BEAM BASED DEVELOPMENT OF A FIBER BEAM LOSS MONITOR FOR THE SPring-8/XFEL

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Abstract

To select the best candidate for a fiber based beam loss monitor, glass fibers of different diameter (100~600 μm), index profile (graded/stepped) and from different makers were characterized (signal strength, attenuation, dispersion) at the SPring-8 Compact SASE Source (SCSS). Beam tests showed that at 250 MeV the detection limit corresponding to a 10 mV signal is below 1 pC/bunch over 60 m and 3 pC/bunch over 120 m, with a position accuracy better than 30 cm. The fiber lifetime has been estimated to be over 13000 hours from dose measurements at the SCCS.

INTRODUCTION

Optical fibers have been used as radiation detectors for more than 20 years in a wide range of experiments. Recently several facilities have worked on the development of fiber-based local beam loss detection systems [1]. Fiber-based beam loss monitors offer the possibility to detect beam losses over long distances in real time, with good position accuracy and sensitivity at a reasonable cost. For the undulator section of the 8 GeV SPring-8/XFEL [2], radiation safety considerations set the desirable detection limit at 1 pC (corresponding to a 0.1% beam loss) over more than a hundred meter. While the intensity of the Cerenkov radiation generated in and transmitted down a multimode fiber has been predicted theoretically [3,4], the selection of the optimum fiber is not straightforward. A beam-based approach was therefore chosen to characterize different glass fibers (signal strength, attenuation, dispersion).

EXPERIMENTAL SET-UP

The experiments were carried out at the SCSS, a 1/16th model of the future SPring-8/XFEL The SCSS has a maximum electron energy and repetition rate of 250 MeV and 60 Hz respectively. The optical fiber was set along (for beam loss measurements) or across (for attenuation/dispersion measurement) the accelerator vacuum chamber (Fig. 1). The signals from the photomultiplier tubes (PMTs) set at both end of the fiber are read out with an oscilloscope. A trigger signal from the accelerator master oscillator is used as time reference. The beam current was measured with current transformer (CT) monitors placed along the beam accelerator. Inserting the screen of an optical transition radiation (OTR) monitor into the beam path generates an electromagnetic shower: This artifice is used to simulate a beam loss (stray electrons hitting the vacuum chamber). To measure the attenuation/dispersion of the light signal, the fiber is set across behind an OTR screen. The signal is then measured for different distances (A, B in ig 1b.).

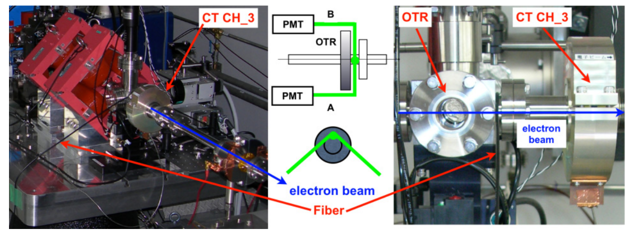

Figure 1: Experimental set-up used for the measurement of the attenuation of the beam loss monitor.

Several kinds of fibers (different diameters, numerical aperture and index profile) were tested (Table 1). All fibers were coated to limit the noise from ambient light. The choice of the photomultiplier (Hamamatsu H6780-02) resulted from a compromise between the fiber attenuation and the characteristics of Cerenkov spectrum. An additional criterion was the possibility to add a connector: The fibers were equipped with FC connectors at both ends to insure easy ("plug and play") and clean connections (low insertion loss) as well as a good reproducibility. With this experimental set-up, it is possible to test the response (signal strength, attenuation, dispersion) of these fibers in realistic (The continuous spectrum of a Cerenkov signal from stray charged particles) and standardized conditions.

Table 1: Main characteristics of the fibers. The numerical aperture of the Fujikura and Corning fibers are respectively 0.2 and 0.39.

Maker	Reference	Index	Length [m]
Mitsubishi	ST100	Step	10.1
Fujikura	GC200/250	Graded	10.2
	GC400/500	Graded	61.4
	GC600/750	Graded	10.1
	SC200/220	Step	10.1
	SC400/440	Step	32.4 & 121.4
Corning	COR200VIS39	Step	25.4

SIGNAL STRENGH AND ATTENUATION

Figure 2 shows the strength of the Cerenkov signal as a function of the fiber length. The signal from the PMT has been normalized by the average beam charge impacting the screen of the OTR monitor. The error bars reflect the standard deviation from the PMT signal (typically taken over a few hundreds samples) as well as the standard deviation of the CT signal (typically less than one

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percent) and its accuracy (10%). The lines are fits from the measured value according to:

$$S\left[\mathrm{V/nC}\right] = S_0\left[\mathrm{V/nC}\right]10^{-\alpha[\mathrm{dB/km}]x[\mathrm{km}]} \quad (1)$$

where α is the attenuation of the Cerenkov signal expressed in dB/km. α is a convolution of the attenuation of the fiber and the PMT sensitivity. The values obtained from the fit are given in Fig. 3, the uncertainty being larger for the shorter (~ 10 m) fibers.

