OPTICAL-FIBER BEAM LOSS MONITOR FOR THE KEK PHOTON FACTORY

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Abstract

A beam loss monitor using optical fibers has been developed to determine the loss point of an injected beam at the Photon Factory (PF) 2.5-GeV electron storage ring. Large-core optical fibers were installed along the vacuum chamber of the storage ring that cover the entire storage ring continuously. Two injection systems: kicker magnets and a pulsed sextupole magnet, are used for routine operation at the PF. In this paper, details of the loss monitor system and the difference in beam loss when using the two injection system are reported.

INTRODUCTION

In the KEK Photon Factory (PF) 2.5-GeV storage ring, an electron bunch is injected directly from a linear accelerator (linac) that is shared by KEKB-HER, -LER and PF-AR [1]. The three rings (PF, KEKB-HER, -LER) share the linac pulse-by-pulse at a maximum rate of 50 Hz. Because ambient temperature affects the stability of a large water cooling plant, we sometimes need to adjust the injection parameters—such as injection energy or injection angle to the storage ring. A beam loss monitor with high position and time resolution is strongly desired for this kind of tuning procedure for the PF-Ring.

Many kinds of loss monitor have been proposed and used in many different facilities [2]. For example, a loss monitor with a PIN diode can detect very small losses, but is easy to saturate with background X-rays or lost electrons during injection. Another problem is that a large number of detectors is required to cover the entire ring. A pulse-counter type detector is suitable for average loss detection, but the time resolution is no better than 1 revolution time (624 ns) in the PF-Ring. The other candidate is an ionization chamber constructed using coaxial cable applying a high voltage. We did not select this type of detector due to the limited space in our ring, and they are relatively heavy and an obstacle to maintenance work.

The use of a beam loss monitor using optical fibers is common in many linear accelerators or FEL facilities[3-6]. In the KEK linac, loss detection using optical fibers has been developed—starting from an arc sensor for the accelerating tube—since before 2007 [7]. Optical fibers are suitable for our purpose because of the ease of covering the entire ring with them, they have better time and position resolution than other methods, and they are cost effective. On the other hand, they have disadvantages, such as needing an external trigger, their difficulty in detecting CW loss, they provide small coverage in the plane perpendicular to the beam, and there is difficulty in the calibration of absolute beam loss.

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In this study, first we tested the fiber beam loss monitor in a location where the normalized horizontal aperture is small, then we installed a total 10 fibers to cover the circumference of the entire ring circumference.

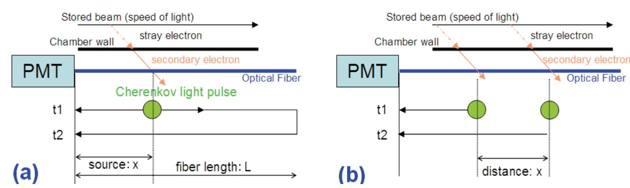

Figure 1: Schematic drawing of detection principle for: one loss point (a), and two loss points (b). In both cases, the loss is coming from a single bunch.

PRINCIPLES OF LOSS DETECTION

Electrons that are not captured in the storage ring hit the vacuum chamber wall and produce secondary electrons outside the vacuum chamber. Secondary electrons that run through quartz fiber generate Cherenkov light provided the energy of the electrons is high enough. As shown in Fig. 1, a photomultiplier tube (PMT) is used for the detection of a light pulse. There are three candidates for the PMT layout: one PMT at the upstream end, one PMT at the downstream end, and a PMT at both ends of the fiber. We opted to use one PMT on the upstream side because of its better time resolution than the downstream end, and the small reflection produced by the opposite side of a fiber can determine the exact location of the light pulse.

With one loss point, as shown in Fig. 1(a), the source position is determined by measuring the arrival time of the direct light (t_1 in the figure) and the reflected light (t_2), using simple arithmetic $x=L-(t_2-t_1)*v_{fiber}/2$, where v_{fiber} is the speed of light propagation in a glass medium, which is equal to $^2/_3$ the speed of light in a vacuum (v_c).

Figure 1(b) shows a case where two light pulses are produced by a single passage of a bunch. The time difference between two direct pulses becomes longer because the direction of the electron bunch and the light pulse are opposite. It is useful to introduce an "effective" propagation time for the calculation of two direct pulses: $v_{eff}=2/5*v_c$ (equivalent to 8.3 ns/m).

