Future Accelerator-based Neutrino Physics in Asia

TAKASHI KOBAYASHI
KEK/J-PARC

35+5 min talk
Contents

- Japan-based experiments
  - J-PARC accelerator status and future prospect
  - T2K future
  - HK
  - Extended T2K
- Asian activities and ideas
  - Indian activity
  - Chinese idea
  - Korean idea
Workshop for neutrino programs with facilities in Japan
Aug.4-6, 2015, J-PARC

Hereafter referred to as “Future Nu in J WS” in this presentation

- Main goal of my talk on the program in Japan is to digest discussion in this workshop

http://www-conf.kek.jp/ws_nu_prog_in_jp/

- Workshop for Neutrino Programs with facilities in Japan
  - Discussion subjects
    - T2K upgrade (beam, near detectors and Super-K)
    - J-PARC accelerator upgrade
    - Super-K upgrade
    - Hyper-K project and the connection/relation with T2K and Super-K
    - Any new ideas to make the neutrino program with Japanese facilities more fruitful
  - Scientific Program
    - The workshop program is available on the KEK Document Server (KDS, Indiko @ KEK). (Username/Password will be shown in the prompt dialog of your web browsers.)
  - Conference Venue:
    - Ibaraki Quantum Beam Research Center (IQBRC) (Access Information).
Accelerator neutrino program in Japan

- Toward understanding of whole picture of neutrino mixings and masses
  - Precision measurements of oscillation → testing 3x3 PMNS picture
  - Determination of CPV phase
  - Contribution to mass hierarchy determination
  - Search for new phenomena
    - Sterile, Lorentz invariance violation, NSI, etc

To attack big questions in particle physics, such as Quark-Lepton unification, origin of matter dominated universe, etc

- by international collaboration
- Under the global context of coherent/competitive efforts
- using
  - J-PARC proton beam with increasing beam power
  - Super-K → Hyper-K at ~300km
J-PARC accelerator status and prospects
Japan Proton Accelerator Research Complex: J-PARC

Bird's eye photo in January of 2008

South to North

Neutrino Beams (to Kamioka)

3 GeV RCS

Design intensity
RCS for MLF: 1MW
MR for PN: 750kW

30 GeV MR

CY2007 Beams
JFY2008 Beams
JFY2009 Beams

Hadron Exp. Facility

Materials and Life Experimental Facility

Japan Proton Accelerator Research Complex (KEK/JAEA)
Accelerator status

- Recent upgrades
  - LINAC energy is upgraded from 181 MeV to design 400 MeV in 2013
  - LINAC frontend (Ion source, RFQ) upgraded from 30 mA → 50 mA in 2014
  - MR inj collimator capacity increased
  - MR RF → introducing FT3L new cores for higher acc grad/higher harmonic.

Demonstration of 1 MW-equivalent.

~350 kW stable operation achieved!
Path toward >750kW

- Higher #p/bunch
  - LINAC upgrade
    - 400MeV (2013)
    - Frontend (Ion source, RFQ) 30→50mA (2014)

- Reduce beam loss in MR
  - MR RF higher harmonic (2013-2017)
  - BxB/Intra bunch feedback (installed)
  - Injection kicker pulse shape correction (2014-2015)

- Increase MR collimator capability
  - → 3.5kW loss

- Higher rep late (2.48s → ~1s, x2)
- Replace MR magnet PS: plan 2016-2018

Enable RCS operation upto 1MW
The high repetition rate scheme is adopted to achieve the design beam intensity, 750 kW. Rep. rate will be increased from ~ 0.4 Hz to ~1 Hz by replacing magnet PS’s and RF cavities. [Assuming MR-PS upgrade is funded as scheduled]
High Intensity beam study in MR

- at the new betatron tune (22.239, 21.310) -

High power trial with two bunches

Extracted beam: 6.82e13 ppp (132 kW eq.)

Total beam loss ~ 420 W

Became possible to aim beyond 750kW

Beam loss due to the horizontal instability

<table>
<thead>
<tr>
<th>Bunch number</th>
<th>repetition period (sec)</th>
<th>Beam power (kW)</th>
<th>Beam loss (kW)</th>
<th>Notes</th>
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<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>2.48</td>
<td>132</td>
<td>0.42</td>
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<td></td>
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<td>measurement</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>2.48</td>
<td>530</td>
<td>1.7</td>
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<td>estimation</td>
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<td>8</td>
<td>1.3</td>
<td>1000</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>estimation</td>
</tr>
</tbody>
</table>
Present experiment: T2K
T2K latest achievements

The T2K Experiment

Beam Operations

Stable operation at 345kW
Maximum beam power: 371kW

Kirsty Duffy, Oxford Aug. 11 talk

Start measuring CPV phase

First $\bar{\nu}_e$ app search

$\bar{\nu}_\mu$ disapp. meas.

$\sin^22\theta_{23} = 0.46^{+0.14}_{-0.06}$

$\Delta m^2_{32} = 2.50^{+0.3}_{-0.2} \times 10^{-3} eV^2$

Best fit values:

3 cand.

$\nu_\mu$ disapp. meas.

Start world leading meas.
T2K future

- Will accumulate $7.8 \times 10^{21}$ POT (750kW x 5 “year”) (7xnow)
  - With similar amount of POT for $\nu$ and $\bar{\nu}$
- Updated physics goals after $\nu_e$ appearance discovery
  - Precision measurements of $\nu_\mu$ disappearance
    - $\delta(\sin^2 \theta_{23}) \sim \pm 0.05 \sim \delta(\sin^2 2\theta_{23}) \sim 0.01$, $\delta(\Delta m^2_{23}) \sim < 10^{-4}$ eV$^2$
  - Precision measurements of $\nu_e$ appearance
    - Syst err $\sim 5\%$ ($\sim 10\%$) for $\nu$ ($\bar{\nu}$)
- Measurement of CPV phase $\delta$
- Contribution to mass hierarchy determination
- Cross section measurements
- New physics search (NSI, etc)

Assuming MR-PS upgrade as scheduled and latest power projection

**POT accumulation expectation**

~2021 at earliest

April 1, 2015
Expected T2K sensitivities

**ν_e appearance sample**

<table>
<thead>
<tr>
<th>δ</th>
<th>ν_e signal</th>
<th>ν_e bkg.</th>
<th>ν_e signal</th>
<th>ν_e bkg.</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>98.2</td>
<td>26.8</td>
<td>25.6</td>
<td>16.3</td>
</tr>
<tr>
<td>−90°</td>
<td>121.4</td>
<td>26.4</td>
<td>19.0</td>
<td>17.2</td>
</tr>
</tbody>
</table>

* bkg includes wrong-sign

**ν_µ disappearance sample**

<table>
<thead>
<tr>
<th>Mode</th>
<th>ν_µ-mode</th>
<th>10^36 POT</th>
</tr>
</thead>
<tbody>
<tr>
<td>w/o oscillation</td>
<td>2,648</td>
<td>1,007</td>
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<tr>
<td>w/ oscillation</td>
<td>741</td>
<td>342</td>
</tr>
</tbody>
</table>

Sensitivity to CP violation at 7.8E21 POT

NH case (IH case gives better sensitivity)
1:1ν-mode:ν-mode running

**combining w/ NOvA**

- sin²θ_{23} = 0.5
- solid: stat. only
- dash: 5% sys. error

T2K has > 90% C.L. sensitivity if δ_{CP} = −90°
Next generation experiment: J-PARC to Hyper-Kamiokande

The Hyper-Kamiokande Experiment
Physics with the J-PARC beam

Francesca Di Lodovico
Queen Mary University of London

Workshop for Neutrino Programs with facilities in Japan
J-PARC - August 4-6, 2015
Hyper-Kamiokande

- Next-generation gigantic multi-purpose detector
  - 560kt fiducial mass
  - 20% photo-coverage with 99k 20-inch PMTs

- Physics
  - Neutrino oscillation
    - Accelerator based LBL
    - Atmospheric nu
    - Solar nu
    - ...
  - Proton decay
  - Astrophysics neutrinos
    - Supernova, SRN, dark matter, etc

Tokai to Hyper-Kamiokande

Use upgraded J-PARC neutrino beam line (same as T2K) with expected beam power 750kW, 2.5° off-axis angle.

- Narrow-band beam at ~600MeV at 2.5° off-axis
- Take advantage of Lorentz Boost and 2-body kinematics in $\pi^{-} \rightarrow \mu^{-} \nu_{\mu}$
- Pure $\nu_{\mu}$ beam with ~1% $\nu_{e}$ contamination
International collaboration on Hyper-K

Hyper-K in the World

- 13 countries, ~250 members and growing
- Governance structure has been defined
  - International Steering Committee, International Board Representatives, and Working Groups, Conveners Board
- R&D fund and travel budget already secured in some countries, and more in securing processes.

