RCS Beam Quality
(and recent status)

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and J-PARC 2nd Accelerator section
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  – Parameter and scheme
• Beam quality at high power operation
  – Achieved beam power
  – Transverse profile for MLF and MR
• Scope for DeeMe experiments
• Recovery and power up scenario
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**What is 3GeV-RCS in J-PARC**

**Parameters**

- Circumference: 348.333 m
- Superperiodicity: 3
- Harmonic number: 2
- No of bunch: 2
- Injection energy: 181 MeV (400 MeV )
- Extraction energy: 3 GeV
- Repetition rate: 25 Hz
- Particles per pulse: 1.7e13 – 2.5e13 (8.3e13 with 1 MW)
- Output beam power: 0.2- 0.3 MW (1 MW)
- Number of dipoles: 24
  - quadrupoles: 60 (7 families)
  - sextupoles: 18 (3 families)
  - steerings: 52
- RF cavities: 12 (11 at present)

The beams are extracted by kicker magnets and DC septum magnets at the extraction section and then transported either to MLF or to MR with a pulsed bending magnet placed in the 3NBT line.

The H0 dump is used to dump unstripped beams at the stripping foil. The capacity is 4kW.

The stripping foil in the injection section is used to convert H- beam from the linac into protons.

RCS has a three-fold symmetric lattice whose circumference is 348.3m.

One of the three-fold symmetric lattice comprises two arc modules and a long straight insertion.

Each arc module has a missing-bend cell.
Intermediate bunches are injected into the 2 RF buckets of RCS for duration of macro pulse width. Max. macro pulse length: 500μsec
Max. Intermediate bunch length: 600nsec
RCS accelerates the beam to 3GeV in 20msec in a sinusoidal curve as shown in figure.
In MR cycle of 3.64 sec, 8 RCS bunches are injected into 8 out of 9 MR buckets.
In the latest operation, MR cycle is 3.04 sec. Then the total batch number is 3.04/0.04=76.

Itemize
✓ MR: 4 batches
✓ Blank: 2 batches
(Due to fall time of the pulsed bending magnet for 3-N and 3-50 BT)
✓ MLF: 70 batches
Achieved beam power(1): User operation

- Due to the discharge problem of the RFQ, the RCS beam power was limited to 20 kW for a long period.
- By the vacuum improvement of the RFQ section, the performance of the RFQ was recovered.
- Then the RCS beam power was increased to 120 kW from Nov. 2009.
- The RCS beam power became >200 kW for MLF before earthquake.
Achieved beam power(2) 
:High power trial

420kW-eq particles(1 shot) trial indicates that there are no significant loss except to ring collimator. Measured loss is about 0.5%. On the other hand, Calculated loss is about 0.35%. In both case, most losses occurred in the first few msec and localized on the ring collimator. So far we enough understand and control the RCS beam.

->Tune shift by the space charge at 181MeV-inj, 300kW-eq particles ≲ tune shift at 400MeV-inj, 1MW-eq particles!!

Demonstrate a potential for 1MW operation.

<table>
<thead>
<tr>
<th></th>
<th>Beam transmission</th>
<th>Beam loss</th>
<th>Beam loss power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement</td>
<td>99.50 %</td>
<td>0.50 %</td>
<td>127 W</td>
</tr>
<tr>
<td>Simulation</td>
<td>99.65 %</td>
<td>0.35 %</td>
<td>82 W</td>
</tr>
</tbody>
</table>

*Collimator capacity:4kW
Transverse profile for MLF and MR

Requirement

• MLF: wider profile in order to mitigate the target damage from the beam shock.
• MR: beam with less halo in order to reduce the loss at 3-50BT collimator

→ We investigated the better operation parameter set for each requirement respectively.
Transverse profile for MLF and MR (Con’t)

