Future of Neutrino Beam Facilities

Tetsuro Sekiguchi (KEK, IPNS)

August 10, 2019
• Overview of neutrino beam facilities
• Planned future facilities
• International cooperation on high power neutrino beam
• Summary
Outline

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Overview

Next generation experiments are aiming to reveal the full picture of neutrino oscillation with precise measurements of CP and mixing parameters.

- Sensitivity for CP violation is currently ~2σ, and it will be increased to >5σ in the future.
- More than 10 times the statistics are needed.

To achieve this, we need:

- ~10 x larger new detectors
- >1MW-class beam power needed

The number of neutrinos, $N_v$, is given by:

$$N_v \propto \Phi_v(E) \times \sigma_v(E) \times \text{target}$$

**Beam power** vs. **Detector volume**
How To Produce Neutrino Beam?

Conventional neutrino beam from pion decay (since 1960’s)

- High intensity proton beam hit a graphite target
- Secondary $\pi/K$’s focused by magnetic horns and decay to neutrinos
  - Neutrino beam from $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - Antineutrino beam from $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
  - Changing neutrino beam mode by flipping the horn polarity
- All hadrons absorbed by beam dump
- High energy muons penetrating beam dump measured by muon monitors
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Proton $\rightarrow \pi^+ (\pi^-), K^+ (K^-)$

$\nu_\mu (\bar{\nu}_\mu)$

Target station

Decay volume

Horn-focused beam developed at CERN by Simon van der Meer (1984 Novel Prize)
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Operating Facilities

**J-PARC**
- 400 MeV Linac
- 3 GeV Rapid Cycling Synchrotron (RCS)
  - Material and life science, muon science
- 30 GeV Main Ring Synchrotron
  - Neutrino experiment (T2K)
  - Nuclear and particle experiments

**Fermilab**
- 400 MeV Linac
- 8 GeV Booster
  - Short baseline neutrino experiments
- 120 GeV Main Injector
  - Neutrino experiments (NOvA, etc)
  - Muon experiments
Progress on High Power Neutrino Beam

Neutrino beam facilities for long baseline experiments

<table>
<thead>
<tr>
<th>Facility</th>
<th>Accelerator</th>
<th>Energy [GeV]</th>
<th>Current [μA]</th>
<th>Experiment</th>
<th>1999 00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17</th>
<th>Beam Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>KEK</td>
<td>PS</td>
<td>12</td>
<td>0.5</td>
<td>K2K</td>
<td>6 kW</td>
<td>1st generation: O(10) kW</td>
</tr>
<tr>
<td>Fermilab Main Injector</td>
<td></td>
<td>120</td>
<td>2.5</td>
<td>MINOS</td>
<td></td>
<td>NuMI 300 kW</td>
</tr>
<tr>
<td>CERN</td>
<td>SPS</td>
<td>450</td>
<td>1.1</td>
<td>OPERA</td>
<td></td>
<td>CNGS 500 kW</td>
</tr>
<tr>
<td>J-PARC Main Ring</td>
<td></td>
<td>30</td>
<td>16.7</td>
<td>T2K</td>
<td></td>
<td>NuMI 700 kW → 1 MW</td>
</tr>
<tr>
<td>J-PARC Main Injector</td>
<td></td>
<td>120</td>
<td>5.8-8.3</td>
<td>NOvA</td>
<td></td>
<td>NuMI 700 kW → 1 MW</td>
</tr>
<tr>
<td>J-PARC Main Ring</td>
<td></td>
<td>30</td>
<td>25-43</td>
<td>T2K-II → HK</td>
<td></td>
<td>3rd generation: O(1) MW</td>
</tr>
<tr>
<td>Fermilab Main Injector</td>
<td></td>
<td>60-120</td>
<td>10</td>
<td>DUNE</td>
<td></td>
<td>LBNF 750 kW → 1.3 MW</td>
</tr>
</tbody>
</table>

Note: Beam power (kW) = Beam energy (GeV) x Current (μA)
Status of J-PARC Neutrino Beam

- Started physics data taking in January 2010
- \( \sim 500 \text{ kW} \) stable operation: \( 2.5 \times 10^{14} \) ppp \( \Rightarrow \) world-highest intensity in fast-extracted beam from proton synchrotron
  - Beam power limited by space charge effect, beam instability due to insufficient RF voltage
- Provide \( 3.16 \times 10^{21} \) protons on target (POT) to T2K
  - \( \nu \) mode POT: \( 1.51 \times 10^{21} \), anti-\( \nu \) mode POT: \( 1.65 \times 10^{21} \) POT
NuMI operation for NOvA started in 2014