As of Apr. 2015

<table>
<thead>
<tr>
<th>Region</th>
<th>Members</th>
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<tbody>
<tr>
<td>Asia</td>
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<tr>
<td>Japan</td>
<td>63</td>
</tr>
<tr>
<td>Korea</td>
<td>6</td>
</tr>
<tr>
<td>Europe</td>
<td>1/2</td>
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<td>France</td>
<td>10</td>
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<td>Italy</td>
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<td>Spain</td>
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<tr>
<td>Canada</td>
<td>17</td>
</tr>
<tr>
<td>USA</td>
<td>44</td>
</tr>
</tbody>
</table>

World-wide R&D

Intense R&D world wide, but large number of things to do.
Open to new collaborators.
Recent news

Hyper-K Proto-Collaboration
Inaugural Symposium, Kashiwa, January 31, 2015

KEK-IPNS and UTokyo-ICRR signed a MoU for cooperation on the Hyper-Kamiokande project.

Important moment. The proto-collaboration is born.

First Meeting of the proto-collaboration: June 29-July 1, @Kashiwa
PMT R&D

Photosensors Candidates

R&D going to get better performance and lower costs

<table>
<thead>
<tr>
<th></th>
<th>Established (SK PMT)</th>
<th>R&amp;D (HighQE/CE PMT)</th>
<th>R&amp;D (HighQE hybrid det.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantum Eff. (QE)</td>
<td>22%</td>
<td>30%</td>
<td>30%</td>
</tr>
<tr>
<td>Collection Eff. (CE)</td>
<td>80%</td>
<td>93%</td>
<td>95%</td>
</tr>
<tr>
<td>Timing resol (FWHM)</td>
<td>5.5 nsec</td>
<td>2.7 nsec</td>
<td>1 nsec</td>
</tr>
</tbody>
</table>

Super-K ID PMTs
- Used for ~20 years
- Guaranteed
- Complex production
- Lower risk

Under development
- Better performance
- Same technology
- Lower risk

Under development
- Far better performance
- Simple structure
- Lower cost
- New technology
- Higher risk

Ongoing tests in EGADS

Photosensors covered by protective case (currently under R&D)

Great improvement achieved

- x1.4 higher QE

High QE achieved

- High Quantum Efficiency (QE) of ~30% has been achieved! for 50cm B&L PMT and HPD
- Current studies open to other photo-sensor options as well to achieve a better performance and/or reduced cost
Hyper-K Sensitivity to $\delta_{CP}$

- CPV discovery sensitivity to $\delta_{CP}=0,\pi$ w/ MH known
  - Assume MH is known
  - Will be improved with updated errors

- Fractional region of $\delta(\%)$ for CPV ($\sin \delta \neq 0$) > 3.5 $\sigma$
  - CPV > 3$\sigma$ (5$\sigma$) for 76%(58%) of $\delta$
  - 5y-only with 1.5MW beam power

- 1$\sigma$ uncertainty of $\delta$ as a function of the beam power:
  - $< 19^\circ (6^\circ)$ for $\delta = 90^\circ (0^\circ)$
Sensitivity to $\theta_{23}$ and $\Delta m^2_{23}$

- $\sin^2 2\theta_{23}$ and $\Delta m^2_{23}$ free parameters as well as $\sin^2 2\theta_{13}$ and $\delta_{CP}$ in the fit.
- Octant resolution w/ reactor $\theta_{13}$: $\sim 3\sigma$
  - wrong octant rejection for $\sin^2 2\theta_{23} < 0.46$ or $>0.56$

<table>
<thead>
<tr>
<th>True $\sin^2 \theta_{23}$</th>
<th>$1\sigma$ err $\sin^2 \theta_{23}$</th>
<th>$1\sigma$ err $\Delta m^2_{23}$ ($10^{-5}$eV$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45</td>
<td>0.006</td>
<td>1.4</td>
</tr>
<tr>
<td>0.50</td>
<td>0.015</td>
<td>1.4</td>
</tr>
<tr>
<td>0.55</td>
<td>0.009</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Important combination with reactors

Octant degeneracy resolved with a constraint from the reactor experiments
Physics after CPV were found.

Global Study of Leptonic Unitarity

Preliminary

- Hyper-K Beam + Atmospheric measurements:
  - Contribute to normalizations
    - $\alpha = \mu$ (red line)
    - $\alpha = \tau$ (orange line)
    - $i = 3$ (brown line)

- Contribute to closure of triangles
  - $\alpha, \beta = e, \mu$ (cyan line)
  - $\alpha, \beta = \mu, \tau$ (orange line)
  - $i, j = 2, 3$ (brown line)

Hyper-K can provide high statistics measurements with full systematic correlations to improve (overconstrain) our understanding of these relations.
Combination with Atmospheric neutrino

- MH can be determined >3σ
- Discrimination of MH can help single out solution of CPV phase $\delta$

Hyper-K Sensitivity 10 Years

CPV sensivity

+Atm $\nu$
Proton decay

Nucleon Decay Physics Potential

Hyper-K's Sensitivity to $p \rightarrow e^+ \pi^0$
- Baseline Analysis
- Improved Analysis cuts
- BKG Reduced by 50% (n tagging)
- BKG Reduced by 70% (n-tagging)

- Super-Kamiokande has demonstrated neutron tagging via
  - $n + p \rightarrow d + \gamma$ (2.2 MeV)
  - Hyper-K's tagging depends on detector configuration, Photocoverage, Gd doping etc.
- If no signal is observed lifetime limits $\tau/B > 10^{35}$ years possible with
  - 3.6 Mton year (red, default)
  - 3.0 Mton year (green)
  - 2.4 Mton year (blue)
- Background reduction is an essential component of the Hyper-K nucleon decay program
  - potential for large sensitivity gains exists

Hyper-K's Sensitivity to $p \rightarrow \nu K^+$
- Red: All
- Blue: $\nu \gamma$
- Green: $\pi^+ \pi^-$
- Black: $\mu$

<table>
<thead>
<tr>
<th>Hyper-K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal $\epsilon$</td>
</tr>
<tr>
<td>BG / Mton yr</td>
</tr>
<tr>
<td>10yr. Sens. 90%</td>
</tr>
<tr>
<td>SK Limit 90%</td>
</tr>
</tbody>
</table>

- Backgrounds from atmospheric neutrino kaon production
  - $\nu + p \rightarrow n K^+ \gamma$ (poorly measured)
  - $\nu + p \rightarrow \mu^+ p + \gamma$
- Signal efficiency gains possible (likely):
  - Improve $\gamma$ (faster PMTs)
  - Improve $\pi^+$ tagging (fitter, improvement)
  - Background reduction with n tagging

Recently Super-K has found two candidates in this mode (BG = 0.87)
Excellent motivation
- Reduce backgrounds further!
- Build a larger detector!
The Hyper-Kamiokande Timeline

~2017 Major design decisions finalized
~2018 Construction starts
~2025 Data taking start
> 2025 Discoveries!
Hyper-K status in Japan

- Recommendation by **HEP community**

- **KEK roadmap** includes Hyper-K
  - [http://kds.kek.jp/getFile.py/access?sessionid=1&resId=0&materialId=0&confId=11728](http://kds.kek.jp/getFile.py/access?sessionid=1&resId=0&materialId=0&confId=11728)

- **Cosmic Ray community** endorses Hyper-K as a next large-scale project

- **Science Council of Japan** selects Hyper-K as a top priority project in the "Japanese Master Plan of Large Research Projects" (27 chosen out of 192 in all science area).

- It is not in the list of MEXT roadmap 2014. **We seriously challenge the roadmap 2017 for the approval of budget.**

The next action

- Design Report is requested by KEK/ICRR.
- To be prepared in 2015 toward the budget request. The next processes of the SCJ master-plan and MEXT roadmap will be in 2016-2017.
- Optimum design, Construction cost&period, Beam & Near detector, International responsibilities
- The international review will proceed under KEK/ICRR to promote the project.
- Once the budget is approved, the construction can start in 2018 and the operation will begin in ~2025.

- **It is a critical time to promote the project.**
- **Open for new Collaborators**

T.Nakaya, Apr.2015 @ 2nd International Meeting for Large Neutrino Infrastructures
New Initiatives: “T2K-extended” Intermediate experiment before HK/DUNE era
T2K-extended (name not yet defined)

- Neutrino community started to work to propose “extended T2K”
- Interconnect “desert” between T2K/NOVA and DUNE/HK era
- Make full use of present existing facilities with modest upgrades
  - J-PARC MR upgrade $\rightarrow$ possibility upto ~1.3MW operation
- ~$2\times10^{22}$pot by around 2026 before HK/DUNE start operating
- Another ~50% increase of effective statistics by
  - Horn current 250kA $\rightarrow$ 320kA
  - analysis improvements
- Extract best possible/most precise physics outputs
- Provide learning ground for next generation experiment
  - Realize >1MW high power stable beam operation (acc/beamline)
  - Systematic errors down to a few %
Integrated POT projection

(working assumption)

No running LBL experiments?

