First results of the high repetition operation in J-PARC MR

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NuFACT 2022, August 2, 2022

Outline

1. Introduction
2. Hardware upgrade
3. Results of beam study after upgrade
4. Midterm plan of MR
5. Summary

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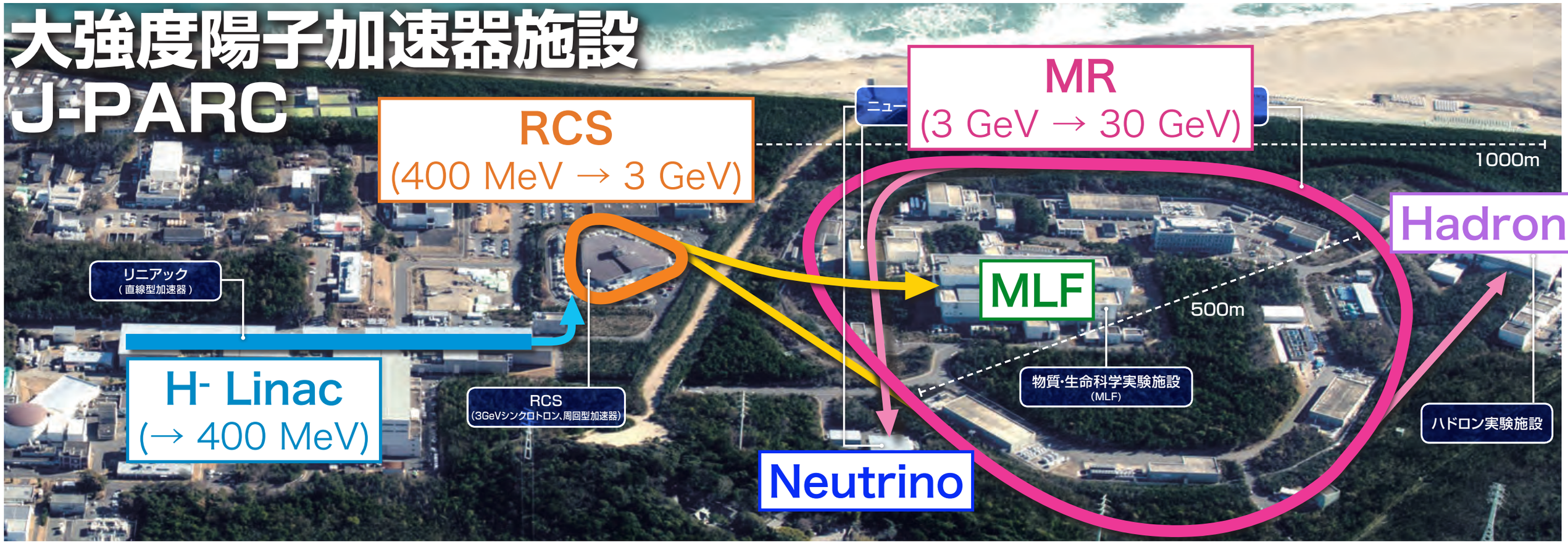
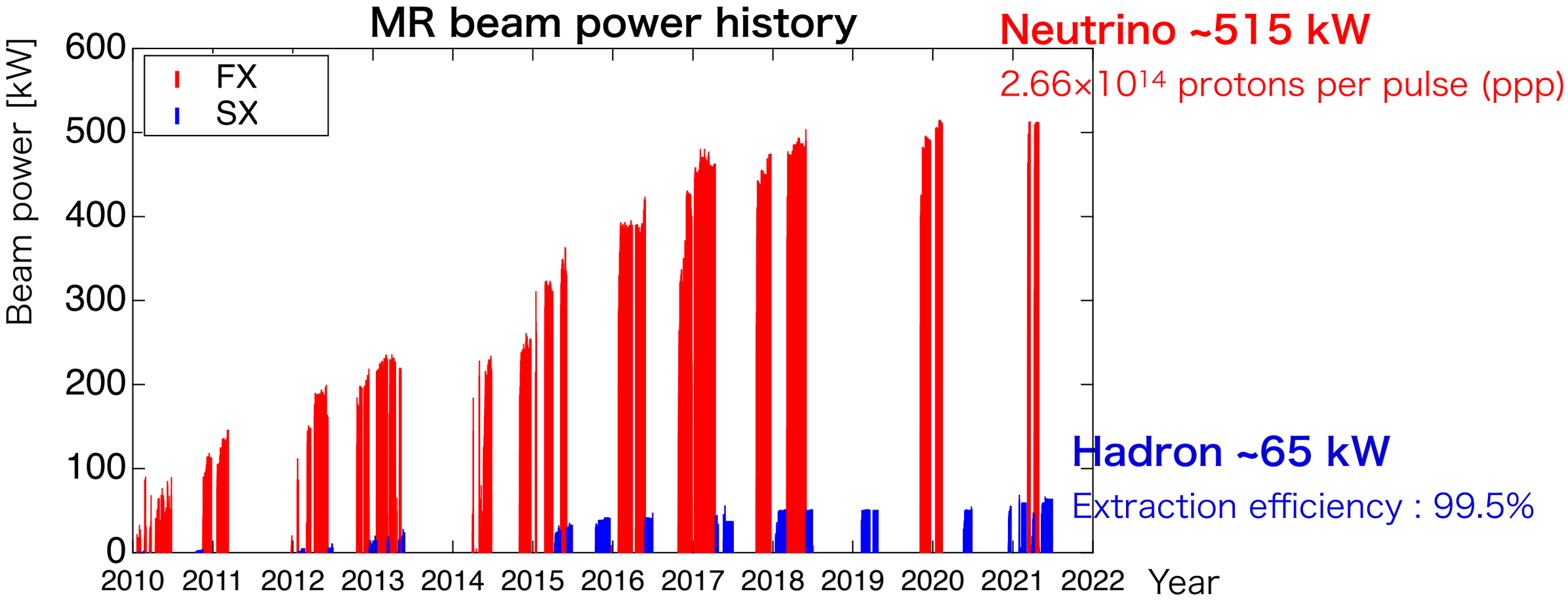
J-PARC



The main ring synchrotron (MR) provides
high power proton beams with a kinetic energy of 30 GeV
to neutrino and hadron experimental facilities.

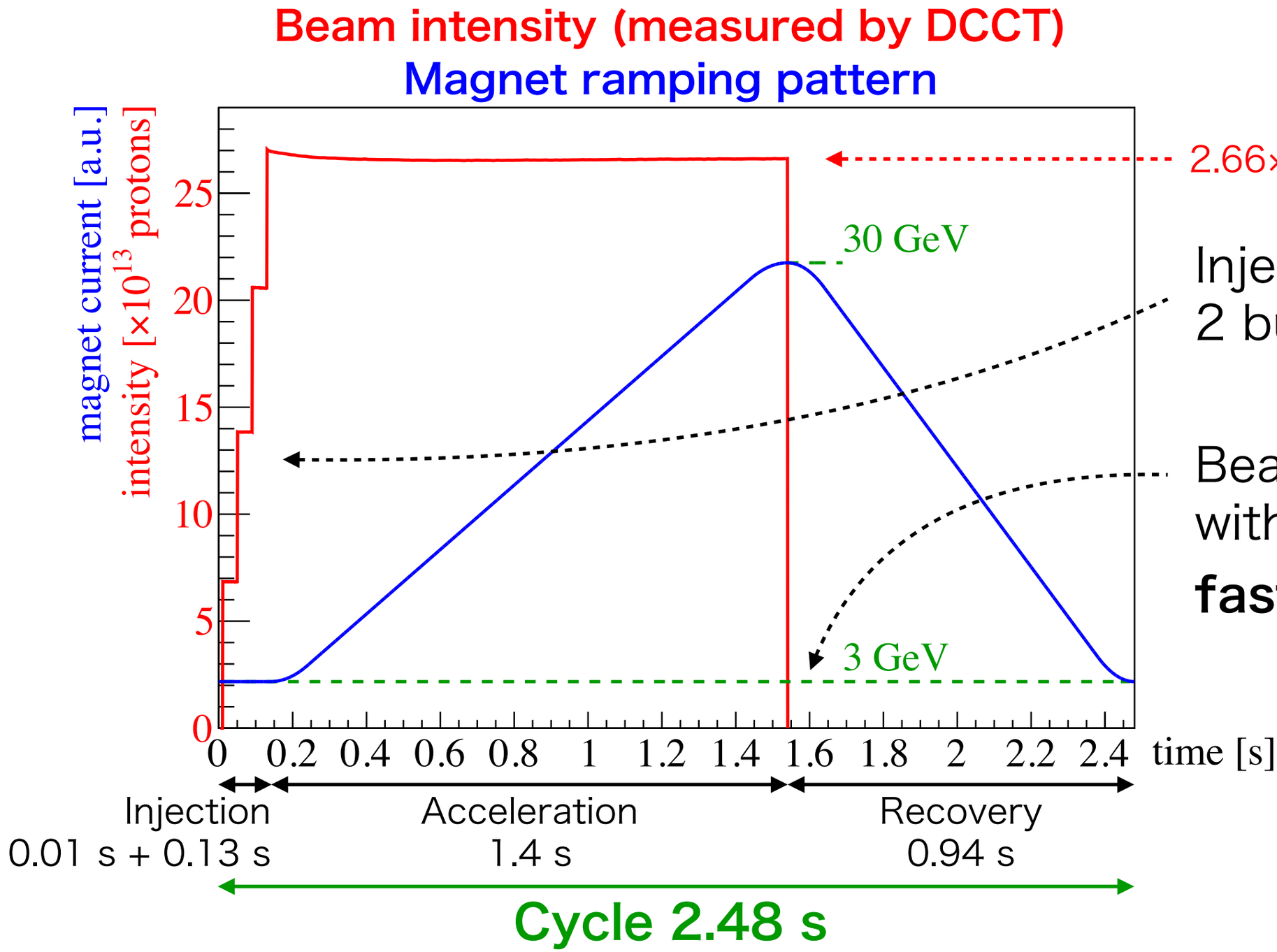
MR beam power history

To accumulate the statistics of neutrinos and hadrons,
stable beam operation with higher power is required.



Upgrade plan : 1.3 MW operation for neutrino experiments

Typical FX operation status



2.66×10¹⁴ ppp → 515 kW

Injection:
2 bunches × 4 times

Beams are extracted within one turn:

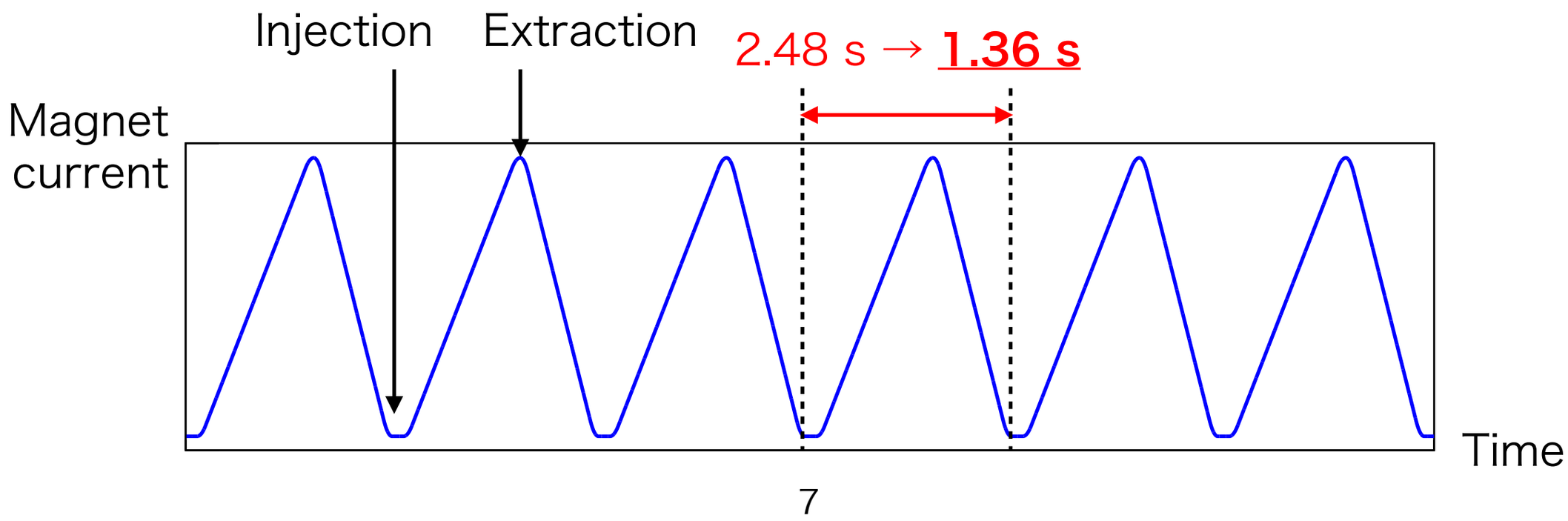
fast extraction (FX)

