MR Upgrade and Power Management

Y. Morita
KEK/J-PARC

Proton Driver Efficiency Workshop
Paul Scherrer Institut
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Contents

- Overview of MR Upgrade

- Magnet Power Supply

- High Gradient Accelerating Cavity

- Summary

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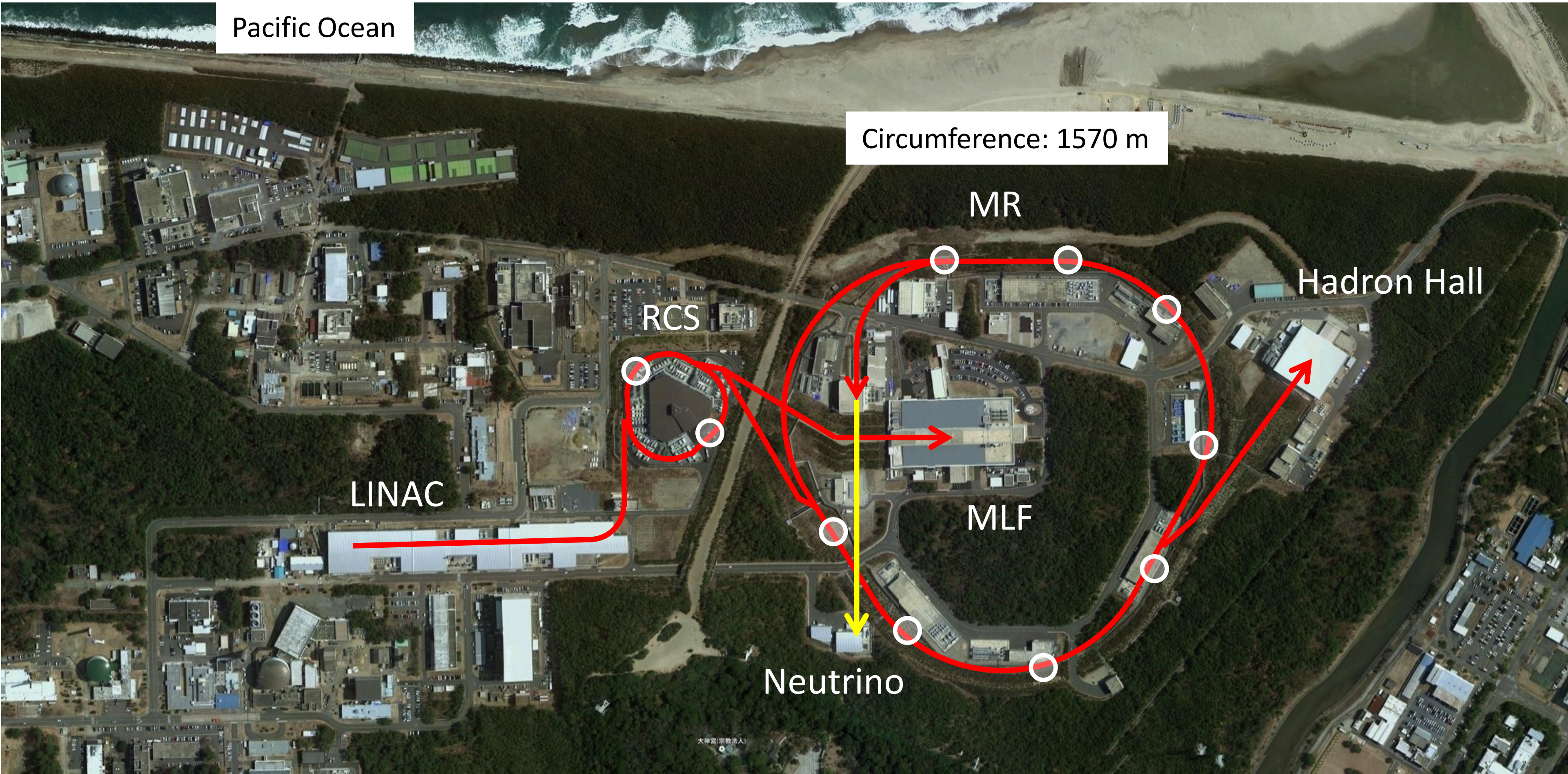
J-PARC Main Ring (MR)

