Optics tuning of 3-50 beam transport line in the J-PARC

Contents:
• J-PARC
• 3-50 beam transport line
• Measurement and correction of dispersion function
• New method of beta function measurement
• Result of beta function measurement
• Summary

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J-PARC
RCS & MR

<table>
<thead>
<tr>
<th>RCS (FX / SX)</th>
<th>MR</th>
</tr>
</thead>
<tbody>
<tr>
<td>circumference</td>
<td>348.333 m</td>
</tr>
<tr>
<td>Injection energy</td>
<td>181 (400) MeV</td>
</tr>
<tr>
<td>Extraction energy</td>
<td>3.0 GeV</td>
</tr>
<tr>
<td>cycle</td>
<td>0.04 sec</td>
</tr>
<tr>
<td>Beam power</td>
<td>0.6 (1.0) MW</td>
</tr>
<tr>
<td>Physical aperture</td>
<td>&gt; 486π mm mrad</td>
</tr>
<tr>
<td>Collimator aperture</td>
<td>324π mm mrad</td>
</tr>
<tr>
<td>Limit of collimator</td>
<td>4 kW</td>
</tr>
<tr>
<td>Current beam power</td>
<td>0.3 MW</td>
</tr>
<tr>
<td>Maximum beam power</td>
<td>0.54 MW</td>
</tr>
</tbody>
</table>

<High-intensity proton accelerator>

- Nonlinearly increase the beam loss and halo by space charge effect, nonlinear fields and lattice imperfection
- Localize the beam loss by beam collimator
- Limit the beam power by beam loss
What’s 3-50 beam transport line

- Transport the beam without beam loss
- Match the optics and orbit to the next ring (MR)
- **Collimate the beam tail/halo to specified emittance by the collimator system**
  1. Tune the dispersion to free in the collimator area ($\Delta x = \eta \Delta p/p$)
  2. Understand the beta function in the collimator area ($\Delta x = \sqrt{\varepsilon \beta}$)
Dispersion function measurement

<Knob>
Momentum $\Delta p / p_0$ of extracted beam from the RCS

<Monitor>
Beam center (x / y) at monitors
- Beam position monitors : 14
- Profile monitors : 8

Dispersion functions ($\eta_x$ or $\eta_y$) were measured from the response of beam position for the beam momentum.

$$\eta_x = \frac{\Delta x}{\Delta p / p_0} \quad \eta_y = \frac{\Delta y}{\Delta p / p_0}$$
The measurement results and correction for the dispersion free

✓ The difference of dispersion functions ($\eta_x$) between the calculated and measured values.
✓ Fitting the first 4 quadrupoles (K1) from the measured first 4 data in model.
After correction

Correction factors of first 4 quadrupole magnets
QDE1: 109.8%, QFE1: 94.1%, QDE2: 94.2%, QFE2: 99.8%

⇒ Successfully correct the dispersion functions in 3-50 BT line
New method of beta functions in beam transport line (1)

Relation of transfer matrix $M$, beam position $x$ and angle $x'$ are

\[
\begin{pmatrix}
  x_m \\
  x'_m
\end{pmatrix}
= M
\begin{pmatrix}
  x_1 \\
  x'_1
\end{pmatrix}
\]

\[
M(S_1 \mid S_m) = \begin{pmatrix}
  m_{11} & m_{12} \\
  m_{21} & m_{22}
\end{pmatrix}
\]

\[m_{12} = \sqrt{\beta_1 \beta_m} \sin(\phi_{1m})\]

Beam positions $\Delta x$ for kick angles $\Delta x'$ by the steering magnets (STR1 and STR2) are

\[\Delta x_{1m} = \sqrt{\beta_1 \beta_m} \sin(\phi_{1m}) \Delta x'_1\]

\[\frac{\Delta x_{1m}}{\Delta x'_1} \frac{1}{\sqrt{\beta_1}} = \sqrt{\beta_m} \sin(\phi_{1m})\]

\[\Delta x_{2m} = \sqrt{\beta_2 \beta_m} \sin(\phi_{2m}) \Delta x'_2\]

\[\frac{\Delta x_{2m}}{\Delta x'_2} \frac{1}{\sqrt{\beta_2}} = \sqrt{\beta_m} \sin(\phi_{2m})\]

$\phi_{1m} = \phi_{12} + \phi_{2m}$ is inserted and then

\[
\beta_m = \left\{ \frac{\Delta x_{1m}}{\Delta x'_1} \frac{1}{\sqrt{\beta_1}} - \frac{\Delta x_{2m}}{\Delta x'_2} \frac{1}{\sqrt{\beta_2}} \cos(\phi_{12}) \right\}^2 \\
\pm \sin(\phi_{12}) + \left( \frac{\Delta x_{2m}}{\Delta x'_2} \frac{1}{\sqrt{\beta_2}} \right)^2
\]
New method of beta functions in beam transport line (2)

\[
\beta_m = \left\{ \begin{array}{l}
\frac{\Delta x_{1m}}{\Delta x'_1} \frac{1}{\sqrt{\beta_1}} - \frac{\Delta x_{2m}}{\Delta x'_2} \frac{1}{\sqrt{\beta_2}} \sin(\phi_{12}) + \cos(\phi_{12}) \\
\pm \sin(\phi_{12})
\end{array} \right\}^2 + \left( \frac{\Delta x_{2m}}{\Delta x'_2} \frac{1}{\sqrt{\beta_2}} \right)^2
\]

