First Observation of Quasi-Monochromatic Optical Cherenkov Radiation in a Dispersive Medium (Quartz)

A. Potylitsyn[1], G. Kube[1], A. Novokshonov[1], A. Vukolov, S. Gogolev, B. Alexeev, P. Klag[2], W. Lauth[2]

[1] *Deutsches Elektronen Synchrotron (DESY)*

[2] *Institute of Nuclear Physics, Johannes Gutenberg University.*

2022 IBIC International Beam Instrumentation Conference

HELMHOLTZ

Agenda

1 Introduction (Motivation)

2 Theoretical Model (Polarization Currents Approach)

3 Experimental Setup

4 Results

5 Summary

A. Potytltsyn, G. Kube, A. Novokshonov et al*, "First Observation of Quasi-Monochromatic Optical Cherenkov Radiation in a Dispersive Medium (Quartz)",* Phys. Lett. A, Vol. 417

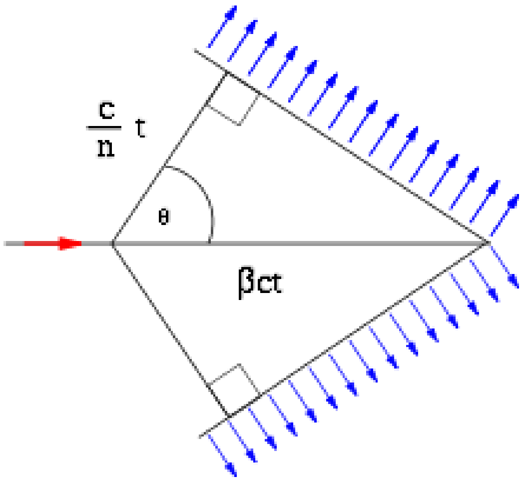
Introduction

1 **Discovered by P. Cherenkov (1934) and described by I. Tamm and I. Frank (1937)**

2 **Cherenkov Radiation (ChR) is widely used in different fields:**

- **elementary particle physics**
- **as an intense source of EM radiation**
- **beam diagnostics (loss monitors, length measurements)**

L. Bobb, R. Kieffer, T. Lefevre, S. Mazzoni, T. Aumeyr, P. Karataev, M. Billing, J. Conway, and J. Shanks, Phys. Rev. Accel. Beams 21, 032801 – Published 5 March 2018



3 **The applications are based on its directivity:** $\theta_{ch} = \arccos\left(\frac{1}{\beta\, n(\lambda)}\right)$

4 **There is a threshold:** $\beta\, n(\lambda) > 1$

Introduction (Motivation)

- **Cherenkov Radiation is not widely used in the beam profile diagnostics**
- **Although it could possibly be a substitute to such standard techniques as the scintillating screens and the optical transition radiation (OTR)**
- **A thin ChR radiator (crystal plate) has to be used**
- ***Consequently such parameters as a point-spread-function (PSF) and a spectrum have to be studied***

