

TWO-DIMENSIONAL AND WIDE DYNAMIC RANGE PROFILE MONITOR USING OTR /FLUORESCENCE SCREENS FOR DIAGNOSING BEAM HALO OF INTENSE PROTON BEAMS

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Abstract

The use of Optical Transition Radiation (OTR) and fluorescence screens to obtain a high dynamic range approximately six orders of magnitude in light intensity for two-dimensional beam profile measurement was demonstrated with intense 3GeV proton beams in the J-PARC in 2013[1]. A new four-section alumina screen for beam-halo measurement was installed just in front of the pre-existing titanium screen this year in order to measure the beam halo and the beam core simultaneously. Two-dimensional beam profile measurements with a high dynamic range are described in this paper.

INTRODUCTION

The objective was to measure the two-dimensional intensity distribution from the beam core to the beam halo of the injection beam to the Main Ring (MR) of the J-PARC. The beam halo brings serious contamination by radio-activation to the accelerator by beam losses in the case of beam intensities greater than 1.5×10^{13} / bunch. In order to measure such a beam profile, a high dynamic range up to six orders of magnitude in light intensity was required. By using such a wide measurement range, we can

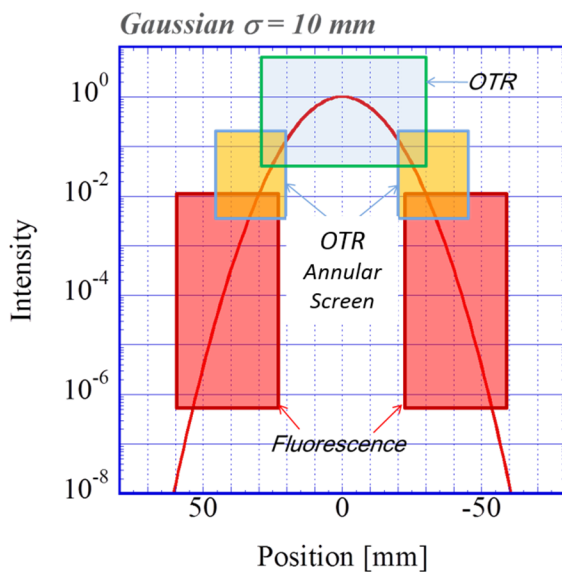


Figure 1: Six orders of magnitude measurement with three kinds of screens.

not only evaluate the beam-halo eliminations by the collimator, but also perform precise beam diagnosis for the

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Rapid Cycling Synchrotron (RCS) in beam extraction, which is a preceding accelerator of the MR.

CONCEPTS

Function of OTR and Fluorescence

We used the OTR from the titanium screen and the fluorescence from the chromium-doped alumina screen. Optical intensities of the light depend on the beam intensity at the positions of these screens. In order to detect the light, a Charge-Injection-Device (CID) camera attached to a gated Image Intensifier (II) was employed. The gain of the II was optimized for these optical intensities.

Figure 1 shows the functional range for each kind of screen. The beam intensity distribution curve shown in the figure assumes that the beam intensity is over 10^{13} proton/bunch and the sigma of the Gaussian distribution is 10 mm. The measurement techniques and their ranges are as follows: the OTR from the beam core covers down to - 1.5 orders of magnitude, the next OTR from the beam tail from the 50 mm diameter annular screen covers down to - 2.5 orders, and finally the fluorescence from the beam halo covers down to almost -6 orders from the peak.

Energy Losses in Screens

The screen materials for intense proton beams should be chosen carefully. Preferred materials include a 10 micron thick titanium foil for the OTR production and alumina screens of 500 μm thickness for the fluorescence production. As for the energy loss with 3 GeV proton beam, alumina has 48 times larger loss than titanium as shown in Table 1. However, when it is only used in the halo region where the intensity is two orders of magnitude lower than the peak values, the total energy loss of alumina becomes about half of that of titanium: i.e. $4.7\text{e-}3$ J/bunch equivalent. These energy losses are small enough to avoid damaging the screens.

Table 1: Energy losses in material [2] in the case of proton beam energy of 3 GeV, and bunch intensity of 1×10^{13} protons.

