Nuclear Instruments and Methods in Physics Research A 673 (2012) 32–45

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Design, development, and operation of a fiber-based Cherenkov beam loss monitor at the SPring-8 Angstrom Compact Free Electron Laser

X.-M. Maréchal [1], Y. Asano *, T. Itoga [1]

XFEL Project, RIKEN/SPring-8 1-1-1 Koto Sayo Hyogo 678-5148, Japan

ARTICLE INFO

Article history:
Received 14 October 2011
Accepted 23 December 2011
Available online 12 January 2012

Keywords:
Radiation safety
Radiation damage
Beam-loss
Cherenkov
Light sources
FEL

ABSTRACT

A fiber-based Cherenkov beam loss monitor (CBLM) consisting of large core (400 μm), long ($\geq$ 150 m) multimode fibers, has been developed as an online long-range detection tool with high sensitivity and good position resolution for the 8 GeV SPring-8 Angstrom Compact Free Electron Laser: primarily designed for radiation safety in order to limit the dose outside the shielding of the machine, this monitor also serves as an early warning tool to avoid radiation damages done by lost electrons to the undulator magnets. This paper presents the approach chosen to insure that the required sensitivity ($\leq$ 1 pC) could be obtained over more than 100 m. A beam-based approach was used to characterize (attenuation and signal strength) different fibers (diameter, index profile, and numerical aperture) and to select the most appropriate one. The response of the detector has also been studied numerically for different geometries (vacuum pipe and in-vacuum type undulators), beam energies, and beam loss scenarios, to determine the optimum number of fibers and their position in order to achieve the required detection limit. The results of the first few months of operation show that the SPring-8 CBLM can detect beam losses of less than 0.5 pC over the full 150 m length of the fiber.

1. Introduction

Optical fibers have been used as radiation detectors for more than 20 years in a wide range of experiments, from the diagnostic system used in the LANL nuclear testing program [1], to beam diagnostic in accelerator [2,3] calorimetry in high energy physics [4], dosimetry in radiation therapy [5], or fission reactor monitoring [6]: Being small, flexible, and acting both as the detection and the transmission medium, optical fibers allow the measurement of particle distributions in remote/hard to access locations [7,8]. For particle accelerators, optical fibers offer the possibility to monitor beam losses over long distances in real time, with good position accuracy and sensitivity at a reasonable cost: 10 years ago several high energy physics accelerators and light sources (synchrotrons and free electron lasers) have started to work on the development of fiber based beam loss monitors using the scintillation and/or Cherenkov effects (Table 1). These detectors are used to monitor and control the beam losses in order to limit the dose outside the shielding of the machine and/or prevent damage to critical components such undulators in free electron lasers.

The SPring-8 Angstrom Compact Free Electron Laser (SACLA) consists of a 400 m long accelerator, with a maximum electron energy of 8.5 GeV and a 60 Hz repetition rate, and up to five beamlines set in parallel, with 110 m long undulators. Beam losses are an important radiation safety issue in the undulator hall where shielding considerations impose a stringent 0.1% limit on beam losses: A fiber based monitor was chosen as the best candidate to achieve the required detection limit over more than a hundred meter with sub-meter position resolution and in real time. Beam losses are also a concern for the lifetime of the permanent magnets of the in-vacuum type undulators: radiation damage to permanent magnets are known to be a challenge for light sources [19]. FLASH simulations give a 10% FEL power loss for a 0.5% field loss [20]. For the SACLA a 1% demagnetization of the undulator magnets over 10 years has been arbitrarily set as the maximum allowable limit. Although the geometry of magnets being different (a direct extrapolation is not straightforward) experimental results for 8 GeV electrons [21], suggest that this can be reached with $\sim 10^{14}$ electrons hitting the magnet array. With a target detection limit of 1 pC/pulse (corresponding to a 0.1% beam loss of the initial 1 nC/pulse) or 6×10^{6} electrons/pulse, the monitor can easily serve as an early warning tool.

In the following, we report on the design, development and operation of a fiber based Cherenkov beam loss monitor (CBLM) at the SACLA. First the performances of scintillating fibers and glass fibers (Cherenkov effect) were compared to find the best candidate for the realization of a long (> 100 m) beam loss monitor. Glass fibers of different diameters, grades, and index profiles were then tested and characterized (signal strength and attenuation) using a beam based approach. Tests were done at the SPring-8 Compact

* Corresponding author. Tel.: +81 791 58 0802x3843; fax: +81 791 58 2946.
E-mail address: asano@spring8.or.jp (Y. Asano).
[1] Present address: Japan Synchrotron Radiation Research Institute, 1-1-1 Koto Sayo Hyogo 678-5178, Japan.

0168-9002/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2011.12.094

Table 1
Summary of experiments done by different facilities to develop of a fiber-based beam loss monitor. This list does not pretend to be exhaustive but to present a broad overview of recent research efforts. The fiber reference, type (Sci: scintillation fiber based monitor; Cer.: Cherenkov based monitor), diameter, length, and relevant references. The J-PARC studies were carried out at KEK.

Facility	Particle	Energy (MeV)	Fiber	Type	φ (mm)	L (m)	Ref
KEK	Proton	40–500	Kuraray SCSF-81M	Sci.	2	3	[9–11]
			Fujikura 600/750	Cer.	0.6	3	
FLASH	Electron	4	Mitsubishi ST 100/150	Cer.	0.1	40, 50	[12–15]
		135	Mitsubishi ST 100/150	Cer.	0.1	100	
		230	Loptek	Cer.	0.1×7		
		1000	Heraeus Tenevo SSU	Cer.	0.3	35	
DELTA	Electron	1500		Cer.	0.3		[16,17]
J-PARC	Proton	500	Kuraray SCSF-81M	Sci.	1.5		[18]

Table 2
Main characteristics of the fibers: maker, maker's reference, index, core diameter, numerical aperture (*NA*) and length of the sample.

