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

KEK/J-PARC
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Introduction

1. J-PARC consists of 400 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

1. **Transition-free lattice**

   to avoid unwanted beam loss during acceleration.

   RCS : a high $\gamma_t = 9.14 > 3$

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

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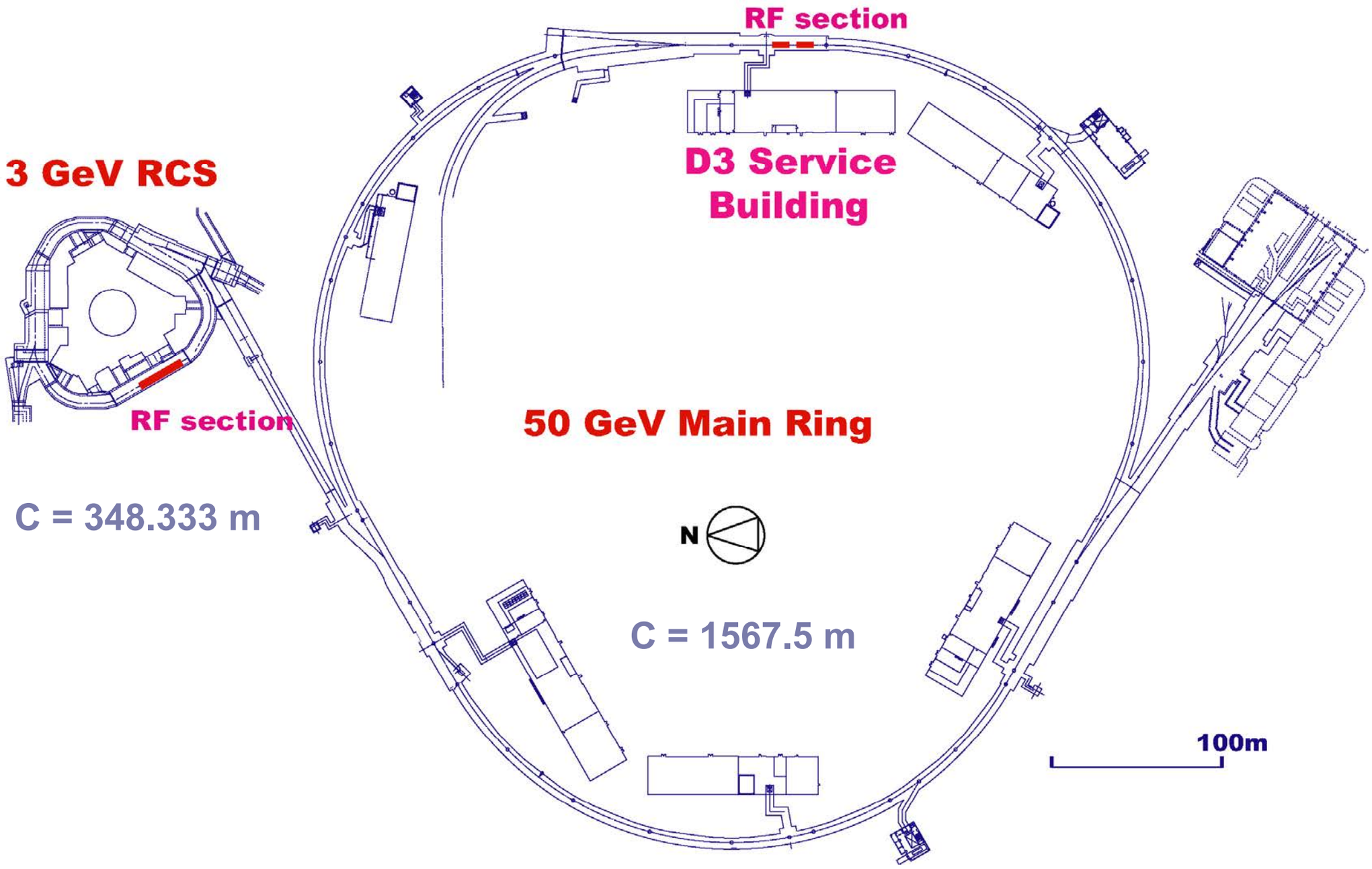
3. Magnetic alloy loaded cavity with a full digital LLRF

> achieved high field gradient system (20kV/m)

> realized precise and reproducible fine longitudinal control

Locations of the RCS and MR RF Stations

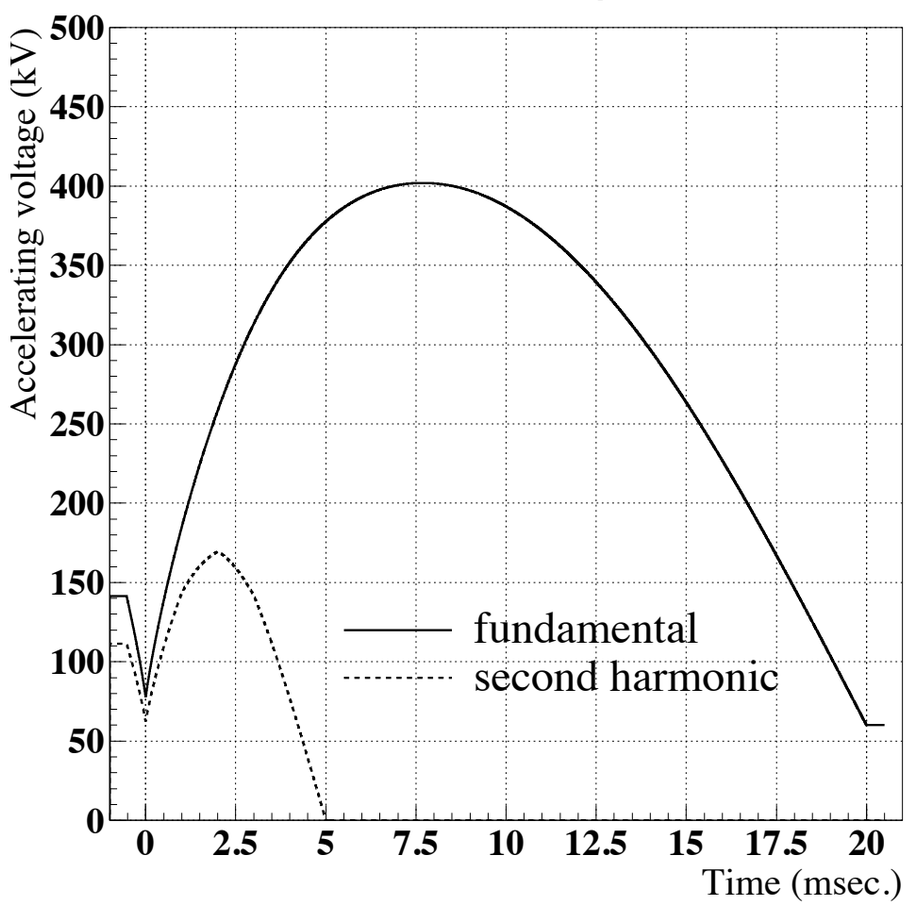


RF systems are located the place where is the lowest radiation level for hands-on maintenance.

RCS beam commissioning

Energy	400MeV - 3GeV
Intensity	8.3 x 10^{13} ppp
Power	1000 kW
harmonics / N_b	2 / 2
Frequency	1.23 - 1.67 MHz
# of cavities	12
Peak V_{acc}	450 kV
Cycle	25 Hz

RCS Acceleration pattern



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.

Nuclear Instruments and Methods in Physics Research A 621 (2010) 15–32,
"Simulation of longitudinal beam manipulation during multi-turn injection in J-PARC RCS" M. Yamamoto

Beam Injection from the Linac

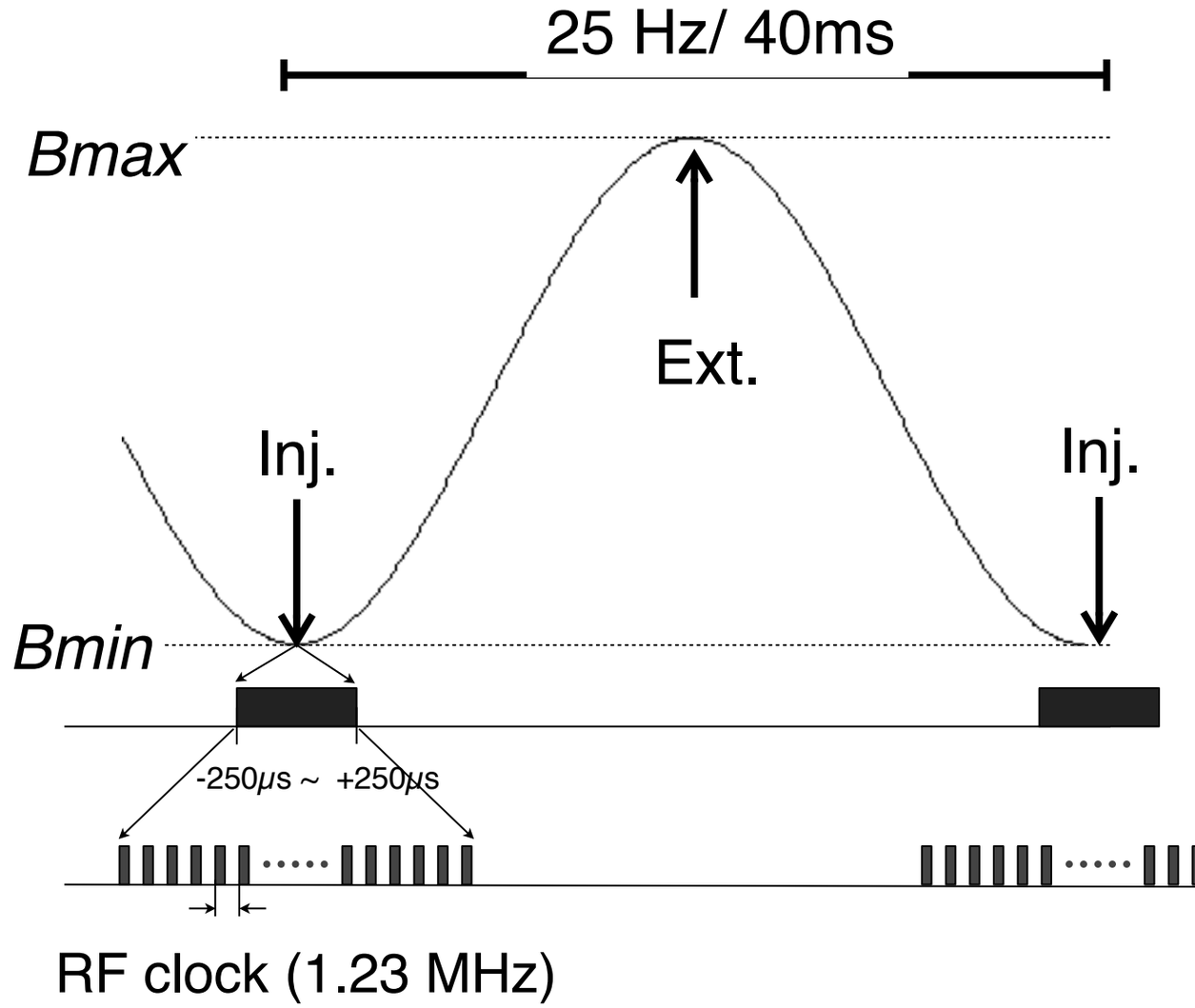
Linac Beam Pulse : 40 mA, 500μs
dp/p , ±0.03 %