Beam power upgrade plan

Power = Energy × **Number of protons** / **Cycle time**

Energy: 30 GeV

JFY2021	515 kW	2.66×10^{14} ppp	2.48 s
JFY2023	750 kW	2.1×10^{14} ppp	1.36 s
Future	**1300 kW**	3.3×10^{14} ppp	**1.16 s**



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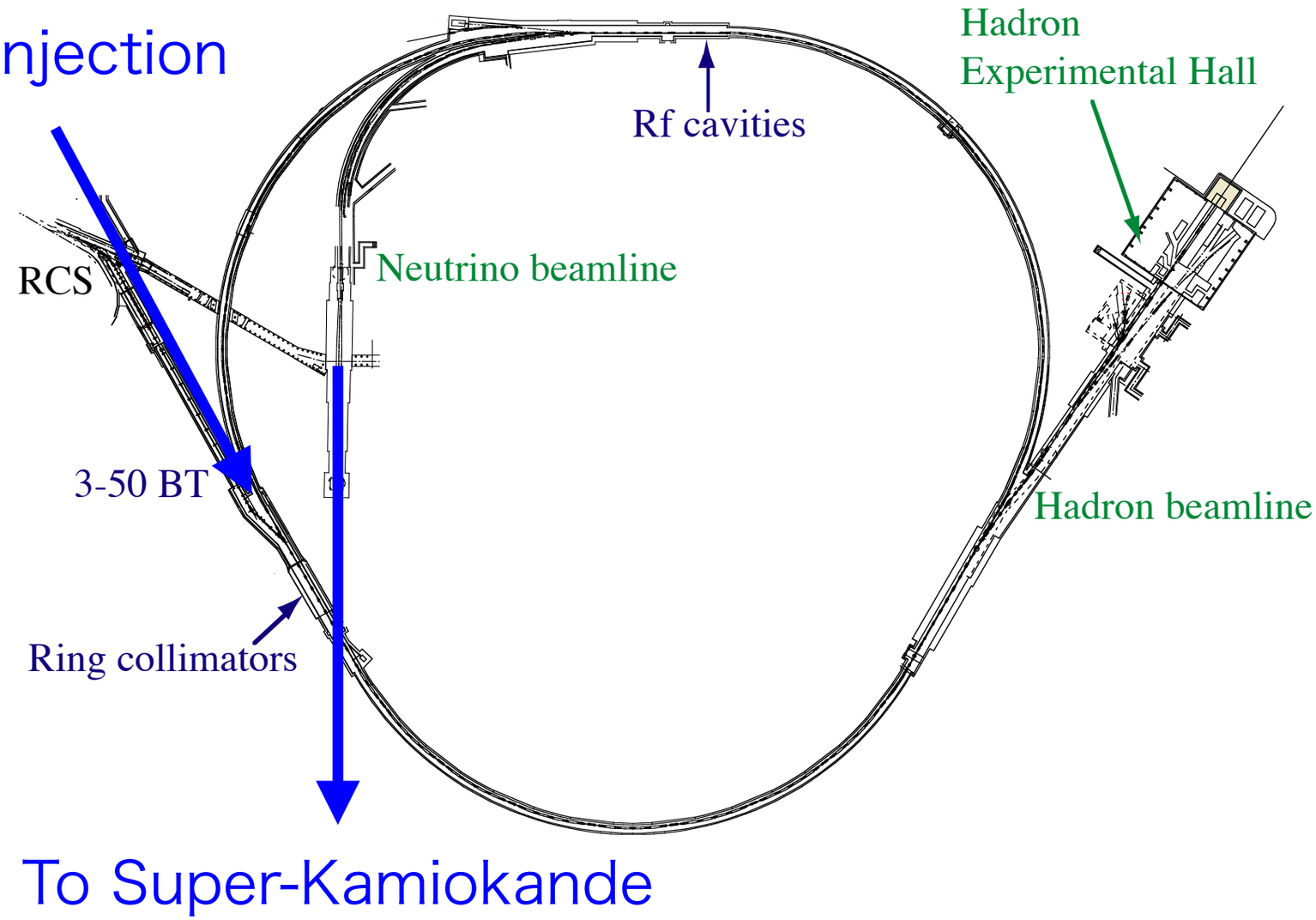
Hardware upgrade

Contents of hardware upgrade

1. Power supplies
   of main magnets
2. RF system
3. FX septum magnets
4. Collimator system
   (in summer)



Hardware upgrade

Contents of hardware upgrade

1. **Power supplies of main magnets**

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3. FX septum magnets

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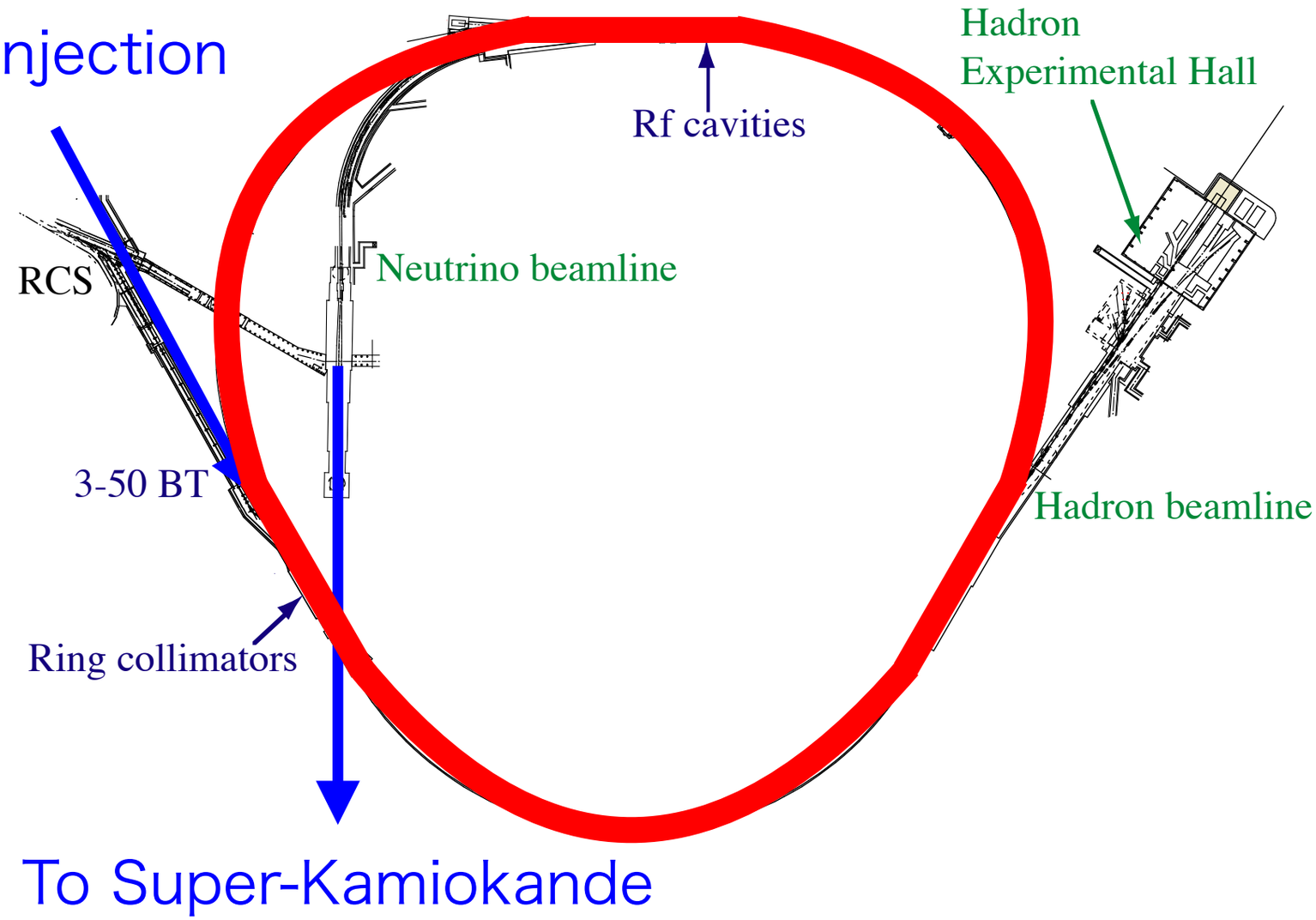

Upgrade of power supplies of main magnets

The power supplies (PSs) of main magnets were upgraded for faster cycling.

	Family label	Num of family	Num of magnets	Strategy
Bends	BM	6	16 each	New PSs with capacitor bank
Quadrupoles in arc sections	QFN	1	48	
	QDN	1	48	
	QFX	1 → 2	48 → 24 each	Reuse of present PSs (Family divided)
	QDX	1 → 2	27 → 13+14	
Quadrupoles in straight sections	QFS	1 → 2	6 → 3 each	
	QDS	1 → 2	6 → 3 each	
	QFT	1 → 2	6 → 3 each	
	QFP	1	6	Reuse of present PSs
	QFR	1	9	
	QDT	1	6	New PSs without capacitor bank
	QDR	1	6	
Sextupoles	SFA	1	24	
	SDA, SDB	2 → 1	24+24 → 48	

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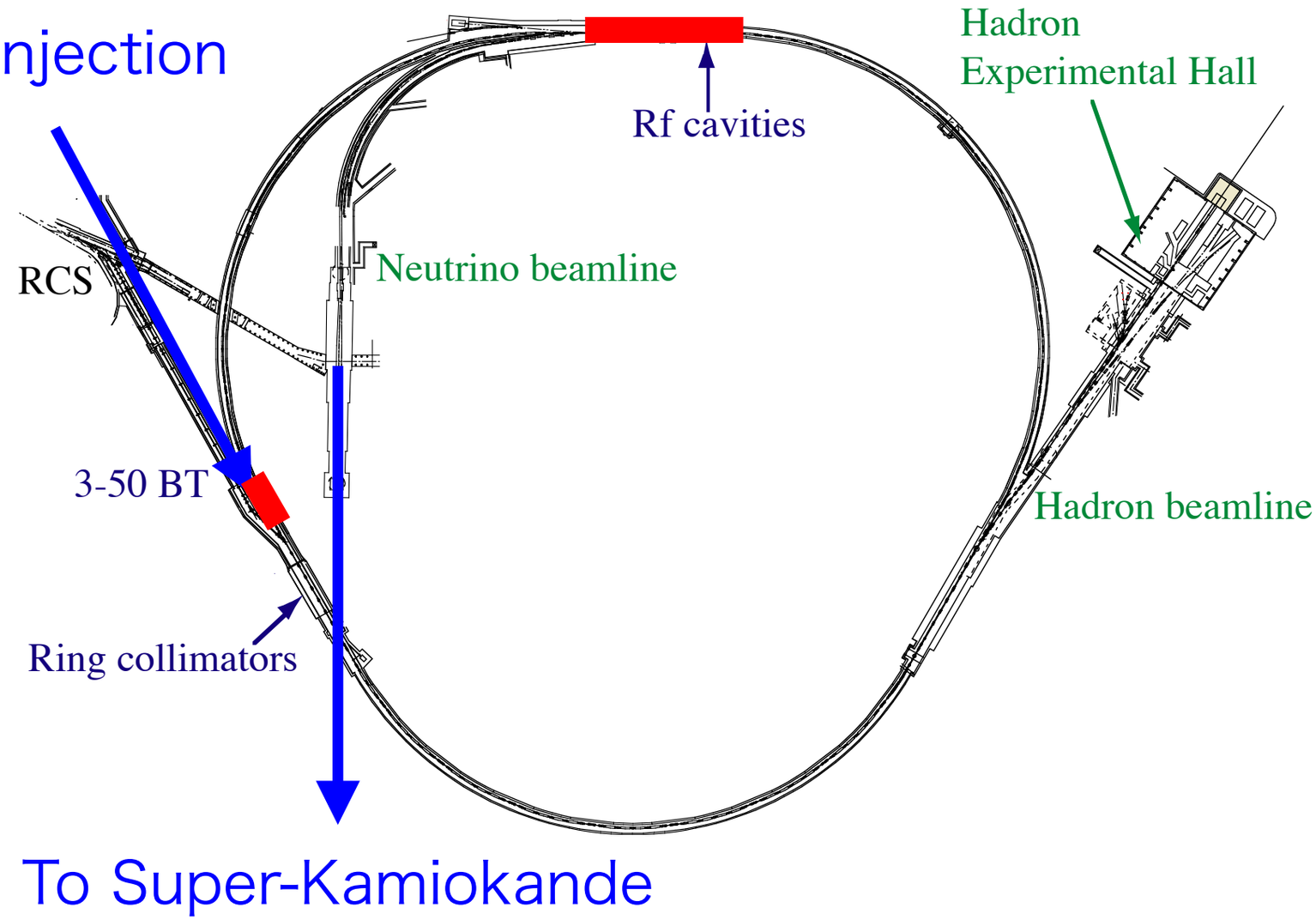


RF system upgrade

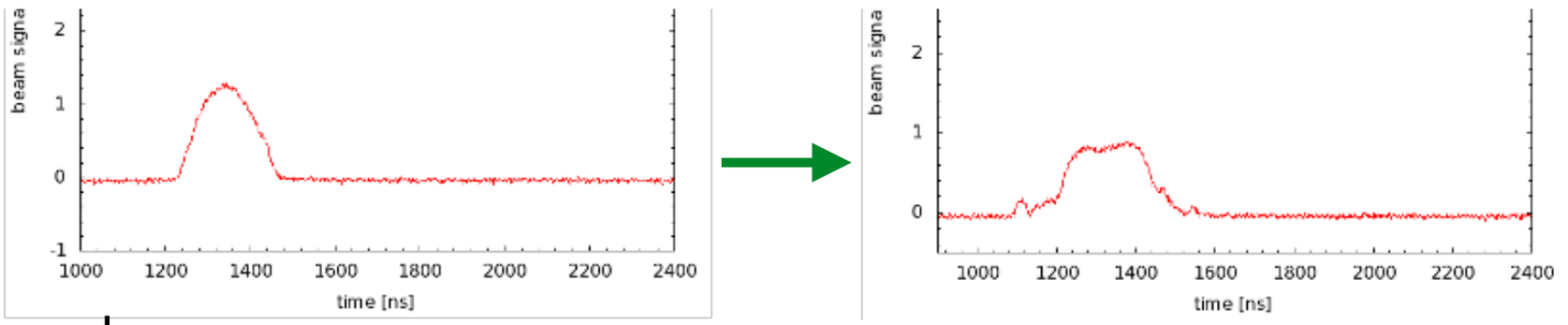
Higher RF voltages are necessary for faster cycling.

