Multiharmonic beam loading compensation in the J-PARC synchrotrons

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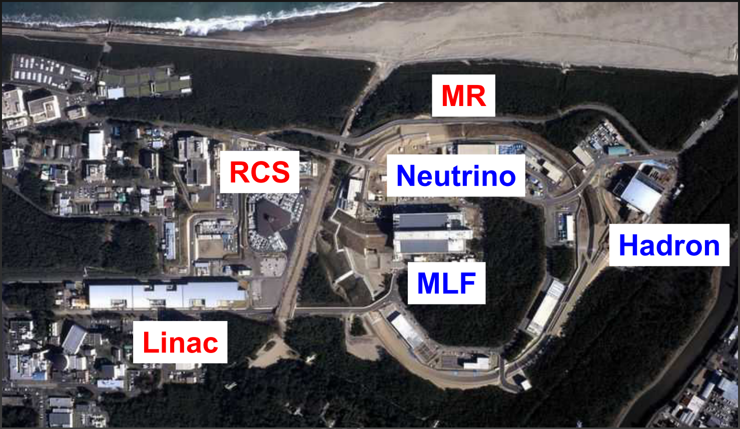
Overview

- introduction
- multiharmonic feedforward system
- commissioning of feedforward
- summary

Japan Proton Accelerator Research Complex (J-PARC)



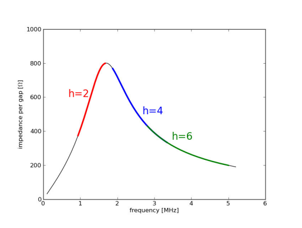
J-PARC top view.

RCS: rapid cycling synchrotron, 300 kW user operation
MR: main ring, 220 kW user operation

J-PARC RCS parameters

circumference	348.333 m
energy	(design) 0.400–3 GeV
	(present) 0.181–3 GeV
beam intensity	(design) 8.3×10^{13} ppp
	(achieved) 4.5×10^{13} ppp
repetition	25 Hz
accelerating frequency	0.938–1.671 MHz
harmonic number	2
maximum rf voltage	(design) 450 kV
	(achieved) 400 kV
No. of cavities	(design) 12
	(installed) 11
Q-value of rf cavity	2

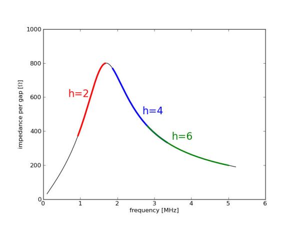
Wide-band ($Q = 2$) MA cavity in RCS



- high accelerating voltage (400 kV maximum by 11 cavities)
- wide-band ($Q = 2$): covers wide accelerating frequency sweep (0.938–1.671 MHz) without tuning bias. Also, bunch shaping by second harmonic is possible

Cavity gap impedance and wake voltage just before extraction (measured by turn off accelerating voltage)

Wide-band ($Q = 2$) MA cavity in RCS



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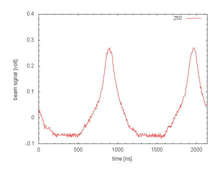
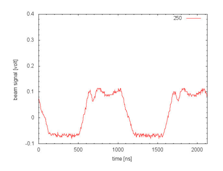
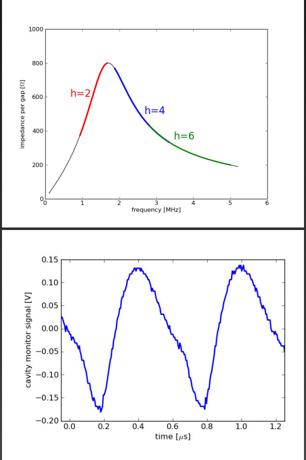




WCM waveform just after injection (left) without and (right) with dual harmonic operation.