Material	Thickness [μm]	Energy Loss [keV/proton]	Total Energy Loss [J/bunch]
Ti	10	6.79	$9.8\text{e-}3$
Cr + Al ₂ O ₃	500	330	$4.7\text{e-}1$

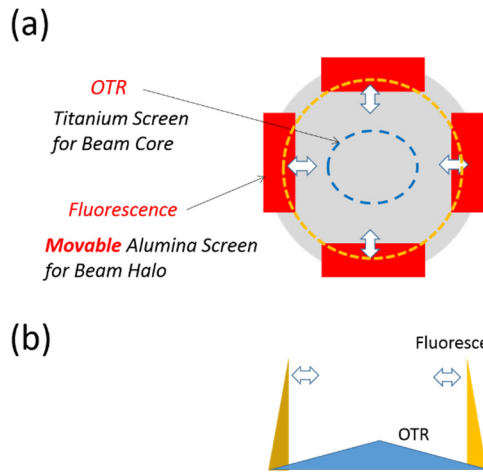


Figure 2: Configuration of screens. (a) Front view, (b) A layout of horizontal projected beam profiles.

Configuration of Screens

Figure 2 shows the configuration of the screens. The grey circle is the titanium foil screen for OTR production by the beam core. Immediately in front of the circle, four red rectangles indicate the alumina screens located in the beam halo region. These alumina screens are movable in the horizontal and the vertical directions as shown.

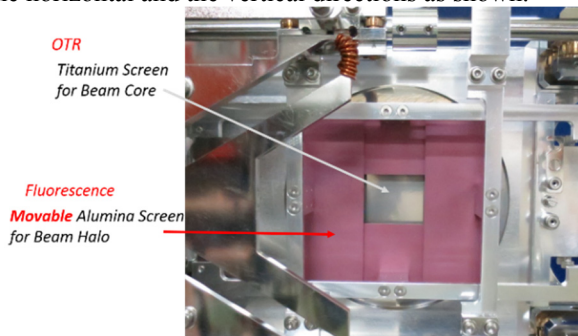


Figure 3: A photograph of the screens from the front side. The titanium screen positioned to the rear is of triple screen construction (Fig.4).

These screen targets consist of layered structures, as shown in Figs.3 and 4. The front side of the target is a new four-section alumina screen which was installed this year. The aperture between the edges of the opposed screen can be changed from 125 mm down to 30 mm, in both the horizontal and vertical directions.

The rear side of the target is the pre-existing triple screen [1] shown in Fig. 4, which is inserted just after the four-section alumina screen. Figure 5 shows a sectional layout of these screens. The alumina screen is located 13 mm in front of the titanium screen. Shadow masks made of 0.5-mm thick stainless steel were put on the back of the alumina screen to prevent the fluorescence from lighting up the titanium screen. The OTR with an angular distribution [1] is emitted from the titanium screen, in contrast, the fluorescence radiates isotropically.

