A DEVELOPMENT OF HIGH SENSITIVE BEAM PROFILE MONITOR USING MULTI-SCREEN

Yoshinori Hashimoto[#], Masaki Tejima, Takeshi Toyama, KEK/J-PARC, Tokai, Ibaraki, Japan
Toshiyuki Mitsuhashi, KEK, Tsukuba, Ibaraki, Japan
Satoru Otsu, Mitsubishi Electric System & Service Co. Ltd., Japan.

Abstract

In order to absorb the halo component, a beam collimator system was installed in the beam transport line from a 3 GeV rapid cycling synchrotron (RCS) to the main ring (MR) in J-PARC, which is called as the 3-50BT line. The observation of beam halo as well as beam core is very important for the adjustment of the beam collimator system. We have developed a monitor to observe two-dimensional beam profile with a large dynamic-range. The monitor has been installed in 122 m downstream from the beam collimator in the 3-50BT line. For measuring the beam core and the halo alternatively, the monitor has three kinds of screens. The first one is titanium foil OTR screen (thickness of 10 μm) to measure a beam core, the second one is aluminum foil OTR screen (thickness of 100 μm) with a hole (50 mm diameter) in the center and the last one is a pair of alumina fluorescent screen with a separation of 80 mm in horizontal to observe the beam halo in surroundings. We designed an optical system based on the Offner optics for the observation of OTR and fluorescence. This optical system has an entrance aperture of 300 mm and it can cover the large opening angle (± 13.5 degree) of the OTR from 3 GeV protons. A CCD camera with an image intensifier (II) was use to observe the profile. We have succeeded to observe a profile of beam halo to 10^{-6} order to the peak of beam core by using proton beams of 3 GeV, 9.6 x 10^{12} protons / pulse by this multi-screen scheme.

INTRODUCTION

The beam profile monitor which is detectable halo region, particularly in operation for high intensity accelerator, has important role of diagnosing beam tail after the beam collimation for preventing beam loss. Further the two dimensional beam profile offers more advanced information.

We had first developed a two-dimensional beam profile monitor [1] using OTR. The monitor had detected light produced by proton beam intensity of more than 5x10^{11} pulse / bunch.

At present we are developing in order to obtain high sensitivity for halo measurement particularly. Concretely, we are making progress on sensitive detector and on larger yield in light focusing. These points of view are improvement in sensitivity for OTR only. From another viewpoint it is considerable using other light from more sensitive screen not only using OTR light, and we employed this time to use fluorescence (FL). Particularly alumina screen of Chromium (Cr) doped Al_2O_3 has highly light emission and longer persistence. These characteristics become advantage for sensitivity up, because larger light yield is gained with longer exposure.

MULTI-SCREEN AND OPTICAL SYSTEM

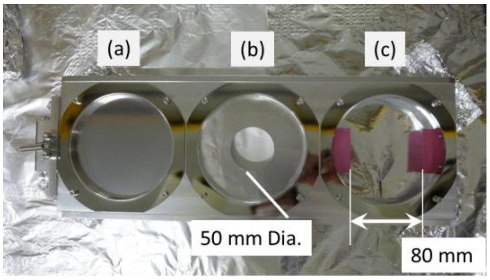

Figure 1: The multi-screen. (a) solid Screen, (b) hole-screen, (c) alumina screen.

The multi-screen consists of triple circular screen housed in a rectangle frame as shown in Fig.1. Each inner diameter of the ring is 120 mm and the pitch is 150 mm. The frame moves horizontally by linear actuator with stepping motor for changing screen and for positioning edges of alumina screen.

The un-flatness of the solid screen (Fig.1 (a)) made of titanium foil is 22 (± 7.5) mm [2]. The hole-screen having 50 mm diameter hole in the center (Fig.1 (b)) has a role of using in measurement around the beam core by OTR, alumina screen (Fig.1 (c), Kyocera A486) has a role of halo detection using FL.