Halo measurement of MR injection beam

Loss at the 3-50BT collimator

~90 W assuming 3-sec MR cycle « 4 kW

<table>
<thead>
<tr>
<th>Data ID</th>
<th>$\epsilon_{tp}$ ($\pi$ mm mrad)</th>
<th>$V_{2\text{nd}}$ (%)</th>
<th>$\phi_{12}$ (deg)</th>
<th>$\Delta p/p$ (%)</th>
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<tbody>
<tr>
<td>2</td>
<td>-</td>
<td>80</td>
<td>-100</td>
<td>-0.0</td>
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<tr>
<td>3</td>
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<tr>
<td>4</td>
<td>-</td>
<td>80</td>
<td>-100</td>
<td>-0.2</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
<td>80</td>
<td>-100</td>
<td>-0.2</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>80</td>
<td>-100</td>
<td>-0.2</td>
</tr>
<tr>
<td>7</td>
<td>150</td>
<td>80</td>
<td>-100</td>
<td>-0.2</td>
</tr>
</tbody>
</table>

normalized 99.5 %emittance (Calc.)

The painting parameter “6” gives a beam loss minimum both for the RCS and 3-50BT collimators.
Transverse profile for MLF and MR (Con’t)

• So far, a parameter set that takes least loss in the RCS is also best for both (MLF and MR) operations. (Transverse painting: \(100\pi\) mm mrad., 2\(^{nd}\) RF 80\%, \(\Delta p/p\) offset -0.2\%.)

• If need, we can choose the best parameter set (Transverse and longitudinal painting pattern, RF acceleration pattern, Excitation pattern of dipole and sextupole correction magnets ) respectively and change them during 20msec(interval of acceleration).
Scope for DeeMe Experiment

Estimation of the rest proton after extraction

Begin Ext. Ins

STR+BPM

STR+BPM

7859

布局 of Extraction Line

8

∑ KM Kick angle ≈ 17 mrad

1

Naive estimation:
If the rest proton exists and extracts
without pulse kicker magnets, a particle
needs to have an inclination (x’) ≥ 17 mrad

⇒ An emittance of ≈ 2200 π mm mrad!

⇒ 4 times of the RCS phisycal aperture
(486π mm mrad) or 7 times of the RCS
collimator aperture (324π mm mrad).
**Scope for DeeMe Experiment (Con’t)**

Estimation of the rest proton after extraction

Beam outer ellipse (H) at the “begin Ext. INS” (324 ~ 5000 \( \pi \) mm mrad)

We estimated the possible initial conditions that the proton can extract with no kicker excitation. As a result, the protons that has 2500\( \pi \) emittance can partially extract. however, some particles hit the branch chamber.

→ We can catch the proton existence after extraction by monitoring loss monitor signals near this point!
**Scope for DeeMe Experiment (Con’t)**

Preliminary measurement of the proton existence after extraction

- Measurement -> 2/8 15:00-2/19 9:00
- Accelerated protons: 4e20
- Signals overlaid by Persistent mode
- It seems that there are no signal except the kicker noise.
- We will improve the measurement system (Aoki-san’s talk)
Scope for DeeMe Experiment (Con’t)

Probability of a proton existence after extraction

• We think that there are no proton after extraction.
• The only one scenario that makes it possible is ...
  A) Particle remains after kicker excitation.
  B) This particle returns near the RCS acceptance ($486\pi$) by some reason (scattering by the gas or chamber?). Then it can circulate RCS ring.
  C) Scattered again at the vacuum chambers and It’s a good thing that such scattered particle has suitable emittance ($\approx 2500\pi$) for no kicker excitation at just the extraction branch point. This particle also must have enough momentum to pass through 3NBT magnets until it hits the Mu-target.

Is this really exist?
Recovery from the earth quake

So far...

- **Sub tunnel Area : Water Pipes and Cables**
  - No significant damages.
- **Main Tunnel : Accelerator**
  - No significant damages to the eye. No water leakages.
- **Utilities inside the RCS building**
  - No significant damages.
- **The outdoor yard and the surrounding road fell off and the electric infrastructures on the yard were inclined.**
  - We cannot check the magnets and RF systems with electrical power supply as yet.
  - Nothing can be concluded at this moment.
Damage - RCS -

The subsidence of the outdoor yard and the surrounding road is extensive at the RCS.

RCS bld.

Power receiving equipment

Wavy road. Bump in the middle means that beam pipe is underneath it. Both sides of the bump were sinking.

Condenser Bank for 3 GeV

Leaning is observed as shown in the figure.

Condenser bank was waved. Cables were distorted with heavy weight on them.
Road Repair
Temporarily repair finished. This place is important to fix cooling tower and electric power stations.

