Optical Cherenkov Diffraction Radiation as a Tool for Non-invasive Charged Particle Beam Diagnostics

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• Basic concept
• Advantages and Motivation
  – Theoretical expectation
• Experiment at Cornell CesrTA facility
  – Observation of Cherenkov Diffraction Radiation
  – Beam size
  – Beam direction
  – Electron-positron beam collision control
• Experiment at KEK-ATF2 extraction line
  – Beam size measurements
• Conclusion
  – Main achievements
  – Future plans and prospects
• Cherenkov radiation was discovered in 1958 by Pavel Cherenkov;
• It appears when a fast charged particle moves in a medium with velocity higher than the speed of light.

The angle $\theta$ is defined by a simple relation

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

where $\beta$ is the speed of charged particle in units of the speed of light and $n$ is the refractive index.
Basic Concept – Cherenkov Diffraction Radiation

- To generate Cherenkov radiation the particle does not have to move through the material;
- In relativistic case the charged particle field can reach macroscopic dimensions;
- Passing in the vicinity of a medium a fast charge particle will polarize the surface of it generating Cherenkov radiation;

However:
- The target does not surround the particle beam anymore. It introduces a new angular distribution, different from classical ChR;
- Dependence on impact parameter adds additional wavelength dependence.
Advantages and motivation

• Advantages:
  – Non-invasive way to generate;
  – High directivity enabling to separate the ChDR from co-propagating synchrotron radiation background;
  – High intensity, which can be adjusted by increasing the length of the radiator

• Motivation:
  – Development of diagnostics instrument:
    • Beam size, emittance, position, direction and arrival time.
• Polarization Current Approach (PCA) references:

Calculation parameters:
• $a = 18.5$ mm
• $\phi = 30^0$
• $E_e = 5.1$ GeV
• $\varepsilon(\lambda) = 2.1$
Theoretical expectations

- **Angular distribution:**
  - Vertical polarization component
  - Horizontal polarization component
• **Spectrum:**

![Graph showing spectrum and theoretical expectations.](image)

- $l = 600 \pm 10\text{nm}$
- $l = 400 \pm 10\text{nm}$

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*Imperial College London*

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Theoretical expectations

- Dependence on impact parameters:

\[
\text{Photon yield (ph/e) } \times 10^{-3}
\]

<table>
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<th>Impact parameter (mm)</th>
<th>Total</th>
<th>V - polarization</th>
<th>H - polarization</th>
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Experimental installation in Cornell Uni.

- **CesrTA: Cornell Electron/positron Storage Ring Test Accelerator**

  Both image and angular distribution can be measured

Experimental installation in Cornell Uni.

Two target geometries (fused silica)

• a) Prismatic radiator

\[ \text{SiO}_2 \quad (\epsilon(\omega), \sigma(\omega)) \]

\[ \text{ChDR} \quad 40^\circ \]

\[ 90^\circ \quad 29^\circ \quad 46^\circ \]

Positron \((\beta, \gamma)\) \rightarrow \rightarrow \rightarrow \rightarrow \rightarrow \rightarrow


• b) Flat radiator

\[ \text{Sand-blasted surface} \quad \text{(diffusivity of 20 degree)} \]

\[ \text{Optical detection system at 40°} \]

\[ \text{SiO}_2 \quad (\epsilon(\omega), \sigma(\omega)) \]

\[ \text{ChDR} \quad 46^\circ \]

Positron \((\beta, \gamma)\) \rightarrow \rightarrow \rightarrow \rightarrow \rightarrow \rightarrow

Two target geometries

• Positrons with energy of 5.3 GeV

(a) Cherenkov Diffraction Radiation

(b) Cherenkov Diffraction Radiation

Comparison between experiment and theory

- Angular distribution

**H – polarization**

**Experiment**

- **Theory**

• Dependence on impact parameter

Image of ChDR and Beam Size

- Positrons with energy of 5.3 GeV

• Positrons with energy of 5.3 GeV

\( r = 1.37 \text{ mm} \)
\( r = 1.32 \text{ mm} \)
\( r = 1.08 \text{ mm} \)
\( r = 0.9 \text{ mm} \)

Dependence on impact parameter


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Prismatic target

Optical detection system at 40°

Electrons

Positrons

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Beam size changes from sub-micron to hundreds of micron dimensions
Experimental installation at KEK-ATF2
Experimental installation at KEK-ATF2
OTR reference beam size measurement

Profiles

Image - noise pedestal with negative to 0

Horizontal rms is: 30.08±0.93 um

Vertical rms is: 67.22±1.36 um
Experimental results at KEK-ATF2

Optical ChDR beam size measurement

Vertical beam profile

ChDR image

Vertical rms: 63.49 μm
Main Achievements

- Directly observed ChDR from a fused silica target;
- Good consistency with theory:
  - Angular distribution
  - Dependence on impact parameter
- Sensitivity to the beam parameters
  - Beam direction in two dimensions
  - Beam position
  - Beam size down to 65µm, actual resolution?
  - Beam divergence, emittance, arrival time are yet to be measured
Conclusion

• Plans and Prospects:
  – Develop theory for a Line Spread Function;
  – Observe the LSF in KEK-ATF2:
    • Determine actual resolution
    • Emittance diagnostics
  – Detailed studies of Coherent ChDR
    • Bunch length diagnostics
    • THz radiation generation
  – Develop simulation technology
    • CST Studio Suite; V-SIM; ZEMAX
  – Optimize radiator geometry for a given application