Transverse Intra-Bunch Feedback System at J-PARC MR and Design of Stripline Electrode Shape for a Better Frequency Response

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Performance of Transverse Intra-Bunch Feedback System at J-PARC MR*

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Bird View of J-PARC Complex

- J-PARC (JAEA & KEK)
- Neutrino Beam Line to Kamioka (NU)
- Materials & Life Science Facility (MLF)
- Hadron Experimental Hall (HD)
- 400 MeV H⁻ Linac [181 MeV at present]
- 3 GeV Rapid Cycling Synchrotron (RCS)
- 50 GeV Main Ring Synchrotron (MR) [30 GeV at present]

JFY 2006 / 2007
- Yellow: JFY 2008
- Light Blue: JFY 2009
The present bunch-by-bunch feedback system (BxB FB) at MR effectively suppresses observed transverse dipole oscillations, together with help from the chromaticities, allowing to attain the 230 kW beam power.
The BxB FB can damp only the dipole oscillations of the center of mass motions of the whole bunches.

Even when it is on, internal bunch oscillations have been still observed, which are causing additional particle losses.

To suppress intra-bunch oscillations, a more wideband and elaborate feedback system has been developed.

The new intra-bunch feedback system divides an RF bucket into 64 segments (~10ns long).

It acts on each segment (bin) as if it is a small bunch (bunchlet) in a narrowband mode, even if it is empty.
Exponentially Tapered Electrodes

- A new stripline BPM for the intra-bunch feedback system for J-PARC MR has exponentially tapered electrodes for an improved frequency response, compared to rectangular ones (Linnecar, CERN-SPS).

More details will be discussed later in this talk!
## Main Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>@Routine Operation</th>
<th>@Beam Test in May</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Circumference</strong></td>
<td></td>
<td>1568m</td>
</tr>
<tr>
<td><strong>Energy</strong></td>
<td>3-30GeV</td>
<td>3GeV</td>
</tr>
<tr>
<td><strong>Repetition Period</strong></td>
<td></td>
<td>2.48s</td>
</tr>
<tr>
<td><strong>Beam Power</strong></td>
<td>230kW (30GeV)</td>
<td>0.5 kW (3GeV)</td>
</tr>
<tr>
<td><strong>RF Frequency</strong></td>
<td>1.67-1.72MHz</td>
<td>1.67 MHz</td>
</tr>
<tr>
<td><strong>Number of Bunches</strong></td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td><strong>Synchrotron Tune</strong></td>
<td>0.002-0.0001</td>
<td>0.0017</td>
</tr>
<tr>
<td><strong>Betatron Tune (hor./ver.)</strong></td>
<td></td>
<td>22.41/20.75</td>
</tr>
<tr>
<td><strong>Intensity (/pulse)</strong></td>
<td>1.3x10(^{14})</td>
<td>2.7x10(^{12})</td>
</tr>
<tr>
<td><strong>Bunch Length</strong></td>
<td>50-200 ns</td>
<td>150-200 ns</td>
</tr>
<tr>
<td><strong>Chromaticity (hor./ver.)</strong></td>
<td>-4 / -1</td>
<td>+0.5/+1.2</td>
</tr>
<tr>
<td><strong>Horizontal Feedback</strong></td>
<td></td>
<td>BxB FB/Intra-bunch FB on/off</td>
</tr>
<tr>
<td><strong>Vertical Feedback</strong></td>
<td></td>
<td>BxB FB Always on</td>
</tr>
</tbody>
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Intra-Bunch FB, Chin
Horizontal Beam Tests on May 7, 2014

- Single bunch, $N_b = 2.7 \times 10^{12}$

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Intra-Bunch FB, Chin
Horizontal Oscillations inside a Bunch

- **BxB FB off and Intra-Bunch FB off**
  - The large horizontal oscillations are excited around the 262th turn due to the mismatching field of the injection kicker magnets.
On/Off of BxB and Intra-Bunch FBs

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Time Evolution of Oscillation Envelopes at Every 100 Turns

- BxB off
- IB off
- BxB on
- IB off
- BxB off
- IB on

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Intra-Bunch FB, Chin
Simple Simulations with Neither Wake Field Nor Non-Linear Field

All FBs off

Damping time ~2000 turn

Only BxT FB on

Only IB FB on

Damping time ~40 turn
Oscillation Envelops at 100-th Turn after the Initial Perturbation

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Preliminary Results for Vertical Instabilities at Onset of Acceleration

- $N_b = 0.12 \times 10^{13}$
- Vertical BxB off; IB off

![Vertical Wave Form Graph]

Bunch= 1 - 1
Turn= 201 - 210
Title: RUN55_2014-05-09-13-19-41 V:BxB Off IB:Off Nb=0.12x10**13
**Vertical Intra-Bunch FB Turned On**

- $N_b = 0.9 \times 10^{13}$
- Vertical $B \times B$ off; IB on
More Tuning of IB FB and Help from Chromaticity Needed

