LLRF and beam loading cancellation

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Overview

- introduction
  - magnetic alloy cavities of J-PARC RCS and MR
- low level rf system
- beam loading compensation
- experience of 1 MW-eq beam acceleration
- conclusion
All rf cavities in RCS and MR are magnetic alloy (finemet) cavities.
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J-PARC RCS/MR parameters

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High intensity:
- RCS: 1 MW-equivalent achieved, 500 kW user operation
- MR: 350 kW user operation for neutrino experiments
Magnetic Alloy (finemet)

Ring core formed by winding ribbon:
- large size core is possible
- RCS: 85 cm, MR: 80 cm

High gradient:
- constant shunt impedance
- high curie temperature
- lower $\mu Q_f$ & $R_p$, heat must be removed by proper way, need strong rf amplifier chain

Wideband / low $Q$:
- can follow frequency sweep during acceleration without tuning bias loop, more simple LLRF
- dual harmonic operation is possible (RCS)
- wake voltage is multiharmonic → discussed in my latter part

Production process of finemet cores.

80 cm finemet cores for MR.
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RCS cavity can be driven by dual harmonic.
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Typical wake voltage in RCS cavity.
RCS and MR cavities

- 3-gaps / cavity, 18 cores / cavity
- \(\sim2\) m long, maximum 40 kV / cavity
- strong rf power source: push-pull amplifier with TH558K, 10–12 kV, 92 A anode PS,
Further upgrade: new FT3L cavity

- Finemet FT3L, annealed with B-field has higher shunt impedance than FT3M
- We developed large size core annealing system using big magnet.

All existing 3-gap MR cavities will be replaced 4- and 5-gap FT3L cavity.
- existing amplifier chain and anode PS are used as is
- rf voltage 45 kV $\rightarrow$ 75 kV
- will generate 560 kV (present: 280 kV) for shorter cycle (2.48 s $\rightarrow$ 1 s)

First 5-gap cavity is successfully installed in the tunnel and operated.
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Low level rf control systems
J-PARC LLRF control system overview

- developed JFY 2003–2006
- VME based, 9U height
- designed to handle multiharmonic signals
- FPGA based, no DSPs
J-PARC LLRF control system overview

Block diagram of RCS LLRF control system (MR is similar).

- developed JFY 2003–2006
- VME based, 9U height
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J-PARC LLRF control system overview

LLRF functions:
- fixed system clock (36 MHz)
- DDS (direct digital synthesis)-based multi-harmonic RF generation for cavity drive and signal detection
- common feedbacks for stabilizing the beam
  - AVC, cavity voltage control
  - phase FB (RF phase)
  - radial FB (frequency)
- rf feedforward system for compensating the heavy beam loading
- misc. functions; synchronization, chopper timing
Dual harmonic AVC

RCS: wide-band cavity, $Q = 2$

- No tuning loop
- A single cavity is driven by the superposition of multi-harmonic RF signals
  - the fundamental RF ($h = 2$): for acceleration of the beam
  - the second harmonic RF ($h = 4$): for the bunch shape control by modifying the RF bucket. Increasing the bunching factor to alleviate the space charge effects

Precise control of the harmonic voltages is necessary.
Dual harmonic AVC

- frequency is low (several MHz): cavity voltage is directly converted into digital by ADC (36 Ms/s)

  - harmonic detection blocks
    - amplitudes of \((h = 2)\) and \((h = 4)\) are detected
  - compared with the amplitude patterns
  - PID (Proportional-Integral-Derivative) controllers

- coordinate transformer, \((R, \theta)\) to \((X, Y)\)
  - RF signal is generated, using phase pattern
  - \((h = 2)\) and \((h = 4)\) RF signals are summed; dual-harmonic RF signals

DAC
Harmonic detection block.

- I/Q demodulation technique is used
- the LPF must reject the nearest harmonics: \((h = 1)\) and \((h = 3)\).
  Minimum separation is at injection, 0.47 MHz
- I/Q vector: \(I_{(2,4)} = A_{(2,4)} \sin(\phi_{(2,4)})\), \(Q_{(2,4)} = A_{(2,4)} \cos(\phi_{(2,4)})\)
- Coordinate transformer, \((X, Y)\) to \((R, \theta)\)
Dual harmonic AVC

- the amplitudes of the fundamental and the second harmonic are detected and compared with the patterns
- the amplitude of each harmonic is controlled independently
- dual-harmonic AVC is working very well

Cavity voltage monitor signal. Green: fundamental only, Pink: with 80% second harmonic.