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

➡ minimize beam loss during bunching process

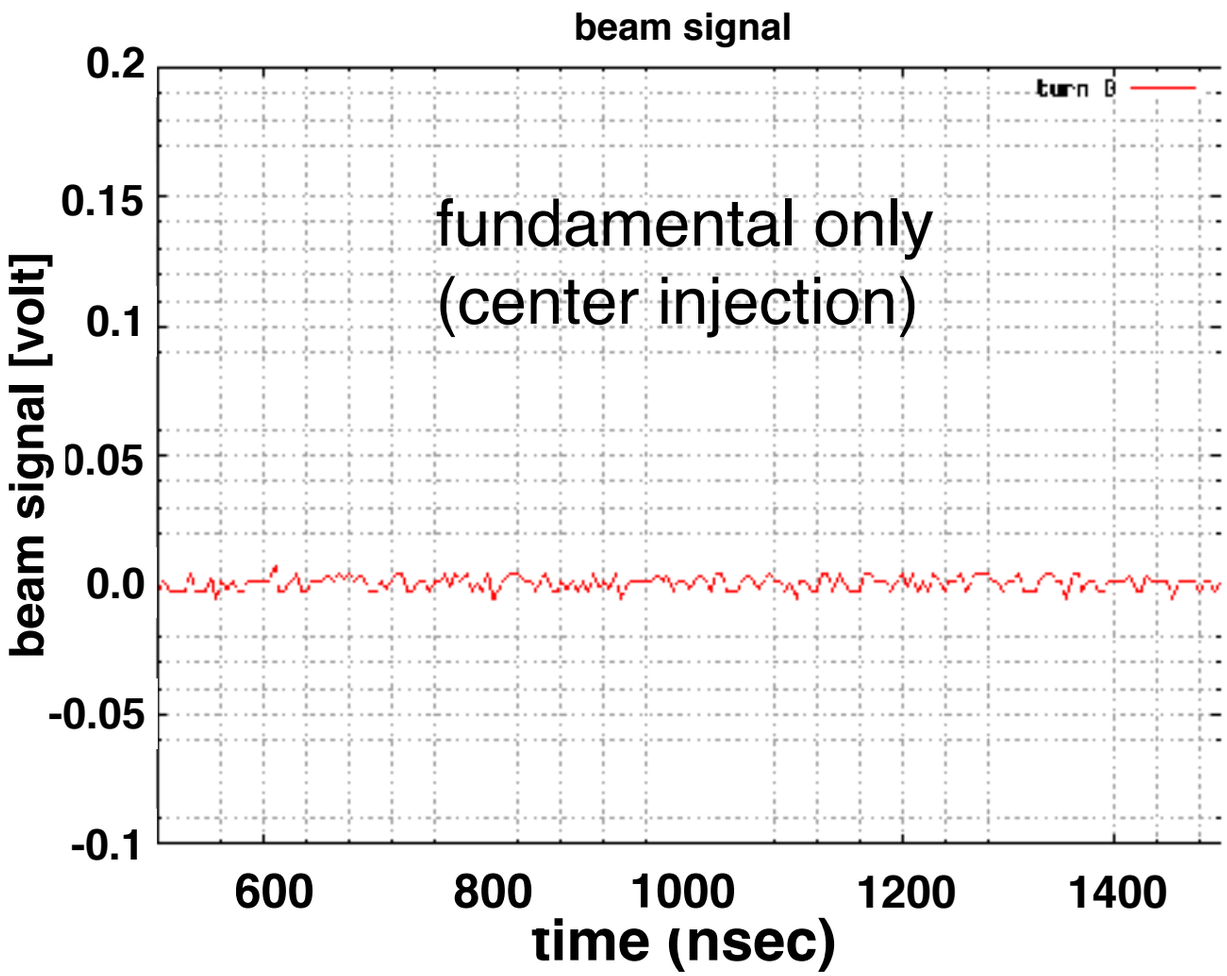
- Momentum offset
- Amplitude control for 2nd harmonic RF
- 2nd harmonic phase sweep

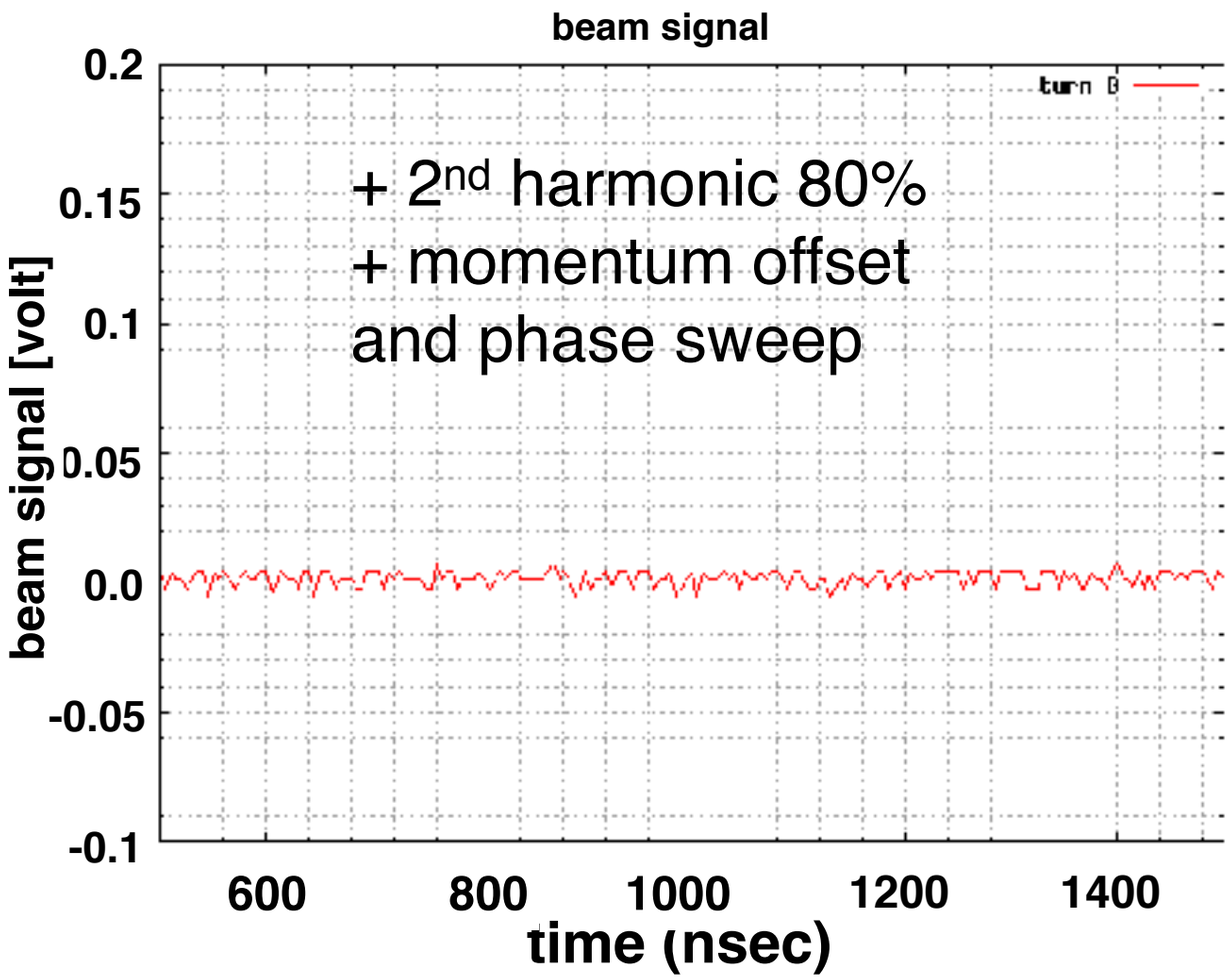
➡ increase bunching factor
➡ $B_f > 0.4$ required

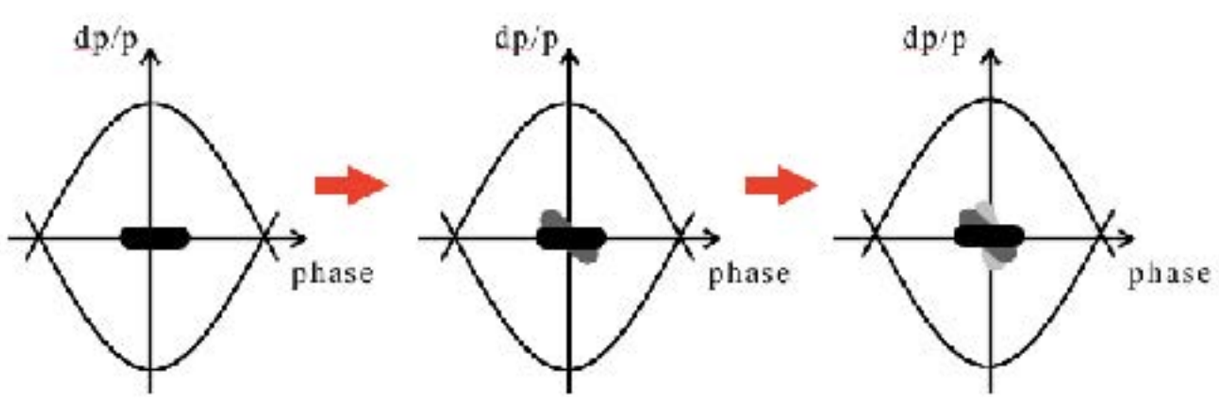


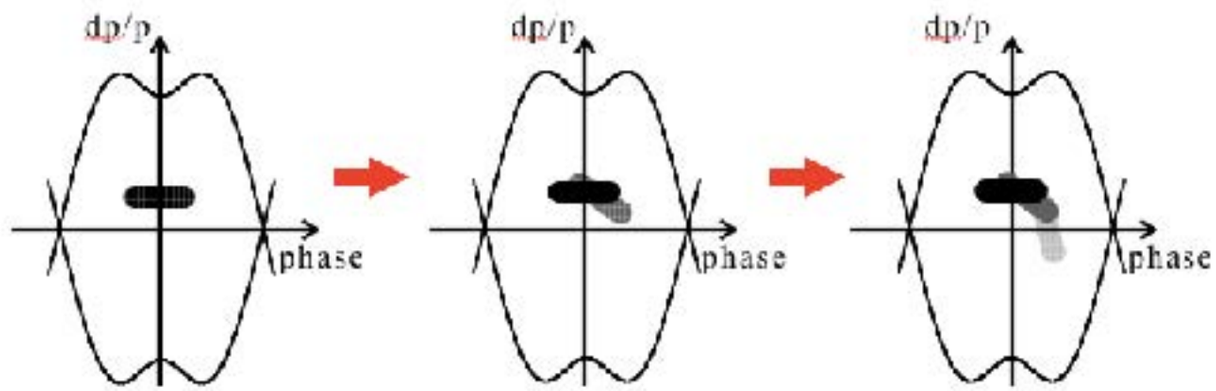
Longitudinal painting at J-PARC RCS injection

