DEVELOPMENT OF OFFNER RELAY OPTICAL SYSTEM FOR OTR MONITOR AT 3-50 BEAM TRANSPORT LINE OF J-PARC

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Abstract

An extremely wide aperture relay optical system based on Offner system has been developed for Optical Transition Radiation (OTR) monitor at 3-50 beam transport line (3-50BT) from RCS to MR in J-PARC. Diagnostics for beam profile and halo at the 3-50BT are very important to optimize the injection of MR. For this purpose, an OTR monitor is planned to install for an observation of image of the beam and halo after the beam collimators in the 3-50BT. Since the opening of OTR is very wide due to small Gamma; 4.2, extremely wide aperture (500 mrad) optics will necessary to efficient extraction of OTR. We developed Offner type relay optics for the effective extraction of OTR. As a result, we obtained a clear aperture which covers 100 × 100 mm aria on the target screen. An optical design of OTR monitor and results of optical testing are presented in this paper.

INTRODUCTION

Japan Proton Accelerator Research Complex (J-PARC) is composed of three accelerators which are a 400 MeV (currently operating at 180 MeV) linear accelerator (LINAC), a 3 GeV rapid cycling synchrotron (RCS), a 50 GeV (currently 30 GeV) main ring (MR) [1]. The MR provides 30 GeV proton beams to beamlines in the Hadron Experimental Hall for hadron physics and to the neutrino beam line. The produced neutrino beams are sent to the Kamiokande facility which is located in Kamioka, 300km apart from J-PARC. Figure 1 shows the schematic drawing for the layout of beam transport line from RCS to MR.

14 Beam Position Monitors (BPMs), 50 Beam Loss Monitors (BLMs), 5 Fast Current Transformers (FCTs) and 9 Multi Wire Profile Monitors (MWPMs) are installed in the 3-50BT [2]. Those beam diagnostics systems are used for the measurement and regulation of the beam orbit, the beam loss and the beam size of the 3-50BT. In summer 2013, the linac energy will upgrade from 181 MeV to 400 MeV, and the intensity of protons those extracted from the RCS will be increased by double. For this upgrade, we will have a plane to diagnostic the two-dimensional profile of the beam core and the beam halo to reduce radio-activation of the MR as small as possible. For this purpose, we plane to install a new profile monitor in the 3-50BT to observe the two-dimensional beam profile.

Since the beam aperture of the MR was designed to 81π mm mrad, the permissible emittance of the injection beam is 54π mm mrad [3]. On the other hand, we estimated that the beam from the RCS should have a large halo surrounding of the beam core. Including the beam halo, the emittance of the beam in 3-50BT is estimated up to 216π mm mrad. The collimators those set in the 3-50BT is designed to removes the halo surrounding of the beam core to reduce pollution of the residual radioactivity of the MR. The effective diagnostic for the beam halo is very important to eliminate it by the beam collimator. The optical profile monitor using the OTR is suitable for this purpose, because the OTR is emitted from the surface of thin metal target (typically 10 µm thickness), and we can reduce radiation from the metal target as discussed in after.

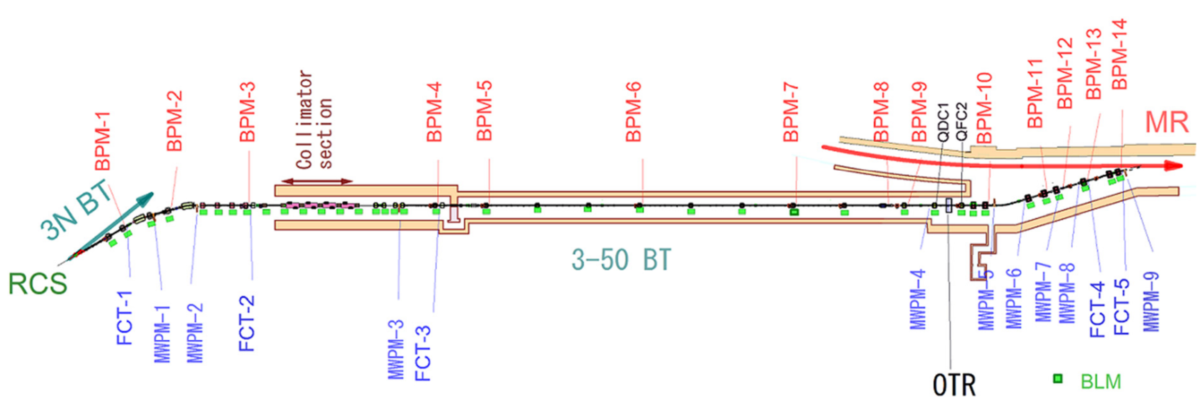

Figure 1: A schematic drawing for layout of beam instrumentations for 3-50BT in J-PARC. New beam profile monitor using the OTR is planed to set between QDC1 and QFC2. The collimator section locates between BPM3 and BPM4.

