Acceleration of High-Intensity Protons in the J-PARC Synchrotrons

KEK/JAEA J-PARC
M. Yoshii

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Introduction

1. J-PARC consists of 181 MeV Linac, 3 GeV Rapid Cycling Synchrotron (RCS) and 50 GeV Main synchrotron Ring (MR).
2. High Intensity Proton Facility:

	RCS	**MR**
Intensity (ppp)	8.3×10^{13}	3.4×10^{14}
Output Beam Power	1 MW	0.73 MW

- 100 times higher than the intensity of KEK-PS (1976-2007)

Features

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to avoid unwanted beam loss during acceleration.

RCS : a high $\gamma_t \rightarrow 9.14$

MR: an imaginary $\gamma_t \rightarrow j31.6$

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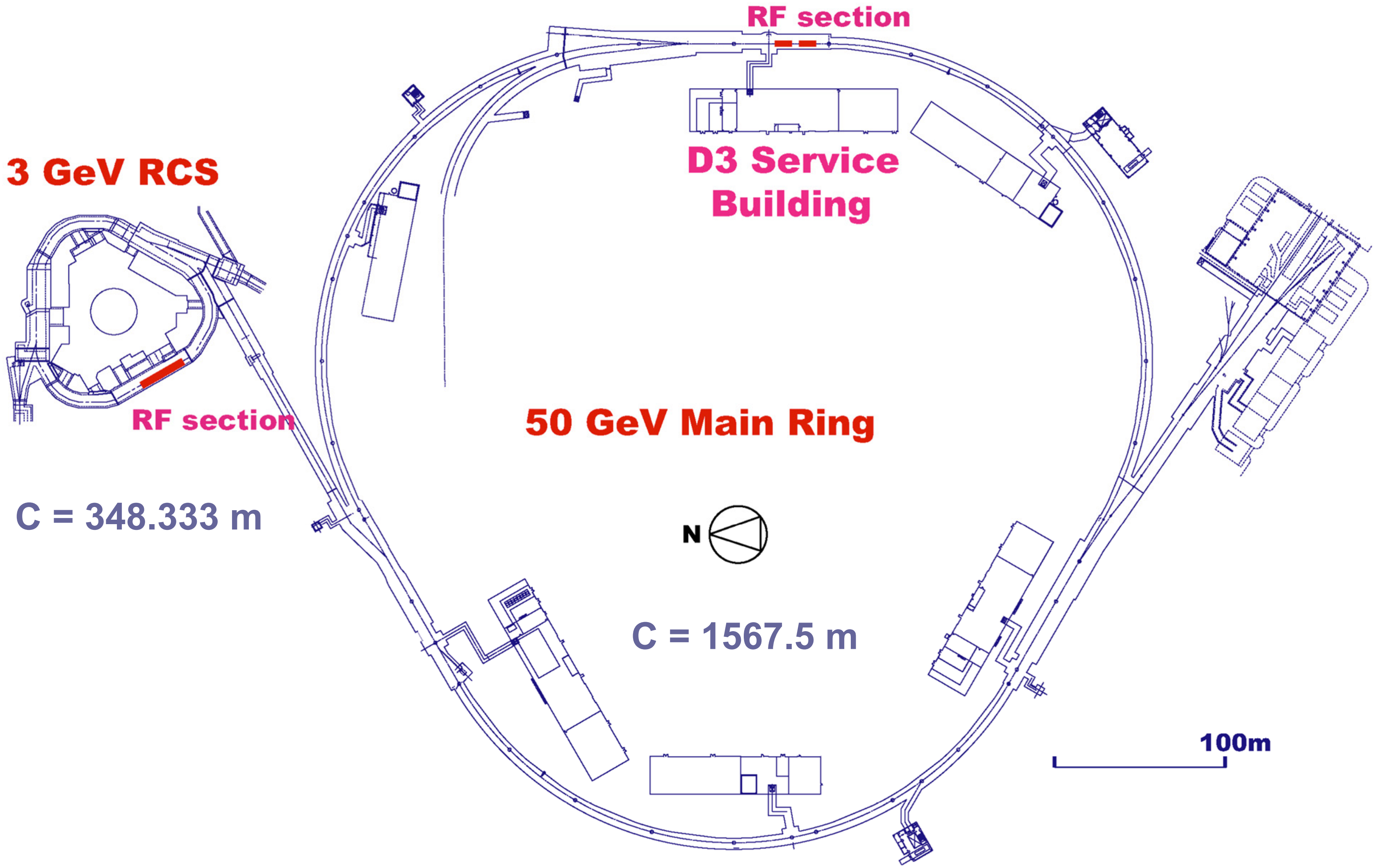
3. **Magnetic alloy loaded cavity with a full digital LLRF**

   to achieve high field gradient system (20kV/m)

   to realize precise and reproducible fine longitudinal control

Locations of the RCS and MR RF Stations



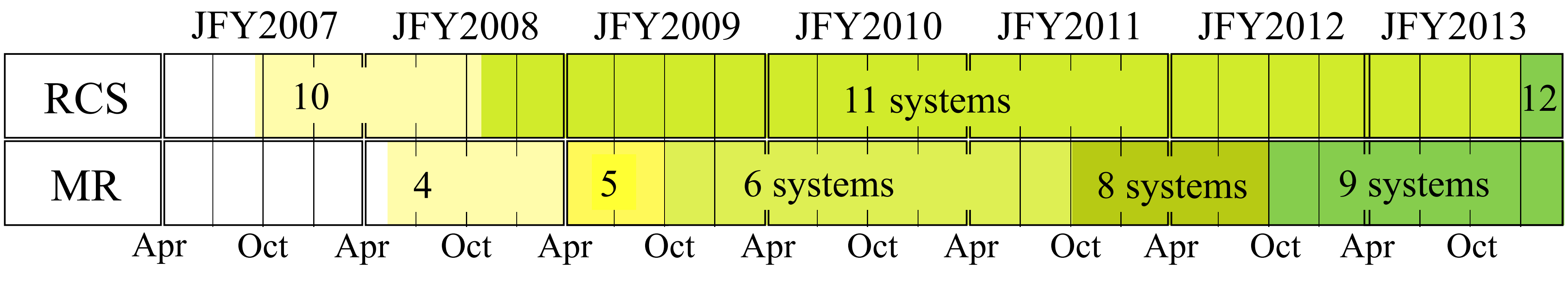
RF systems are located the place where is the lowest radiation level for hands-on maintenance.

Beam Commissioning

1. RCS beam commissioning started in October 2007 with 10 RF systems. Protons were accelerated successfully up to 3 GeV in 31 October 2007.