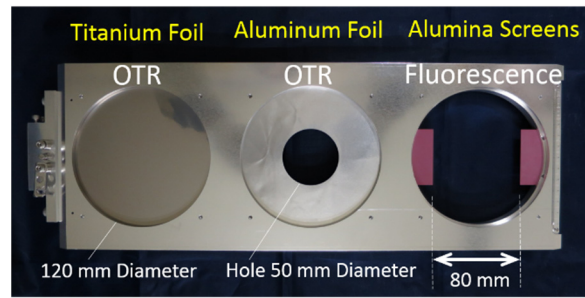


Figure 4: Triple screen geometry

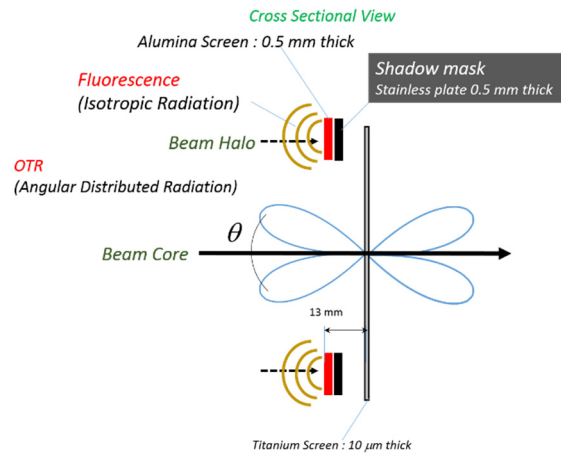


Figure 5: Cross-sectional view of the target screen

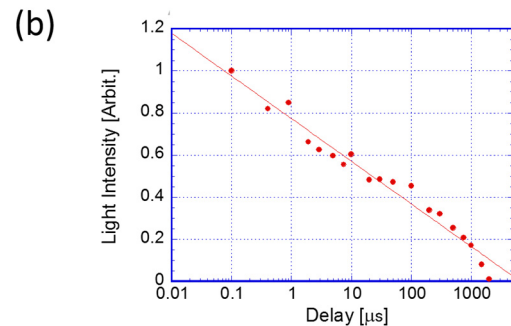
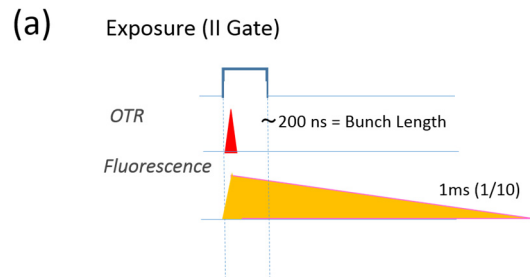


Figure 6: Fluorescence time of alumina with 3 GeV proton. (a) Schematic comparison with the emission time of OTR, (b) Measured data were taken by sweeping the gate timing of the II with a gate width of 10 μs.

Persistence Times

The persistence time of the fluorescence from the alumina screen was over 1 ms as shown in Fig.6 (b). These data were measured with a 3 GeV proton beam. The fluorescence decays logarithmically.

On the other hand, the OTR emits for only about 200ns, corresponding to the length of the beam bunch (Fig.6 (a)). It is an advantage that the yield ratio of the fluorescence to the OTR can be controlled by changing the exposure time of measurement with the gate of the II.

DEVICE CONFIGURATION

Figure 7 shows the device configuration schematically. Devices drawn within the skeleton frame of the vacuum chamber [1] were pre-existing at the 3-50 Beam Transport line (3-50 BT) in the J-PARC, in addition, the new four-section alumina screen (Fig.3) was installed at the target point this year. The Offner optical system has a large acceptance angle of ± 15 degrees for focusing the OTR [1] having larger peak-spread angle of ± 13.5 degrees. We observe a beam image focused on the projection screen within the vacuum chamber from the back side with the II attached CID camera located outside across a viewport.

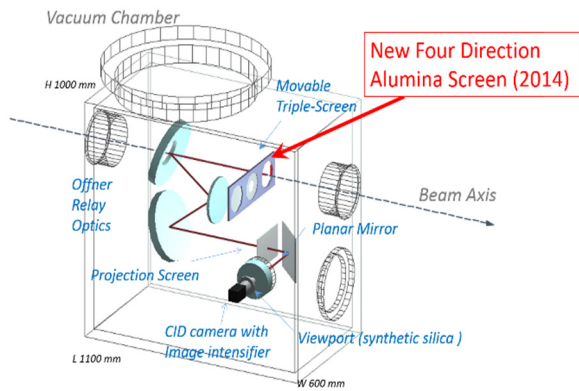


Figure 7: Device configuration.

SCALING FOR UNIFIED PROFILE

The features of our method to obtain higher dynamic ranges are as follows: i) the gain of the II is optimized depending on the region of the beam to be measured, ii) two kinds of light with different emission efficiencies are

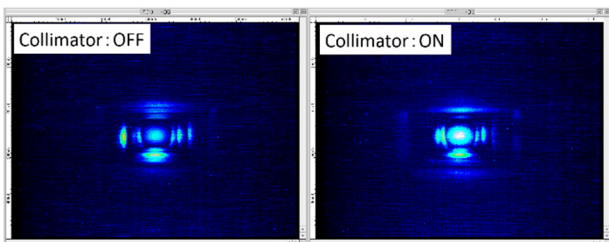


Figure 8: Superimposed beam images with 25 different various alumina screen positions each.