Electric Power Stations
Power receiving equipment fell off. We are trying to jack up the entire floor.
RCS power up scenario

- Not only injection energy
- But also peak current

Alignment?

- Previous estimate
- New estimate

- 400MeV installation
- Summer shut down

300kW 1 hour

- 420kW 1 shot

eq.-300kW for MR

Japanese Fiscal Year

RCS Output Power (MW)
Summary

- We successfully achieved power ramp up on schedule so far.
- Strong earthquake bring serious damages.
- We must carefully check and recover it.
- We will also install upgrade components in this shutdown.
- Resume user operation as soon as possible with beam power of 100kW for MLF users.
- We can enough suppress the background signals for DeeMe Experiments.
Backup  Slides
**Issue 3: Asymmetry components from inj-ext magnets**

Normalized emittance calculated with systematic combination of lattice imperfections

- Leakage fields ($K_1$ & skew $K_1$) from the extraction line:
  - causes a beta modulation & linear coupling
  - excite various random resonances

- Edge focus of the injection bump magnet ($K_1$):
  - causes a strong beta modulation especially in the vertical plane
  - excite various random resonances relating to the vertical motion

⇒ Shrinkage of the dynamic aperture

This can be one of the main reasons of the large beam loss that appears for large transverse painting.

- Extra alignments

We plan to install the correction magnets for these local modulations.
The run cycle of Run#38 began on March 2, and beam delivery to neutrino users and to MLF users at \textit{220kW} started on March 4 and March 7, respectively.

The MR RF cavity which stopped running in the previous run restored, and the beam tuning made it possible to deliver \textit{145kW} beam to the neutrino.

\textit{In the morning on March 11,}

the beam operation of the RCS and the MR was stopped for the radiation survey in the accelerator tunnels as scheduled.

Meanwhile the beam study had been carried out in the LINAC.

\textit{The earthquake} occurred when the beam was stopped temporarily to shift to the beam destination from the LINAC to the RCS. The beam was stopped as it was and also high-power equipment stopped.

\textit{In the RCS}, all devices were in-service but the beam operation was stopped for the radiation survey as scheduled.

All devices suddenly shut down because of high power equipment and cooling water stopped then.
Arc section

● Dipole magnet
- Number of magnet: 24
- Pole Gap: 210 mm
- Core Length: 2770 mm
- Field strength: 0.27T ~ 1.1T

● Quadrupole magnet
- Number of magnet: 60
- Bore Radius: 140 mm
- Field gradient: < 4.5 T/m

● Sextupole magnet
- Number of magnet: 18
- Bore Radius: 140 mm
- Field gradient: 26.2T/m²

● Steering magnet
- Number of magnet: 52
Resonant network and power supply for BM

**AC power supply**
- Voltage: 5832 Vp
- Current: 1587 Ap
- Rating: 3273 kW

**Chokes (25 units)**
- Inductance: 62 mH
- Mass: 42 ton

**DC power supply**
- Voltage: 2661 V
- Current: 1667 A
- Rating: 4436 kW

**Capacitors (25 units)**
- Voltage: 11108 Vp
- Capacitance: 1325 uF
- Mass: 11 ton

**Bending Magnet**
Resonant network and power supply for QM

60 QM are excited in 7 independent resonant networks.

(1) The power supply provided both AC and DC components simultaneously is inserted in series by halving one of the resonant meshes.

(2) The QM networks consist of 3 or 6 meshed each.

Power Supply
Voltage : 1200 Vp
Current : 1180 Ap
Rating : 193 kW

Choke Transformer
Type : All-in-one
Inductance : 144 mH
Mass : 29 ton

Resonant Capacitor
Voltage : 3587 Vp
Capacitance : 1740 mF
Mass : 12 ton

Q magnet
**Straight section (RF section)**

- RF Cavity
  - Number of RF Cavity: 11 (12)
  - Length: 1.65 m
  - Gap: 3
  - Gap Voltage (Max.): 43kV (14.4kV/gap *3)

- RF Cavities installed in the RCS tunnel
- Amplifiers installed in the RCS tunnel
The injection scheme was hard to design for the large beam aperture.