- alleviating space-charge effects

Wide-band ($Q = 2$) MA cavity in RCS



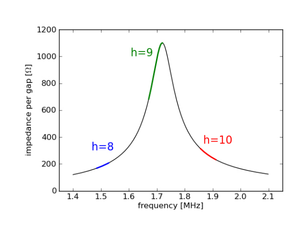
Cavity gap impedance and wake voltage just before extraction (measured by turn off accelerating voltage)

- high accelerating voltage (400 kV maximum by 11 cavities)
- wide-band ($Q = 2$): covers wide accelerating frequency sweep (0.938–1.671 MHz) without tuning bias. Also, bunch shaping by second harmonic is possible
- wake contains higher harmonic components, multiharmonic compensation necessary
- rf feedforward method employed in J-PARC

J-PARC MR parameters

circumference	1567.5 m
energy	3–30 GeV
beam intensity	(achieved) 1.0×10^{14} ppp
accelerating frequency	1.67–1.72 MHz
harmonic number	9
number of bunches	8
maximum rf voltage	280 kV
repetition period	2.56 s
No. of cavities	8
Acc. gaps in a cavity	3
cavity resonant freq	1.72 MHz
Q-value of rf cavity	22

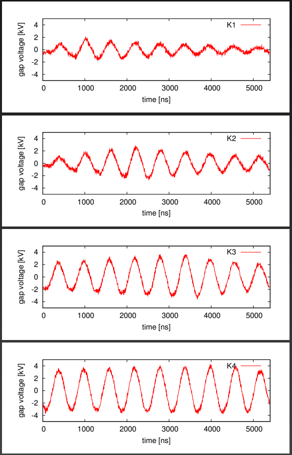
MR cavity ($Q = 22$)



Cavity gap impedance

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

MR cavity ($Q = 22$)



Typical waveform of the wake voltage just after K1–K4 timings. (Top) K1, (second top) K2, (third top) K3, and (bottom) K4 timing.

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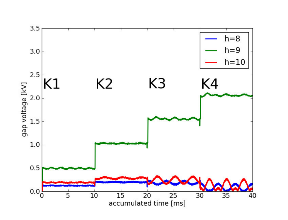

Typical harmonic components of the wake voltage during injection period.

- driven by single harmonic ($h = 9$)
- ($Q = 22$): covers accelerating frequency (1.67–1.72 MHz) and also neighbor harmonics ($h = 8, 10$)
- not all buckets are filled; wake contains accelerating and neighbor harmonic components
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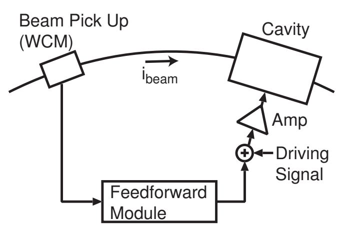
Multiharmonic rf feedforward system

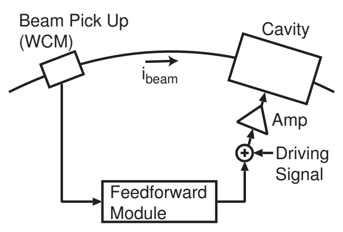


Conceptual diagram of rf feedforward method.

- pick up beam current by WCM
- in addition to driving rf current to generate accelerating voltage, $-i_{beam}$ fed to cavity
  - cancel wake voltage
- wake is multiharmonic; feedforward must be multiharmonic

Multiharmonic feedforward systems have been developed as parts of LLRF control systems for RCS and MR.

Multiharmonic rf feedforward system



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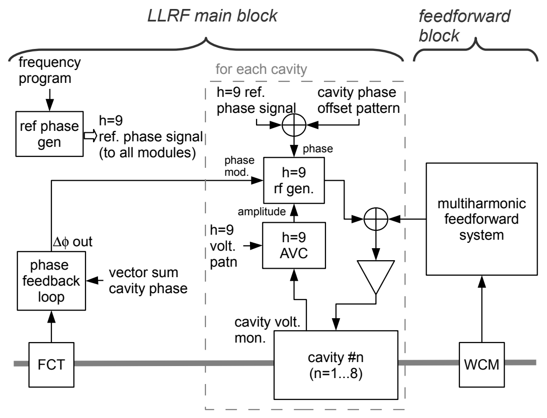
Multiharmonic feedforward systems have been developed as parts of LLRF control systems for RCS and MR.

