FIBER BEAM LOSS MONITOR FOR THE SPRING-8 X-FEL: A NUMERICAL STUDY OF ITS DESIGN AND PERFORMANCE

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Abstract

A fiber beam loss monitor is under development for the SPring-8 X-FEL with a target detection limit of 0.1 pC over 120 meters. Various parameters come into account in the final performance of the system, such as the impact angle and energy of the lost electrons, the fiber position with respect to the point of impact, the fiber characteristics, etc. Numerical studies have been carried out to investigate the performances of the system and compared with the experimental results obtained at the 250 MeV SPring-8 Compact SASE Source (SCSS), a 1/16th model of the future 8 GeV X-FEL.

MODEL AND METHOD

A fiber beam loss monitor (BLM) is under development for the SPring-8 X-FEL [1][2]. It is based on the detection of the Cerenkov light generated by charged particles ("Cerenkov emitter") hitting an optical fiber set along the vacuum chamber. Its response and detection limit have been evaluated from measurements at 250 MeV: The sensitivity of the BLM has been estimated to be better than 1.2 pC for the upstream and 0.15 pC downstream signals respectively, at 250 MeV over the 120 meters of the fiber. The performances of the BLM have been investigated numerically at 8 GeV.

The intensity of the Cerenkov radiation transmitted by bound rays in the fiber is proportional to

$$\frac{1-1/\beta^2 n^2}{\sin\psi_e}\cos^{-1}\left[\frac{\beta\sqrt{n^2-NA}-\cos\psi_e}{\sin\psi_e\sqrt{\beta^2 n^2-1}}\right] \qquad (1)$$

where n and NA are respectively the core index and the numerical aperture of the fiber [3][4][5]. The velocity of the Cerenkov emitter β (β=v/c) and ψ_e, the angle between the direction of propagation of the Cerenkov emitter and the fiber axis, were obtained from the distribution of the electromagnetic cascade calculated with EGS5 [6] for a filament beam of mono energetic electrons. Only part of the Cerenkov light is transmitted in the fiber. The light is transmitted if:

$$|\theta_c-\theta_A| \le \psi_e \le \theta_c+\theta_A \qquad (2)$$

where $\theta_c = \cos^{-1}(1/\beta n)$ and $\theta_A = \sin^{-1}(NA)$. For relativistic particles, n=1.46 and NA=0.219, the lower and upper limits are 34° and 60° respectively. At low energies these limits are shifted down to smaller angles (≥12.4°) .

In the following, the fiber response has been studied as a function of the angular position θ of the fiber with respect to the loss point, and of the angle of impact φ of the primary at 250 MeV and 8 GeV (Fig. 1). The index and numerical aperture were chosen to be 1.46 and 0.219 respectively, and are relevant to the fiber chosen for the SPring-8 X-FEL BLM.

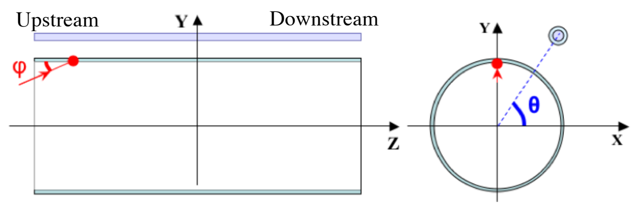

Figure 1: Geometry used in the calculations.

PRIMARY IMPACT ANGLE

Figure 2 shows the fiber response as a function of the impact angle of the primary on the vacuum chamber φ, for two fiber settings: Fiber just above the point of impact (θ=+90°) and at the opposite of it (θ =-90°). As

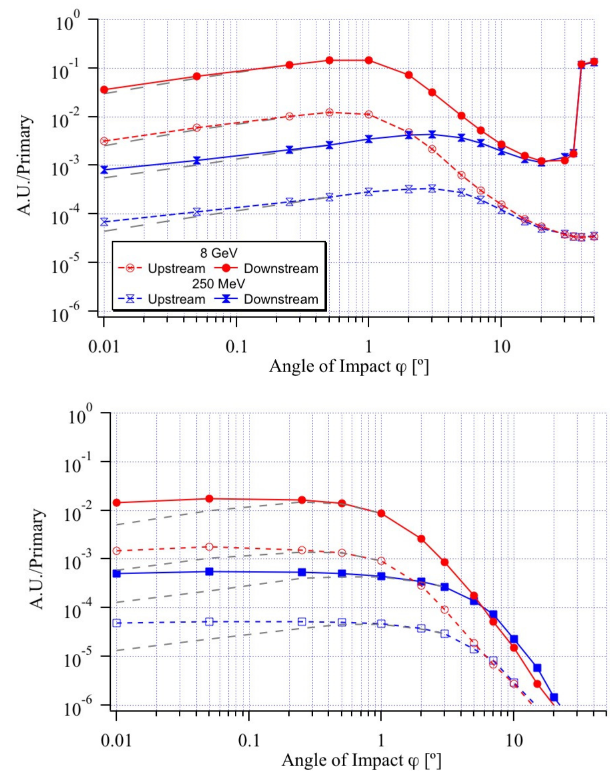

Figure 2: Fiber responses per primary electron as a function of φ the impact angle of the electron beam for a fiber located just above the point of impact (θ = 90°, top) and opposite (θ = - 90°, bottom). The grey dotted lines are for the responses measured within ±1 m of the point of impact.