longitudinal painting using 2nd harmonic voltages





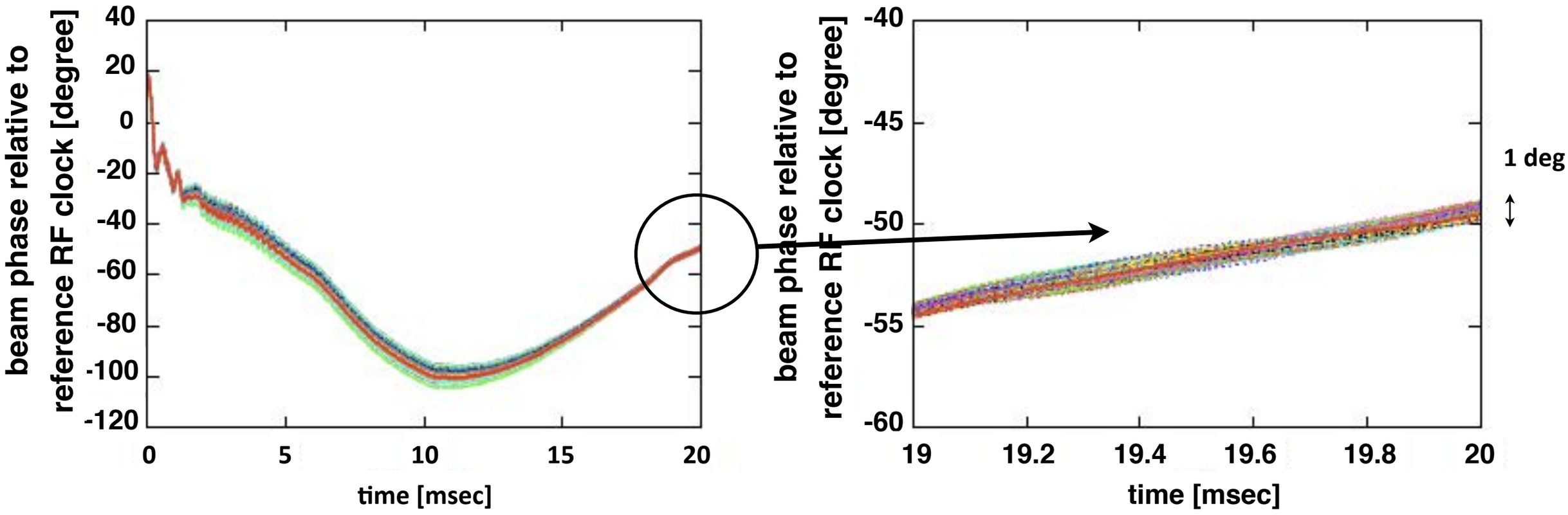




Stable acceleration of 300kW beams in RCS

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

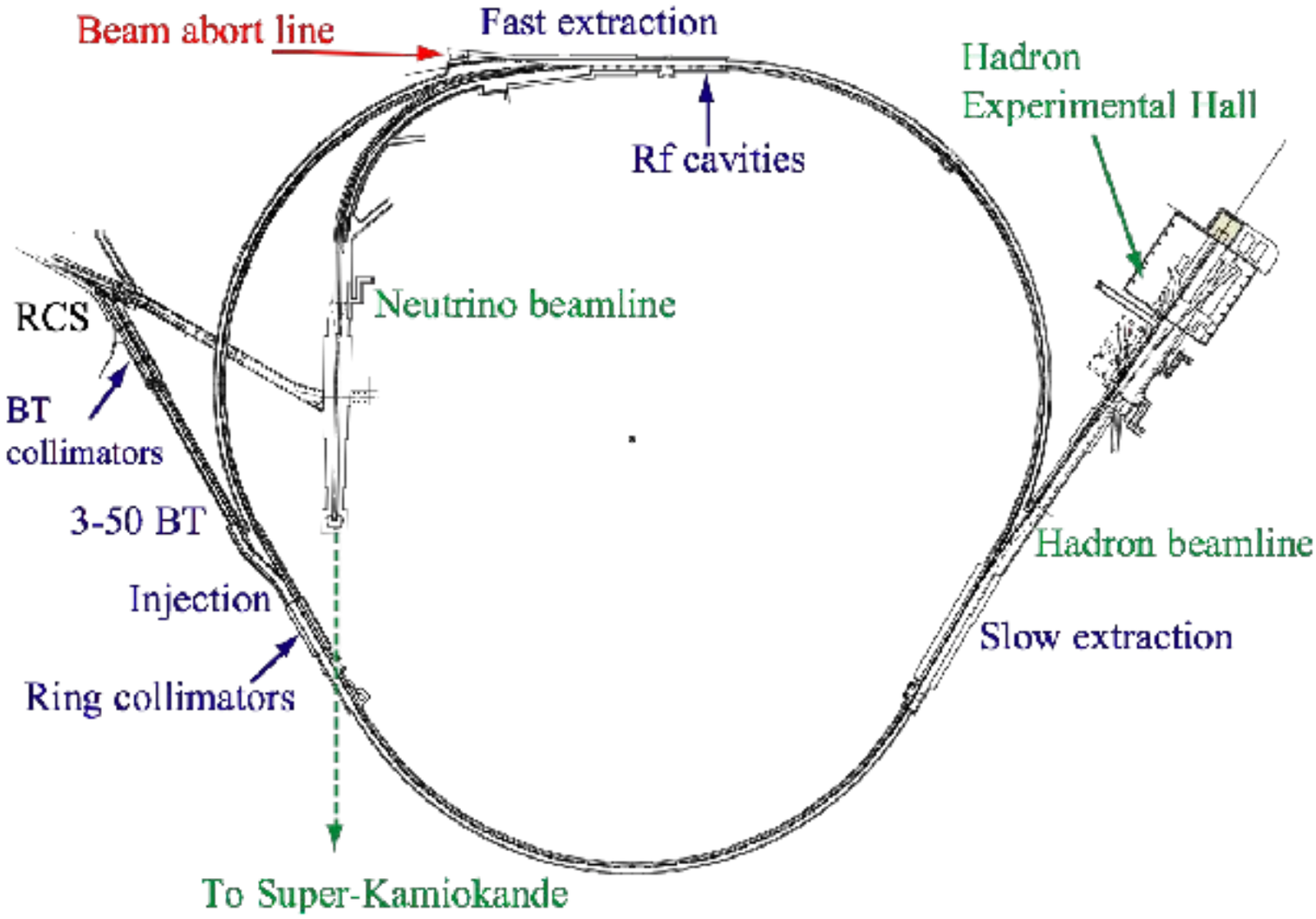
Ultra low-jitter extraction (jitter full width: 1deg = 1.7nsec)



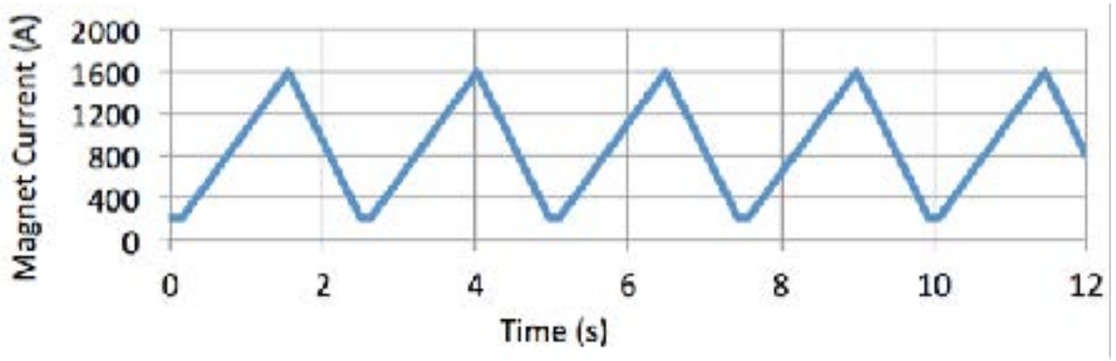
Beam phase plot during 1-hour 300kW operation (190 shots plotted). Right: magnified (19 - 20ms).

MR Design and Operation Modes

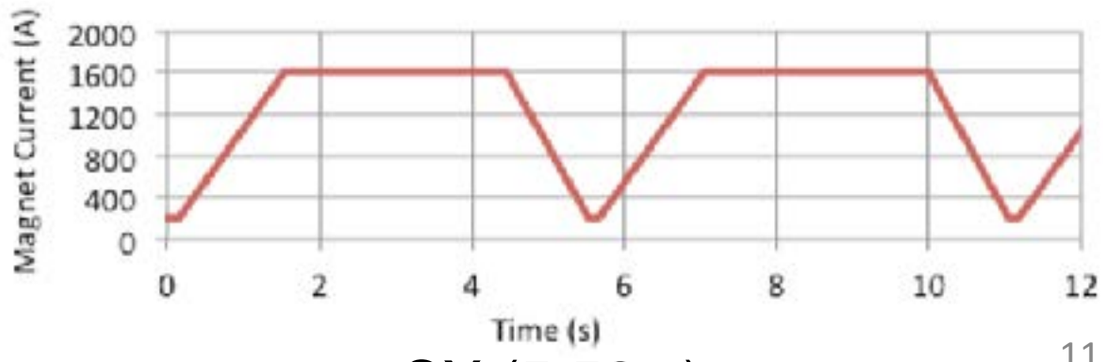
- Circumference 1567.5 m
- Three-fold symmetry
- Injection Energy 3GeV
- Extraction Energy 30 GeV
- Design Beam Power: 750 kW
- The first beam in MR
  - Injection: May 2008
  - Acceleration and extraction: Dec. 2008



- Fast extraction mode (FX) for the neutrino Facility: 1 turn extraction.
- Slow extraction mode (SX) for the hadron hall: 2 s – spill extraction.