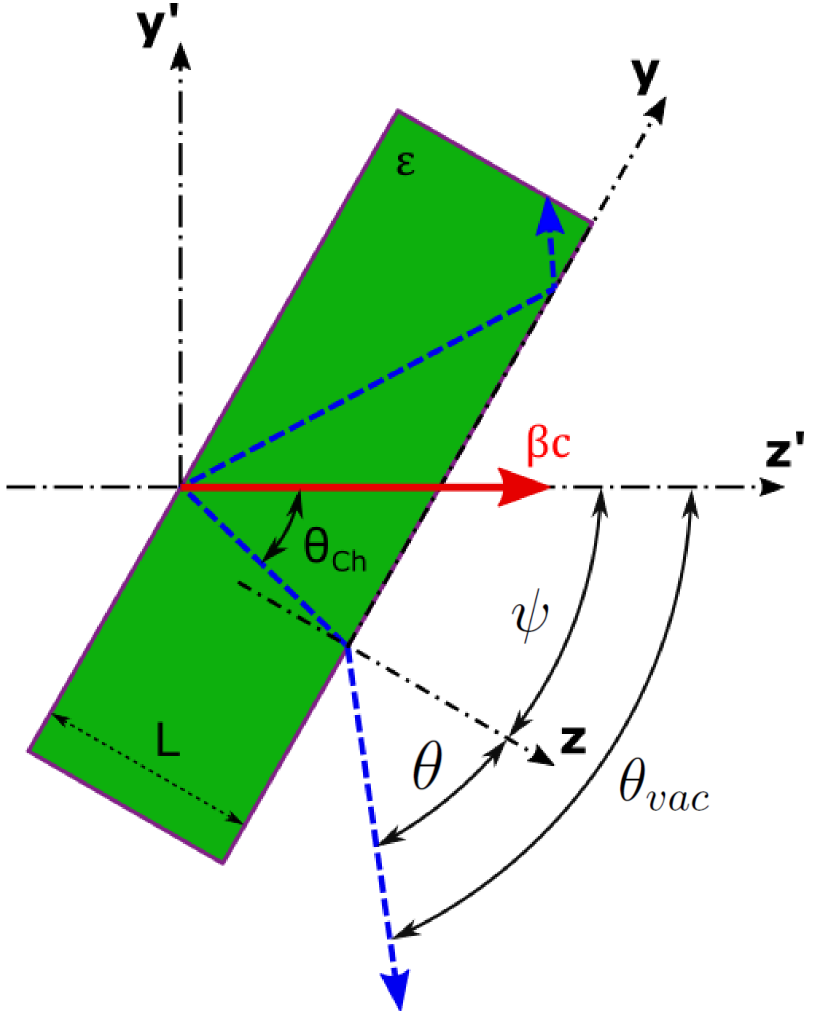
Introduction

$$\theta_{vac} = \psi + \theta = \psi + \arcsin\{n(\lambda)\,\sin(\theta_{ch} - \psi)\}$$

$$\theta_{vac} = \psi + \arcsin\left\{n(\lambda)\,\sin\left[\arccos\left(\frac{1}{\beta\, n(\lambda)}\right) - \psi\right]\right\}$$

- **The outgoing angle depends on the wavelength, the particle energy and the crystal tilt**

- **Rotating the crystal one can obtain separate spectral lines from the whole ChR spectrum**



Theoretical Model

- **ChR from a dielectric plate with infinite transverse sizes an finite thickness was first time calculated by V. Pafomov**
  - *“V. E. Pafomov, Proceedings P. N. Lebedev Physics Institute, v. 44, 1971”*

- **However the approach is cumbersome…**

- **A. Potylitsyn and D. Karlovets developed another approach**
  - *“D. Karlovets, A. Potylitsyn, Universal description for different types of polarization radiation, 2010”*

- **The approach has polarization currents induced by a particle as the radiation origin:**
  - the particle drives the polarization current whilst going through the medium
  - the current generates a magnetic field
  - the field quits the media

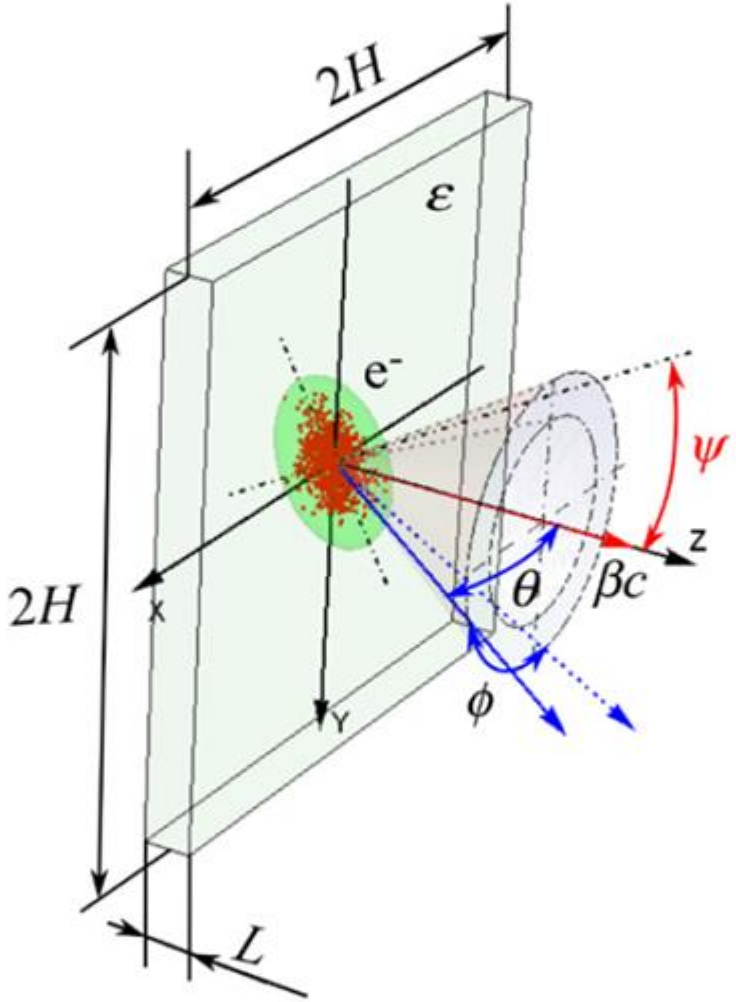
Theoretical Model

Number of photons per wavelength and solid angle:

$$\frac{\mathrm{d}^2 N}{\mathrm{d}\lambda\,\mathrm{d}\Omega} = 4\alpha \frac{\cos^2\theta}{\left((1-\beta_y n_y)^2 - \beta_z^2\cos^2\theta\right)^2} \left|\frac{\varepsilon - 1}{\varepsilon}\right|^2 \frac{L^2}{\lambda^3}\,\mathrm{sinc}^2\left(\pi\frac{L}{\lambda}\frac{1-\beta_z Z - n_y\beta_y}{\beta_z}\right) \times$$
$$\left(\beta_y^2\beta_z^2\sin^2\varphi \times (|Z|^2 + \sin^2\theta)\left|\frac{\sqrt{\varepsilon}}{\cos\theta + Z}\right|^2 + \right.$$
$$\left.\left|\frac{\varepsilon}{\varepsilon\cos\theta + Z}\right|^2 \left|(\beta_z^2 + n_y\beta_y + \beta_z Z - 1)\sin\theta - \beta_y\beta_z\cos\varphi\, Z\right|^2\right)$$

