OPTICAL TRANSITION RADIATION MONITOR FOR HIGH INTENSITY PROTON BEAM AT THE J-PARC

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Abstract

The OTR (Optical Transition Radiation) is a powerful tool to observe 2-dimensional information of beam profile at the high intensity beam line because the OTR intensity only depends on the screen reflectivity so that we can minimize a beam loss. However, it is necessary to overcome large background due to the Cerenkov radiation and low radiation tolerance of camera system. The purpose of the present effort is to achieve small background and good S/N and to prolong the lives of the camera system. This requires that amount of potential Cerenkov radiator be minimized and radiation level at the camera system be suppressed. For this requirement, we design and develop an OTR monitor with the optical system of a Newtonian telescope type. Detail design of the optical system and a result of background measurement performed at one of primary proton beam lines of our old 12 GeV Proton Synchrotron are presented.

INTRODUCTION

For the purpose of improving overall intensity of proton beam in response to a demand from nuclear and particle physics, precise measurement of beam profile is now becoming important. A beam monitor for such high intensity beam line should satisfy the following conditions.

- High resistance for radiation
- Perturbation to the beam by the monitor itself as small as possible

The OTR monitor is a good candidate for this purpose, because the OTR light intensity is only dependent on the reflectivity of the screen, so that we can minimize a thickness of the screen. The OTR also has good features as a profile monitor such as providing 2-dimensional information, directional characteristic leading to a S/N.

The OTR is emitted when a charged particle passes through a boundary between two materials with different dielectric constant. This was first predicted theoretically by Ginzburg and Frank [2], and experimentally measured by Goldsmith and Jelly [3]. Wartski et al. [4] first applied the OTR to the beam diagnosis. After that, the OTR was widely used at electron and proton accelerators for the profile measurement [5] [6].

J-PARC [1] hadron beam line under construction shown in Figure 1 will provide high intensity proton beam whose beam power is 750 kW for experiments of particle and nuclear physics experiments. A 50 GeV proton is slowly extracted into the switch yard and focused on the T1 target to produce secondary particles such as pions, kaons, and so on. The residual proton beams are transported into 750 kW beam dump. The OTR detectors are designed for monitors located just downstream of the extraction point.

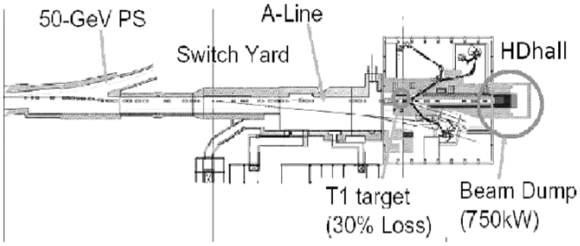

Figure 1: J-PARC hadron beam line

PREVIOUS EXPERIMENTAL RESULT

We need to overcome the following difficulties for development of the OTR monitor at J-PARC.

- A Lorentz gamma factor is small (γ = 32; 30 GeV), so that the directional characteristic is degraded.
- Background level is expected to be large because the OTR monitor will be installed near a loss point.
- An effective OTR intensity decreases due to the time evolution measurement following the standard RS-170 format. A designed beam duration is about 0.7 s.
- At a commissioning stage, we need to measure a profile with a beam intensity less than 10^{12} protons per pulse.

Test experiment with proto-type OTR monitor

To check the OTR light yield and a background shape, we developed a proto-type OTR monitor and performed test experiments at the slow-extraction beam line of the KEK 12-GeV PS (γ = 12.8), whose intensity is 2 x 10^{12} protons per pulse.

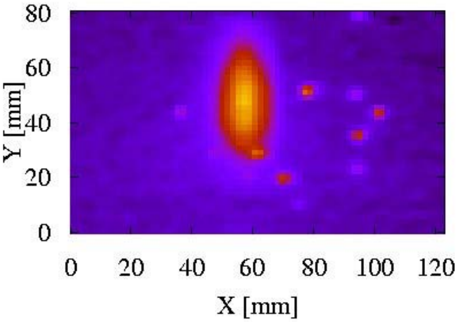

Figure 2: Typical beam image measured by the proto-type OTR monitor

As shown in figure 2, we successfully measured the OTR profile with a beam intensity of down to 4 x 10^{11} protons per pulse. We prepared a SPIC (Segmented Parallel Plate Chamber [7]) profile monitor as a reference, and checked that the OTR monitor performs well as a profile monitor.

