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A WIDE DYNAMIC-RANGE HALO MONITOR FOR 8 GeV PROTON BEAMS AT FNAL*

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Abstract

Eliminating harmful beam halos is the most important technique for high-intensity proton accelerators. Therefore, beam halo diagnosis is indispensable and becomes more and more important. At J-PARC, a wide dynamic range monitor was installed in the beam transport line in 2012. The device is a two-dimensional beam profile monitor, and it has a dynamic range of approximately six digits of magnitude by using of Optical Transition Radiation and fluorescence screens. The FNAL accelerator complex has been upgrading in increasing beam intensity and beam quality. A new beam halo diagnostic device is required in the beam transport line between booster and Recycler. It will be manufactured in a collaboration between J-PARC and FNAL as a part of U.S.-Japan Science and Technology Cooperation Program in High Energy Physics. We are redesigning the monitor to satisfy FNAL specifications: the beam energy, intensity, and size. The equipment will be manufactured at J-PARC and will be shipped to FNAL in 2024. In this report, the design of the device will be described.

INTRODUCTION

A two-dimensional beam profile monitor with a six-digit dynamic range was developed in 2012 at J-PARC. It has proved effective for precise beam halo diagnosis for injecting beams in 3 GeV beam transport to the main ring [1, 2]. At J-PARC, we have been developing Unit-2 for diagnosing the halo of the injected beam on the main ring and diagnosing the beam cut effect by MR collimators [3]. In the configuration, it is also a new theme to perform beam halo measurements in phase space by performing simultaneous measurements with Units -2 and -1. In high-intensity proton accelerators, beam diagnostics using equipment for accurately diagnosing such beam halos has been progressed.

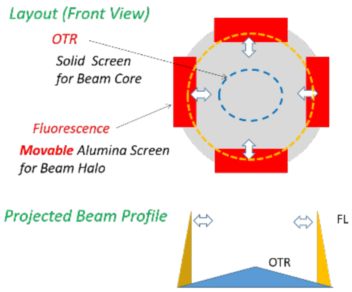

Figure 1: Screen configuration.

These instruments at J-PARC consist of two parts: the beam core is measured by OTR from a metal thin film target such as titanium, and the beam halo is captured by fluorescence from alumina target. High-sensitivity image measurement is performed by adjusting the gain of the image intensifier (Fig. 1). It makes sense to introduce a precise two-dimensional beam profile monitor with such a high dynamic range to the 8 GeV beam transport line (Fig. 2) of the Recycler from Booster, in upgrading the accelerator at FNAL. In the Japan-US cooperation project: Accelerator and Beamline Research and Technology Development for High-Power Neutrino Beam, we concluded an agreement between KEK and FNAL in FY 2021, and within that framework, we decided to develop this device in a three-year plan. In formulating the specifications of the equipment, we basically take the policy of applying it to FNAL based on the results of J-PARC Unit-1.

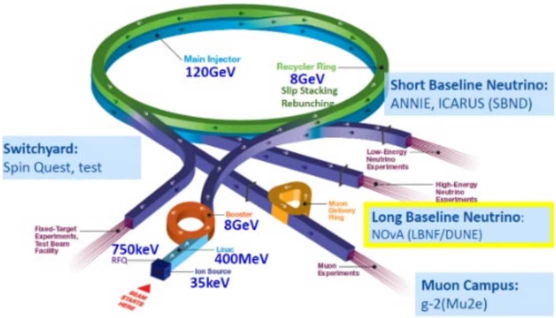

Figure 2: FNAL accelerator complex.

OPTICAL SYSTEM DESIGN FOR FNAL 8 GeV BEAM

8 GeV Proton Beam

Table 1 shows the beam intensity and beam size per bunch of the J-PARC 3 GeV beam and the FNAL 8 GeV beam. The value of J-PARC beam intensity was used the lowest intensity for measuring a 6-digit beam halo. Assuming a Gaussian beam, each beam profile is shown in Fig. 3. For the FNAL peak, 0.08, which is obtained by multiplying the intensity ratio with J-PARC by the square of the beam size ratio as a packing factor, was used. This curve can be said to be the light intensity ratio of OTR and fluorescence generated at the target. In other words, when measured with the same set as J-PARC, the light at FNAL is one order of magnitude smaller than at J-PARC. In the following, we discuss how to measure the beam halo with a high dynamic range of 6 orders of magnitude or more even with FNAL.

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Table 1: Beam Intensity and Beam Size

	Beam intensity [p/bunch]	Beam size (σ) [mm]
3 GeV (J-PARC)	1×10^{13}	10
8 GeV (FNAL)	5×10^{10}	2.5

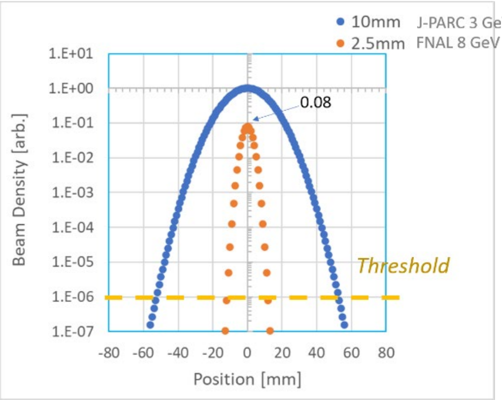

Figure 3: Beam profile in density.

