Status of T2K experiment

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IPNS, KEK
Contents

• Summary of recent events
• Data Bay Results
• T2K plan
• Summary of beam commissioning
• Horn recovery status & plan
• March data taking status
• Analysis
• T2K plan and requests
Summary of recent events
(especially after the last PAC, Jan 13-15)

- Dec. 22: Horn PS was broken
- Dec. 24-26: First beam aft the earthquake w/o horn operation
- (Jan.13-15: PAC meeting)
- Jan. 20-25: Second beam commissioning w/o horn operation
- Jan. 23-28: Collaboration meeting
- Feb: Reinstallation and testing of old Horn PS, disassembling & investigation of the broken PS during SX experiments
- Mar. 2: FX beam tuning w/ old horn PS.
- Mar. 5: Just before starting physics data taking, the horn PS thyristor broken
- Mar. 8: After replacing thyristor to the spare, physics data taking was started at horn current 200kA
- (Mar. 8: Daya Bay result)
Daya Bay results

• We are happy to hear that
  – The T2K results of observing appearance excess (0.7% or 2.5σ) is confirmed by Daya Bay
  – The T2K result of large $\theta_{13}$ ($\sin^2 2\theta_{13} = 0.11$) is also confirmed

• This is a good news in neutrino physics and their efforts to accomplish this in such a short time should be praised!

Observed: 9901 neutrinos at far site,
Prediction: 10530 neutrinos if no oscillation

$R = 0.940 \pm 0.011$ (stat) $\pm 0.004$ (syst)

$\sin^2 2\theta_{13} = 0.092 \pm 0.016$(stat) $\pm 0.005$(syst)
Indication of $\nu_e$ appearance (non-zero $\theta_{13}$)

6 $\nu_e$ candidates found!

- Prob. of 6 are all BG: 0.7% (2.5$\sigma$ equiv)

\begin{align*}
(\Delta m_{23}^2 > 0) & \quad 0.03 < \sin^2 2\theta_{13} < 0.28 \\
(\Delta m_{23}^2 < 0) & \quad 0.04 < \sin^2 2\theta_{13} < 0.34
\end{align*}

\begin{align*}
\sin^2 2\theta_{13} = 0.11 & \quad \text{Central value} \\
\text{assuming } \Delta m_{23}^2 = 2.4 \times 10^{-3} \text{ eV}^2, \sin^2 2\theta_{23} = 1, \delta_{\text{CP}} = 0
\end{align*}

Expected BG 1.5 ± 0.3 evts

Allowed region

$\sin^2 2\theta_{23} = 1$

$\Delta m_{23}^2 = 2.4 \times 10^{-3} \text{ eV}^2$
T2K program

- We want to improve significance of our **APPEARANCE** signal as soon as possible
  - $>3\sigma$ with $>\times2$ POT for this summer
    - Nu2012 (June 4-9@ Kyoto), ICHEP (July 4-11, Melbourne), etc etc
  - $\sim5\sigma$ w/ $O(10^{21})$ pot before 2013 long shutdown

- **Precision** measurement of appearance
  - Tighter constraint on $\theta_{13}-\delta$ relation
  - Compare with reactor results
  - First trial to detect possible hint on CPV and mass hierarchy
  - Precise determination of $\Delta m_{13}$

- **Precision** measurement of disappearance
  - $\theta_{23}, \Delta m_{23}$
  - Whether maximal mixing or not?

- Pursue possibility of anti-nu measurements

- Various cross section measurements at near detector
Beam commissioning overview (J-PARC Run #40, #41)
# Beam time & Commissioning schedule

<table>
<thead>
<tr>
<th>Month</th>
<th>Linac</th>
<th>RCS</th>
<th>MLF</th>
<th>MR</th>
</tr>
</thead>
<tbody>
<tr>
<td>12月</td>
<td>1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1月</td>
<td>1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2月</td>
<td>1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3月</td>
<td>1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Commissioning Goal**
  - Jan. (Run #40)
    - Check the beam line alignment using beam other than horn.
    - Check the readiness for high power operation.
  - Mar. (Run #41)
    - Check the alignment of horn using beam.
    - Start physics run!

