DEVELOPMENT OF RADIATION REGISTANT OPTICS SYSTEM FOR HIGH INTENSITY PROTON BEAMLINE AT THE J-PARC*

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Abstract

Optical beam measurement such as OTR (Optical Transition Radiation), ODR (Optical Diffraction Radiation), gas Cherenkov, and so on is a powerful tool to observe a two-dimensional information of high intensity beam profile, so that this method is widely used at various electron and hadron accelerators. However, high radiation field to damage an optical system gradually becomes a major issue with increasing the beam intensity to explore new physics. Our present effort is devoted to develop a high efficient optical system to resist such high radiation field. We newly designed an optical system composed of two spherical mirrors which do not have any lenses vulnerable to radiation. We performed an optical test and confirmed that this optics has a resolution of 1.10±0.13 mm, which is within the design value of 2.95 mm. Also we conducted a beam test experiment of this optics system combined with an OTR screen performed at high intensity proton extraction beamline of the J-PARC.

INTRODUCTION

J-PARC hadron beamline provides a high intensity proton beam (750 kW 15μA), whose momentum is 30 GeV (50 GeV, design value). A proton beam is slowly extracted from a main ring (MR) to a switch yard (SY) section, and injected into a T1 target (Pt or Ni) with 50 % or 30 % beam loss. The beam duration is about 1 second. Generated secondary particles such as pions and kaons are provided for nuclear and particle physics experiments. Residual beam is safely introduced to 750 kW beam dump.

For stable operation of such high intensity beamline, we prepared two types of profile monitors, such as a resudial gas ionization profile monitor (RGIPM) and an OTR monitor. The RGIPM is the best monitor for a high intensity beamline because no beam loss is expected in principle. However, this method is not suitable to monitor a profile at the most upstream part of the SY section. This section is high vacuum section directly connected to MR, so the gas ionization rate is much smaller than that at the downstream part with low vacuum. We thus need to use a signal amplifier such as a micro-channel plate (MCP), but it is not usable around the extraction point due to lack of resistance to radiation. So that we prepared OTR monitors for this section.

An OTR is one of the best tools to measure a profile of high intensity beam. It is a surface phenomenon and its intensity does not depend on thickness of radiator, so that we can minimize beam loss. Also optical beam monitor such as an OTR has an advantage of small cost of a detector and a DAQ system by using commercial products. So this method is widely applied to a profile measurement at many electron and proton accelerators [1-3]. However, a problem of radiation damage to optical system such as lenses and cameras becomes more serious with increasing beam intensity.

We first performed test experiments at the KEK 12 GeV-PS with a proto-type OTR monitor, and found that serious spiky Cherenkov background covered the OTR signal. We evaluated beam loss dependence of Cherenkov background, and concluded that not direct camera hit but Cherenkov radiation generated at a lens position is the most harmful source of the background [4].

To suppress the above Cherenkov background, we developed catadioptric-type optical system composed of a first parabolic mirror and a set of 4 planer-convex lenses, and estimated its resolution is about 1.1 mm with an optical test experiment [5]. We also developed the OTR chamber and a transporting optics, and installed and finely aligned the OTR monitor system into the SY beamline at the J-PARC. We finally observed a clear OTR signal with no Cherenkov background even at the lowest beam intensity down to 1.5 x 10^{11} protons/spill [6]. In this optics, we used lenses to compensate insufficient focusing power of the main mirror. Development of a new optical system without lenses is necessary to deal with further power upgrade of an accelerator.

OPTICS DESIGN

We designed new optics composed of only mirrors with ZEMAX [7] simulation code. Calculation conditions are listed as follows:

- Working distance (WD) is 5000 mm to reduce beam loss at a camera.
- Diameter of a first mirror (D) is 300 mm to cover the OTR opening angle.
- Composite focal length (f) is about 550 mm to ensure optical magnification of 8.
- Spot RMS radius at image is 200 μm or less.
- Each mirror component has f-number larger than 3 to suppress optical aberration.
- OTR radiator size is 100 mm x 100 mm.

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- Number of mirrors is 3 or less to reduce cost. This is also good to reduce reflection light loss.

First we calculated off-axis optical system to maximize detection efficiency. As optics composed of two mirrors, we calculated Scheifspiegler type composed of a convex first mirror and a concave second mirror and Yolo type composed of a concave spherical first mirror and a convex spherical second mirror. The Scheifspiegler type suffers from low optical magnification with all combination of two focal lengths. The Yolo type can have enough optical magnification, but its resolution is estimated as low as 560 μm. As optics composed of three mirrors, the following optical systems remain as candidates to have enough optical magnification.