The LLRF system was replaced to the new system.

Fundamental cavity : for acceleration

2nd harmonic cavity : for suppressing peak current

New cavity



(simulation)

	Cycle	Number of cavities		Voltage	
		Fundamental	2nd	Fundamental	2nd
2021	2.48 s	7	2	300 kV	110 kV
2023	1.36 s	9	2	510 kV	110 kV
2026	1.16 s	11	2	600 kV	110 kV

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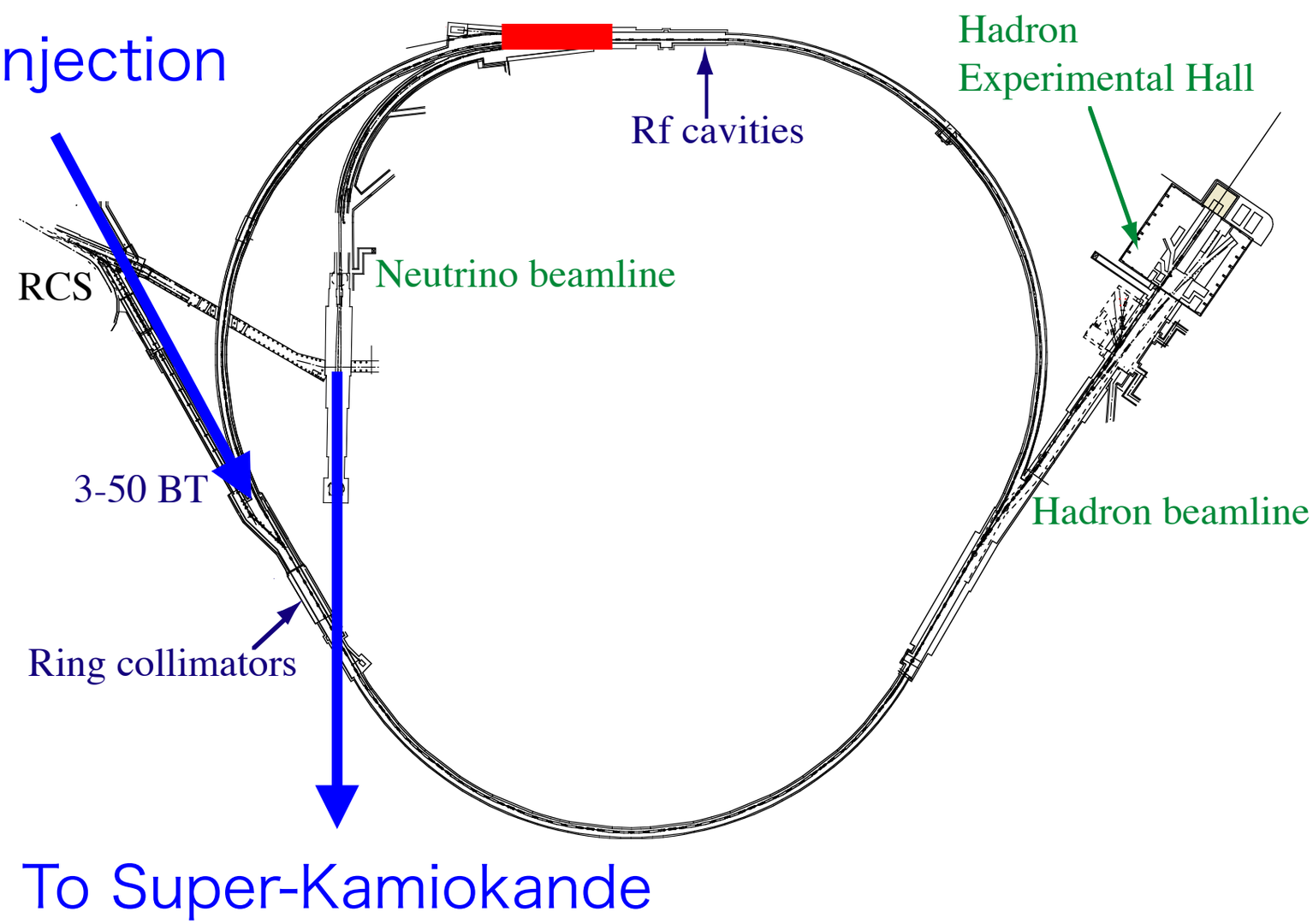
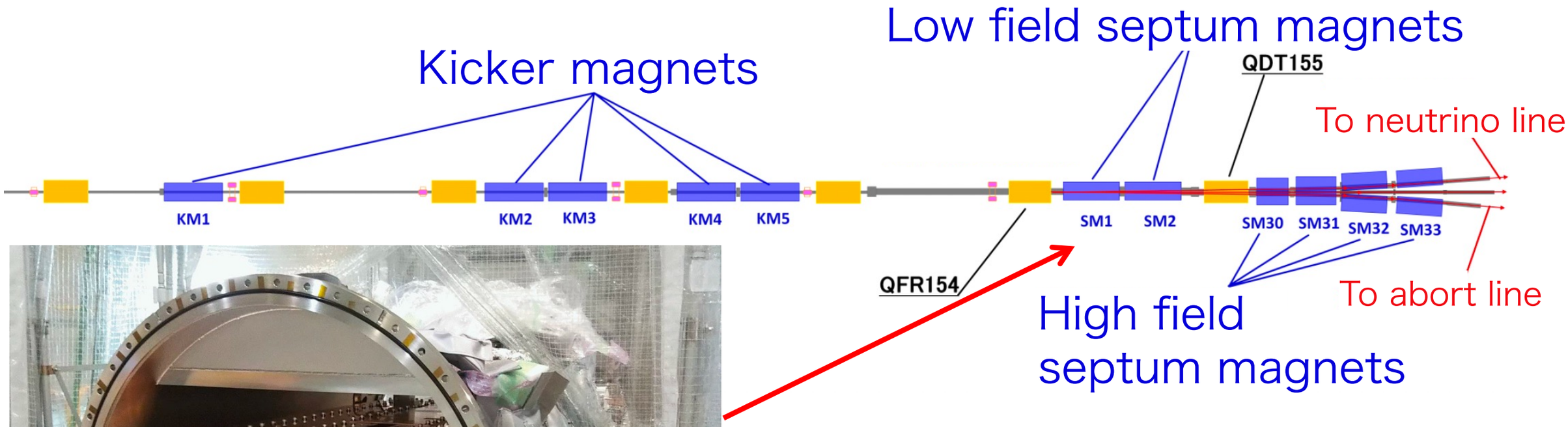
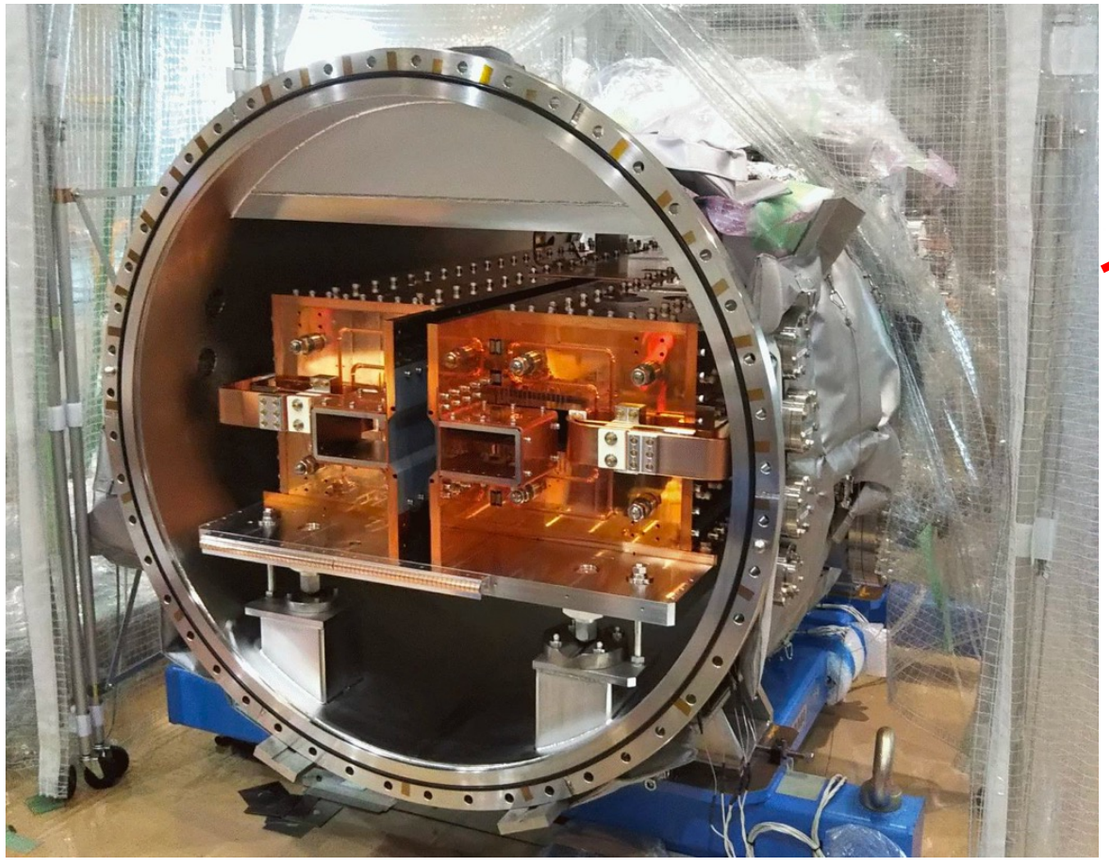


Upgrade of FX septum magnets

All the FX septum magnets were replaced for faster cycling.





New eddy current septum magnet

Low field septum magnets were replaced by eddy current magnets.

Leakage field was reduced (described later).