- ~700 kW stable operation: 756 kW hourly beam power recorded

- $2.38 \times 10^{21}$ POT (14kt-equivalent) in total since 2014
  - $\nu$-mode POT: $1.11 \times 10^{21}$ POT (14kt-equivalent), anti-$\nu$ mode POT: $1.27 \times 10^{21}$ POT

- NuMI upgrade to ~1 MW (PIP-I+)
  - 1 MW-capable target scheduled to be installed during this summer shutdown
  - Booster improvements for PIP-II by 2023 will allow 900 kW

- NuMI operation until start of long LBNF shutdown in 2025
Outline

• Overview of neutrino beam facilities
• Planned future facilities
• International cooperation on high power neutrino beam
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Staged accelerator upgrade toward 1.3 MW

- **Shorter cycle** (2.48s → 1.32s) for >750 kW (FY2021)
  - MR PS upgrade
  - 2nd harmonic RF cavities

- **Higher beam intensity** for 1.3 MW (~FY2027)
  - Increase # of RF cavities (9 → 11)
  - RF anode PS upgrade

- Upgrade of neutrino beamline is also needed

### Power

\[ \text{Power} \propto E_{\text{beam}} \times \text{Intensity} \times 1/\text{cycle} \]

<table>
<thead>
<tr>
<th>Current</th>
<th>Upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam power [ MW ]</td>
<td>0.5</td>
</tr>
<tr>
<td>Proton intensity [ 10^{14} / pulse ]</td>
<td>2.5</td>
</tr>
<tr>
<td>Cycle [ s ]</td>
<td>2.48</td>
</tr>
</tbody>
</table>
MR Upgrade Status

- **New power supply**
  - Commissioning with actual bending magnet (BM3) was successfully performed
  - More than 2-hour continuous operation with 1.32 s cycle was confirmed

- **RF upgrade**
  - New 2nd harmonic RF system for 1.32 s operation was assembled

- A new power supply was designed with capacitor banks for the cycle of 1.3 s.
- The power supply for the BM3 family was constructed and installed at D4.
- It has been tested with the BM3 family.

- New 2nd harmonic cavity with 4 accelerating gaps

- Small current ripple @ 1580A also confirmed
**J-PARC Accelerator Upgrade**

FX: The higher repetition rate scheme: Period 2.48 s —> 1.3 s for 750 kW.  
(= shorter repetition period) —> 1.16 s for 1.3 MW  
SX: Mitigation of the residual activity for 100kW

<table>
<thead>
<tr>
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<tbody>
<tr>
<td><strong>Event</strong></td>
<td>New buildings</td>
<td>HD target</td>
<td>Long shutdown</td>
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<td></td>
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<tr>
<td>FX power [kW]</td>
<td>475</td>
<td>&gt;480</td>
<td>&gt;480</td>
<td>&gt;480</td>
<td>&gt;700</td>
<td>800</td>
<td>900</td>
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<tr>
<td>SX power [kW]</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>70</td>
<td>&gt;80</td>
<td>&gt;80</td>
<td>&gt;80</td>
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<tr>
<td>Cycle time of main magnet PS</td>
<td>2.48 s</td>
<td>2.48 s</td>
<td>2.48s</td>
<td>2.48s</td>
<td>1.32s</td>
<td>&lt;1.32 s</td>
<td>&lt;1.32 s</td>
<td></td>
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<tr>
<td>New magnet PS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mass production installation/test</td>
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<tr>
<td>High gradient rf system</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Manufacture, installation/test</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2nd harmonic rf system</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Ring collimators</td>
<td>Add.collimators (2 kW)</td>
<td></td>
<td></td>
<td>Add.colli. (3.5kW)</td>
<td></td>
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<tr>
<td>Injection system</td>
<td>Kicker PS improvement, Septa manufacture /test</td>
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<tr>
<td>FX system</td>
<td>Kicker PS improvement, FX septa manufacture /test</td>
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</tbody>
</table>
J-PARC Neutrino Beamline Upgrade

- **Baseline design**
  - Beamline components designed to accept $3.3 \times 10^{14}$ ppp
  - Replaceable components designed for 750 kW (can be upgraded later)
  - Non-replaceable components (HV, DV, BD) designed for 3-4 MW

- **Necessary upgrade toward 1.3 MW**
  - Improve cooling capacity to remove larger heat generated by higher power beam
    - Target He cooling, water cooling for horn, He vessel etc
  - Accommodate shorter cycle operation
    - Horn operation, DAQ
  - Accommodate larger amount of radioactivity produced by higher power beam
    - Upgrade radioactive waste disposal facility
  - Safe and reliable control of higher power beam
    - Improved control system and beam monitors
Target Upgrade

- **Original target design**
  - To survive thermal shock by $3.3 \times 10^{14}$ ppp beam $\Rightarrow$ $3.2 \times 10^{14}$ ppp should be OK
  - Cooling capacity only **900 kW**