Comparison of the program and measurement.
Phase feedback

Roles of phase feedback:

- suppress longitudinal dipole oscillation (accelerating harmonic, $h = 2$)
- lock second harmonic ($h = 4$) rf phase to fundamental rf

Block diagram of phase feedback.

- phase modulation used (not frequency modulation). For second harmonic, it is natural
- good for phase control of extracted beams (discussed later)
Phase feedback

\[ G(s) = K_P + \frac{K_I}{s} \] (\( K_P, K_I \) are proportional and integrator gain), the transfer function with feedback is:

\[
\frac{\delta \phi_{\text{diff}}(s)}{\delta \phi_{\text{rf}}(s)} = \frac{B'(s)}{1 + B'(s)G(s)} = \frac{s^2}{(K_P - 1)s^2 + K_Is - \omega_s^2}
\]

- if \( K_I = 0 \), the pole \( s = \pm \sqrt{\frac{\omega_s^2}{K_P - 1}} \) is real or pure imaginary, **not stable**
- transfer function with only integration gain:

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\frac{\delta \phi_{\text{diff}}(s)}{\delta \phi_{\text{rf}}(s)} = \frac{-s^2}{s^2 - K_Is + \omega_s^2}
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if \( K_I < 0 \), the real part of the pole becomes negative and the oscillation damped.
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Block diagram of phase feedback.

Bode plots without and with phase feedback (\( f_s = 1000 \text{ Hz} \)).
Damping of dipole oscillation

Comparison of radial excursions.

- without phase feedback, dipole oscillation continues till end of acceleration
- by phase feedback of accelerating harmonic ($h = 2$), the oscillation is damped successfully
Damping of dipole oscillation

Comparison of radial excursions.

- without phase feedback, dipole oscillation continues till end of acceleration
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Second harmonic phase sweep

- The second harmonic phase is swept so that the RF bucket shape is modified during the injection period
- Efficient way to distribute the particles

\[ \phi(h=4) = \frac{\phi_{\text{sweep}}}{T_{\text{inj}}} \left( t - \frac{T_{\text{inj}}}{2} \right) - 2\phi_s \text{ [deg]} \]

\( \phi(h=4) \): the second harmonic phase  \\
\( \phi_{\text{sweep}} \): the sweep range that was set to 80 deg  \\
\( T_{\text{inj}} \): the duration of the injection  \\
\( \phi_s \): the synchronous phase

Second harmonic phase sweep example. horizontal-axis: time [ms], vertical axis: relative phase of the second harmonic to the fundamental minus \( \phi_s \).
Achievement of longitudinal injection painting

Using the LLRF functions, longitudinal injection painting during RCS injection period is achieved:

- momentum offset $-0.2\%$ (by frequency offset)
- large amplitude ($\sim 80\%$ of fundamental) second harmonic rf
- second harmonic phase sweep, 100 degrees
Achievement of longitudinal injection painting
Without (left) and with (right) longitudinal painting

- Flat bunch generated by longitudinal painting
Achievement of longitudinal injection painting

Without (left) and with (right) longitudinal painting

- flat bunch generated by longitudinal painting
Achievement of longitudinal injection painting

Bunching factor improved, 0.25 → 0.45.
Frequency correction without radial feedback

- B-field is stable after the warming-up
- frequency is reproducible thanks to DDS
- we adjust the accelerating frequency pattern without radial loop
- we take an orbit signal of a full accelerating cycle and correct the frequency pattern:

\[ \Delta f_{\text{correction}} = f_r \times \eta \times \frac{dp}{p} \]

\[ dp/p \] is obtained using a set of BPM at high dispersion
- orbit correction working well with a few iterations
- \( dp/p \) is stable after correction
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dp/p with initial frequency pattern, assumed that B-field is sinusoidal.
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Synchronization

Synchronization to the neutron chopper and MR rf bucket is important.

Very small tolerance of beam timing jitter:

- MLF: for neutron chopper: ±100 ns
- MR: several degrees of rf phase: ±10ns
Synchronization

Our solution: neutron chopper and beam are synchronized to fixed 25 Hz timing.

