Upgrade of the machine protection system toward 1.3MW operation of the J-PARC neutrino beam-line

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Contents

• Operation status and upgrade plan of the J-PARC neutrino beam-line

• Status of Machine Protection System upgrade: new interlock for beam position and profile at target

• Summary
J-PARC & Neutrino beam-line

Linac
25Hz, 330m
H- 400MeV, 50mA

3GeV Synchrotron (RCS)
25Hz, 350m, 1MW

30GeV MR
0.3Hz, 1.6km, 485kW (present) → 1.3MW

Neutrino beam-line & Near detector

Material/Life Science Facility

Hadron Experimental Facility

Bird’s eye photo in January of 2008
Producing a high intense neutrino beam for T2K(present), T2K-II and HK
One of main physics motivations is 

\[ \text{CP violation in neutrino oscillation} \]

\[ \Rightarrow \text{hint for the origin of matter dominate universe} \]
T2K current status

- Recently, 485kW stable operation
- $3.16 \times 10^{21}$ protons on target (POT) collected until the end of May 2018
- Based on data collected until Dec. 2017, CP conserving values (0, $\pm \pi$) are outside of 2$\sigma$ region

Indication of CP violation?
Toward discovery of CPV

Plan to accumulate more data up to $2 \times 10^{22}$ POT by 2026 (T2K extension proposal, J-PARC E65 [T2K-II])

- Increase of MR beam power up to 1.3MW
- Increase of signal statistics by both hardware and analysis improvement
- Improvement of systematic uncertainty by the near detector upgrade

![Graph showing $\Delta \chi^2$ to exclude $\sin \delta_{CP} = 0$ vs. Protons-on-Target (x10$^{21}$) with different $\sin^2 \theta_{23}$ values and 90% C.L., 99% C.L., and 3$\sigma$ C.L. regions. The graph indicates the work in progress for CP violation discovery.

$\delta_{CP} = -\frac{\pi}{2}$

$>3\sigma$ CPV sensitivity
Beam power upgrade scenario

- Increase the MR beam power up to 1.3MW by increasing the number of protons per pulse (p/pulse) and shortening the repetition time ($T_{\text{rep}}$).
- Power $\propto 30\text{GeV} \times \# \text{ of protons} \times 1/T_{\text{rep}}$.
- 520kW w/ 2.48sec, $2.7\times10^{14}$ p/pulse (1.1MW equivalent beam) has been successfully tested.
- Plan to upgrade MR main power supply in 2021.
- Upgrade of RF, collimator and Inj./FX devices are also planned.

<table>
<thead>
<tr>
<th>Achieved</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam power [MW]</td>
<td>0.49</td>
</tr>
<tr>
<td># of protons per pulse</td>
<td>$2.5 \times 10^{14}$</td>
</tr>
<tr>
<td>Rep. Time [sec]</td>
<td>2.48</td>
</tr>
</tbody>
</table>

Figure 5 shows a circuit diagram of power supply (PS).

Figure 6: The newly constructed three buildings for the PS's have been approved by the Japanese government. The construction of the buildings has been finished in JFY2017 as shown in Fig. 6. The per-Kamiokande project is assuming the 1.3 MW beam power of the MR from the start. When we consider that the MR will be operated with half-localized beam loss in the collimator section, the repetition time will be reduced if we can successfully achieve to get supplemental budget for manufacturing the magnets power supplies. Therefore, the demonstration shows that the MR has a feasibility to reach the beam power of 1MW with the magnets.
Neutrino beam-line upgrade plans

- All of the components were designed for 0.75MW with original beam parameters
  - Already tolerable for the thermal shock
- To realize 1.3MW operation, we plan to upgrade:
  - Cooling capability of target, horn etc.
  - Horn, DAQ for ~1Hz operation
  - Capacity of the radioactive waste (activated cooling water etc.)
  - Beam monitors
  - Machine Protection System (MPS)

<table>
<thead>
<tr>
<th></th>
<th>Original</th>
<th>New</th>
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<tbody>
<tr>
<td>Beam power [MW]</td>
<td>0.75</td>
<td>1.3</td>
</tr>
<tr>
<td># of protons per pulse</td>
<td>3.3 x 10^{14}</td>
<td>3.2 x 10^{14}</td>
</tr>
<tr>
<td>Rep. Time [sec]</td>
<td>2.1</td>
<td>1.16</td>
</tr>
</tbody>
</table>

See also related posters:
- MOPB07: Beam Parameter Measurements for the J-PARC High-Intensity Neutrino Extraction Beamline, M. Friend (J-PARC/KEK)
- WEP08: Optical System of Beam Induced Fluorescence Monitor Toward MW Beam Power at the J-PARC Neutrino Beamline, S. Cao (J-PARC/KEK)
MPS at neutrino beam-line