- Measured components (response of beam position for kick angle)

We must check whether these parameters are right or not.
"3 steering fitting method"

We can select the 3 pairs in 3 steering magnets. They satisfy the relation equation as

\[
\beta_m = \left\{ \frac{\Delta x_{1m}}{\Delta x'_1} \frac{1}{\sqrt{\beta_1}} - \frac{\Delta x_{2m}}{\Delta x'_2} \frac{1}{\sqrt{\beta_2}} \cos \phi_{12} \right\}^2 + \left( \frac{\Delta x_{2m}}{\Delta x'_2} \frac{1}{\sqrt{\beta_2}} \right)^2
\]

We estimate the true values of 5 parameters \((\beta, \phi)\) from the measured response so that \(\chi^2 \approx 0\).
Characteristics of the new method

\[
\beta_m = \left\{ \frac{\Delta x_{1m}}{\Delta x'_1 \sqrt{\beta_1}} \frac{1}{\cos(\phi_{12})} - \frac{\Delta x_{2m}}{\Delta x'_2 \sqrt{\beta_2}} \cos(\phi_{12}) \right\}^2 + \left( \frac{\Delta x_{2m}}{\Delta x'_2 \sqrt{\beta_2}} \right)^2
\]

\[
\frac{\Delta x_{1m}}{\Delta x'_1 \sqrt{\beta_1}} \sin(\phi_{23}) + \frac{\Delta x_{3m}}{\Delta x'_3 \sqrt{\beta_3}} \sin(\phi_{12}) - \frac{\Delta x_{2m}}{\Delta x'_2 \sqrt{\beta_2}} \sin(\phi_{13}) = 0
\]

- No effect of dispersion function because the measured beam positions are used instead of the beam profile.
- It is possible to measure at not just the beam profile monitors but the beam position monitors.
- It is easy to analyze the response of beam position for kick angle from the viewpoint of linearity.
- It is possible to check and estimate the beta functions of steering magnets and phase advance between steering magnets from the measured position response if there are 3 steering magnets.
Measurement of beta function in 3-50BT line

**<Knob>**

Horizontal steering: (STR1: ESEP3, STR2: B01, STR3: PB)
Vertical steering: (STR1: Y01, STR2: ZSV01)
※ Note: Cannot use “3 steering fitting method” for vertical plane

**<Monitor>**

Beam position monitor: 14
Beam profile monitor: 8
Measurement results of response \( \left( \frac{x}{\Delta x'} \right) \)

\[
\beta_m = \left( \frac{\Delta x_{1m}}{\Delta x'_1} \frac{1}{\sqrt{\beta_1}} - \frac{\Delta x_{2m}}{\Delta x'_2} \frac{1}{\sqrt{\beta_2}} \cos(\phi_{12}) \right)^2 + \left( \frac{\Delta x_{2m}}{\Delta x'_2} \frac{1}{\sqrt{\beta_2}} \sin(\phi_{12}) \right)^2
\]

Beam position @ BPM for kick angle of STR1

Beam position @ BPM for kick angle of STR2

Beam position @ BPM for kick angle of STR3

\( \Delta x'_1 \, [\text{mrad}] \, @ \, \text{ESEP3} \)

\( \Delta x'_2 \, [\text{mrad}] \, @ \, \text{B01} \)

\( \Delta x'_3 \, [\text{mrad}] \, @ \, \text{PB} \)
Estimation of $\beta$ and $\phi$ by “3 steering fitting method” (only horizontal plane)

$$\frac{\Delta x_{1m}}{\Delta x'_1} \frac{1}{\sqrt{\beta_1}} \sin(\phi_{23}) + \frac{\Delta x_{3m}}{\Delta x'_3} \frac{1}{\sqrt{\beta_3}} \sin(\phi_{12}) - \frac{\Delta x_{2m}}{\Delta x'_2} \frac{1}{\sqrt{\beta_2}} \sin(\phi_{13}) = 0$$

$\beta'_1 = \beta_1 + \Delta \beta_1$, $\beta'_2 = \beta_2 + \Delta \beta_2$, $\beta'_3 = \beta_3 + \Delta \beta_3$,