- ***ε*** – permittivity which depends on **wavelength**
- ***θ*** and ***φ*** are polar and azimuthal radiation angles
- $\boldsymbol{\beta_{x,y,z}}$ are the particle velocity components
- $\boldsymbol{n_{x,y,z}}$ are the ChR direction cosines

$$Z = \sqrt{\varepsilon - \sin^2\theta}$$



The radiation intensity proportional to *L²/λ³*.

The *sinc()* function defines width of the ChR spectral line.

Theoretical Model

- **The ChR spectral line width depends also on the medium *ε(λ)* dispersion**

- **The empirical Sellmeiers formula has been taken:**

$$\varepsilon(\lambda) = n^2(\lambda) = 1 + \frac{0.6961663\,\lambda^2}{\lambda^2 - 0.0684043^2} + \frac{0.4079426\,\lambda^2}{\lambda^2 - 0.1162414^2} + \frac{0.8974794\,\lambda^2}{\lambda^2 - 9.896161^2}$$

- **It is proven for silicon glasses at the wavelengths lower than 700 nm**
  - *"R. Kitamura, L. Pilon and M. Jonasz, Optical constants of silica glass from extreme ultraviolet to far infrared at near room temperature, 2007"*

Theoretical Model

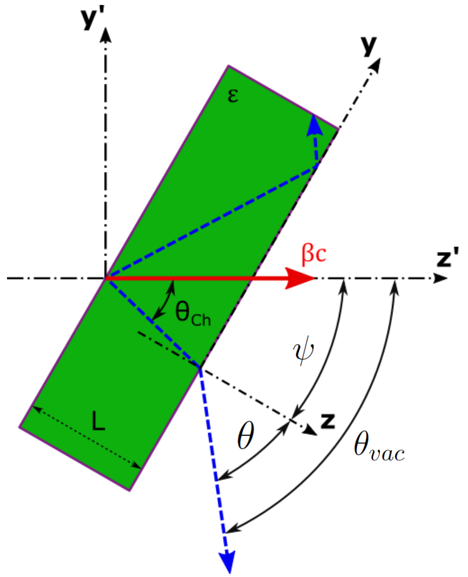
Required steps to calculate the ChR:

1

$$\theta_{vac} = \psi + \arcsin\left\{n(\lambda)\,\sin\left[\arccos\left(\frac{1}{\beta\, n(\lambda)}\right) - \psi\right]\right\}$$

2

$$\varepsilon(\lambda) = n^2(\lambda) = 1 + \frac{0.6961663\,\lambda^2}{\lambda^2 - 0.0684043^2} + \frac{0.4079426\,\lambda^2}{\lambda^2 - 0.1162414^2} + \frac{0.8974794\,\lambda^2}{\lambda^2 - 9.896161^2}$$