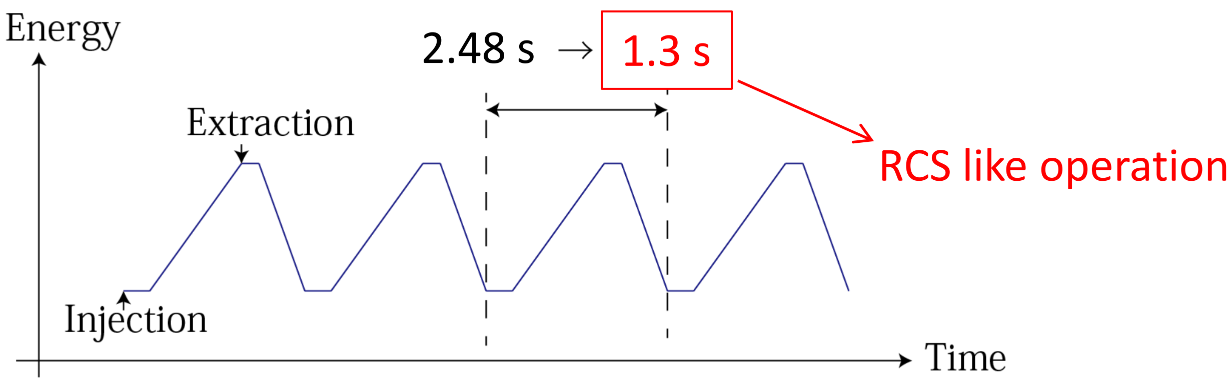
Acceleration: 3 GeV to 30 GeV
Circumference: 1570 m
3 insertion sections
8 bunches in one cycle
2 experimental halls (Neutrino, Hadron)



In order to achieve the MR beam power of 750 kW,

the scheme of Increasing Repetition Rate is adopted.

Increasing Repetition Rate from 0.40 Hz to 0.77 Hz



Main components to be upgraded

Magnet Power Supply (PS)

- High output voltage
- Capacitive energy storage

RF Accelerating Cavity

- High accelerating gradient
- High performance Magnetic Alloy (FT-3L)

Contents

Issues on high repetition rate operation

1. High Output Voltage

Output voltage for Inductive Load

$$V_{out} = L\frac{dI}{dt} + RI$$

As the repetition rate is faster, *dI/dt* becomes larger.

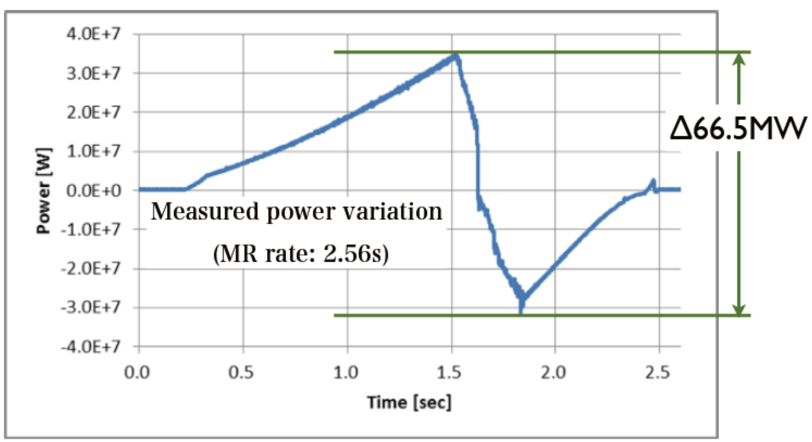
Output voltage increases beyond rated voltage of PS

Solution

Developing new PS consisting of several PS units in series

2. Power Variation at Electrical System

2.56 sec cycle



S. Nakamura

1.3 sec cycle

~~~Δ140MW~~

Not allowed by electric power company

Solution

Installing energy storage system
~~~