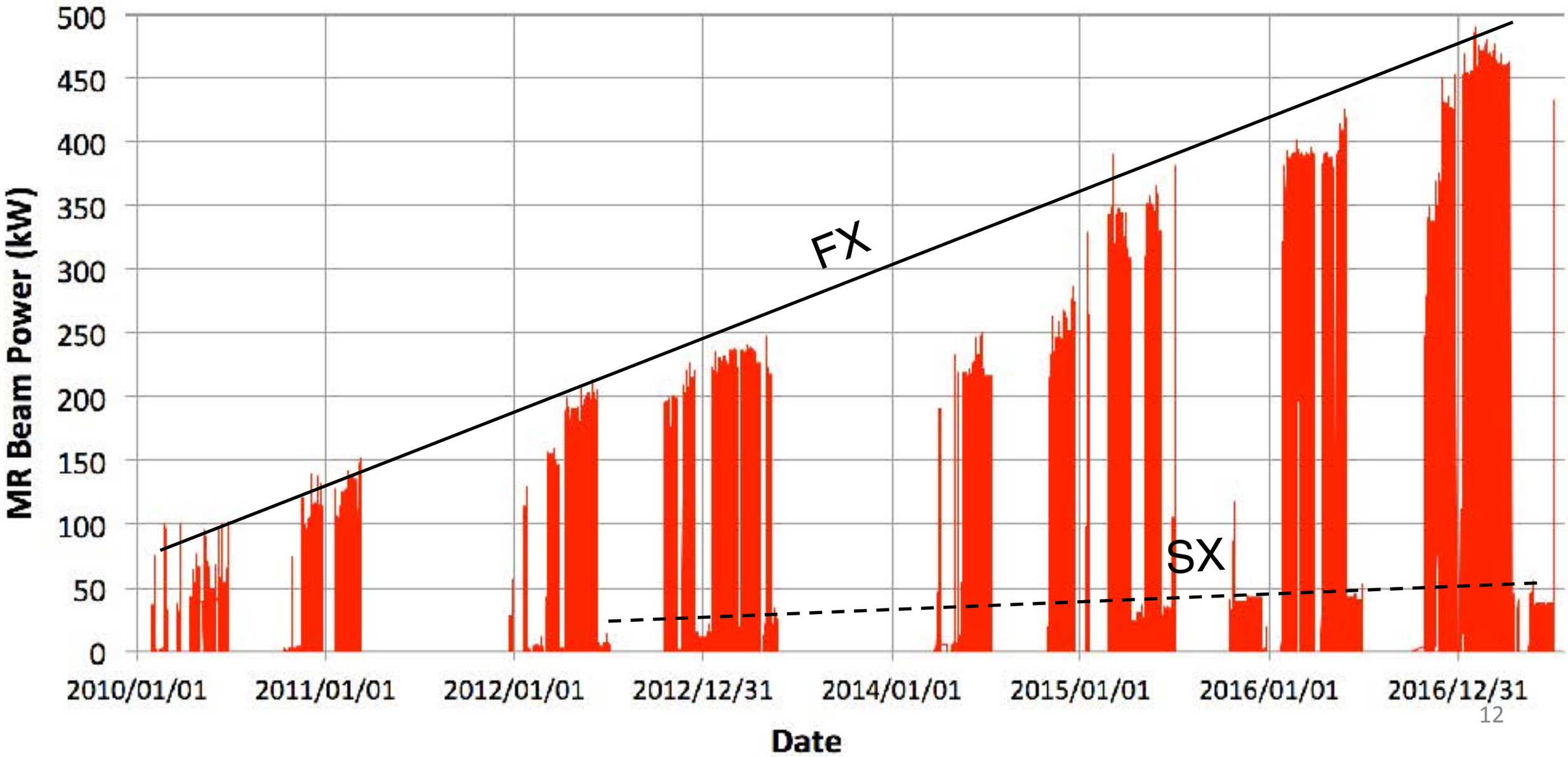
FX (2.48 s)



SX (5.52 s)

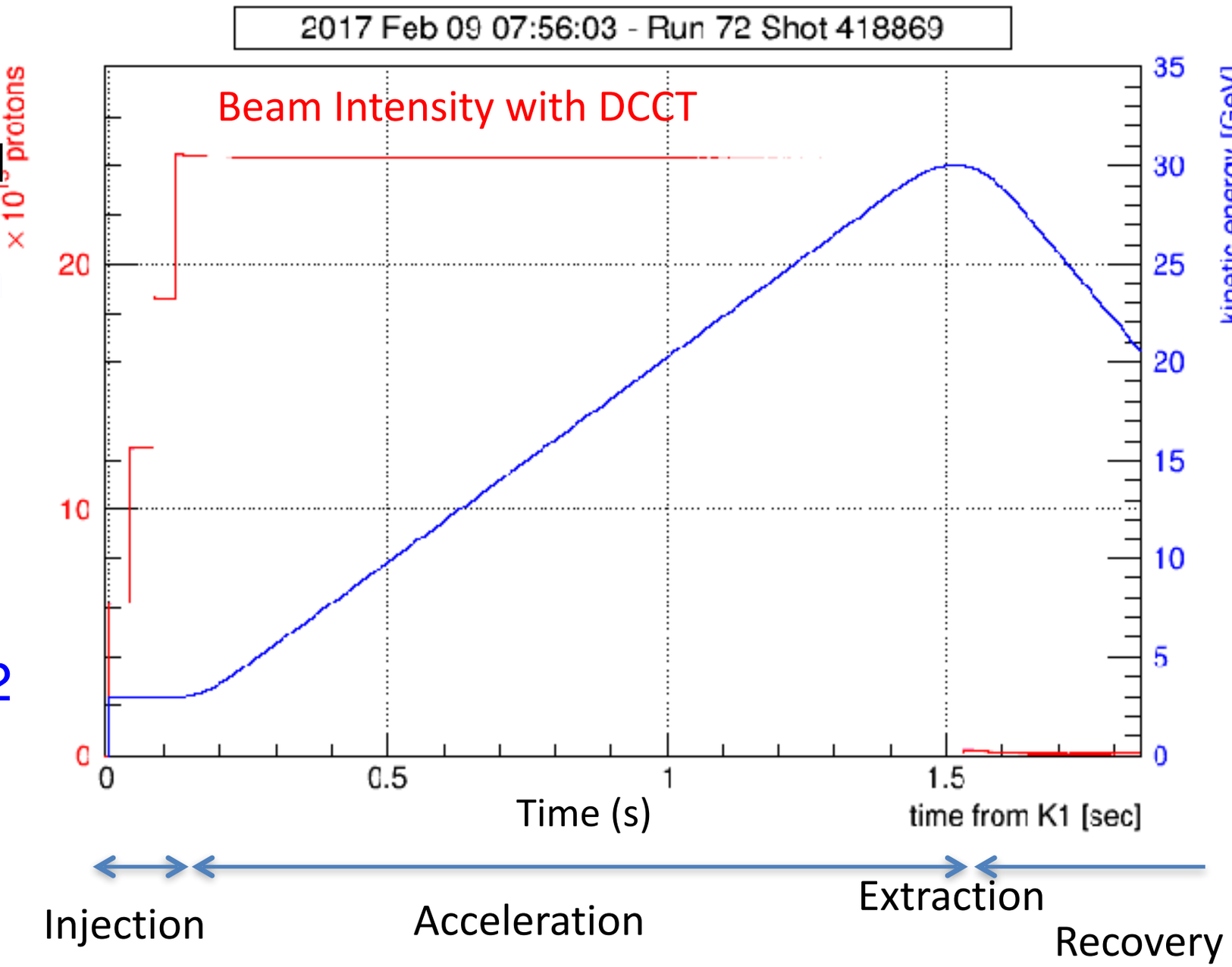
MR Beam Power History

- The beam power of 470 kW has been recently achieved with 2.44×10^{14} protons per pulse (ppp) and the cycle time of 2.48 s.
- The designed beam power of 750 kW will be achieved by making the cycle time shorter (1.3 s) and with 2×10^{14} ppp.
- The milestone for the number of accelerated protons has already been passed.



Typical Operation Status for FX

- Power : 471 kW
- Repetition : 2.48 sec
- 4 batch (8 bunch) injection during the period of 0.13 s
- 3.1e13 protons per bunch (ppb) × 8 @ Injection
- 2. 44e14 ppp @ P3 (end of acceleration)
- Loss during the injection : 220 W
- Loss in the beginning of acceleration (0.12 s) : 572 W
- Loss power is within the MR collimator limit of 2 kW
- Loss at 3-50BT : 100 W, < 3-50BT collimator limit of 2 kW



MR beam commissioning

Energy	3 - 30 GeV
Intensity	2.4 x 10^{14} ppp
Power	470 kW
harmonics / N_b	9 / 8
Frequency	1.67 - 1.72 MHz
# of cavities (h=9)	7
Peak V_{acc}	300 kV
# of cavities (h=18)	2
Peak V_{acc} (h=18)	110 kV
Repetition (period)	2.48 s/5.52s
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

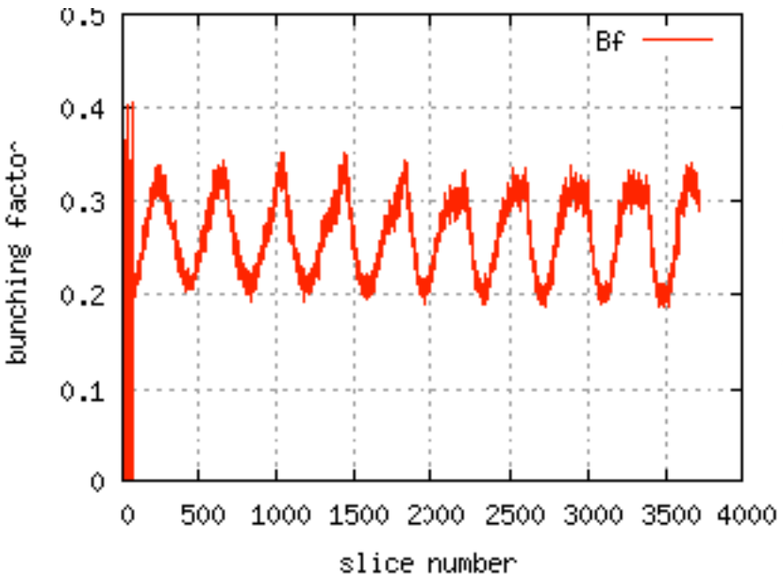
- frequency pattern is modified offline.