Hardware upgrade

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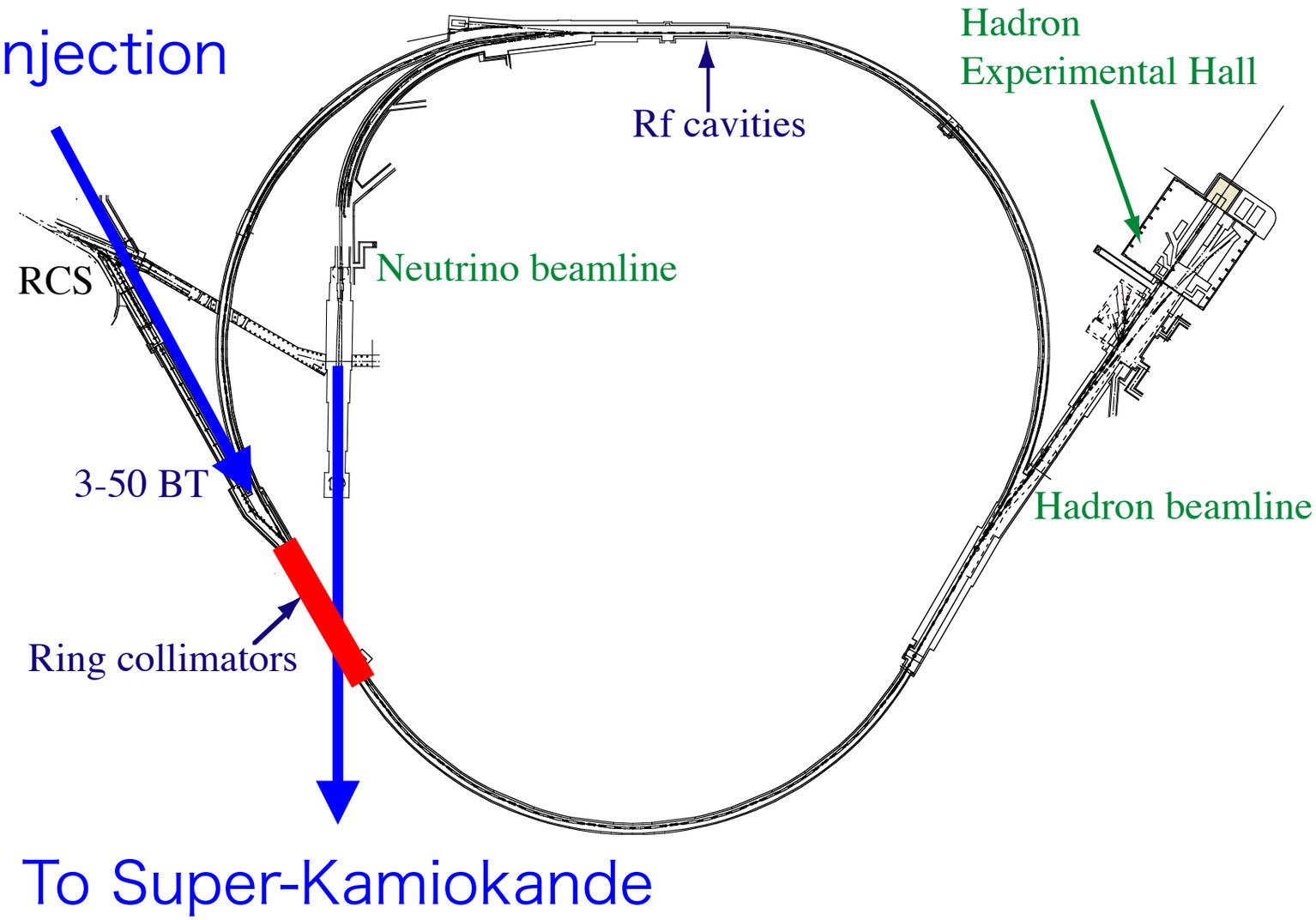


Requirement for beam losses

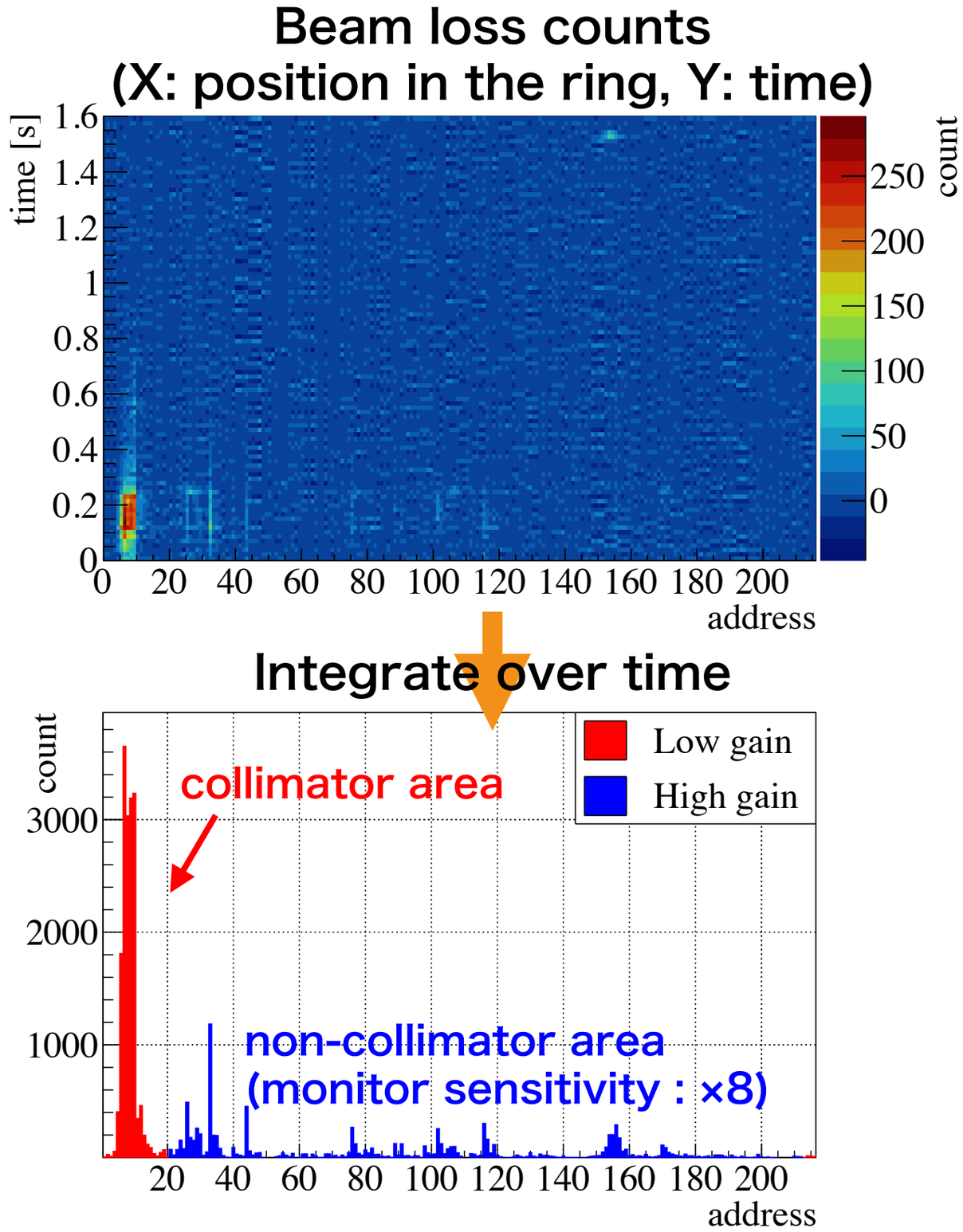
Beam losses are localized at collimator area.

Non-collimator area has been kept clean.

Requirement for beam losses

Non-collimator area should be maintainable by hands

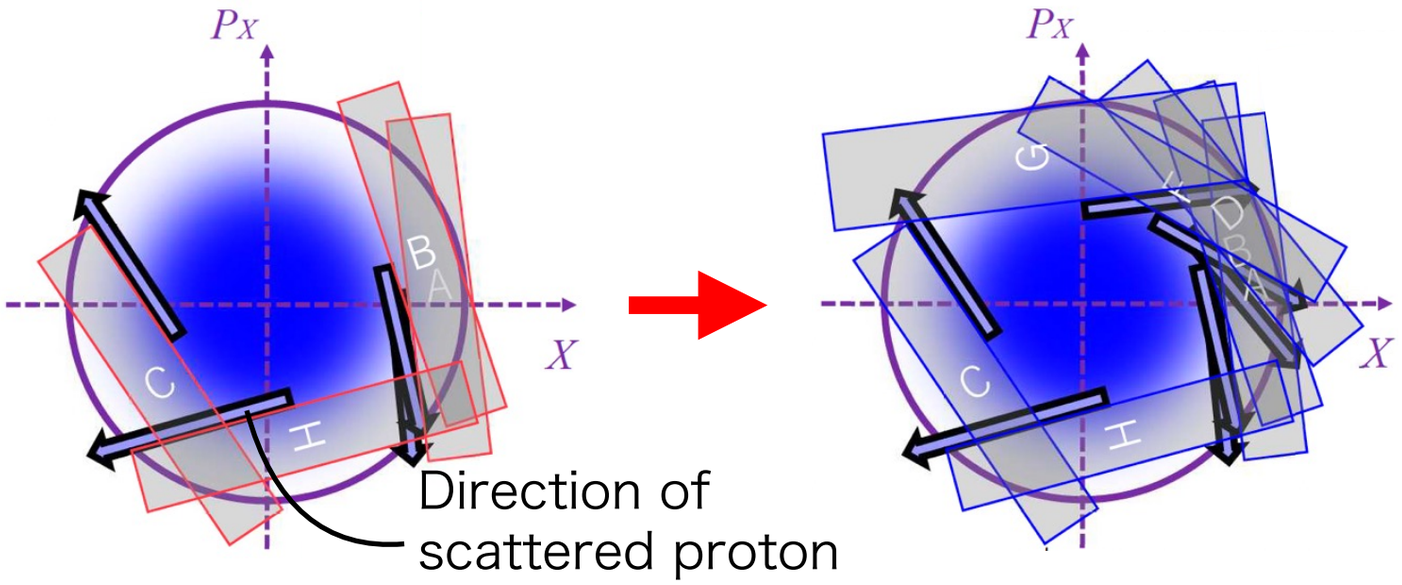
< 300 μSv/h at 1 foot
4h after user operation



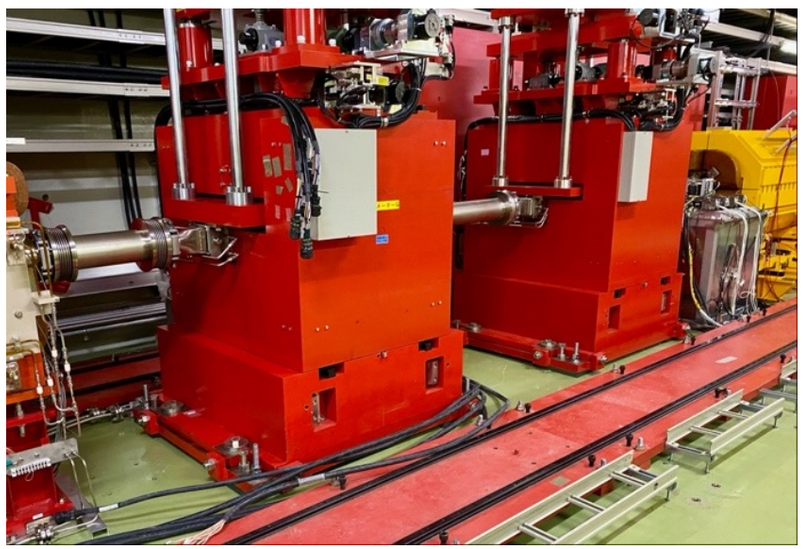
Upgrade of collimators

As the cycle time becomes short, the loss wattage increases.

	Cycle [s]	Coll. number	Coll. capacity [kW]	Beam loss [kW]
Present	2.48	4	2.0	0.8
JFY2022	1.36	7	3.5	?



Previous New



New collimators (red)

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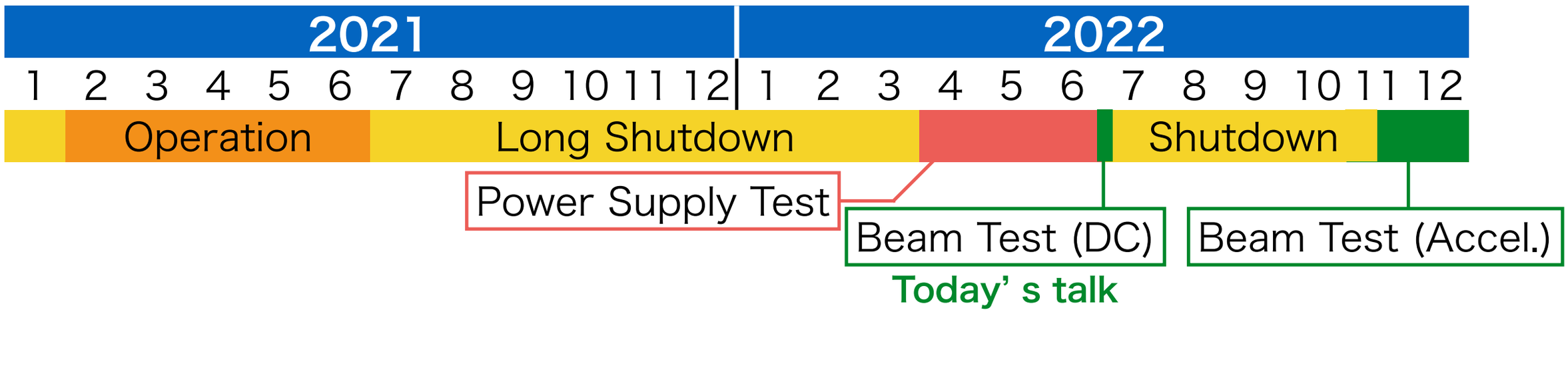
Schedule and contents of the beam study



Beam study was performed for a week in June with DC mode with cycling period of 1.36 s.

