# PROGRESS REPORT ON DEVELEPEMENT OF A HIGH RESOLUTION TRANSVERSE DIAGNOSTIC BASED ON FIBER OPTICS*

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*Abstract*

A beam profile monitor utilizing the technological advances in fiber optic manufacturing to obtain micron level resolution is under development at RadiaBeam Technologies. This fiber-optic profiling device would provide a low cost, turn-key solution with nominal operational supervision and requires minimal beamline real estate. Preliminary results of Cherenkov light generation in fiber is presented.

## INTRODUCTION

The advances towards ultrashort electron beams are driven from multiple directions including applications such as micro x-ray beams [1], and techniques such as laser driven advanced accelerators [2]. The tools to measure and diagnose these shorter, higher density beams need to keep in step with the rapidly growing compression methods and applications. This investigation puts forth a novel, high-resolution beam-profile monitor capable of measuring beam-distributions without complex optics and with a minimal longitudinal insertion-size. The diagnostic does not rely on transition radiation, and is therefore immune from recently reported coherent effects that obscure the beam profile [3].

Electron beam sizes naturally scale with the frequency of the accelerating structure and power source [4]. Advanced accelerator schemes, seeking higher gradients and higher beam densities, employ ever shorter wavelengths to drive novel structures [5]. Laser driven accelerating schemes and Compton sources have particularly stringent requirements on the electron beam transverse dimensions, and therefore demand beam-profile measurement techniques with a resolution of a few microns or better [6]. Simultaneously, these electron beams, whether employed to produce high luminosity colliders, high brightness light sources, or ultra-short bunches tend to use relatively low bunch charges (on the order of tens of pC) making it difficult to apply conventional high-resolution beam-profile measurement-techniques such as optical transition radiation (OTR) monitors. In the context of fourth generation light sources, ever brighter beams, as in FEL and ICS systems, are placing new demands on diagnostics including higher resolution transverse beam profiles operable in ultra-intense beam fields. These challenges are compounded for test systems that have low beam-energies, complex beam-profiles and often require diagnostic insertion adjacent to an interaction point (IP). In light of these diagnostic needs, we propose a method of measuring the transverse profile of electron beams using a fiber optic array, readout by a CCD array detector.

## RADIATION SIGNAL AND CAPTURE

An ultra-relativistic electron propagating through the core of a fiber emits Cherenkov radiation at an angle $\theta_c$, defined by the core index of refraction, $n$.

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

For a typical fiber of $n$~1.5, the Cherenkov angle is about 50° (Figure 1):

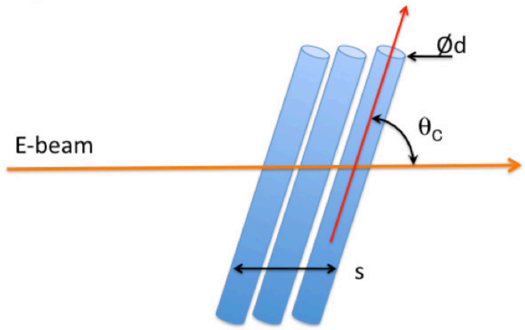

Figure1: Conceptual diagram of the fiber-mesh beam profile monitor. The fibers are arranged along the Cherenkov angle for maximum capture.

The analysis in this section revolves around incoherent and coherent (Cherenkov) radiation calculations for typical fibers. The maximum photon yield is achieved when the fibers are positioned at the Cherenkov angle (Figure 1) and that the photon flux at this angle is large enough for detection. The total spectral fluence of Cherenkov radiation from relativistic electron into the fiber in the optical frequency range can be calculated, using Frank-Tamm formula [7]:

$$\frac{dE}{dz\,d\omega} \approx \frac{e^2\omega}{4\pi\varepsilon_0 c^2}\sin^2(\theta_C). \tag{2}$$

