A HIGH RESOLUTION TRANSVERSE DIAGNOSTIC BASED ON FIBER OPTICS

R. Agustsson, G. Andonian, A. Murokh, R. Tikhoplav,
RadiaBeam Technologies LLC, 1717 Stewart Street, Santa Monica, CA 90404, USA
David Griscom, retired, Naval Research Laboratories, Washington D.C.

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 lost cost, turn-key solution with nominal operational supervision and requires minimal beamline real estate. We are currently studying and attempting to mitigate the various technical challenges faced by a fiber optic based diagnostic system with a focus on radiation damage to the fibers and its effect on signal integrity. Preliminary irradiation studies and conceptual operation of the system are presented.

INTRODUCTION

The advances towards ultrashort electron beams is 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 proposal 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.

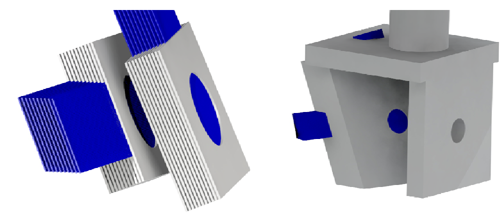

Figure 1 Conceptual depiction of the fiber array and holder

RADIATION SIGNAL AND CAPTURE

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

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

For a typical fiber of n~1.5, the Cerenkov angle is about 50° (Figure 2):

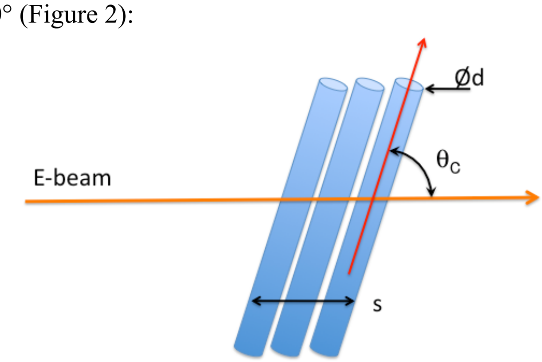

Figure 2: Conceptual diagram of the fiber-mesh beam profile monitor. The fibers are arranged along the Cerenkov angle for maximum capture.

The analysis in this section revolves around incoherent and coherent (Cerenkov) radiation calculations for typical fibers. It will be shown that the maximum photon yield is achieved when the fibers are positioned at the Cerenkov angle (Figure 2) and that the photon flux at this angle is large enough for detection. The individual studies include the following:

- The angular acceptance of the fiber, as a fraction of the Cerenkov emission cone for an ideally positioned fiber, is calculated. Small angular deviations are also included.

- The anticipated photon yield (N_{ph}) as a function of electron beam parameters is calculated. It will be shown that N_{ph} is sufficiently large for presently available detection schemes.
- Signal contamination due to coherent effects, which may be deleterious, are considered.
- The fiber mesh exposed radiation background is calculated.
- Possible cross-talk effects, due to beam scattering, between fibers are studied using Monte Carlo simulations.
- A brief beam dynamics simulation is presented to determine the effects on the electron beam parameters (emittance, energy) important for consideration as a quasi-nondestructive diagnostic.

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]:

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

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:

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

where α 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 electrons, with the RMS transverse size of σ_x is given by,

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

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:

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

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.

RADIATION DAMAGE STUDIES

Radiation sensitivity of optical fibers has been a major historical issue [8]. To ensure that the fiber-based diagnostics will work properly and will have a long life expectancy, the proper selection of the fiber should be made, with a main criterion being the survivability of the fiber in a harsh radiation environment.

The following criteria have been considered in particular:

- radiation susceptibility, including long term and short term,
- reversible vs irreversible damage (i.e., actual damage versus increased absorption during irradiation),
- life expectancy of a fiber in different irradiation regimes (different dose accumulation rates)
- no change of photon yield as a function of irradiation time.
- chemical content (with respect to radiation susceptibility): High OH vs low OH and feasibility of doped fibers.9

Fiber diameter was also given a serious consideration since it will ultimately determine the resolution of the device (core and cladding as well as multimode vs single mode): the smaller the better, preferably no more than 80μ total OD, which is the smallest industry standard.