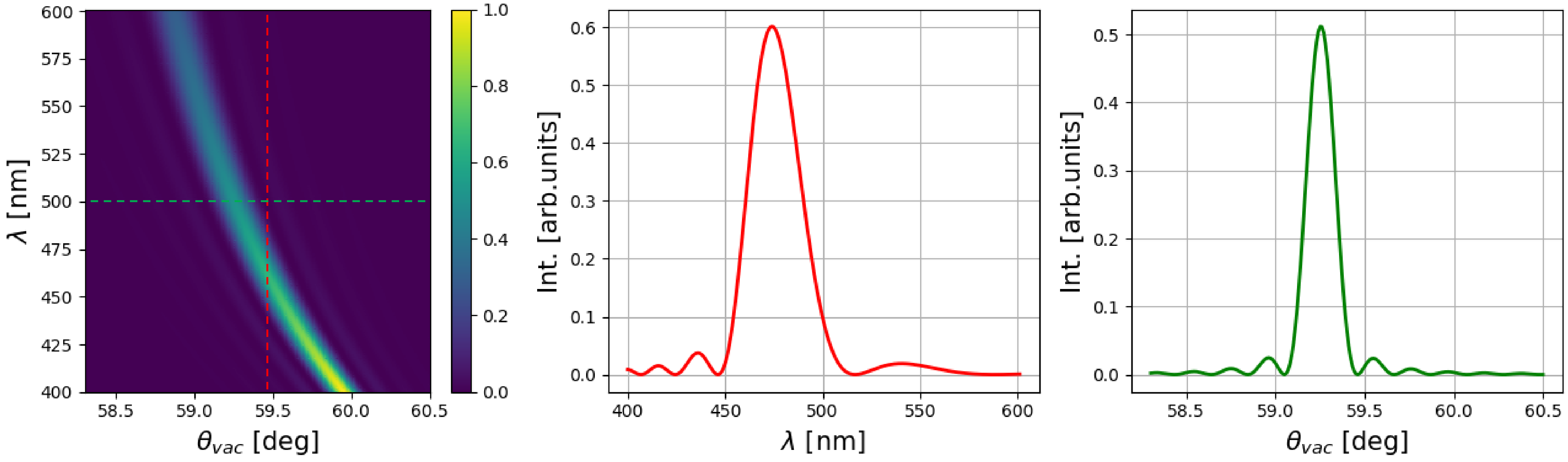
3

$$\frac{\mathrm{d}^2 N}{\mathrm{d}\lambda\,\mathrm{d}\Omega} = 4\alpha \frac{\cos^2\theta}{\left((1-\beta_y n_y)^2 - \beta_z^2\cos^2\theta\right)^2} \left|\frac{\varepsilon - 1}{\varepsilon}\right|^2 \frac{L^2}{\lambda^3}\,\mathrm{sinc}^2\left(\pi\frac{L}{\lambda}\,\frac{1-\beta_z Z - n_y\beta_y}{\beta_z}\right) \times \left(\beta_y^2\beta_z^2\sin^2\varphi \times (|Z|^2 + \sin^2\theta)\left|\frac{\sqrt{\varepsilon}}{\cos\theta + Z}\right|^2 + \left|\frac{\varepsilon}{\varepsilon\cos\theta + Z}\right|^2 \left|(\beta_z^2 + n_y\beta_y + \beta_z Z - 1)\sin\theta - \beta_y\beta_z\cos\varphi\, Z\right|^2\right)$$

Theoretical Model

- **With the formulas we calculate the ChR intensity dependence on the wavelength and the vacuum outgoing angle**

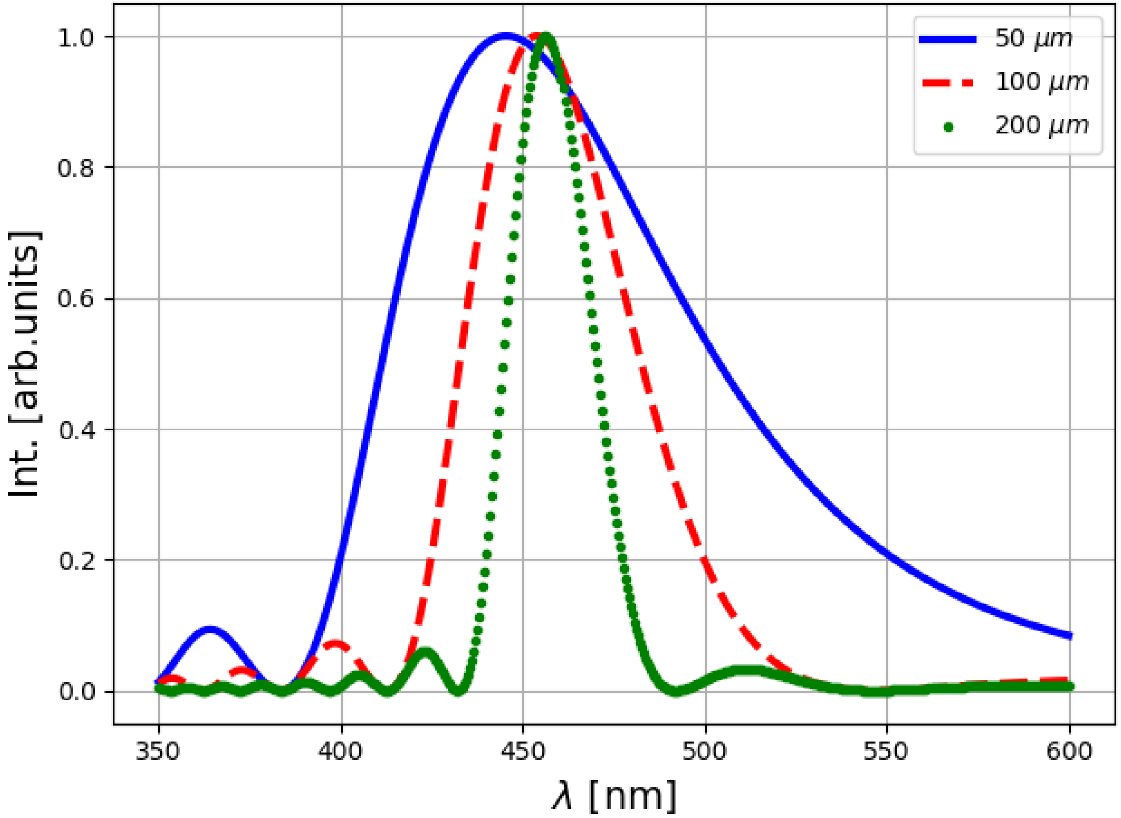
- **E = 855 MeV, L = 200 μm, Crystal Tilt (Ψ) = 23 deg**