- 3 x ½ days for NU
- 5 x ½ days for NU
- 23 days for NU

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*Note: The table and diagram illustrate the 2011 Accelerator maintenance & Operation Plan, with specific commissioning schedule details marked for January and March.*
Primary beam tuning in Jan.

Before tuning / After tuning

1/26 90kW beam

All the beam monitor is working fine and beam is tuned well. The residual from ideal orbit is 1.5mm(H)/3mm(V) max.

Beam size @ target is set to design value ($\sigma_x = \sigma_y = 4$mm).

→ Ready for physics run.
Beam commissioning in Run ~#40

- Alignment check using beam
  - Primary line (SSEM)-secondary line (OTR) consistency
    - Consistent within survey precision.
  - Alignment of Baffle (collimator to protect horn)
    - DX=-1.2mm, DY=0.1mm < tolerance = 2mm

Offset is within the survey precision

Checking baffle position from its shadow for the intentionally shifted beam.
Check the stability of beam

- Run #40 90kW continuous spills
  → All spill pass the criteria for physics analysis as same as before the earthquake.

The beam stability is good enough for physics run.
Muon/Neutrino yield w/o horn

Si/CT5 = 8.6 nC/10^{12} ppp (beam at target center)

K. Suzuki @ 2010

Jan data 8.6 nC/10^{12}

New rates are consistent with previous running w/o horn

<table>
<thead>
<tr>
<th>Run</th>
<th>Event rate of neutrino events + sand muon events</th>
</tr>
</thead>
<tbody>
<tr>
<td>RUN40</td>
<td>1.56 ± 0.04(stat.) events / 10^{16} POT</td>
</tr>
<tr>
<td>RUN39</td>
<td>1.52 ± 0.04(stat.) events / 10^{16} POT</td>
</tr>
<tr>
<td>RUN34 w/o horn</td>
<td>1.48 ± 0.04(stat.) events / 10^{16} POT</td>
</tr>
</tbody>
</table>

Good agreement with before the earthquake!
280m off-axis detector
First event in SK aft. the earthquake

Jan.26, 2012, 02:45 w/o horn operation
Status for Broken Power Supply

• Inspection
  – **Capacitors**: electrical measurement revealed all capacitors were healthy.
  – DC chargers: disassembled and delivered to company. Now under investigation.
  – Control units: Now under investigation in company.
  – Cabling check: done for all the components. All except for broken parts were OK.

• Procurement
  – **IGBT**: ordered and will be delivered in this fiscal year.
  – Thyristors: already delivered and existing ones will be replaced with new ones.
  – Capacitors: public bidding for spare capacitors on going.

• Recovery
  – Recovery plan is under discussion.
    • **Some modifications to improve safe operation are under investigation.**
  – Recovery plan will be decided once all the inspection are done.
Horn power supply status

- Old PS was refurbished and operation test was started on Feb. 7th
  - Succeeded to operate upto 260kA
- 3 horns are operated in serial by 1 PS (first trial)
  - Input load $\rightarrow$ x1.5
- Voltage spike (12.3kV peak) exceeding cable spec was reduced by introducing RC LPF down to 8.3kV $\rightarrow$ OK

- Horn current up to 260kA tested.
- Charging voltage 7kV as expected.
- High frequency noise (118kHz) makes a spike.
- Measured peak voltage 12.3kV > 9.3kV (rated)
- Adopt low pass filter to reduce peak voltage.
Horn PS thyristor failure

• Operation stopped by interlock on Mar. 5th => Thyristor switches broken.
• A concern is an inrush current at thyristor: $\frac{dI}{dt} = 500\text{A/\text{ms}}$ (should be less than $300\text{A/\text{ms}}$(rated))
• Replaced with a spare one (which has $250\text{A/\text{ms}}$(rated)).
• Various trials done to reduce inrush current by changing route of ground lines. => reduced to $300\text{A/\text{ms}}$ at 250kA.
• **For safety, we restricted current to 200kA (measured inrush current:250A/\text{ms}) for the moment**
• We continue to try to reduce inrush current to achieve 250kA operation.
  – Plan to test a saturable inductor.
200kA vs 250kA