The optical system had been designed with assumption of OTR light produced by 3 GeV proton beam. OTR light has characteristics strongly depends on relativistic factor of γ. Emitted photon number is described below as a function of emitted wavelength region between ω_1 and ω_2[3],

$$N = \frac{2e^2}{\pi\hbar c}\left|\ln(2\gamma)-\frac{1}{2}\right|\ln\frac{\omega_2}{\omega_1} \qquad (1)$$

In case of 3 GeV proton incident, emitted photon number in visible light region becomes 2.5×10^{10} photons / 10^{13} protons [1]. Next angular distribution of the emitted light is depends on γ and light velocity ratio of β as described below [3],

$$I(\theta)=\frac{1}{\gamma^2}\left|\frac{-\sin(\theta)}{1-\beta\cos(\theta)}\right|^2 \qquad (2)$$

[#] yoshinori.hashimoto@kek.jp

The opening angle of 3GeV proton incident has large peak separation angle of about 27 degree (Fig.2).

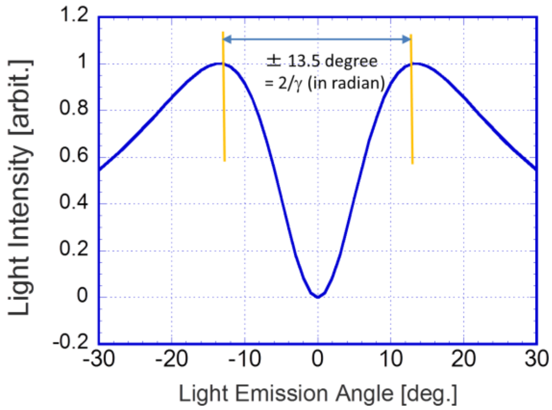

Figure 2: Calculated OTR opening angle ($I(\theta)$).

Besides our typical beam size including halo at the setting point was estimated as about 100 mm. Then we had fabricated an optical system based on an Offner relay optical system (OOS), which having large angle acceptance of about 30 degree [1, 2] (Fig.3). For an original Offner scheme, in our scheme a concave mirror is separated into two segmented mirrors of the upper and the lower, further the upper concave mirror has beam hole at the center of 120 mm diameter. The outer diameter of the concave mirrors is 300 mm, and the radius of the curvature is 500 mm. At the focal point of OOS, a projection screen was placed. The observation optics is focused on the screen.

The characteristics of OOS were measured at a test bench. The focal depth was ± 10 mm against total path length of 1640 mm between beam target (object) and the projection screen. By a grid pattern test, a clear aperture was 200 mm in the horizontal direction and 90 mm in the vertical direction as shown in Fig.4. At the central region spatial resolution was almost 0.2 mm. A reason that the field of view was poor in upper side than lower side one was shadow of the convex mirror.

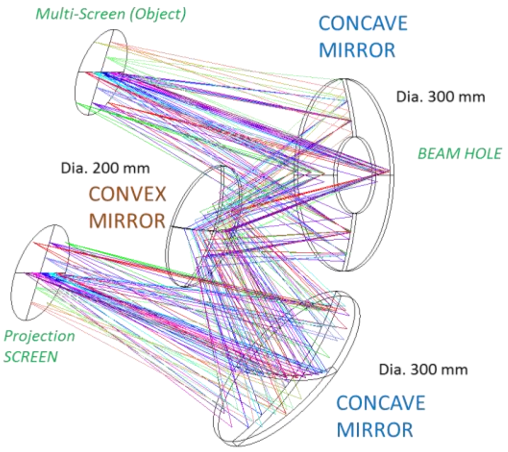

Figure 3: Large acceptance optics.

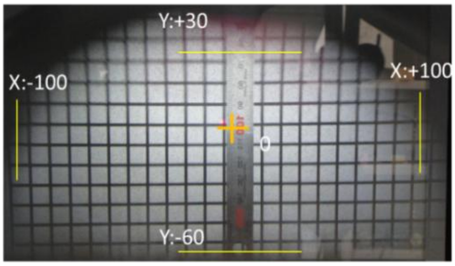

Figure 4: A result of a grid pattern test (10 mm spacing).