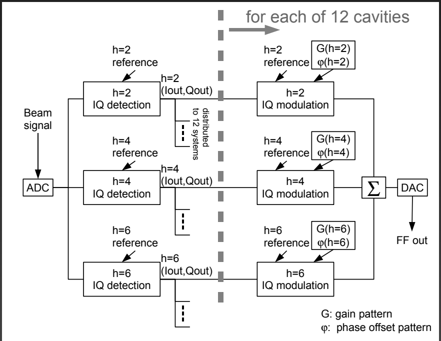
J-PARC LLRF overview



MR LLRF control system block diagram (RCS is similar except dual harmonic AVC).

- fixed clock system (36 MHz)
- frequency pattern, generation of phase reference signal
- no tuning FB
- voltage control
- phase feedback to damp dipole oscillations

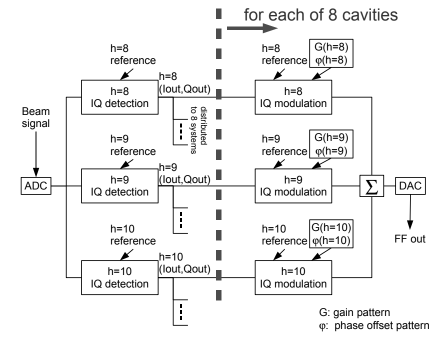
Multiharmonic rf feedforward system (RCS)



Block diagram of feedforward (RCS).

- I/Q vectors $(h = 2, 4, 6)$ are generated from WCM signal
  - phase reference signal by DDS
- distributed to 12 systems
- for each cavity and harmonic, gain and phase patterns are programmed. By I/Q modulation, compensation rf signal generated
- tracking BPF with passbands at $(h = 2, 4, 6)$ with arbitary gain and phase
  - perfect tracking to frequency sweep thanks to DDS

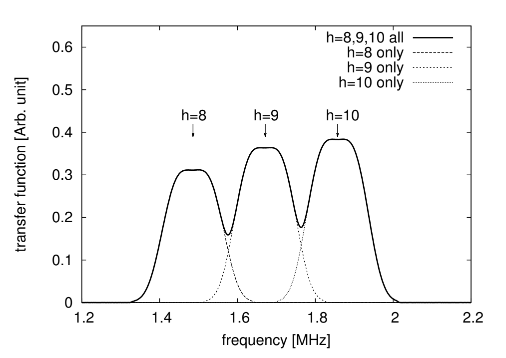
Multiharmonic rf feedforward system (MR)



Block diagram of feedforward (MR).

- similar structure to RCS FF
- for $(h = 8, 9, 10)$
- pattern sampling 0.2 ms (RCS: 1 μs)
  - for longer cycle (2.56 s to 6 s) than RCS (40 ms)

Transfer function of FF system



Typical transfer function of MR system.

- gain and phase of each harmonic are set arbitrary

Commissioning of feedforward

- commissioning of feedforward is adjustments of the gain and phase patterns
- beam test is necessary to adjust the patterns
- it is not trivial work
  - rf parameters (frequency, accelerating voltage, peak beam current, etc.) vary during the acceleration period
- 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

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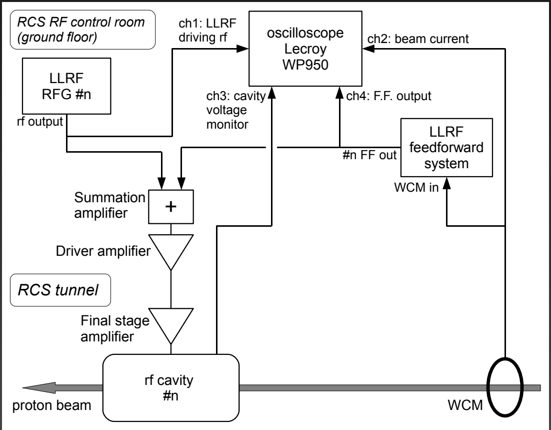
Commissioning setup

Waveforms from injection to extraction are taken.