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φ increases, the angular distribution (ψ_e in Eq. 1) of the electromagnetic cascade goes from broad (for $\varphi \leq 1^o$) to sharp with a peak at the value of the impact angle: Most of the emitted Cerenkov light falls outside the collection limit of the fiber (Eq. 2) and the fiber response decreases. As φ reaches the lower limit of the collection range (around 40º), most of the light is collected and the fiber response increases.

The number of the secondary particles is maximum above the point of impact and decreases away of it. As φ increases above 1º, the number of particles hitting the fiber decreases, and the amplitude of the signal drops sharply by several orders of magnitudes (Figure 2, bottom).

Finally, one should note that the response of the fiber is independent of the energy of the primary for impact angles above 10º.

ANGULAR POSITION OF THE FIBER

The results presented in figure 3 show how the angular position of the fiber with respect to the point of impact of the stray electrons on the vacuum chamber will affect the BLM sensitivity: The response of the fiber is plotted as a function of the angular position of the fiber (θ = -90º ~ 90º) for impact angles of the primary ranging from φ = 0.01º to 10º. Both the upstream and downstream signals follow the same distribution: A maximum at θ = 90º (Where the fiber just above the point of impact), followed sharp drop to a broad minimum around θ = 40º~50º and a slow rise to wide plateau (θ = 0º~ -90º).

The ratio of the maximum (θ = 90º) to minimum ($\theta \approx$ 40º-50º) fiber response increases with the value of the impact angle: From over one order of magnitude for φ = 1º to over two orders of magnitude for φ = 10º. It is difficult to use only one fiber to detect a loss occurring anywhere on the vacuum chamber circumference: While it is possible to increase the diameter of the fiber to improve the BLM sensitivity this is not enough to compensate for a decrease of one order in sensitivity. Therefore, to insure a minimum detection limit over a wide range of conditions it is necessary to set several fibers around the vacuum chamber. Finally, the flatness of the response in the half circle opposite to the loss point (-90º < θ < 0º) has to be taken into account when estimating the transversal distribution of the beam loss from the respective strengths of the signals of fibers set around the vacuum chamber.