DETECTOR

The detector consists with a focusing lens, an image intensifier (II), a relay lens, and a charge injection device (CID) camera as shown in Fig.5, and these main specifications are summarized in Table 1. The distance between the projection screen and the focusing lens front is 560 mm. The output analog video signal from CID camera is transmitted to a local control room via a coaxial cable (5D, about 400m). Then the video signal is converted into digital signal by a 10 bit video ADC.

The gain curve of II is shown in Fig.6. This curve was obtained by measured light quantities of beam profiles.

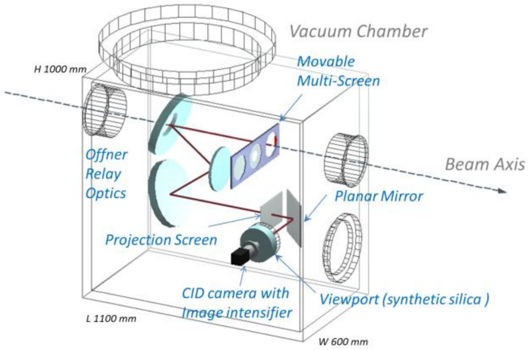

Figure 5: The solid view for the beam profile monitor using multi-screen.

Table 1: Specifications of the Detecting Devices

Device	*Item*	*Specification*
Focus Lens	Focal Length	17 mm
[YakumoYMV2595N]	F number	0.95
	Front Aperture	26.8 mm
Image Intensifier	MCP	Single Stage
[HPK V2697U]	Luminous Gain	12000[lm/m^2/lx]
CID Camera	Radiation	300kGy
[ThermoFisher8725D]	Sensitivity	0.1 lx

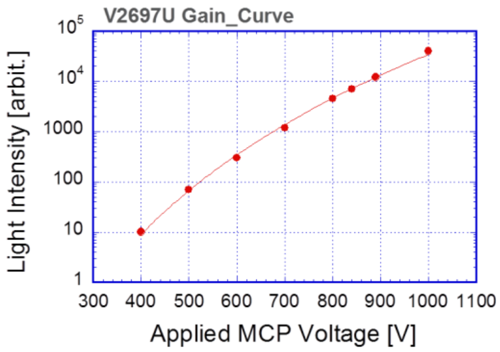

Figure 6: The gain curve of the image intensifier.

BEAM PROFILE MEASUREMENT

High Intensity Beam Profile by OTR

A trial was done with intense beam of $4.2\text{x}10^{13}$ protons / 2 bunches which was greater than usual operating intensity of $3\text{x}10^{13}$ protons / 2 bunches. A beam profile with good S/N was measured by one-shot taking of two bunches as shown in Fig.7. The MCP voltage of the II was 850 V. Its projections were almost agreed with a Gaussian fit.

Combination Measurement

Beam profiles from beam core to halo region were measured with two bunch beams having constant intensity of $9.6\text{x}10^{12}$ protons / 2 bunches, which beams were the same condition for the slow-extraction operation. In these measurement, three kinds of screen as shown in Fig.1 were worked. Suited II gain was adopted in each measurement. The gate time of II was fixed with 10 μs, and all measurements were done with five-shot taking including two bunches. Also all data were subtracted by background data taken without beam. Whole taken data were superimposed in one image as shown in Fig.8 (a). A ellipsoid beam core placed central was taken with screen of the solid screen by OTR, crescent-shaped tail-part images positioned just both outside of the core were taken with the hole-screen by also OTR, and set of three pieces of images positioned left and light respective further outside regions were taken with the alumina screen by FL. Note that all analysis after this was made with horizontal projection.