Theoretical Model

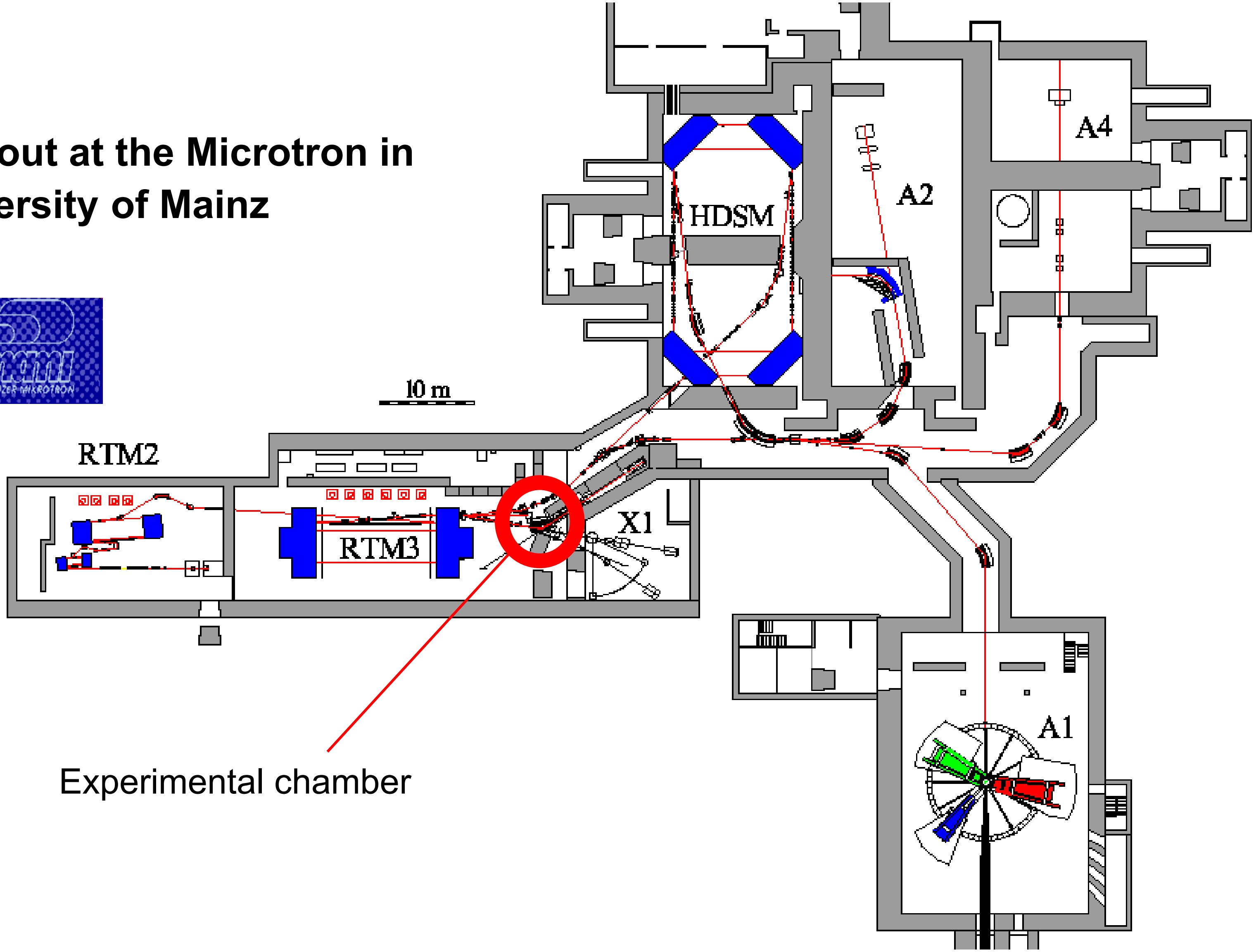
- **The spectral line also depends on the crystal thickness L which was approximately derived in the original Tamm's theory:**

