CHERENKOV CONVERTER FOR LARGE DYNAMIC RANGE, HIGH SENSITIVITY DETECTORS FOR USE ON WIRE-SCANNERS*

J. F. Gubeli, P. Evtushenko
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

Abstract

We are developing a wire-scanner with a dynamic range of 1e+6 or larger. In addition to the large dynamic range (LDR), high sensitivity is very desirable so that measurements can be made with a small amount of beam or small duty cycle beam. This high sensitivity requirement makes photo multiplier tubes (PMT) the preferred detector. Low dark current PMTs have maximum quantum efficiency in the visible wavelength range. We describe a converter where Cherenkov radiation (CR) is used to generate visible photons from electrons and positrons that are present due to wire-beam interaction. Also described is an optical system that collects and couples the CR into an optical fiber that delivers the visible photons to the PMT outside of the accelerator area, reducing background. The high directivity of the CR is used in a way that, when CR in the radiating medium is generated by particles not directed from the wire-beam interaction point to the converter, the CR is not coupled into the optical fiber and therefore does not create background for the wire-scanner measurements. Sensitivities to the refractive index of the radiating medium, alignment and mechanical tolerances are also presented.

INTRODUCTION

Particle accelerators have been using wire scanners as a valuable diagnostic tool to measure the spatial extent of their beam for many years. Several methods of determining the beam profile have been used, including measuring the induced current on the wires [1], by collecting the optical transition radiation [2] or by the use of scintillators [3]. We are developing a wire scanner that utilizes the shower of charged particles generated by the scattered electrons from the wire-beam interaction that impinge on the beam tube. We describe a method of converting these particles to photons by use of Cherenkov radiation and measuring the photons with a photomultiplier tube.

CHERENKOV RADIATION

Cherenkov radiation is electromagnetic radiation created when charged particles travel through an electrically polarizable medium faster than phase velocity of light in that medium. The threshold velocity of a particle to generate Cherenkov radiation is $\nu_n < \nu_p$ where ν_n is the phase velocity of light in a medium ($\nu_n = c/n$) and ν_p is the velocity of the charged particle. The velocity of an electron can be derived from the relativistic kinetic energy equation $E_k = (\gamma - 1)\, mc^2$ where $\gamma = (1 - \beta^2)^{-0.5}$ and $\beta = \nu_p/c$.

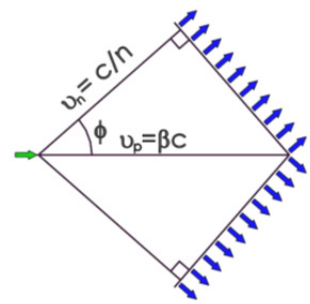

Figure 1: Cherenkov radiation geometry.

Cherenkov radiation is emitted in a cone where the angle is related to the velocities as $\cos\phi = (n\beta)^{-1}$ (Fig. 1). By solving for β in the relativistic kinetic energy equation, we can describe the emitted center wavelength angle as a function of n and E_k (MeV), equation 1.

$$\phi(E_k, n) := \operatorname{acos}\left(\frac{1}{n\cdot\frac{\sqrt{E_k^2 + 2\cdot E_o\cdot E_k}}{E_k + E_o}}\right) \quad (1)$$

The Frank-Tamm formula describes the number of Cherenkov photons generated per angle and per wavelength of the generated photon [4], equation 2. The right side of this equation S_{CR} is a measure of the spectral distribution of the emitted photons.

$$\frac{d^2N}{d\Omega d\lambda} = S_{CR} = \left(\frac{\alpha\cdot n(\lambda)\cdot L^2}{\lambda^3}\right)\cdot\sin(\theta)^2\cdot\left(\frac{\sin(k\cdot\pi)}{k\cdot\pi}\right)^2 \quad (2)$$

$$k = \frac{L}{\beta\cdot\lambda}\cdot(1 - \beta\cdot n(\lambda)\cdot\cos(\theta)) \quad (3)$$

CHERENKOV GENERATION CELL

The Cherenkov generation cell for this experiment consists of a 100 mm long water cell with a thin aluminium input window and a quartz output window (Fig. 2). For an index of refraction of 1.337, the phase velocity of light in water is ν_n = 0.748c. To generate Cherenkov radiation, the minimum energy of an electron/positron traveling in water must be greater than 0.259 MeV.

