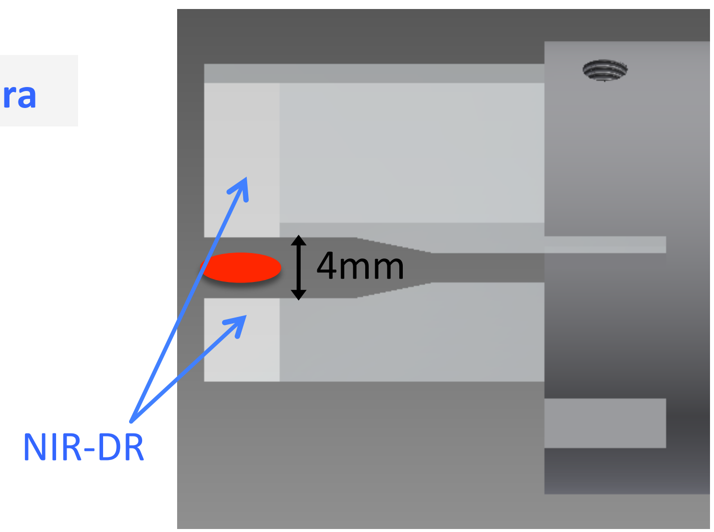




Test at Cornell Electron Storage Ring

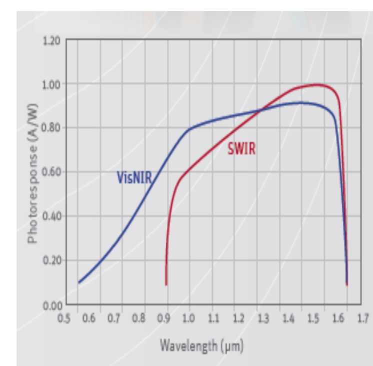
- Design a 1cm long SiO2 Diffraction and Cherenkov Diffraction target in IR (0.9-1.7um)
  - **4mm 20° angle tilted DR slit for imaging purpose to help centering the beam in the slit**





Xenics Bobcat 640 GigE

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



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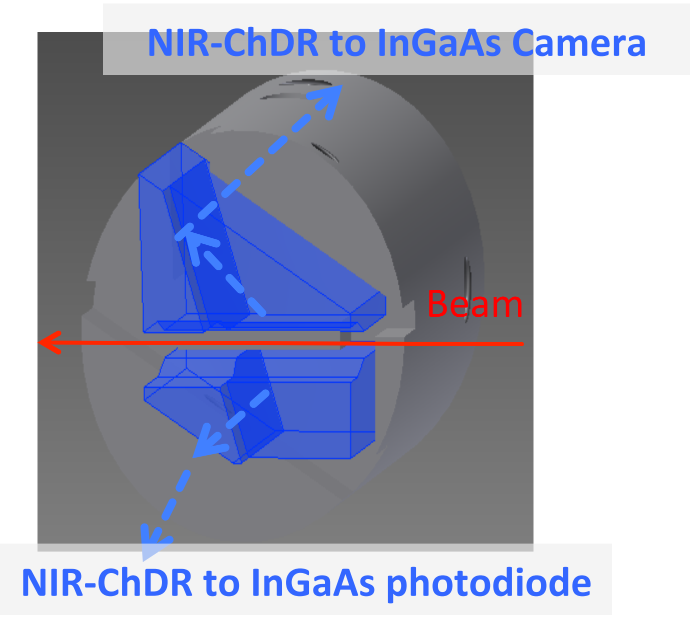
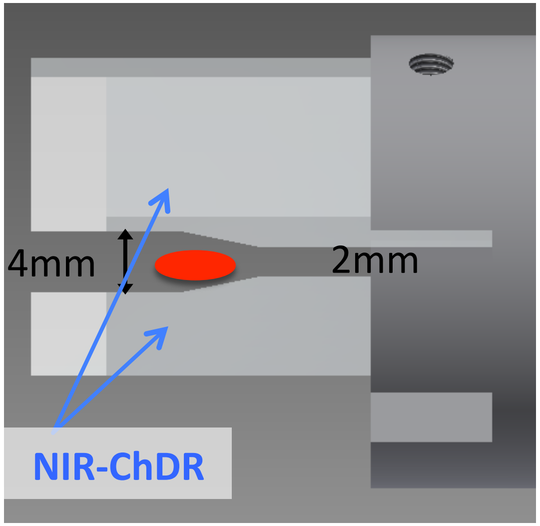
  - 4mm 20° angle tilted DR slit for imaging purpose to help centering the beam in the slit
  - **4mm and 2mm aperture Cherenkov diffraction radiation slit target**