Integrating Eq. 2 over the fiber bandwidth, and an average passage length through the fiber $\langle z\rangle = d/\sqrt{2}\sin(\theta_C)$, yields an average photon flux into the fiber per electron:

$$N_0 \approx 2\pi\alpha\left[\frac{d\sqrt{2}\sin(\theta_C)}{\lambda}\right]\left(\frac{\Delta\omega}{\omega}\right), \tag{3}$$

where $\alpha$ is a fine structure constant, and $\Delta\omega/\omega$ fiber bandwidth. The number of electrons, passing through the fiber at the core of a symmetric Gaussian beam of $N_e$

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electrons, with the RMS transverse size of $\sigma_x$ is given by,

$$N = \frac{N_e}{\sqrt{2\pi}\sigma_x}\left[2\int_0^{d/2} e^{-\frac{x^2}{2\sigma_x^2}}dx\right] \approx \frac{N_e d}{\sqrt{2\pi}\sigma_x}, \qquad (4)$$

Combining Eq. (3) and (4), and using a single fiber's angular acceptance coefficient, $K=NA/\sin(\theta_c)\pi$, one obtains the expression for peak Cherenkov photon flux delivered into the fiber at the core of the electron beam:

$$N_{ph} \approx \frac{2\alpha}{\sqrt{\pi}} N_e \left[\frac{d^2}{\lambda\sigma_x}\right]\left(\frac{\Delta\omega}{\omega}\right) NA \quad . \qquad (5)$$

It is possible to immediately perform an order of magnitude evaluation of the Eq. (5), to validate the applicability of the proposed diagnostics method. In a typical single mode fiber, $NA \propto \Delta\omega/\omega \propto \lambda/d \propto 10^{-1}$. For a typical electron beam of $10^9$ electrons, and assuming an RMS transverse size within an order of magnitude of the fiber diameter, the resulting Cherenkov photon capture by a single fiber is $N_{ph} \sim 10^5$. This is a reasonably large signal intensity, which can be resolved with at least 8-bit resolution, leaving some room for inevitable losses during transport and at the back end.

## EXPERIMENTAL METHODOLOGY

The Cherenkov emission in the fiber mesh diagnostic will provide a photon count of $N_{ph}$~$10^5$, as shown in the previous sections. The next design challenge is the detection of the emission with minimal loss.

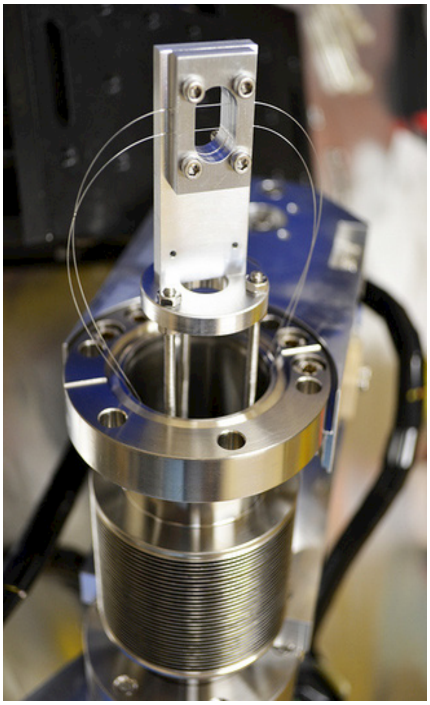

Figure 2: Fiber holder on a plunger with a rotational degree of freedom. Two fibers are visible: single-mode and multimode.

The three detector considerations included intensified CCD, photomultiplier tubes, and linear arrays. The final selection was based on sensitivity, cost, integrability into diagnostic, and coupling of fiber signal into detector. Even though the most appealing detector option is the linear image sensor (CCD array), we started our experimental investigation with a photomultiplier tube (Thorlabs PMM02).

To ensure the fiber mesh feasibility, we used the fibers that were originally tested in radiation environment to determine their life expectancy and damage threshold [8]. Two types of fibers were used: Fujikura radiation resistant multimode ($SiO_2$ core size 50 µm) and single mode ($SiO_2$ core size 8.6 µm) fibers, FC/PC terminated at both ends, cladding 125 µm (F-$SiO_2$), coating 245 µm, NA=0.2, 850 nm optimized. These fibers were chosen since they have been studied extensively and utilized at CERN to run signals in the high radiation environment of a Large Hadron Collider (LHC) [9]. The fibers were inserted into UCLA Pegasus beamline (30 pQ, 3.5 MeV, 1 mm-mrad) using a specially designed holder, see Figure 2.