*Work supported by US DOE Office of Basic Energy Sciences early career program; DOE award number FWP#JLAB-BES11-05

ISBN 978-3-95450-176-2

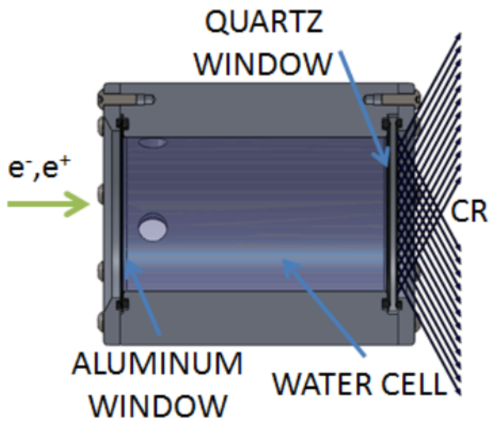

Figure 2: Cherenkov generation cell.

The photon angle leaving the generation cell can be determined by applying Snell's Law, $\sin(\phi_w)n_w = \sin(\phi_q)n_q = \sin(\phi_a)n_a$ for water, quartz and air. The equality allows the index of the quartz window to be ignored as long as the angle of incident doesn't exceed the critical angle $\theta_c = \text{asin}(n_2/n_1)$. Substituting this equality into equation 1 results in an expression of the photon exit angle as a function of the energy of the charged particle (MeV) and the index of refraction of water, equation 4.

$$\phi(E_k, n) := \text{acos}\left(\frac{1}{n \cdot \frac{\sqrt{E_k^2 + 2 \cdot E_o \cdot E_k}}{E_k + E_o}}\right) \quad (4)$$

The plot of Fig. 3 shows that the change in the exit angle is negligible with particle energy in excess of 20MeV.

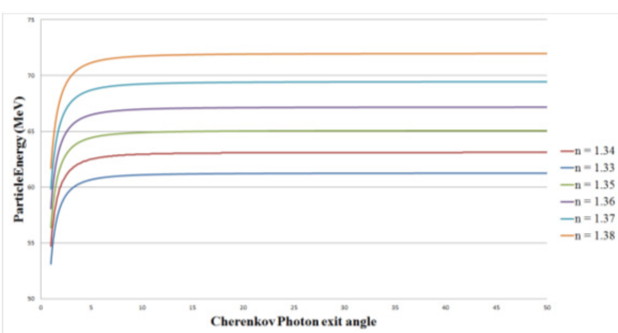

Figure 3: Plot of the cell exit angles as a function of energy and refractive index.

This plot varies the index of refraction of water [5-7] with wavelengths between 250nm and 600nm and temperatures 19°C to 24°C. The cell exit angle for this range of n at high particle energy goes from 61.7° at longer wavelengths to 71.5° at shorter wavelengths.

The spectral distribution of the radiation leaving the cell is obtained by substituting the angular relationship of the generation angle to that of the angle leaving the cell in equation 3 by use of Snell's Law. The plot of Fig. 4 is the normalized spectral distribution of the photons leaving a 20°C cell generated by 20MeV particles. The number of photons generated by the 100mm long cell per electron ranges from ~700 at 250nm to ~100 at 600nm (Fig. 5). The number of photons can be as large as 700 x 6.25e8 for 100pC electron bunch charges.

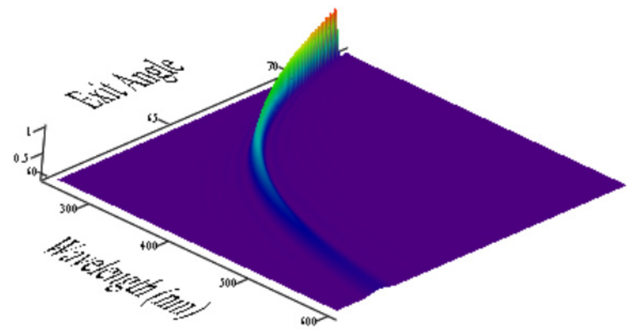

Figure 4: Normalized spectral distribution of the emitted photons leaving the generation cell.

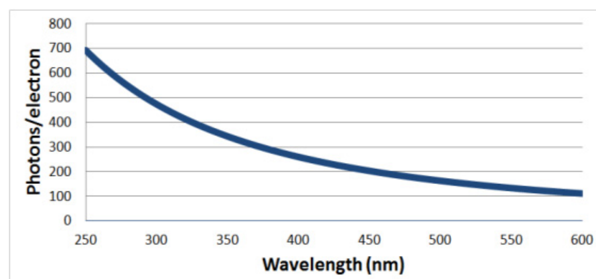

Figure 5: Number of photons per electron produced in a 100mm long water cell.