Result of the optical fiber system

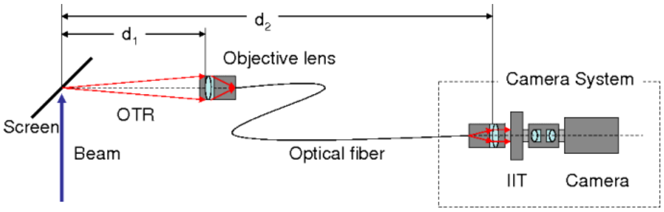

Figure 3: Schematic figure of an OTR monitor with an optical fiber system

Using the above result of the test experiment, we concluded the OTR monitor can be used even on condition of high background and low intensity. However, scattered backgrounds around OTR signal prevents us from getting a clear profile as shown in figure 2, so that we need to refine light detecting system. One of methods to reduce background is to keep a detector as far away as possible. For this purpose, we developed the optical fiber system as shown in figure 3. It is also important that this system leads to reduce radiation level at a position of camera system which has low radiation tolerance.

We performed a test experiment with this optical fiber system in the same way as that with the proto-type OTR monitor and successfully measured a beam profile. However, measured background level is not so low as expected, so that we carefully measured a background level with gradually changing distances of d_1 and d_2 in figure 3. By this research, we found two things as follows.

- Using data set of distance d_2, a background level is confirmed not to depend on the beam loss at a camera position.
- Using data set of distance d_1, a total background sum (BG in arbitrary unit) is described as:

$$BG = 0.114 \times loss + 0.197,$$

where `loss` is a beam loss at an objective lens measured by a loss monitor in unit of nC.

The former result shows direct hit of scattered particles on a camera system is not a main component of the background. The latter result shows some reduction factor exists because a parameter of the order zero is not negligible. One of possible explanations is to assume that a main OTR background comes from a Celenkov radiation produced at an objective lens or an optical window. With putting an objective lens closer to a beam line, a beam loss increases while an effective acceptance of Celenkov radiation decreases.

Thus it is concluded that this method is not effective to reduce an OTR background, but reduces radiation damage to camera system.

OPTICAL SYSTEM

To minimize amount of materials as a Celenkov radiator near a beam line, we developed optical system using a telescope with large solid angle. An optical system using a reflector should satisfy the following conditions.

- Large solid angle to cover the OTR light opening angle. A peek of the opening angle is 31 mrad corresponding to $\gamma = 32$.
- Magnification factor of 8.3. Designed OTR screen target dimension is about 100 mm x 100 mm.
- Keep a camera with low resistance to radiation as far away from the beam line as possible.
- Keep possible background source such as lens and windows as far away from the beam line as possible.
- Suppress an aberration of the system to ensure spatial resolving power of 1 mm or less. This requirement needs to ensure a depth of field to cover an OTR screen enough.
- Minimize cost by reducing number of focusing components.

Considering the above conditions, we determine to use Newtonian telescope type as shown in figure 4. We determine a subject distance to be 5000 mm considering a beam line tunnel size, a depth of field, and radiation level. A diameter of a main reflector is optimized to be 350 mm to cover the OTR light dispersion. To realize the magnification factor of 8.3, a focal length of the main reflector is shortened to be 1000 mm in range of proper aberration. With the help of bright large main reflector, a convergent system is simplified, so that we do not need to use compound lens system which does not have enough radiation tolerance.

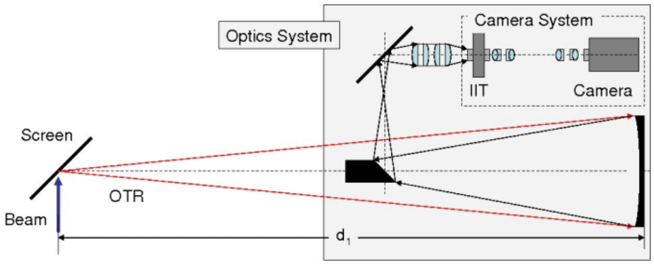

Figure 4: Schematic view of the Newtonian optics system.

OPTICAL PROPERTIES

Figure 5: Newly-developed optical system using a Newtonian reflecting telescope.

We developed optical system based on design works described above sections as shown in figure 5. A light arising at the screen is focused by the main reflector, and lead to a surface of an image intensifier (IIT) whose diameter is 18 mm using four sets of plano-convex lenses. IIT fluorescence is introduced to a camera using a method of a relay lens composed of four sets of achromatic lenses.