3. phase feedback: closed.

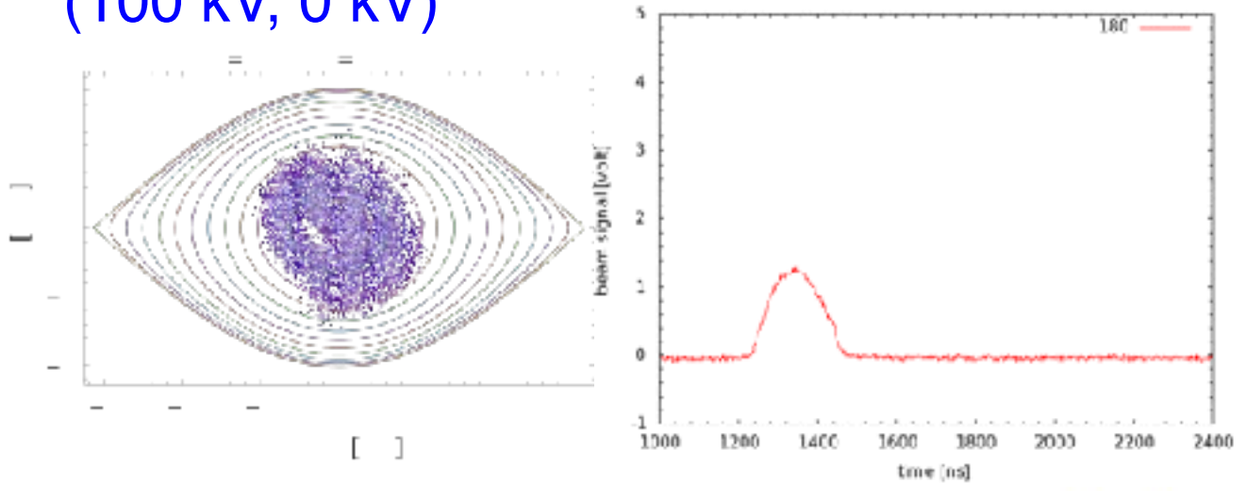
4. Multi-harmonic RF Feed-forward: ON for each of the cavities.

2nd Harmonic RF Operation

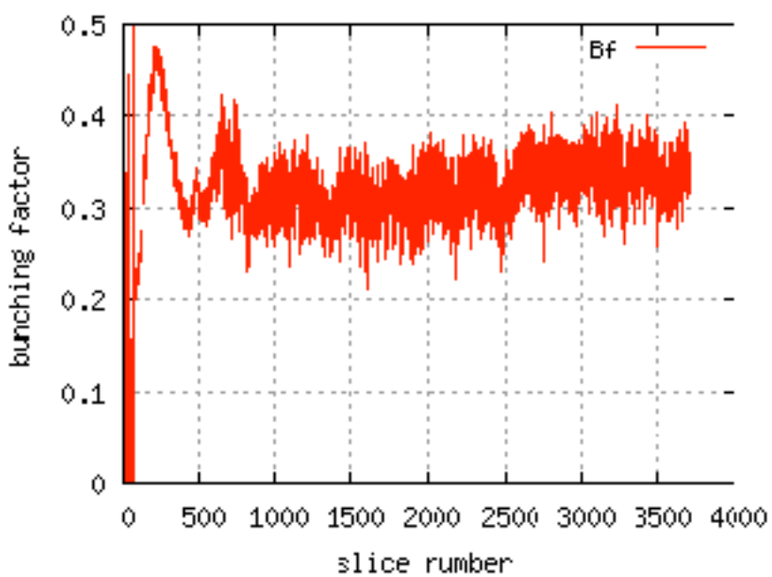
Fundamental 100 kV
2nd harmonic 0 kV
Bunching factor
0.2 ~ 0.3
Bunch length
~200 ns



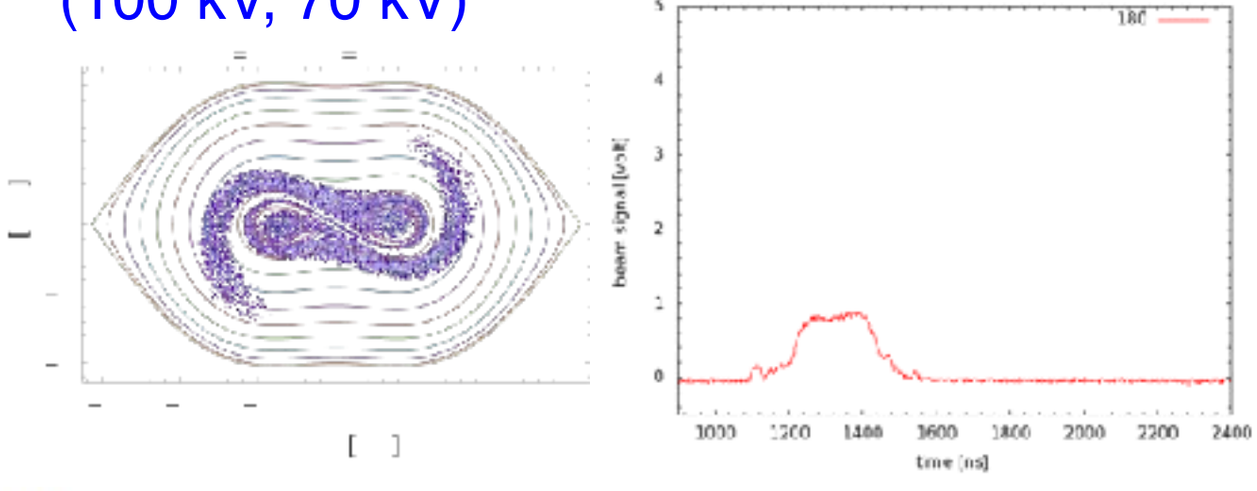
Simulation
(100 kV, 0 kV)



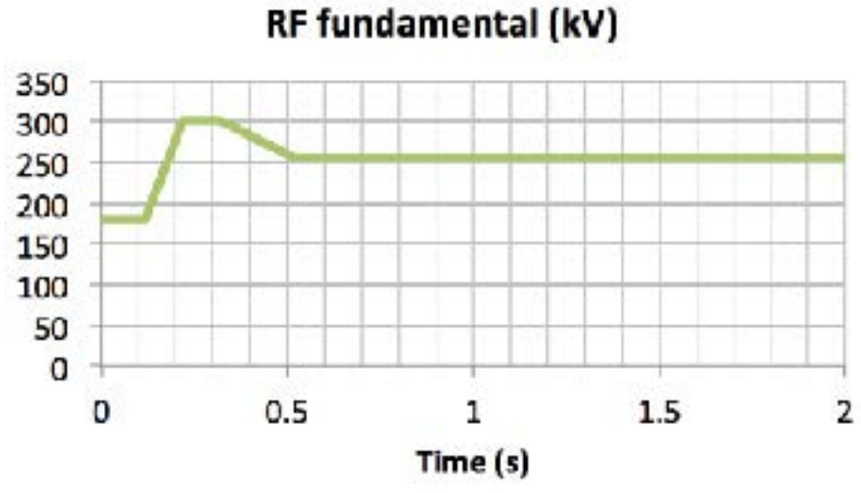
Fundamental 100 kV
2nd harmonic 70 kV
Bunching factor
0.3 ~ 0.4
Bunch length
~400 ns

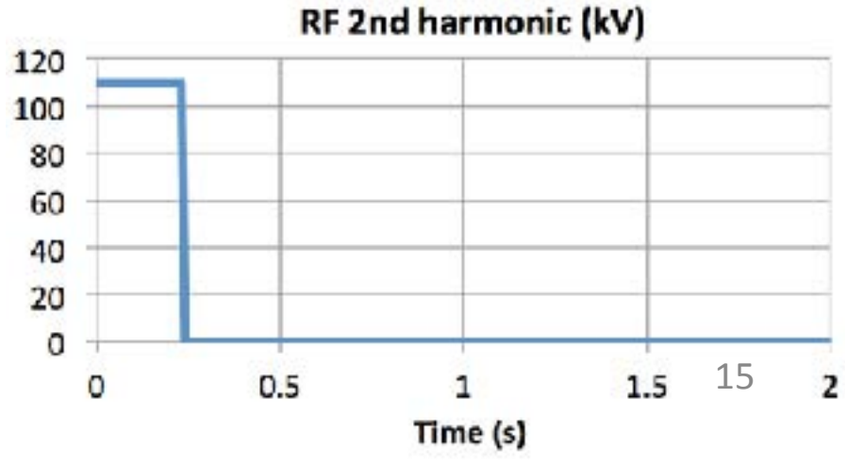


Simulation
(100 kV, 70 kV)



RF Pattern for operation:
Injection :
180 kV (fundamental),
110 kV (2nd harmonic)
Acceleration :
300 kV → 256 kV
(fundamental)