Assuming MR-PS upgrade funded as scheduled

7.80E+21

1.00E+22

1.50E+22

2.00E+22

2.50E+22

3.00E+22

Integrated POT

2014 2016 2018 2020 2022 2024 2026 2028 2030

Next gen experiments start operation

Physics outputs?

Slide from Future nu in Japan WS

T2K approved 10MWx1e7s
Assumed beam power and running time

Beam power (kW) vs. Running time (days)

- Reaches ~1.3MW
- Running time assuming:
  - 5 cycles/year
  - 23 days/cycle (~22 incl acc study)
  - 90% running efficiency (~80%)
  - (Achievement so far)
Integrated POT projection

(working assumption)

- Integ. POT
- Eff Integ POT
- T2K approved
- 10MWx1e7s

14MWx10^7s
2.9x10^{22}POTeq
T2Kx3.7
26xPresent

Assuming MR-PS upgrade funded as scheduled

Next gen experiments start operation

Physics outputs?

Slide from Future nu in Japan WS

2x10^{22}POT
Possible improvements from analysis side

T2K-SK Status and Outlook

Mike Wilking
Workshop for Neutrino Programs with Facilities in Japan
August 4th, 2015

- In total we should be able to aim at around +50% increase in effective statistics

Expanding the Selection

- CP violation sensitivity is limited by $\nu_\alpha$ statistics
- Current $\nu_\alpha$ selection efficiency is 66% (assuming 2 m fiducial volume cut)
- Cuts with the most efficiency loss:
  - Single-ring (86.7%)
  - Zero Michels (89.1%)
  - $E_{\text{rec}} < 1250$ MeV (95.9%)
  - $\ell T\text{Qun} \pi^0$ cut (92.0%)
- Further Improvements
  - Expanding the fiducial volume
    - ~30% of SK ID volume is not used
  - Improved reconstruction ($\ell \text{TQun}$)
  - Better PID, ring-counting, etc.

Summary

- T2K-SK $\nu_\alpha$ statistics increase of 40% to 60% may be possible (my rough guess)
- CC$\pi^+$ with below Cherenkov pions (~13%)
- Multi-ring events (CC$\pi^+$, CC$\pi^0$, etc.) (up to 20%)
- Looser and better $\pi^0$ and $E_{\text{rec}}$ cuts (~5%)
- Enlarge the fiducial volume (10-15%)
- Purity may also suffer somewhat
Expected # of events

Statistics at $7.8 \times 10^{21}$ and $25 \times 10^{21}$ POT

<table>
<thead>
<tr>
<th></th>
<th>$\nu_e$ signal</th>
<th>$\nu_e$ bkg.</th>
<th>$\bar{\nu}_e$ signal</th>
<th>$\bar{\nu}_e$ bkg.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>7.8E21 POT</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\delta = 0$</td>
<td>98.2</td>
<td>26.8</td>
<td>25.6</td>
<td>16.3</td>
</tr>
<tr>
<td>$\delta = -90^\circ$</td>
<td>121.4</td>
<td>26.4</td>
<td>19.0</td>
<td>17.2</td>
</tr>
<tr>
<td><strong>25E21 POT</strong></td>
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</tr>
<tr>
<td>$\delta = 0$</td>
<td>314</td>
<td>85.9</td>
<td>82.1</td>
<td>52.2</td>
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<tr>
<td>$\delta = -90^\circ$</td>
<td>389</td>
<td>84.6</td>
<td>60.9</td>
<td>55.1</td>
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* bkg includes wrong-sign

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<tr>
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<th>$\bar{\nu}_\mu$-mode</th>
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<tr>
<td><strong>7.8E21 POT</strong></td>
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<td><strong>25E21 POT</strong></td>
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<tr>
<td>w/o oscillation</td>
<td>8,519</td>
<td>3,228</td>
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<tr>
<td>w/ oscillation</td>
<td>2,375</td>
<td>1,096</td>
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</table>

50% $\nu-$ + 50% $\bar{\nu}$-mode

- Assuming same horn current and analysis with present T2K yet
CP sensitivity & precision

Aim around here

>3σ possible for max CPV

Need to control syst error <~a few %

\[ \Delta \chi^2 \]

\[ \text{POT [x10^{21}]} \]

\[ 50\% \nu^- + 50\% \bar{\nu} \text{-mode} \]

True \( \delta_{CP} = -90^\circ \), true MH = NH

\[ \delta_{CP} \text{ Precision} \]

- NH (known), \( \delta_{CP} = -90^\circ \), \( \sin^2 \theta_{23} = 0.5 \)
- \( 25 \times 10^{21} \text{ POT} : \sigma \sim 36^\circ \text{(no syst. err.)}, \sim 45^\circ \text{(w/ 2\% syst. err.)} \)
- \( 7.8 \times 10^{21} \text{ POT} : \sigma \sim 63^\circ \)
Precision of disappearance measurements

\[ \sin^2 \theta_{23} = 0.5 \]

- Measurement at \( 25 \times 10^{21} \text{ POT} : \theta_{23} = 45 \pm 1.9^\circ \)
- Current best measurement is \( 46 \pm 3^\circ \) by T2K
T2K-extended: Plan

- In Future Nu in J WS, agreed to write LoI → Proposal to J-PARC PAC
  - Next PAC is Jan 2016

- There are lots of rooms for new ideas and contributions
  - Accelerator/beam power upgrade
  - Detector upgrade
  - Analysis upgrade

- Your ideas and participations are highly welcome
Keys for the future

Statistics

Integrated beam power

Realization of high power:
350kW (realized) $\rightarrow$ 750kW $\rightarrow$ 1.3MW $\rightarrow$ MultiMW?

- Accelerator
- Beam line

Realization of stable operation = Availability

Improvement of analysis

Realization of Hyper-K

Systematics

Flux extrapolation

- “NA61”-type experiment indispensable
- Support for such measurements important

Cross sections
Design Philosophy of Neutrino Beamline

- **Tolerance for high power beam**
  - All beamline components designed for 750 kW beam
  - Equipments that cannot be replaceable after irradiation are designed for 3 or 4 MW beam.

- **Remote maintenance**
  - Secondary beamline equipments are highly irradiated with more than 1 Sv/h.
  - Beamline components inside Target Station can be replaceable remotely.

Prospect for Hardware Upgrade

- **Cooling capacity**
  - Apparatuses themselves can withstand 1.3 MW beam.
  - Improvement of flow rate both for water and helium circulations is needed.
    - Replacement with larger pumps
    - Replacement with larger-size plumbing
    - These will be feasible but need 1 year for modification.

- **Radiation**
  - **Radioactive air**
    - Reinforcement of air-tightness => 1.3 MW can be manageable.
  - **Radioactive water disposal**
    - Enlargement of dilution tank
    - Modification of existing tank => ~1.3MW
    - New facility building for water disposal => 2MW
    - 2 years for construction (no beam stop needed)

10 Year Term Plan of Beam Power Improvement

- **Design beam power = 750 kW**
  - Will be achieved in 2018
  - Beam power over 750 kW is recently being considered.

- **Aim for 1.3 MW beam by 2026**
  - Proton intensity = 3.2×10^{14} protons/pulse.
  - Repetition cycle = 1.16 sec, with new MR power supplies.

Can our beamline accommodate to 1.3 MW beam?

<table>
<thead>
<tr>
<th>Beam Power</th>
<th># of protons/pulse</th>
<th>Rep. rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>350 kW (achieved)</td>
<td>1.8×10^{14}</td>
<td>2.48 sec.</td>
</tr>
<tr>
<td>750 kW (proposed) [original plan]</td>
<td>2.0×10^{14} [3.3×10^{14}]</td>
<td>1.30 sec. [2.10 sec.]</td>
</tr>
<tr>
<td>1.3 MW (proposed)</td>
<td>3.2×10^{14}</td>
<td>1.16 sec.</td>
</tr>
</tbody>
</table>
Yes, we can.