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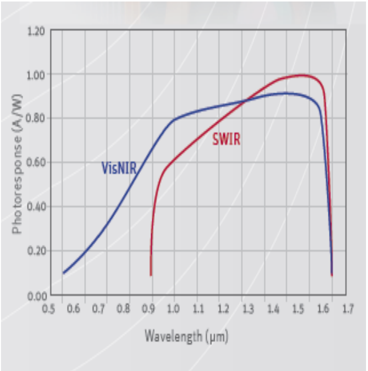
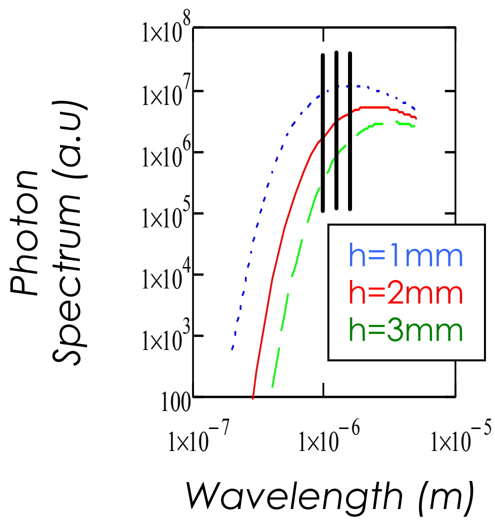


Test at Cornell Electron Storage Ring

- **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

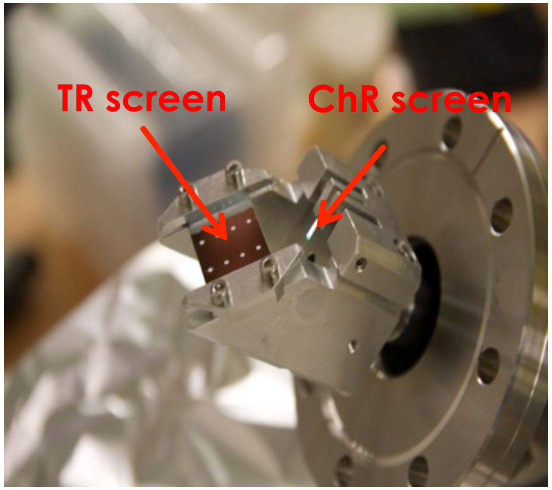


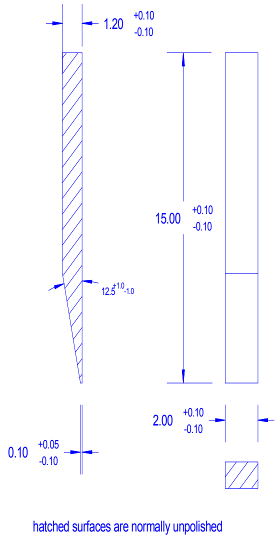
- **Test with positron and check the light directivity**

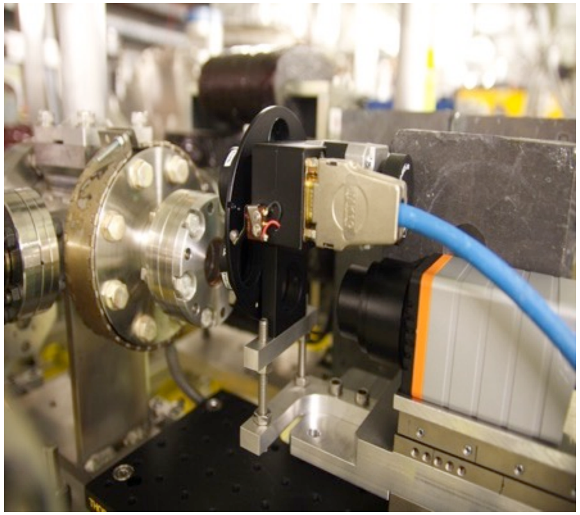
- **Measure any possible effects on the beam**
  - CESR lifetime is around 30minutes (limited by Touschek scattering)
  - Typical SR damping time of 50ms and emittance 20pm (vert) and 3nm (hor)
    - To be compared with 2 minutes damping time for 2mm slit aperture 1cm long radiator

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







Conclusions

- Possible applications of Incoherent Cherenkov Diffraction Radiation for Beam diagnostic, Beam cooling or as Source of radiation are under investigation
- Several beam tests (including tests of crystal collimator) have been prepared and will investigate the properties of the emitted photons
- Optimisation of the crystal geometry should be studied
  - How thick can the radiator be ? Microns to mm thicknesses ?
  - Best shape/configuration for light extraction ?
- Beam dynamic involved in ChDR should be studied and understood
  - How does particle recoil in a given geometry ?
  - Is beam cooling via ChDR possible ?
    - What would be the equilibrium emittance in both planes ?
    - Does the beam halo cool faster ?

Thanks