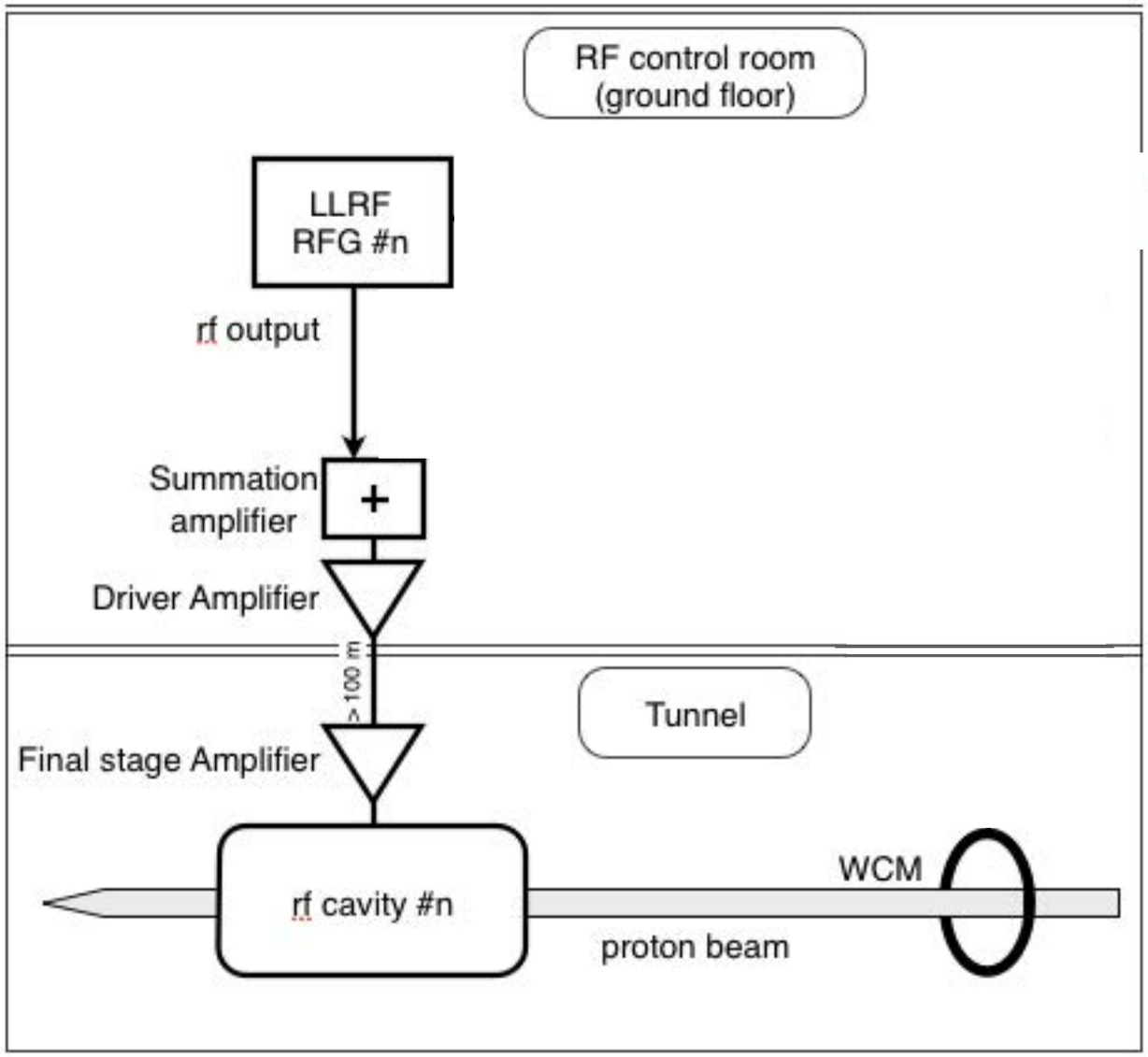




Beam loading issues

- Beam loading by circulating high intensity proton beam of 4.12×10^{13} protons per bunch is the most important issue to be taken into account for stability of the RF system.
- RF system requires both RF beam power and RF generating power to obtain the design gap voltages.
  - ✓ 3.1 MW peak beam power in RCS to obtain by 12 RF systems (255kW)
  - ✓ 2.3 MW peak beam power in MR to obtain by 9 RF systems (250kW)
- For keeping the stability of the system. The relative loading parameter, $Y = I_B / I_0$, is chosen to be smaller than 1 as much as possible.
- MA loaded cavity has a wide-band frequency response. The Q-value is Q ~ 2 for the RCS cavity and Q ~ 25 for the MR cavity.
- Multi-harmonic feedforward system has been developed to compensate the beam induced wake voltages.

Block view of the Multi-harmonic RF Feedforward

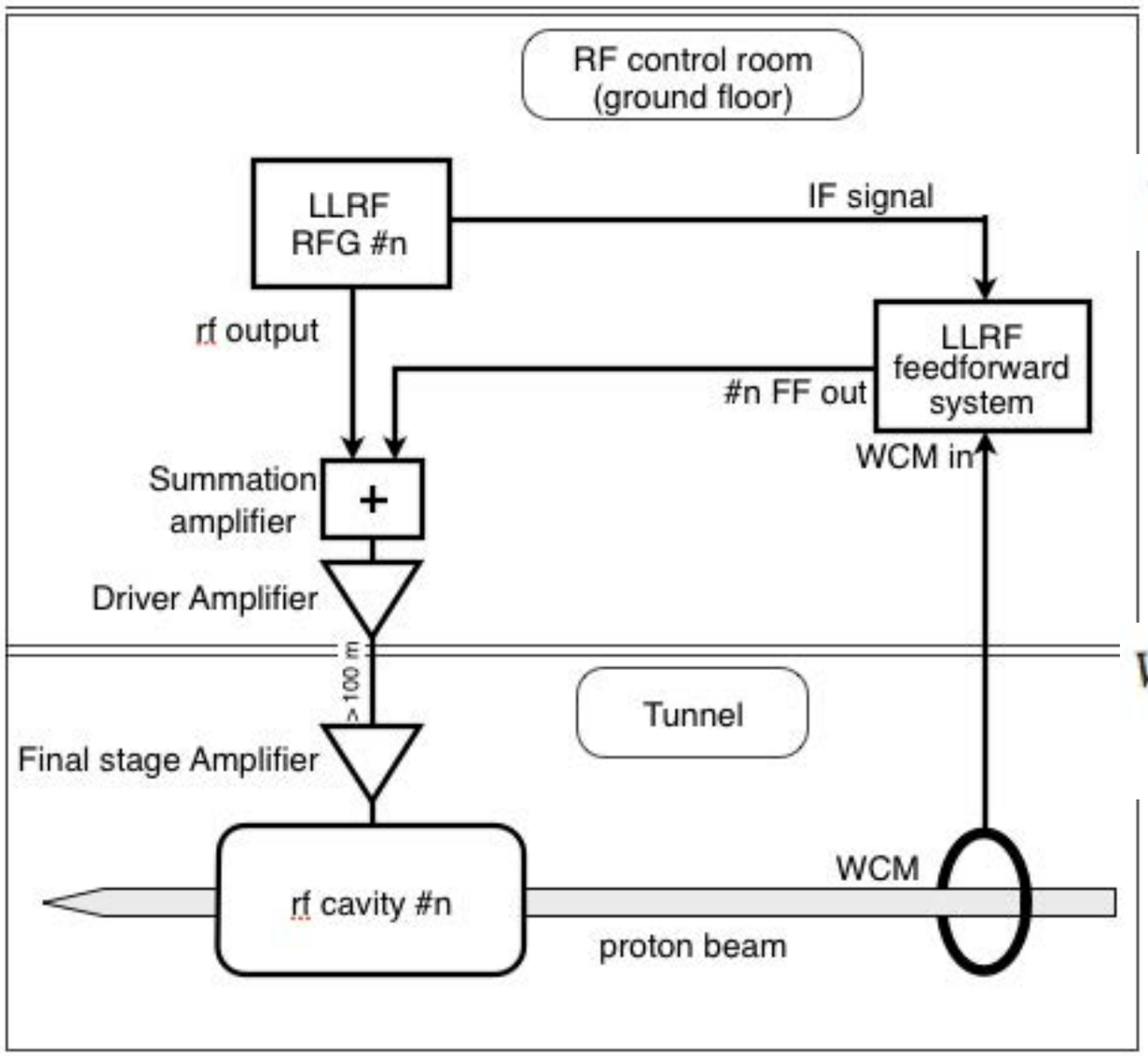


- without feedforward

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

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

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

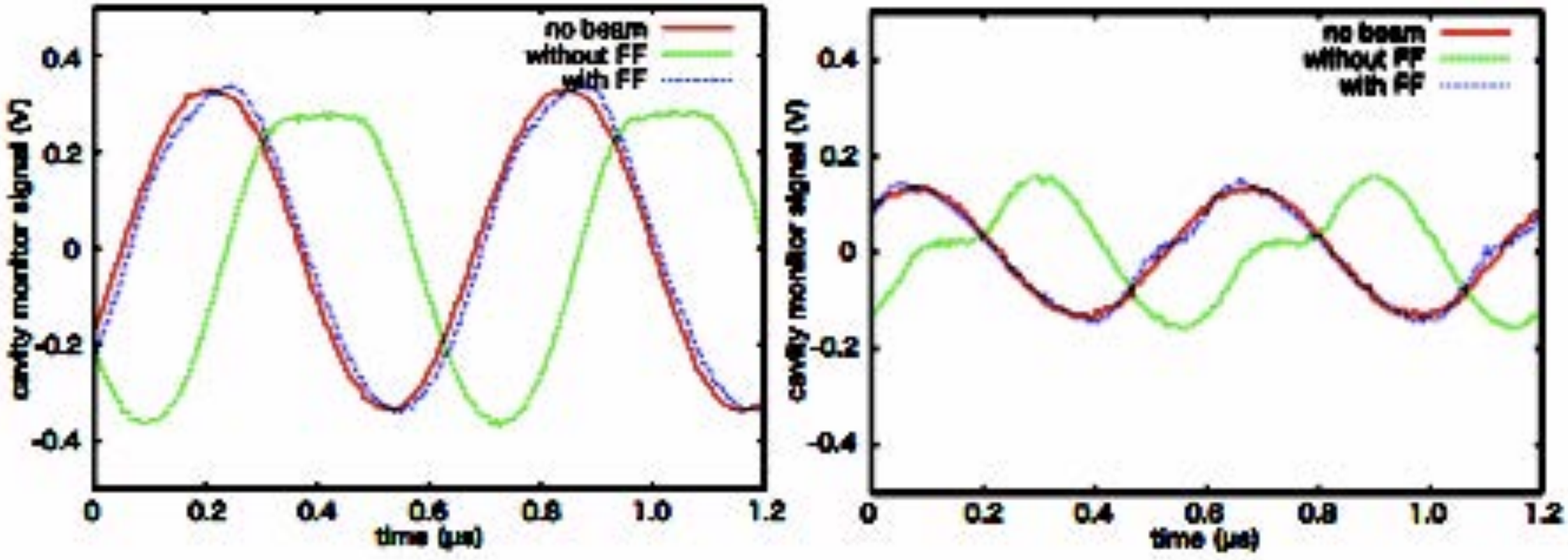
- with feedforward

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

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

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

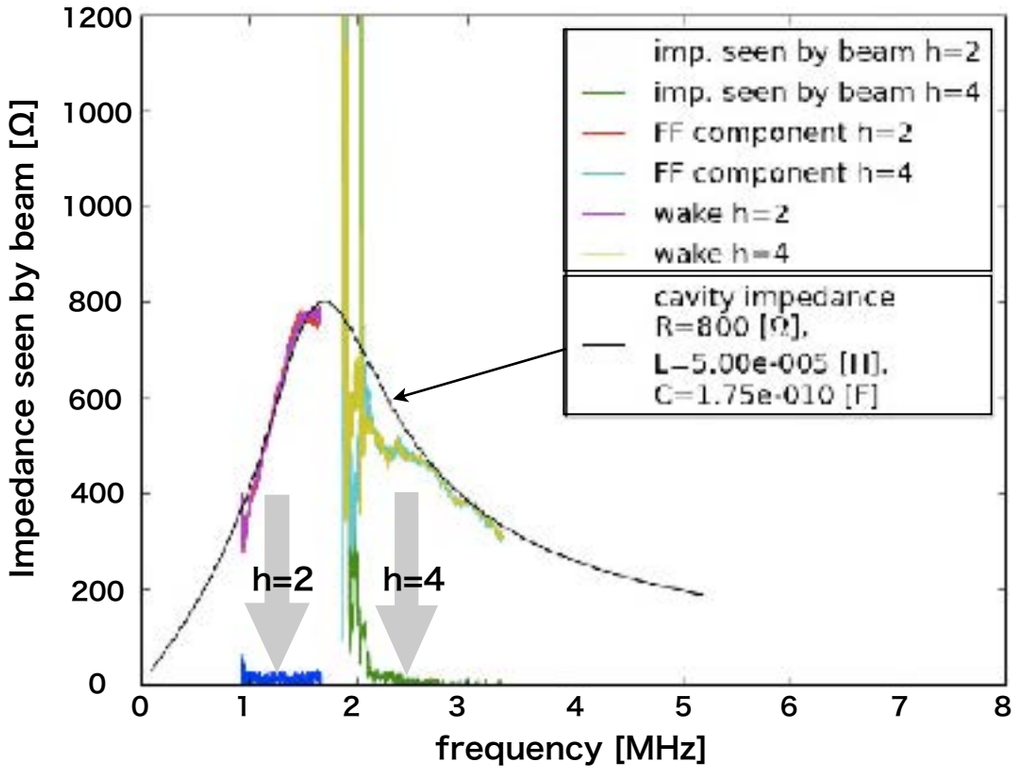


FIGURE: Frequency-domain Impedance seen by the beam: (RCS cavity#1)