Test setup, #n is cavity number

Commissioning performed for each cavity.

1. driving rf (ch1)
2. WCM signal (ch2)
3. cavity gap voltage monitor (ch3)
4. FF output (ch4)

- harmonic analysis by PC

Commissioning methodology

Commissioning is performed in frequency domain.

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

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

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

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

($V_{\mathrm{dr}}(h,t)$, $V_{\mathrm{cav}}(h,t)$: complex amplitudes)

Commissioning methodology

Commissioning is performed in frequency domain.

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

$$
\begin{aligned}
V_{\mathrm{cav}}(h,t) &= \\
& V_{\mathrm{cav,dr}}(h,t) + V_{\mathrm{cav,wake}}(h,t) + V_{\mathrm{cav,FF}}(h,t) \\
&= H_{\mathrm{dr}}^{\mathrm{cav}}(h,t) \cdot V_{\mathrm{dr}}(h,t) + Z'_{\mathrm{cav}}(h,t) \cdot I_{\mathrm{beam}}(h,t) \\
&\quad + Z_{\mathrm{FF}}(h,t) \cdot I_{\mathrm{beam}}(h,t)
\end{aligned}
$$

- $Z_{\mathrm{cav}}(h,t)$: cavity impedance under the tube current for generating the accelerating voltage, obtained without FF. Superposition is:

$$
\begin{aligned}
V_{\mathrm{cav}}(h,t) &= V_{\mathrm{cav,dr}}(h,t) + V_{\mathrm{cav,wake}}(h,t) \\
&= H_{\mathrm{dr}}^{\mathrm{cav}}(h,t) \cdot V_{\mathrm{dr}}(h,t) + Z'_{\mathrm{cav}}(h,t) \cdot I_{\mathrm{beam}}(h,t)
\end{aligned}
$$

Commissioning methodology

Commissioning is performed in frequency domain.

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

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

- $Z_{\mathrm{FF}}(h,t)$: transfer function from beam current to FF component
- impedance seen by the beam with FF:

$$Z'_{\mathrm{cav}}(h,t) + Z_{\mathrm{FF}}(h,t)$$

to be minimized

Commissioning methodology

Commissioning is performed in frequency domain.

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

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\begin{aligned}
&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}}_{\text{dr}}(h,t) \cdot V_{\text{dr}}(h,t) + Z'_{\text{cav}}(h,t) \cdot I_{\text{beam}}(h,t) \\
&\quad + Z_{\text{FF}}(h,t) \cdot I_{\text{beam}}(h,t)
\end{aligned}
$$

- pattern corrected so that

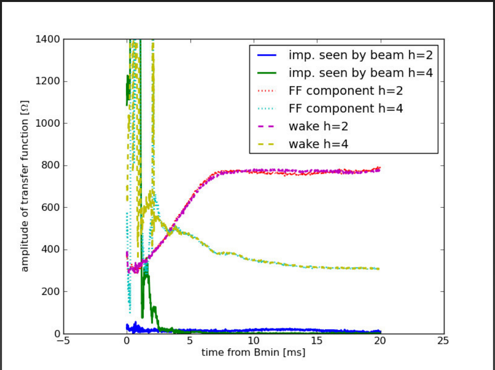
$$
\begin{aligned}
|Z_{\text{FF}}(h,t)| &= |Z'_{\text{cav}}(h,t)| \\
\text{Arg}(Z_{\text{FF}}(h,t)) &= -\text{Arg}(Z'_{\text{cav}}(h,t))
\end{aligned}
$$

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

RCS commissioning results

Commissioned by using 300 kW equivalent (2.5×10^{13} ppp)

Cavity impedance $Z'_{\mathrm{cav}}(h, t)$, FF transfer function $Z_{\mathrm{FF}}(h, t)$, impedance seen by the beam $Z'_{\mathrm{cav}}(h, t) + Z_{\mathrm{FF}}(h, t)$ (amplitude)