A beam collimation system is prepared to localize and to control the beam loss.
## Components of RCS

<table>
<thead>
<tr>
<th>Monitor (Number)</th>
<th>Profile</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPM</td>
<td>60</td>
<td>9 (MWPM:7, IPM:2)</td>
</tr>
<tr>
<td>BLM</td>
<td>134</td>
<td>Current 10 (DCCT:1, SCT:1, MCT:2, Tune 2 (Horizontal:1, Vertical:1))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FCT:1, WCM:3</td>
</tr>
</tbody>
</table>

1st arc section

2nd arc section
## Components of RCS

<table>
<thead>
<tr>
<th>Vacuum (Number)</th>
<th>100</th>
<th>Ti Chamber &amp; Ti Bellows</th>
<th>~300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramics Chamber</td>
<td>9</td>
<td>Pump</td>
<td>44 (turbo:24, ion pump:20)</td>
</tr>
</tbody>
</table>

![Image of RCS components with labels](image-url)
Vacuum test

No serious problems was found!

Vacuum pressure of each section after 4 hours pumping

- Turbo molecular pump
- Scroll pump

After 4 hours:
- 5.2x10^{-5} Pa
- 3.1x10^{-4} Pa
- 3.7x10^{-5} Pa
- 2.4x10^{-5} Pa
**Status of RCS devices**

3 GeV Main Ring

No obvious damages were observed.

Sub Tunnel at RCS

Main Tunnel at RCS

The confirmation of the vacuum system, rf system and so on has been carried out by securing the lighting with a diesel engine power generator for a while.

*Big problem has not been found* so far. It is necessary to use heavy machines to check the soundness of the equipment in the yard.
The confirmation of the vacuum system etc. has been carried out by securing the lighting with a diesel engine power generator for a while.
Abnormality that may lead big problems has not been found so far.

- **Sub tunnel Area : Water Pipes and Cables**
  - No significant damages.
- **Main Tunnel : Accelerator**
  - No significant damages. No water leakages. Concerning ceramics chambers, vacuum tests are definitely necessary.
  - Nothing can therefore be concluded at this moment.
  - Both temperature and humidity are very high.
- **2nd Floor below zero : Cooling water and air conditioning**
  - No significant damages.
- **1st Floor below zero : Pulse Power Supplies, cooling water, air conditioning**
  - No significant damages.
- **First Floor (Electric Power Room) : Main Magnet and RF power supplies**
  - No significant damages.

It is necessary to use heavy machines to check the soundness of the equipment in the yard. To perform this, confirmation of safety becomes first because there are many hollows under the base of the equipment.
- As the first step, the restoration of the surrounding road was started on May 11.
On J-PARC Recovery Schedule

Since the earthquake occurred on March 11, we, members of the J-PARC center team, have dedicated to promote an action program to recover the facility performance which suffered from damage due to a tremendous strong quake. Right after the event, we have worked on in creating a recovery master schedule. Although the present plan is by one week later than anticipated, we came to a result for the master plan which gives a goal for endeavor from now on, as follows:

1) We will confirm the facility recovery by a beam injection.

2) User program will be restarted with beam time of about 50 days that will be provided to users until the end of March 2012. (within Japanese fiscal year of 2011)

Please see a time chart of the schedule for the recovery on the next page.

* Note that, the schedule is assumed to be valid when the budget requested in each action program is delivered on time.
* In addition, the schedule is strongly influenced by the progress of infrastructural recovery, e.g., access roads, electric power supplies, cooling water supplies, etc.
The restoration schedule of some conventional items becomes an issue such as damage of cables in the power electrical system, unavailability of cranes, cooling water system and air-conditioning system, etc.

Beam stability and availability are · · · · · ??
Answer for recommendation (2) Systematics for dose rate

- H0 Branch
- Arc Dispersion Max Point
- Branch duct of H0 dump line and downstream BPM
- Duct between Injection septum 1 and 2
- Downstream of the Sec. Col. #1
- H0 Dump line H-Steering Magnet
- Duct between Injection septum 1 and 2@30cm
- Downstream of the Sec. Col. #1@30cm
- H0 Branch@30cm
- Arc Dispersion Max Point@30cm
- H-Steering Magnet in the H0 dump line

First Commissioning Stage


120kW User Op.