OPTICAL DESIGN / SIGNAL PROCESSING

The design specifications for the optical design are to first collimate the Cherenkov radiation leaving the generation cell, then to focus the light in to an optical fiber. The fiber would then transport the light to a photomultiplier tube located outside the radiation environment to increase the signal to noise ratio. This design also requires that the angular acceptance of the fiber coupling be small to ensure that only particles generated by the wire-beam interaction would be detected. The two factors that vary the angular trajectory of the generated photons in a water cell are the charged particle energy and the index of refraction. As the energy of the accelerator that we would use to test this system was well above 20MeV, causing little variation to the emitted photon angle, we looked at narrowing down which index of refraction the system would accept. The index of refraction of water changes slowly with small changes in temperature and pressure making the largest consideration the wavelength. The wavelength was

ISBN 978-3-95450-176-2

chosen that would maximize the number of Cherenkov photons generated, minimize the attenuation in water and in the fiber and maximize the sensitivity of the photomultiplier [8]. We used 350nm as our target wavelength and thus 65° as the angle for the emitted photons.

The photons exiting the Cherenkov generation cell are first reflected off a cylindrical mirror to a conical mirror with a cone angle of 32.5° (65°/2). An off-axis parabolic mirror is used to focus the photons into a 600µm diameter optical fiber. A three-armed support structure with a small cross-sectional area in the photon direction maintains the alignment of these two optics to the generation cell (Fig. 6). The cell as well as the cylindrical and conical mirrors are made of 7075-T6 to facilitate a mirror polish.

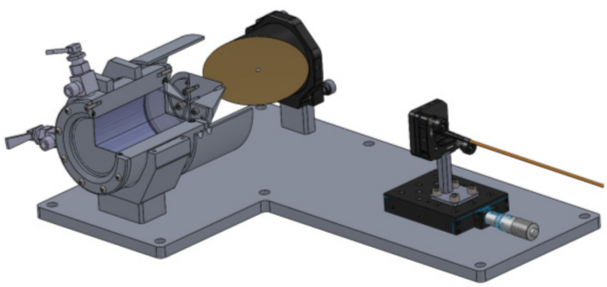

Figure 6: Cherenkov assembly.

This all-reflective layout was chosen for its wavelength independence. A raytrace was performed with 150,000 source rays generated by creating 100 sets of cones of 1,500 radially symmetric rays each. A 1mm diameter mask was created at the plane of the fiber input to display the irradiance map of the raytrace. All of the incident flux was captured by a 600µm disk with the charged particles striking generation cell normal to the entrance. A small misalignment of 0.35mrad will result in a 35% loss of detected signal (Fig. 7). This optical design is intentionally sensitive to the angle on incidence (AOI) of the charged particles to the generation cell. This sensitivity ensures that only the Cherenkov photons created by particles from the wire-beam interaction are captured. An AOI of 0.4 mrad will result in a 50% loss of signal (Fig. 8).

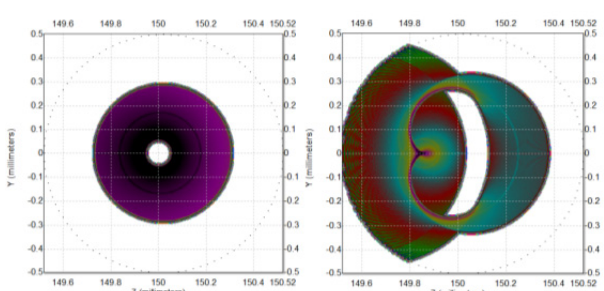

Figure 7: Irradiance map on the plane of the fiber input. Left image for charged particles aligned to the generation cell, right image charged particles misaligned by 0.35mrad.

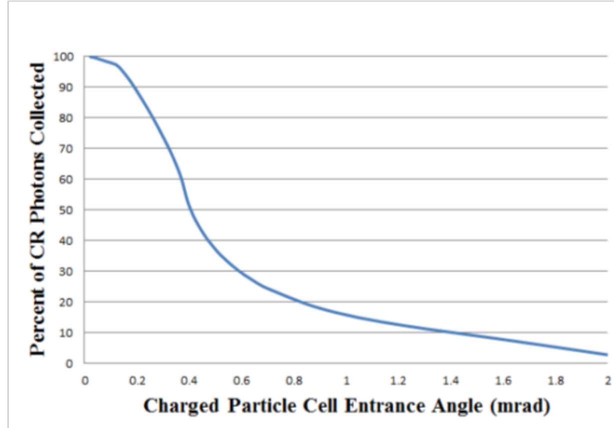

Figure 8: Percentage of Cherenkov photons coupled into the optical fiber as the angle of the charged particles move off the axis of the generation cell.