- **Improvement**
  - Higher He flow rate needed to improve cooling performance
    - 0.5 MPa pressure needed $\Rightarrow$ high pressure tolerance
  - He compressor upgrade
  - Thermal analysis for 1.3 MW $\Rightarrow$ max temp. $\sim 900^\circ C$ expected
  - Further optimization to be done
  - New target production with high pressure tolerance $\Rightarrow$ to be installed in **FY2021**
  - He circulation system upgrade scheduled in **FY2023**

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**Comparison Table**

<table>
<thead>
<tr>
<th></th>
<th>0.75 MW</th>
<th>1.3 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Helium pressure</strong></td>
<td>1.6 bar</td>
<td>5 bar</td>
</tr>
<tr>
<td><strong>Pressure drop</strong></td>
<td>0.83 bar</td>
<td>0.88 bar</td>
</tr>
<tr>
<td><strong>Helium mass flow</strong></td>
<td>32 g/s</td>
<td>60 g/s</td>
</tr>
<tr>
<td><strong>Heat load</strong></td>
<td>23.5 kW</td>
<td>40.8 kW</td>
</tr>
<tr>
<td><strong>US window temp</strong></td>
<td>105 ° C</td>
<td>157 ° C</td>
</tr>
<tr>
<td><strong>DS window temp</strong></td>
<td>120 ° C</td>
<td>130 ° C</td>
</tr>
<tr>
<td><strong>Target core temp</strong></td>
<td>736 °C</td>
<td>909 °C</td>
</tr>
</tbody>
</table>
Horn Upgrade

- **Horn electrical system upgrade for 320 kA at 1 Hz**
  - Horn current 250 kA → 320 kA (design)
  - ~10% flux gain for right-sign neutrinos
  - 5~10% flux reduction for wrong-sign neutrinos
- **Three power supplies to drive three horns (one-by-one)**
  - New electrical system (PS, transformer, striplines) developed
- **Staged upgrade**
  - 1 Hz (@250kA) operation achieved by two PS configuration (FY2021)
  - 320 kA to be achieved with third PS and transformer (FY2023)
- **Stripline cooling improvement (for Horn2)**
  - Current He flow cooling not enough for 1.3 MW
  - Water-cooled striplines under development
  - R&D indicates proven results ⇒ to be installed in FY2021
<table>
<thead>
<tr>
<th>Acceptable beam power</th>
<th>FY2019</th>
<th>FY2020</th>
<th>FY2021</th>
<th>FY2022</th>
<th>FY2023</th>
<th>FY2024</th>
<th>FY2025</th>
</tr>
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<tbody>
<tr>
<td>1.3 MW</td>
<td></td>
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<tr>
<td>1 MW</td>
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<td>750 kW</td>
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<tr>
<td>500 kW</td>
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</tbody>
</table>

- **Horn PS**: 1 Hz 320 kA
- **DAQ/control upgrade**: 1 Hz
- **Horn stripline cooling**: Development → Install
- **High power horn**: Production → Install
- **Radio-active water disposal**: Construction
- **Concrete shielding**: 
- **HV/DV/BD water cooling**: 
- **Target He cooling**: 

**Timeline**

- **FY2019**: 1 Hz
- **FY2020**: 1 Hz
- **FY2021**: Development → Install
- **FY2022**: Production → Install
- **FY2023**: Construction
- **FY2024**
- **FY2025**
• New neutrino beamline for DUNE
• Primary protons in energy range of 60-120 GeV to LBNF target
• All systems designed for 1.2 MW initial proton beam power. Facility upgradable to 2.4 MW proton beam power.
• Aim to start operation from FY2027
Fermilab Accelerator Upgrade: PIP-II

- **PIP-II**
  - **800 MeV superconducting linac** to inject higher intensity proton beam to Booster
    - Higher energy will help to reduce space-charge effect
    - International contribution from many countries
  - **Status**
    - PIP2IT for Front End components to be completed in FY2021
    - Facility construction started in 2019

**PIP2IT**

<table>
<thead>
<tr>
<th>IS</th>
<th>LEBT</th>
<th>RFQ</th>
<th>MEBT</th>
<th>$\beta$</th>
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</thead>
<tbody>
<tr>
<td>DC</td>
<td>162.5 MHz</td>
<td>325 MHz</td>
<td>650 MHz</td>
<td>$\beta=0.11$ $\beta=0.22$ $\beta=0.47$ $\beta=0.61$ $\beta=0.92$</td>
</tr>
</tbody>
</table>

0.03 MeV 0.03 -10.3 MeV 10.3 -185 MeV 185 -800 MeV

L. Merminga @ Jul.2018 Fermilab Community Advisory Board

PIP2IT is a complete systems-integration of the PIP-II Front End - coming to completion in FY21
LBNF Target Hall Design

Air-filled target chase (NuMI) ⇒ $\text{N}_2$-filled hermetic vessel + He-filled Decay pipe

Target Chase: 2.2 m/2.0 m wide, 34.3 m long nitrogen-filled and nitrogen plus water-cooled (replaceable cooling panels).
1.2 MW optimized three horn design
- 300 kA horn current
- Heat deposit calculation and FEA analysis completed. Results look satisfactory.