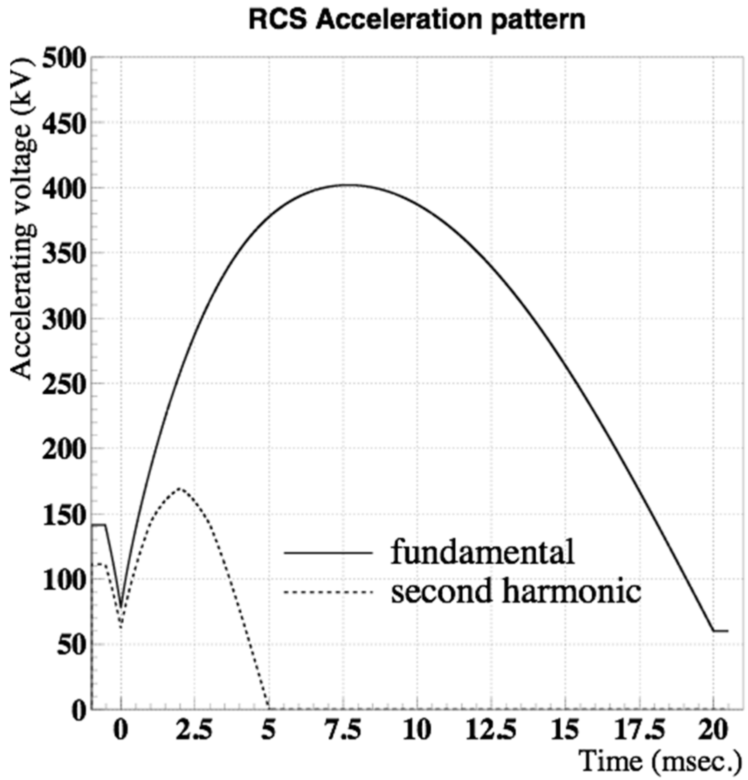
2. MR beam commissioning started with 4 RF stations in May 2008. Proton beam acceleration started in December 2008. Protons were successfully accelerated up to 30GeV in 23 December 2008.

3. The RF systems were upgraded every year.



RCS beam commissioning

Energy	181MeV - 3GeV
Intensity	2.5 x 10^{13} ppp
Power	300 kW
harmonics / N_b	2 / 2
Frequency	0.938 - 1.67 MHz
# of cavities	11
Peak V_{acc}	400 kV
Cycle	25 Hz



1. RCS rf system: Q ~ 2, dual-harmonic (h=2, 4) operation.

2. radial feedback: not closed, because it is not necessary.

- stable and reproducible Linac energy and RCS dipole field

- frequency pattern is modified offline.

3. phase feedback: closed for high intensity operation

4. Multi-harmonic RF Feed-forward: ON for each of the cavities.

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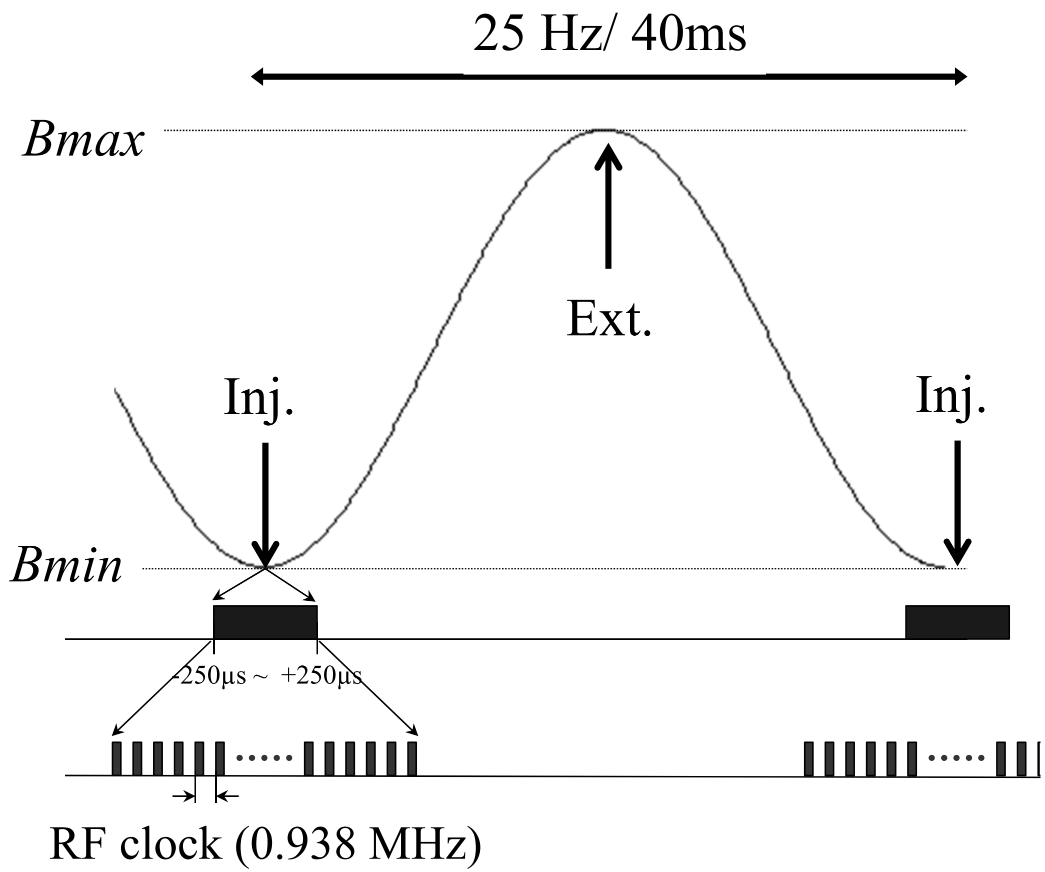
"Simulation of longitudinal beam manipulation during multi-turn injection in J-PARC RCS" M. Yamamoto

Beam Injection from the Linac

Linac Beam Pulse : 15 mA, 500μs
dp/p , ±0.03 %

- Chopping by the RCS RF clock
- Chopped pulses are injected into the RCS RF waiting bucket