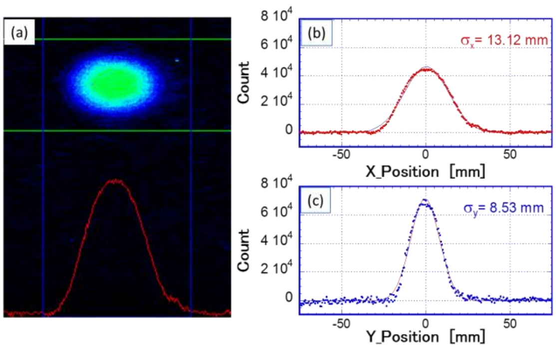

Figure 7: A one-shot beam profile by OTR with a two bunches its total intensity was $4.2\text{x}10^{13}$ protons. (a) The beam image, (b) the horizontal projection, and (c) the vertical projection. Each fitting is Gaussian.

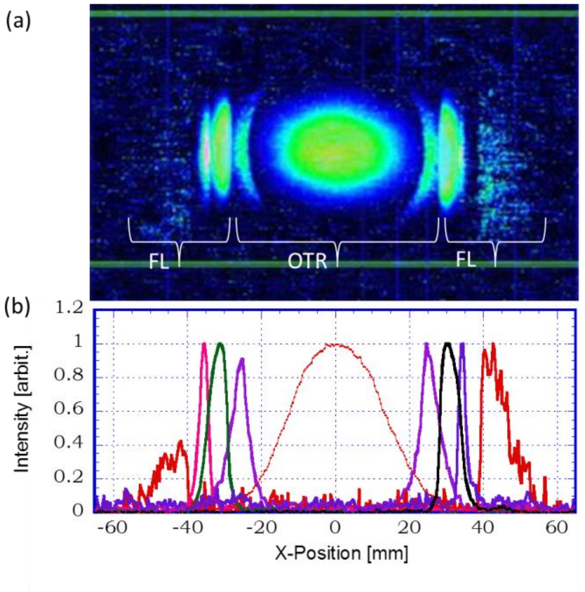

Figure 8: A superimposed beam profiles. (a) beam image, (b) projections in the horizontal direction with normalization by each own peak value.

Scaling for Obtaining Unified Projection

In order to obtain a unified profile in common vertical scale with all data of Fig. 8, we use two ratio as follows: i) gain ratio of the image intensifier (G_R), ii) yields ratio between FL/OTR (Y_R). Thus, we scaled the data with simple treatment as below.

$$\text{OTR data scaled} \rightarrow \text{data}/G_R \tag{3}$$

$$\text{Fluorescence data scaled} \rightarrow \text{data}/G_R/Y_R \tag{4}$$

For obtaining a yield ratio between FL and OTR of Y_R, a comparison measurement of OTR with FL was done. The OTR data was taken by the hole-screen, and the FL data were taken by the alumina screen set at ± 25 mm, as shown in Fig.9. The MCP voltages of II were 1000 V and 500 V for OTR and FL measurement respectively. The yields ratio of Y_R, is expressed as next equation, by Y_{MR} means the measured light quantity ratio and by the image intensifier gains of each measurement of G_{OTR} and G_{FL}.

$$Y_R = Y_{MR} \times G_{OTR}/G_{FL} \tag{5}$$

Firstly measured light quantity ratio (Y_{MR}) was obtained by integration of the interval of [26.5, 35] mm absolutely in the projections (Fig.9). The results of the ratio were 1.90 and 1.77, on the beam left and on the beam right sides respectively. Y_{MR} was determined their average of 1.84 (± 0.07). they yielded an average of FL/OTR area ratio corresponds to FL/OTR light measured ratio equaled 1.84 (±3.7%). Secondly, we obtained the ratio of image intensifier gain by the gain curve (Fig.6). By using the curve, G_{OTR} was 5.0e4 (1000 V), and G_{FL} was 7e1(500 V), then the gain ratio of G_{OTR}/G_{FL} was obtained as 714.3. Finally Y_R (Eq. 5) was obtained as 1314.6.

