High Power Operation and Beam Instrumentations in J-PARC Synchrotrons

Takeshi Toyama
KEK / J-PARC

IPAC2013, May 12-17 2013, Shanghai China
Japan Proton Accelerator Research Complex

Tokai, Ibaraki

Kamioka

LINAC
15 mA
(50 mA)

3 GeV RCS
120 kW ← operation
(1 MW) ← (goal)

30 GeV MR
145 kW
(750 W)

Hadron hall
Outline

• Introduction
  – Beam power history of the J-PARC RCS and MR
  – Beam monitors and the beam parameters

• Operational aspect of the instruments
  – Identify & manipulate small beam losses:
    Current monitors, loss monitors
  – Precise machine modeling:
    BPMs with Beam based calibration
  – Profile, tail and halo measurements
  – Stripline kicker, "Exciters"
    for slow extraction

• Summary
Introduction

Beam power history of the J-PARC RCS and MR
RCS output beam power history

- Beam commissioning of the linac: November 2006 ~
- Beam commissioning of the RCS: October 2007 ~
- Startup of the MLF user operation: December 2008 ~
MR operation history from Jan 2010 to Feb 2013

Beam commissioning of the MR
First beam to the Hadron target with slow extraction
T2K neutrino beamline started operation

May 2008
Feb 2009
Apr 2009

T. Koseki
Introduction

Beam monitors and the beam parameters
Beam parameters

3 GeV
~ $2.6 \times 10^{13}$ ppp / 2 bunches
300 kW (goal: 1MW)
$\sigma_x, \sigma_y \sim 50 - 200 \, \text{mmrad}$
length $\sim 10 - 500$ ns
$\nu_x, \nu_y \sim 6.45, 6.42$

Charge-exchange injection with carbon foil

30 GeV
~ $1.4 \times 10^{14}$ ppp / 8 bunches
220 kW (goal: 750kW)
$\sigma_x, \sigma_y \sim 1 - 50 \, \text{mmrad}$
length $\sim 10 - 200$ ns
$\nu_x, \nu_y \sim 6.45, 6.42$

181 MeV (400 MeV)
$\text{H}^{-} \sim 20$ mA (goal: 50mA)
$\sigma_x, \sigma_y \sim 0.1 \, \text{mmrad}$
length $\sim 0.1$ ns
Monitors in J-PARC

ACS: under construction
Additional devices are in preparation.

*Monitors not counted for beam transport lines to the utilities, 3N BT, Hadron BT, ν BT
Operational aspect of the instruments

Identify & manipulate small beam losses: Current monitors, loss monitors
Required Resolution for Intensities, Losses

- Power is limited by the beam losses

- $1 \text{ W/m @RCS}$
- $0.5 \text{ W/m @MR}$

$\rightarrow$ Resolution of beam current measurement

$\Delta I / I < 0.1\%$

In practice we check residual activities along the rings.
Machine study of the high intensity beam @RCS

Intensity dependence of beam loss
Injection beam: 24.5 mA, 100-500 µs, 640 ns, 2 bunches
Transverse painting: 100π-mm-mrad correlated painting
Longitudinal painting: $V_2/V_1$ 80% (5ms), $\Delta \phi_1 2$ -100~0 deg, $\Delta p/p$ -0.2%

Beam power < 540 kW

Dynamic range:
$I < 0.15, 1.5, 15$ A
Resolution:
$$\frac{\Delta I}{I} \leq 0.1-0.8\%$$
Frequency bandwidth:
f <10k-20kHz
(Bergoz DCCT)

THPWO033 Hideaki Hotchi, High Intensity Beam Trial of up to 530 kW in J-PARC RCS
Current monitor vs beam loss monitor

Intensity dependence of beam loss

Beam survival: ratio of output intensity (RCS DCCT or SCT) to input intensity (L3BT SCT76)

- 539 kW (Li pulse 500 µs)
- 433 kW (Li pulse 400 µs)
- 325 kW (Li pulse 300 µs)
- 217 kW (Li pulse 200 µs)
- 104 kW (Li pulse 100 µs)

Calibrate

~2% loss
1~1.5% loss
~<0.5% loss

Time structure of beam loss

Scintillation type BLM @ Primary collimator

The beam loss appears only for the first 4 ms in the low energy region.