○ minimize beam loss during bunching process

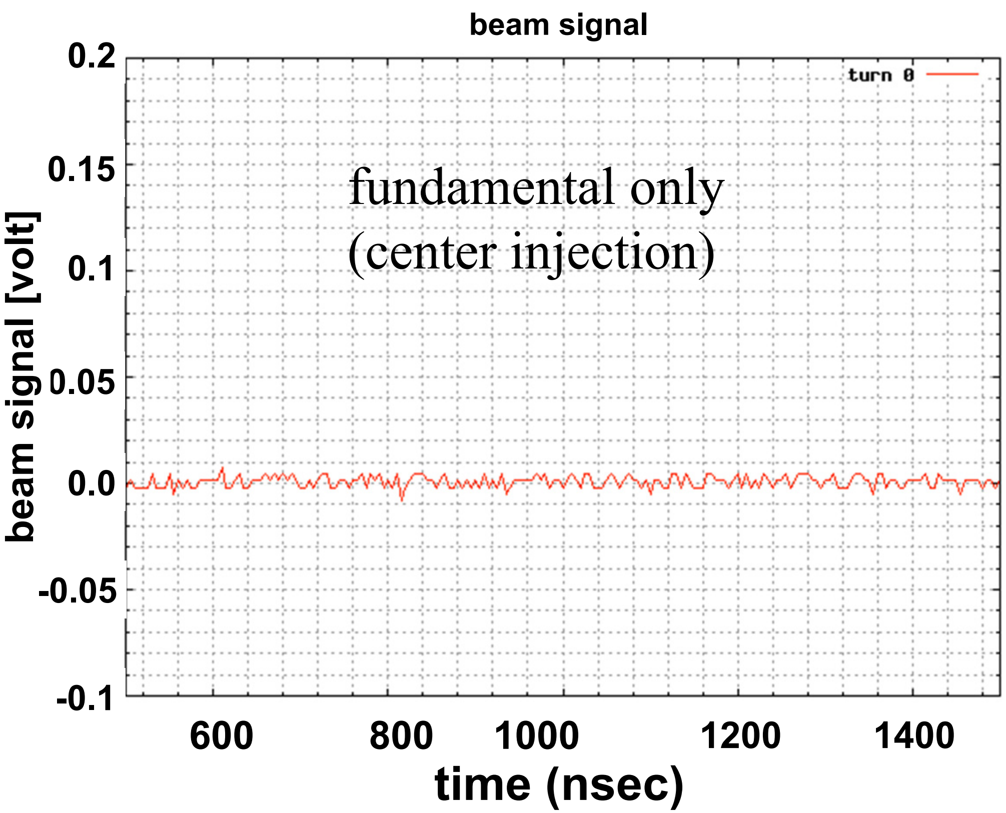


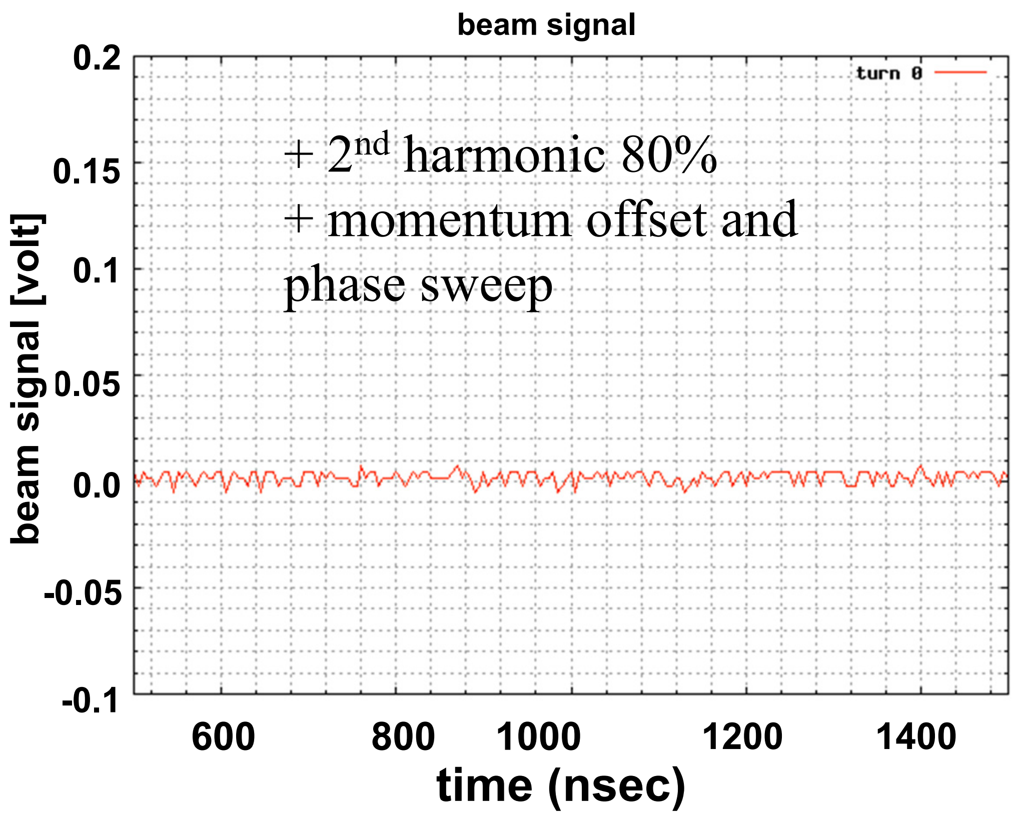
- Momentum offset
- Amplitude control for 2nd harmonic RF
- 2nd harmonic phase sweep

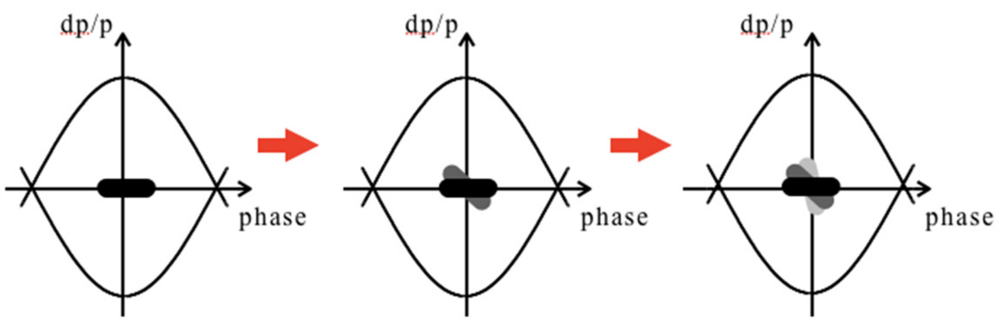
○ increase bunching factor
○ $B_f > 0.4$ required

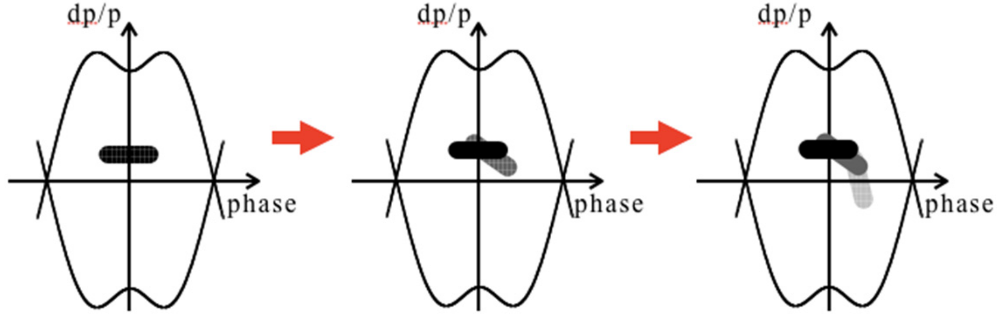
Longitudinal painting at J-PARC RCS injection