Though note that two conditions should be considered about this result as below. Firstly gate time of II causes integration effect in FL measurement because a longer persistence as more than several hundred ms. On the other hand, in case of OTR, the emitting interval is net of the beam time. In our case gate time of II was fixed 10 μs, then FL were persisted during whole gate time, against net beam time was 400 ns (two bunches) for OTR. The second one is different opening angle of light emission on the screen between OTR and FL. Because the FL one is distributed to isotropic, then its transmission efficiency in the optical system is higher than the OTR's.

Results of Combination Measurement

By adopting the same scaling procedures (Eq. 3, 4) to remaining profile data, we obtained unified curve as shown in Fig. 10. Thus whole data were converted into FL equivalent one with a constant II gain. Whole data were connected approximately smoothly, and we confirmed that the data to 10^{-6} or less for a peak were obtained. The yellow solid line is a curve of a Gaussian fitting only using the data of the OTR from beam core, and its σ was 10.3 mm. We understood that the spatial beam region extended to 100 mm or more. In addition, paying attention to the shape, measured data are slender than the fitting curve in a region of A and A'. It might be shown a beam cut shape by a collimator which was located upstream of 122 m from the measurement spot. Furthermore, the data extend again in the region of B and B'. It might be shown the cut beam generated new hello. By changing the collimating position, we plan to study on the correlation with the shape of the beam hello with the collimating in near future.

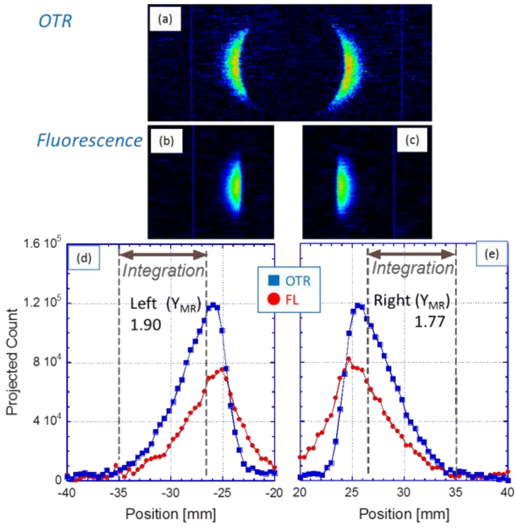

Figure 9: Comparison of beam profiles of by OTR with by FL. (a), (b), and (c) are beam images, (d) and (e) are their horizontal projection.

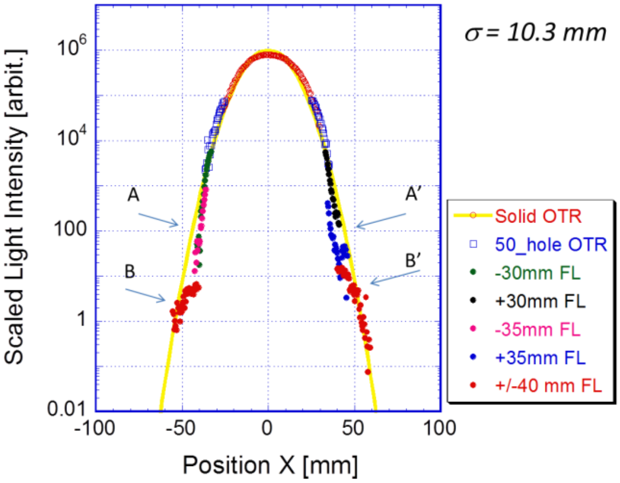

Figure 10: A unified projection curve with OTR and FL.

SUMMARY AND FUTURE PROSPECT

We demonstrated a high sensitive measurement as horizontal spatial distribution of a beam by around six orders of light intensity ratio with using combination measurement by OTR with FL from a chromium doped alumina screen. To obtain a unified projection, we used a simple scaling method by the image-intensifier-gain ratio and by the light yield ratio between FL and OTR. For the next step we are planning a one-shot measurement for beam core and halo in the horizontal and the vertical direction simultaneously.

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