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PROPERTIES OF OTR ON 3-50BT

Luminous Intensity and Radiation Angle of OTR

When a charged particle beam is incident on a metal target perpendicularly, the OTR is emitted to the radiation angle sharp axially of the beam [4]. The OTR gives maximum intensity at almost opening angle of 1/γ. The angular distribution of the OTR is given by [5];

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

where β is the velocity of the charged particle divided by the velocity of light (c), and θ is the angle of radiation.

The proton beam at 3-50BT is accelerated by an energy of 3GeV, and corresponding γ is 4.2. The angular distribution using eq. (1) at γ=4.2 is shown in Fig. 2 .

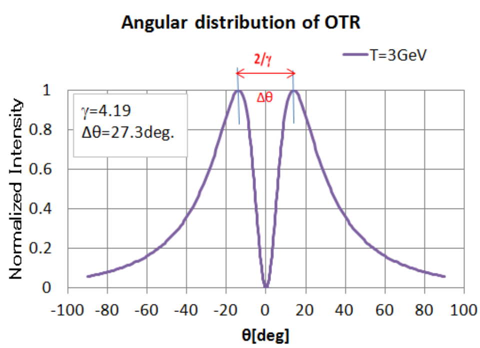

Figure 2: The angular distribution of OTR emitted from 3 GeV (γ=4.2) proton beam.

From Fig. 2, the opening of OTR for 3GeV proton beam is very wide, and opening angle of the maximum of the distribution is 2/γ (about 27 degree). Due to this large opening of OTR, we need an optics having a very large acceptance for efficient use of OTR.

Intensity of OTR from 3GeV Proton Beam

The intensity of OTR emitted in a frequency range ω_1-ω_2 is given by [6];

$$N(\gamma)=\frac{\alpha}{\pi}\left|\ln(2\gamma)-\frac{1}{2}\right|\ln\left(\frac{\omega_2}{\omega_1}\right), \qquad (2)$$

where α is the fine structure constant (CGS units). Since the intensity of OTR is proportional to ln (2γ), OTR intensity from 3.5GeV proton is 1/2 of OTR intensity from 30GeV proton. The result of γ dependence of intensity of OTR in the visible light region is shown in Fig. 3. The intensity of OTR is roughly 2.5×10^{10} photons / 10^{13} protons for 3.5 GeV proton.

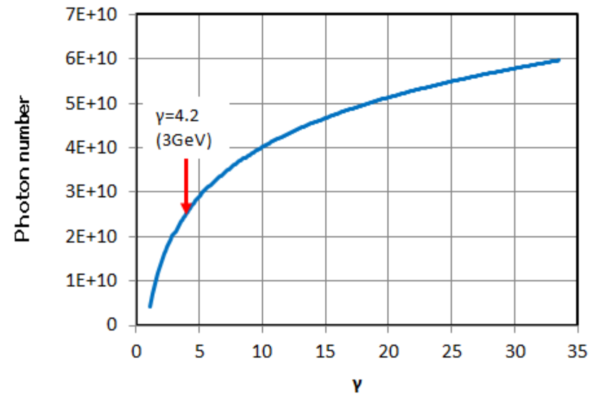

Figure 3: γ dependence of intensity of OTR in the visible light region.

Energy Loss in the Metal Target

We plan to use two types of metal targets, one is target made of aluminium and other is made of titanium. The energy loss (Stopping-power) of the proton beam whish passed through the metal target is estimated by using the database published by NIST (National Institute of Standards and Technology) [7]. The result of thestopping power for Aluminium is shown in Fig. 4.