longitudinal painting using 2nd harmonic voltages





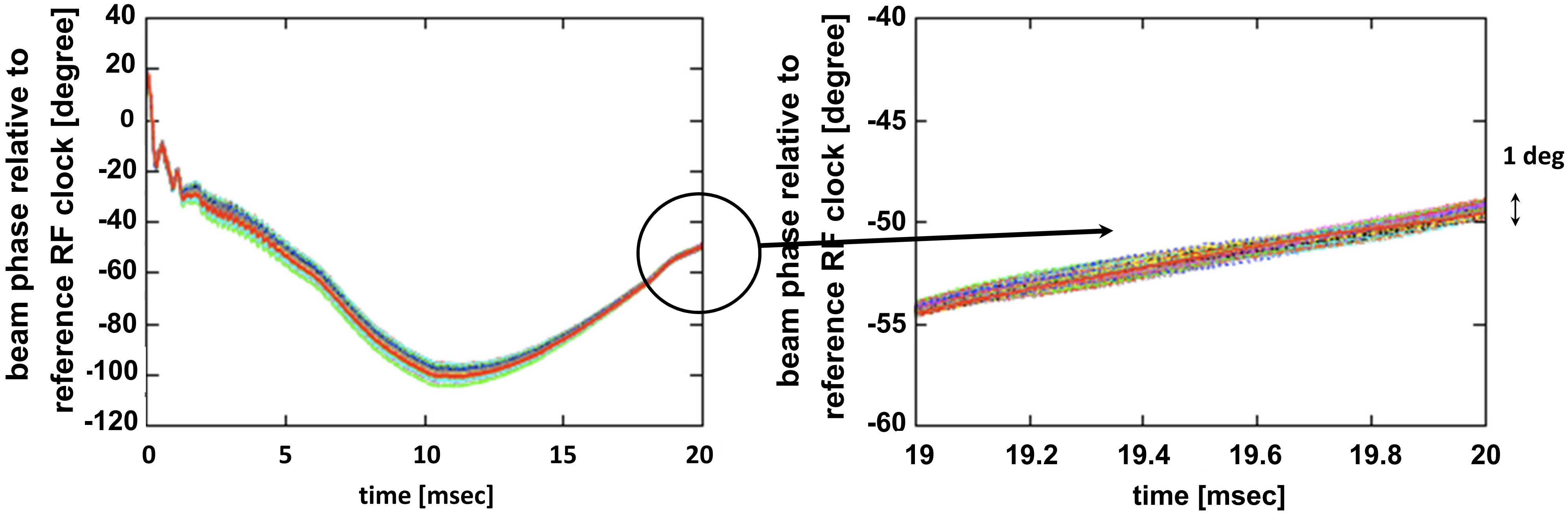




Stable acceleration of 300kW beams in RCS

1. non AC-line synched timing system
2. no radial feedback

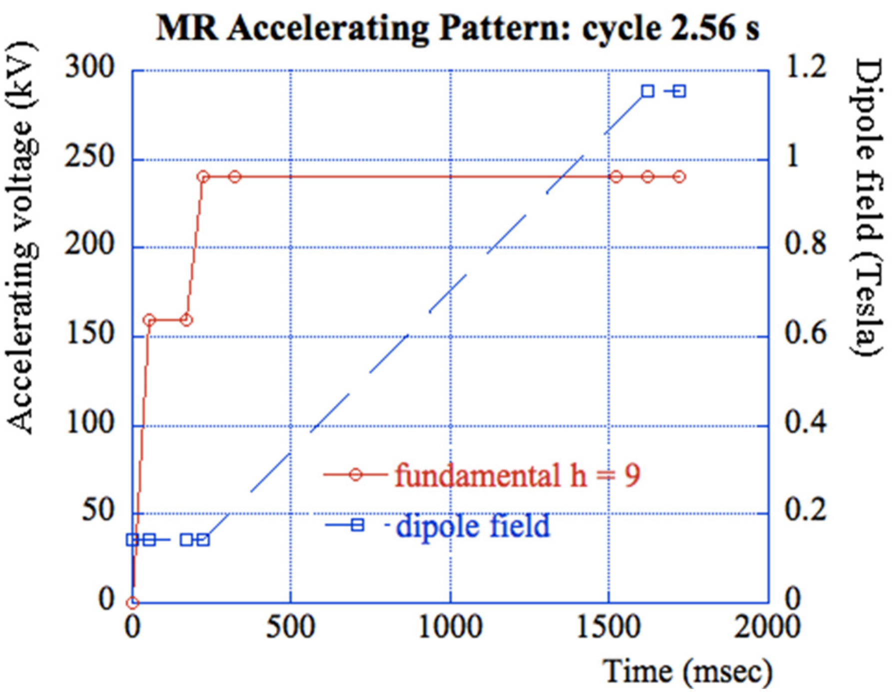
Ultra low-jitter extraction (jitter full width: 1deg = 1.7nsec)



Beam phase plot during 1-hour 300kW operation (190 shots plotted). Right: magnified (19 - 20ms).

MR beam commissioning

Energy	3 - 30 GeV
Intensity	1.1 x 10^{14} ppp
Power	210 kW
harmonics / N_b	9 / 8
Frequency	1.67 - 1.72 MHz
# of cavities	7
Peak V_{acc}	240 kV
Repetition (period)	2.56 s
Accel. time	1.4 s



1. MR rf system: Q ~ 25

Fundamental and 2nd harmonic systems are separated.

2. radial feedback: not closed, because it is not necessary.

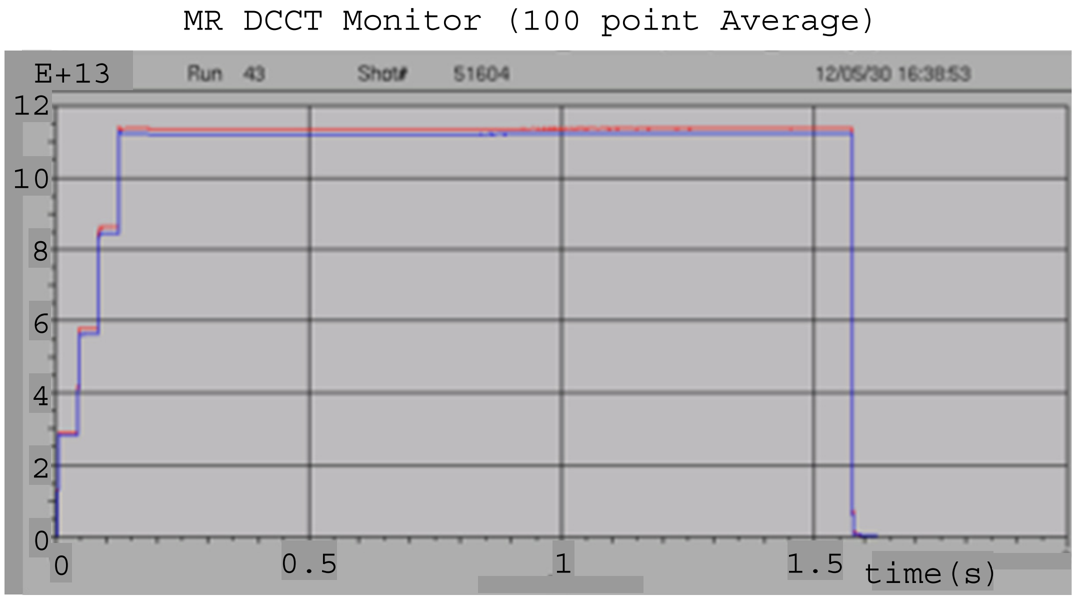
- stable and reproducible RCS energy and MR dipole field