Another parameter witch can be varied to optimize the overall FMD performance is the index of refraction difference between the core and cladding since it is responsible for the acceptance angle; however our choice is very limited here unless a custom fiber is drawn for our applications, since typically the indices are optimized for low loss in fibers of great lengths (km range).

To check the fiber mesh feasibility, the fibers should first be tested in radiation environment to determine their life expectancy and damage threshold. The preliminary test was performed at the Sterigenics X-ray facility for doses of 10 kGy, 80 kGy, 300 kGy and 1,000 kGy.

Table 1: Experimental transmission data of the different fibers for three different wavelengths.

	658 nm Power Throughput, mW (%)	**808 nm** Power Throughput, mW (%)	**1310 nm** Power Throughput, a.u. (%)
Fibers pre-exp. (ave.)	7.88±0.09 (100%)	2.27±0.02 (100%)	29.6±0.6 (100%)
Fiber1 (10 kGy)	6.61±0.01 (84%)	1.99±0.01 (88%)	27.4 (93%)
Fiber2 (80 kGy)	4.76±0.04 (60%)	1.98±0.01 (87%)	28.2 (95%)
Fiber3 (300 kGy)	2.31±0.02 (29%)	2.01±0.01 (89%)	27.6 (93%)
Fiber4 (1,000 kGy)	0.96±0.01 (12%)	1.99±0.01 (88%)	25.5 (86%)

Four identical fibers were used: Fujikura radiation resistant multimode fibers (RRMMA type), 2m long, FC/PC terminated at both ends, core size 50 μm (SiO_2), 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) [10]. Each fiber received the dose shown above and one fiber was kept unexposed as a reference. To determine the residual radiation damage, the throughput of each fiber was measured before and after the radiation exposure by connecting to the FC coupled laser source (Thorlabs MCLS1, 658 nm, 808 nm and 1310 nm) and the detector (Thorlabs D400FC). To limit the radiation exposure of the FC terminators which are much thicker (5mm) than the fiber (250 µm) and therefore are more susceptible to the shower effect, the terminators were shielded by 1cm of steel.

The test yielded excellent results. 658 nm shows significant decay in the range of irradiation (10 kGy-1,000 kGy) with the 1/e attenuation rate of 250-300 kGy; on the other hand, IR (808 nm and 1310 nm) shows virtually no loss (there is an offset of the pre-exposed level and after exposure most likely due to a laser power drift (~10%) between different days). We expect 658 nm to be about two orders of magnitude more susceptible to irradiation than IR. For our range of interest (near-IR), we estimate the 1/e attenuation rate to be greater than ~10 MGy for a two meter fiber. Since the real time exposure length will be in the order of a mm, the life expectancy of the FMD is estimated to be in the order of tens of GGy making it a promising diagnostic tool in a real life accelerator laboratory environment.

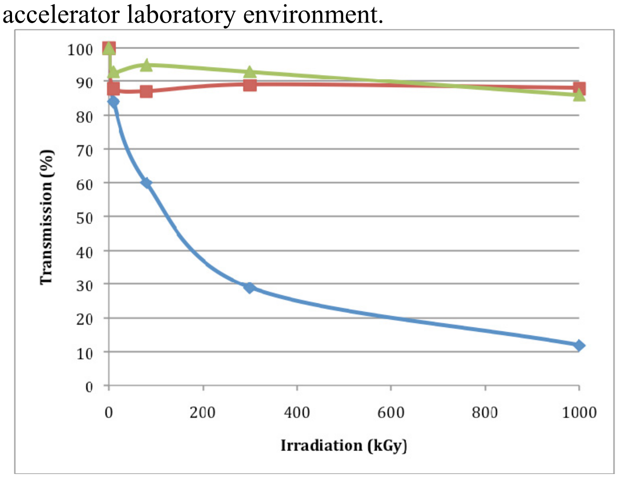

Figure 3: The transmission curves for the fiber irradiation experiment demonstrating acceptable attenuation at near-IR.

SYSTEM DESIGN CONSIDERATIONS

The Cerenkov 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. 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. Using the results of the previous section (N_{ph}~10^5) for sensitivity, and assuming 250 micron thick fiber and rectangular packing form factor, the corresponding photon density is $1.6\mathrm{x}10^8$ ph/cm^2, the most appealing detector option is the linear image sensor (CCD array). The linear array belongs to the fiber bundle detector classification. 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.

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.

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