employed, namely the OTR and the fluorescence. For this reason, the pixel intensities of the image data must be scaled to obtain a unified beam profile. We use two coefficients in this scaling as follows: i) the gain value of the II in measurement as G , ii) the yield ratio of the fluorescence to the OTR as Y_R . Thus, we scaled the pixel data with a simple treatment as follows,

$$\text{OTR data scaled} \rightarrow \text{data}/G \quad (1)$$

$$\text{Fluorescence data scaled} \rightarrow \text{data}/G/Y_R \quad (2).$$

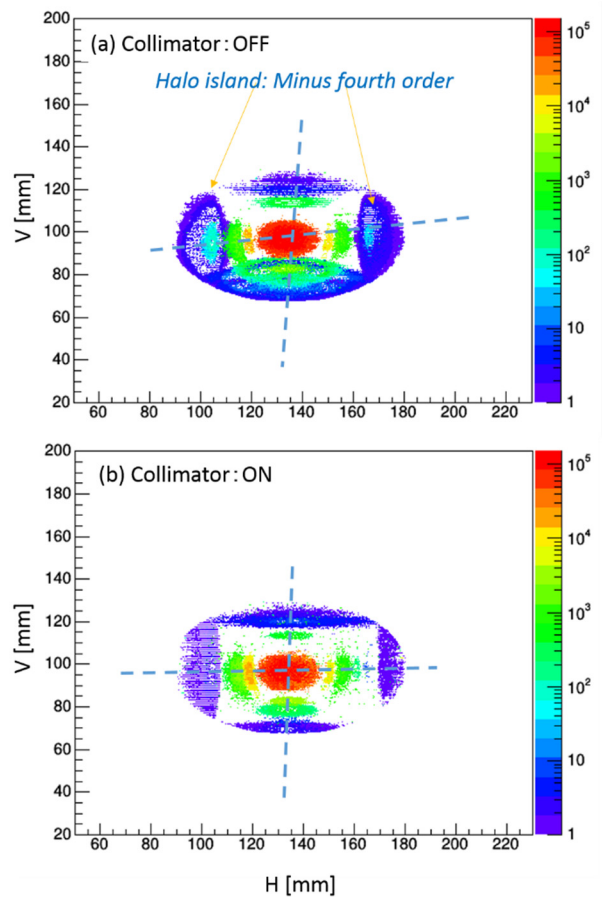


Figure 9: Two-dimensional color contour map with log scale obtained by the scaling. (a) Collimator OFF, and (b) Collimator ON.

We have obtained Y_R by comparison of actual light quantity between the fluorescence and the OTR with a measurement [1]. In our usual case, the gate time of the image intensifier was $10 \mu\text{s}$, and then Y_R was measured as 1314.6.

COMBINATION MEASUREMENT WITH OTR AND FLUORESCENCE

Effect of Beam-Halo Elimination

The effects of the beam-halo elimination by the 3-50 BT collimator [3] were examined from the point of view of the two-dimensional beam distribution. Figure 8 shows superimposed beam images which were taken by changing the position of the alumina screens 25 times in the horizontal and in the vertical directions with a certain distance step. The gain of the II was changed to the appropriate value in each step. So with these pictures alone we cannot properly understand the beam shapes and the distributions; these data must be modified with the scaling treatment shown in equations (1) and (2). After the scaling,

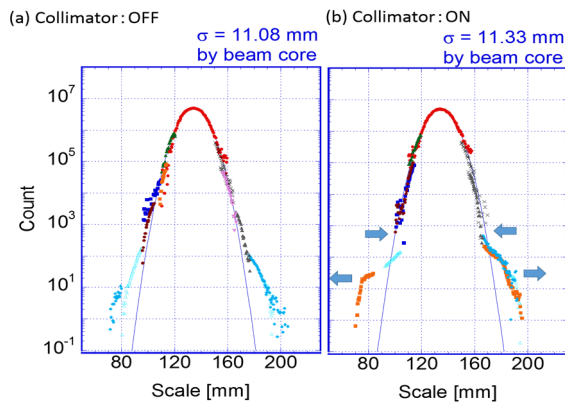


Figure 10: Projection beam profiles in the horizontal direction. (a) Collimator OFF, and (b) Collimator ON.

two-dimensional colored contour maps with log scale are obtained as shown in Fig. 9. The color scale is five orders of magnitude from red to blue.