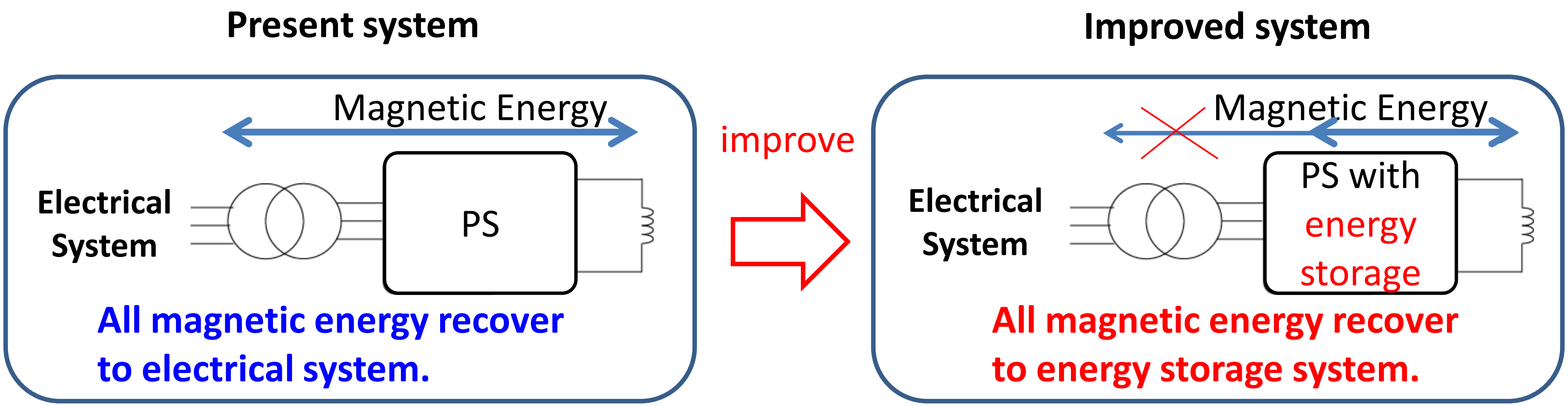
List of MR Main Magnets and PSs

		Power Supply	Total Inductance at 30 GeV [H]	Flat Base Current [A]	Flat Top Current [A]	Output Voltage [kV] 2.5 sec / 1 sec
Large PS	B Magnets	BM1~6	1.47	190	1570	2.6 / 5.8
	Q Magnets at Arc Sections	QFN	2.93	86	710	2.7 / 5.6
		QDN	3.46	86	710	3.1 / 6.7
		QFX	2.39	88	730	2.6 / 4.8
		QDX	1.75	86	710	1.6 / 3.4
Small PS	Q Magnets at Linear Sections	QFR	0.57	77	640	0.5 / 1.3
		QDR	0.44	75	620	0.4 / 0.7
		QFP	0.20	77	640	0.3 / 0.4
		QFS	0.30	81	670	0.3 / 0.5
		QDS	0.35	110	890	0.5 / 0.9
		QFT	0.32	95	780	0.4 / 0.7
		QDT	0.37	90	750	0.4 / 0.7
	S Magnets	SFA	0.42	23	200	0.3 / 0.4
		SDA	0.41	19	160	0.2 / 0.3
		SDB	0.41	19	160	0.2 / 0.3

Required Performance of PS for MR Main Magnets (e.g. single B magnet family)

	Cycle [sec]	Output Current [A]	Output Voltage [kV]	Output Power [MW]
Present	2.48	1600	3	5
High repetition	1.3	1600	~ 6	~ 10