The optical fiber transports the collected photons outside of the beam accelerator to a PMT. Placing the PMT outside of the beam accelerator reduces the risk of environmental electrons striking a dynode and contributing to both signal and background. The PMT's negative output current is sent to a current mirror that first inverts then makes multiple "copies" of this current [9]. The current mirrors are sent to gated integrators (GI) (Fig. 9) at 100% and 1% of the PMT current and then digitized with a 16-bit ADC at 4 MS/s. The arrangement of these two GI's combined with the PMT allows for dynamic ranges of 10^8 to be reached.

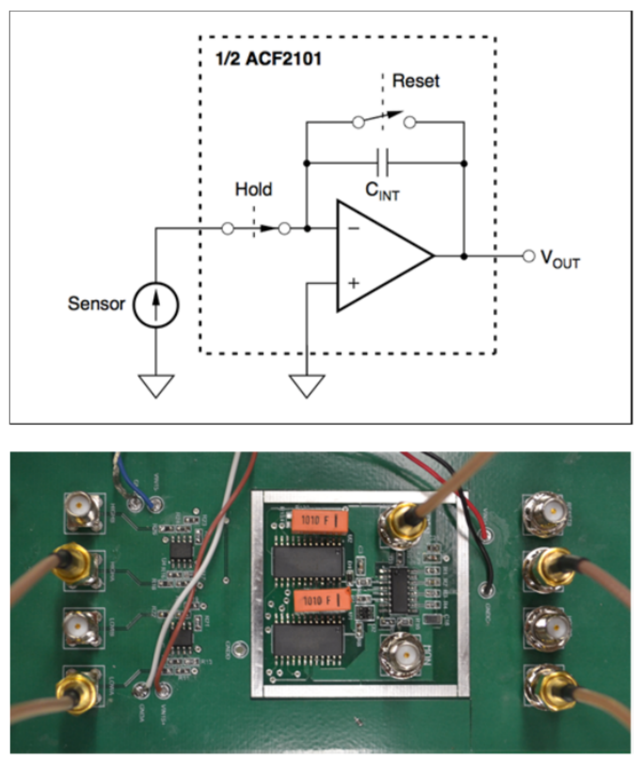

Figure 9: Gated Integrator circuit and board.

CONCLUSION

We have presented a method to measure the beam profile using Cherenkov radiation of charged particles generated by wire-beam interaction. A 100mm long water cell is used as the Cherenkov generation medium converting charged particles of 20MeV and larger to 350nm photons that are focused on an optical fiber. Due to the small angular acceptance of the optical system, only those electrons entering the generation cell parallel to the axis of the cell are captured. A PMT coupled with two gated integrators will allow measurements of low duty cycle beams with a dynamic range of 10^8.

REFERENCES

[1] M.C. Ross et al., "Experience with wire scanners at SLC", SLAC-PUB-6014.

[2] P. Elmfors et al., "Wire-scanners in low energy accelerators", NIM A 396 (1997) 13-22.

[3] H. Grabosch et al., "Test of a wire scanner in the diagnostic section of PITZ", Proc. FEL, Novosibirsk, Russia (2007).

[4] C. Grupen, "Teilchendetektoren", BI-Wiss.-Verl., 1993.

[5] S. Kedenburg et al., "Linear refractive index and absorption measurements of nonlinear optical liquids in the visible and near-infrared spectral region", Opt. Mat. Express 2, (2012), p. 1588-1611.

[6] M. Daimon et al., "Measurement of the refractive index of distilled water from the near-infrared region to the ultraviolet region", Appl. Opt. 46, (2007), p. 3811-3820.

[7] G. M. Hale et al., "Optical Constants of Water in the 200-nm to 200-µm Wavelength Region", Appl. Opt. 12, (1973), p. 555-563.

[8] Hamamatsu preliminary data, "Photomultiplier Tube R7378A", TPMH1288E01 (2004) [http://www.hamamatsu.com/resources/pdf/etd/R7378A_TPMH1288E.pdf].

[9] P. Evtushenko et al., "Design of Wire-Scanner (electronics) for Large Dynamic Range Beam Profile Measurements", Poster IBIC 2014, Monterey, CA, USA (2014).

ISBN 978-3-95450-176-2