- timing system based on precise master clock by synthesizer, not synchronized to the AC power line → eliminate effects due to variation of AC line frequency (0.1 Hz maximum)
- DDS (direct digital synthesis) based rf signal generation → reproducible rf signal / phase generation
- no radial feedback, which modulates rf frequency

For low intensity beams, the solution above is enough. → issues for high intensity beams.
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18 kW beam, superposition of \( \sim 1000 \) beam waveforms at the extraction beam line. Very low timing jitter of 354 ps (RMS) was achieved.

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For acceleration of high intensity beams, the phase feedback to damp the longitudinal dipole oscillation is necessary.

- phase feedback accumulates the subtle variation of the beam, and affects the extraction beam phase
- source of pulse-to-pulse jitter

Low beam jitter and suppression of oscillation, both must be achieved.

Solution:
The source of dipole oscillation is during the beginning of acceleration

- apply a gain pattern for phase feedback. The gain is maximum until the middle of acceleration, is reduced toward the end of acceleration. It becomes zero just before extraction
- at the extraction, rf / beam phase is as programmed

→ minimum pulse-to-pulse jitter of 1.7 ns (full width) achieved
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Beam loading compensation by feedforward
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For beam loading, cavity Q value is important:

- **RCS**: $Q = 2$
- **MR**: $Q = 22$
Wake voltage in J-PARC MA cavities

RCS \((Q = 2)\):
- covers wide accelerating frequency sweep \((0.938–1.671\ MHz)\) without tuning bias
- bunch shaping by second harmonic is possible
- wake contains higher harmonic components

MR \((Q = 22)\):
- driven by single harmonic \((h = 9)\)
- covers accelerating frequency \((1.67–1.72\ MHz)\) and neighbor harmonics \((h = 8, 10)\)
- not all buckets are filled; periodic transient
- possible source of coupled bunch instability

RCS cavity gap impedance \((Q = 2)\).

WCM waveform just after injection (left) without and (right) with dual harmonic operation.
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Wake voltage just before extraction (measured by turn off accelerating voltage)
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In both RCS and MR, multiharmonic beam loading compensation is necessary.
Multiharmonic rf feedforward

J-PARC RCS and MR employ rf feedforward method for multiharmonic beam loading compensation.

- in case of direct rf feedback, FB amplifier must be located in tunnel near cavity, limited space

Feedforward method:

- pick up beam current by WCM
- in addition to driving rf current to generate accelerating voltage, \(-i_{\text{beam}}\) fed to cavity
- cancel wake voltage
Multiharmonic rf feedforward system

- I/Q vectors \((h = 8, 9, 10)\) are generated from WCM signal
- distributed to each cavity system
- for each cavity and harmonic, gain and phase patterns are programmed. By I/Q modulation, compensation rf signal generated
- tracking BPF with passbands at \((h = 8, 9, 10)\) with arbitrary gain and phase

Delicate adjustments of the gain and phase patterns are necessary. We established the commissioning methodology.
Commissioning methodology

Cavity voltage is superposition of driving rf, wake, FF component

for the selected harmonic $h$,

$$V_{cav}(h, t) = V_{cav,dr}(h, t) + V_{cav,wake}(h, t) + V_{cav,FF}(h, t)$$

$$= H_{dr}^{cav}(h, t) \cdot V_{dr}(h, t) + Z'_{cav}(h, t) \cdot I_{beam}(h, t) + Z_{FF}(h, t) \cdot I_{beam}(h, t)$$

($V_{cav}, V_{dr}, I_{beam}$: complex amplitude)

cavity voltage is a superposition of driving rf voltage, wake, and feedforward: separation of them is important to analyze the impedance seen by the beam, however, they cannot be measured directly.

