J-PARC Accelerator and Neutrino Beamline Upgrade Programme
for Neutrino 2016

Megan Friend

High Energy Accelerator Research Organization (KEK) and J-PARC Center

July 9, 2016
• J-PARC has a new (very much achievable!) goal of reaching 1.3+ MW

• For the J-PARC neutrino programme:
  • T2K : $\sim$2021 (H. Tanaka – Mon. Talk)
  • T2K Phase 2 : 2021$\sim$2026 (M. Friend – P4.022)
  • T2HK : 2026$\sim$ (F. Di Lodovico – Wed. Talk, M. Jiang – P2.021, C. Simpson – P3.007)
Reminder: How to Make a Conventional Neutrino Beam

- Slam high-energy high-intensity proton beam into long carbon target
- Focus outgoing hadrons (esp. pions) in electro-magnetic horns
  - Switch between $\nu$- or $\bar{\nu}$-mode by changing the horn polarity
- Pions decay to muons and $\nu_\mu$'s in long decay volume
- Stop interacting particles in beam dump; neutrinos continue on to near and far detectors
J-PARC Overview

- Composed of 400 MeV Linac, 3 GeV RCS, 30 GeV MR
- Design beam power: 750 kW (Currently ~420 kW)
  → New goal beam power: 1.3+ MW
J-PARC Overview

- Composed of 400 MeV Linac, 3 GeV RCS, 30 GeV MR
- Design beam power: 750 kW (Currently $\sim$420 kW)
  $\rightarrow$ New goal beam power: 1.3+ MW
• Continued increase of beam power with time
• Achieved 420 kW this year!
• Relatively pure flux of right-sign $\nu_{\mu}$ peaked at $\sim600$ MeV achieved with 250 kA horn current
  • $\nu$-mode right-sign purity is better than $\bar{\nu}$-mode
Upgrade Overview

J-PARC is a conventional neutrino beam – how do we increase the number of neutrinos?

→ Of course first step is to increase the number of protons

- Two ways to increase the proton beam power:
  1. Increase the frequency, number of beam spills
     - Increase beam repetition rate
     - (Maximize beam operation time..)
  2. Increase the number of protons per spill
     - Reduce beam instabilities
     - Reduce beam losses

- Of course, after increasing the proton beam power, all parts of the neutrino beamline must be able to handle the increased power
- – And – there are ways to increase the *effective* number of protons
  - i.e. increase the horn current for better right-sign pion focusing
Where Are We Now?  
How Can We Get To 1.3+ MW?

Current J-PARC MR Parameters:
- Reached stable 420 kW running
- At:
  - 2.48 s repetition rate
  - $\sim 2.2 \times 10^{14}$ protons per pulse
- Equivalent to 800 kW at 1.3 s repetition rate!
  - Note: plan to increase repetition rate to 1.3 s by JFY2018

Plans:
- Increase repetition rate to get to 800 kW
- Continue to reduce beam losses, increase beam stability to get beyond, to 1.3 MW

Goal J-PARC MR Parameters:
- 1.3+ MW
- At:
  - 1.1 s repetition rate
  - $\sim 3.1 \times 10^{14}$ protons per pulse ($\sim$original design intensity)

<table>
<thead>
<tr>
<th>Beam Power (kW)</th>
<th>420 (Achieved)</th>
<th>800</th>
<th>1000 (Demonstrated)</th>
<th>1326</th>
</tr>
</thead>
<tbody>
<tr>
<td>$#p/p \times 10^{12}$</td>
<td>220</td>
<td><strong>220</strong></td>
<td>270</td>
<td><strong>320</strong></td>
</tr>
<tr>
<td>Rep T (s)</td>
<td>2.48</td>
<td><strong>1.3</strong></td>
<td><strong>1.3</strong></td>
<td>1.16</td>
</tr>
</tbody>
</table>
J-PARC MR Overview

- J-PARC Main Ring 30 GeV proton synchrotron w/:
  - 3-fold symmetric straight and bending sections
  - 1568-m circumference
  - 8-bunch beam structure

- 3 116-m-long straight sections dedicated to:
  - Injection and beam collimators
  - Slow extraction
  - Fast extraction and RF system
  → Fast extraction scheme to neutrino target
J-PARC MR Hardware Upgrades

- J-PARC must upgrade MR power supplies for 1 Hz operation
  - To decrease magnet ramping time
  - Power supplies to be replaced in 2017–2018
- Newly developed high gradient RF system also being implemented