Normalized to be 2%
~1.2 % loss
~<0.5% loss

~0.7 ms:
End of foil scattering

Beam Loss monitor data

H. Hotchi et al., 2013
Compared to the simulation results

Measurements vs improved calculations: beam loss

The improved calculations well reproduce the measured time dependence and intensity dependence of beam loss.

THPWO033 Hideaki Hotchi, High Intensity Beam Trial of up to 530 kW in J-PARC RCS
Beam tail measurement at 350BT Collimator using BLMs

Beam tail are removed by the movable L shaped collimator jaw. The beam intensity was identified by the calibrated BLMs, short AIC and Long AIC.

Differentiation yields beam tail profile

K. Satou, M. Shirakata, Y. Sato
Difficulty in some cases

In the case that the beam loss is not localized
Not all the BLMs have been calibrated
→ DCCT resolution, accuracy required!

So far we calibrated the BLMs at the straight section, "Insertion-B" for SX
to estimate the extraction efficiency of the slow beam extraction.
DCCT response correction with the beam

Better precision required: to detect the beam loss of a few 10 W, $\Delta I \sim 100\mu A$ especially in the injection transient

Typical beam in the MR

Calibrated using step response at the end
Corrected response

Blue: no correction  red: with correction
Corrected response

The response drifts during recent high power operation under investigation

Blue: no correction  red: with correction
Operational aspect of the instruments

Precise machine modeling:
BPMs
with Beam based calibration
Beam Position Monitors (BPMs) and profile monitors (BT): important device for ring modeling: basis of beam simulations and control at high intensities

BPMs in J-PARC:

<table>
<thead>
<tr>
<th></th>
<th>RCS</th>
<th>350BT</th>
<th>MR</th>
</tr>
</thead>
<tbody>
<tr>
<td>L3BT</td>
<td>48</td>
<td>54 (COD)</td>
<td>14 (+3 planned)</td>
</tr>
<tr>
<td></td>
<td>8 (others)</td>
<td>186 (COD)</td>
<td>2 (others)</td>
</tr>
</tbody>
</table>

Position data provides a lot of informations:

\[
x, \ y = \sqrt{\epsilon \beta} \cos \left[ \left( v_0 + \xi \frac{\Delta p}{p} \right) \phi + \psi_0 \right] + \eta \frac{\Delta p}{p}
\]

COD bunch position

intra-bunch position

need precision, resolution
Machine parameter measurements

Examples from MR data
Beam based Alignment of BPMs

- Ordinary Beam based alignment
  Using one QM for one BPM

\[
x_{2m} = -a_{mn} \Delta K (x_{1n} + x_{2n}) = -\frac{a_{mn} \Delta K (x_{1n})}{1 + a_{nn} \Delta K}.
\]

  \(m\): BPM location
  \(n\): QM location

- Extension to multiple BPMs with a QM family

\[
x_{2m} = -\Delta K [ \begin{array}{ccc} a_{mn} & a_{ml} & a_{ms} \end{array} ] (I + \Delta K A)^{-1} \vec{x}_1
\]

  \(m\): BPM location
  \(n,l,s\): QM location

N. Hayashi et al., IPAC10, and HB2010
RCS  54 BPM

7 QM families (60 QMs)

BBA with QM families

$\sigma \sim 500\mu m$

BPM itself:

$\sigma \sim 20\mu m$  (averaged)
$\sigma \sim 300\mu m$  (turn-by-turn)

Figure 3: COD correction without (open circle) and with (closed circle) using BBA results. Upper is for horizontal and lower is vertical one.

N. Hayashi et al., NIM A677 (2012) 94-106
MR
186 BPMs
11 QM families (216 QMs)

Comparison of BBA with one QM and with QM families

$\sigma \sim 100\mu m$

Figure 3: MR BBA offset estimation of BPM attached to QFS family magnets. Upper and lower are horizontal and vertical, respectively. Most left data is determined by single QM sweeping and reference. Eight data sets are independent measurements for different initial orbits defined by various steering magnets.