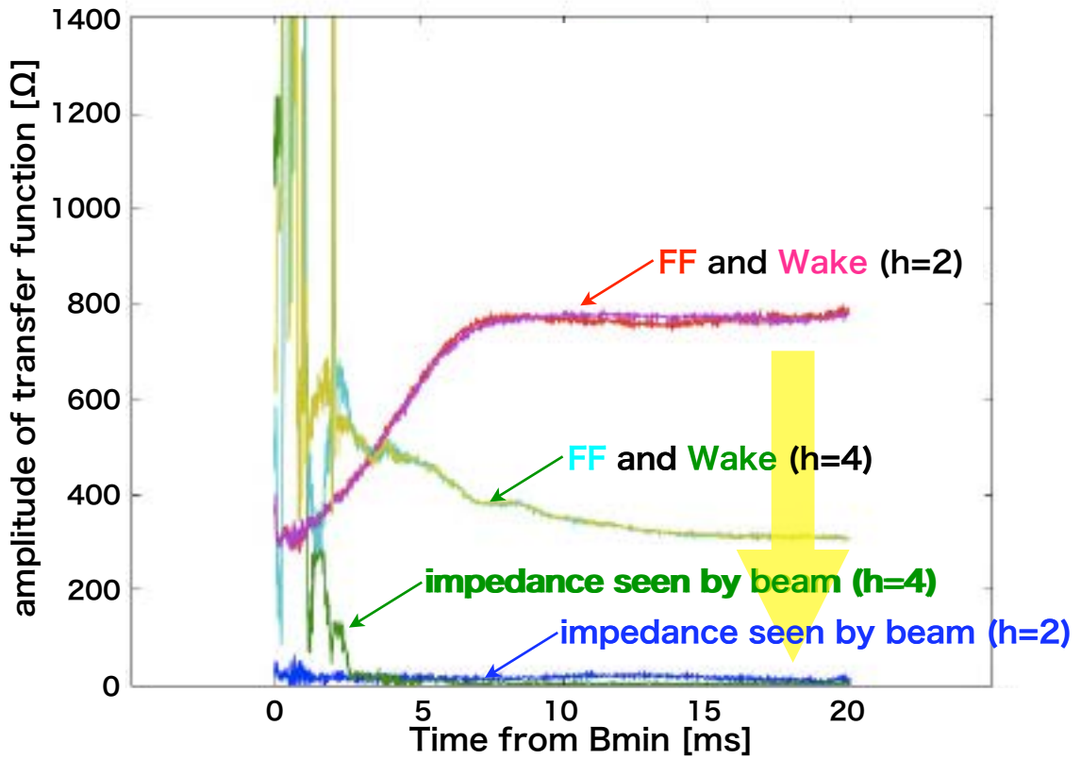


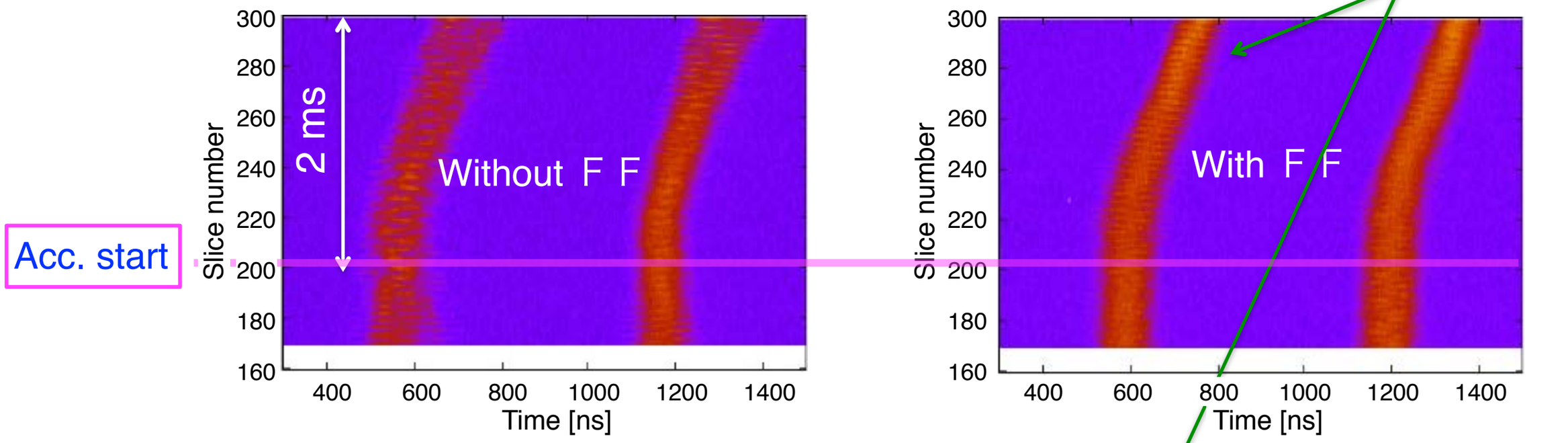
FIGURE: Time-domain Impedance seen by the beam: (RCS cavity#1)

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

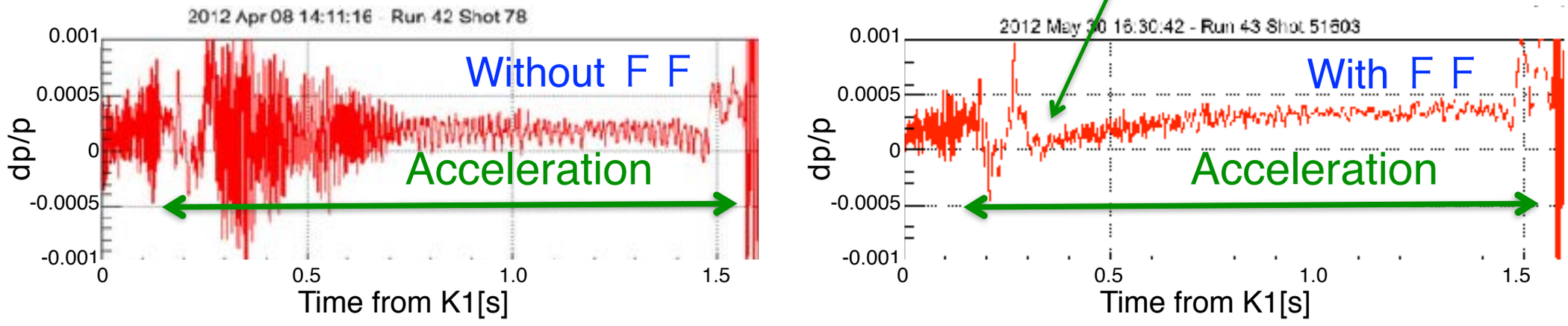
Beam loading compensation in MR

Mountain Plots of injection beam
(2 bunches)

Longitudinal oscillation during the acceleration suppressed with FF

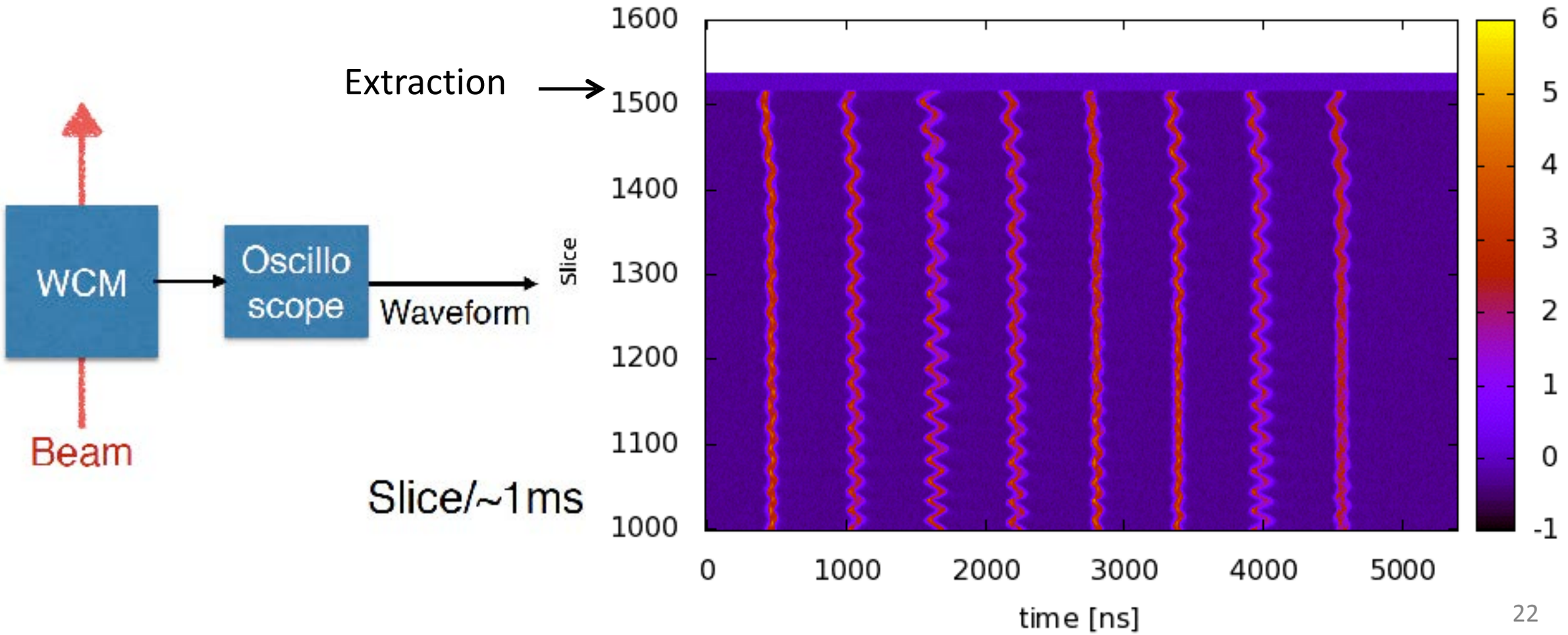


dp/p measured by BPM



Longitudinal Oscillations

- Longitudinal oscillations were observed for high beam power of > 470 kW.
- Each bunch seems to have different phase in dipole oscillation.
- A feedback system to suppress the oscillations is in preparation.