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Event</td>
<td></td>
<td></td>
<td>Li. current 30 -&gt; 50</td>
<td>New PS Buildings</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- FX [kW] (study/trial)
  - 240-320
  - 30~40
- SX [kW] (study/trial)
  - 50
- Repetition period
  - 2.48 s
- New magnet PS
  - R&D
  - Large prototype
  - Mass production
    - 1.3 s
    - 1.3 s
    - 1.25 s
- Present RF system
- High grad. rf system
- 2nd harmonic cavity
- VHF cavity
- Ring collimators
  - Back to JFY2012 (2kW)
  - Add. colli. C,D
  - Add. colli. E,F
- Injection system
  - FX system
    - Kicker PS improve., Septa manufac./test
- SX collimator / Local shields
  - Kicker PS improve., LF & HF septa manufac./test
- Ti ducts
  - Ti chamber for SX
    - Beam ducts
    - ESS
MR Power Supply Upgrade Status

- All MR magnet power supplies are being upgraded for 1 Hz operation
  - Currently run at 2.48 s repetition rate
  - Main issue towards quick upgrade was budget – budget has been approved for upgrade from JFY2016!
- Prototype system has been fabricated, tested – working well
- Now working on infrastructure, large-scale production
- Plan to finish installation, turn on at 1.3 s repetition rate in 2018

- Results of the middle scale prototype PS -

Self-learning control system

Power recovery by C-bank
MR RF Upgrade Status

- New, high gradient RF cavity development, large-scale fabrication is also under-way

- New cavities use a new type of magnetic alloy core (FT3L) allowing for increased impedance
  - Field gradient increased by $\sim$50%

- Gradually replacing current/old cavities with new ones
- 5 new RF cavities have been in use and working well since last year
  - 4 more to be installed this year
### MR RF Upgrade Plan

**Before Replacement**

<table>
<thead>
<tr>
<th>Year</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
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<tr>
<td>Li 400 MeV</td>
<td>Present FT3M cavities</td>
<td>9</td>
<td>8</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Li 50mA</td>
<td>New FT3L Cavities</td>
<td>0</td>
<td>1</td>
<td>5</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>MR 1.3-sec operation</td>
<td>New FT3L 2nd cavity</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Available voltage</td>
<td></td>
<td>315 kV</td>
<td>355 kV</td>
<td>485 kV</td>
<td>602 kV</td>
<td>602 kV</td>
</tr>
<tr>
<td>(2nd Harmonic)</td>
<td></td>
<td>(35 kV)</td>
<td>(70 kV)</td>
<td>(70 kV)</td>
<td>(70 kV)</td>
<td>(70 kV)</td>
</tr>
<tr>
<td>Number of cavity cells</td>
<td></td>
<td>27</td>
<td>29</td>
<td>36</td>
<td>43</td>
<td>43</td>
</tr>
</tbody>
</table>

**After Replacement**

- 3 cavities/long straight

**Space between Kickers**

**4 cavities/Long Straight**

**Required voltage:** 280 kV (~2017), 540 kV (2018~)
New MR Betatron Tune for Higher Power

- Resonance diagram shows tune regions (points), betatron resonances (lines)
  - Avoid resonances (lines) to enhance accelerator stability
  - Left plot: J-PARC MR betatron tune resonance diagram

- Now that new tune has been established, can continue to optimize:
  - RCS beam parameters (painting, tune, and chromaticity) for MR
  - RF voltage pattern for fundamental and 2nd harmonic
  - Compensation kicker for new tune point
  - Collimators for loss localization
  - Octupole magnets (Currently 2 magnets are being used)
  - Trim quadrupole and trim sextupole patterns
  - Beam optics at extraction timing for beam loss reduction
  - Instability damping with intra-bunch feedback and chromaticity
Feedback System

- Bunch-by-bunch and Intra-Bunch feedback systems very important for correcting beam orbit/reducing beam instabilities → beam losses

- Tuning/improvement of feedback systems allow for further stability improvements

- New intra-bunch feedback system reduced losses 350 W → 170 W in 2014
Internal Bunch Motion

After kick  
feedback off

100turn after

200turn after

300turn after

BxB feedback

Intra-bunch feedback
### (Outdated) High-Power Beam Test

Results of 2 Bunch High-Power Beam Test at New MR Tune in 2015:

<table>
<thead>
<tr>
<th>Bunch number</th>
<th>repetition period (sec)</th>
<th>#p/pulse (10^{12}) equiv</th>
<th>Beam power (kW)</th>
<th>Beam loss (kW)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.48</td>
<td><strong>270</strong></td>
<td>132</td>
<td>0.42</td>
<td>measurement</td>
</tr>
<tr>
<td>8</td>
<td>2.48</td>
<td><strong>270</strong></td>
<td>530</td>
<td>1.7</td>
<td>estimation</td>
</tr>
<tr>
<td>8</td>
<td>1.3</td>
<td><strong>270</strong></td>
<td>1000</td>
<td>3.2</td>
<td>estimation</td>
</tr>
</tbody>
</table>

- MR can achieve >1 MW with this beam tune w/ 1 Hz operation!
- Although beam loss needs to be further reduced
  - Plan to design a new collimator scheme for 3 kW beam loss capacity
  - Beam loss at high power will also be reduced with betatron tune fine tuning, feedback improvements, etc
- PPP can be further increased with upgraded RF system, upgraded fast extraction kicker, optimized beam tune

#### Beam Power (kW)

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<td></td>
<td>1.3</td>
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<td>1.16</td>
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Timeline for Expected MR Beam Power Improvement

- Official T2K (+ Phase 2) + MR beam power improvement schedule
- Already achieved continuous $\sim 420$ kW with new MR tune (+ 440 kW test to MR abort dump, 530 kW equiv. 2 bunch test)
  - 2 years ahead of “official” schedule!

![Diagram showing MR beam power improvement timeline and performance metrics.](image-url)
J-PARC Neutrino Beamline Upgrades

- Neutrino beamline must be ready for 1.3+ MW
J-PARC $\nu$ Primary Beamline

Primary beamline consists of:

- Series of normal- and super-conducting magnets
- Proton beam monitors

Arc SC magnets

Final Focusing NC magnets

Beam Position Monitor
Preparation of J-PARC $\nu$ Primary Beamline for High Power

- Primary beamline magnets and power supplies all designed for high power
- Possibly need some magnet configuration change
- Or, could need to increase beam-pipe apertures in case of beam blow up due to space-charge effects at high beam power
  - However, so far things look OK

Proton beam monitors:

- Beam current, position, loss monitors are designed for high power
- Could be some issue with beam loss/radiation/monitor degradation for destructive beam profile monitoring
  - Now working on R&D for new beam profile monitors
- Readout (flashADC) for some monitors must be upgraded for 1Hz

- Biggest issue: irradiation of down-stream beamline components
- Need to develop remote maintenance scheme
J-PARC Profile Monitor Upgrade R&D

• Towards higher beam power, need:
  • Monitors that are more robust
  • Cause less beam loss

• Segmented Secondary Emission Monitor (SSEM) used to monitor beam profile during beam-tuning (destructive monitor)
  • 3 5-µm-thick Ti foils
    → Each monitor causes 0.005% beam loss

• Now working on 2 new beam profile monitors:
  ① More robust SEM using wires rather than foils → ~10x less material in the beam = ~10x less beam loss
  ② Beam Induced Fluorescence Monitor
    • Measure proton beam profile by beam interactions with gas injected into the beamline
    • Non-destructive, continuous monitoring

 Beam Induced Fluorescence Monitor
 Schematic:

(NIMA 492 (2002) 74-90)
Secondary Beamline Upgrade Plans

Secondary beamline consists of:

- Target
- Horns
- Decay volume
- Muon monitors

Target + remote handling system
## High Power J-PARC Secondary Beamline

J-PARC secondary beamline infrastructure (shielding, decay volume, hadron absorber) were all designed for 3–4 MW

