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UPGRADE OF THE MACHINE PROTECTION SYSTEM TOWARD 1.3 MW OPERATION OF THE J-PARC NEUTRINO BEAMLINE

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Abstract

The machine protection system (MPS) is one of the essential components to realize safe operation of the J-PARC neutrino beamline, where a high intensity neutrino beam for the T2K long baseline neutrino oscillation experiment is generated by striking 30 GeV protons on a graphite target. The proton beam is extracted from the J-PARC main ring proton synchrotron (MR) into the primary beamline. The beamline is currently operated with 485 kW MR beam power. The MR beam power is planned to be upgraded to 1.3 MW. The neutrino production target could be damaged if the high intensity beam hits off-centered on the target, due to non-uniform thermal stress. Therefore, in order to protect the target, it is important to immediately stop the beam when the beam orbit is shifted. A new FPGA-based interlock module, with which the beam profile is calculated in real time, was recently developed and commissioned. This module reads out signals from a titanium-strip-based secondary emission profile monitor (SSEM) which is placed in the primary beamline. An overview of the upgrade plan of the MPS system and the results of an initial evaluation test of the new interlock module will be discussed.

INTRODUCTION

T2K(Tokai-to-Kamioka) is a long-baseline neutrino oscillation experiment. One of the main physics motivations is a search for CP (Charge-Parity symmetry) violation in neutrino oscillation. If CP is not conserved in neutrino oscillations, it may indicate a significant hint for the origin of our matter dominate universe. T2K can measure the CP asymmetry by comparing the oscillation probabilities between $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$. Since those probabilities are small, a high intensity neutrino beam is essential to measure the CP asymmetry. A high intensity muon neutrino beam is produced at the Japan Proton Accelerator Research Complex (J-PARC) at Tokai village, Ibaraki, Japan. The muon neutrino (anti-neutrino) beam is then directed to the Super-Kamiokande detector located 295 km away from J-PARC.

Recently, T2K operated stably with 485 kW of MR beam power. Figure 1 shows the accumulated protons on target (POT) and the beam power since 2010. T2K collected 3.16×10^{21} POT up to the end of May 2018. Based on the data collected until December 2017, T2K made a preliminary report that the CP conserving phase values $(0,\pm\pi)$ are outside of 2σ region [1]. This result indicates a hint of neutrino CP violation, although the significance is still low.

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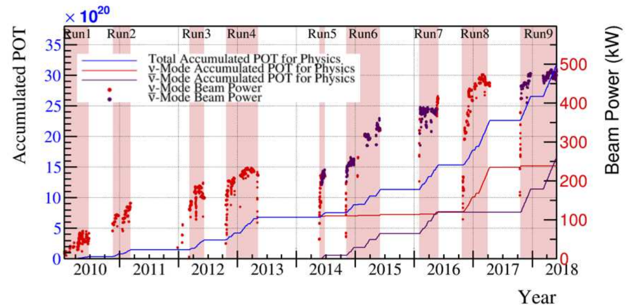

Figure 1: T2K accumulated protons on target (POT) and the beam power as a function of year.

In order to confirm the measurement of CP violation, T2K plans to collect more data up to 2×10^{22} POT by 2026 (T2K extension proposal, J-PARC E65 [2]). The expected sensitivity to CP violation with the exposure of 2×10^{22} POT is 3σ assuming certain values of the oscillation parameters. In the T2K extension proposal, three upgrades are planned; (1) upgrade of the J-PARC MR beam power up to 1.3 MW, (2) increase of signal statistics by both hardware and analysis improvements, and (3) improvement of systematic uncertainties by upgrade of the T2K near detector.

The MR beam power will be upgraded up to 1.3 MW by both shortening the repetition time from 2.48 s to 1.16 s, and increasing the number of protons per pulse up to 3.2×10^{14} [3]. Table 1 shows the achieved and target values. For the shortened repetition time, the MR main magnet power supplies will be upgraded. Intensive development work on the new power supply design has been performed. Installation of these new power supplies will be completed by 2021. For the increase of the number of protons per pulse, intensive MR beam studies are in progress. So far, 520 kW with 2.7×10^{14} protons per pulse and 2.48 s repetition has been successfully performed. The total beam loss in the MR was estimated to be $\sim$ 1 kW. Although further beam loss reduction is necessary, this demonstrates that the MR has the capability of achieving $\sim$ 1MW beam operation with 1.3 s of the repetition time.