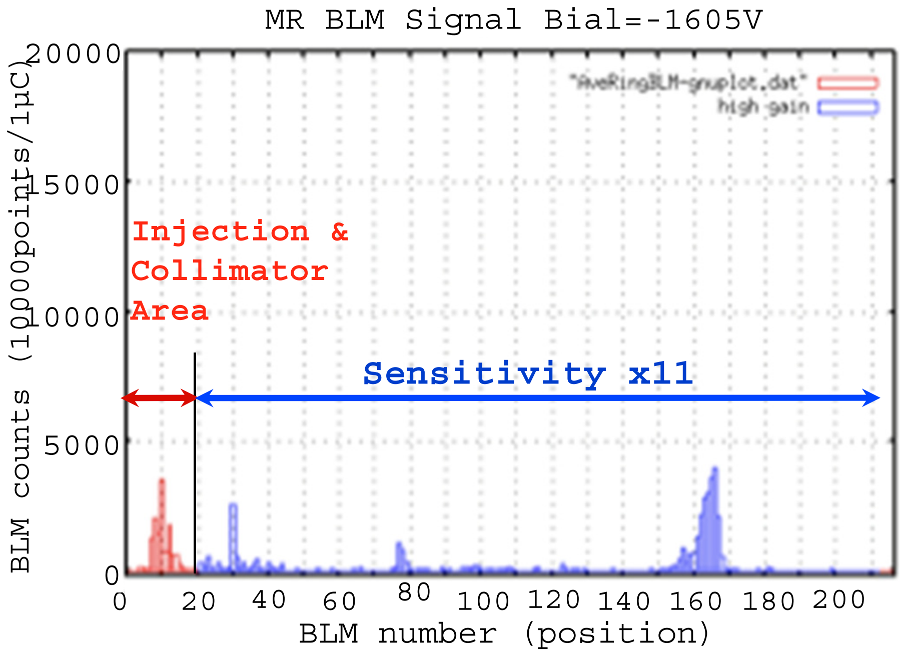
- frequency pattern is modified offline.

3. phase feedback: closed.

4. Multi-harmonic RF Feed-forward: ON for each of the cavities.

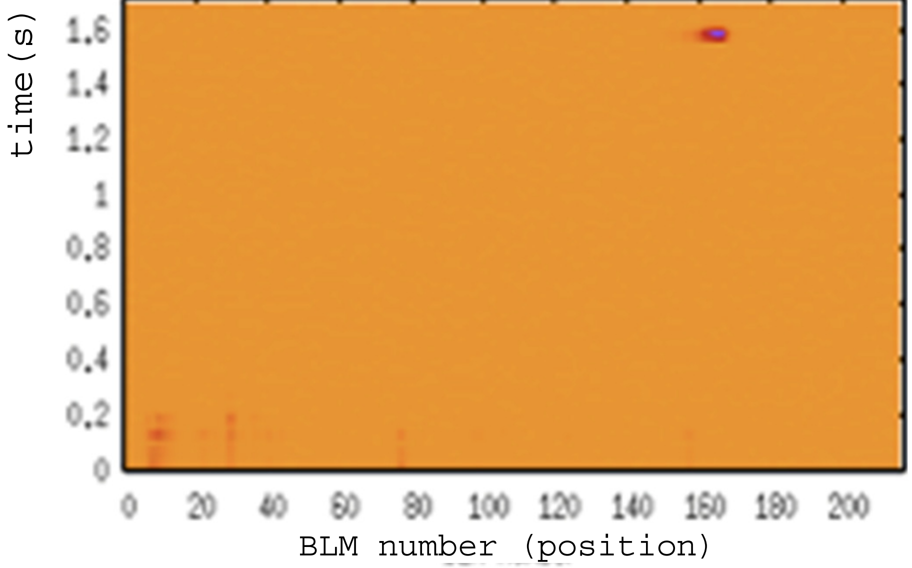
Demonstration of 210kW equivalent operation





Demonstration of 210 kW eq. beam operation

- Extracted beam is 1.14 x10^{14} ppp ~ 213 kW at 2.56 s cycle
- Measured beam loss is 410 ~ 520 W in the 210 kW operation.