OTR from 8 GeV Proton Beam

OTR has a gamma dependence of the incident proton beam (Fig. 4). It describes as emitted photon number in a light band (ω_2-ω_1) from a metal target as follows [4],

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

The gamma of a 3 GeV proton beam is 4.2 and that of 8 GeV is 9.5. The number of photons emitted from the target per 1×10^{13} proton can be estimated as 2.5×10^{10} at 3 GeV and 3.3×10^{10} at 8 GeV. At FNAL, the OTR intensity is 1.32 times that of J-PARC. The emission angle distribution of OTR also depends on the gamma of the incident beam (Fig. 5). The divergence angle of the double peaks is ± 13.5 degrees for 3 GeV protons and ± 6 degrees for 8 GeV protons. As for OTR, FNAL can yield light with a smaller mirror aperture angle compared to J-PARC.

Offner Optics

For the measurement optical system, we decided to adopt the Offner optical system, which is the same method as J-PARC, which faces the target perpendicular to the beam axis. A method of tilting the target by 45 degrees to the beam axis was also considered, but it was not adopted because the emission angle distribution of the OTR may become asymmetrical in the horizontal plane.

We hoped to make the optical system as small as possible, but there were two points that we should pay attention to. One is that the diameter of the beam hole in the first concave mirror (Fig. 6(a)) is 100 mm, which aperture angle corresponds to the dipole peak angle of OTR in Fig. 5.

The second is to change location of the diffuser screen installed at the focus position from J-PARC Unit-1 and set it in the atmosphere describes as the section 2.4. The position of the diffuser screen had to be at least 185 mm in horizontal distance from the back of the convex mirror (Fig. 6(a)).

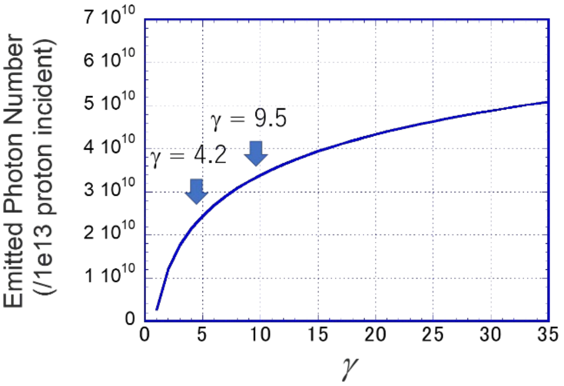

Figure 4: Emitted photon number by OTR.

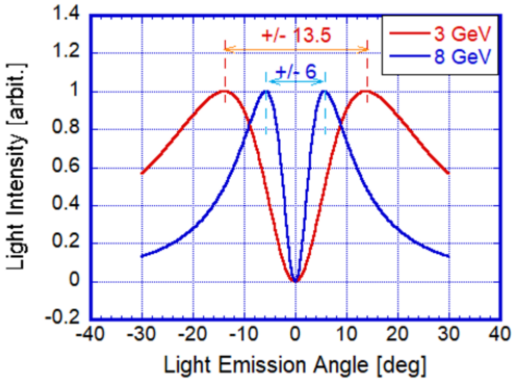

Figure 5: Angular distribution of OTR.

Figure 6 shows the Offner optical system determined with these constraints. A ray-tracing was carried out in a field of view of ±25 mm vertically and horizontally in the optical system. Figure 6 (b) shows focal points in cases of vertical angle of ±5 degree in each ray. Although this map shows a fairly uniform distribution, the rays with an angle of −5 degrees at the bottom in the Y direction has a deviation of about 0.5 mm from the ideal focal position. This means that slight astigmatism may occur. We plan to evaluate fabricated optical systems with actual test light to correct beam measurements. It is noted that in J-PARC Unit-1, the acceptance of the optical system was ±2 degrees from each point in the field of view of 120×120 mm^2, but in the case of FNAL, it was ±5 degrees. This means 2.5 times increase in light yield in the case of fluorescence which has isotropic emission.

Secondary Optical System

The secondary optical system handles light from the diffuser screen to the image intensifier (I.I.) that is part of the detector (Fig. 8). In the diffuser screen which is to be grinded with F300 grain, the light with OTR angular distribution is converted into isotropic-emission light. At J-PARC Unit-1, the working distance (WD) of the lens was 561.5 mm because the screen was set in a vacuum [1, 2].