Schemes for Energy Storage



Possible Solutions

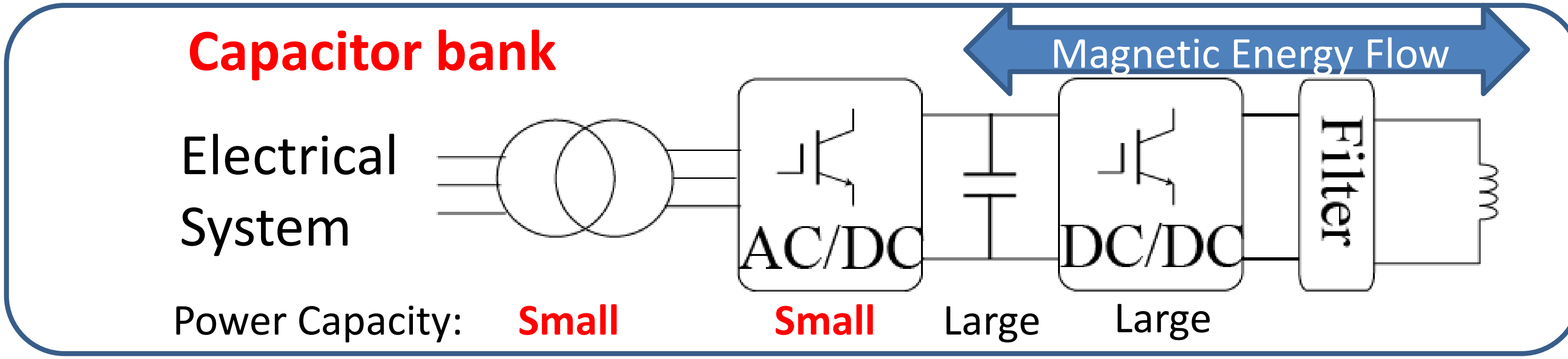
- **Capacitor bank**

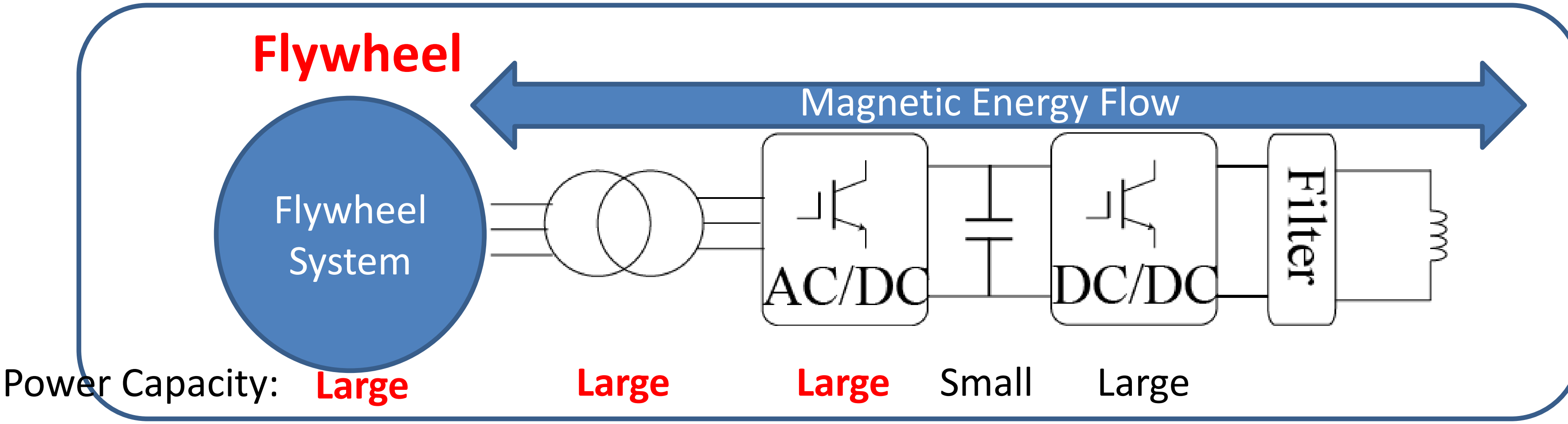
  Energy is stored in capacitors. (electrostatic energy)

- **Flywheel**

  Energy is stored in a rotor. (kinetic energy)

Capacitor bank and Flywheel





Capacitor Bank : Large capacitor is required.

Flywheel : Large transformers, Flywheel system, and large rectifiers are required.

Total cost of capacitor bank is expected to be less than that of flywheel.

The capacitor bank scheme was adopted based on the recommendation in the PS review committee meeting held in 2014.

Example of Capacitor Bank

CERN proton synchrotron

Capacitor banks to store energy from magnets.

Dry-type film capacitors are installed in the containers.

Jean-Paul Burnet, POCPA2010

List of MR Main Magnets and PSs

B magnets are the largest power variation sources.

Capacitor banks for the BMPSs are indispensable.