$$\mathrm{FWHM}^T \approx \frac{2\lambda}{\pi L \sin\theta_{ch}}$$



Experimental Setup

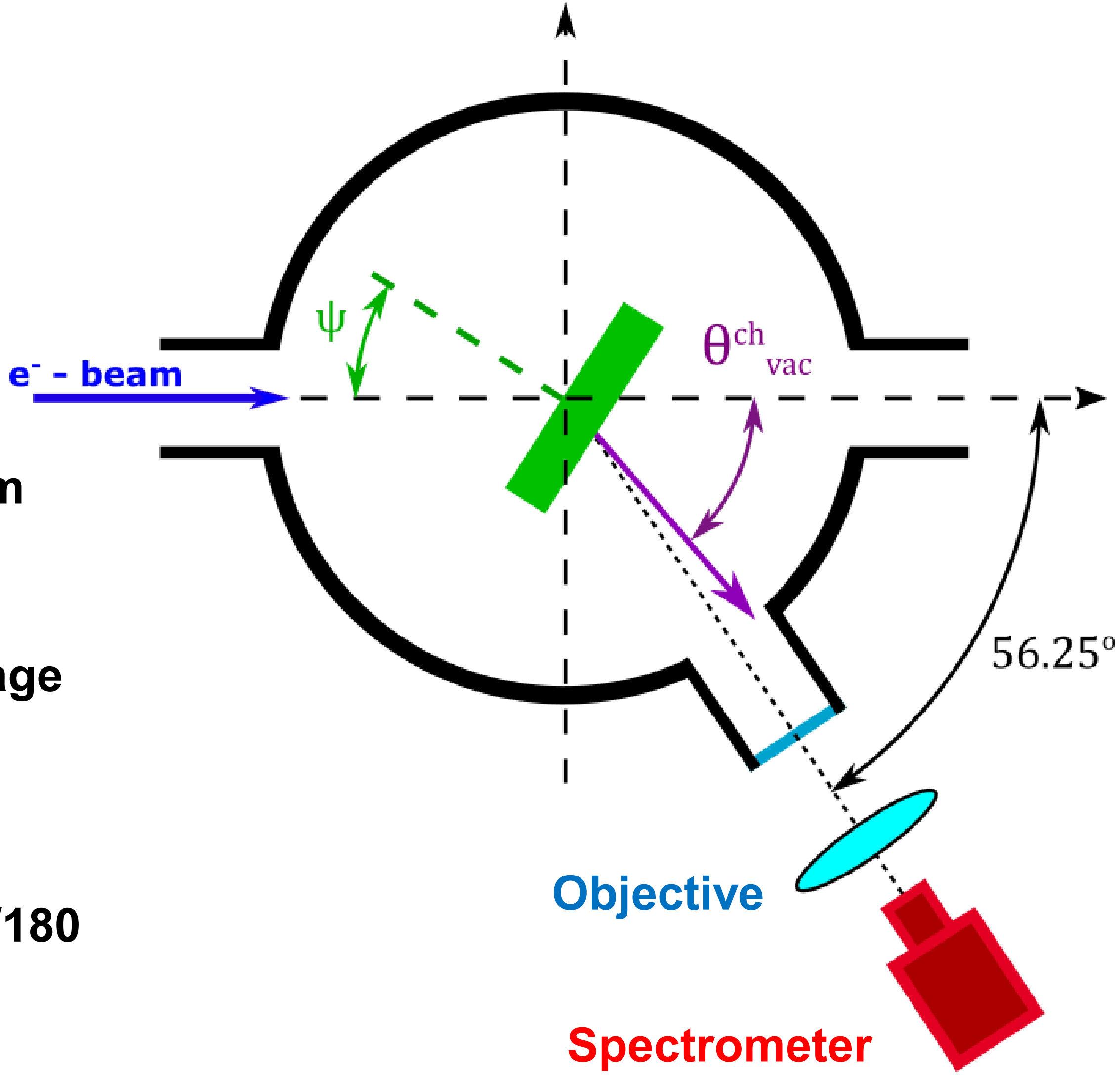
- **The experiment has been carried out at the Microtron in Institute of Nuclear Physics, University of Mainz**