For Wang et al. [3] the Cerenkov output power is proportional to the square of the fiber diameter D. The results obtained here show that the detector output is proportional to $D^{1.5}$. A bundle of fibers will give a signal weaker than that of a single fiber of equivalent diameter. For the SPring-8/XFEL, the detection limit and length to be surveyed give a minimum diameter of 400 µm.

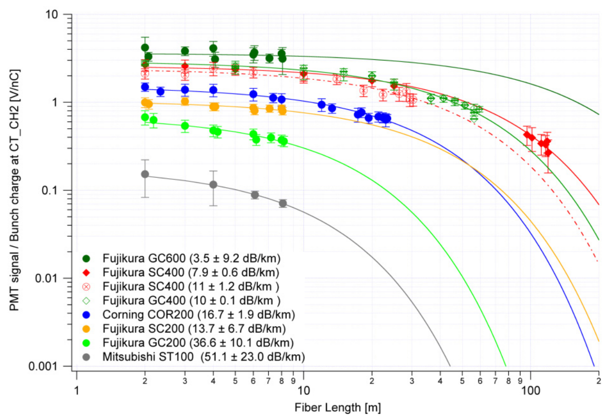

Figure 2: Signal from the PMT normalized by the average beam charge impacting the OTR screen as a function of the fiber length. The legend gives the values of the attenuation obtained from the fits.

DISPERSION

Multimode and chromatic dispersions distort the optical signal as it travels down the fiber, resulting in pulse broadening: Dispersion will affect the time and therefore

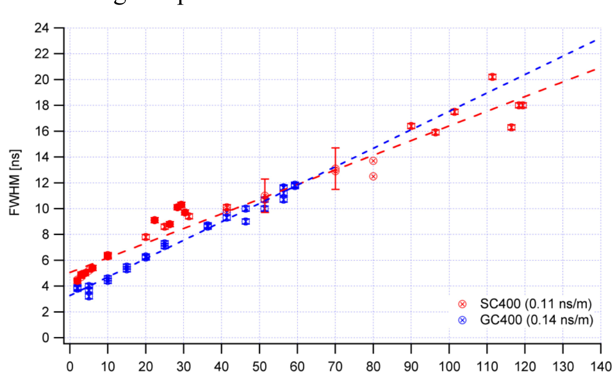

Figure 3: FWHM of the PMT signal as a function of the fiber length.

the spatial resolution of the beam loss detector. Fig. 3 shows the full width at half maximum of the Cerenkov signal measured with the PMTs as a function of the fiber length for the Fujikura GC and SC 400. As can be seen from Fig. 3, the GC and SC 400 have the similar dispersion (≈ 0.14 ns/m within experimental errors): The dispersion of the Cerenkov signal in the fiber is mainly due to chromatic dispersion.

DETECTION LIMIT

Two methods have been used to evaluate the detection limit of the system: With the fiber set along the accelerator, one has measured either the signal generated by inserting an OTR screen, or the signal from a natural beam loss. In each case, both the signal detected upstream and downstream (with respect to the direction of propagation of the electron beam) were measured. The results, calculated for a detection level set at 10 mV, are summarized in Table 2 for the Fujikura SC400 fiber.

Table 2: Detection limit (Fujikura SC400) at 10 mV

Fiber Length	**OTR induced loss**		**Natural Beam loss**	
	Direction with respect to the e- of propagation			
	Upstr.	Downstr.	Upstr.	Downstr.
60 m	0.6 pC	0.9 pC	< 1pC	< 0.1pC
120 m	1.8 pC	2.6 pC	< 3pC	< 0.3 pC

Figure 4 shows a typical signal measured during user operation (lasing at 60 nm) in the SCSS chicane located just before the undulators. No beam loss is detected from the difference between the upstream and CT monitors. The downstream signal is four times larger than the upstream signal: The detection of both signals is therefore important for an optimum operation of the beam loss monitor. The fine structure of the main peaks is also clearly visible: With a temporal discrimination of a few ns, it becomes possible to detect different beam losses occurring within a short distance from each other.

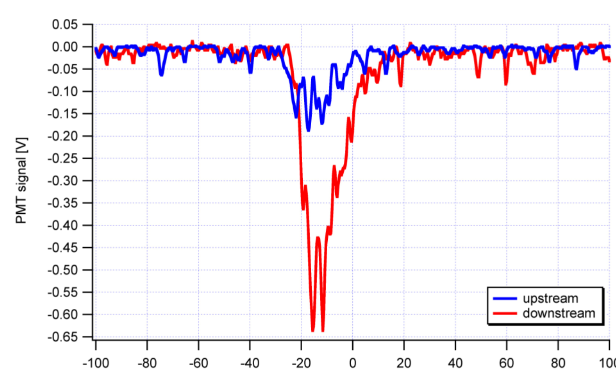

Figure 4: Beam loss signal (Fujikura SC400, single shot, 2.5 GS/s). The fiber is set so that the PMT is located 120 m upstream/downstream from the loss point.