		Power Supply	Total Inductance at 30 GeV [H]	Flat Base Current [A]	Flat Top Current [A]	Output Voltage [kV] 2.5 sec / 1 sec
Large PS	B Magnets	BM1~6	1.47	190	1570	2.6 / 5.8
	Q Magnets at Arc Sections	QFN	2.93	86	710	2.7 / 5.6
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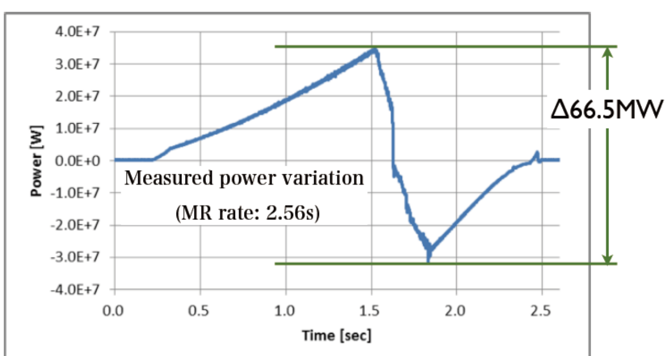
<u>2.56 sec cycle</u>

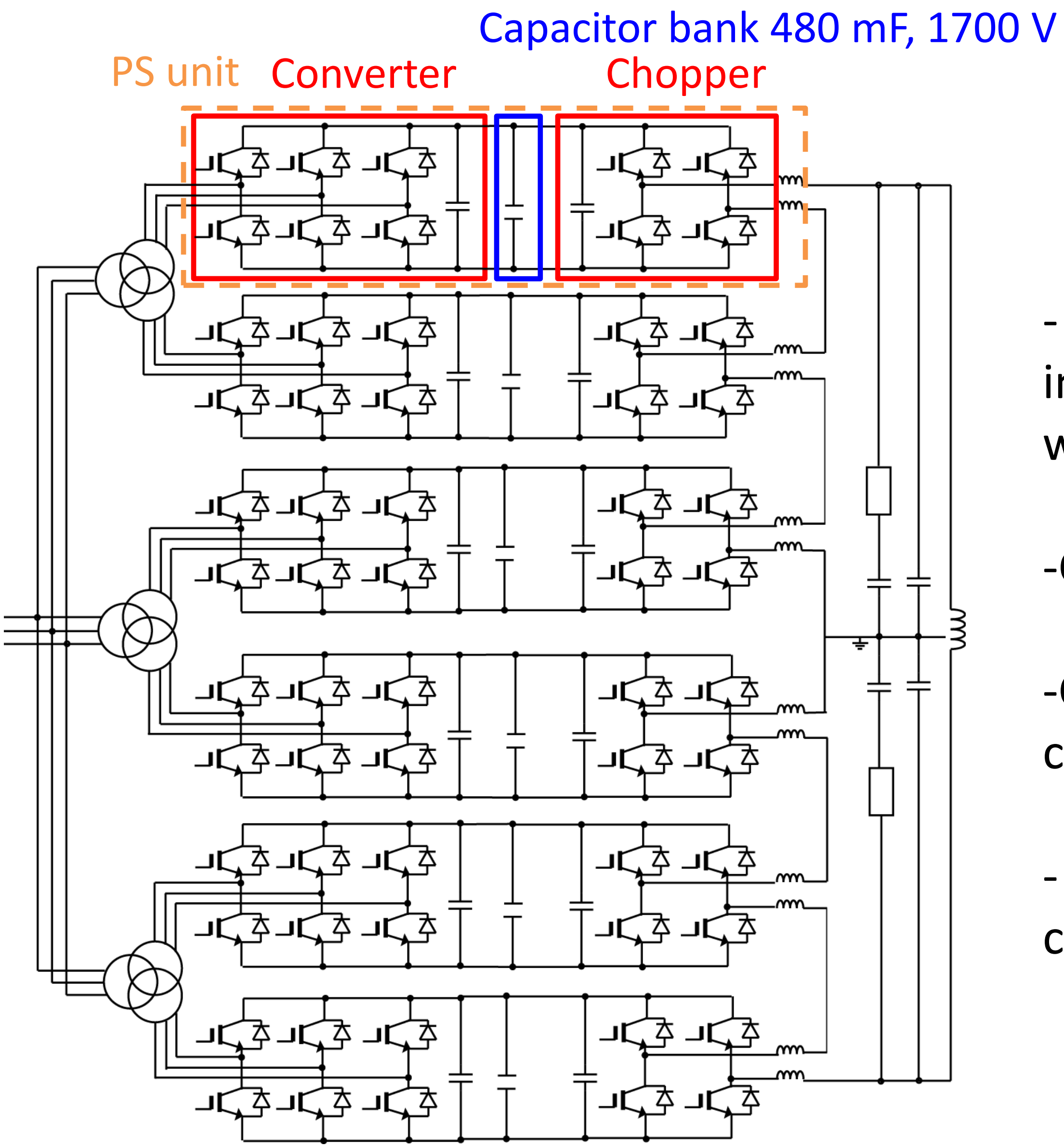


<u>1.3 sec cycle</u>

w/o Capacitor Bank: ~Δ140 MW

w/ Capacitor Bank: Keep the Present Value

Design of Large PS



- Six PS units are connected in series to realize sufficient withstand voltage.