### Improved Acceptable Beam Power

<table>
<thead>
<tr>
<th>Component</th>
<th>Limiting factor</th>
<th>Acceptable value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>Thermal shock</td>
<td>3.3×10</td>
</tr>
<tr>
<td></td>
<td>Cooling capacity</td>
<td>&gt;1.5 MW</td>
</tr>
<tr>
<td>Horn</td>
<td>Conductor cooling</td>
<td>2 MW</td>
</tr>
<tr>
<td></td>
<td>Stripline cooling</td>
<td>1.25 MW</td>
</tr>
<tr>
<td></td>
<td>Hydrogen production</td>
<td>&gt;1 MW</td>
</tr>
<tr>
<td></td>
<td>Operation</td>
<td>1 sec. &amp; 320 kA</td>
</tr>
<tr>
<td>He Vessel</td>
<td>Thermal stress</td>
<td>4 MW</td>
</tr>
<tr>
<td></td>
<td>Cooling capacity</td>
<td>&gt;1.5 MW</td>
</tr>
<tr>
<td>Decay Volume</td>
<td>Thermal stress</td>
<td>4 MW</td>
</tr>
<tr>
<td></td>
<td>Cooling capacity</td>
<td>&gt;1.5 MW</td>
</tr>
<tr>
<td>Beam Dump</td>
<td>Thermal stress</td>
<td>3 MW</td>
</tr>
<tr>
<td></td>
<td>Cooling capacity</td>
<td>&gt;1.5 MW</td>
</tr>
<tr>
<td>Radiation</td>
<td>Radioactive air disposal</td>
<td>&gt;1 MW</td>
</tr>
<tr>
<td></td>
<td>Radioactive water</td>
<td>0.75→1.3 or 2 MW</td>
</tr>
</tbody>
</table>

- After appropriate upgrade
Systematics: Cross sections

(NEEDLESS TO SAY,..) WE NEED TO KNOW TO WHAT PRECISION WE NEED TO KNOW WHAT (SYSTEMATIC ERROR SOURCES) TO KNOW WHAT (PHYSICS) TO WHAT PRECISION

TO WHAT PRECISION CAN WE ACHIEVE WITH PRESENT SETUP?

IF IT IS NOT SUFFICIENT TO REALIZE PHYSICS GOAL, THEN WE NEED TO BUILD NEW THING

UPGRADING NEAR DETECTOR

NEW TYPE OF DETECTOR: nuPRISM, TITUS

nuSTORM (SOMewhere IN THE WORLD)

INCREMENTAL APPROACH IS IMPORTANT

These kind of detailed studies are necessary.
CP asymmetry (1\textsuperscript{st} order approx.)

\[ A_{CP} \equiv \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} = A' \left\{ 1 + \frac{2P'^2}{P'^2 - 2P'^2} \left( \delta_\sigma + \delta_\varepsilon \right) \right\} \]

\[ A' \equiv \frac{P' - \bar{P}'}{P' + \bar{P}'}, \quad \delta_\sigma \equiv \frac{\bar{r}_\sigma}{r_\sigma} - 1, \quad \delta_\varepsilon \equiv \frac{\bar{r}_\varepsilon}{r_\varepsilon} - 1 \quad (r_\sigma = \sigma_e / \sigma_\mu, \ r_\varepsilon = \varepsilon_e / \varepsilon_\mu) \]

\[ P'_{\mu \rightarrow e}(E_{\text{true}}) \equiv \frac{N_e(E_{\text{true}})}{N_{\mu}^{\text{exp}}(E_{\text{true}})} \quad \text{FD } \nu_\mu \text{ obs. } E_{\nu} \text{-unfoiled} \]

\[ \quad \text{FD } \nu_\mu \text{ unosc. exp’ed normalized by ND } \nu_\mu \text{ meas} \]

- Ratio of e/\mu cross-section ratio & e/\mu efficiency ratio enter
Where we are & Where we go

**Current T2K systematic errors**

<table>
<thead>
<tr>
<th></th>
<th>$\nu_e$ sample</th>
<th>$\bar{\nu}_e$ sample</th>
<th>$\bar{\nu}_\mu$ sample</th>
<th>$\nu_e$ sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$ flux</td>
<td>16%</td>
<td>11%</td>
<td>7.1%</td>
<td>8%</td>
</tr>
<tr>
<td>$\nu$ flux and cross section</td>
<td>21.8%</td>
<td>26.0%</td>
<td>9.2%</td>
<td>9.4%</td>
</tr>
<tr>
<td>$\nu$ cross section due to difference of nuclear target btw. near and far</td>
<td>2.7%</td>
<td>3.1%</td>
<td>3.4%</td>
<td>3.0%</td>
</tr>
<tr>
<td>Final or Secondary Hadronic Interaction</td>
<td>3.0%</td>
<td>2.4%</td>
<td>2.1%</td>
<td>2.2%</td>
</tr>
<tr>
<td>Super-K detector</td>
<td>4.0%</td>
<td>2.7%</td>
<td>3.8%</td>
<td>3.0%</td>
</tr>
<tr>
<td>total</td>
<td>23.5%</td>
<td>26.8%</td>
<td>14.4%</td>
<td>13.5%</td>
</tr>
<tr>
<td>w/ ND measurement</td>
<td>7.7%</td>
<td>6.8%</td>
<td>11.6%</td>
<td>11.0%</td>
</tr>
<tr>
<td>w/o ND measurement</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

There are on-going efforts to reduce this nucleus-dependent errors with water target measurements in T2K near detectors.

* 2014 errors don’t include the effect of multi-nucleon bound state at the neutrino interaction.

- Need to aim at a few % level
- Cannot achieve in “1 day”, need learning process
- “T2K-extended” can provide important opportunity
Ideas of new detectors

Already on-going projects:
- WAGASHI 80% H₂O

Water target emulsion chamber:
- Emulsion films in Water target chamber
  - Water layer: 2mm

Ideas to upgrade present ND in UA1 mag:

WAGASCI in ND280 magn:
- Side view
- Side-TPC
- Down TPC

NuPRISM:

TITUS:
- 2kton Gd-doped (0.1%) water Cherenkov detector
- 2km from J-PARC
- 2.5° off-axis

Magnetized muon-range detectors
Ideas of new detector

- Draw your favorite detector

Your participation for the discussions and for the projects are welcome!
Ideas for even higher power

- Second booster in J-PARC
  - Introduce new 8GeV booster for MR injection to “eliminate” space charge effect at injection
  - Upto 3.2MW when RCS is 2MW

- “Circular” Linear accelerator
  - Utilize TRISTAN/KEKB tunnel at Tsukuba campus
  - 9GeV, 100mA, 1%duty = 9MW
Non-LBL experiments
J-PARC E56: JSNS$^2$ at MLF

- aims to measure the neutrino oscillation with sterile neutrino ($\mu^+ \rightarrow \bar{\nu}_\mu \rightarrow \bar{\nu}_e$)

- **Stage-1 status granted**

- Experimental setup
  - baseline: 24m
  - Fiducial volume: 50 tonnes
  - Energy resolution $\sigma_E : 15%/\sqrt{E}$ [MeV]
  - Delayed coincidence method: neutrons are observed as $\gamma$s from Gd-capture
  - PID($\gamma/n$) capability by Cherenkov and/or Pulse Shape Discrimination (PSD)

- Advantage: Low duty beam from scinchrotron

---

Next beam is 40ms later

---

Another new idea: KPIPE

Searching for the Sterile Wave:
A $\nu_{\mu}$-disappearance search using Kaon decay-at-rest
Workshop for Neutrino Programs with Facilities in Japan
August 5th, 2015

“KPipe” is a proposal for a short-baseline muon neutrino disappearance experiment at the J-PARC MLF that uses neutrinos from Kaon Decay at Rest (KDAR)

A (BIG) pipe, 3 m diameter and 120 m long, filled with liquid scintillator

No proposal/LoI submitted to PAC yet
Asian activities and ideas

- Indian participation to US projects
  - Beside INO
- Chinese idea for future neutrino beam “MOMENT”
- Possibility of neutrino beam from J-PARC to Korea
Indian participation to US projects

Raj Gandhi

Proposal from India to build DUNE near Detector

There is an Indian proposal to build the near detector for DUNE. The proposed conceptual design has been accepted by the collaboration as the Reference Design for the DUNE-ND, and has undergone extensive technical reviews both on the US and Indian side.

a) Measurements which will reduce systematic uncertainties in LBL FD oscillation analyses and will allow FD to reach full physics potential.

b) Precision measurements of parameters in SM neutrino interactions (Cross-section measurements in 0.5 to 20 GeV energy region, Weinberg angle, Sum rules, structure functions, ...)

c) Search for new physics (Heavy Neutrinos, Sub-GeV Dark matter...)

