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

T. Lefevre, LER 2018, CERN
Measuring the beam size from the visibility $I_{\text{min}}/I_{\text{max}}$ 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).
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 $\rightarrow$ 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 (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**

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

- $\alpha$, fine structure constant
- $\beta$, normalised beam velocity
- $\gamma$, beam relativistic factor
- $\theta$, angle of observation

T. Lefevre, LER 2018, CERN
Experimental set-up on CESR (1/3)

- Re-using the DR vacuum chamber and optical system

T. Lefevre, LER 2018, CERN
Design a 2cm long SiO2 (n=1.46) Cherenkov Diffraction Radiation target

- Testing with 2.1GeV e⁻ and measuring in IR (0.9-1.7μm) – April 2017

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

“The red curve as been scaled down by 1/3 for better presentation”
Design a 2cm long SiO2 (n=1.46) Cherenkov Diffraction Radiation target

- Testing with 5.3GeV e⁻ / e⁺ and measuring in visible (0.3-0.7um) – October 2017
Two different geometries have been tested

- **Prismatic radiator**

  - Cherenkov target for polarization studies

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

  - Sand-blasted surface (diffusivity of 20°)
  - Optical detection system at 40°
Cherenkov radiators (2/2)

- Pictures of the radiators

- Depolished & Coated
- Depolished Area - no coating
- Polished & Coated

T. Lefevre, LER 2018, CERN
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 5.3 GeV

Angular distributions with Prismatic radiator: Comparison with simulations

Horizontal polarization

Vertical polarization

Measurements

Simulations

T. Lefevre, LER 2018, CERN
Experimental data: Electron at 2.1 GeV

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

‘Cherenkov photons yield increasing strongly for smaller impact parameter’
Steering the beam vertically: comparison with simulations

No wavelength filter – No polarizer

Light integral (arb. units) vs. Impact parameter (μm)
Experimental data: Positron at 5.3GeV

Measuring the horizontal Beam size:

- **Horizonal polarization**
- **Vertical polarization**

‘Vertically polarized photons give the best spatial resolution ($\sigma_y=2$mm)’

T. Lefevre, LER 2018, CERN
Experimental data: Positron at 5.3 GeV

Rotating the target:

- Target angle, $\alpha$

ChDR @600 ±10nm; $h_{\text{mean}} = 1.5\text{mm}$

- $\alpha = 4.28\deg (74\text{mrad})$
- $\alpha = 0.98\deg (17\text{mrad})$

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

T. Lefevre,LER 2018, CERN
Experimental data: Measuring counter-propagating beams

- Measuring counter-propagating beams using the prismatic target
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

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
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.

T. Lefevre, LER 2018, CERN
Perspectives for beam instrumentation

- Imaging system for relativistic beam
  - What is 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 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

T. Lefevre, LER 2018, CERN
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

Diamond

T. Lefevre, LER 2018, CERN
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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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

[Diagram showing Positron Beam, Cherenkov Diffraction Radiation]
Experimental data: Positron at 5.3 GeV

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

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 2.1 GeV

- 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 lose the highly directional ChDR emission.
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

End of 2017 two ChDR experiments foreseen, in the infrared range:
  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.

**Goal:** Comparison between OTR, Cherenkov, and ChDR light emission.

**Already tested cameras on that setup:**
- **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)*

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

Installation on going in CALIFES
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
- $\beta$ is the relative particle velocity

$\theta_c$ is the Cherenkov light emission angle

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

- $d$ the length of the Cherenkov radiator

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

$$N_{ph} = 2 \times d \times \frac{1}{a} \div \frac{1}{b} \div \frac{1}{(n)^{\frac{1}{2}}}$$

- Almost no dependency on beam energy
Emitted (measurable) power spectrum depends on the material transparency \( (Tr(\lambda)) \).
...Using beam parameters of LHC
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 10 microns in 10-20 seconds at a distance of few mm from the beam.

LHC collimator aperture (≈1mm) at 7 TeV

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 10 microns in 10-20 seconds 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

\[
dP = 2 \cdot \frac{L \cdot Tr(\cdot) \cdot e^{-\frac{4 \cdot \hbar}{\lambda} \left(\frac{1}{n^2}\right)}}{d^2}
\]

\[
\text{Silicon – } n=3.45
\]

Photon spectrum only calculated over the transmission bandwidth of corresponding material
Number of ChDR photons and ChDR power spectrum as function of beam Energy (LHC-FCC)

- 1m Si crystal and impact parameter $h = 2$mm

Proton Beam Energy (MeV) vs. $N_{ph}$ per proton for LHC 450GeV, LHC 7TeV, and FCC. The $N_{ph}$ values are $300$, $11500$, and $39000$ respectively.

Better to Detect in the FIR

Photon Spectrum (a.u.) vs. Wavelength (m) for $450$GeV, 7TeV, and 50TeV proton beams.
e.g. Positioning of Crystal collimator in LHC or FCC

- 3mm long Silicon Crystal and 7TeV protons
- Emitted Photon power for $h=1\text{mm}$ (typical for primary collimators) $\approx 5\text{watts for full LHC beam}$
  
  2808 nominal bunches (1.1E11 protons)
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 Beam cooling?
ChDR for Beam cooling?

- During normal operation, LHC luminosity drops over a fill due to beam losses.
- Synchrotron Radiation cooling time is 21 hours.
  - Particle energy lost by SR is approximately 7 keV per turn (80 MeV.s⁻¹) with a critical energy at 42 eV.
  - 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.
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

Turn 1 ----------------------------- > Turn n

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 equilibrium 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 $h$

\[ \Delta \varepsilon = e^{-\frac{t}{E_0/E_{\text{loss per hour}}}} \]

- $h=1\text{mm}$
- $h=1.5\text{mm}$
- $h=2\text{mm}$

Assuming 10x 1m long Diamond radiators
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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bending magnet photon flux
ChDR as source of Radiation?

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**bending magnet photon flux**

**ChDR from a 1cm long diamond radiator**

- **Beam energy**: 3 GeV
- **Beam current**: 200mA
- **Ring Circonference**: 220m
- **Wavelength (m)**
- **Flux (photons/s/0.1%BW)**
  - **h=1mm**
  - **h=2mm**
  - **h=3mm**

**h=1mm**

**h=2mm**

**h=3mm**

**Flux (photons/s/0.1%BW)**

**Wavelength (m)**
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
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
ODRI at ATF2

Direct Image of the ODRI

2D Angular distribution of the ODRI