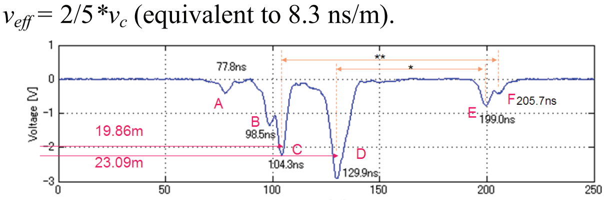

Figure 2: Determination of loss location.

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Figure 2 shows an example of PMT output measured in the PF-Ring during injection. We can observe large peaks marked as B, C, and D in the figure and small peaks at E and F. In order to determine which pulses are coming from a direct path or a reflected path, we attached a reflector on the downstream end of the fiber.

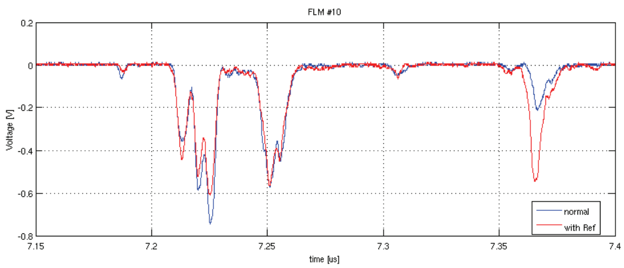

Figure 3: Signal without (blue) and with (red) reflector.

Figure 3 shows examples with and without a reflector. In this way, we determined that peaks E and F in Fig. 2 are reflections from the downstream end. Next, by assuming peak E to be a reflection from D and by applying the method in Fig. 1(a), the distance from the PMT to peak D is estimated to be 23.08 m. In the same way, the distance of peak C is estimated to be 19.86 m from the PMT by assuming peaks C and F are a pair. We can conclude that the distance between peaks C and D is 3.23 m from the reflection signal.

To cross-check this measurement, it is important to utilize the time difference of peaks C and D. By applying the procedure in Fig. 1(b), the distance between C and D is estimated to be 3.1 m, which shows good agreement with 3.23 m. On the downstream-end of the fiber, peaks B and C are squeezed and only one peak—F—is observed.

MEASUREMENT SETUP

We selected 600-µm core, all-silica, low-OH, step-index large-core optical fibers, manufactured by OFS Furukawa Co. They were installed along the inner wall of the vacuum chamber to cover the entire storage ring continuously. Figure 4 shows an example of installation. In total, 10 optical fibers with a length of 30 m were used. Both ends of the fibers are fed out through the radiation shield of the ring, and a photomultiplier tube (H10721-110, Hamamatsu Photonics, with a wavelength of 230-700 nm) is attached to the upstream side of the fibers. The sensitivity of the PMT is sufficiently high to detect loss at the PF-Ring, and its short rise-time of about 0.6 ns is fast enough to determine the location of the beam loss point. The PMT has a built-in high-voltage power supply. A standard oscilloscope (Rohde&Schwarz RTO1024) together with the external injection trigger was used for the measurements.

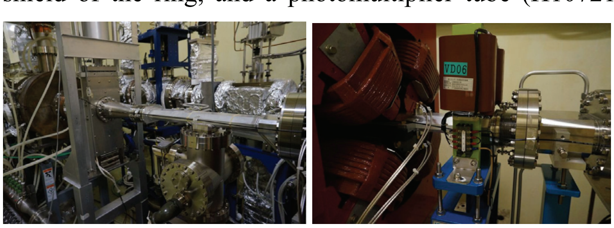

Figure 4: Black cables mounted on the side of the vacuum chamber are the optical fibers for the loss monitor. The fibers can be fed through the magnet due to the non-magnetic nature of the medium.

In order to reduce the number of PMTs and fibers, the PMTs can be sited on the inside of the radiation shield wall or optical fiber cables longer than 50 or 100 m can be used. The disadvantages of such an approach includes the fact that identification of the beam loss point becomes slightly more complicated, connecting or removing PMTs during machine operation is not possible, and the attenuation of the light pulse becomes larger. We are reviewing the optimal number and length of fibers, before putting optical fibers on the outside, top and bottom of the vacuum chamber.

