Overview

- Introduction
  - timing requirements
- Stabilization of beam extraction timing
- Beam test results
- Summary and outlook
Introduction

Fig. 1: The beams from the RCS are delivered to the MLF (materials and life science facility) and MR. Typically 4 pulses to MR, 87 pulses to MLF.

2009/10/15
RCS parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>circumference</td>
<td>348.333 m</td>
</tr>
<tr>
<td>energy</td>
<td>0.181–3 GeV</td>
</tr>
<tr>
<td>accelerating frequency</td>
<td>0.938–1.671 MHz</td>
</tr>
<tr>
<td>harmonic number</td>
<td>2</td>
</tr>
<tr>
<td>repetition</td>
<td>25 Hz</td>
</tr>
<tr>
<td>cavity Q-value</td>
<td>2</td>
</tr>
</tbody>
</table>
Timing requirement: MLF

Fermi chopper spectrometer: a key of MLF

- A fast rotating iron, 500 Hz to 1 kHz
- Chopper and proton beam must be synchronized within 300 ns
  - high resolution / efficient use of neutrons
- Large inertial moment, difficult to change quickly the rotating phase
  → Rotating speed fixed, extracted beam timing must be very stable and must have low jitters

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Timing requirement: MR

- Bucket-to-bucket transfer
  - MR: $h = 9$, RCS: $h = 2$
  - To fill the 8 RF buckets in 9 buckets, 4 RCS cycles are used
  - Injection period: over 120 ms
- Must be injected into the proper RF buckets
- A precise phase control is required to avoid the dipole oscillation in the MR
Timing requirement

For both of MLF and MR, very stable beam timing is necessary
Common sense?

- Accelerators should be synchronized to the AC power line for stable operations
- Without strong RF feedback loops, the proton acceleration in a synchrotron is impossible

→ the beam timing is under the influence of both AC line: 0.1% frequency variation
KEK PS-boost: beam timing accuracy is $\sim 10\mu s$
In J-PARC case:

- Non-AC-line-synchronized timing system is employed. The accelerators are operated without synchronization to the AC power line.
- Radial feedback loop is not necessary to accelerate the proton beam in the J-PARC RCS, thanks to the magnetic alloy cavity, the digital LLRF, stable B-field.

→ the beam timing is very stable!
Non-AC-line-synchronized timing system

Center Control Bldg
- 12MHz Master CLK
- 25Hz "Trigger CLK"
- "Type" code

MR

Linac

RCS

MLF, HD, NU...

- Optical cables

12MHz master clock generated by high-quality synthesizer
25Hz "Trigger clock" by counting master clock
"Type" code: information of operation during next 40ms

- CCB to all J-PARC accelerator bldg via fan-outs and optical cables, star configuration

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Non-AC-line-synchronized timing system

- Master clock: also used as reference of system clocks of digital systems, such as the digital LLRF control systems of the synchrotrons
- Trigger: defined by a delay from trig clk

*Overall trigger jitter: several hundred ps*
Power supply stability

**Question:** Power supplies operated with non-AC-line-synchronized timing is stable?

- Synchrotrons: switching power supplies, not affected by the AC line
- Klystron DC power supplies (linac) may get influence
  - Amplitude/phase variations of linac RF: output energy fluctuation
Linac RF stability

- RF feedback system for the compensation of the voltage sag and long-term drift of the klystron DC power supply
- With FB: amplitude/phase controlled in $\pm 1\%$ and $\pm 1$ [deg] (meets requirements)
  - without FB: $\pm 5\%$ and $\pm 15$ [deg]
- Cycle-to-cycle variations: also kept small
Linac RF stability

- SD of amplitude/phase: less than 2 [Arb. unit] / 0.05 [deg] (over 20 RF pulses)

![Amplitude and phase variations over 20 RF pulses. Red: average, green: standard deviation.](image)

Variation of the linac beam energy: ±0.01%

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Magnetic Alloy (MA) cavity

Fig. 3: RCS RF system
Magnetic Alloy (MA) cavity

- Twice high Acc. field to ferrite cavity
- Wide-band \( Q = 2 \): no tuning control necessary to cover frequency sweep: treated as a passive device
- Response is predictable and reproducible
- Simple Low-level RF (LLRF) control
Digital Low-level RF (LLRF) control

- Full-digital LLRF based on DDS (direct digital synthesis)
  - $10^{-7}$ frequency resolution, stable, reproducible
  - Analog VCO: only $10^{-4}$

No radial feedback loop necessary with MA cavity, digital LLRF, stable B-field

Stable beam timing possible
Beam stability measurement

Fig. 4: Beam stability measurement setup.

Delay from trigger to beam was measured

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Beam stability measurement

Table 2: Beam parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>repetition</td>
<td>25 Hz</td>
</tr>
<tr>
<td>macro pulse width</td>
<td>100 µs</td>
</tr>
<tr>
<td>linac peak current</td>
<td>5 mA</td>
</tr>
<tr>
<td>chopping width</td>
<td>560 ns</td>
</tr>
<tr>
<td>number of bunch</td>
<td>2</td>
</tr>
<tr>
<td>beam power</td>
<td>18 kW</td>
</tr>
</tbody>
</table>
Beam stability measurement

Fig. 5: Measured beam signals. Ch.2 (blue): the trigger signal, Ch.1 (yellow): the beam signal, Ch.3 (pink): the kicker trigger signal.
Beam stability measurement

Fig. 6: Magnified view of the beam signal (the first peak) with an infinite persistence.
# Beam stability measurement

<table>
<thead>
<tr>
<th></th>
<th>mean</th>
<th>max</th>
<th>min</th>
<th>St. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam</strong></td>
<td>1.797 µs</td>
<td>1.796 µs</td>
<td>1.799 µs</td>
<td>354 ps</td>
</tr>
<tr>
<td><strong>Kicker Trig.</strong></td>
<td>859.3 ns</td>
<td>858.7 ns</td>
<td>860.5 ns</td>
<td>233 ps</td>
</tr>
</tbody>
</table>

Extremely low jitter!
Multi-batch injection to MR

Fig. 7: Three batches are injected without synchronization (only bucket selection)
Summary and outlook

- Beam jitter less than 1 ns is achieved
  - Non-AC-line-synchronized timing
  - Wide-band MA cavity
  - Digital LLRF control based on DDS

- For high intensity, phase FB is necessary
  - beam phase is affected
  - should be still reproducible
  - beam loading compensation, synchronization system are prepared