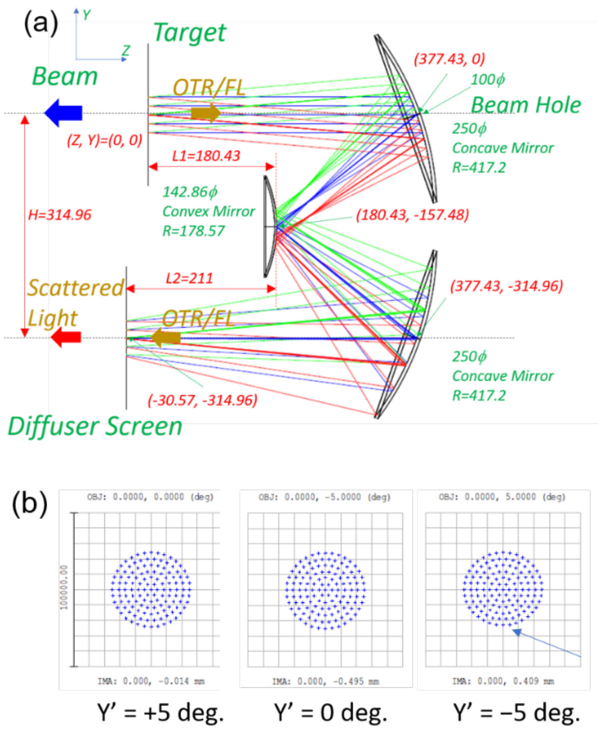

Figure 6: Offner optics, (a) configuration, and (b) ray tracing with varying vertical (Y) position.

With this WD, the image on the screen was focused by an F 0.95 fast-lens [5] attached to an I.I.. Its solid-angle was 1.02×10^{-4} where the solid angle is expressed as (aperture/WD)^2. J-PARC Unit-2 [3] adopts a method of setting the screen in the atmosphere (downstream of the viewport). It allows the WD of the lens to be reduced, which leads to an increase in light yield. In this FNAL design also employs this method. At this time, by using a lens with low distortion, short working distance, and wide angle performance (for example in [6]) for the lens attached to the I.I., the solid-angle becomes 0.0126, and the light yield becomes 12.59 times that of J-PARC Unit-1. As a result, the FNAL optical density peak in Fig. 3 can be changed from 0.08 to 1.01.

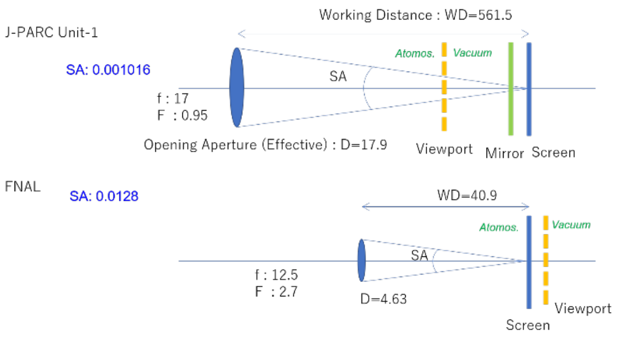

Figure 7: Secondary optical system.

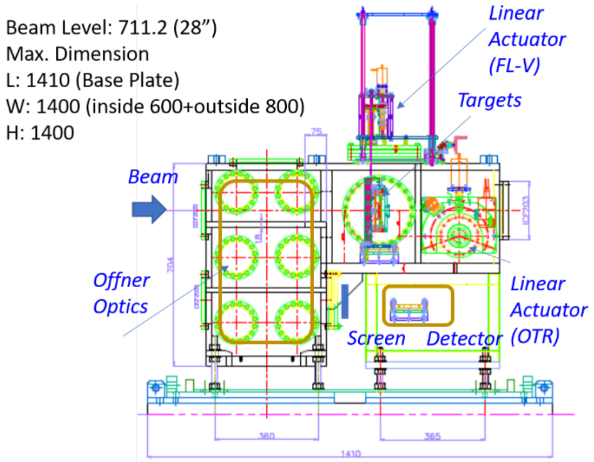

Figure 8: FNAL Equipment layout (under design).

BASIC CONFIGURATION OF THE DEVICE

Figure 8 shows the basic layout of the device together with the dimension limits in FNAL 8 GeV beam transport. The main change from J-PARC Unit-1 is to put the screen mentioned above in the atmosphere. Also, as a minor change, it has folded the linear introducer for the triple targets [1-3], for the titanium target for the OTR, to reduce the length outside the chamber to keep it within limits. Detailed mechanical design is currently underway.

PLANS

This subject started in FY2021 as a part of the Japan-US collaboration. KEK is in charge of manufacturing the device, and plans to complete the device at the end of FY2023. Then KEK will ship it to the FNAL. Fabrication of the device is scheduled to begin in the fall of 2022. FNAL members are also planning to travel to Japan to arrange equipment production and evaluate optical systems in FY2023.

SUMMARY AND PROSPECTS

The profile monitor will be installed at FNAL based on J-PARC Unit-1 design and is estimated to have a dynamic range of 6 digits or more. In the future, we plan to perform detailed optical calculations of the transmittance of the optical system, the light yields, and the spatial sensitivity distribution. In the production of the optical system, evaluation by actual measurement will be also performed.

ACKNOWLEDGEMENT

Prof. Toshiyuki Mitsuhashi of KEK has cooperated in evaluating various characteristics of the optical system particularly. This work is supported by U.S.-Japan Science and Technology Cooperation Program in High Energy Physics.

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