- Optical system composed of three spherical concave mirrors.
- Optical system composed of a parabolic concave first mirror, a spherical convex second mirror, and a parabolic concave third mirror.

Optical system with three mirrors has good advantage of cancellation of each mirror aberration. The above second optics is tuned to have small spot RMS radius as low as 100 μm. This value is for a paraxial beam, so that optical aberration for peripheral rays is estimated. It is concluded that this optics is not usable because the coma aberration cannot be suppressed to 200 μm level with all combinations of conic constants.

We second estimated on-axis optical system. This system has disadvantage of signal light decrease, but advantage of smaller aberration for peripheral rays. The Cassegrain telescope type and the Gregorian telescope are estimated not to have enough optical magnification. We finally found a solution as shown in Figure 1.

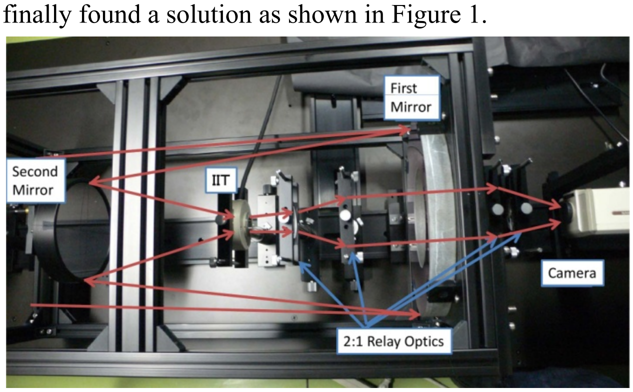

Figure 1: New optics configuration.

This new optics is based on the Gregorian telescope composed of two concave mirrors, but a second mirror is placed before a focus point of a first mirror to achieve a large optical magnification. For the first commissioning run with low intensity down to 1E11 protons/spill, we prepared an image intensifier (IIT). Output light emitted from the IIT is transported to a camera with two-to-one relay optics designed by ZEMAX calculations. For this relay optics, the first mirror has a hole whose diameter is 150 mm. The IIT is planned to be removed when an accelerator power reaches up to design value of 750 kW. An OTR has a ring shape peak of its emission, so that a second mirror shadow on a first mirror is not so much harmful for its detection.

OPTICAL TEST

We performed an optical test to check a resolution of the new optics. For the main optics to the IIT, we prepared a grid target instead of an OTR radiator and put a camera at the IIT position. For the relay optics from the IIT to camera, a grid target is placed on an outlet port of the IIT. Table 1 shows a result of comparison between measured resolution and ZEMAX calculation.

Table 1: Comparison of Resolution between the Optics Test and the ZEMAX Calculation

Resolution (mm)	Optics test	ZEMAX calculation
Main optics	0.904±0.095	1.88
Relay optics	0.073±0.020	0.294
Total	1.10±0.13	2.95

It is noted that the resolution value of the main optics and that of the total optics are on target, but that of the relay optics is on the IIT outlet part. A leading contribution to the total resolution comes from the main optics in the case of the optical test contrary to the calculation. A spot RMS radius of the optics test is 121 μm, which is much less than the target value of 200 μm. We also performed the Hartmann test to check the above optical test, and confirmed that the resolution is 1.20±0.17 mm on target, which is consistent with the above value of 1.10±0.13 mm.

BEAM TEST AND DISCUSSION

Figure 2 shows a configuration of OTR detectors at the most upstream part of the SY section. We applied the newly-developed optics to the OTR3 detector. To check its performance, we prepared a luminescence screen at just upstream of the OTR3 chamber. Beam duration is 1 s, beam repetition is 6 s, and beam intensity ranges from 2.5E11 to 3.2E12 protons/spill.

An OTR monitor configuration, data acquisition system, and analysis methods are the same as that used in Ref. [6]. An OTR light generated at the OTR screen of a sheet of 7 μm aluminium foil is transported to the new optics, 5 m away from the beamline. A PAL image from a camera is captured by a capture board. The captured image is averaged and projected into X and Y axis to acquire a projection histogram. The projected histogram is fitted by background and Gaussian signal, and amount of signal, its sigma width, and its position are evaluated.

Figure 3 shows a beam intensity dependence of OTR signal amount. A clear linear dependence in this intensity region is confirmed, so that the IIT, the camera, and capture system are proved not to be saturated. The OTR signal is well observed down to beam intensity as low as 2.5E11 protons/spill.