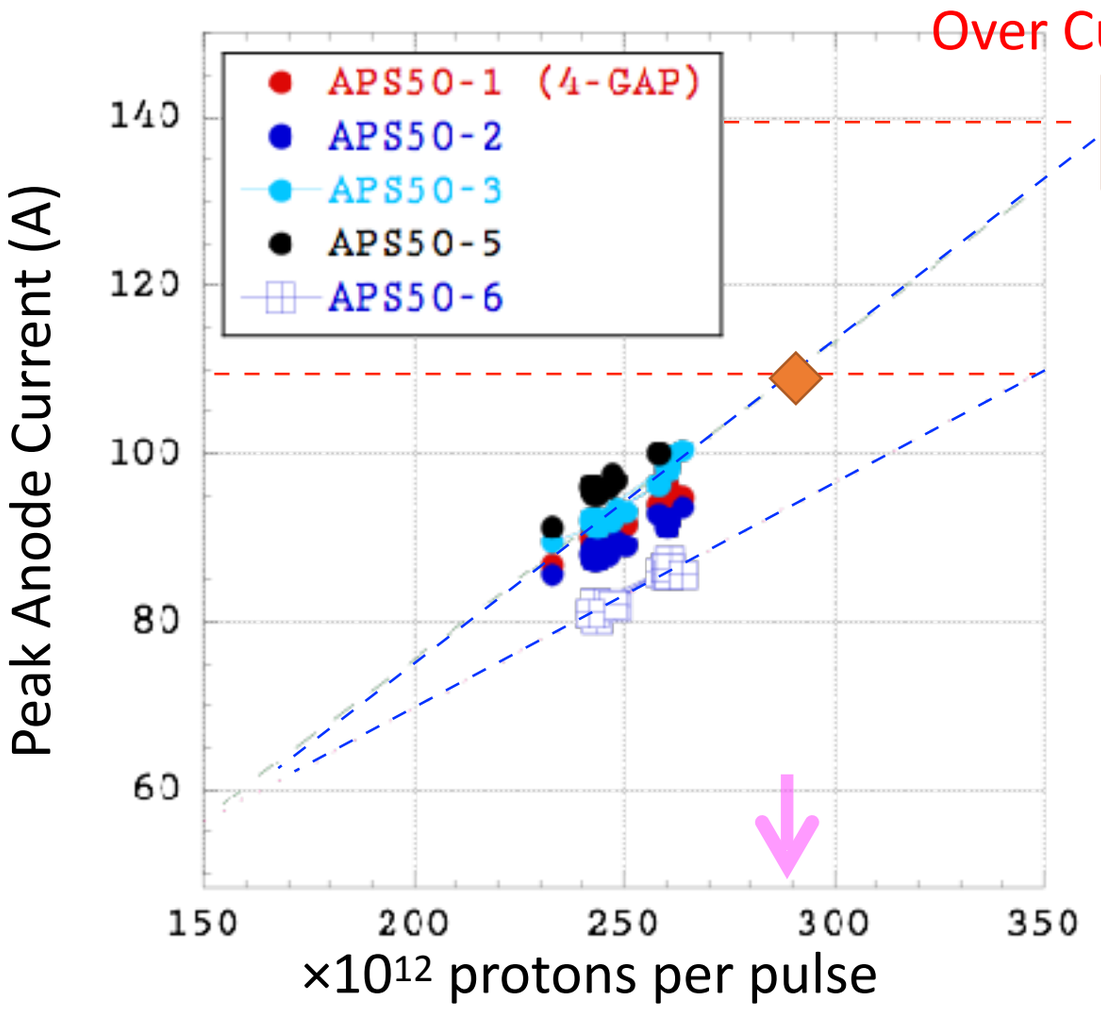
Mid-term plan of MR

- Repetition period will be faster, 2.48 s → 1.3 s, for the beam power of 750 kW and more.
- Magnet power supplies, rf, injection and extraction devices are being upgraded.

JFY	2015	2016	2017	2018	2019	2020	2021	2022
		New buildings →			Long shutdown			
FX power [kW]	390	470	480-500	> 500	700	800	900	1060
SX power [kW]	42	42	50	50-60	60-80	80	80-100	100
Cycle time of main magnet PS New magnet PS	2.48 s	Mass production installation/test →		2.48 s	1.3 s	1.3 s	1.3 s	1.3 s
High gradient rf system 2nd harmonic rf system	Installation →	Manufacture, installation/test →						
Ring collimators	Add.collimators (2 kW)				Add.colli. (3.5kW)			
Injection system FX system	Kicker PS improvement, Septa manufacture /test →	Kicker PS improvement, FX septa manufacture /test →						
SX collimator / Local shields					Local shields →			
Ti ducts and SX devices with Ti chamber			ESS					

RF Anode Current as a function of Beam Intensity

- For 1.3 MW, 11 RF cavities and 19-inverter unit modification are necessary.
- For 470 kW, the peak anode current is getting closed to the limit of 15-inverter units.
- Events of serious damages of the inverter units happens more frequently.
- Noise filters were implemented for some of the gate circuits of the inverter units.



ppp (x10¹²)	200	240	300	330	#of AccRF	VRF(h=9)	#of 2ndRF	VRF(h=18)
2.48s	*390kW*	*465kW*	*580kW*	*640kW*	*7*	*280kV*	*2*	*110kV*

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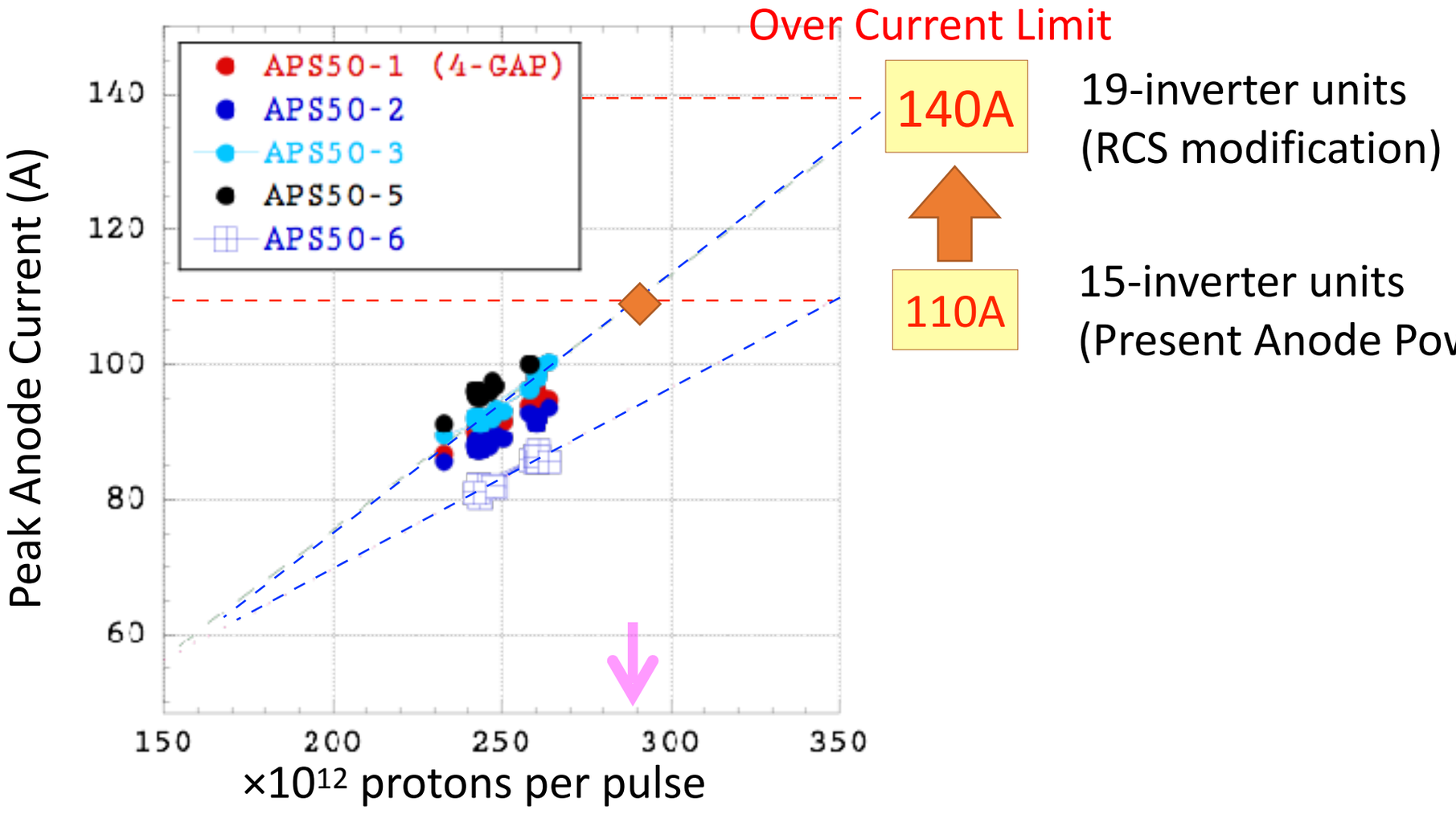

ppp (x10¹²)	200	240	300	330	#of AccRF	VRF(h=9)	#of 2ndRF	VRF(h=18)
2.48s	390kW	465kW	580kW	640kW	7	280kV	2	110kV
1.28s	750kW	900kW	1100kW		9	510kV	2	110kV
1.16s	830kW	1000kW	1.2MW	1.3MW	11	600kV	2	110kV

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.
- Beam power of 470 kW has been achieved for FX user operation with 2.44×10^{14} protons per pulse (ppp) and the cycle time of 2.48 s.
- The target beam power of 750 kW will be achieved with the faster cycling 2.48 s → 1.3 s.