International Partners/India

- Indian Institutions-Fermilab Collaboration (IIFC) created in fall 2007
  - Signatories: Fermilab, BARC (Mumbai), IUAC (Delhi), RRCAT (Indore), VECC (Kolkata)
  - Encompasses R&D on
    - Superconducting accelerating modules
    - HLRF and LLRF
    - Cryogenics
    - Instrumentation
    - Magnets

- U.S. DOE-Indian DAE Implementing Agreement “for Cooperation in the Area of Accelerator and Detector Research & Development for Discovery Science” signed July 2011

- Annex I to the DOE-DAE Implementing Agreement signed in January 2015
  - Enables significant Indian contribution to PIP-II R&D and construction
  - Up to $200M (direct) authorized under the 12th and 13th Indian Plans
    - $60/140M
  - Calls for joint DOE-DAE evaluation of R&D accomplishments in 2018, prior to initiation of 13th plan.

- Pitamber Singh (BARC) participating in this meeting as an official observer
MOMENT: A New Idea on $\nu$ Beam

High-power proton linac (15MW, 1.5GeV)

• Neutrinos from muon decay
• Proton LINAC for ADS ~15 MW
• Energy: 300 MeV/150 km
• Phys. Rev. STAB 17, 090101 (2014)

Jingyu TANG and several talks in NuFact15, Jun Cao, private communication

Neutrinos after the target/collection/decay similar to NuFact: ~ $10^{21}$ $\nu$/year
MOMENT Status

- MOMENT is a new nu beam aiming at the next generation experiment, after DUNE and T2HK.

- It depends on
  - R&D Progress of the 15MW ADS proton LINAC
  - What’s the physics after DUNE and T2HK?
  - If there is physics, will a neutrino factory be built?

- Working on
  - Optimizing the beamline, considering the suitable detector technology
  - Critical R&D such as targetry, Super-conducting Magnets

ICFA-neutrino panel:
- Aiming at headline discoveries
- Looking for emerging scenarios
Possibility of beam from J-PARC to Korea

~ 1,300 km baseline of 1.0-2.5 degree off-axis (i.e. second oscillation maximum)

Kaoru Hagiwara, Naotoshi Okamura, Ken-ichi Senda, JHEP 1109 (2011) 082
Yoshitaro TAKAESU, NuFact15 Poster

RENO-50
18 kton LS Detector
~47 km from YG reactors
Mt. Guemseong (450 m)
~900 m.w.e. overburden
Summary

- Japanese accelerator-based experiments
  - J-PARC accelerators
    - RCS demonstrated 1MW beam
    - MR achieved ~350kW, aim 700~900kW(2018~2020) → 1.3MW(by ~2026)
    - Multi-MW ideas: 2nd booster/9MW linac at Tsukuba
  - LBL
    - T2K upto approved 7.8x10^{21} POT by around 2021 at earliest
    - “T2K-extended”: Aim to search CPV >3σ with ~2x10^{22} POT &~50% improvements in experiments by ~2026
      - Good smooth connection from T2K to Hyper-K, good entry point for new groups
      - Plan to submit LoI/Proposal to PAC soon. Your ideas and participation are highly welcome
    - J-PARC → Hyper-Kamiokande: aim to start construction ~2018, operation ~2025
      - Your ideas and participation are highly welcome
  - Non-LBL
    - JSNS^2 @ J-PARC MLF search for sterile neutrino: Stage-1 granted
      - New ideas are emerging

- Asian activities and ideas
  - Indian participation to US projects
  - Chinese idea for future neutrino beam “MOMENT”
  - Possibility of neutrino beam from J-PARC to Korea

**Incremental (~staging) approaches are important**

- CPV (maximal?), Cross section meas. ~8%→5%→a few%, nuFact R&D with physics objectives
The international workshop on future potential of high intensity proton accelerator for particle and nuclear physics (HINT2015)

ABOUT THIS WORKSHOP

The international workshop on future potential of high intensity proton accelerator for particle and nuclear physics (HINT2015) will be held at J-PARC, Tokai-Village, Ibaraki, Japan from 13th to 15th October, 2015. This workshop follows the workshop held in December 2012 at J-PARC on "Future direction of Proton Intensity Frontier".

The workshop will focus on future prospects of high intensity proton accelerators and beams toward Multi-MW beam power and, new frontier of particle and nuclear physics enabled by the high intensity beams.

First bulletin

TOPICS

There will be sessions covering the following topics;

• Present status and future plan of world high intensity proton accelerators
• Technical challenges to realize Multi-MW accelerators
• Technical challenges to realize Multi-MW beam facilities
• Neutrino physics with high intensity beam
• Kaon particle physics with high intensity beam
• Muon particle physics with high intensity beam
• Hypernuclear physics with high intensity beam
• Hadron physics with high intensity beam
• Neutron physics with high intensity beam

Registration: Sept.13
Poster registration extended to Aug.31
Backup
**SK+T2K results**

Kameda (ICRR, U.Tokyo)  
Aug.11

\( \theta_{13} \) Fixed  
SK + T2K \( \nu_{\mu}, \nu_{e} \), Normal Hierarchy  

Moderate Preliminary

<table>
<thead>
<tr>
<th>Fit (517 dof)</th>
<th>( \chi^2 )</th>
<th>( \delta_{cp} )</th>
<th>( \theta_{23} )</th>
<th>( \Delta m_{23} \times \text{10}^{-3} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK + T2K (NH)</td>
<td>651.53</td>
<td>4.887</td>
<td>0.525</td>
<td>2.5</td>
</tr>
<tr>
<td>SK + T2K (IH)</td>
<td>654.73</td>
<td>4.189</td>
<td>0.550</td>
<td>2.4</td>
</tr>
</tbody>
</table>

- \( \chi^2_{\text{NH}} - \chi^2_{\text{IH}} = -3.2 \) (-3.0 SK only)
- CP Conservation (\( \sin \delta_{cp} = 0 \)) allowed at (at least) 90% C.L. for both hierarchies
**CP measurement**

**Observables**

$$N_e(E_{rec}) = N_{obs}(E_{rec}) - N_{BG}(E_{true})$$

$$= \int dE_{true} \Phi_\mu(E_{true}) \cdot P_{\mu\rightarrow e}(E_{true}) \cdot \sigma_e(E_{true}) \cdot \varepsilon_e(E_{true}) \cdot r_e(E_{true}, E_{rec})$$

**μ flux**

**cross det. eff**

**det. response sec.**

**unfold det. response**

$$N_e(E_{true}) = \Phi_\mu(E_{true}) \cdot P_{\mu\rightarrow e}(E_{true}) \cdot \sigma_e(E_{true}) \cdot \varepsilon_e(E_{true})$$

**Divide by exp’ed # of ν_μ events w/o oscillation**

$$P'_{\mu\rightarrow e}(E_{true}) \equiv \frac{N_e(E_{true})}{N_{\mu}^{\exp}(E_{true})} = \frac{N_e(E_{true})}{\Phi_\mu^{\exp} \cdot \sigma_\mu \cdot \varepsilon_\mu} = \frac{N_e(E_{true})}{\Phi_\mu^{\exp} \cdot \sigma_e \cdot \varepsilon_e} \times r_\sigma \cdot r_\varepsilon$$

$$= P_{\mu\rightarrow e}(E_{true}) \cdot r_\sigma(E_{true}) \cdot r_\varepsilon(E_{true})$$

2001.11.9
T.K. in WS@ICRR
CP Asymmetry

\[ A_{CP} \equiv \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} = \frac{P'/r_\sigma r_\varepsilon - \bar{P}'/\bar{r}_\sigma \bar{r}_\varepsilon}{P'/r_\sigma r_\varepsilon + \bar{P}'/\bar{r}_\sigma \bar{r}_\varepsilon} \]

\[ = A' \left\{ 1 + \frac{2\bar{P}'^2}{P'^2 - \bar{P}'^2} (\delta_\sigma + \delta_\varepsilon) \right\} \]

where

\[ A' = \frac{P' - \bar{P}'}{P' + \bar{P}'}, \quad \delta_\sigma = \frac{\bar{r}_\sigma - r_\sigma}{r_\sigma}, \quad \delta_\varepsilon = \frac{\bar{r}_\varepsilon - r_\varepsilon}{r_\varepsilon} \quad (r_\sigma = \sigma_e/\sigma_\mu, \quad r_\varepsilon = \varepsilon_e/\varepsilon_\mu) \]

Only differences of e/\mu cross section ratios and efficiency ratios
Cross sections

$\nu_e$, $\nu_\mu$ CC cross sections

\[ \sigma \left(10^{-38}\text{cm}^2\right) \]

\[ E_\nu \text{(GeV)} \]

$\nu_e$ CCtot
$\nu_\mu$ CCtot
$\bar{\nu}_e$ CCtot
$\bar{\nu}_\mu$ CCtot
$\nu_e$ CCqe
$\nu_\mu$ CCqe
$\bar{\nu}_e$ CCqe
$\bar{\nu}_\mu$ CCqe
Cross section difference