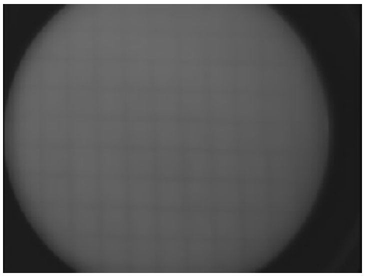

Figure 6: A test target image measured by a CCD camera.

To check optical properties of this system, we prepared an optical test target located at the OTR screen position. A size of the target is 141 x 100 mm which is the same as the real OTR screen, and placed at 45-degree angle. This target is divided into ten by lines of 0.2 mm thickness for both X axis and Y axis. A 2/3'' CCD camera is used to measure a test target image.

Figure 6 shows a measured image of this system. There is a little bit distortion, but this is not a problem because it can be corrected by computer software. We successfully measured a target image of about 100 mm x 90 mm area, so that a magnification is enough. We analyze this image to check the optical properties by computer as follows.

Resolution analysis

Sigma (mm)	X direction	Y direction
Centre	1.16 mm	0.94 mm
Left	0.68 mm	1.54 mm
Top	1.26 mm	0.90 mm
Mean	1.03 mm	1.13 mm

Table 1: Resolution analysis result is shown.

Our optics system requires a resolution of about 1 mm for a profile measurement. There is a possibility that a resolution depends on a position in the target due to a lack of a depth of field, so that we evaluated a resolution in three regions such as central, left, and up regions. After that, we projected the image into X and Y axis, and fitted it with a Gaussian function. Table 1 shows a result of this fitting. A resolution width is evaluated by a Gaussian sigma in the unit of mm. There is a little position dependence, but about 1 mm resolution is confirmed to be achieved. A main reason of this resolution deterioration is assumed to come from a low IIT resolution.

Luminance flatness analysis

There is a possibility that a limb darkening disturbs a precise measurement of a beam profile, so that we need to check whether the image has enough good flatness of luminance. To evaluate this, it is necessary to normalize the image by a luminance distribution of the test target, which is not always constant. Figure 7 shows an analysis result of the luminance flatness. A bottom figure shows the ratio of the CCD image to the target luminance distribution is flat enough to measure a profile.

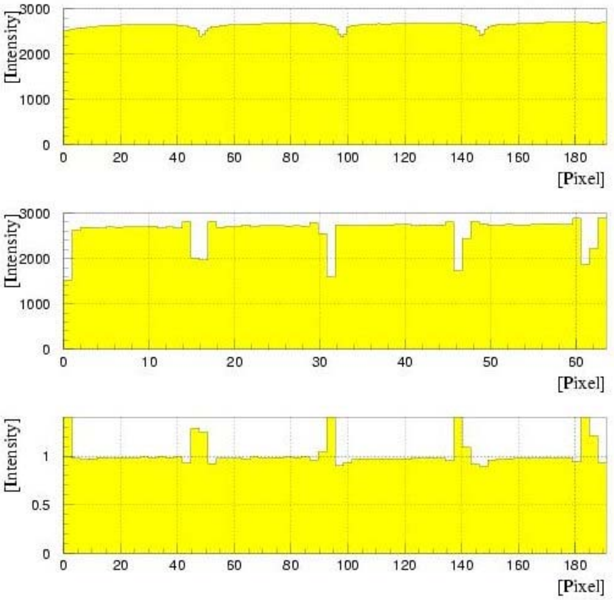

Figure 7: Luminance flatness analysis. Horizontal axis is a y projection of each image in the unit of pixel. Vertical axis is luminance intensity in arbitrary unit. A top figure is for a measured image. A middle one is for a target image captured by a digital camera directly. A bottom one is a division of the top figure by the middle figure.

CONCLUSION

Using the result of the previous test experiments including an OTR background estimation, we successfully developed an OTR monitor applicable to a high radiation and high background circumstance. A detector resolution is estimated to be about 1 mm. Detector luminance flatness is measured to be good enough. It is expected that this monitor can be used from intensity of 4 x 10^{11} protons per cycle. This monitor can be used as a profile monitor located at the extraction point of the J-PARC hadron beam line.

REFERENCES

[1] http://www.j-parc.jp
[2] V.L. Ginzburg and I.M. Frank, JETP 16 (1946) 15.
[3] P. Goldsmith and J.V. Jelly Phil. Mag., 4 (1959) 836.
[4] L. Wartski et al., Appl. Phys., 46 (1975) 3644.
[5] J. Bosser et al., Nucl. Inst. Meth., A238 (1985) 45.
[6] V.E. Scarpine et al., IEEE Trans. Nucl. Sci., 51 (2004) 1529.
[7] K.H. Tanaka et al., KEK preprint 91-2.