2^{nd} harmonic RF effect on MR beam

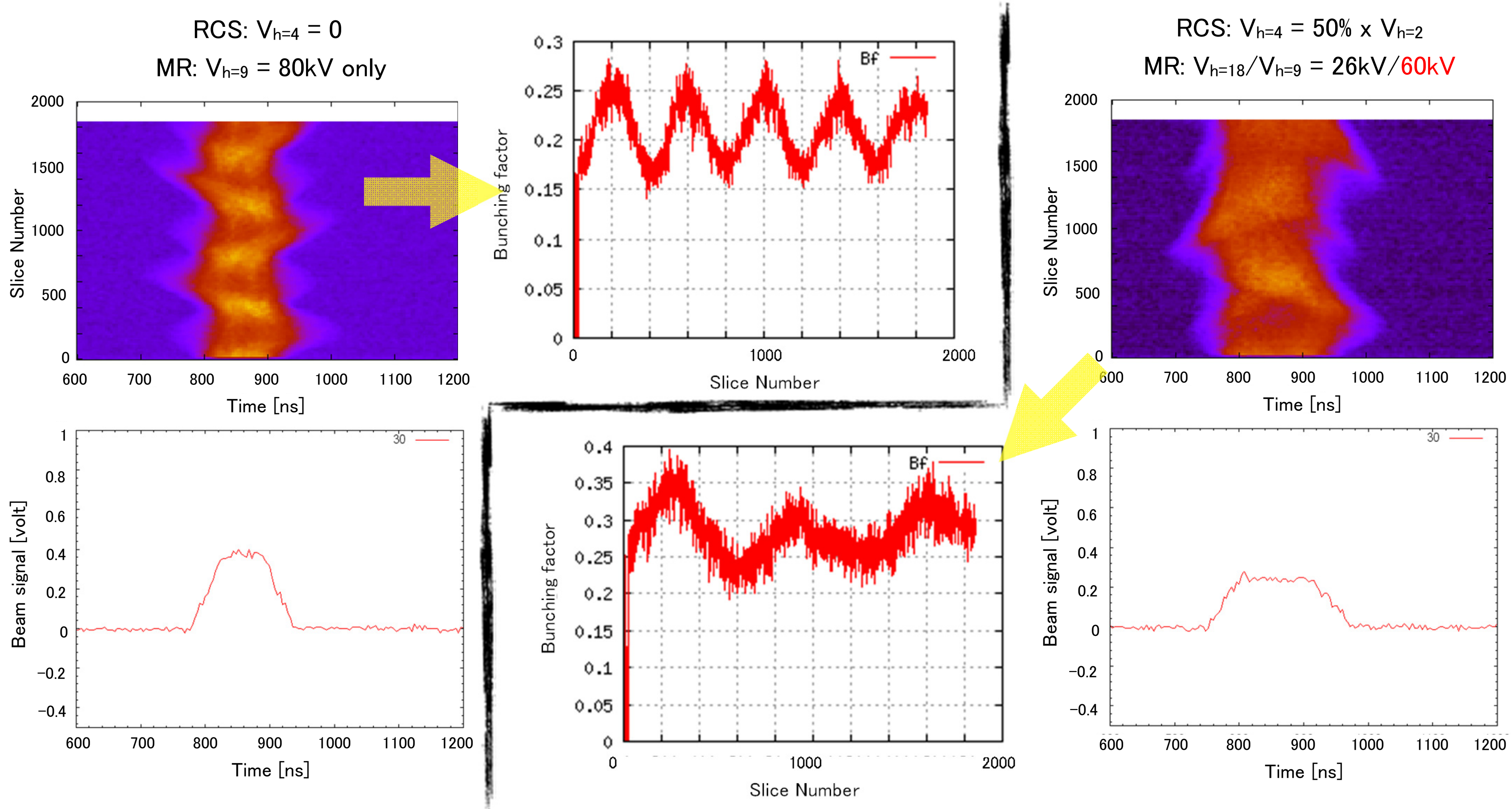
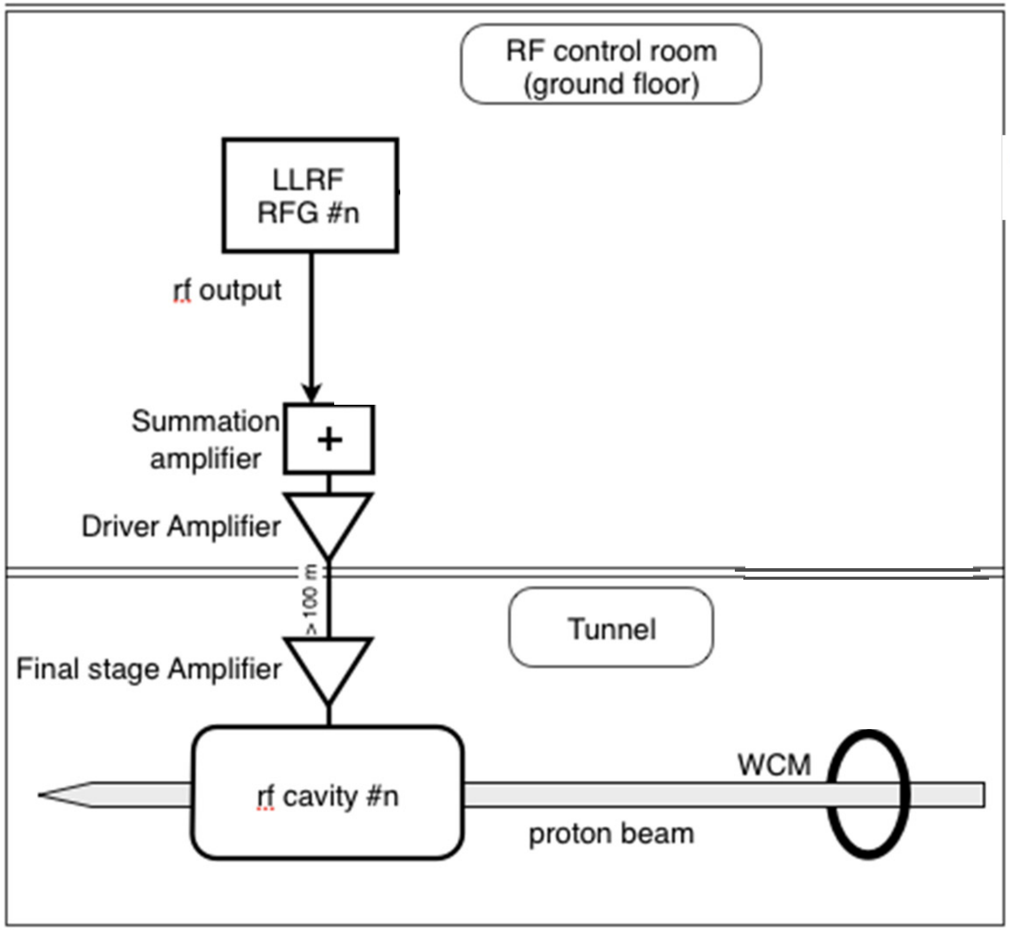


FIGURE: Mountain view, bunching factor and bunch shape at MR injection - 2^{nd} harmonic operation at RCS extraction and 2^{nd} harmonic system at MR injection work fine.