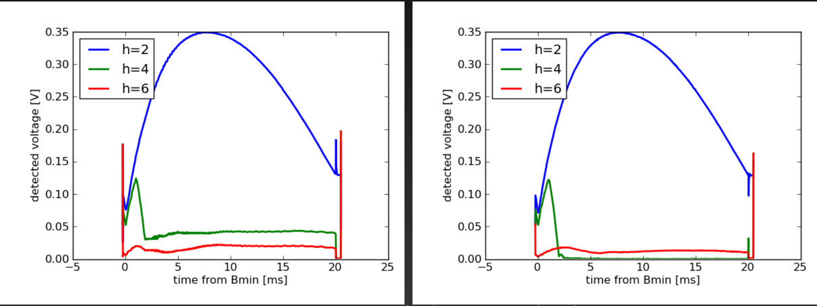


Comparison of impedances and transfer functions, time variation.

- impedance seen by the beam: less than 25 Ω
  - shunt resistance $\sim 800\Omega$: reduced to $1/30$

RCS commissioning results

cavity voltage without / with feedforward

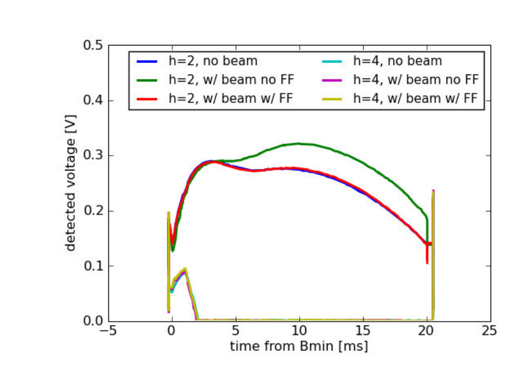


Harmonic components of cavity #1 voltage monitor, (left) without FF, (right) with FF after commissioning.

- fundamental accelerating harmonic is same because of AVC
- fairly good suppression of second harmonic, limited in case of the third

RCS commissioning results

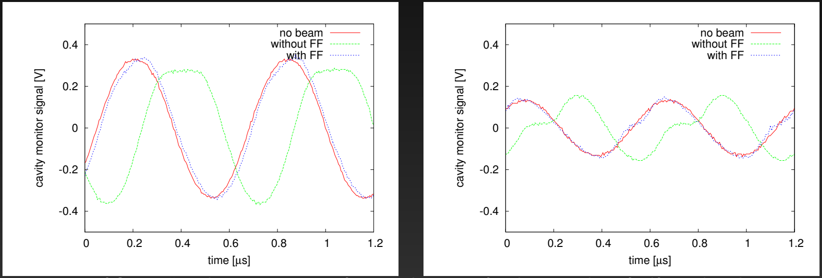
Harmonic components of LLRF driving signal



A comparison of the driving rf voltage of no beam, without and with the feedforward. The cases of no beam and with feedforward are very close.

- by FF, the load seen by LLRF AVC is close to the case of no beam

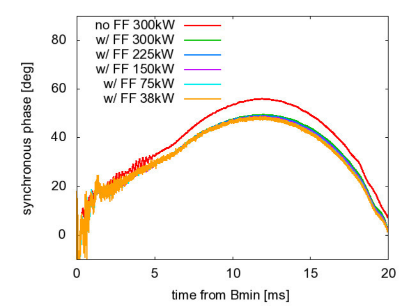
RCS commissioning results



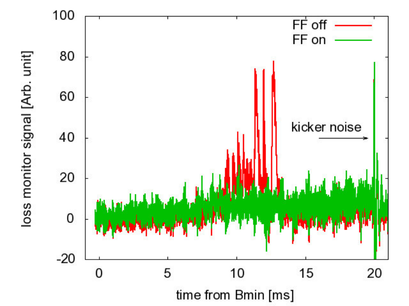
comparisons of Cavity #1 voltage monitor waveforms in the cases of no beam, without feedforward, with feedforward. The beam intensity is 300 kW equivalent. (Left) middle of acceleration period and (right) just before extraction.