1.5-2m long He-cooled graphite target (by RAL-UK)
- Graphite cylindrical segments centered in coaxial Titanium tubes carrying He gas
- Graphite at higher temperature ⇒ can reduce radiation damage

Significant increase in flux
- Covers 1st (2.4 GeV) and 2nd (0.8 GeV) osc. max.
Hadron Absorber Design

- Al water-cooled core blocks: 1 ft thick modular hanger replaceable via remote handling
- Surrounding iron blocks: air cooling
- Hadron monitor in front of the absorber
- Muon monitors behind the absorber: ionization detectors
• Overview of neutrino beam facilities
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International Cooperation on High Power Neutrino Beam

- **Good relationship among KEK, Fermilab, CERN experts since 1999** (including participation from many other institutes)
  - Detailed discussions and information exchange in Neutrino Beam and Instrumentation (NBI) workshop series
  - Many lessons learned from other facilities
  - NBI2019 at Fermilab (Oct. 22-25) : 20th anniversary !
  - [https://indico.fnal.gov/event/21143/](https://indico.fnal.gov/event/21143/)
- **US-Japan Cooperative Programs in High Energy Physics**
  - Accelerator and beamline R&D for high power neutrino beam since 2014
  - KEK-Fermilab collaboration in accelerator and neutrino beamline development
  - LBNF-specific program launched since 2018
  - KEK-Fermilab collaboration for LBNF
- **CERN-KEK cooperation for accelerator and beamline technology**
  - Accelerator technology (RF, beam monitors, etc)
  - Expanding to other fields (radiation damage, beamlines)

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**KEK contribution to LHC upgrade on RF**

**CERN Courier Jul/Aug 2017**

**HL-LHC**

LHC luminosity upgrade accelerates

CERN has recently implemented two important steps toward the High Luminosity LHC (HL-LHC) - an upgrade that will increase the intensity of the LHC's collision significantly from the early 2030s. Preparing CERN's existing accelerator complex to cope with more intense proton beams poses several challenges, in particular concerning the system that injects protons into the LHC. At a ceremony on July 5th, a major new high-energy accelerator, Linac 4, was officially inaugurated. Linac 4, which has been in service since 1974, is CERN's current accelerator responsible for the LHC and is used to feed the accelerator complex with higher energy particle beams. After an extensive testing period, Linac 4 will be connected to the existing infrastructure during the long technical shutdown in 2019/2020.

To cope with the higher intensity and higher-energy beam beams, Linac 4 will be replaced by a new Linac 4U which will replace the existing Linac 4. This Linac 4U, in combination with a redesigned high-intensity booster (P3B), which is the second accelerator of the LHC injector chain, will be completely overhauled during that same period. At the beginning of June, the first radio-frequency cavity of the new PSB acceleration system was completed, with a further 27 under assembly. The new cavities are based on FINEMET developed by Hitachi Metals, which allows them to operate with a large bandwidth and means that a single cavity can cover all necessary frequency bands. The PSB cavity project was launched in 2012 in collaboration with KEK in Japan, and involved extensive testing at CERN of the FINEMET cores and shared its experience with similar technology.
Canadian Efforts on J-PARC Neutrino Beam

- **Optical Transition Radiation (OTR) monitor in front of target**
  - Lead by **York U, U of Toronto**
  - Long-standing effort over 10 years
  - Significant contribution to beamline operation and analysis

- **Remote handling system in Target Station**
  - Lead by **TRIUMF**
  - Remote manipulator and lead glass window produced and installed in 2008
  - TRIUMF experts contributed to actual remote maintenance work for target
Summary

• High power neutrino beam is key for future neutrino programs
• Ongoing facilities
  • J-PARC : ~500 kW
  • Fermilab NuMI : ~750 kW
• Future facilities
  • J-PARC 1.3 MW upgrade (3.2x10^{14} ppp and 1.16 s cycle)
    • PS and RF upgrade to 750 kW scheduled in FY2021
    • Further RF upgrade thereafter
    • Neutrino beamline upgrade
  • LBNF : facility for DUNE (1.2 MW → 2.4 MW)
    • Accelerator upgrade (PIP-II) : building new 800 MeV SC Linac
    • New neutrino beamline :
      • Three horn + 1.5~2m target optimized for 1.2 MW
      • Upgradable to 2.4 MW
• International cooperation to realize high power neutrino beam facility