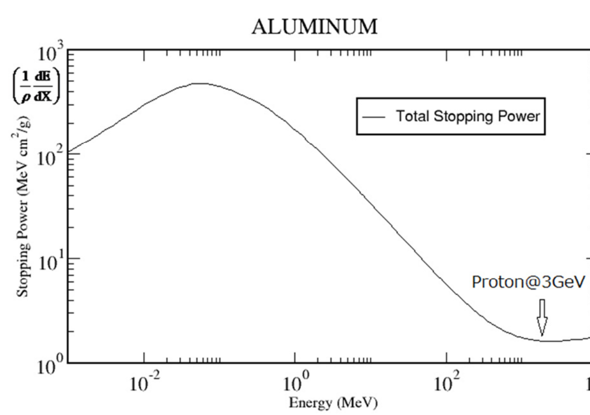

Figure 4: Stopping-power estimated for protons in aluminium.

Results of energy loss for 10^{13} protons to Al and Ti target are listed in table 1. From table 1, energy loss for the Ti (10 μm) and Al (50 μm) target are 11 mJ and 35 mJ and, respectively.

Table 1: Results of Energy Loss of Al and Ti Target

Material	Stopping Power	Density	Thickness	Loss
	[MeV/cm]	[g/cm³]	[μm]	[mJ]
Aluminium	4.36	2.69	50	35
Titanium	6.6	4.45	10	11

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Since the beam of 3-50BT has large size of 60 mm (H) × 30 mm (V) due to large emittance of the proton beam at 3-50BT as described in before, this energy loss in the target will not make any significant thermal damage for the target.

OFFNER OPTICAL SYSTEM AND THE OTR TARGET

In order to extract the OTR from the proton beam axis, usually the target is tilted by 45° from the beam axis. Since large field depth in this configuration, telecentric optics is used in OTR monitor, especially in the object size is large. In our case, mainly due to large o bject size and opening of OTR, the telecentric optics is not useable. Therefore, we must choose a target configuration perpendicular to the proton beam axis. For the efficient extraction of OTR from this target configuration, we developed Offner type optics.

Offner Optics System for Extraction of OTR

In order to efficient extraction of the OTR having a large opening, as shown in Fig. 2, it is difficult to extract the OTR by using a flat mirror inclined to 45°. It is possible to extract the OTR using a rotating elliptical mirror or off-axis parabolic mirror, but the aberration is very significant to cover a large field of view. By this reason, we have developed an optical system for relaying OTR based on Offner optical system [8]. Offner optical system is replacing of Dyson relay system [9] by mirrors, and it is simply composed of two common-centre spherical mirror. Then, the Offner optical system is a kind of 1 by 1 relay system Fig. 5.

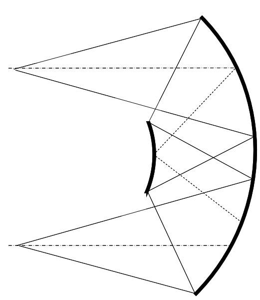

Figure 5: Schematic drawing of Offner optical system.

We designed combination of three mirrors configuration for the Offner optics as shown in Fig 6. We designed an Optical system which consisted of two concave mirrors, D=300 mm, F=500 mm and convex mirror D=200 mm, F=250 mm. The first concave mirror has a hole of 120 mm diameter at centre of mirror for passing the proton beam. Because the angular distribution of OTR as shown in Fig. 2 has valley in the center, intensity loss by this hole is not significant. In the Offner system, the astigmatism becomes significant as the diameter of aperture increases. In beam profile measurement for the proton beam, due to its large size (about 50 mm), the spatial resolution of 1mm should enough for the observation. The width of point spread function at balanced astigmatism point is estimated to smaller than 1mm for clear aperture of 120 mm in our design.

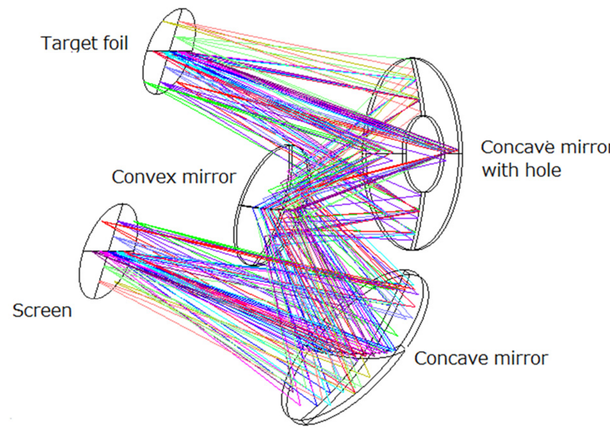

Figure 6: Offner relay system for large aperture.