-Capacitor bank for energy storage

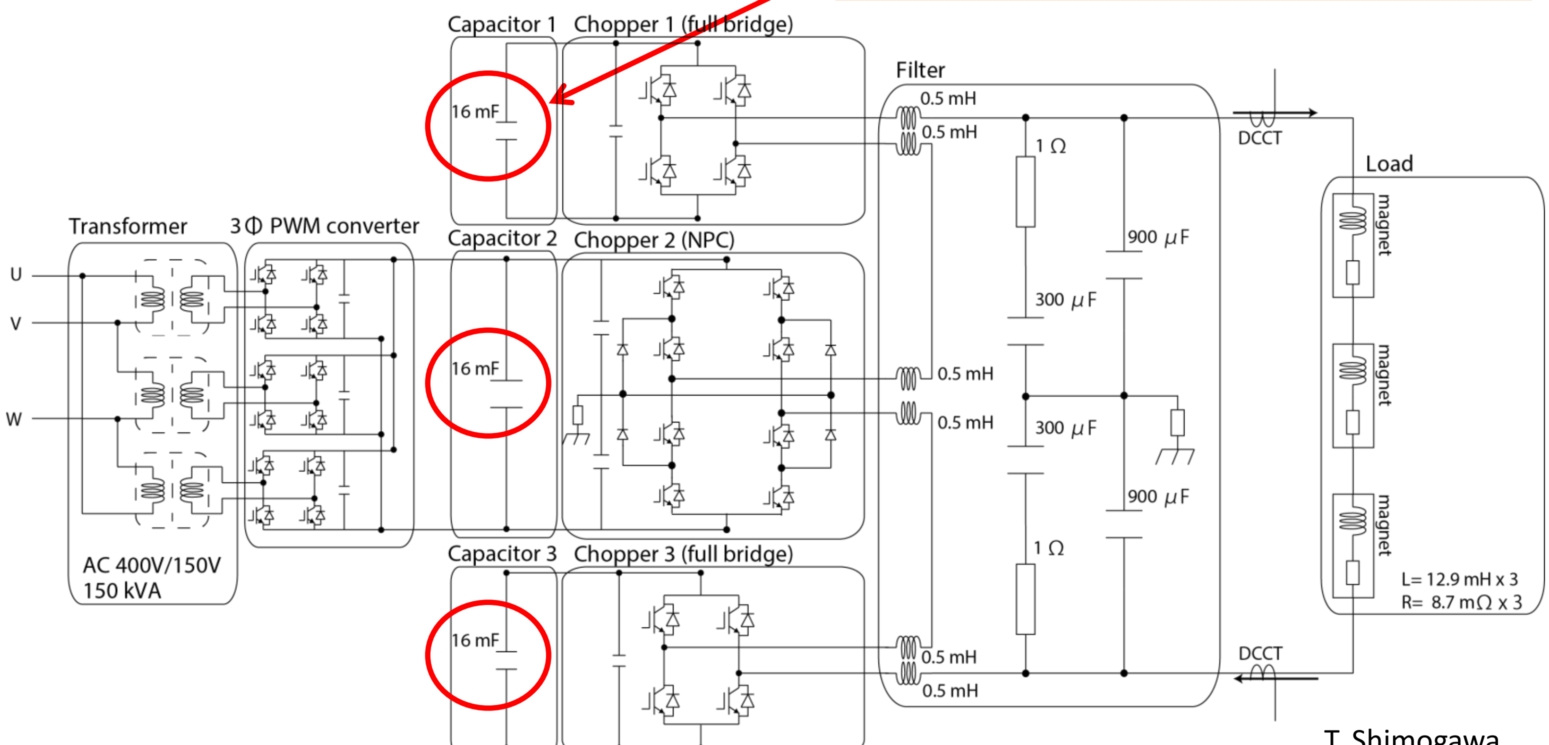
-Capacitor banks are installed in containers

- Symmetrical circuit for common mode rejection.

