Status of J-PARC neutrino beam-line operation and future upgrade plan

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NuFact 2016, 2016 Aug. 23
Contents

- J-PARC neutrino beam-line and its present status
- Future upgrade plan toward 1.3MW operation
  - How to realize the 1.3MW from the present 0.425MW
  - Improvement plan of the neutrino beam-line for 1.3MW operation
Physics motivation w/ J-PARC $\nu$ beam

- Lepton CPV
- $\theta_{23}$ is maximal or not
- Check the 3-flavor mixing framework

$L$(Tokai to Kamioka) = 295km → oscillation peak at 0.6GeV

0.6 GeV narrow band intense $\nu$ beam is key point

by measuring $\nu_e$ appearance, $\nu_\mu$ disappearance mode
High intense neutrino beam

- Accelerator-based $\nu$ beam
  - pure $\nu_\mu$ from $\pi/K$ decays
  - small $\nu_e$ contamination (~1%) from $\mu$ and K decays
  - $\nu$ / $\bar{\nu}$ can be switched by flipping horn polarity
  - $\nu$ energy is narrow with off-axis method

T2K beam:
* OA2.5° ($E_{\text{peak}} = 600\text{MeV}$)
J-PARC Neutrino facility

- Muon Monitor
- Horn
- Beam monitors
- Super-Conducting Magnets
- Si array + IC array
- 3 Horns w/ 320kA of design current
- beam dump
- Decay Volume
- Target
- Graphite, Φ26 x 900 mm long
- Helium cooling
- Near detector (at 280m from target)
- To Far detector
- proton beam
- 96m length
- 30GeV MR
Beam stability

- Event rate is stable ~1%
- Beam direction is controlled to be stable within much better than 1 mrad
  - 1 mrad corresponds to a 2% shift of peak $\nu$ energy at SK
Neutrino flux and its error

- $\nu$ flux is calculated based on
  - measurement of proton beam profile
  - $\pi$, K yield measurements by CERN NA61/SHINE experiment

$\pi^+$ yield from 30GeV $p+C$ interaction

- Total absolute flux uncertainty is ~10% (similar size for anti-nu beam)
- Far-to-near extrapolation is also calculated
Beam-line operation so far

27 May 2016
POT total: 1.510×10^{21}

ν-mode POT: 7.57×10^{20} (50.14%)
ν̄-mode POT: 7.53×10^{20} (49.86%)

425kW operation was achieved!
Beam-line operation so far

27 May 2016
POT total: $1.510 \times 10^{21}$

$\nu$-mode POT: $7.57 \times 10^{20}$ (50.14%)
$\bar{\nu}$-mode POT: $7.53 \times 10^{20}$ (49.86%)

19% of T2K goal
Replacement of activated equipment

- Remote maintenance of activated equipment was established and successfully performed with international cooperation with RAL and TRIUMF

  - Replacement of the horns/target with spares in 2013
  - Fixing of the leak of He gas for target cooling by replacing with a spare in 2015

Target He cooling pipe repair

Replaced by manipulators in the maintenance area
Beam power improvement plan

Increase the MR beam power up to 1.3MW
- Power $\propto 30\text{GeV} \times \# \text{ of protons} \times \frac{1}{T_{\text{rep}}}$.
- Upgrade MR for both shortening the repetition time ($T_{\text{rep}}$) and increasing the number of protons per pulse.

<table>
<thead>
<tr>
<th>Achieved</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam power [MW]</td>
<td>0.425</td>
</tr>
<tr>
<td># of protons per pulse</td>
<td>$2.2 \times 10^{14}$</td>
</tr>
<tr>
<td>Rep. Time [sec]</td>
<td>2.48</td>
</tr>
</tbody>
</table>

Improve the neutrino beam-line
- Modest improvement to realize 1.3MW operation

Increase the effective statistics (x1.5)
- Horn current increase (250kA $\rightarrow$ 320kA) and data analysis improvement
MR upgrade status (1)

- Shorten $T_{\text{rep}}$ by:
  - Replacing magnet power supply (PS)
    - New PS was developed with energy recovery bank capacitor to suppress a power variation at AC main grid
  - Plan to start 1.3sec repetition in 2018 (budget has been approved from JFY2016)
- Improve RF
  - High gradient RF cavity was developed (new type of magnetic alloy core, FT3L)
    - Under installing the new RF cavities (~2018)
  - Plan to upgrade the anode power supply for 1.16s repetition
MR upgrade status (2)

- Increase of # of protons per pulse by reducing beam loss and beam instability

- Recent progress:
  - Bunch by bunch and intra-bunch feedback system is applied during injection and in the beginning of acceleration in order to reduce beam instability
  - New betatron tune operation

Achieved a stable operation with 425kW (2.2x10^{14} protons per pulse, 2.48 sec repetition)

- 440kW operation is planned at this autumn
Further improvement of # of protons

- High intensity beam study was performed in 2015 June
- 6.82x10^{13} protons per bunch x 2bunch (single shot op.)
- MR has capability to reach 1MW (although beam loss needs to be reduced)

<table>
<thead>
<tr>
<th></th>
<th>Measurement (2bunch)</th>
<th>Estimation (8bunch)</th>
<th>Estimation (8bunch)</th>
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</thead>
<tbody>
<tr>
<td>Beam power [MW]</td>
<td>0.13</td>
<td>0.53</td>
<td>1.0</td>
</tr>
<tr>
<td>Rep. Time [sec]</td>
<td>2.48</td>
<td>2.48</td>
<td>1.3</td>
</tr>
<tr>
<td># of protons per pulse (equiv.)</td>
<td>2.7 x 10^{14}</td>
<td>2.7 x 10^{14}</td>
<td>2.7 x 10^{14}</td>
</tr>
<tr>
<td>Beam loss [kW]</td>
<td>0.42</td>
<td>1.7</td>
<td>3.2</td>
</tr>
</tbody>
</table>