SPECIAL DESIGN FOR TARGET TO OBSERVE A BEAM HALO

In the proton beam from RCS has a beam halo, which has about 1% of the beam core intensity. One of very important purpose for the OTR monitor is to observe this beam halo. For this purpose, we designed a spatial target to generate only OTR beam halo. The target design has a hall corresponding to beam core dimension in the centre of target. With this target, the beam core will pass through the central hall (not produce the OTR), only the beam halo will produce the OTR as shown in Fig. 7. We can observe beam halo image without any glare of beam core.

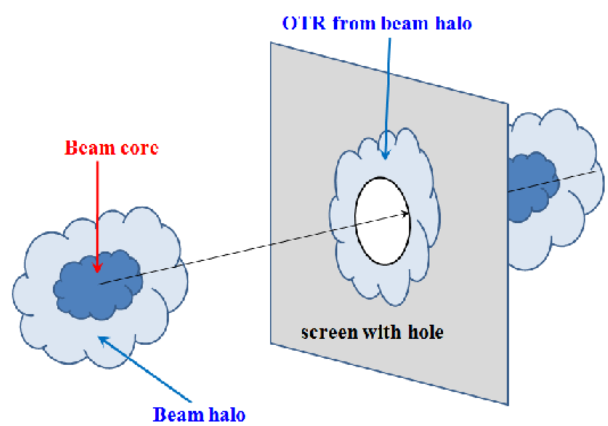

Figure 7: OTR targets for halo monitoring.

LATTICE PARAMETERS AT THE LOCATION OF OTR MONITOR

The lattice parameters of the downstream part in the 3-50 BT is shown in Fig. 8. The OTR profile monitor is installed between the Quadrupole magnets, QDC1 and the

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QFC2. The designed values of the beta function are βx=33 m and βy=18 m at the target position. The beam sizes are σx=42 mm and σy=30 mm when the emittance is 54π mm mrad. We investigated the radiation dose at OTR monitor location during the normal accelerator operation. The result is not exceeding 21 mGy/month, and this value seems enough small doses for the monitor components.

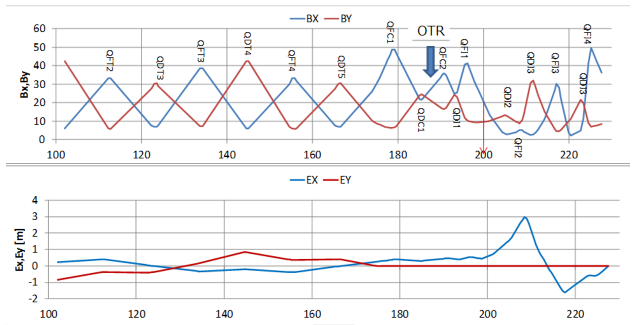

Figure 8: Lattice functions of the downstream part in the 3-50GeV beam transport line.

THE DESIGN OF OTR PROFILE MONITOR AT 3-50BT

A schematics of OTR profile monitor for 3-50BT is shown in Fig. 9. The vacuum chamber is consists of three rooms; (1) the room for targets portion, (2) the room for Offner relay system, (3) the room for a initial stage of final imaging system. The glass window is set side wall of the chamber to extract OTR from the vacuum. The two types of OTR target are set on the linear satage, in order to monitor for beam profile and beam halo. We can select these targets depending on the purpose of the observation. The Offner relay optics is shown in left side. The mirros for Offner system are made of Pyrex glass and an Al coating is applied to surface of the mirror. The Al coating covers the other surfaces, including the backside and the side to prevent the charge up of the glass.

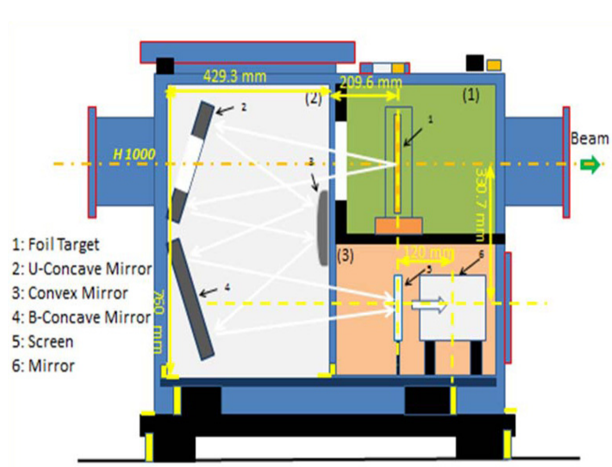

Figure 9: Schematic of the OTR monitor at 3-50BT.