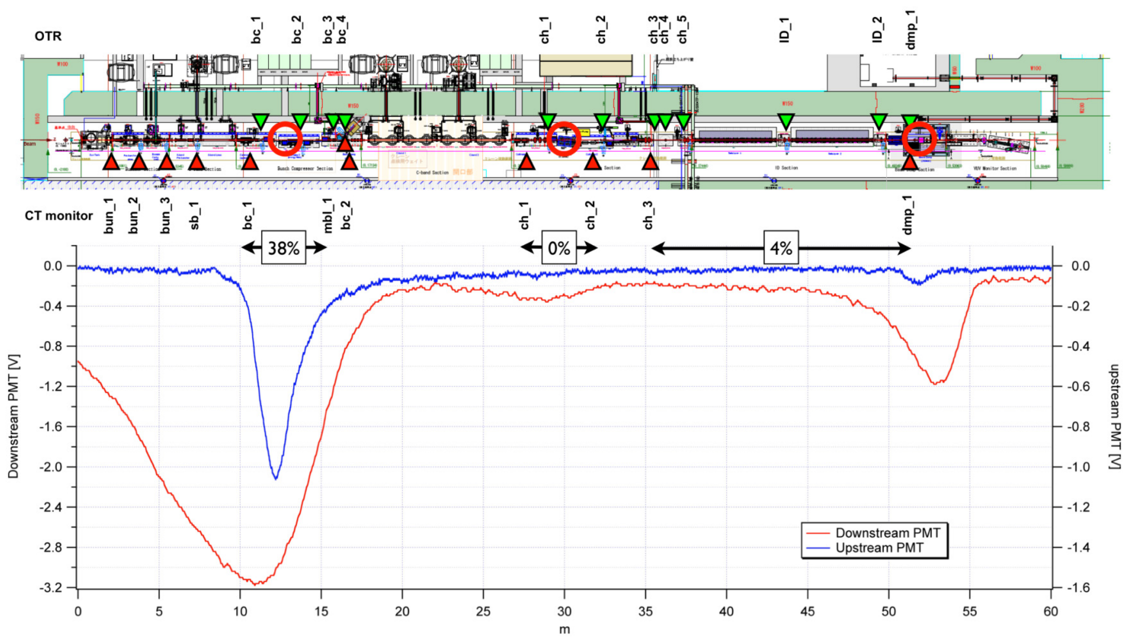

Figure 5: A typical beam loss measured on the SCSS prototype accelerator (single shot). Top: View of the SCSS accelerator with the location of the OTR and CT monitors (green and red triangles respectively). Bottom (b): The signals from the upstream and downstream PMTs. The percentages give the beam losses as measured by the CT monitors. The red circles indicate the position of the loss points.

Figure 5 presents a typical beam loss measured at the SCSS (single shot). The fiber was set along the vacuum chamber, from the first chicane up to the beam dump. The energy of the electron varies from 50 MeV (before the C-band section) up to 250 MeV (after). The signals from both chicanes are clearly visible (although no beam loss is detected by the CT in the second chicane). A few percents of the beam are lost before the beam-dump.

LIFETIME

Optical fibers are known to be susceptible to radiation damage. The production of color centers translates into radiation-induced attenuation, the deterioration of the fiber optical performance being higher at shorter wavelengths. So far no radiation damage has been observed in the 600 to 850 nm range. The fiber lifetime at the Spring-8 8 GeV/XFEL has been estimated using data available for multimode fibers (average 3 dB/km/Gy [5]) and dose measurements at the SCSS (a maximum of 0.008 Gy/h in the ID section in routine operation [6]): Assuming a 1 m length irradiated at the maximum dose, the fiber lifetime is over 13000h for a 1 dB loss.

SUMMARY

The ultimate detection limit of a fiber based beam loss monitor is strongly dependent on the fiber characteristics. While small core fibers are limited to short lengths, for larger core diameters, the practical length will not exceed a few hundred meters, depending on the desired detection level. Beam tests showed that at 250 MeV the detection limit corresponding to a 10 mV signal is below 1 pC/bunch over 60 m and 3 pC/bunch over 120 m. The position accuracy was found to be better than 30 cm.

A practical, online, version of the beam loss monitor is now under development: The signal from fibers set along the vacuum chamber will be read out by a Flash-ADC. The waveforms will be used to determine the position of the beam loss along and perpendicularly to the beam direction. Studies (Numerical and experimental) are planned to estimate the amount of the loss as a function of the amplitude of the signal. First tested on the SCSS this beam loss monitor should be installed on the SPring-8/XFEL when it comes into operation.

ACKNOWLEDGMENTS

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