- MPS is one of the essential components to realize safe operation of 1.3MW beam
  - e.g. $3.2 \times 10^{14}$ p/pulse → 1.6MJ/pulse
- In order to reduce any potential risks during the high intensity beam operation, we plan to upgrade the MPS
One of MPS upgrade items

Serious damage on the target if beam continuously hits off-centered at the target

Graphite target
φ 26mm, 900mm long

(proven T2K target)

In order to avoid this case, we’re developing a new interlock for beam position and profile on the target

Beam shifted by 0.5cm

Stress Analysis for off-center beam

- C. Densham, J. Butterworth (RAL)
- Input: Energy deposit calculated by MARS
  - Stress, displacement by ANSYS

Displacement just after Spill (Unconstraint condition) max: ~4mm

Target can be one piece? Or should be divided?
Development of a new interlock for beam position and profile

- Present scheme
  - Beam profile monitor near the target
  - Analog signal
  - Attenuator + ADC
  - Calculate beam position in PC and issue an interlock if beam position on the target is shifted >1.5mm
  - $\Delta T$ (extraction - next injection) is $\sim 0.95s$

- $\sim 1$ sec
Development of a new interlock for beam position and profile

Present scheme

Beam profile monitor near the target

analog signal

attenuator + ADC

calculate the beam position in PC and issue an interlock if beam position on the target is shifted >1.5mm

~1 sec

$\Delta T(\text{extraction - next injection})$ is $\sim 0.95$ s

New scheme

Developing a new electronics board which can calculate the beam position & profile using FPGA and issue a interlock

the latency is significantly improved

<1 msec

PAPILLON board: http://openit.kek.jp/project/beam_monitor_interlock/beam_monitor_interlock
Development: Okayama-U and KEK
Beam profile monitor

- 19 Segmented Secondary Emission Monitors (SSEMs) are placed along beam-line to measure beam position and profile.
- During continuous beam operation (i.e. T2K physics run), only **SSEM19** is inserted in the beam-line → continuous measurement of the beam position/profile for target protection.

**Horizontal beam size measured by SSEM**

Each SSEM causes ~0.005% beam loss.

5μm thick Ti foils (x3; cathode+2+anode)

- Target
- Cathode plane
- Anode plane
- Compensating charge in each cathode strip is read out as positive polarity signal

<table>
<thead>
<tr>
<th>Beam monitor</th>
<th>Number of monitors</th>
</tr>
</thead>
<tbody>
<tr>
<td>I : Intensity (CT)</td>
<td>5</td>
</tr>
<tr>
<td>C : Beam position (ESM)</td>
<td>21</td>
</tr>
<tr>
<td>P : Profile (SSEM)</td>
<td>19</td>
</tr>
<tr>
<td>P' : Profile (OTR)</td>
<td>1</td>
</tr>
<tr>
<td>Beam loss monitor</td>
<td>50</td>
</tr>
</tbody>
</table>

- Vertical monitor
- Horizontal beam size measured by SSEM
- 24 strips
- 5μm thick Ti foils (x3; cathode+2+anode)

- J-PARC NU SSEM Principle and Design
  - Protons interact with foils
  - Secondary electrons are emitted from segmented cathode plane and collected on anode planes
  - Compensating charge in each cathode strip is read out as positive polarity signal

- SSEM Principle
  - Single anode plane between two stripped cathode planes
  - 5μm thick Ti foils

Prep. section

Arc section

Target
Beam position calculation in the new board

1. Calculate an integrated charge of each strip

\[ Q_s = \sum_{t} (p(t) - \text{pedestal}) \]

where \( t \leq 8 \mu s \)

2. Calculate a weighted mean beam center in [mm]

\[ \text{beam center [mm]} = \frac{\sum_{s=0}^{23} Q_s \times x_s}{\sum_{s=0}^{23} Q_s} \]

with \( x_s \) being strip position in [mm] and \( Q_s \) being charge of each strip.

[Diagram showing the flow of analog signal through the system, including analog signal x 24 strips, 80MHz Sampling ADC, FPGA, Network, Interlock Output, and PC.]
Verification test w/ beam

Setup configuration of verification test w/ beam

- Intentionally changed the beam position with a low current beam
- SSEM06
- 35kW, Proton beam
- 24strip Beam signal data
- Calculate beam position using PAPILLON
- Calculate beam position in FPGA
- Calculate beam position in PC

Confirmed that the beam position calculation in the new board is consistent with one calculated in PC
Prospect of the new interlock

- Further verification tests are also planned to confirm its long-term stability and to check potential intensity dependence etc.
- Beam profile (width) is also important. FPGA firmware is under development
- Plan to finish R&D and install before MR starts operation with shortened repetition time
Summary

- Toward discovery of the CPV in neutrino oscillation, J-PARC MR/neutrino beamline will be upgraded for 1.3MW beam power.

- The Machine Protection System is the essential components to realize safe operation with the 1.3MW beam.

- A new interlock for the beam position and profile is under development as one of MPS upgrade items. The basic performance was verified. This new interlock is promising.