- distortion reduced, waveform with FF is close to the case of no beam
- phase delay, which corresponds to the loading angle, is reduced

Reduction of beam loss at arc



Comparison of ϕ_s without and with FF

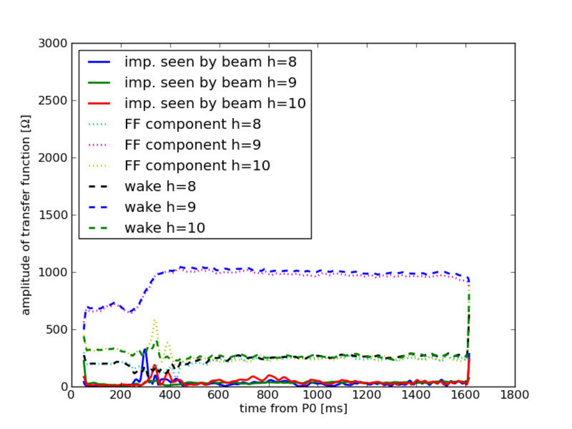


Beam loss monitor signal at arc section with 300 kW equivalent beam.

- ϕ_s deviation due to distortion by the higher harmonic. With FF, ϕ_s is independent of beam power
- Rf bucket become larger, small loss at the arc section disappeared

MR commissioning results

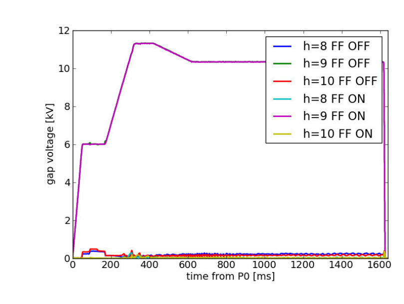
1.0×10^{14} ppp beam is used for commissioning.



Comparison of impedance seen by the beam

- Reduced impedance

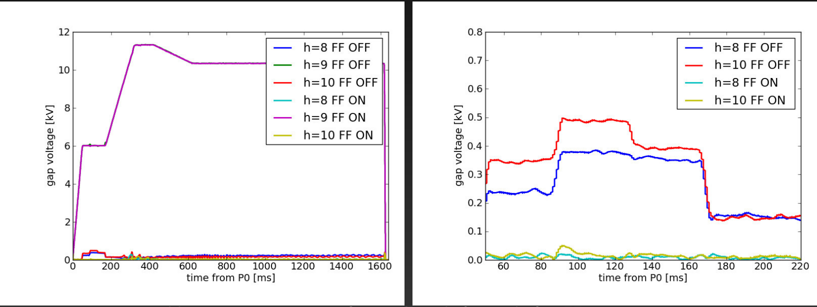
MR commissioning results



Typical harmonic components of gap voltage before and after FF commissioning.

- accelerating harmonic ($h = 9$): controlled by AVC, same
- neighbor harmonics ($h = 8, 10$): suppressed by FF

MR commissioning results



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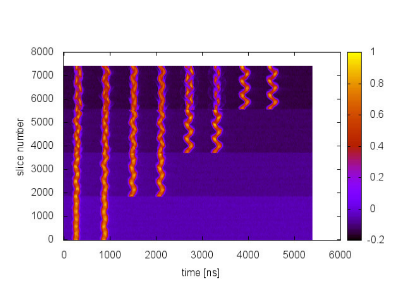
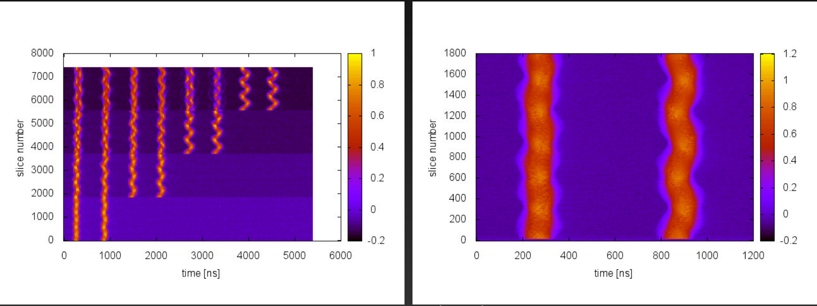
FF OFF, injection period



Mountain plots of WCM during injection period without FF. (Right) magnified view just after K1 injection timing.