Block view of the Multi-harmonic RF Feedforward

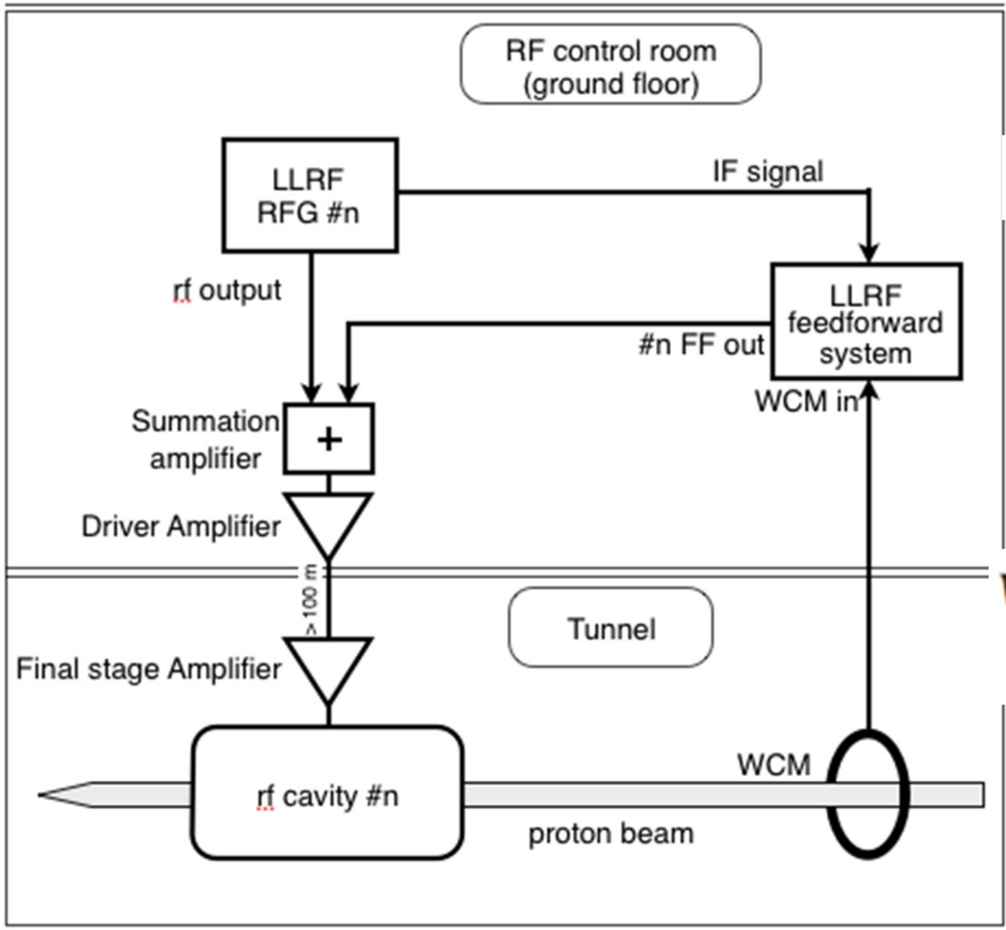


- without feedforward

$$V_{\mathrm{cav}}(h,t) = H_{\mathrm{dr}}^{\mathrm{cav}}(h,t) \cdot V_{\mathrm{dr}}(h,t) + Z_{\mathrm{cav}}^{l}(h,t) \cdot I_{\mathrm{beam}}(h,t)$$

The commissioning of the feedforward system is performed for each of the cavities. In the figure, #N is the cavity number.

Block view of the Multi-harmonic RF Feedforward



- without feedforward

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

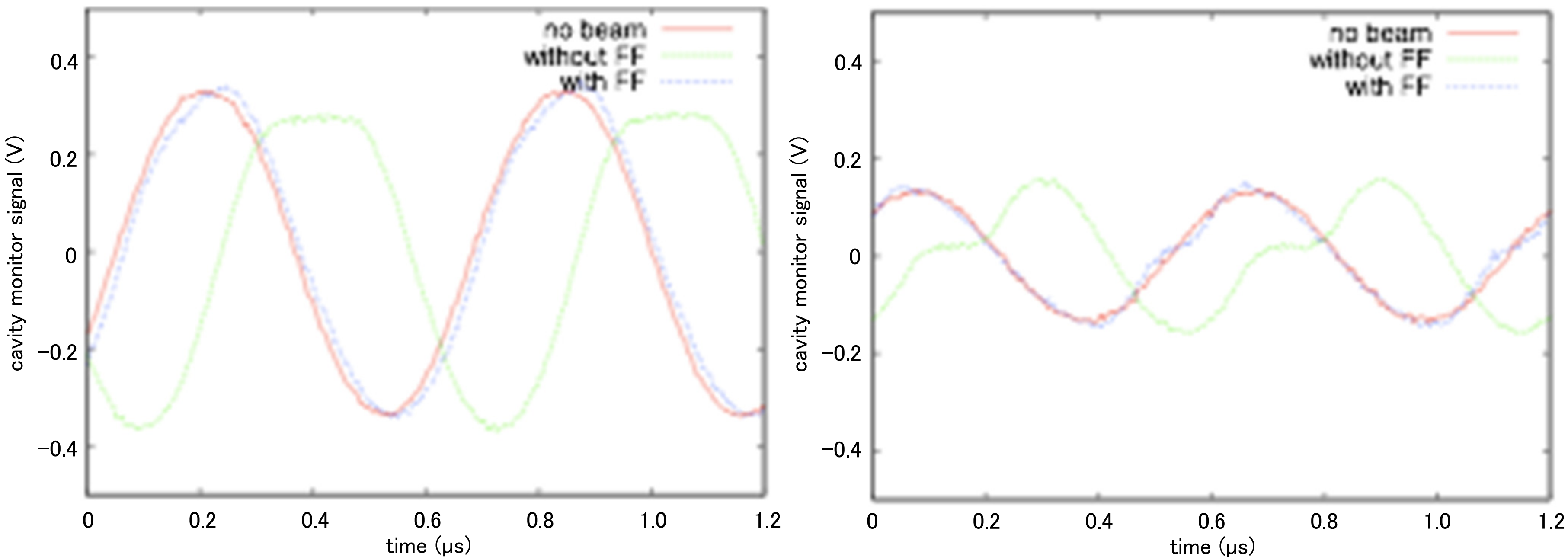
- with feedforward

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

$$Z_{\mathrm{FF}}(h,t) = -Z_{\mathrm{cav}}(h,t).$$

The commissioning of the feedforward system is performed for each of the cavities. In the figure, #N is the cavity number.

Comparisons of voltage monitor waveforms: in the cases of no beam, w/o and w/ feedforward



The beam intensity is 300 kW equivalent—(left) middle of acceleration period and (right) just before extraction. The distortion of the voltage waveform is reduced.

Beam loading compensation by multi-harmonic RF feedforward

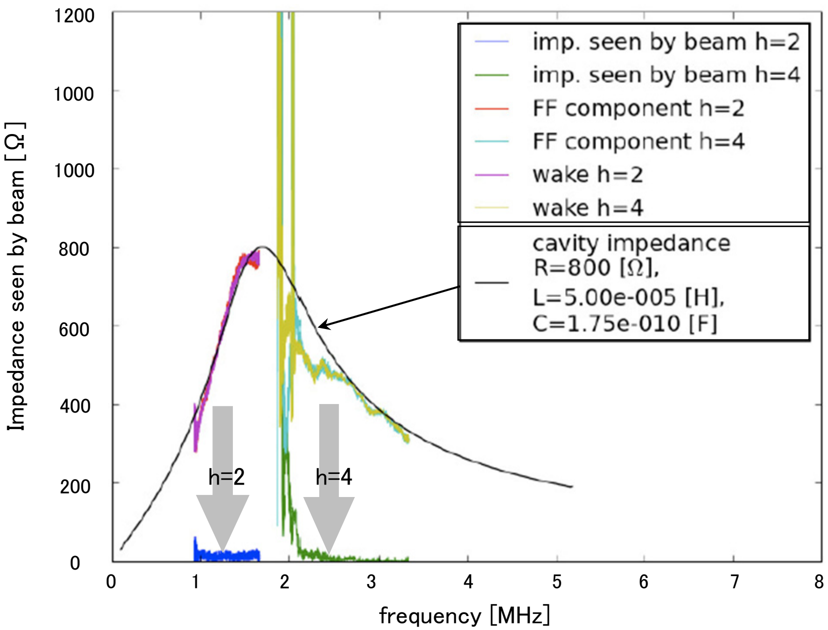


FIGURE: Frequency-domain Impedance seen by the beam:
(RCS cavity#1)