Peak flux ~20% reduction

Nue signal decrease ~14%

<table>
<thead>
<tr>
<th># of evt@SK (@1e19pot)</th>
<th>250kA</th>
<th>200kA</th>
<th>200kA/250kA Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCFV</td>
<td>5.93</td>
<td>5.76</td>
<td>0.97</td>
</tr>
<tr>
<td>Signal ve (@sin^2\theta_{13}=0.1)</td>
<td>0.280</td>
<td>0.241</td>
<td>0.86</td>
</tr>
</tbody>
</table>
Physics data taking started on Mar.8

- Rep cycle: 2.92 sec (3.02sec bfr EQ)
- Beam power is reached at ~137kW (8.4e13ppp)
- Horn current: 200kA at this moment
- 7.5e18 pot delivered during March 8~14 (added ~5% to data bfr EQ = 1.43e20pot)
Machine time usage/allocation

- 167 hr allocated during Mar.5~14, 21:00 (~70% of total time = 24hr x 10days)
- 88.6h used for physics data taking (53.0% of 167hr)
- Many initial failures happened (still “shake down” period)
Quick look: MUMON

- Muon yield
  - 19.4 nC/10^{12}p @ 200kA
  - 31.7 nC/10^{12}p @ 250kA
  - Ratio: 0.61 (MC pred: 0.62)
- Muon yield (#/proton) is stable within 0.7\% (RMS)
- Profiled center is tuned and controlled within required precision (10cm = 1mr)

\[
\begin{align*}
X \text{ Si profile center (cm)} & \quad Y \text{ Si profile center (cm)} \\
\text{After normalization by CT5} & \\
\end{align*}
\]

\[
\begin{align*}
\text{Total charge (nC/10^{12}pp)} \\
08, \text{Mar} & \quad 09, \text{Mar} & \quad 10, \text{Mar} & \quad 11, \text{Mar} & \quad 12, \text{Mar} & \quad 13, \text{Mar} & \quad 14, \text{Mar} \\
\end{align*}
\]

Muon intensity/proton intensity
Stable within 0.7\% RMS

\[
\begin{align*}
\text{Profile X center} & \\
\text{Profile Y center} \\
\end{align*}
\]

\[
\begin{align*}
\text{RMS} \\
X: 0.43cm & \quad Y: 0.65cm \\
\end{align*}
\]
Quick look: INGRID

- Timing is OK
- All 8 bunches are clearly seen
- Event rate ratio (200kA/250kA) is consistent w/ MC prediction < ~4%
- Event rate is stable within stat err
- Central peaking shape clearly observed
- Fitted beam center is consistent with expected center within required precision (1mr = 28cm)

Event rate ratio (200kA/250kA)
Data: 0.80
MC : 0.77
ND280 data quality

All ND280 subdetectors have been taking good quality data with excellent efficiency since the beginning of Run3. In particular, for the most recent of data quality assessment (03/04-03/10):

<table>
<thead>
<tr>
<th>Subdetector</th>
<th>Data taking efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>P0D</td>
<td>100%</td>
</tr>
<tr>
<td>TPC</td>
<td>100%</td>
</tr>
<tr>
<td>FGD</td>
<td>100%</td>
</tr>
<tr>
<td>ECAL</td>
<td>100%</td>
</tr>
<tr>
<td>SMRD</td>
<td>100%</td>
</tr>
</tbody>
</table>

All subdetectors see the same beam structure: 8 bunches with 580ns spacing:
Observation at SK

- 5 SK FC events observed as expected w/ 7.25e18 pot
Analysis status

- Development of new analysis methods w/ shape information ($E_\nu$, $p_\mu - \theta_\mu$) completed

- Improvements of systematic errors for the analysis toward this summer completed
  - BG syst error is reduced from $\sim 20\% \Rightarrow \sim 10\%$
T2K program