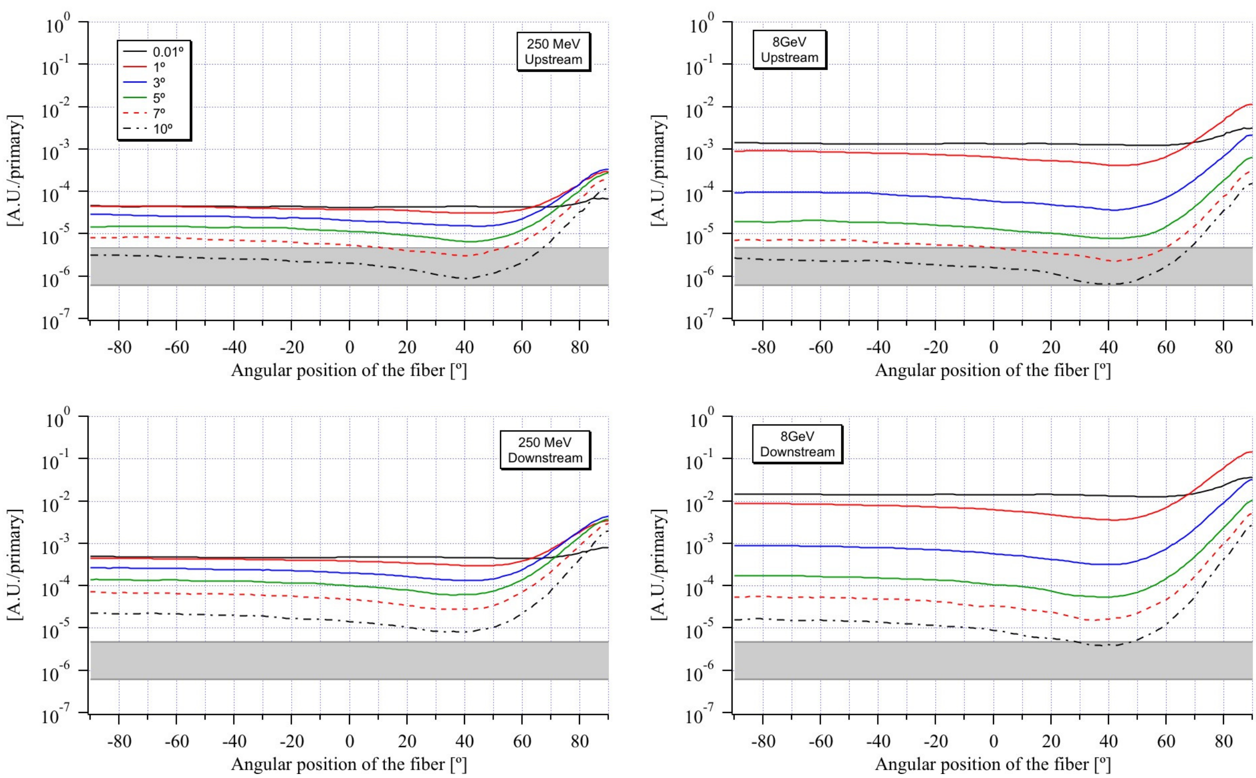

Figure 3: Fiber response per primary electron as a function of the position of the fiber θ for different impact angle of the electron beam (φ = 0.01º: Black line; 1º: Red line, 3º: Blue line; 5º: Green line; 7º: Red dotted line; 10º: Ggrey doted line). At θ = 90º the fiber is located just above the point of impact. Left: 250 MeV electrons. Right: 8 GeV electrons. Top: Upstream signals. Bottom: Downstream signals. Grey box: see text (Discussion).

DISCUSSION

Upstream vs. Downstream Signals

Because the electron beam and the Cerenkov photons move in the opposite direction, the Cerenkov signal travelling upstream gives a better spatial discrimination between consecutive beam losses, than the downstream signal (Cerenkov photons and electron beam moving in the same direction). However, this increased longitudinal resolution comes at the expense of a lower sensitivity: The number of secondary particles emitted upstream being smaller, the amplitude of the upstream signal is also smaller. An analysis of the results presented in Fig. 3 show that the fiber response calculated upstream is smaller by a factor 5 to 15, than the response calculated downstream. For larger impact angles (φ>10º) this effect is even stronger (Fig. 1). The ratio between the signals detected upstream and downstream (with respect to the direction of propagation of the electron beam) was in good agreement with experiments: Measurements of the beam losses in the chicane of the SCSS gave a downstream signal seven times larger than the upstream signal [1]. Both the upstream and downstream signal will be used for a proper detection of the beam loss.

8 GeV vs. 250 MeV

The BLM sensitivity has been evaluated from measurements to be better than 1.2 pC upstream and 0.15 pC downstream at 250 MeV over 120 m. The sensitivity at 8 GeV can be estimated from the results presented in figure 3. At grazing incidence (Impact angle $\varphi \leq 1$º) both the upstream and downstream detection limit of the BLM will improve by at least one order of magnitude at 8 GeV, with an average factor of 20 and a maximum of 45. As the impact angle φ increases, the difference between the fiber response at 250 MeV and 8 GeV decreases. At 3º, the response of the fiber from a 8 GeV beam loss is only 3 times larger in average than the response at 250 MeV (With a maximum of 7). Above 5 º, both the response of the fiber to a 250 MeV or a 8 GeV beam loss are similar.

The results presented in figure 3 can also be compared with the simulation results of experiments using artificially induced losses at the SCSS. In these experiments, a screen was inserted into the beam path and the response of the fiber measured [1]. Simulations give a response of 2.6 10^{-7} A.U./primary for a corresponding 4.1 V/nC signal. Given this value, the limit corresponding to a 10 mV/1pC goes 6.3 10^{-7} (@ 0m) to 4.8 10^{-6} (@120m (Signal attenuation 7.3 dB/km [1]). The upper and lowed edges of the grey box in Fig. 3 show these limits.

Variation of n and NA with the Wavelength

The results presented above are for constant index and numerical aperture. However, both the index and the numerical aperture are wavelength dependent, typically several percents over the range of interest. When calculating the response of the BLM (including the spectral characteristics of the Cerenkov spectrum, the photomultiplier tube sensitivity) should full wavelength dependence be used in the simulations or can constant values used? Often data are not available as was the case for the SC fibers used here (only one value of NA was given by the manufacturer). Using constant values also greatly increase the speed of the simulations. To estimate the effect of the wavelength dependence of n and NA we have compared the results obtained with (Germanium doped core: 1.53 @ 250 nm $\geq$ n $\geq$ 1.46 @ 880 nm; Pure silica clad: 1.51 $\geq$ n $\geq$ 1.45; 0.215 $\geq$ NA $\geq$ 0.206) and without (Average values: Core index n= 1.48 and NA=0.210) wavelength dependence. We found from results at φ = 2º and 10º for θ = -90º ~ 90º that, within the margin of errors of the calculations, the difference is constant over the whole angular range. Using constant value for n and NA is enough to evaluate numerically the relative performance of the BLM.

CONCLUSION

A fiber beam loss monitor is under development for the SPring-8 X-FEL with a target detection limit of 0.1 pC over 120m. Measurements showed that the sensitivity of the BLM is expected to be better than 1.2 pC/bunch (Detection by the upstream PMT) and 0.15 pC/bunch (Detection by the downstream PMT) over 120 m at 250 MeV. Results from simulation show that the sensitivity of the BLM will improve at 8 GeV: For electrons with grazing incidence on the vacuum chamber, the sensitivity will improve by up to one order of magnitude. Results from experiments at 250 MeV compared to simulations indicate that for small angle of incidence ($\varphi \leq 5$º $\approx$ 90 mrad) the BLM will have a resolution better than 1 pC over 120 m, whatever signal is used (Upstream or downstream) at 8 GeV.

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