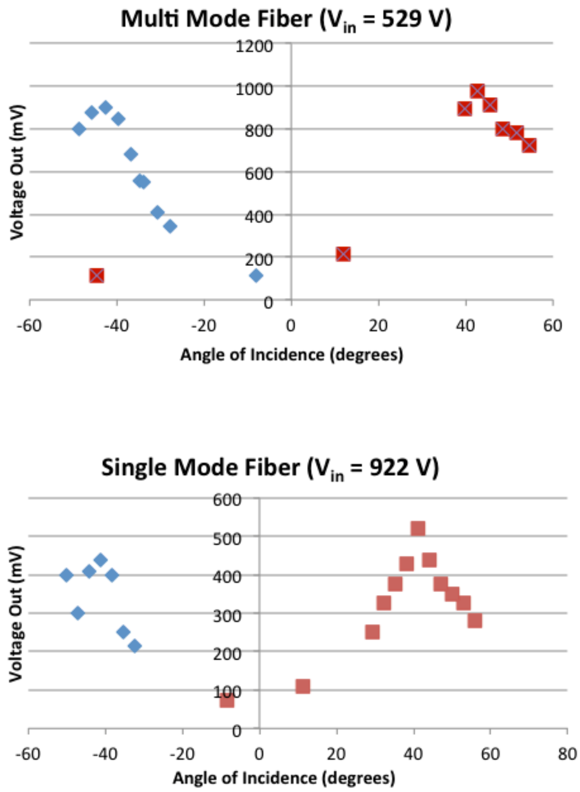

Figure 3: Cherenkov light detected from multimode (top) and single mode (bottom) fibers. Two colors correspond to two ends of fiber where the signal was taken.

Cherenkov light was detected at different angles for both multi- and single-mode fibers with the maximum observed at about 45º, see Figure 3. Multimode fiber produced a signal about two orders of magnitude stronger than the single mode (~1000 photons) which corresponds well to their core sizes.

## SYSTEM DESIGN CONSIDERATIONS

Our next step will be inserting a bundle of fibers. The proper holder has been designed and vacuume tested, see Figure 4. A signal from the whole bundle of fibers (arranged linearly) goes into a CCD and through the image acquisition to the computer. The computer post-processes the image to create a virtual mesh. This scheme does not require a PMT-type intensifier, which significantly reduces the cost and simplifies the operations. The required sensitivity is estimated to be less than ~1000 photon per pixel, based on the fiber output analyses of $10^5$ photons per fiber (dynamic range of ~100), we assume that the core of each fiber is couple to a single pixel of the CCD array chip and the nearby pixels may stay 'empty'. Note, that this is only achievable if the pixel size is greater than the fiber core diameter (difficult but possible). In cases we considered, the pixel size is typically greater than 10 µm.

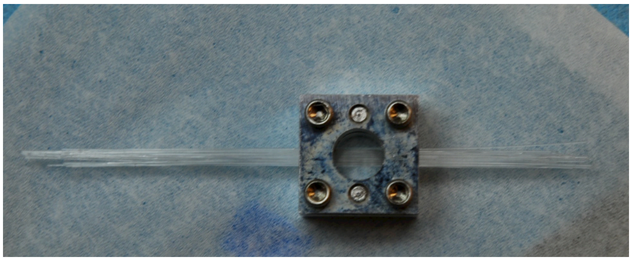

Figure 4: A photograph of the next generation Fiber holder capable of utilizing bundle of fibers arranged linearly.

## CONCLUSIONS

Based on the results of our calculations and irradiation studies, we believe that a fiber optic based beam profile monitor is a promising alternative to conventional transverse beam imaging techniques. The fiber mesh diagnostic, if successfully implemented, will provide <10 µm resolution without the need for complex diffraction limited optics. Further studies are planned for in-situ characterization of the fiber mesh diagnostic under beam operating conditions.

## ACKNOWLEDGEMENTS

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