N. Hayashi et al., IPAC10, and HB2010
Beam-based gain calibration

Gain of 4 pickups are calibrated with the beam.

\[ V_{i,j} = g_i \cdot q_j \cdot F_i(x_j, y_j) \]

- \( g_i \): gain
- \( q_j \): charge of j-th measurement
- \( x_j, y_j \): beam position of j-th measurement

Number of pickups: \( i = 1, 2, 3, 4 \)
Number of measurements: \( j = 1, \ldots, m \)

If the number of unknown parameters < total number of data
\[ 3 + 3 \times m < 4 \times m \]
we can solve the equation
Successfully applied to the KEKB BPMs
Improvement of "consistency"

The four beam positions can also be obtained from the output voltage of any three electrodes chosen out of four electrodes as

\[
\begin{align*}
  x_1 &= F_{1,x}(h_1, v_1), & x_2 &= F_{2,x}(h_2, v_1), & x_3 &= F_{3,x}(h_2, v_2), & x_4 &= F_{4,x}(h_1, v_2), \\
  y_1 &= F_{1,y}(h_1, v_1), & y_2 &= F_{2,y}(h_2, v_1), & y_3 &= F_{3,y}(h_2, v_2), & y_4 &= F_{4,y}(h_1, v_2),
\end{align*}
\]  

(6)

\[
\begin{align*}
  h_1 &= \frac{V_1 - V_2}{V_1 + V_2}, & h_2 &= -\frac{V_3 + V_4}{V_3 + V_4}, & v_1 &= \frac{V_2 - V_3}{V_2 + V_3}, & v_2 &= \frac{V_1 - V_4}{V_1 + V_4}.
\end{align*}
\]  

(7)

"consistency" = root-mean-squares of the four beam positions

Before the gain calibration

After the gain calibration

M. Arinaga et al., Prog. Theor. Exp. Phys. 2013, 03A007
Gain calibration of the diagonal-cut BPM

J-PARC Ring BPM:
- Good linear response

Signal from the electrodes:
- $L_k = \lambda_k (1+x_k/a)$
- $R_k = \lambda_k g_R (1-x_k/a)$
- $U_k = \lambda_k g_U (1+y_k/a)$
- $D_k = \lambda_k g_D (1-y_k/a)$

$\lambda_k$, $x_k$, $y_k$ (k=1, 2, ..., n)
$g_R$, $g_U$, $g_D$

Simplified as follows:
$L_k + R_k/g_R - U_k/g_U - D_k/g_D = 0$

Problem is to solve 3 $g_k$s:

$$
\begin{pmatrix}
-R_1 & U_1 & D_1 \\
& \vdots & \\
-R_k & U_k & D_k \\
& \vdots & \\
-R_n & U_n & D_n
\end{pmatrix}
\begin{pmatrix}
1 \\
\vdots \\
1 \\
\vdots \\
1
\end{pmatrix}
= 
\begin{pmatrix}
L_1 \\
\vdots \\
L_k \\
\vdots \\
L_n
\end{pmatrix}
$$

Test was done with this algorism

<table>
<thead>
<tr>
<th>BPM001</th>
<th>$g_2$</th>
<th>$g_3$</th>
<th>$g_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TLS</td>
<td>1.0062</td>
<td>1.0024</td>
<td>0.9873</td>
</tr>
<tr>
<td>LS</td>
<td>1.0103</td>
<td>1.0045</td>
<td>0.9892</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BPM002</th>
<th>$g_2$</th>
<th>$g_3$</th>
<th>$g_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TLS</td>
<td>0.9568</td>
<td>0.9811</td>
<td>0.9463</td>
</tr>
<tr>
<td>LS</td>
<td>0.9617</td>
<td>0.9838</td>
<td>0.9487</td>
</tr>
</tbody>
</table>

Figure 5: Reconstructed mapping data. Red: $(x, y)$ without correction, Black: $(x, y)$ with TLS.

M. Tejima et al., IBIC2011
Operational aspect of the instruments

Profile, tail and halo measurements
**Vibration wire monitor**

The principle of the VWM is to pick up its temperature rising-induced frequency shift by irradiating vibration wire with a beam.

**Futures of VWM**
- We assume that the VWM potential dynamic range of $10^{-5}$ will be achieved.
- The VWM is insusceptible secondary electrons

In last year, the VWM was installed in L3BT to demonstrate the feasibility of the beam halo measurement.