It is a remarkable collimator effect that islands of the beam halo appeared on both the right and left sides of the minus fourth order in the case of collimator-OFF, but they disappeared in the case of collimator-ON. In addition, two dashed lines can be drawn in each map which link the center of the regions of the beam halo at the top and the bottom sides, or the regions of the left and the right sides. In case of collimator-OFF, these lines had significant angular difference from the horizontal and the vertical

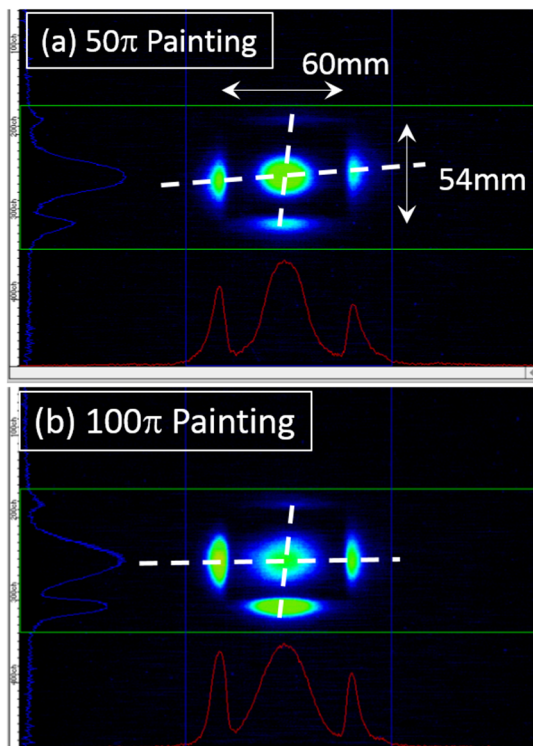


Figure 11: Simultaneous measurement of the beam core and the halo at minus fourth order. The difference between the two beam images is the size of the injection painting area of the RCS.

axes, respectively. But in case of collimator-ON, the angular displacement became smaller.

The horizontal-projection profiles of these data of Fig. 9 are plotted with a vertical log scale in Fig. 10. The solid lines in the plots are the Gaussian curves fitted with only the beam core measured by the OTR from the solid titanium screen. In both cases of collimator-OFF and -ON, the sigma of the Gaussians has the almost same value of 11 mm. And down to around the minus fourth order from the peak, the measured data agree with the Gaussians. In the case of collimator-ON, a waist occurred at about the minus fourth order and the beam size at the minus sixth order or less was expanded. Plotted points can be seen down to the minus seventh order, in these regions the beam sizes spread up to 120 mm. This value of 120 mm is the limit of this instrument, because the apertures of the upper mirror hole of the Offner optical system, of the titanium solid screen, and of the projection screen are all 120 mm.

Simultaneous Measurement of the Beam Core and the Halo

A simultaneous measurement of the beam core and the beam halo was carried out by using the titanium screen and the four-section alumina screen. The following measurement examples examined a correlation of injection beam-painting [4-6] conditions in the RCS and the beam halo of injection beams of the MR. In the measurement the edge distance of the horizontal alumina-screen pair was 60 mm, and that of the vertical pair was 54 mm. In this way the beam halo at the minus fourth order could be measured at the same time as the beam core, as shown in Fig. 11. Each measurement was averaged over five shots with beams consisting of two bunches having an intensity of 3.2×10^{13} protons. Two-dimensional beam profiles were measured with different conditions in painting area of the RCS beam injection as 50π and 100π mm.mrad. Their projections are shown in Fig. 12.

In Fig. 11, the dashed lines mean the same as before; they link the centers of facing pairs of the beam-halo regions. The horizontal dashed line links the left and the right sides of the beam-halo region in the beam image of 50π painting; in this case a remarkable counter-clockwise rotation appeared, although there was no rotation of the beam core. The beam of 100π painting, unlike with the beam of 50π painting, under the fourth-order, the height of the peak of the beam halo was around two times larger in the horizontal direction, and the beam halo at the bottom became remarkably large in the vertical direction. When these beams were injected into the MR, the beam loss was significantly smaller in the case of the 50π beam than in the case of the 100π beam. The rotation shown in the beam image was assumed to be caused by so-called xy-coupling. By taking advantage of the two-dimensional measurement technique, asymmetric beam halos could be measured.