Contents of the beam study in June:

- Beam optics adjustment
- Verification of hardware (Magnet PSs, LLRF, FX septum magnets)
- High power beam test

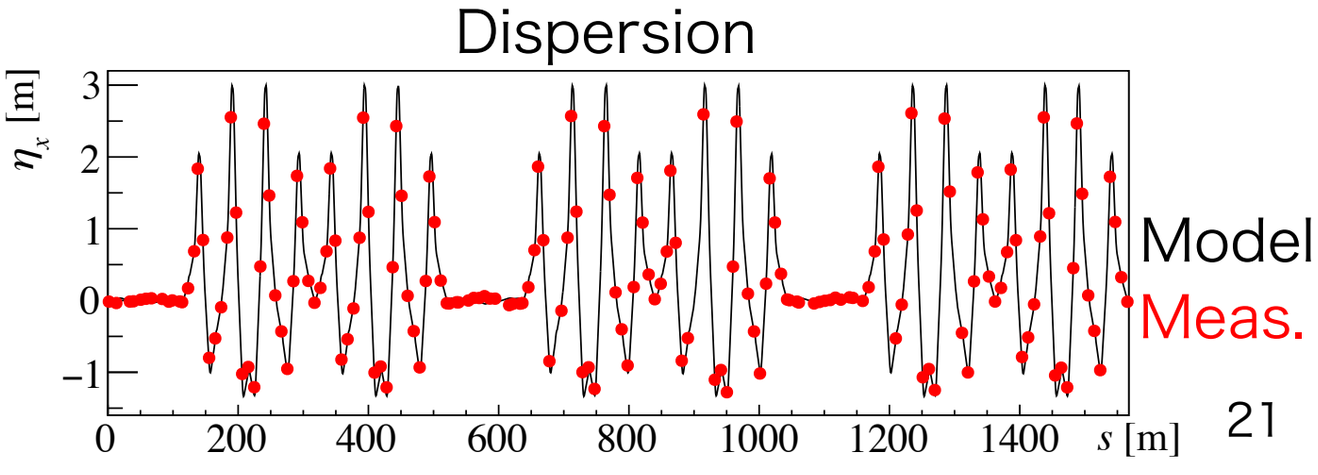
Beam optics adjustment

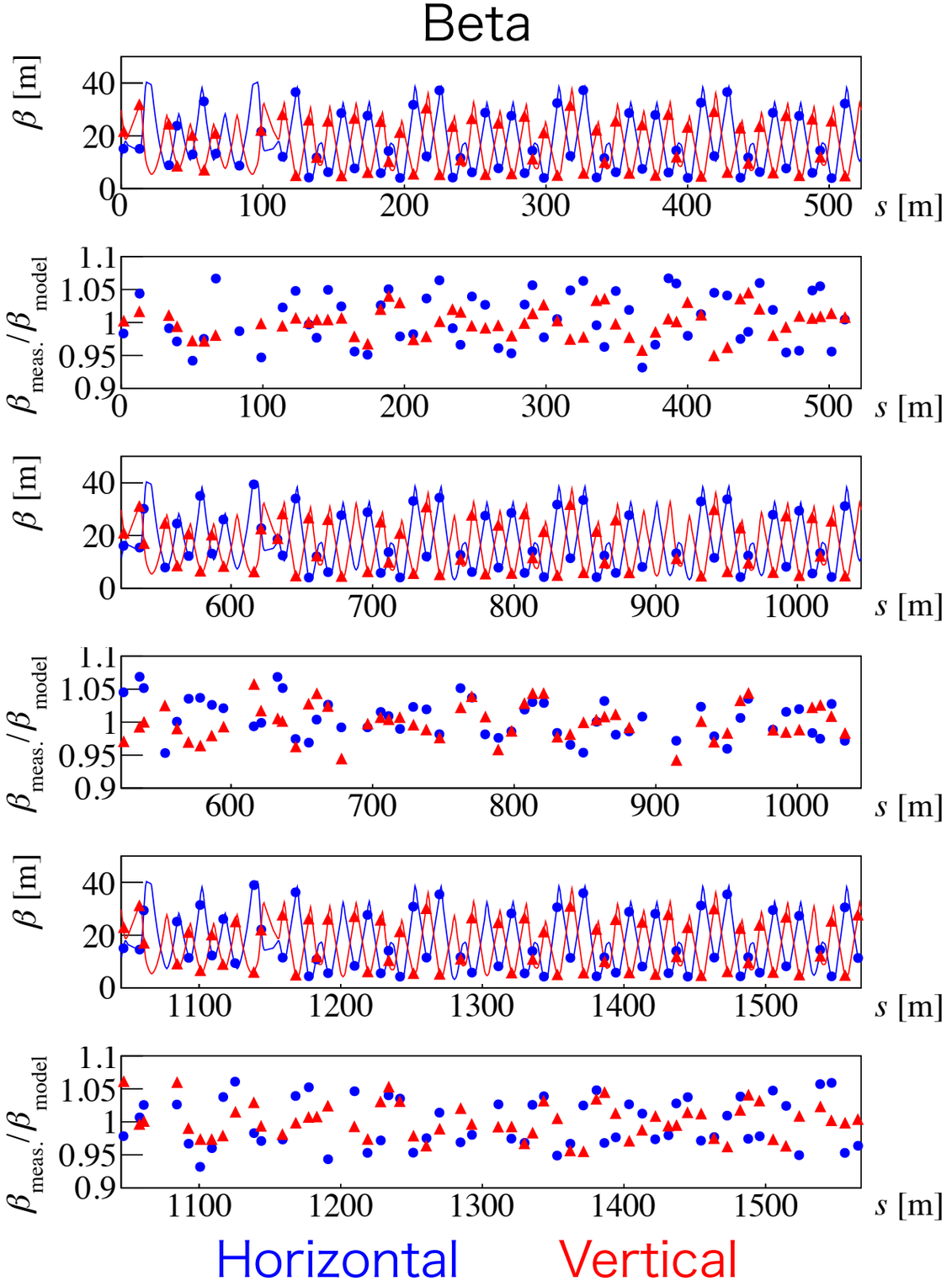
Beam optics was adjusted with sufficient precision based on tune, beta, dispersion measurements.

Tune	Model	Measurement
ν_x	21.35	21.3526 ± 0.0033
ν_y	21.43	21.4313 ± 0.0039

$$(\mathrm{RMS}[\frac{\beta_{x,\mathrm{meas.}}}{\beta_{x,\mathrm{model}}}], \mathrm{RMS}[\frac{\beta_{y,\mathrm{meas.}}}{\beta_{y,\mathrm{model}}}]) = (3.5\%, 2.5\%)$$

$$|\eta_{x,\mathrm{straight}}| < 65\ \mathrm{mm}$$

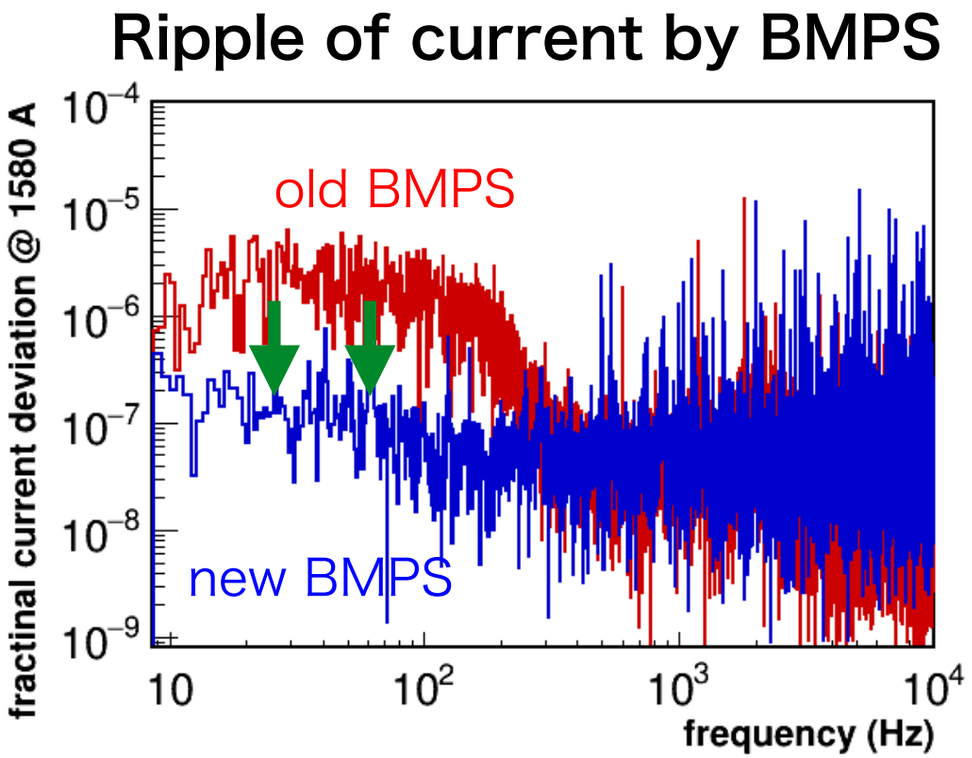




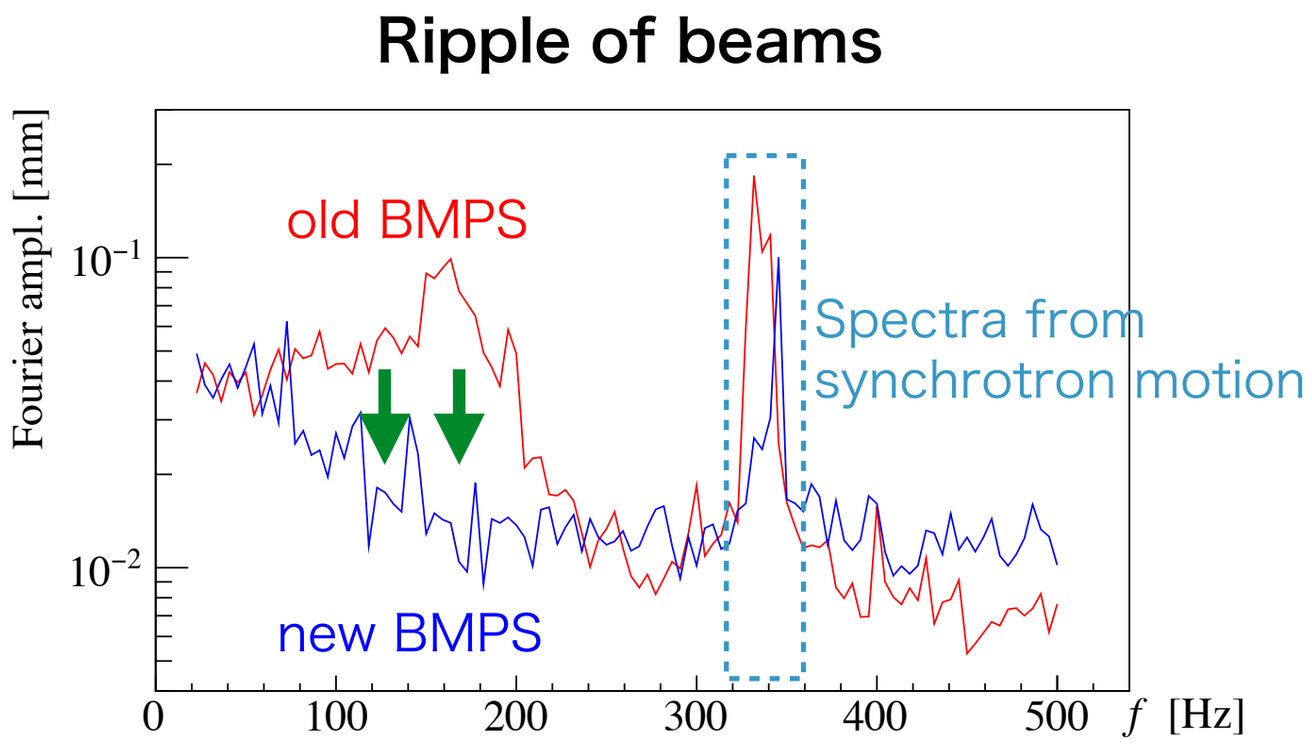
Ripple measurement

Using the new power supplies of bending magnets (BMPSs), ripple of current under 200 Hz was reduced by a factor of 10.

It was confirmed via the Fourier analysis of transverse beam position at high-dispersion position.