S. G. Arutunian, et. al., PRST-AB, 2, 122801 (1999)
Begoz instrumentation

MOPME028 Kota Okabe et al.
Frequency shift with beam irradiation

• The natural frequency of the VWM without beam irradiation was about 1943 Hz.
• The proton beam hit the wire only in a period between 0 sec and 247 sec.
• A frequency decrement of about 53.13 Hz (0.25 Hz) was measured at 1.3mm (-6.7mm) of distance from beam center.
• A length of time before temperature equilibrium is about 120 sec.
Beam profile measurements by the VWM

• The solid line represents the profile of the beam approximated by the mean square method of a gaussian function with a standard deviation of $\sigma_x = 1.498$ mm.

• The beam profile measured by the VWM is almost consistent with the MWPM measurements ($\sigma_x = 1.442$ mm) and integrated BLM signals.
High Power Beam trial:
Intensity 4.2x10^{13} \text{ p / 2bunches}

\sigma_V = 8.53 \text{ mm}

\sigma_H = 13.12 \text{ mm}

M. Tejima, Y. Hashimoto, T. Mitsuhashi, et al. IBIC2012
Fluorescence screen

Targets:
- (1) Ti foil 10\(\mu\)m thick
- (2) Al foil 100\(\mu\)m thick with a hole 50mm diameter,
- (3) fluorescence screen Al\(_2\)O\(_3\)+Cr 500\(\mu\)m thick

Tail, Halo Measurement with fluorescence screen just started
**Flying wire profile monitor**

**Carbon wire, 7 µm diameter**

**Horizontal Beam Profiles**

*(Measurement and Simulation)*

- 2.7e13 ppp (2 bunch injection)
- Flying Wire measurements at K1+10 ms and K1+120 ms.
- SCTR simulation with initial distribution of 16π mm mrad of Horizontal 2σ emittance and 24π for Vertical 2σ emittance.
The carbon wire was broken during measurement of the beam @4.4x10^{13} ppp/2 bunches.

The reason & remedy: under investigation
IPMs (Ionization Profile Monitors)

Electron collection for high intensity beams
E-field uniformity improved

Injection matching (ion collection mode)

Electron collection with magnet is foreseen.

MOPME021 H. Harada et al.,
Ionization Profile Monitor (IPM) of J-PARC 3-GeV RCS

K. Sato et al.
**Improved IPM @RCS**

Calibration with the beam shifted in $\Delta p/p$

Dispersion @IPM $\eta_x = 4.054m$

$\Delta f/f (\Delta p/p)$

**Beam center (Gaussian fit)**

An example of the data (ion collection mode)

Comparison to the expected value

- $\Delta p/p = -0.6\%$
- $\Delta p/p = 0.6\%$

Ion collection mode

- Ratio = 0.934

Electron collection mode

- Ratio = 1.116

MOPME021 H. Harada et al., Ionization Profile Monitor (IPM) of J-PARC 3-GeV RCS
Operational aspect of the instruments

Stripline kicker, "Exciters" for slow extraction
**MR slow extraction @MR**

Transverse BXB feedback (Hor.)
"Stochastic slow extraction"

Transverse BXB feedback (H & V)
Intra-bunch feedback (O. A. Konstantinova et al.)

Third-integer resonance
\[ 3 \nu_x = 67 \]

MR machine-cycle

x-x' phase space

M. Tomizawa et al.
Improvement of the spill duty factor

- Beam spill is deteriorated by the quadrupoles and bends field ripple, which cause tune ripple.

- Evaluation: duty factor

\[ D = \frac{\left[ \int_{T_1}^{T_2} I(t) \, dt \right]^2}{\left( T_2 - T_1 \right) \int_{T_1}^{T_2} I(t)^2 \, dt} \]

- Remedies
  - Transverse RF ("Stochastic slow extraction")
  - Feedback control with "EQ" and "RQ"
  - AUX-coil short-circuited during the flat top
    - the ripple current is bypassed to the AUX coil
  - Power supply improvement

D = 1 for I(t) = constant
ν sweep + stochastic slow extraction

Larger $dN_B/dt$ at local area in phase space → better duty factor and GOOD spill length

Original idea by Van der Meer, longitudinal direction
CERN-PS-AA-78-6 1978, . . . , @ CERN, Jülich, . . .
→ Transverse direction: @ NIRS, J-PARC MR, . . .