• We want to improve significance of our APPEARANCE signal as soon as possible
  – >3σ with > x2 POT for this summer
    • Nu2012 (June 4-9@ Kyoto), ICHEP (July 4-11, Melbourne), etc etc
  – ~5 σ w/ O(10^{21}) pot before 2013 long shutdown

• Precision measurement of appearance
  – Tighter constraint on θ_{13}-δ relation
  – Compare with reactor results
  – First trial to detect possible hint on CPV and mass hierarchy
  – Precise determination of Δm_{13}

• Precision measurement of disappearance
  – θ_{23}, Δm_{23}
    – Whether maximal mixing or not?

• Pursue possibility of anti-nu measurements
• Various cross section measurements at near detector
Expected POT by summer 2012

182kW (2.56s)

Max pwr w/o increasing ion source current

~ Run #38
1.4 × 10^{21} POT

~5/31
3.15 × 10^{20} POT

~7/2
3.9 × 10^{20} POT

~5/31
Near term expected sensitivity

To cover Daya Bay $1\sigma$ region $>3\sigma$, we need beam until end of June.
To reach $5\sigma$ level, need $10^{21}$ pot.

<table>
<thead>
<tr>
<th>(Only norm. analysis)</th>
<th>3.15e20 pot (by end of May)</th>
<th>3.9e20 pot (by end of June)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significance ($@\sin^22\theta_{13}=0.08$)</td>
<td>$2.8\sigma$</td>
<td>$3.1\sigma$</td>
</tr>
</tbody>
</table>
# Beam parameters to be realized

<table>
<thead>
<tr>
<th></th>
<th>137kW Achieved</th>
<th>156kW</th>
<th>182kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion source</td>
<td>15mA</td>
<td>15mA</td>
<td>15mA</td>
</tr>
<tr>
<td>LINAC pulse width</td>
<td>500us</td>
<td>500us</td>
<td>500us</td>
</tr>
<tr>
<td>LINAC bunch thinning factor</td>
<td>28/32 87.5%</td>
<td>32/32 100%</td>
<td>32/32 100%</td>
</tr>
<tr>
<td>#p/bunch</td>
<td>1.05x10^{13}</td>
<td>1.19x10^{13}</td>
<td>1.19x10^{13}</td>
</tr>
<tr>
<td>MR rep cycle</td>
<td>2.92s</td>
<td>2.92s</td>
<td>2.56s</td>
</tr>
<tr>
<td>Horn current (sig decrease)</td>
<td>205kA (-14%)</td>
<td>250kA as soon as possible</td>
<td></td>
</tr>
</tbody>
</table>

- Reduce beam loss at MR collimator (close to capacity)
- MR PS small modification
Precision measurement of appearance

Statistical error will reach ~6% at 750kW.5x10^7s
By achieving similar or less systematic error,
We can reach <10% total error
Combination with reactor

Complementarity of Reactor-accelerator $\theta_{13}$ measurement

- $\theta_{13}$ degeneracy
- Matter effect
- $\delta$ dependence

Rich Physics!

$P_{MC}(\nu_\mu \rightarrow \nu_\tau) = \frac{0.50 \pm 0.11 \sin^2 2\theta_{13} \pm 0.045 \sin 2\theta_{13} \sin \delta}{(1 \pm 0.00017 L/km)}$

$\sin^2 2\theta_{23} = 0.95$

- $\Delta m^2_{32} > 0$
- $\Delta m^2_{32} < 0$

Suekane

- Hypothetical reactor measurement
- 5% precision

- First trial to probe CPV phase (& mass hierarchy)
  - ~6% stat err at 3.75MW.1e7s expected at present central value
    - Syst err (~20% at present, soon ~10% level) needed to be improved too
  - Accelerator Measurement

- T2K $\theta_{13}$ sensitivity 3.75MW.1e7s (unofficial)
Summary

• T2K restarted physics data taking on Mar.8
  – 137kW operation, 7.5e18pot delivered by Mar.15
  – w/ spare old PS at 200kA for now
  – All components are working fine
  – Muon/neutrino yield is consistent w/ prediction and stable enough within requirement
  – 5 FC events observed at SK as expected