T. Shimogawa *et al.*, in *Proc. IPAC'19*, pp. 1266-1268.



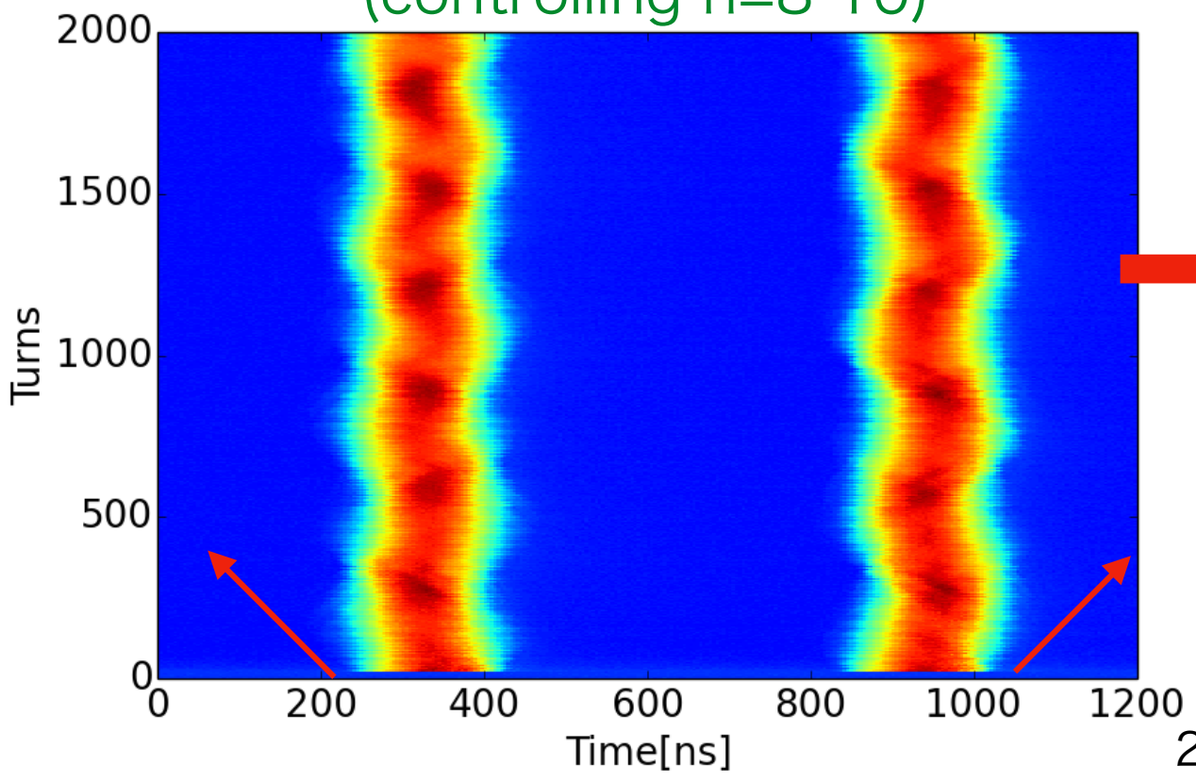
Verification of the new LLRF system

The harmonic number of the MR is 9.

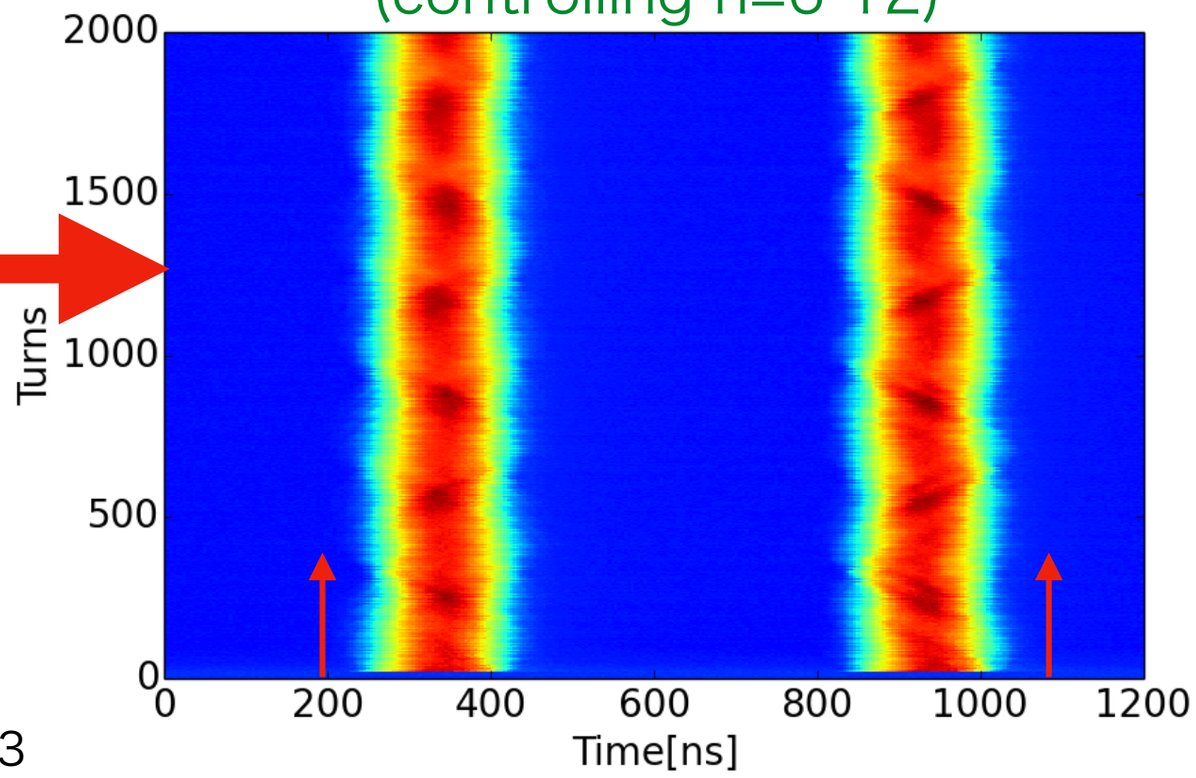
Other side harmonics cause coupled-bunch oscillations.

The new LLRF system can control the harmonic 6-12 by feedback, resulting in suppression of coupled-bunch oscillations.

Previous LLRF system
(controlling h=8-10)

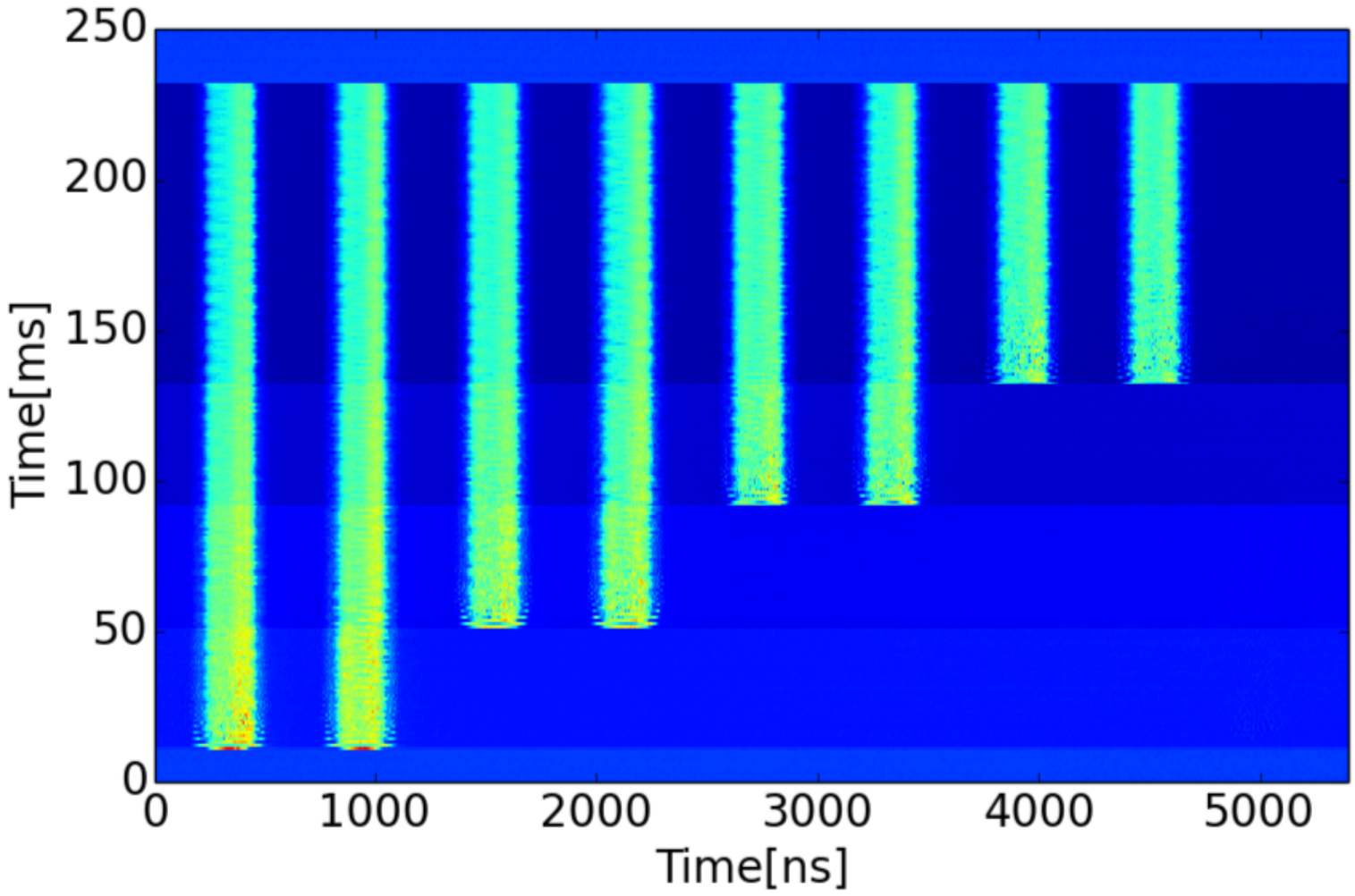


New LLRF system
(controlling h=6-12)



Verification of the new LLRF system

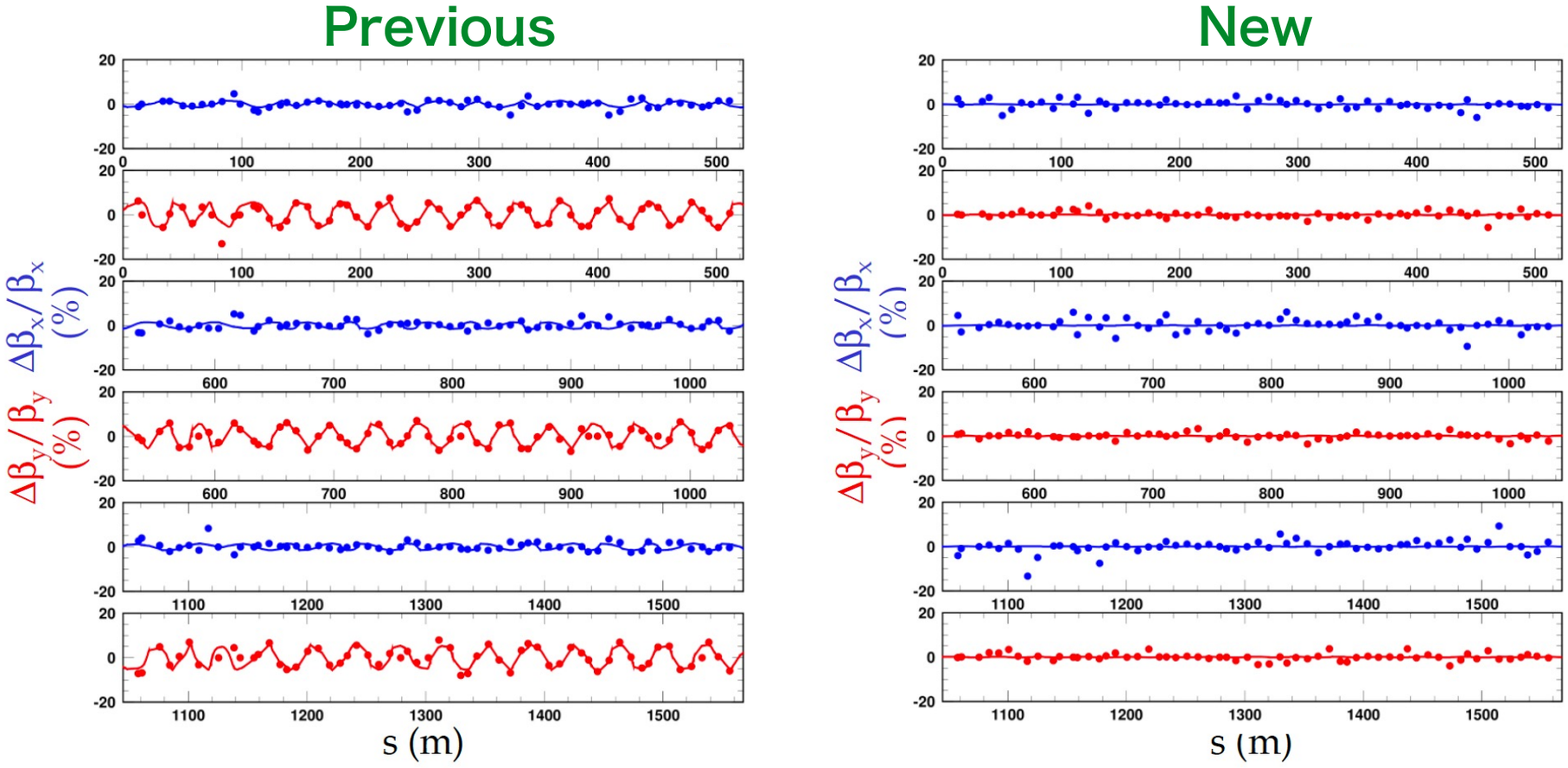
The 2.5×10^{14}-ppp beam was successfully circulated using the new LLRF system without longitudinal coupled-bunch oscillations.