FIG. 1

Diffusion: small local density, high mean particle flux
Transverse kick by the EXCITER2

\[ f = 100k - 100 \text{ MHz}, \quad P = 3 \text{ kW} \]

Stripline kicker
length \( \sim 0.75 \text{ m} \)

Hor.

Cable length matched to
\( fc \sim 47 \text{M} \) or \( 95 \text{ MHz} \)

D3 power-supply building
Generation of "transverse RF"

Narrowband Noise signals
with minimized amplitude variation
in time domain

\[ I(t) = A(t)\cos\phi(t) \]
\[ Q(t) = A(t)\sin\phi(t) \]

Modulation in amplitude, A, and phase, \( \phi \).
IQ modulation

Narrowband Noise signals with minimized amplitude variation

Up conversion

\[ Ae^{j\phi} \times e^{j\omega_c t} \approx 47\text{M or 95MHz} \]
Suppression of the multipacting

Coating of the electrodes

Solenoid windings

Coating is not sufficient. Field of \(~30\) G is introduced to suppress the multipacting (vacuum pressure rise).

Two exciters
solenoids: reverse polarity

Beam
Spill duty improvement @ 15 kW beam

\[f_c = 95.0730 \text{MHz}\]

0.0-1.2s edge -0.8KHz width 0.2KHz P=3dBm
1.2-2.4s edge -0.2KHz width 0.2KHz P=3dBm

Duty : \sim 17\% \quad (\text{wo tr.-RF}) \quad \rightarrow 46\% \quad (\text{w tr.-RF})

T. Simogawa, M. Tomizawa et al.
Optimization

- Center frequency: 0 = 47.471937 MHz
- Bandwidth: 0.2 kHz
- Edge: -0.2 kHz

- Duty: ~45%
- Ext. efficiency: 99.54%

※ Error: 5-shot’s σ
Summary

• Beam intensities and losses are investigated in the order of 0.1 % or less in the machine commissioning, studies and operation.

• BPMs have been calibrated with the beam RCS all 54 BPMs,
  MR 15 for H, 3 for V / 186 BPMs.
  with the uncertainties of 100µm – 500µm.

• Measurements of
  high intensity beam profiles; Flying wire, IPM, OTR
  high intensity beam tail and halo; collimator & BLM, VWM, OTR/Fluorescence
  are ongoing.

• "Exciters" have been successfully applied to
  Bunch by bunch feedback (transverse)
  Transverse RF to mitigate the spill ripple in slow extraction
Acknowledgment

**Beam monitor of MR:**
Dai Arakawa, Mitsuhiro Arinaga, Kotoku Hanamura, Yoshinori Hashimoto, Masashi Okada, Shigenori Hiramatsu, Susumu Igarashi, Seishu Lee, Hiroshi Matsumoto, Junichi Odagiri, Kenichiro Sato, Masaki Tejima, Makoto Tobiyama

**Beam monitor of RCS:**
Hiroyuki Harada, Naoki Hayashi, Kazami Yamamoto, Shuichiro Hatakeyama

**Beam commissioning:**
Tadashi Koseki, Yoichi Sato, Susumu Igarashi, Masashi Shirakata,
Hideaki Hotchi, Hiroyuki Harada

**SX:**
Ryoji Aragaki, Katsuya Okamura, Takuro Kimura, Ryotarou Muto, Hikaru Sato, Tetsushi Shimogawa, Hisayoshi Shirakabe, Fumihiko Tamura, Masahito Tomizawa, Hideaki Nakagawa, Daisuke Horikawa, Shigeru Murasuhgi, Kouichi Mochiki, Eiichi Yanaoka,
Masahito Yoshii, Alexandre Schnase

**Control group:**
Norihiko Kamikubota, Noboru Yamamoto

**Vacuum Group:**
Yoichiro Hori, Masahiko Uota, Masayuki Shimamoto, Yoshihiro Sato

**System commissioning group:**
Takao Oogoe, Chikashi Kubota