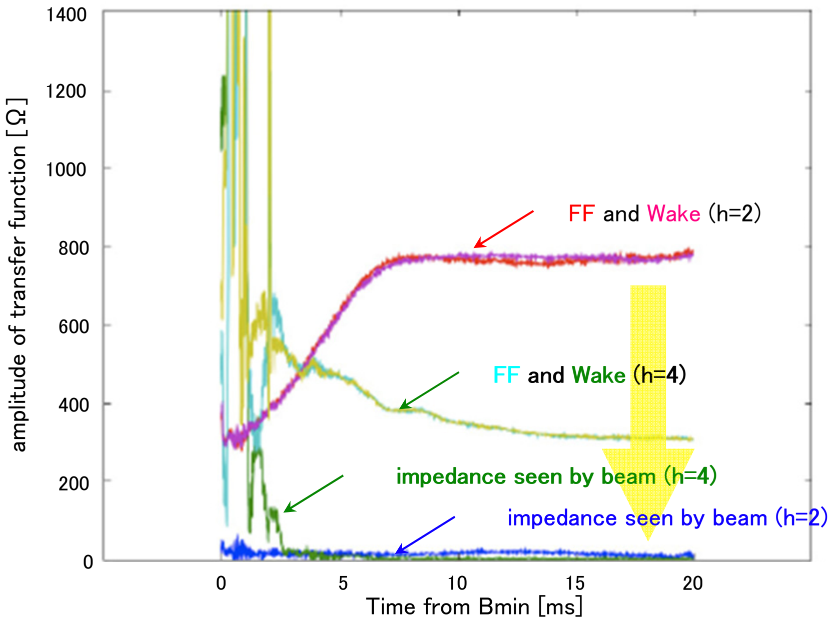


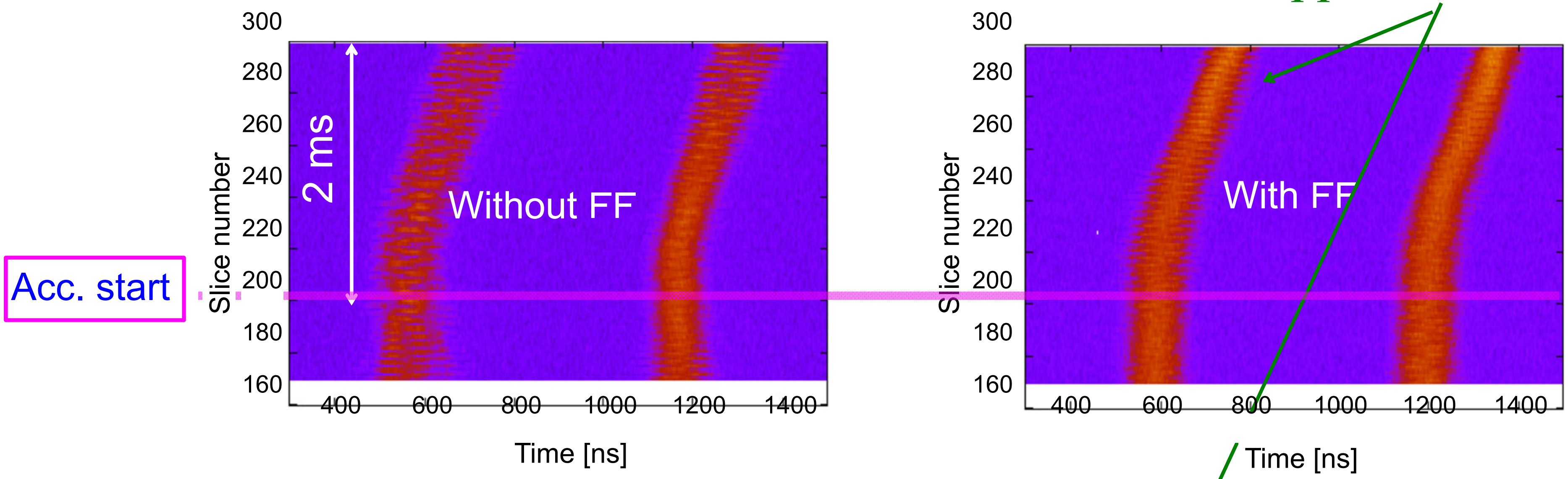
FIGURE: Time-domain Impedance seen by the beam:
(RCS cavity#1)

Impedance at RCS extraction is reduced from 788Ω to 10Ω.

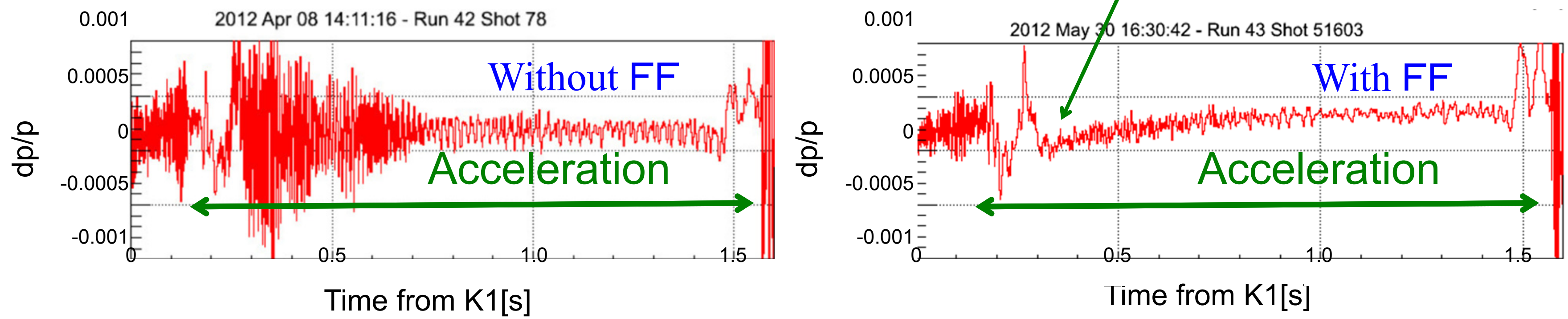
Beam loading compensation in MR

Mountain Plots of injection beam (2 bunches)

Longitudinal oscillation during the acceleration suppressed with FF



dp/p measured by BPM



Summary

• Transition-free lattice and non AC-line synched timing system allow to realize clean and high quality beam operation, which also owes to the stabilities of the Linac energy and Bending field of both synchrotrons.

• By using the MA loaded RF systems,

✓ more than 20 kV/m of high field gradient

✓ Dual harmonic operation in the RCS

✓ No radial tuning loop and the full digital LLRF offer simple, precise and reproducible longitudinal beam control.

✓ Time-jitter of extracted beam from the RCS is only 1.7 ns. Scheduled extraction is possible to the Fermi chopper at the MLF facility.

• Multi-harmonic RF feedforward system has been developed to compensate a heavy beam loading.

✓ The systems are used for the routine operations at RCS and MR and reproducible and offer an excellent suppression of impedance seen by the beam.