Maker	Reference	Index	Diameter (μm)	*NA*	Length (m)
A	COR-200VIS39	Step	200	0.39[(1)]	25
B	GC200/250	Graded	200	0.21	10
	GC400/440	Graded	400	0.21	61
	GC600/750	Graded	600	0.21	10
	SC200/250	Step	200	0.22	10
	SC400/440	Step	400	0.21	32
	SC400/440	Step	400	0.22	121, 151 × 3
C	ST100A	Step	100	–	10

SASE Source (SCSS) test facility, a 1/16th model of the full scale XFEL [22]. One hundred and fifty meter long fibers were installed on the first two SACLA beamlines. The commissioning of the detector, as well as numerical evaluation of the monitor performances and actual beam losses are presented.

2. Fiber based beam loss monitor

Fibers from different makers, various types (regular and scintillating fibers), diameters, numerical apertures, and index profiles (step or graded) have been tested (Table 2). The attenuation of the scintillating fibers (>100 dB/km) is at least one order of magnitude stronger than that of the glass fibers: tests carried out at the SCSS have emphasized the superiority of a system based on the Cherenkov effect (long detector length and better position resolution) over scintillation (large attenuation limiting the practical length of the fiber, sensitivity to a wide range of particles, several ns decay time). An example of signals measured at the SCSS with a regular glass fiber (Cherenkov emission) and a scintillating fiber is shown in Fig. 1: the fibers were set parallel to the vacuum chamber in the chicane section located after the C-band accelerator, and the signal measured with and without the main electron beam. In the first case, the RF power is on but the main beam is off: only the beam loss due to the dark current originating from the C-band structures is visible: The signal from the glass fiber (Cherenkov) has actually the same time structure as the pulse of dark current. In the second case, the main beam is switched on and an upstream screen monitor is lowered down into the beam pass to generate a beam loss. While scintillating fibers have a strong response to irradiation, their high attenuation limits their use to few tens of meters length. Conversely, the Cherenkov signal is significantly smaller for minute beam losses, but since attenuation lengths are at least one order of magnitude lower, longer fiber can be used. The sharpness of the Cherenkov signal when compared to the broad scintillation peak is also of prime importance for the spatial resolution of the system. This made Cherenkov radiation and glass fibers the most suitable combination for a beam loss detector covering a large area with submeter accuracy.

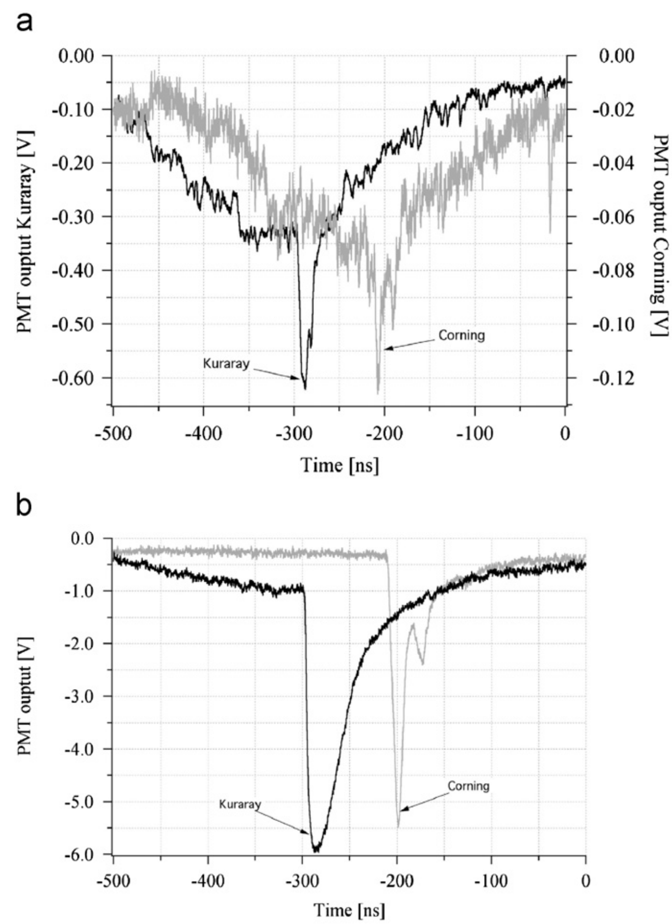

Fig. 1. Scintillation and Cherenkov signals measured in the last chicane of the SCSS (electron energy 250 MeV): without (left) and with (right) a screen inserted into the beam path. Both the fibers (scintillation: Kuraray SCSF-3HF(1500 J), diameter 1 mm; Cherenkov: corning, diameter 0.4 mm) were set parallel to the beam path, in contact with the vacuum chamber. The signals (left) are actually the signature of the dark current originating from the upstream C-band accelerator being lost in the chicane. The Cherenkov signal is only a few percents of the scintillating signal. The time distribution of the Cherenkov signal corresponds to the FWHM of the dark current (≈ 250 ns). The broadness of the scintillating fiber signal limits the monitor resolution. When a screen is inserted into the electron beam pass both signal have comparable amplitude.

The choice of the photomultiplier tube (PMT) results from a compromise between the attenuation and characteristics of the Cherenkov spectrum. Fig. 2 shows the amplitude of the Cherenkov spectrum after propagating in two typical UV–vis/NIR large core optical fibers (B: SC and GC) for distances of 2–200 m: the typical range of useful wavelength lies within 300–1000 nm. An additional