OPTICAL TESTING OF OFFNER RELAY SYSTEM

We have performed several optical testing i.e., knife edge test, Ronchi test grid chart test to check the optical performance of Offner system. From the Ronchi test, we have no significant spherical aberration and astigmatism.

To testing the imaging performance of the Offner optical system, we check the imaging performance by using a grid testing chart. A result of image of grid testing chart is shown in Fig. 10. From this figure, no significant deformation of the filed in +50 mm ~ -60 mm in the vertical, and -100 mm ~ +100 mm in the horizontal. The spatial resolution is 0.2 mm in the centre, and better than 1 mm in the marginal.

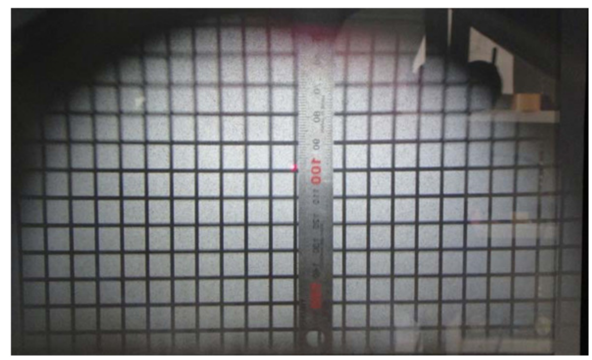

Figure 10: Test of grid pattern for Offner relay system. Grid spacing is 10 mm.

SCREEN FOR OBSERVATION OF BEAM PROFILE IMAGE

We will apply a next optics with CCD camera to observe real image of beam profile on the imaging plane of Offner system. Since effective aria of the CCD camera is not wide (typically 1/3 to 1/2 inch), we must reduce image size less than 1/10 by next optics. The angular magnification of optical system is given by inverse of transverse magnification. The transverse magnification of 1/10 means angular magnification of 10. The acceptance of Offner system is designed to cover a opening of 600 mrad, then the opening of light will be 6 rad after the 1/10 magnification.

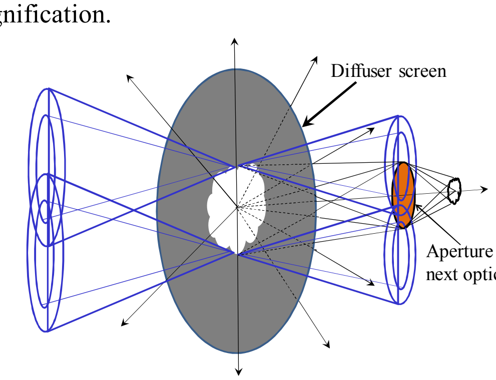

Figure 11: Diffuser screen to convert the angular distribution of OTR into uniform illumination for next optics.

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It is no sense that the acceptance of optical system beyond 3.14 rad under the condition of limited acceptance of the CCD camera, so we cannot escape from some intensity loss.

Otherwise, the angular distribution of OTR will not cover the aperture of next optics with uniform intensity, marginal of image of the beam profile becomes dark. To convert this angular distribution into more uniform illumination, we put a diffuser screen on the image plane of Offner system as shown in Fig. 11. With this screen, the intensity loss about 1/30 will occur, but aperture of next optics will cover more uniform illumination. The diffuser screen is made of fused silica plate with 1 mm thickness.

SUMMARY

An Offner type relay optical system having an extremely wide aperture has been developed for OTR monitor at 3-50 beam transport line (3-50BT) from RCS to MR in J-PARC. The Offner system consisted of two concave mirrors, D=300 mm, F=500 mm and convex mirror D=200 mm, F=250 mm. The first concave mirror has a hole of 120 mm diameter at centre of mirror for passing the proton beam. We have performed several optical testing i.e., knife edge test, Ronchi test grid chart test to check the optical performance of Offner system, and we did not find significant spherical aberration and astigmatism. We also check the imaging performance by using a grid testing chart. As a result, we obtained a clear aperture which covers 100 mm in diameter on the target screen. To obtain uniform illumination for next imaging optics, we put a diffuser screen on the image plane of Offner system.

The entire OTR monitor assembly will install in the 3-50BT in December 2012.

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