- Further improvement of # of protons per pulse up to 3.2 x 10^{14} protons per pulse is planned with upgraded RF system, fast extraction kicker and optimized beam tune
Timeline toward MW beam

Reaches ~1.3MW

Realizing 1.3MW operation before 2025
Neutrino beam-line improvement

- All of the components were designed for 0.75MW with original beam parameters
- decay volume and beam dump itself are already tolerable for 3-4MW
- Modest improvement to realize 1.3MW operation
  - Horn 1Hz operation
  - Cooling capability of target, horns, decay volume and beam dump
  - Capacity of the radioactive waste (activated cooling water etc.)
  - Proton beam monitors
  - Beam-line DAQ and control system

<table>
<thead>
<tr>
<th></th>
<th>Original</th>
<th>New</th>
</tr>
</thead>
<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>
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</table>
Horn upgrade plan

- Present operation is 250kA with 2.48sec repetition
  - Limitation: the operation voltage of PS becomes too high at 1Hz
- Also, increase the current to 320kA: 10% increase of flux at far detector and 5~10% reduction of wrong-sign components at peak energy
- Plan to install additional power supply, new current transformers and new strip-lines with lower R and L

![Graph showing Flux Improvement @ 320kA](image)

- Flux Improvement @ 320kA
  - Horn current: 250 kA ⟹ 320 kA (rated)
  - 10% improvement of neutrino flux at far detector
  - 5~10% reduction of wrong-sign neutrinos around $E_{\nu}$ peak

![Graph showing Neutrino Energy vs Flux Ratio](image)

- Neutrino Energy (GeV)
  - Flux ratio 320kA/250kA
    - 0.6
    - 0.7
    - 0.8
    - 0.9
    - 1
    - 1.1
    - 1.2
    - 1.3
    - 1.4
- Neutrino mode
  - $\nu_{\mu}$
  - $\bar{\nu}_{\mu}$
- Anti-neutrino mode
  - $\nu_{\mu}$
  - $\bar{\nu}_{\mu}$

Courtesy of T. Nakadaira
Upgrade of radioactive water disposal system

- Limitation due to the size of dilution tank
- 750kW is acceptable with taking activated water by a improved method
- Plan to enlarging the tank → 1.3MW is acceptable
Improvement of cooling capacity

- It is necessary to improve the cooling capacity for the target, horns, beam window, decay volume and beam dump by increasing the flow rate for both water and helium for 1.3MW operation
- Replacement with larger pumps and larger size plumbing
- Ahead replacement is planned for horn strip-line cooling for 0.75MW
Timeline of secondary beam line upgrade

- 1.3 MW: FY2016
- 750 kW: FY2017
- 500 kW: FY2018

Target/Beam Window
- He cooling

Horn stripline cooling

Horn operation

Water cooling

Radio-active water disposal

Reinforce He flow system
- 320 kA/1Hz

Upgrade system

Water-cooled striplines

Enlarge dilution tank

Upgrade system
Primary beam-line

- Basically ready for high beam power
- Possibility to modify the configuration of normal-conducting magnet against any extraction failures
- Beam orbit from the extraction to the target is controlled anytime in order to keep less beam loss at the primary beam-line
  - Less beam loss is achieved at 425kW operation
Proton beam monitor upgrade

- New beam monitors which are more robust and cause less beam loss are under development
  - Ti-wire secondary emission monitor (SEM)
    - 10 times less material in the beam compared to the foils-based SEM which presently used in the beam-line → 10x less beam loss
  - Beam induced fluorescence monitor
    - Measure proton beam profile by fluorescence light induced by proton beam interactions with gas in the beam-line
    - Continuously and non-destructive monitor proton beam profile

New Ti Wire SEM:

Beam Induced Fluorescence Monitor Schematic:

(NIMA 492 (2002) 74-90)
Beam-line DAQ upgrade

- Signal data (proton beam monitors, muon monitors and some magnet waveforms) are collected by the beam-line DAQ
- All the data should be collected before next beam injection in order to avoid any abnormal beam into the neutrino beam-line
- Limitation: readout electronics for some beam monitor has a large latency → need to improve
- New readout electronics (with a network-based readout embedded SiTCP) is under development
Improvement of beam interlock

- Beam should be stopped if properties of the extracted beam is NOT normal
- if such beam continues, the beam-line components could be destroyed
- In present, beam is stopped based on online monitor analysis results but its latency is large
- New electronics module which calculate the beam profile and position using FPGA is under development

Stress Analysis for off-center beam

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

Logic diagram of new module

- Beam shifted by 0.5cm
- Target can be one piece? Or should be divided?

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

Beam interlock for displaced beam position and/or very narrow width beam
- if such beam continues, the target is destroyed due to non-uniform thermal shock
- one of idea is to develop a hardware which calculates beam position/profile using FPGA/DSP and use it for beam monitor readout
- another idea is to develop a segmented target (alternative? we may need both)
- present T2K target
Prospect

- T2K approved goal is $7.8 \times 10^{21}$ protons on target
- T2K-II (proposed extension) target is $20 \times 10^{21}$ protons on target by 2025~2026
  - > 3σ C.L. sensitivity for CPV
Summary

- J-PARC MR and neutrino beam-line 425kW operation is achieved without any major issues
- Future upgrade toward 1.3MW is planned
  - shorten the repetition time from 2.48s to 1.2s gradually
    - start 1.3s operation at 2018 (budget approved)
  - increase # of protons per pulse to $3.2 \times 10^{14}$
- The neutrino beam-line is being improved for higher power operation
- Realizing 1.3MW operation before 2025