• We would like to improve our APPEARANCE significance
  – Aim to release >3σ results this summer
    • ~180kW (or higher) & 250kA operation should be realized as soon as possible
  – ~5σ level before 2013 Summer long shutdown which require (10^{21}) pot

• Rich physics continues
  – Precision measurements of appearance, disappearance
  – First trial to probe CPV & matter effect
  – Cross section measurements
  – Possibility of anti-nu measurement
Neutrino Failures happened in Run #41

- Horn Power supply: 27H to recover (including 12H in MR study time)
  - Thyristor was broken
  - Operation current is reduced (250kA → 200kA): Additional study time (2 hours)
- SC Magnet quench: 24H to recover (including 12H in MR study time)
  - Reason is unknown. It seems due to the noise happened in MSS.
  - The quench happened 1 magnet cause the quench happened in other 8 magnets. Fix the suspicious bad contact at the cables inside the MSS electronics.
- Cooling water circulation of Horn-target was stopped. (5.5H)
  - Main circulation pump stopped due to over current. Change to use the second pump.
- Stop of vacuum pump at FF section (3H)
  - 1 of 4 pumps become out of order.
- He leak from TS-DV Helium vessel (No beam time loss)
  - He tube at O2/Dew point monitor in NU3 B1 was broken
  - He is filled and restart after checking the effect by Air contamination.
- MPS due to large beam loss MR-FX/NU-most upstream. (~3H loss)
  - When the beam power is increased to 137kW, Beam loss at MR-FX/NU-most upstream part frequently exceed the limit.
  - Beam loss it 10 times larger than that measured before the 145kW operation before the earthquake. Expected radiation of the magnet after 1 week operation is about 1mSv/h.
  - Beam loss is reduced after the MR vertical extraction orbit tuning by factor 1/3. (Additional 3H for beam tuning)
Physics data taking started on Mar.8!

Integrated POT per day

Run #40
horn-off data
$8.52 \times 10^{17}$ POT

Run #41 (~3/12)
horn 200kA
$5.92 \times 10^{18}$ POT

~ Run #38
$1.46 \times 10^{20}$

~5/31
$3.18 \times 10^{20}$ POT

~7/2
$3.93 \times 10^{20}$
Here we are

significant vs POT

May

June

$\sin^2 2\theta_{13} = 0.11$

$\sin^2 2\theta_{13} = 0.08$

$\sin^2 2\theta_{13} = 0.03$
To realize our hope

A case study (1mon = 1e7s/6 = 19.3days)

<table>
<thead>
<tr>
<th>CY</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acc/Nu</td>
<td>NU</td>
<td>NU</td>
<td>NU</td>
<td>NU</td>
</tr>
<tr>
<td>MR Power</td>
<td>175</td>
<td>200</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>Mon/yr</td>
<td>4</td>
<td>6</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Integ. Power</td>
<td>185</td>
<td>385</td>
<td>535</td>
<td>935</td>
</tr>
<tr>
<td>Integ. POT</td>
<td>3.9E+20</td>
<td>8.0E+20</td>
<td>1.1E+21</td>
<td>1.9E+21</td>
</tr>
</tbody>
</table>

Milestones: \( O(10^{21}) \) 2\( \sim 3 \times 10^{21} \)

Statistical error will reach \(~6\%\) at 750kW, 5x10^17's
By achieving similar or less systematic error, We can reach <10% total error

Fractional error on \( \sin^2 2\theta_{13} \)

(Width of above plots)
Vs NOVA

$\sin^2 2\theta_{13}$ sensitivity (90% CL)

- NOvA (baseline)
- Double CHOOZ
- Daya Bay
- T2K (before earthquake)
Neutrino vs Anti-neutrino

Daya Bay: $\sin^2 2\theta_{13} = 0.092 \pm 0.017 \ (1\sigma) \ (0.075 - 0.109)$