$\rightarrow$ From $V_{cav}, V_{dr}, I_{beam}$, transfer functions and impedance are obtained

- waveforms from injection to extraction are taken by a long memory oscilloscope (RCS: 200 Ms/s, 4 M points)
- harmonic analysis by PC
  1. LLRF driving rf: $V_{dr}(h, t)$
  2. WCM signal: $I_{beam}(h, t)$
  3. cavity voltage monitor: $V_{cav}(h, t)$
Commissioning methodology

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$$V_{\text{cav}}(h, t) = V_{\text{cav,dr}}(h, t) + V_{\text{cav,wake}}(h, t) + V_{\text{cav,FF}}(h, t)$$

$$= H_{\text{cav,dr}}(h, t) \cdot V_{\text{dr}}(h, t) + Z'_{\text{cav}}(h, t) \cdot I_{\text{beam}}(h, t) + Z_{\text{FF}}(h, t) \cdot I_{\text{beam}}(h, t)$$

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→ From $V_{\text{cav}}, V_{\text{dr}}, I_{\text{beam}}$, transfer functions and impedance are obtained

- $H_{\text{dr}}(h, t)$: transfer function from LLRF driving signal to gap voltage, obtained without accelerating beam

  $$H_{\text{dr}}(h, t) = \frac{V_{\text{cav}}(h, t)}{V_{\text{dr}}(h, t)}$$

- $Z'_{\text{cav}}(h, t)$: cavity impedance under the tube current for generating the accelerating voltage, obtained without FF.

  $$V_{\text{cav}}(h, t) = V_{\text{cav,dr}}(h, t) + V_{\text{cav,wake}}(h, t)$$

  $$= H_{\text{dr}}(h, t) \cdot V_{\text{dr}}(h, t) + Z'_{\text{cav}}(h, t) \cdot I_{\text{beam}}(h, t)$$
Cavity voltage is superposition of driving rf, wake, FF component

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$$V_{\text{cav}}(h, t) = V_{\text{cav,dr}}(h, t) + V_{\text{cav,wake}}(h, t) + V_{\text{cav,FF}}(h, t)$$

$$= H_{\text{dr}}^cav(h, t) \cdot V_{\text{dr}}(h, t) + Z'_{\text{cav}}(h, t) \cdot I_{\text{beam}}(h, t)$$

$$+ Z_{\text{FF}}(h, t) \cdot I_{\text{beam}}(h, t)$$

($V_{\text{cav}}, V_{\text{dr}}, I_{\text{beam}}$: complex amplitude)

- $Z_{\text{FF}}(h, t)$: transfer function from beam current to FF component (obtained with FF.)

- impedance seen by the beam with FF: $Z'_{\text{cav}}(h, t) + Z_{\text{FF}}(h, t)$

To minimize the impedance, pattern is modified

$$|Z_{\text{FF}}(h, t)| = |Z'_{\text{cav}}(h, t)|$$

$$\text{Arg}(Z_{\text{FF}}(h, t)) = -\text{Arg}(Z'_{\text{cav}}(h, t))$$

- by several iterations, impedance seen by the beam can be greatly reduced

Commissioning methodology of feedforward has been established.

cavity voltage is a superposition of driving rf voltage, wake, and feedforward: separation of them is important to analyze the impedance seen by the beam, however, they cannot be measured directly.

→ From $V_{\text{cav}}$, $V_{\text{dr}}$, $I_{\text{beam}}$, transfer functions and impedance are obtained
RCS commissioning results

Commissioned using 300 kW eq. \((2.5 \times 10^{13})\) high intensity beams.

- impedance seen by the beam is successfully suppressed \((1/30)\)
- distortion reduced, waveform with FF is close to the case of no beam
- phase delay, which corresponds to the loading angle, is reduced
- beam loss due to the distortion disappeared

Comparison of impedance seen by the beam without and with feedforward.

Comparison of gap voltage waveform just before extraction.

BLM signal at the arc section.
MR commissioning results

Commissioned using 200 kW eq. (1.0×10^{14} ppp) high intensity beams. Impedance seen by the beam for \((h = 8, 9, 10)\) successfully reduced.

Mountain plots of WCM during injection period without FF.

Typical beam loss monitor signal in the arc sections without and with feedforward.

- by FF, rf phase jumps due to loading angle are reduced, less dipole oscillation
- compensation of neighbor harmonics \((h = 8, 10)\): periodic transient reduced, forward and rear bunches oscillate similarly
- oscillation reduced throughout the accelerating period
- beam losses in the arc sections due to large amplitude dipole oscillation disappeared
multiharmonic feedforward system developed for RCS and MR
commissioning methodology established
feedforward compensation is now indispensable for high beam power operation

- FF systems for $h = 2, 4, 6$ and $h = 1, 3, 5$ are working in RCS
- $h = 8, 9, 10$ and $h = 17, 18, 19$, fundamental / second harmonic and neighbors in MR
Experience of 1 MW-eq beam acceleration
1 MW beam acceleration: first trial

The first trial in October 2014 was not successful due to shortage of the capacity of anode power supply.