RESULTS

Figure 5 shows the results for turn-by-turn loss detection of an injected beam. Note that the vertical axis is auto-scaled, and not every turn is plotted. On the first turn, the beam is lost upstream of undulator U#02 indicated as 1 and 2 in red in the figure. On the second turn or fourth turn, a large loss is detected downstream of

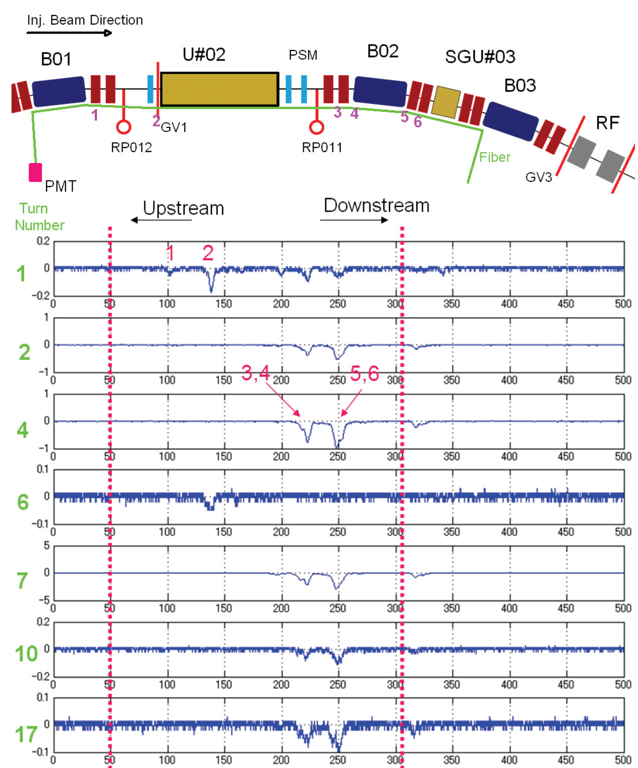

Figure 5: Layout of storage ring components and optical fibers (top) and detected loss signal (bottom) on each turn. The electron beam travels from left to right in the figure.

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the pulsed sextupole magnet (PSM). Large losses are observed on the 2nd , 4th , 7th turns because the horizontal tune is equal to 9.60 in the KEK-PF. Taking into account the injection angle and normalized apertures of the storage ring, the result agrees with the simulation.

Triggering the septum and kicker magnets without an injection beam does not result in a peak in the PMT output, and we confirmed the beam loss shown in Fig. 5 is not emanating from a stored beam. The signal-to-noise ratio is good enough to distinguish the loss from the stored beam or other PMT noise from the loss signal of the injected beam.

The peaks in the figure appear in locations where the fibers are attached to bellows or the thickness of the chamber wall is thinner than in other locations.

Position resolution depends on the rise time of the PMT and the length of the fibers and cables between the PMT and oscilloscope. From the output signal, we can distinguish two peaks at 2-3 ns apart, which corresponds to a position resolution of about 30 cm. The resolution is good enough compared with the distance between accelerator components.

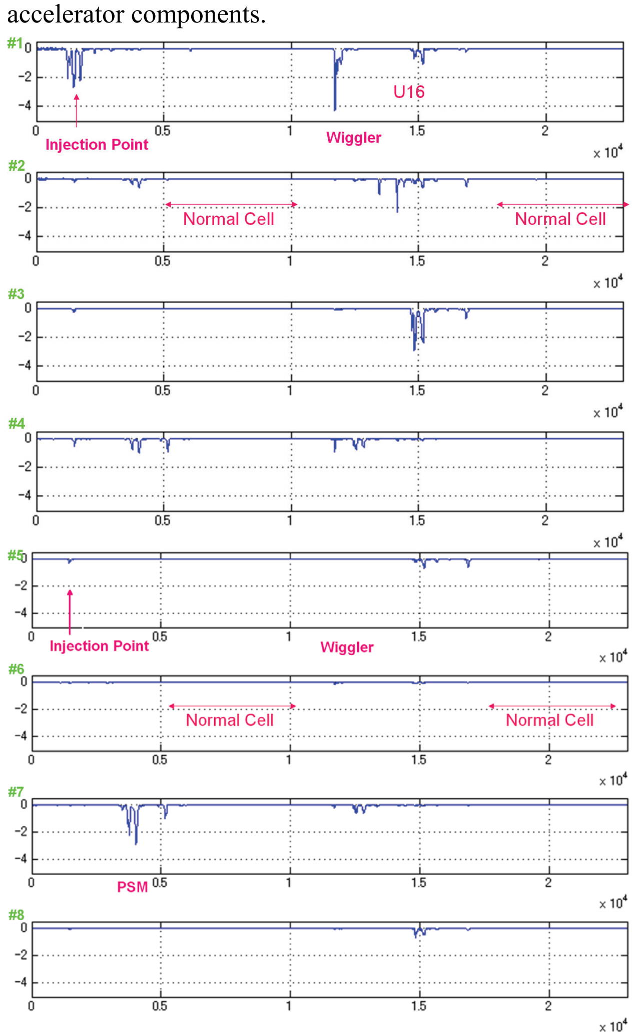

Figure 6: Beam loss over the whole ring. In each row, the horizontal full scale corresponds to the entire ring circumference of 187 m.