CCqe ratio diff
1~5% @ energy window

~5%
J-PARC accelerator
Linac

- Particle: $^1H$
- Energy: 400 MeV
- Peak current: 30 mA (~ June 2014)
  50 mA by replacing front-end in 2014
- Repetition: 25 Hz
- Pulse width: 0.5 msec

Front-end = IS + LEBT + RFQ + MEBT

SDTL

DTL

100-deg dump

90-deg dump

30-deg dump

400 MeV

181 MeV

50 MeV

3 MeV

(7 m)

(27 m)

(84 m)
RCS (Rapid Cycling Synchrotron)

Two purposes of the RCS:
- Proton driver for neutron/muon production in MLF
- Booster of the MR injection

Charge-exchange & Painting injection

From Linac

To MLF

To MR

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>348.3 m</td>
</tr>
<tr>
<td>Injection energy</td>
<td>0.4 GeV</td>
</tr>
<tr>
<td>Extraction energy</td>
<td>3.0 GeV</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>25 Hz</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>2</td>
</tr>
<tr>
<td>Design beam power</td>
<td>1 MW</td>
</tr>
</tbody>
</table>
Main parameters of MR

- **Circumference**: 1567.5 m
- **Cycle time**: 6 s for SX, 2.48 s for FX
- **Injection energy**: 3 GeV
- **Extraction energy**: 30 GeV
- **Superperiodicity**: 3 h
- **Number of bunches**: 8
- **Rf frequency**: 1.67 - 1.72 MHz
- **Transition $\gamma$**: j 31.7 (typical)

**Physical Aperture**
- **3-50 BT Collimator**: 54-65 $\pi$.mm.mrad
- **3-50 BT physical ap.**: > 120 $\pi$.mm.mrad
- **Ring Collimator**: 54-65 $\pi$.mm.mrad
- **Ring physical ap.**: > 81 $\pi$.mm.mrad

Three dispersion free straight sections of 116-m long:
- Injection and collimator systems
- Slow extraction (SX) to Hadron experimental Hall
- MA loaded rf cavities and Fast extraction (FX) (beam is extracted inside/outside of the ring)
  - outside: Beam abort line
  - inside: Neutrino beamline (intense $\nu$ beam is send to SK)
**Mid-term plan of MR**

**FX**: The high repetition rate scheme is adopted to achieve the design beam intensity, 750 kW. Rep. rate will be increased from ~0.4 Hz to ~1 Hz by replacing magnet PS’s and RF cavities.

**SX**: Parts of stainless steel ducts are replaced with titanium ducts to reduce residual radiation dose. The beam power will be gradually increased toward 100 kW watching the residual activity.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Li. current upgrade</td>
<td>New PS buildings</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>FX power [kW] (study/trial)</strong></td>
<td>320</td>
<td>&gt;360</td>
<td>400</td>
<td>450</td>
<td>700</td>
<td>800</td>
<td>900</td>
</tr>
<tr>
<td><strong>SX power [kW] (study/trial)</strong></td>
<td>-</td>
<td>33 - 40</td>
<td>50</td>
<td>50-70</td>
<td>50-70</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td><strong>Cycle time of main magnet PS</strong></td>
<td>2.48 s</td>
<td>Large scale 1st PS</td>
<td>Mass production installation/test</td>
<td>1.3 s</td>
<td>1.3 s</td>
<td>1.2 s</td>
<td></td>
</tr>
<tr>
<td><strong>New magnet PS</strong></td>
<td></td>
<td></td>
<td></td>
<td>Higher rep rate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>High gradient rf system</strong></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td><strong>2nd harmonic rf system</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>VHF cavity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Ring collimators</strong></td>
<td>Add.collimators</td>
<td>Add.collimators (3.5kW)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Injection system</strong></td>
<td>Kicker PS improvement, Septa manufacture /test</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>FX system</strong></td>
<td>Kicker PS improvement, LF septum, HF septa manufacture /test</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SX collimator / Local shields</strong></td>
<td>Local shields</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Ti ducts and SX devices with Ti chamber</strong></td>
<td>Beam ducts</td>
<td>ESS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

[Assuming MR-PS upgrade is funded as scheduled]
New power supplies for 1 Hz operation

Large scale PS for bending magnets and quad. magnets in arc sections

Self-learning control system

Power recovery by C-bank

Repetition rate < 1.3sec, Ripple $\sim 10^{-6}$

(1) Proof of principle by a desk-top PS (2012)
(2) R&D of the small prototype PS (2013)
(3) R&D of the middle prototype PS (2014)
R&D of new power supplies for 1 Hz operation (cont’d)

Small scale PS for Quad. Magnets in straight section and sextupole magnets

Diode rectifiers, two 1kV choppers are connected in series, symmetric power module circuit

It is possible to build with the combination of existing products.

The model PS system was tested using the real sextupole magnet network.

Mass production will start in JFY2016 if the budget request is approved by the government.
# Plan of PS mass production

<table>
<thead>
<tr>
<th>JFY</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>New buildings for new power supplies</td>
<td></td>
<td>D4,D5,D6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large PS (10) (B (6), Q (4))</td>
<td></td>
<td>B (3) Q (2)</td>
<td>B (3) Q (2)</td>
<td></td>
</tr>
<tr>
<td>Middle PS (1) (Q(1))</td>
<td>Leading PS for mass-production</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small PS (9) (Q (6), S (3))</td>
<td></td>
<td>Q (6) S (3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooling water system</td>
<td></td>
<td>D4,D5,D6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation &amp; tuning</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- New buildings for new power supplies
- Large PS (10) (B (6), Q (4))
- Middle PS (1) (Q(1))
- Small PS (9) (Q (6), S (3))
- Cooling water system
- Installation & tuning

- D4, D5, D6
- B (3), Q (2)
- Q (6), S (3)
- D4, D5, D6
High impedance rf system

A new type of the magnetic alloy (MA) core, FT3L (made by Hitachi Metal), is adopted to increase shunt impedance of the rf cavity. The core is processed by annealing with magnetic field.

Comparison of field gradient of rf cavities for hadron rings.

Performance of cavities depends on core materials: ferrite and MA. J-PARC already achieved very high field gradient.
### RF system for high repetition operation

**Configuration of rf cavities**

- Before Replacement: 4 cavities/Long Straight
- After Replacement: 3 cavities/long straight

#### Table:

<table>
<thead>
<tr>
<th></th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Li 400 MeV</strong></td>
<td>9</td>
<td>8</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Li 50mA</strong></td>
<td>0</td>
<td>1</td>
<td>5</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td><strong>Present FT3M cavities</strong></td>
<td>9</td>
<td>8</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>New FT3L Cavities</strong></td>
<td>0</td>
<td>1</td>
<td>5</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td><strong>New FT3L 2nd cavity</strong></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong>Available voltage</strong></td>
<td>315 kV</td>
<td>355 kV</td>
<td>485 kV</td>
<td>602 kV</td>
<td>602 kV</td>
<td>602 kV</td>
</tr>
<tr>
<td><strong>(2nd Harmonic)</strong></td>
<td>(35 kV)</td>
<td>(70 kV)</td>
<td>(70 kV)</td>
<td>(70 kV)</td>
<td>(70 kV)</td>
<td>80 kV</td>
</tr>
<tr>
<td><strong>Number of cavity cells</strong></td>
<td>27</td>
<td>29</td>
<td>36</td>
<td>43</td>
<td>43</td>
<td>43+8(2nd)</td>
</tr>
</tbody>
</table>

**Present FT3M cavities**

- 2013: 9
- 2014: 8
- 2015: 4
- 2016: 0
- 2017: 0
- 2018: 0

**New FT3L Cavities**

- 2013: 0
- 2014: 1
- 2015: 5
- 2016: 9
- 2017: 9
- 2018: 9

**New FT3L 2nd cavity**

- 2013: 0
- 2014: 0
- 2015: 0
- 2016: 0
- 2017: 2
- 2018: 2

**Available voltage**

- 2013: 315 kV
- 2014: 355 kV
- 2015: 485 kV
- 2016: 602 kV
- 2017: 602 kV
- 2018: 602 kV

**Number of cavity cells**

- 2013: 27
- 2014: 29
- 2015: 36
- 2016: 43
- 2017: 43
- 2018: 43+8

**Required voltage:**

- 280 kV (~2017)
- 540 kV (2018~)
Injection and FX septum systems

New injection septum magnet I and FX low field septum for high repetition rate operation have been manufactured and tested.