- The beam accelerations of up to 770 kW was achieved with no significant beam loss.
- But, the 1-MW beam acceleration was not reached due to the RF trip.
- When the beam intensity got to over 800 kW, the anode power supply of the RF system tripped due to the over current.
1 MW beam acceleration: quick measures

- Quick measures against the RF trip
  - The interlock level was increased; $110 \, \text{A} \rightarrow 125 \, \text{A}$
  - The resonant frequency of the RF cavity was shifted to decrease the anode current required for the 1-MW beam acceleration; $1.7 \, \text{MHz} \rightarrow 2.1 \, \text{MHz}$

Date: Dec 26-27, 2014 (Run#59)
- Injection beam condition
  - Injection energy: 400 MeV
  - Peak current: $44.4 \, \text{mA}$ at the entrance of RCS
  - Pulse length: 0.5 ms
  - Chopper beam-on duty factor: 60%
  - $8.32 \times 10^{13}$ particles/pulse, corresponding to $999 \, \text{kW}$ at 3 GeV

By shifting the cavity resonant frequency ($1.7 \rightarrow 2.1 \, \text{MHz}$), anode currents decreased and we could accelerate 1 MW-eq beams.
1 MW beam acceleration: result of trial in Jan 2015

After fine tuning, no intensity loss was observed by DCCT, however...
Subtle beam losses at arc sections were observed. RF group (especially I) was not completely happy because the loss is longitudinal losses.
Subtle beam losses at arc sections were observed. RF group (especially I) was not completely happy because the loss is longitudinal losses.
Comparison between 1 MW and 560 kW beams

Mountain plots of 1 MW (left) and 560 kW (right) beam and comparison of bunching factor (bottom).

- Not very different
- A bit more oscillation in case of 1 MW, also $B_f$ oscillates
- Oscillation source?
Effect of wake voltage odd harmonics

After shifting of resonant frequency, sometimes front and rear bunches oscillate differently.

- beam signal and cavity voltage have odd harmonics components
Effect of wake voltage odd harmonics

After shifting of resonant frequency, sometimes front and rear bunches oscillate differently.

- beam signal and cavity voltage have odd harmonics components

Harmonic components of (left) beam signal and (right) cavity voltage monitor. Odd harmonics are significant around 2–3 ms.

The resonant frequency shift is good for reduction of anode current, but not best for longitudinal motion.

- feedforward of odd harmonics is not sufficient to suppress this kind of wake
- narrow band voltage feedback is now considered in addition to feedforward
Conclusion

- LLRF control systems for J-PARC RCS and MR were designed and built to handle multiharmonic rf signals,
  - voltage control
  - phase feedback
and the systems work properly
- multiharmonic beam loading compensation by rf feedforward greatly reduces impedance seen by the beam
- improvements foreseen toward our goal
  - anode power supply consolidation is planned this summar
  - narrowband vector voltage control is considered
Backup slides
Dual harmonic AVC

![Diagram of Dual harmonic AVC](image)
Phase feedback

\[
\begin{align*}
\text{phase detection block} & \quad \text{phase ref signal (h=2,4)} \\
\text{FCT} & \quad \text{A/D} \\
h=2 \text{ detect} & \quad h=4 \text{ detect} \\
I,Q & \quad I,Q \\
(I,Q) \text{ to (R,}\theta) \text{ trans.} & \quad (I,Q) \text{ to (R,}\theta) \text{ trans.} \\
\text{phase correction.} & \quad \text{phase correction.} \\
\phi_{\text{beam2}} \text{ to feedback block} & \quad \phi_{\text{beam4}}
\end{align*}
\]
Vector sum of cavity voltage for phase detection.
Phase feedback

- Vector sum cavity phase (h=2)
- Vector sum cavity phase (h=4)
- (h=4) phase pattern ($\phi_s$ + sweep pattern)
- $\phi_{FB4}$

$\phi_{FB4} = \text{vector sum cavity phase (h=2)} - \text{vector sum cavity phase (h=4)} - (\phi_s + \text{sweep pattern})$