Table 1: MR Operation Parameters for the Achieved and Target Beam Power. N_p represents the number of protons per pulse.

	Achieved	**Target**
Beam Power [MW]	0.49	1.3
N_p	2.5×10^{14}	3.2×10^{14}
Repetition Time [s]	2.48	1.16

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MACHINE PROTECTION SYSTEM AT J-PARC NEUTRINO BEAMLINE

Figure 2 shows an overview of the neutrino beamline at J-PARC. High intensity protons from the MR strike a graphite target and produce charged pions and kaons. Neutrinos (anti-neutrinos) can be produced from decays of positive (negative) charged pions in their flight in the decay volume. Either sign pions can be selected by flipping the horn electromagnet current direction. Toward 1.3 MW operation, some of the neutrino beamline equipment will be upgraded. For example, the cooling system of the horn and the target will be reinforced in order to remove the heat generated by the 1.3 MW beam. The horn power supplies and beamline data acquisition system will be upgraded to accept ~ 1 Hz operation.

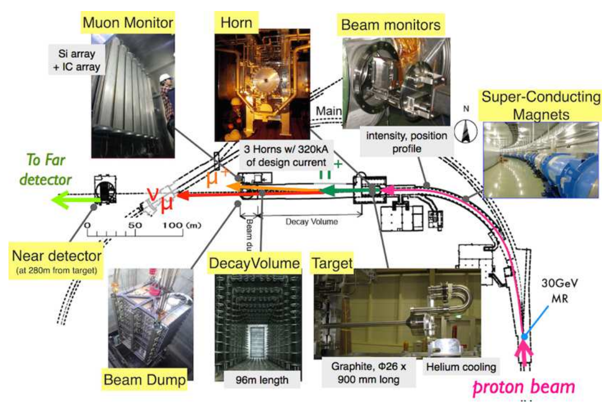

Figure 2: Overview of the neutrino beamline at J-PARC.

The machine protection system (MPS) at the neutrino beamline will be also upgraded in order to realize safe and stable operation with 1.3 MW beam. When any failure of beamline equipment and/or high beam loss in the primary beamline occur, then MPS immediately extracts the beam in the MR to the abort line and stops the next beam injection. The energy of single pulse at 1.3 MW operation (i.e. 3.2×10^{14} protons per pulse) corresponds to 1.6 MJ/pulse. There is a potential risk in such high intensity beam operation due to the high energy. For example, serious damage will occur when a high intensity beam pulse hits certain beamline equipment. As another example, serious damage to the target will occur if the high intensity beam pulse continuously hits off-centered at the target. In order to avoid these cases, an interim interlock system for the beam position and profile at the target is currently adopted.

DEVELOPMENT OF BEAM POSITION AND PROFILE INTERLOCK MODULE

Figure 3 shows the present scheme of the beam position interlock. Signals from a beam profile monitor are digitized by readout electronics and those data are collected by a data acquisition (DAQ) system. One online monitor PC in the DAQ system performs a real-time calculation of the beam position and issues an MPS if the beam position on the target is shifted by more than 1.5 mm in order to avoid the case that the beam continuously hits off-centered at the target. However, this scheme needs more than 1 second to issue the MPS after the beam is injected to the primary beamline, and therefore the next beam pulse is occasionally already injected to the MR. Cases like this will increase when the MR repetition time becomes short in the future. This situation is undesirable because the injected beam in the MR will be extracted to the abort line while the capacity of the abort dump is currently limited.

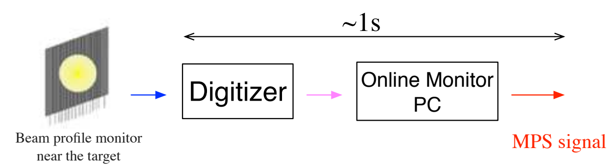

Figure 3: The present scheme of the beam position interlock.