New injection septum:
- Stable (low vibration)
- Small leakage field $\sim 10^{-4}$
  (the current septum: $4 \times 10^{-3}$)

Eddy current type is adopted to the new FX low field septum
- Small Power Consumption (possible at low cooling capacity)
- Small Leakage Field $\sim 10^{-4}$
  (the current type septum: $10^{-3}$)
- Stable (low vibration)
- Thin Septum Thickness $\sim 7$ mm
  (the current septum: 9.5mm)

They will be installed in the 2015 summer shutdown.
Feasibility of the RCS

Injection beam parameters:
Energy : 400 MeV
Peak current : 50 mA~100 mA
Pulse length: 0.5 ms
Chopper-beam on duty : 0.53

RCS collimator limit ~4 kW
→ RCS has a feasibility to operate 2 MW

- Linac 100 mA/0.5 ms (50 mA/1.0 ms) operation is required.
  R&D of ion source / long pulse operation of linac
- The rf system should be replaced to compensate a heavy beam loading.
- The collimator capability should be upgraded to get a margin for the beam loss.
- Activation downstream of the charge exchange foils should be reduced.

---

<table>
<thead>
<tr>
<th>RCS intensity</th>
<th>Loss</th>
<th>Loss power at 25 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 MW</td>
<td>~0.3%</td>
<td>400 W</td>
</tr>
<tr>
<td>1.1 MW</td>
<td>~0.3%</td>
<td>440 W</td>
</tr>
<tr>
<td>1.2 MW</td>
<td>~0.3%</td>
<td>480 W</td>
</tr>
<tr>
<td>1.3 MW</td>
<td>~0.3%</td>
<td>520 W</td>
</tr>
<tr>
<td>1.4 MW</td>
<td>~0.3%</td>
<td>560 W</td>
</tr>
<tr>
<td>1.6 MW</td>
<td>~0.5%</td>
<td>1067 W</td>
</tr>
<tr>
<td>1.8 MW</td>
<td>~0.7%</td>
<td>1680 W</td>
</tr>
<tr>
<td>2.0 MW</td>
<td>~1.5%</td>
<td>4000 W</td>
</tr>
</tbody>
</table>
The maximum beam intensity is limited by the physical aperture of the MR. The scenarios for achieving much larger beam power than the design specification for neutrino experiment are now discussed.

1. Booster ring for the MR (emittance damping ring)
   The BR with an extraction energy ~ 8 GeV, is constructed between the RCS and the MR

2. New proton linac for neutrino beam production
   (Construction site may not be the Tokai campus)
   - Linac with an beam energy > 9 GeV
   - The MR is operated only for the SX users
The 8-GeV booster ring

Beta & Dispersion for 1-superperiod

\[ \beta_{x,y}(m) \]
\[ \eta_{x,y}(m) \]

Phase plot @ inj.(3GeV) & extr.(8GeV)

@ 3GeV
\[ \varepsilon > 125.5\pi \sim 0.04\% \]

@ 8GeV
\[ \varepsilon > 54\pi \sim 0.06\% \]

Injection energy 3 GeV
Extraction energy 8 GeV
Circumference 696.666 m
Superperiodicity 4
Transition gamma \sim 15 GeV
Collimator Aperture 126\pi.mm.mrad
Physical Aperture 189 \pi.mm.mrad

8 GeV injection in the MR using new septa\&kickers

RCS : 1.6 MW
MR > 2.6 MW
RCS : 2 MW
MR > 3.2 MW
Outline of the Proton Driver using ILC Cavity

- Outline of acceleration:
  - 1.2 GeV in 1st straight.
  - 3.3 GeV in 2nd straight.
  - +2.9 GeV in 3rd and 4th straight.
    \[ 3.3 + 2.9 \times 2 = 9.0 \text{ GeV} \]

- Peak current: 100 mA (pulse)
- Beam duty: 1 %

- Beam power:
  \[ 9000 \text{ MeV} \times 0.1 \text{ A} \times 1 \% = 9 \text{ MW} \]

- \( \beta_g \) of SC cavities:
  - 2nd straight: \( \beta_g = 0.93 \)
  - 3rd and 4th straight: \( \beta_g = 1.0 \)

- Normalized RMS emittance
  - Transverse: 0.30 \( \pi \cdot \text{mm} \cdot \text{mrad} \)
  - Longitudinal: 0.37 \( \pi \cdot \text{MeV} \cdot \text{deg} \)
Hyper-Kamiokande
Expected Events

Appearance $\nu$ mode

<table>
<thead>
<tr>
<th>Appearance</th>
<th>Signal</th>
<th></th>
<th>Background</th>
<th></th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$ mode</td>
<td>3016</td>
<td>28</td>
<td>11</td>
<td>0</td>
<td>503</td>
</tr>
<tr>
<td>$\bar{\nu}$ mode</td>
<td>396</td>
<td>2110</td>
<td>4</td>
<td>5</td>
<td>222</td>
</tr>
</tbody>
</table>

Disappearance

<table>
<thead>
<tr>
<th>Disappearance</th>
<th></th>
<th></th>
<th></th>
<th>NC</th>
<th></th>
<th></th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$ mode</td>
<td>17225</td>
<td>1088</td>
<td>11</td>
<td>1</td>
<td>999</td>
<td>49</td>
<td>19372</td>
</tr>
<tr>
<td>$\bar{\nu}$ mode</td>
<td>10066</td>
<td>15597</td>
<td>7</td>
<td>7</td>
<td>1281</td>
<td>6</td>
<td>26964</td>
</tr>
</tbody>
</table>

Large expected number of events. NH, $\sin^2 2\theta_{13} = 0.1$ and $\delta_{CP} = 0$
Expected Events

Neutrino mode: Appearance

Antineutrino mode: Appearance

Also shape relevant for CPV
Sensitivity on MH and octant from HK Atm-nu measurements

Hyper-K Sensitivity 10 Years

- Expect better than ~3σ sensitivity to the mass hierarchy using atmospheric neutrinos alone
- 3σ Octant determination possible if $\sin^2 \theta_{23} < 0.99$
Gadolinium Option


- Gd-doping proposed in 2004 mainly to greatly enhance supernova neutrino detection.
- It can help also other physics
  - Beam physics → distinguish $\nu$ and $\bar{\nu}$; CCQE and other $\nu$-interactions
  - Proton decays → reduce background
- R&D programme started with EGADS (200ton scale model of Super-K)
- Now finishing → Super-K will run with the Gd-doping
- Considered as possible option for Hyper-K

EGADS Facility in Kamioka Mine

April 2015: fully loaded (0.2%) with Gd sulfate, and functioning perfectly.

SK will have Gd. It could be an option for HK
Site(s) and Cavern(s)

Two sites are being investigated:
- Tochibora mine:
  - ~8km South from Super-K
  - Identical baseline (295km) and off-axis angle (2.5°) to Super-Kamiokande
- Mozumi mine (same as Super-K)
  - Deeper than Tochibora
- Rock quality in the two sites similar
- Confirmed HK cavern can be built w/ existing techniques

Two options but nominal case is Tochibora.
Hyper-K Sensitivity to $\delta$

- Based on experience and prospects of T2K.
- Three main categories of systematic uncertainties:
  - Flux and cross section uncertainties constrained by the fit to current ND.
  - Cross section uncertainties not constrained by the fit to current ND data: errors reduced as more categories of samples are added to ND fit.
  - Uncertainties on the far detector reduced as most of them are estimated by using atmospheric neutrinos as a control sample (larger stat at Hyper-K).

<table>
<thead>
<tr>
<th>Errors (%) on the expected number of events</th>
<th>$\nu$ mode</th>
<th>$\bar{\nu}$ mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\nu_e$</td>
<td>$\nu_\mu$</td>
</tr>
<tr>
<td>Flux &amp; Near Detector (ND)</td>
<td>3.0</td>
<td>2.8</td>
</tr>
<tr>
<td>ND-independ. xsect</td>
<td>1.2</td>
<td>1.5</td>
</tr>
<tr>
<td>Far Detector</td>
<td>0.7</td>
<td>1.0</td>
</tr>
<tr>
<td>Total</td>
<td>3.3</td>
<td>3.3</td>
</tr>
</tbody>
</table>

- Planning to update errors and thus sensitivities based on the discussions on the T2K upgrade.
“Other” Beam Physics

Apart from the mixing parameters, there is a rich landscape of physics topics:

• Cross section measurements – mainly at the near detector suite.
• Consistency checks of three flavour framework (e.g. PMNS unitarity), combination with other LBN and atmospheric experiments, etc.
• Physics that goes beyond the three flavour paradigm, examples:
  ➢ Non-standard interactions → deviations from the three-flavor mixing model
  ➢ Lorentz and CPT violation → sidereal neutrino oscillations
  ➢ New long-distance potentials arising from discrete symmetries
  ➢ Sterile neutrino states that mix with the three known active neutrino states

Studies currently under way to estimate the sensitivity.
Comment on Leptonic Unitarity