$\phi_{12}' = \phi_{12} + \Delta \phi_{12}$, $\phi_{23}' = \phi_{23} + \Delta \phi_{23}$, $\phi_{13}' = \phi_{13} + \Delta \phi_{13}$,

$$\frac{\Delta x_{1m}}{\Delta x'_1} \frac{1}{\sqrt{\beta'_1}} \sin(\phi_{23}') - \frac{\Delta x_{3m}}{\Delta x'_3} \frac{1}{\sqrt{\beta'_3}} \sin(\phi_{12}') + \frac{\Delta x_{2m}}{\Delta x'_2} \frac{1}{\sqrt{\beta'_2}} \sin(\phi_{13}') = A_m$$

$$\chi^2 = \sum_{m=1}^{14} (A_m)^2 \quad \text{No. of BPM: 14}$$

All parameters ($\beta_1$, $\beta_2$, $\beta_3$, $\phi_{12}$ and $\phi_{23}$) are scanned and then $\chi^2$ is calculated. Optimum values of $\beta_1$, $\beta_2$, $\beta_3$, $\phi_{12}$ and $\phi_{23}$ are estimated from the condition $\chi^2 \sim 0$ and iteration.
### β @ STRs and φ between STRs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Calculated Value</th>
<th>Estimated Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>βx@STR1 [m]</td>
<td>22.51</td>
<td>22.01</td>
</tr>
<tr>
<td>βx@STR2 [m]</td>
<td>21.52</td>
<td>22.14</td>
</tr>
<tr>
<td>βx@STR3 [m]</td>
<td>25.35</td>
<td>24.37</td>
</tr>
<tr>
<td>Δφx (STR1-STR2)</td>
<td>0.0600</td>
<td>0.0629</td>
</tr>
<tr>
<td>Δφx (STR1-STR3)</td>
<td>0.1063</td>
<td>0.1155</td>
</tr>
<tr>
<td>Δφx (STR2-STR3)</td>
<td>0.0463</td>
<td>0.0526</td>
</tr>
</tbody>
</table>

*NOTE: Use the calculated values for vertical plane*

### β measurement results @ monitors

<table>
<thead>
<tr>
<th>Monitor</th>
<th>βx [m] by STR1-2</th>
<th>βx [m] by STR1-3</th>
<th>βx [m] by STR2-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPM1</td>
<td>13.54±0.22</td>
<td>10.67±0.04</td>
<td>12.22±0.35</td>
</tr>
<tr>
<td>BPM2</td>
<td>35.44±0.77</td>
<td>33.63±0.14</td>
<td>51.34±2.15</td>
</tr>
<tr>
<td>BPM5</td>
<td>53.56±0.96</td>
<td>55.82±0.25</td>
<td>84.74±2.99</td>
</tr>
<tr>
<td>BPM1</td>
<td>13.94±0.22</td>
<td>14.14±0.05</td>
<td>14.14±0.28</td>
</tr>
<tr>
<td>BPM2</td>
<td>37.70±0.76</td>
<td>37.29±0.13</td>
<td>38.56±1.13</td>
</tr>
<tr>
<td>BPM5</td>
<td>57.43±0.93</td>
<td>57.43±0.22</td>
<td>58.57±1.46</td>
</tr>
</tbody>
</table>

β estimated from calculated values

β estimated from optimum values
β function measurement results after dispersion correction

- Measured β functions for vertical plane are only “rough measured values”.
- Measured β functions for horizontal plane are also agreed with calculated one.
Summary

✓ It is very important to scrape the beam tail/halo of the RCS beam at J-PARC 3-50BT line for the high-intensity operation of the MR.

✓ For taking full advantage of beam collimation, it is required “to correct the dispersion functions in the collimator area to dispersion free”, and then “to understand the beta functions”.

✓ The dispersion functions were successfully measured and corrected to dispersion free based on the online model calculation.

✓ Method of beta function measurement was newly devised and established. Beta functions for horizontal plane were also understood in the 3-50 BT line.

✓ In the future, the new monitors and the steering magnet for vertical plane will be added. We aim to achieve the optics measurement and control based on the model calculation in all of 3-50 BT line.

✓ As the result, it will be possible to discuss the quantitative beam tail/halo of the RCS extracted beam from scanning the beam collimation. We aim to decrease the tail/halo of the RCS extracted beam as the MR injector by optimization of the RCS parameters.
Thank you for your attention!

My son (Age : 4)
Back up
Fudge Factor estimation of steering magnets

1. Measure the response of beam position for kick angle of magnet with drift space (QM Off between steering magnet and BPM)
2. Estimate the fudge factor of steering magnet from the measured response and distance between the steering magnet and BPM.

\[ y = 0.8744x - 1703.7 \]

<table>
<thead>
<tr>
<th>STR Name</th>
<th>Fudge Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESEP3@3N</td>
<td>0.970</td>
</tr>
<tr>
<td>B01@3N</td>
<td>0.961</td>
</tr>
<tr>
<td>PB@3-50</td>
<td>0.880</td>
</tr>
<tr>
<td>Y01@3N</td>
<td>1.066</td>
</tr>
<tr>
<td>STR1@3-50</td>
<td>1.062</td>
</tr>
</tbody>
</table>

Current of PB [A] \(0.29283 \text{[mrad/A]} \Rightarrow 0.25762 \text{[mrad/A]}\)