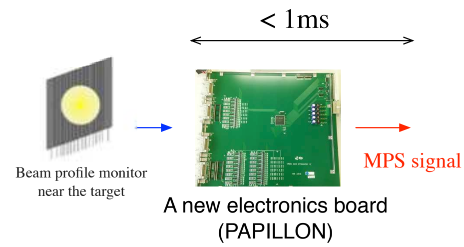

Figure 4: The new scheme of the beam position interlock using a newly developed electronics board, PAPILLON.

Figure 4 shows an idea of a new scheme for the beam position interlock. An electronics board named PAPILLON[1] is newly developed [4]. In the PAPILLON, signals from a beam profile monitor are digitized and sent to a FPGA which is embedded on the board. The FPGA can perform a real-time calculation of the beam position and generate the MPS signal if the calculated position is outside the pre-defined acceptable range. In this new scheme, the latency to issue the MPS signal can be significantly improved.

The PAPILLON board utilizes signals from a beam profile monitor located at the primary beamline, Segmented Secondary Emission Monitor (SSEM) [5]. There are 19 SSEMs along the beamline, as shown in Fig. 5. Figure 6 show a schematic view of an SSEM. Twenty-four strips 5 µm thick Ti foil in each plane (horizontal and vertical, total 48 strips) are used to measure the beam profile. Since each SSEM causes 0.005% beam loss, all of the SSEMs are only inserted in the beamline during beam tuning except for one (SSEM19), which is placed at the most downstream end of the primary beamline. SSEM19 is utilized to continuously monitor the beam position and profile in order to protect the target.

The analog signal from each strip of the SSEM is fed into the PAPILLON board and digitized by an 80 MHz sampling ADC. There are 24 analog input channels on the board. The digitized signal of all 24 channels are gathered by a FPGA

[1] PAPILLON stands for beam Position And ProfILe interLock mOdule for Neutrino experiment

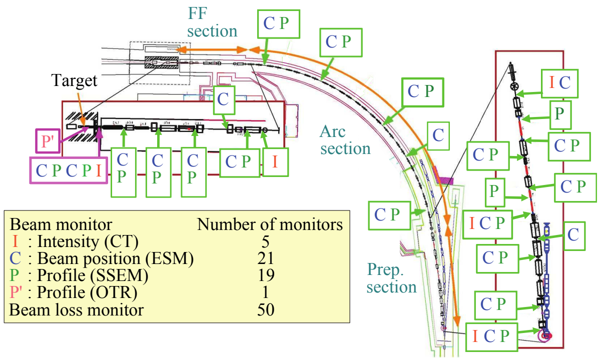

Figure 5: Beam monitors at the primary beamline.

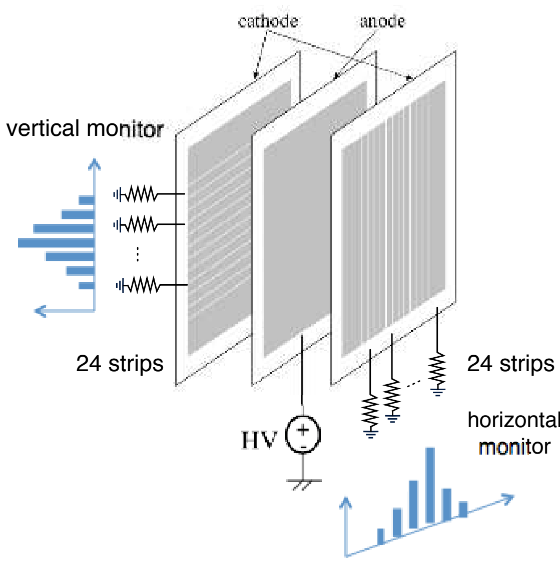

Figure 6: A schematic view of the SSEM.

(Xilinx Artix-7 families). An ethernet interface is adopted on the board in order to configure some of the parameters used in the PAPILLON and to transfer the data to a DAQ PC. In the FPGA, the beam position is calculated by the following procedures;

1. calculate an integrated ADC value for each strip (Fig. 7 (a)) over the single pulse beam duration,
$$Q_s = \sum_{t}^{t\leq 8\mu s} (p(t) - pedestal),$$
where $p(t)$ is the ADC value at the time of t measured by the 80 MHz sampling ADC, and *pedestal* is the offset value of the strip signal,

2. calculate the beam position as the weighted mean of the profile of Q_s, $\frac{\sum_{s=0}^{23} Q_s \times x_s}{\sum_{s=0}^{23} Q_s}$, where x_s is the center position of the strip s (Fig. 7 (b)).