Test with Manufacturer

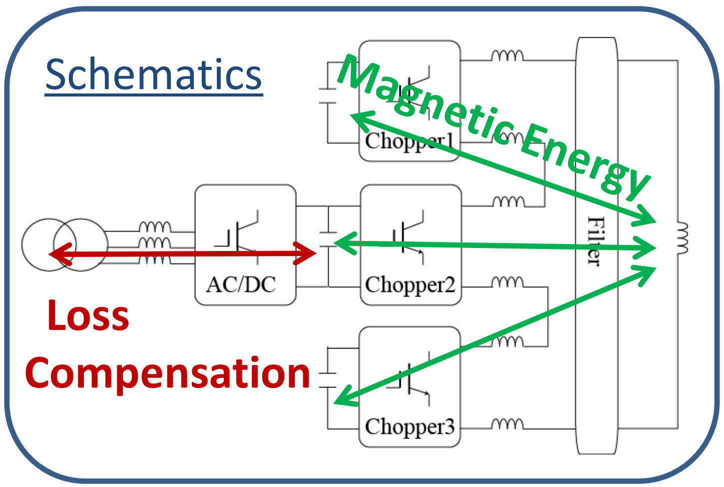
<u>Minimum hardware and our developed control system were tested at the manufacturer's factory</u>

- Switching units are **real scale.**
- Capacitor Bank: 16 mF, 2500V
  No container in this test



T. Shimogawa

Test Result



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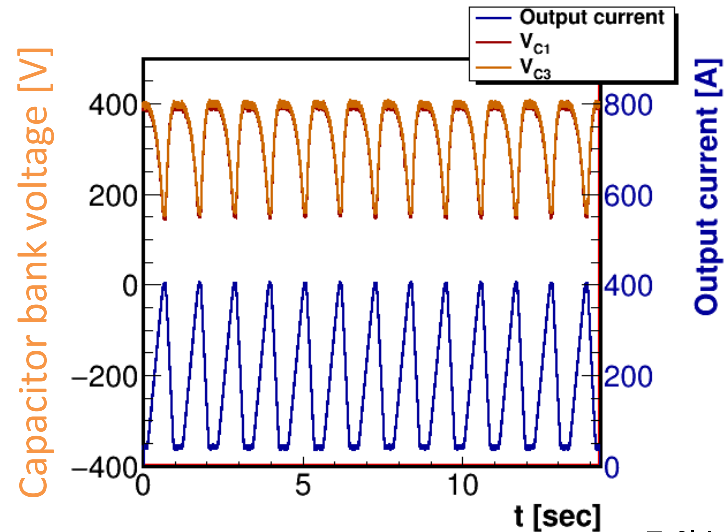
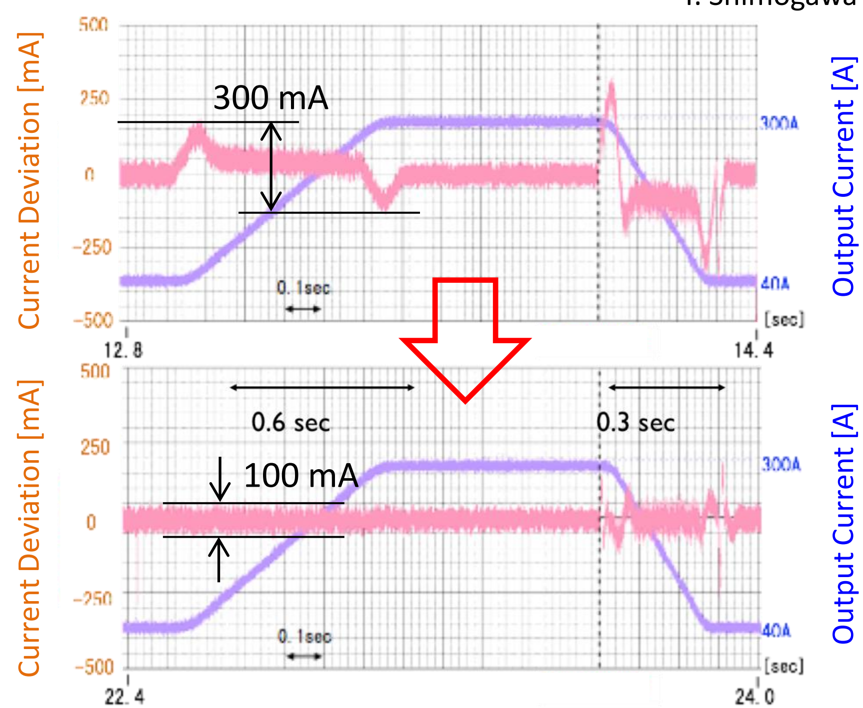