- rf voltage phase jumps corresponding to the loading angle at every injection make dipole oscillation (especially K3, K4)
- by periodic transient effects the oscillation of forward and rear bunches are different

FF OFF, injection period



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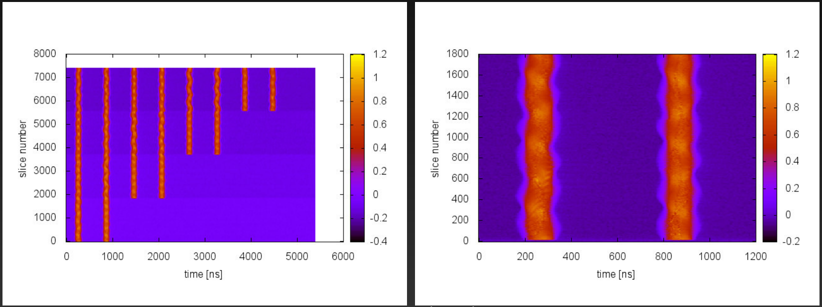
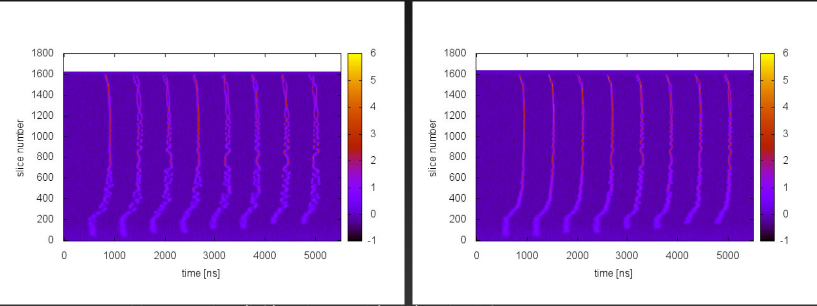


Mountain plots of WCM during injection period with FF. (Right) magnified view just after K1 injection timing.

- 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

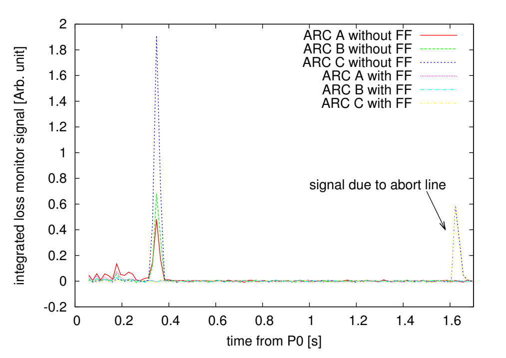
Full accelerating period



Mountain plots (left) without and (right) with FF from injection to extraction.

- oscillation reduced throughout the accelerating period

Beam loss reduced by FF



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

- beam losses in the arc sections due to large amplitude dipole oscillation disappeared
- more than 200 kW operation is now possible

Summary and outlook

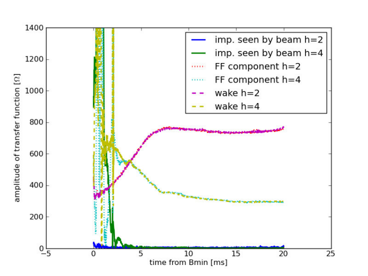
- multiharmonic feedforward system developed for RCS and MR
- commissioning methodology established
- feedforward compensation is now indispensable for high beam power operation

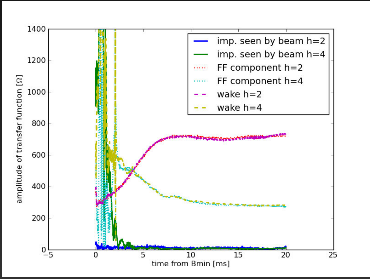
For higher beam power, the commissioning methodology is expected to work.