If the PMNS matrix is unitary we expect these relations (for \( l = e, \mu, \tau \))

\[
\begin{align*}
N_l & \equiv \sum_{i=1,2,3} |U_{li}|^2 = 1 \\
T_{lm} & \equiv \sum_{i=1,2,3} U_{li} U_{mi}^* = 0
\end{align*}
\]

The pieces of the matrix that can be probed depend on L and E of neutrino source

- Hyper-K will have both “fixed” L/E (beam) and “varying” L/E (atmospheric \( \nu \))
- Computations assume that the \( U_{\mu e} \) is unitary, but this can be tested
  - Models of new physics (SeeSaw, SUSY) predict \( U_{\mu e} \) is piece of a larger matrix
- For LBL \( \nu_\mu \) disappearance: 
  \[
  |U_{\mu 3}|^2 \left( 1 - |U_{\mu 3}| \right) \rightarrow \frac{|U_{\mu 3}|^2 (|U_{\nu 1}|^2 + |U_{\mu 2}|^2)}{\sum_i |U_{\mu i}|^2}
  \]
- Hyper-Kamiokande can probe many elements of this matrix by itself with combined beam and atmospheric neutrino measurements
Comment on Leptonic Unitarity

If Unitarity is NOT assumed, then to first order

- LBL $\nu_\mu \rightarrow \nu_\mu$
- LBL $\nu_\mu \rightarrow \nu_e$
- ATM $\nu_\mu \rightarrow \nu_\tau$
- ATM Reson $\nu_\mu \rightarrow \nu_e$
- ATM Sub-GeV $\nu_\mu \rightarrow \nu_\mu$

\[
|U_{\mu 3}|^2 \left( |U_{\mu 1}|^2 + |U_{\mu 2}|^2 \right) \\text{Re} \left\{ U_{\mu 3} U_{e 3}^* \left( U_{\mu 1} U_{e 2}^* + U_{\mu 3} U_{e 2}^* \right) \right\} \\text{Re} \left\{ U_{\mu 3} U_{\tau 3}^* \left( U_{\mu 1} U_{\tau 2}^* + U_{\mu 3} U_{\tau 2}^* \right) \right\} (r |U_{\mu 3}|^2 - 1) \left| U_{\mu 1} \right|^2 \left| U_{\mu 2} \right|^2
\]

- Typically single oscillation channels are sensitive to multiple parts of the mixing matrix
  - true for any experiment
- However atmospheric neutrino measurements have sufficient breadth in L/E to have some sensitivity to both “1-2” and “2-3” columns of the mixing matrix (in principle)
  - separating $U_{\mu 1}$ and $U_{\mu 2}$ with (1.0~3.0 GeV data)
- To really make progress improvements in detector performance and systematic errors (flux, cross-section) will be essential
# Hyper-K's Sensitivity to Other Decay Modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Sensitivity (90% CL) [years]</th>
<th>Current limit [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p \rightarrow e^+ \pi^0$</td>
<td>$13.0 \times 10^{34}$</td>
<td>$1.7 \times 10^{34}$</td>
</tr>
<tr>
<td>$p \rightarrow \nu K^+$</td>
<td>$3.2 \times 10^{34}$</td>
<td>$0.78 \times 10^{34}$</td>
</tr>
<tr>
<td>$p \rightarrow \mu^+ \pi^0$</td>
<td>$9.0 \times 10^{34}$</td>
<td>$1.1 \times 10^{34}$</td>
</tr>
<tr>
<td>$p \rightarrow e^+ \eta^0$</td>
<td>$5.0 \times 10^{34}$</td>
<td>$0.42 \times 10^{34}$</td>
</tr>
<tr>
<td>$p \rightarrow \mu^+ \eta^0$</td>
<td>$3.0 \times 10^{34}$</td>
<td>$0.13 \times 10^{34}$</td>
</tr>
<tr>
<td>$p \rightarrow e^+ \rho^0$</td>
<td>$1.0 \times 10^{34}$</td>
<td>$0.07 \times 10^{34}$</td>
</tr>
<tr>
<td>$p \rightarrow \mu^+ \rho^0$</td>
<td>$0.37 \times 10^{34}$</td>
<td>$0.02 \times 10^{34}$</td>
</tr>
<tr>
<td>$p \rightarrow e^+ \omega^0$</td>
<td>$0.84 \times 10^{34}$</td>
<td>$0.03 \times 10^{34}$</td>
</tr>
<tr>
<td>$p \rightarrow \mu^+ \omega^0$</td>
<td>$0.88 \times 10^{34}$</td>
<td>$0.08 \times 10^{34}$</td>
</tr>
<tr>
<td>$n \rightarrow e^+ \pi^-$</td>
<td>$3.8 \times 10^{34}$</td>
<td>$0.20 \times 10^{34}$</td>
</tr>
<tr>
<td>$n \rightarrow \mu^+ \pi^-$</td>
<td>$2.9 \times 10^{34}$</td>
<td>$0.10 \times 10^{34}$</td>
</tr>
</tbody>
</table>

- Generally speaking, Hyper-K is expected to have an order of magnitude better sensitivity than Super-K to many decay channels.

- For background dominated modes, like $p \rightarrow e^+ X$, $\mu^+ \nu\nu$, $\nu\pi^+$ etc., the improvement is roughly a factor of 4 or 5.
Other Physics at Hyper-K

- Atmospheric neutrino flux measurements
- Tau neutrino studies (oscillation-induced, cross section)
- Non-standard Neutrino Interactions in atmospheric neutrinos
- Search for WIMP annihilation at the center of the Earth
- Various nucleon decay modes
  - $p \rightarrow \nu \pi^+$, $n \rightarrow \nu \pi^0$
  - $p \rightarrow l^+ M^0$ (other antilepton + meson modes)
  - $n \rightarrow l^- M^+$ (Recent theoretical interest)
- B+L modes
- dinucleon decay modes
- $n \leftrightarrow \bar{n}$ oscillations
- Astrophysical neutrino source search
- ...

The statistical uncertainty at Super-K on many of the analyses above is large so generically we can expect improvements at Hyper-K
Hardware Improvement (Assumption)

Flux gain by Horn current $250\text{kA} \rightarrow 320\text{kA}$

- 10% flux gain with 320kA

Implementation plan

- Three power supplies for three horns
  - Two of three already produced.
  - Two new transformers (one currently being produced).
- Aiming to start 320kA operation from 2017 fall.
  - Timely budget approval is necessary.
Possible Analysis Improvement

Development of new event reconstruction algorithm for SK

• Better $\pi^0$ rejection (done)
• Better vertex resolution:
  • Fid. vol. cut from ID wall
    $-2m \rightarrow 1m$ (being studied)
    $-\sim20\%$ gain
• Better PID $\rightarrow \pi/\mu$ separation in SK.
  • Exclusive CC1$\pi$ sample (being studied)
    $-\sim10\%$ gain by using the sample.
Sensitivity of “T2K2” on MH

The graph illustrates the sensitivity of T2K2 on MH with various values of $\sin^2\theta_{23}$, showing contours at 99% and 90% confidence levels.
Super-K-Gd project

- Water Cherenkov detector with Gd dissolved water as neutron absorber

- High efficient neutron tagging using $0.2\% \text{Gd}_2(\text{SO}_4)_3$ dissolved water.
- Delayed coincidence of $\gamma$-ray signal from thermal neutron capture on Gd.

Physics targets:
- Supernova relic neutrino (SRN)
- Reduce proton decay background
- Neutrino/anti-neutrino discrimination (Long-baseline and atm nu's)

and more..

- 5yr evaluation experiment (EGADS) tests water quality, materials, basic techniques,..
- On June 27, 2015, the Super-Kamiokande collaboration approved the Super-K-Gd project.
- Actual schedule including refurbishment of the tank, Gd loading time will be determined soon taking into account the T2K schedule.
Physics requirements vs. detectors
(my personal view)

<table>
<thead>
<tr>
<th></th>
<th>$\nu_e$ cross section</th>
<th>$H_2O$ target</th>
<th>$4\pi$ accept.</th>
<th>Wrong sign BG</th>
<th>NC, Int. $\nu_e$ BG</th>
<th>Muon FS vs. $\nu$</th>
<th>Hadronic FS</th>
<th># of neutron (Gd)</th>
<th>CC$\pi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current ND280</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>ND280 (WAGASCI)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>ND280 (HP-TPC)</td>
<td></td>
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<tr>
<td>ND280 (WbLS)</td>
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<tr>
<td>ND280 (Emulsion)</td>
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<td>$\nu$PRISM</td>
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<td></td>
</tr>
</tbody>
</table>

- **Green** = Good
- **Yellow** = OK
- **Red** = Not Good