Branch duct of H0 dump line and downstream BPM

Duct between Injection septum 1 and 2

Date
RCS Major loss point

Residual radiation level after beam shutdown
- 4 hour after 200kW 20days operation
(10\textsuperscript{th} Feb., 2011)

Red: measured at the chamber surface
Blue: measured at 30 cm
Unit: $\mu$Sv/h

(A) Injection area (B) Collimator section

(A) Injection area
- 5.0, <0.5
- 45, 10
- 9.0, <0.5

(B) Collimator section
- 60, 10
- 45, 4.0
- 530, 95
- 45, 6.0
- 2000, 130
- 1100, 70

Unit: $\mu$Sv/h

- 6200, 220
- 530, 95
- 4500, 400
- 5500, 530
Loss at the H0 dump branch

- The number of foil hits can be reduced
- by the transverse painting
- by optimizing the foil position

Current foil size
110(H) x 40(V) mm²
Linac beam ~7x7 mm²

Next foil size
110(H) x 15(V) mm²

We installed smaller foils in the last summer maintenance period and studied those foils.
Loss mitigation at the H0 dump branch(1): small foil installation

- Vertical 15mm foil reduced branch loss 52% smaller than V 40mm foil case.
- But, charge exchange efficiency was reduced 99.5% → 95%
  Increased non-exchanged fraction caused activation along the dump line. (due to reflective neutrons from H0 dump)
- When V 20mm foil, beam loss was 68% smaller than V 40mm foil, and the charge exchange efficiency was improved to 98%.

→ we choose V20mm foil to balance the branch loss with the charge exchange efficiency.
Loss mitigation at the H0 dump branch(1): small foil installation (Con’t)

• It was found that such worse charge exchange efficiency was due to the wider Linac beam profile.
• After 120kW operation with V 20mm foil, H steering in the H0 dump line became 1.7mSv/hr.
• Linac profile was improved at the present operation. charge exchange efficiency improved to 99%.
• We need more better linac beam quality in order to achieve less branch loss and less non-exchange component. (Fine tuning, L3BT collimation...)
Trajectories of scattered protons (by H. Harada)

30 mrad

Shielding design by MARS

45 cm Iron Shielding

Branch

5.08 Sv/h

Collimator Block

3.91 mSv/h

Paint Bump Duct

581 μSv/h

30 mrad

Branch

BPM

H3

H4

FOIL

QDL

PB

PB

QFM
Loss mitigation at the H0 dump branch(3): Residual dose

- After 200kW, 20-day continuous operation and 4hr cooling, residual dose at branch duct was 4.5mSv/hr on contact and 400μSv/hr at 30cm position.

- After 9 days cooling, residual dose was reduced to 30%.

- We worked one hour at 30cm position from the branch duct during the new year shutdown period in order to measure the dimension of existing septum and duct. Then we were exposed about 10μSv.

- It seemed that this dose level is enough low to work near the branch duct in order to install the new collimator system in this summer shutdown.
Dispersion maximum point

- The RF feed forward compensates the beam loading.
  → Loss at the dispersion maximum point disappeared even if 400kW operation.
- Residual dose was less than 100μSv/hr after 1 month 200kW operation. This level is low enough to allow hands-on-maintenance!
Scattered particle motion in the horizontal phase space.

Here we assumed that there was only a horizontal halo. Plots at the following locations are shown: (a) at the transverse primary collimator. (b) at the first secondary collimator. (c) at the third secondary and (d) at the last (fifth) secondary collimator. (e) at the quadrupole magnet after two dipole magnets. (f) at the maximum dispersion point of the first arc after the collimators. The particles scattered by the horizontal primary collimator (figure a) were absorbed in each secondary collimator (figure b-d). However, few particles leaked from the 486pmm.mrad. acceptance range and were lost when the beam entered the arc(figure e-f). This was because the number of particles suffering a large energy loss though angle scattering was small.
L3BT Scraper test

• Confirmed the loss signal around the L3BT scraper and CT signal at 100deg. Dump (charge exchange)

Scraper 2σ position: 1.2 × 10^{12}ppp

Total current ~ 8.8 × 10^{12}ppp
→ 13% of total beam
→ more than 2σ (95%) tales cutted

Need position fix!