Several verification tests were performed so far. In the latest verification test with actual beam, SSEM06, which is placed in the upstream section of the primary beamline, was utilized to evaluate the PAPILLON performance. The

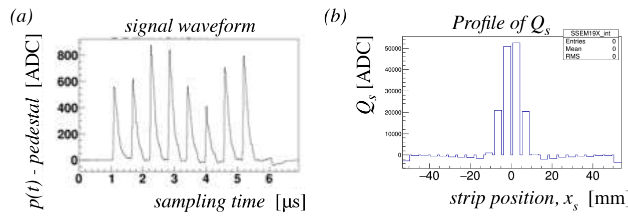

Figure 7: (a) shows an example of signal waveform after the pedestal subtraction, $p(t) - pedestal$. (b) shows an example of the profile of Q_s.

proton beam position at SSEM06 was intentionally changed by changing the upstream dipole and horizontal steering magnets while the beam power was set to 35 kW. The beam position was also calculated in the online monitor PC using a detailed off-line analysis method. Figure 8 shows the comparison between the beam position calculated in the FPGA and the online monitor PC. It is confirmed that the beam position calculation by the PAPILLON board was consistent with the one calculated by the online monitor PC. The latency of the MPS was also measured using the PAPILLON board. The measured value was 9 µs which is fast enough to stop the next beam injection to the MR[2].

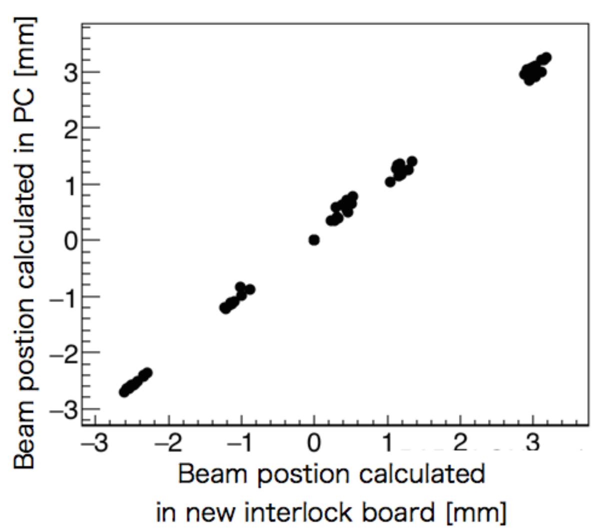

Figure 8: Comparison between the beam position calculated by the FPGA and the online monitor PC

SUMMARY AND PROSPECT

The J-PARC neutrino beamline will be upgraded for 1.3 MW MR beam power toward the discovery of CP violation in neutrino oscillation. The machine protection system is one of the essential components to realize safe operation with such high intensity beam.

A new electronics board which will issue the beam position and profile interlock, PAPILLON, is under development.

[2] The expected time between the beam extraction to the neutrino primary line and the next beam injection to the MR is a few hundred millisecond.

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The basic performance, including the beam position calculation by an FPGA has been verified using actual beam. Further verification tests are also planned to confirm its long-term stability and to check potential dependence of the calculated beam position on the beam intensity. Moreover, in addition to the beam position, the beam profile (width) measurement is also important. Development of FPGA firmware to calculate the beam width is in progress. We plan to install the PAPILLON and start its operation before the MR starts operation with a shortened repetition time.

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REFERENCES

[1] "T2K Status, Results, and Plans" presented by M. Wascko at Neutrino 2018 conference, doi:10.5281/zenodo.1286751

[2] K. Abe *et al.*, "Proposal for an Extended Run of T2K to 20×10^{21} POT," arXiv:1609.04111 [hep-ex].

[3] T. Koseki, "Upgrade Plan of J-PARC MR - Toward 1.3 MW Beam Power," doi:10.18429/JACoW-IPAC2018-TUPAK005

[4] http://openit.kek.jp/project/beam_monitor_interlock/beam_monitor_interlock

[5] M. Friend, "Beam Parameter Measurements for the J-PARC High-Intensity Neutrino Extraction Beamline", presented at IBIC'18, Shanghai, China, Sep. 2018, paper MOPB07, this conference.