Experimental chamber

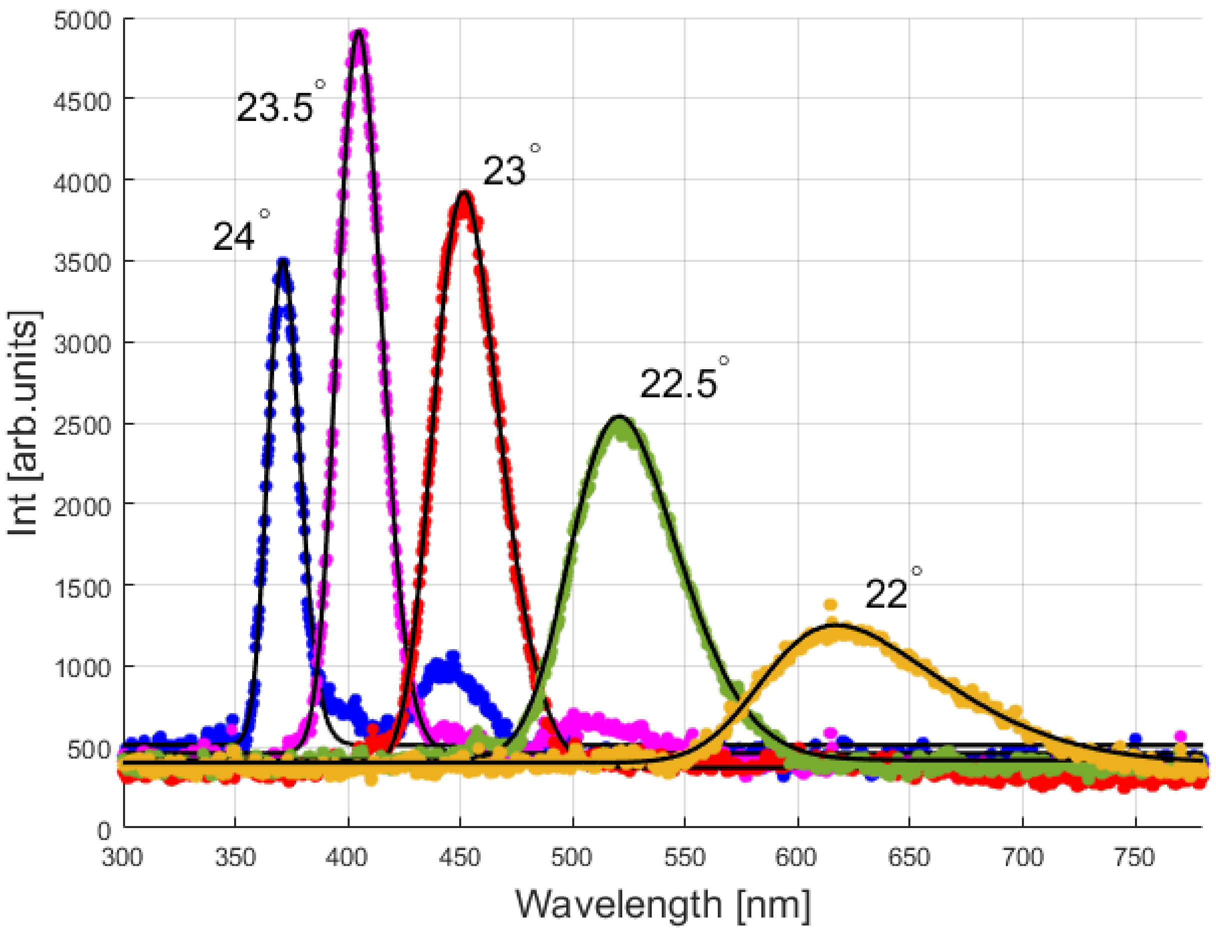
Experimental Setup

- **Main beam parameter:**
  - *continuous wave (cw) mode*
  - $E = 855\ MeV$
  - $I_{beam} = 45\ nA$
  - $\sigma_h = 536\ \mu m;\ \varepsilon_h = 7.8\ nm\ rad$
  - $\sigma_v = 6.3\ \mu m;\ \varepsilon_h = 0.5\ nm\ rad$
- **A fused silica target with 200 µm thickness and 20 mm diameter was used**
- **The target was placed on a multi-axis goniometric stage**
- **Spectrometer – Hamamatsu Spectrometer C10082CA**
- **Objective – Schneider-Kreuznach Makro-Symmar 5.6/180**