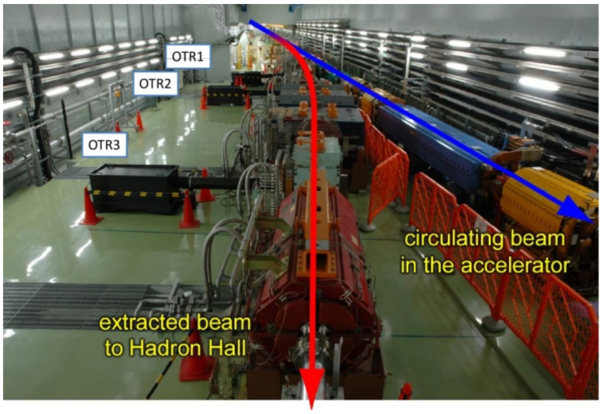

Figure 2: OTR monitors installation.

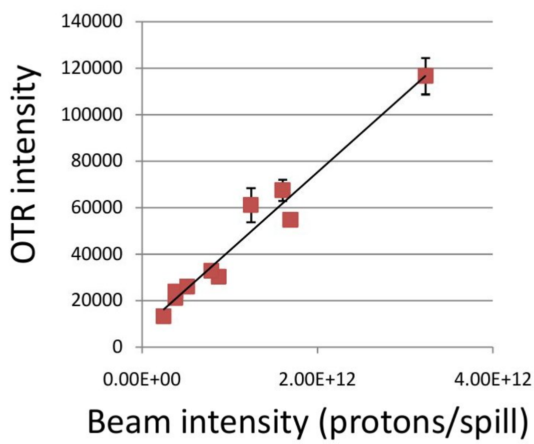

Figure 3: Beam intensity dependence of OTR intensity.

Figure 4 and 5 show a beam sigma width for X and Y axis, respectively. The turtle calculation is always over the measured OTR data. This can be explained by the reason that the actual emittance parameter is larger than that assumed by the turtle calculation. This difference will be solved by an emittance measurement in the next run. For the OTR3, the OTR data is a little bit over the luminescence screen data. An increase of X width is 2.96±1.44 mm, and that of Y width is 2.50±0.94 mm. One of the reasons is difference of optics. The luminescence screen is a temporary monitor, so that we use a conventional camera lens without any radiation tolerance as its optics. This lens has much better resolution than the new optics in exchange for low resistance to radiation. A width increase of 1.1 mm as shown in Table 1 is expected from this reason. The other source is a SUS window located just upstream of the OTR screen. The OTR light generated on this window is reflected at the OTR screen, and transported to the OTR optics. This window is located 500 mm upstream of the OTR screen, so that its focus point is different from that of a true signal. Its resolution is estimated to be 2.1 mm by ZEMAX. The above two reasons well explained the increase of the OTR width. The temporary luminescence screen will be removed after this test experiment, the width increase is expected to decrease down to 1 mm level. .

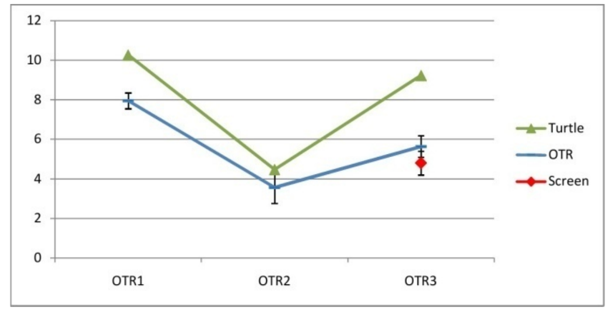

Figure 4: X beam width (σ, in mm) at each OTR position. Green line is for decay turtle [8] calculation with design emittance. Blue line is for measured OTR value. Red line is for measured luminescence screen value.

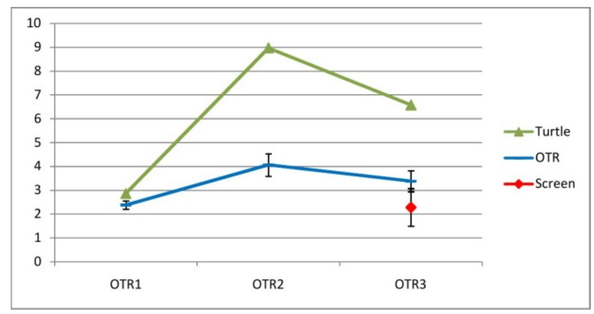

Figure 5: Y beam width (σ, in mm). Line definition is the same as Figure 4.

FUTURE PLAN

For better resolution of this new optics, tuning of a conic constant of each mirror and refinement of relay lens optics are necessary. We optimized an optical system by ZEMAX, and a resolution of 319 μm is achieved.

CONCLUSION

We successfully designed and developed a new optics with small background, high efficiency, high radiation tolerance, wide field of view, and good resolution. Its performance is confirmed by two types of optical tests and beam test experiments at the J-PARC.

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