<table>
<thead>
<tr>
<th>Component</th>
<th>Limiting Factor</th>
<th>Current Acceptable Value</th>
<th>Upgraded Acceptable Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>Thermal Shock</td>
<td>$3.3 \times 10^{14}$ ppp</td>
<td>$3.3 \times 10^{14}$ ppp</td>
</tr>
<tr>
<td></td>
<td>Cooling Capacity</td>
<td>0.75 MW</td>
<td>$&gt;1.5$ MW</td>
</tr>
<tr>
<td>Horn</td>
<td>Conductor Cooling</td>
<td>2 MW</td>
<td>2 MW</td>
</tr>
<tr>
<td></td>
<td>Stripline Cooling</td>
<td>0.54 MW</td>
<td>$&gt;1.25$ MW</td>
</tr>
<tr>
<td></td>
<td>Hydrogen Production</td>
<td>1 MW</td>
<td>$&gt;1$ MW</td>
</tr>
<tr>
<td></td>
<td>Operation</td>
<td>2.48 s &amp; 250 kA</td>
<td>1 s &amp; 320 kA</td>
</tr>
<tr>
<td>He Vessel</td>
<td>Thermal Stress</td>
<td>4 MW</td>
<td>4 MW</td>
</tr>
<tr>
<td></td>
<td>Cooling Capacity</td>
<td>0.75 MW</td>
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<tr>
<td>Decay Volume</td>
<td>Thermal Stress</td>
<td>4 MW</td>
<td>4 MW</td>
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<td></td>
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<td>Beam Dump</td>
<td>Thermal Stress</td>
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<td>3 MW</td>
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<tr>
<td></td>
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</tr>
<tr>
<td>Radiation</td>
<td>Radioactive Air Disposal</td>
<td>1 MW</td>
<td>$&gt;1$ MW</td>
</tr>
<tr>
<td></td>
<td>Radioactive Water</td>
<td>0.5 MW 0.75→1.3 or 2 MW</td>
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</tr>
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J-PARC Secondary Beamline Upgrades

However, need upgrades to improve cooling capacity, radiation containment, and irradiated cooling water disposal for 1+ MW

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<td>Radioactive Air Disposal</td>
<td>1 MW</td>
<td>$&gt;1$ MW</td>
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<td></td>
<td>Radioactive Water</td>
<td>0.5 MW</td>
<td>$0.75 \rightarrow 1.3$ or 2 MW</td>
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Horn Overview

• Electromagnetic focusing horn consists of inner and outer conductor
  • Large magnetic field between conductors achieved by operating at high current (generally 100–300 kA)
• Pions of the correct sign traveling between two conductors are focused
  • Sign of focused pions can be chosen based on horn polarity setting
• Generally cooled by spray water
  • Beam power limits on horn cooling, horn stripline cooling, and activation/disposal of horn cooling water must be considered
• J-PARC has 3 horn configuration
J-PARC Horn Power Supply Upgrade for $\pm 250 \rightarrow \pm 320$ kA

- Move from 2 to 3 power supplies
  - New power supplies with energy recovery system
  - New striplines with low R & L
  - New transformers optimized for 320 kA operation
  - 10% increase in neutrino flux at far detector
  - 5~10% reduction of wrong-sign neutrinos around peak energy
- Upgrade planned in $\sim 2017$

Flux Improvement @ 320 kA
J-PARC Horn Power Supply Upgrade for

- Move from 2 to 3 power supplies $±250 \rightarrow ±320$ kA
- New power supplies with energy recovery system
- New striplines with low R & L
- New transformers optimized for 320 kA operation
- 10% increase in neutrino flux at far detector
- $5\sim10\%$ reduction of wrong-sign neutrinos around peak energy
- Upgrade planned in $\sim2017$

Projected fluxes:
Secondary Beamline Upgrade Schedule

- 1.3 MW
- 750 kW
- 500 kW

FY2016: Target/Beam Window He cooling
FY2017: Horn stripline cooling
FY2018: Horn operation
FY2019: Water cooling
FY2020: Radio-active water disposal
FY2021: Upgrade system

- Reinforce He flow system
- 320 kA/1Hz
- Upgrade system
- Water-cooled striplines
- Enlarge dilution tank
Secondary Beam Monitors

- J-PARC muon monitors – measure secondary muon profile downstream of the beam dump (>∼5 GeV) by 2 redundant measurements using 7x7 arrays of sensors
  - Ionization chambers (IC)
  - Silicon photodiode sensors (Si)
- Some upgrade ideas:
  - IC now uses Ar gas – may saturate at higher beam power
    - Considering He or Ne gas
  - Si sensors degrade over time
    - Now testing diamond and SiC sensors as possibly more robust sensors
• J-PARC MR accelerator upgrades planned to reach 1.3+ MW by:
  1. Increasing beam spill repetition rate from 2.48 s → 1.3 s → ∼1.2 s
     • After magnet power supply upgrade (2018)
  2. Increasing the number of protons per spill from $220 \times 10^{12}$ (current)
     → $270 \times 10^{12}$ (demonstrated) → ∼ $320 \times 10^{12}$
     • By reducing beam instabilities/improving beam tune by lots of small optimizations
• Reach 750+ kW by 2018, 1.3+ MW by 2026
• J-PARC neutrino beamline will be ready for the increased beam power
  • After some (reasonable) upgrades