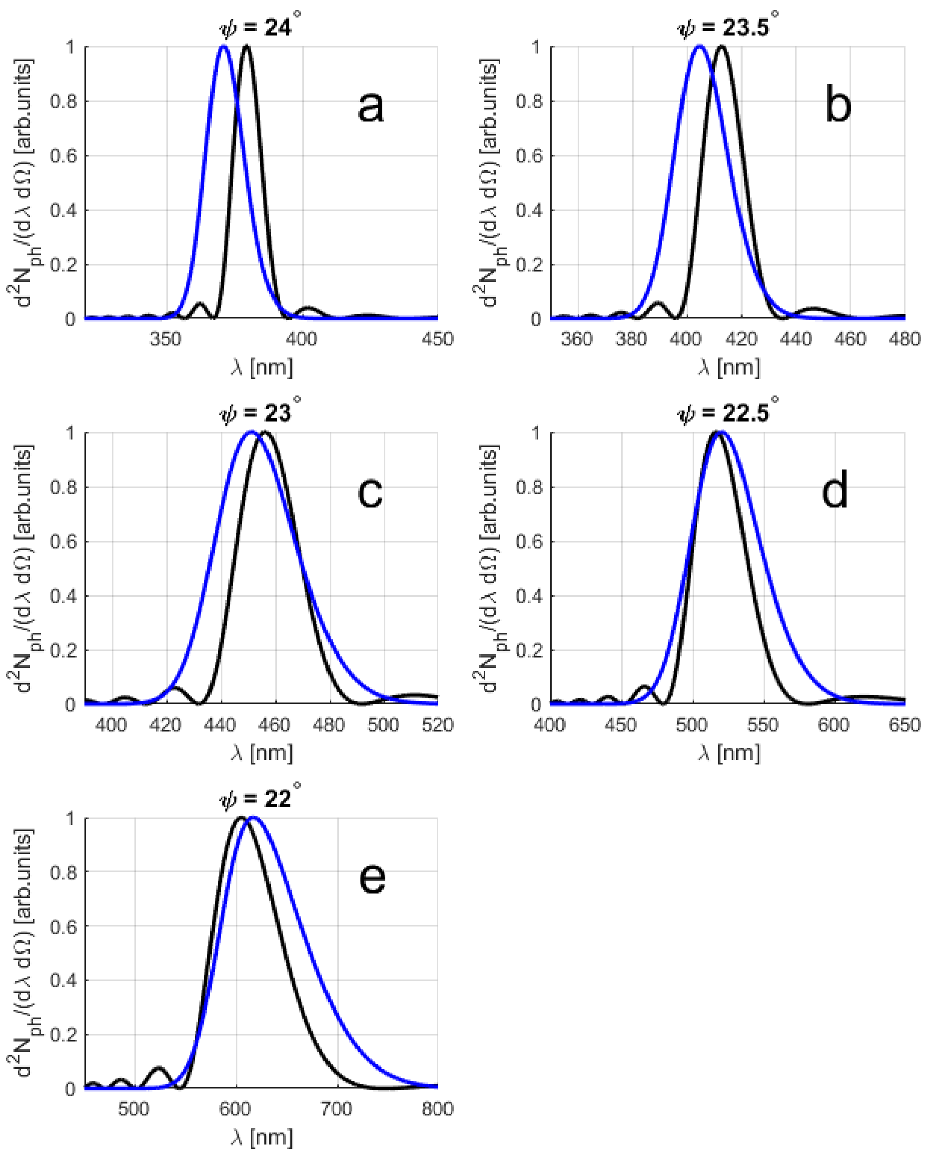


Results

- **The spectra at the different crystal tilt angles Ψ**
- **The chosen exposure time corresponds to 6.25 x 10^{14} electrons crossing the target**
- **Each spectrum is fitted with the Skewed Gaussian**



Results

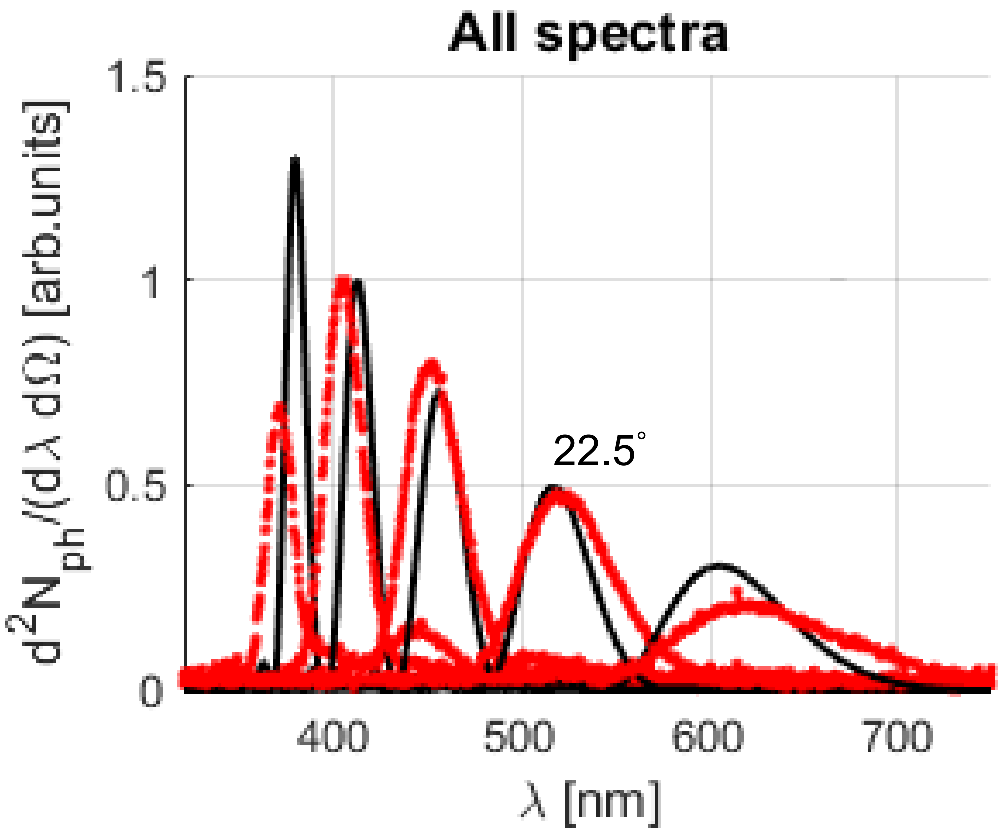


- **The spectra positions coincide at best at the 22.5 degree crystal angle**
- **The disagreement at the other angles may be explained by two factors**

1. **The chosen Sellmeiers parametrization may not describe the crystal perfectly**
2. **The thermal conditions of the crystal have not been taken into account**

Results

- **The comparison of the intensities at each crystal angle**
- **The best agreement is seen at the 22.5 degree angle**
- **However the position 24 degree has a quite valuable disagreement:**
  - **The reason for that are the chromatic effects of the focusing lens - part of the intensity didn't pass the entrance slit of the spectrometer.**



Summary

- **The quasi-monochromatic optical Cherenkov radiation produced in a dispersive medium has been observed**
- **The measurements are well described by the polarization currents model**
- **There are some discrepancies, but those should be investigated in future**
- **Such targets could be of interest among the beam profile diagnostics community as a possible substitute for scintillators and OTR**

Thank you