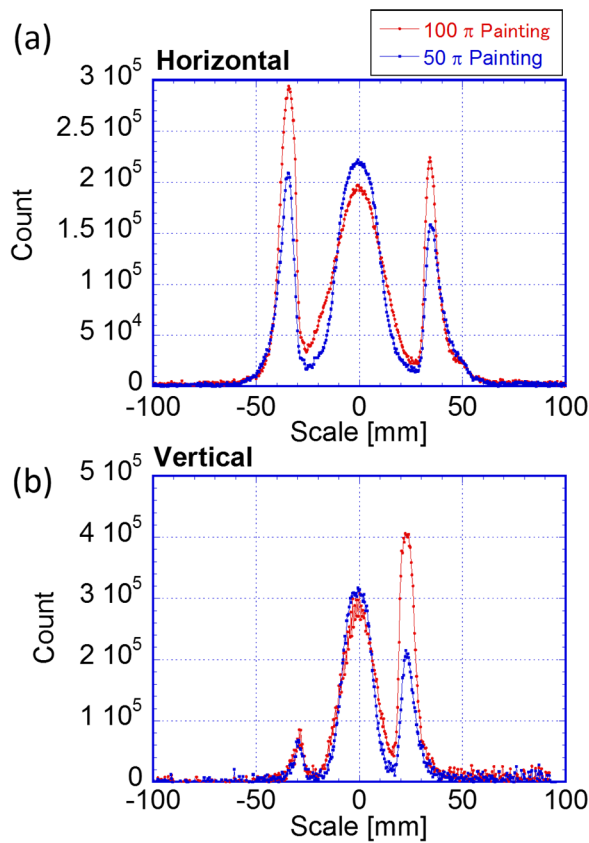


Figure 12: Projections of beam images shown in Fig. 11, (a) in the horizontal and (b) in the vertical directions

Next Steps

The previous simultaneous measurements mentioned above had a gap between the beam core and the beam halo. We have already mentioned above a simple method for the simultaneous measurement so that the gap between the beam core and the halo is almost closed. For such a detection, a detector having around three orders of magnitude of dynamic range should be used, for example, a CMOS camera. And both the light intensity of the OTR from the beam core and the fluorescence from the beam halo should be put in the detector range.

Firstly, it is supposed that two orders of the beam core intensity is to be measured with OTR and three orders of the beam halo is to be measured with fluorescence as indicated in Fig. 13(a). Next, as shown in Fig. 13(b), the fluorescence should be amplified one thousand times more than the OTR. This amplification is achieved by adjusting exposure time with the gate time of the II as mentioned above in the sub-section on persistence time. Finally three orders from the peak of the fluorescence with the OTR should be measured by a camera with appropriate II gain. In order to use such a CMOS camera, note that the camera should be treated with sufficient radiation shielding to reduce the radiation dose down to about several hundred mGy/week.

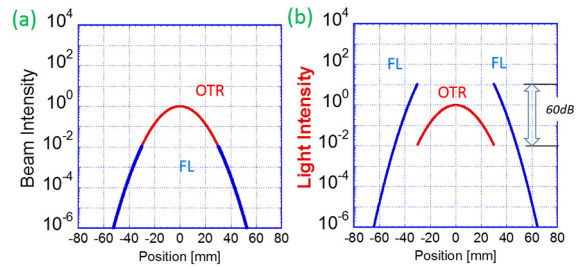


Figure 13: Adjustment of light yield ratio of the fluorescence to the OTR (FL/OTR) for simultaneous measurement of the beam core and the beam halo. (a) Beam intensity distribution curve with the kind of light to be measured denoted by line-color. (b) Light intensity distribution curve in the case where FL/OTR equals one thousand.

CONCLUSIONS

A two-dimensional, high dynamic range profile monitor was developed for intense proton beams by using a combination measurement of the OTR from the beam core with the titanium foil screen and the fluorescence from the beam halo with the alumina screens. Projection beam profile with a dynamic range of around six orders of magnitude was measured for a proton beam whose intensity was about 1.5×10^{13} protons / bunch. The asymmetric beam shape or the rotation in the transverse plane, including the halo, were measured by taking advantage of two-dimensional beam measurement. These results greatly benefit the investigation of beam dynamics.

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