Reduction of leakage field at FX septum magnets

Previous FX septum magnets caused optics modulation.

Beta measurements revealed that the quadrupolar leakage field by the new FX septum magnets was 10 times smaller.



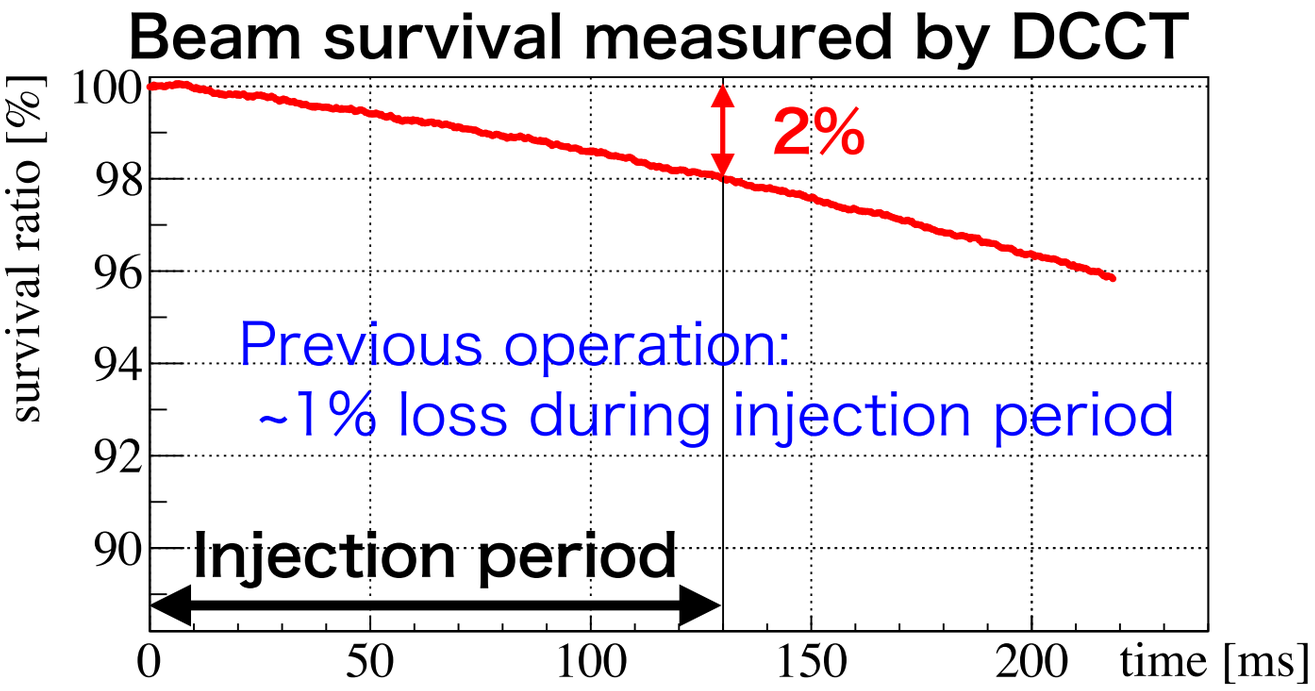
$|\Sigma(\Delta K_1 L)| = 0.00230\ m^{-1}$ → $|\Sigma(\Delta K_1 L)| < 0.00015\ m^{-1}$

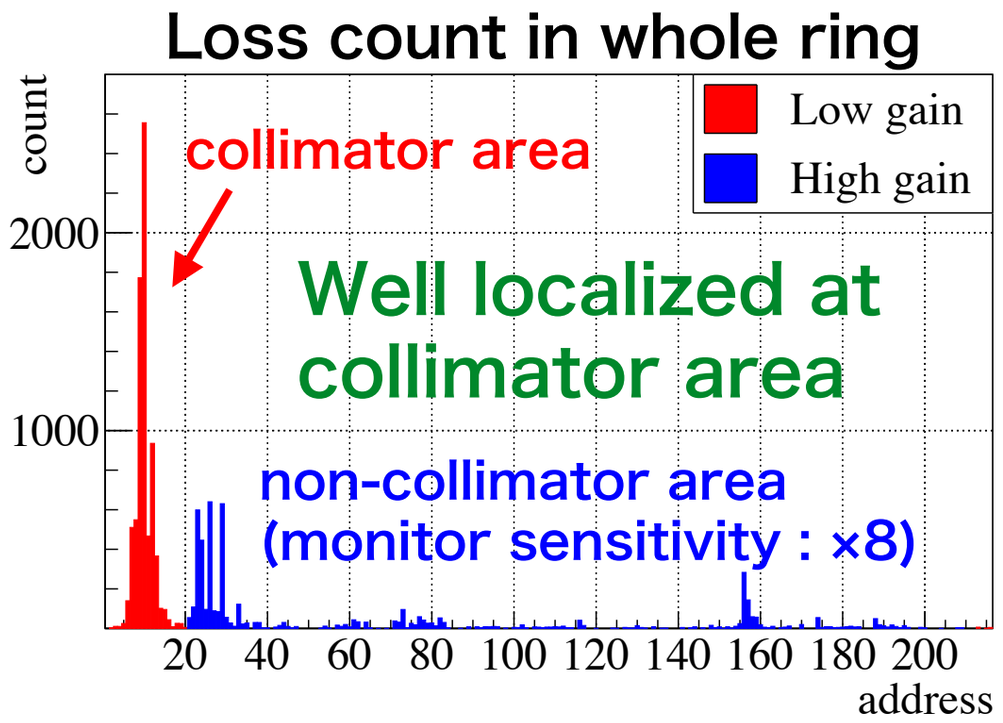
Results of high power beam

High-intensity DC-current beam study was performed
with two bunches beams (2.7×10^{13} ppb).

Although the beam loss during the injection period was worse,
loss localization was very good.

→ **740-kW equivalent protons were accumulated with well-controlled beam loss.**

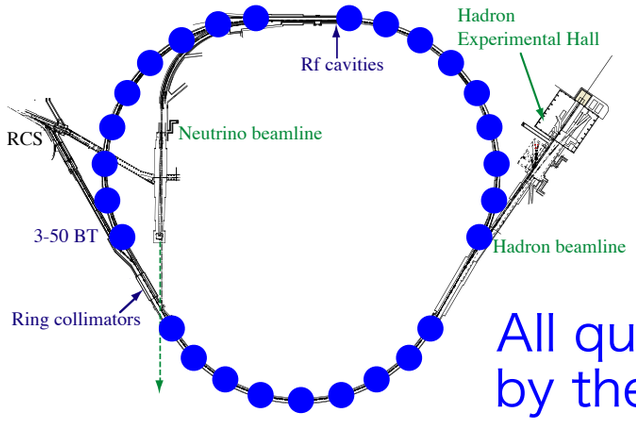




Effects of three-fold symmetry breaking

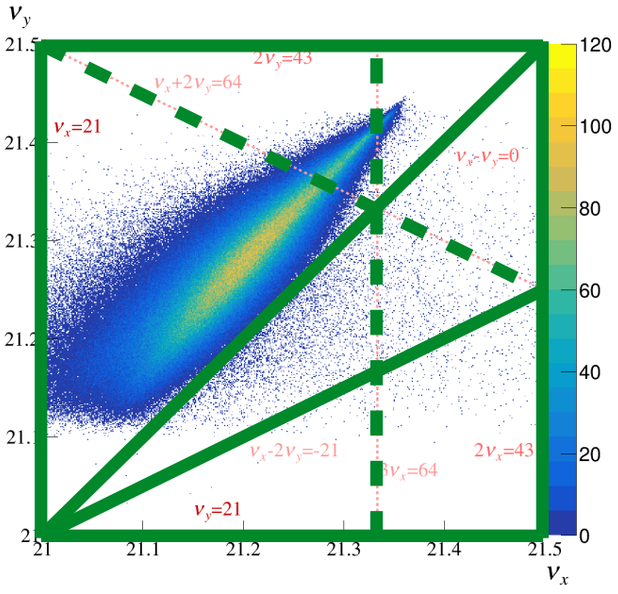
Deterioration of beam survival was caused by three-fold symmetry breaking of the accelerator derived from family splitting in several quadrupole magnets.

Before upgrade



Example of quad family QDX

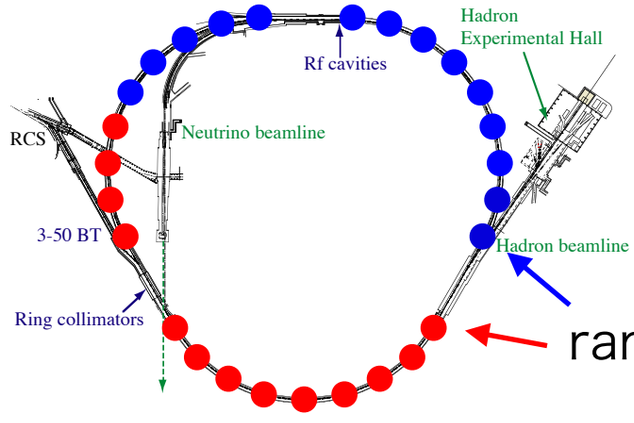
All quads were ramped by the same PS.



Green lines:

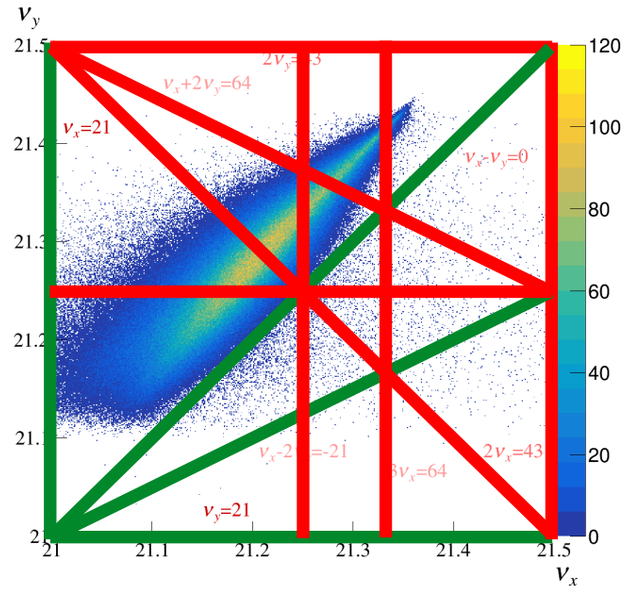
Strong resonances

After upgrade



Split!

ramped by different PSs



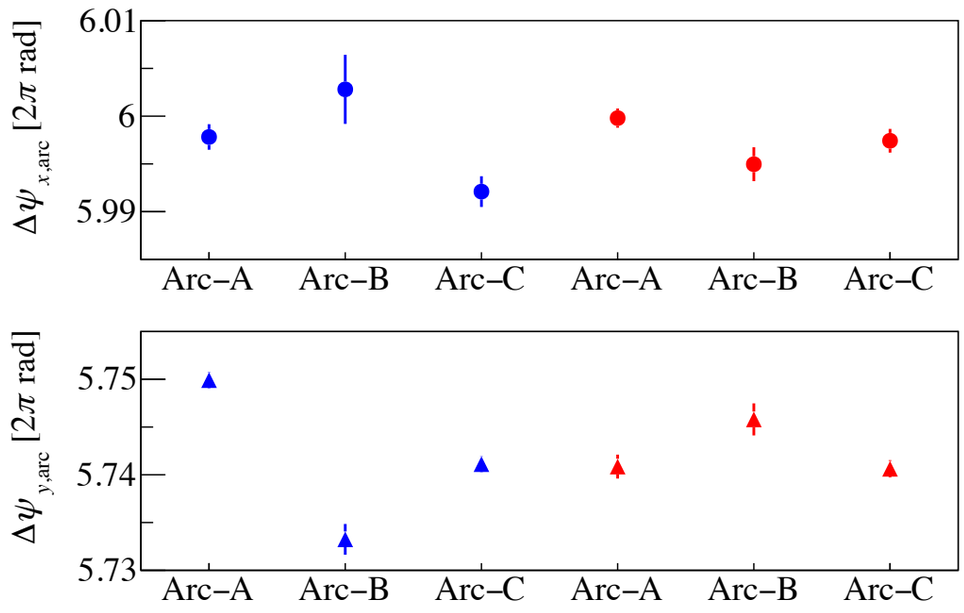
Red lines:

Reinforced or newly appeared resonances

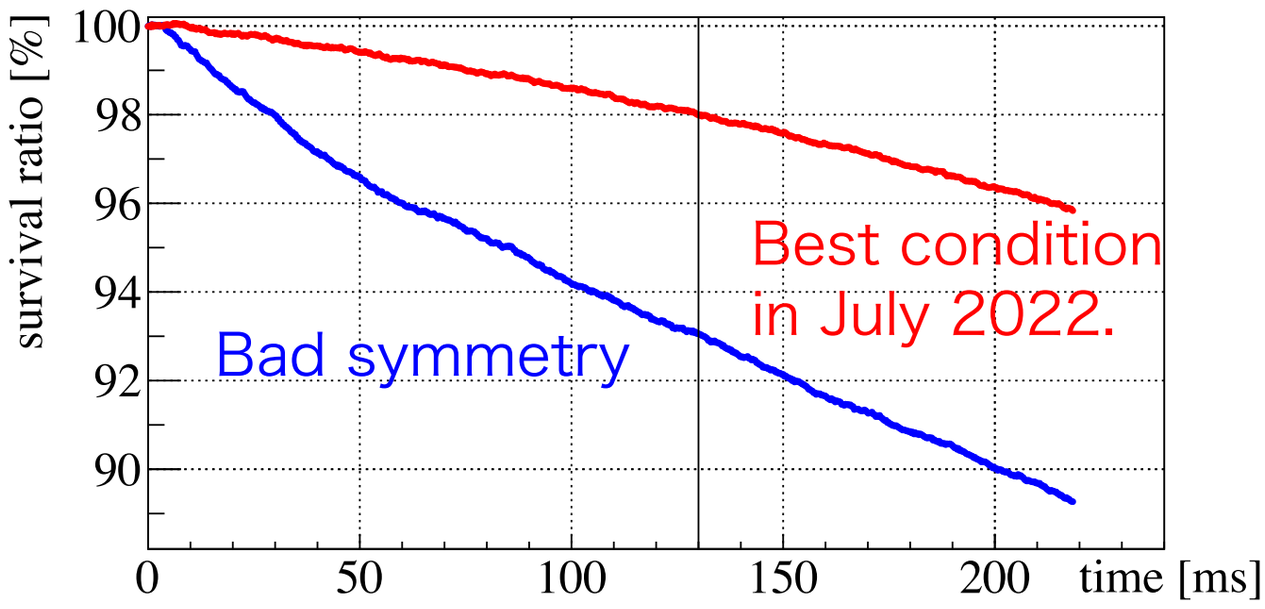
Effects of three-fold symmetry breaking

The dependency of the beam loss on the three-fold symmetry breaking was measured.

Phase advance in arc section



Beam survival ratio

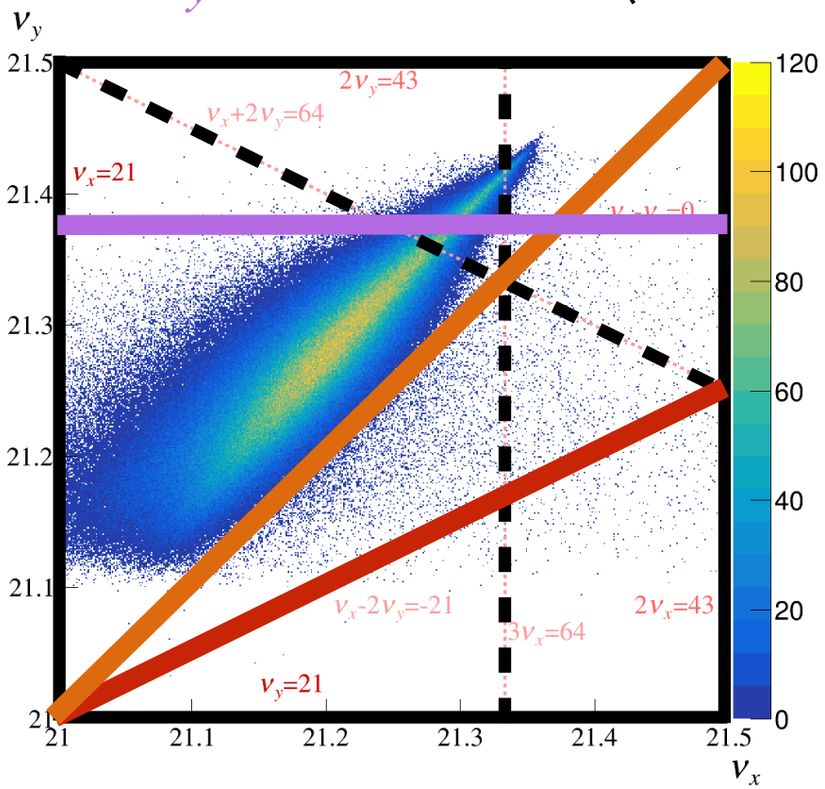


By further phase balancing, the beam survival will be recovered.

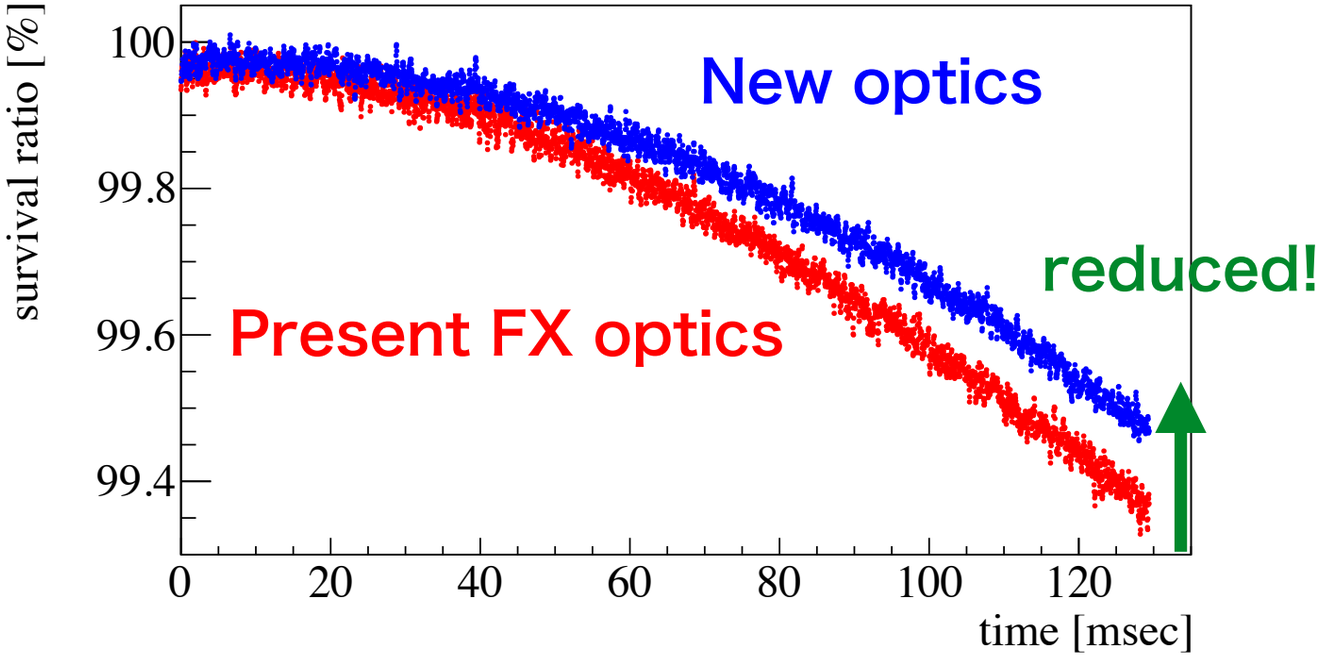
Beam loss reduction by the new optics (plan)

The new beam optics can compensate/weaken some resonances.

- $\nu_x - 2\nu_y = -21$ (driven by sextupole magnetic field) T. Yasui et al., PTEP 2022, 013G01 (2022)
- $2\nu_x - 2\nu_y = 0$ (driven by space charge effects)
- $8\nu_y = 171$ (driven by space charge effects)



Beam survival ratio (measured by DCCT)



We plan to test the new beam optics in November beam study and aim at applying to the user operation for higher intensity.

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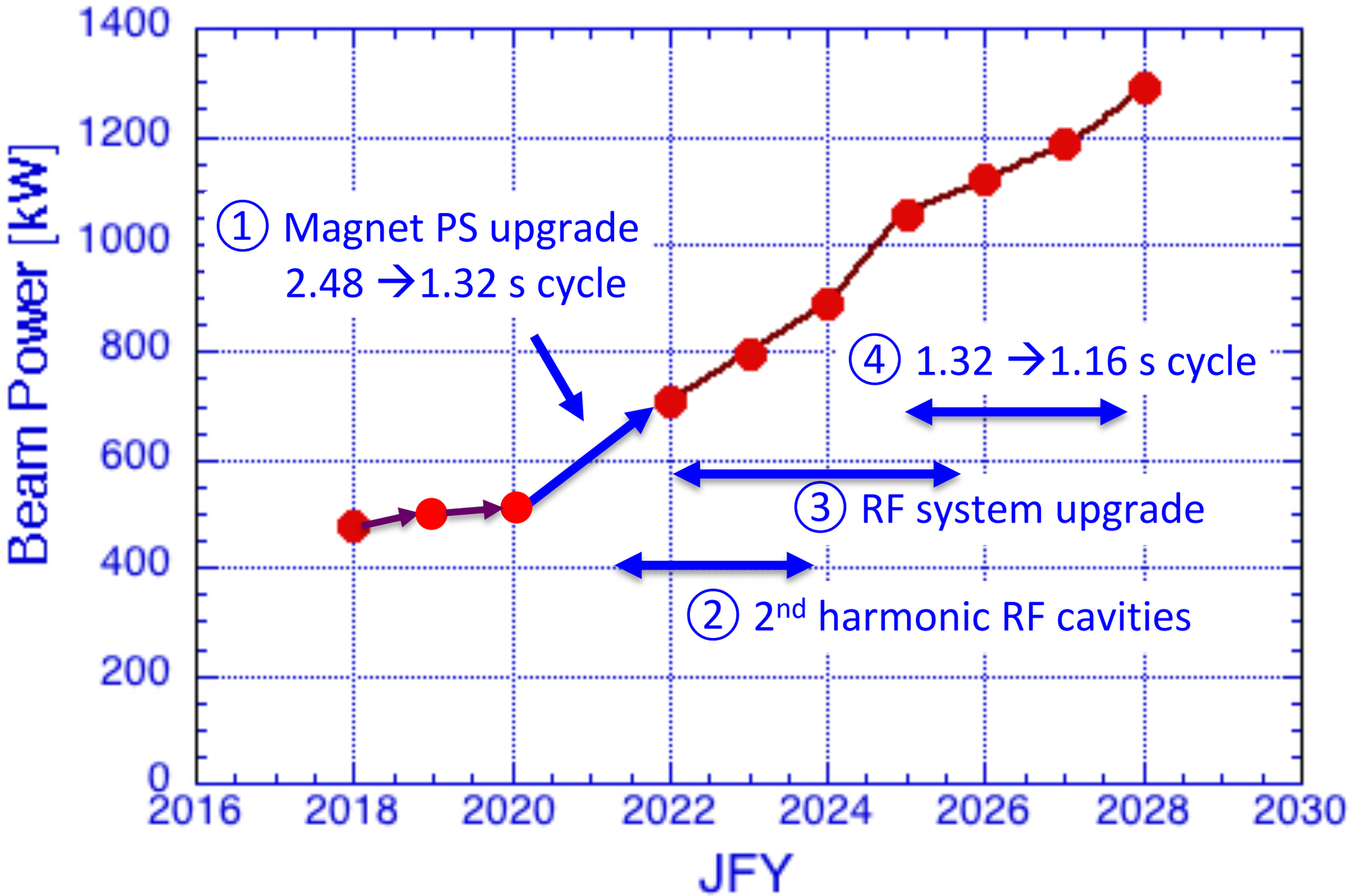
Beam power upgrade plan of MR



Midterm plan of MR

JFY	2020	2021	2022	2023	2024	2025	2026	2027	2028
FX power [kW]	515	-	>700	800	900	>1000	>1100	>1200	1300
Cycle for FX [s]	2.48	-	1.32	1.32	1.32	1.32	<1.32	<1.32	1.16
Event		Long shutdown ⟷							
Magnet PS	Mass production, installation, test →								
RF upgrade			← Fundamental →						
	——— 2nd →								
Collimator system	Add collimators, to 3.5 kW capacity ⟷								
Inj/Ext system	Kicker PS improvement, FX septa manufacture, test →								
Monitors	BPM circuits →								

We also plan to increase the capacity of the MR beam abort dump (KEK/RAL collaboration).

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Summary

To realize 1.3-MW operation, the MR upgraded

- Power supplies of main magnets,
- RF system (in phases),
- FX septum magnets,
- Collimators (in summer),

and they were verified by beam studies.

740-kW equivalent beams were well-controlled.

Splitting quadrupole families caused deterioration of beam loss.
It will be recovered by balancing phase symmetry precisely.

Upgrade scenario is on schedule and the beam power will be gradually increased.