More details in:
RCS: F. Tamura, et al.: Phys. Rev. ST Accel. Beams, 14, 051004 (2011)
MR: F. Tamura, et al.: Phys. Rev. ST Accel. Beams, 16, 051002 (2013)

Backups

Comments on stability

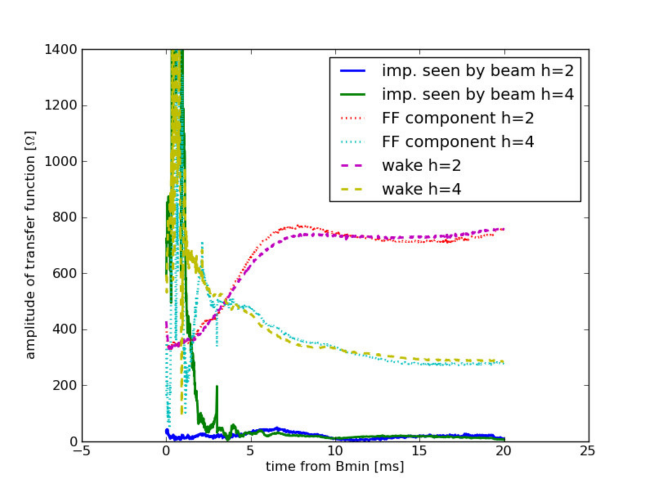




Left: June 2010, right: March 2011, using same pattern.

- adjusted pattern can be used for long time
  - stable digital FF system, amplifier, cavity
  - necessary in case of MA core replacement and voltage pattern change

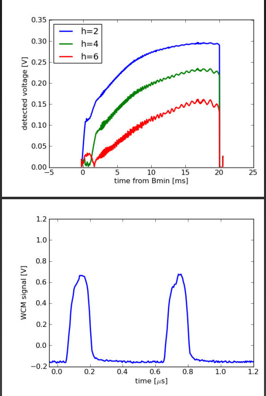
Power dependence



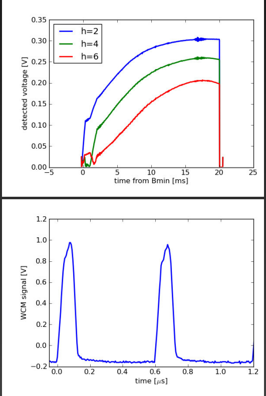
Impedances for 400 kW beam using pattern adjusted by 300 kW beam.

- No re-adjustment necessary for 400 kW beam

Reduction of uncontrolled emittance blowup



Beam current without FF.

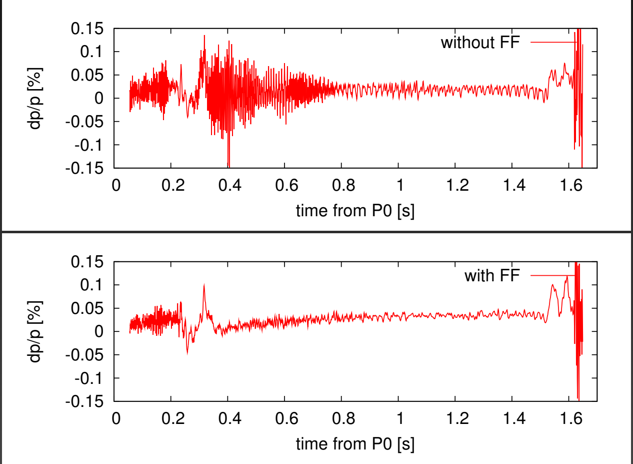


Beam current with FF.

- Beam sees accelerating voltage as programmed
- Reduction of oscillations of the harmonics; uncontrolled emittance blowup reduced → Extracted bunch become narrow

dp/p without and with FF

dp/p calculated by BPM signal:



dp/p from injection to extraction Without FF (top) and with FF (bottom)

oscillation reduced with FF.