Beam Losses of Entire Ring Circumference

Figure 6 shows beam loss for the entire ring. We used the same PMT with the same gain to measure all 10 fibers to ensure the output voltage of the PMT is equal to the same beam loss. Of course this is not an accurate measurement because the detected losses depend on the thickness of the walls of the vacuum chamber, however, it is still useful for an approximation of beam loss around the ring. The beam loss shown in Fig. 6 is the summary of 10 injections. The peak voltage of each signal depends on the charge, energy spread and position of the injected beam. We confirmed the output voltage and the loss location are sometimes different pulse-to-pulse, but show almost a similar loss pattern. Figure 6 shows a typical pattern during kicker injection.

In the KEK-PF, the horizontal normalized aperture is small at three locations: septum magnet, vertical wiggler, and pulsed sextuple magnet. These locations show a large loss, as expected. The aperture is large at a normal cell, and there is almost no loss there.

Kicker and PSM Injection

Two injection systems have been used for routine operation: kicker magnets and a PSM. The fiber loss monitor is useful for analyzing the turn-by-turn difference of the beam loss pattern. Figure 7 shows an example of PMT voltage with the two injection methods measured downstream of the vertical wiggler. Kicker injection shows a large loss at the first turn and fourth turn, whereas PSM injection shows no loss of beam at the first turn, but a large loss at the second turn. The pulsed sextupole magnet deforms distribution in the phase space of the injected beam, so the loss point is different from kicker injection. Detailed analysis and optimization of injection parameter for PSM injection are under way.

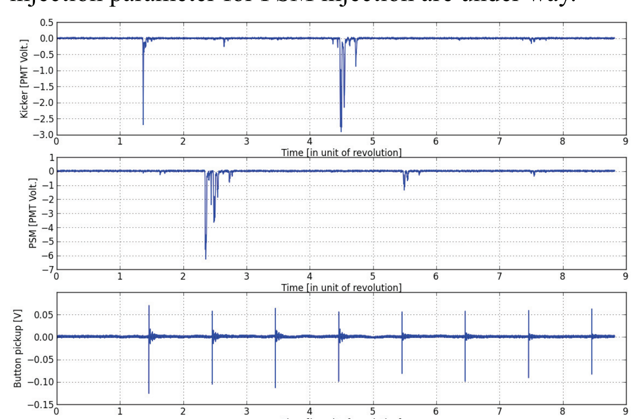

Figure 7: Beam loss measured using two injection systems: kicker magnets (top) and a pulsed sextupole magnet (middle). The bottom figure shows the signal from a button pickup electrode near the vertical wiggler. No beam is stored in the ring prior to injection. The horizontal axis represents the turn number, namely, time in unit of revolution of the PF-Ring.

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DETERIORATION BY RADIATION

At the time of writing, the optical fibers have been mounted on the vacuum chamber for about a year since installation. Total operational time of the PF-Ring was about 9 months during this period. We measured the transmission factor of the optical fibers and found that there was no significant deterioration after the 9 months of operation. One fiber showed a 6 % decrease in transmission factor, but that was located in the normal cell where there is no loss during injection. We assume the decrease to be the result of vacuum working at the location because we must remove the fibers from the vacuum chamber during operation. This factor of 6 % has almost no effect on loss measurement. There remains ambiguity in the transmission factor measurement. Because we did not have a good light source in the range of PMT, we measured the transmission using a wavelength of 850 nm. This is different from the PMT range and is not the wavelength of Cherenkov light. A new light source for the transmission measurement will be available soon.

SUMMARY AND FUTURE PLAN

A beam loss monitor using optical fibers was developed to determine the loss point of an injected beam at the PF-Ring. The time resolution was good enough to distinguish a distance of about 30 cm along the vacuum chamber, and turn-by-turn measurement was achieved.

Development of a real-time display system that can cover the entire ring with every injection bunch is under way. This will become an indispensable tool for the tuning of the linac, beam transport line and injection parameters. The same beam loss detection system will be adopted for the compact ERL in KEK, where beam loss detection is a key issue for operation.

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