- Still large particle losses observed during the acceleration in the case of \( N_b = 0.9 \times 10^{13} / IB \) on:

```
2014 May 09 14:37:11 - Run 55 Shot 1499
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\[ \times 10^{13} \text{ protons} \]

- time from K1 [sec]
Optimization of Stripline Electrode Shape for a Flatter and Wider Frequency Response*

Y.H. Chin, K. Takata (KEK),
and
Y. Shobuda (JAEA)

* Published in PRST-AB, 17, 092801 (2014)
Exponential Electrode: Prototype and Measurement at SPS

(Linnecar, CERN-SPS-ARF-SPS/78/17)
Frequency Response of a Rectangular Electrode (Length=l)

$Z_{\text{strip}} = R_1 = R_2 = 50 \Omega$

$\lambda = 2l$

$\frac{I_b}{2}$

Fourier Transform

$\lambda = 4l$

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Intra-Bunch FB, Chin
If the Electrode Becomes Very Narrow toward Downstream, the Leaving Bunch Will Not See it.

- No pair of green image currents will be generated.

\[ l = 2l \]
\[ l = 4l \]

**Fourier Transform**

\[ Z_{\text{strip}} = R_1 = R_2 = 50\Omega \]

**Intra-Bunch FB, Chin**

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Theory

- **Transfer function:**

\[ F(\omega) = i\omega \int_0^{\frac{2l}{v}} \frac{1}{2} k\left(\frac{vt}{2}\right)e^{-i\omega t} dt = \frac{i\omega}{v} \int_0^l k(z)e^{-\frac{2\omega}{v} z} dz, \]

- **Example**
  - Linnecar’s exponential electrode

\[ k_{\text{linnebar}}(z) = k_0 e^{-\frac{az}{l}}, \]

- **Transfer function**

\[ \lambda = \frac{2\omega l}{v} \]

\[ F_{\text{linnebar}}(\lambda) = \frac{k_0}{2} \left[ \frac{i\lambda(1 - e^{-a - i\lambda})}{(a + i\lambda)} \right]. \]
Improved Exponential Electrode

- To make the end value of $k(z)$ zero, let us subtract the end value $k(l)$ from $k(z)$:

$$k_{\text{linear}}(z) = k_0 \left( \frac{e^{-\alpha z} - e^{-\alpha}}{1 - e^{-\alpha}} \right).$$

- Transfer function

$$F_{\text{linear}}(\lambda) = \frac{k_0}{2} \left[ a(1 - e^{-i\lambda}) + i(1 - e^{i\lambda})\lambda \right].$$

$$\lambda = \frac{2\omega l}{v}$$

Red: Improved exponential
Blue: Original exponential
**Blackman-Harris Window Function**

- **Blackman-Harris window function for \( k(z) \)**

\[
k_{\text{blackman-harris}}(z) = k_0 \left( 0.35875 - 0.48829 \cos\left[\pi\left(\frac{z}{l} - 1\right)\right]
+ 0.14128 \cos\left[2\pi\left(\frac{z}{l} - 1\right)\right] - 0.01168 \cos\left[3\pi\left(\frac{z}{l} - 1\right)\right]\right).
\]

- The function has a zero derivative at the both ends.

Red: Blackman-Harris
Blue: Exponential
Three Conditions for a Flat Response

- Zero value at the end
- Smooth tapering toward zero derivative at the end
- Negative derivative at the beginning

Polynomial Electrode

$$k(z) = k_0 \frac{(l - z)^\sigma}{l^\sigma}$$

![Graph showing electrode half width and function $k(z)$](image)

- $\sigma = 1$
- $\sigma = 2$
- $\sigma = 2.63$

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Optimum $\sigma$

- Let us optimize $\sigma$ which minimize the following function:

$$I(\sigma) = \int_{\lambda_{\text{low}}}^{\lambda_{\text{up}}} d\lambda \left( \left| \frac{F(\lambda)}{k_0} \right| - 0.5 \right)^2.$$  

$\sigma = 2.63$

Red: Polynomial with $\sigma=2.63$
Blue: Original exponential
Simulations with CST Studio

- Simulations with nearly full satisfaction of the impedance matching conditions.
  - Correct width, height, thickness, resistors, etc.

Each electrode needs to be bended so that its height from a chamber varies proportional to its width to have impedance matching.
Summary

- The first beam test successfully demonstrates that the new intra-bunch FB system is quite effective to suppress intra-bunch oscillations.
- The intra-bunch FB system is now used in routine operation at J-PARC MR.
  - The beam loss at injection is reduced from 350W to 170W.
- The polynomial electrode was proposed for a very flat and wider frequency response of a stripline BPM.
- Measurements for proof of its validity are under way.
- More practical shape is under study for easier manufacturing and set-up, and eventually a flatter and wider frequency response in reality.
  - Prototypes will be ready soon for low-power measurements.