T. Shimogawa

②



We have succeeded

①**Energy transfer control between the capacitor bank and magnets**

②**Correction of the current deviation**

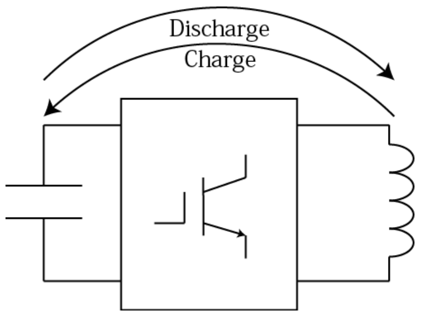
Control method has been established with the real scale PS components.

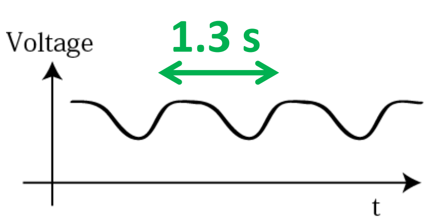
$\Delta I/I_{top} = 3 \times 10^{-5}$ @ 1.5 kHz (SW)

Capacitor for Energy Storage

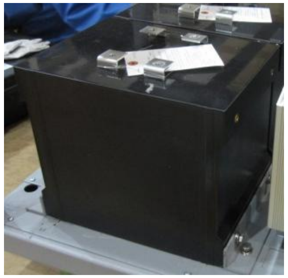
The capacitor should

have longer than 10 years lifetime (~ 10^8 charge-discharge cycles)
not be shorted internally (for safety)



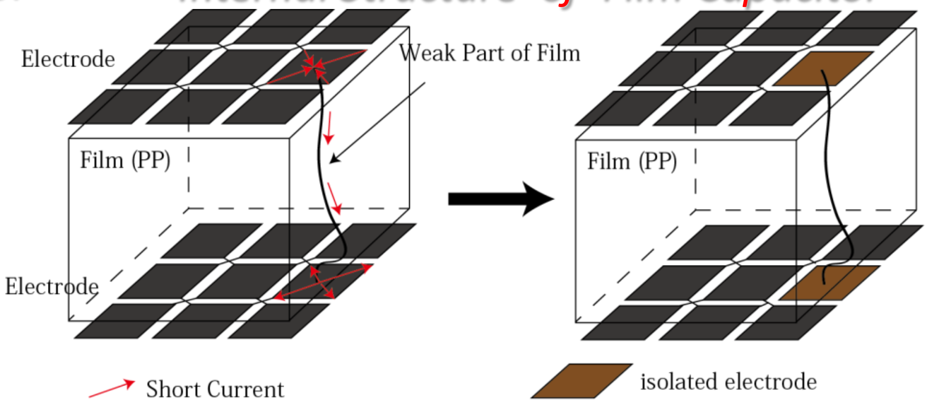


Dry-type film Capacitor



- Long lifetime
- No internal short
  (self-healing structure)

Internal Structure of Film Capacitor



More pixels = Safer

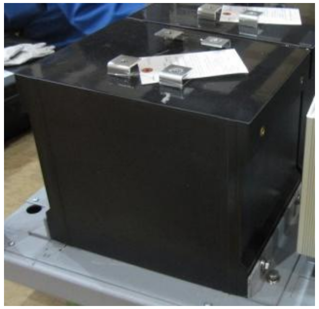
Self-Healing (SH) structure

1. Many small pixel capacitors connect with each other
2. A pixel capacitor with weak part is isolated by over current
3. As a result, the capacitance decreases by 1/10000

Prevention of huge short-circuit current

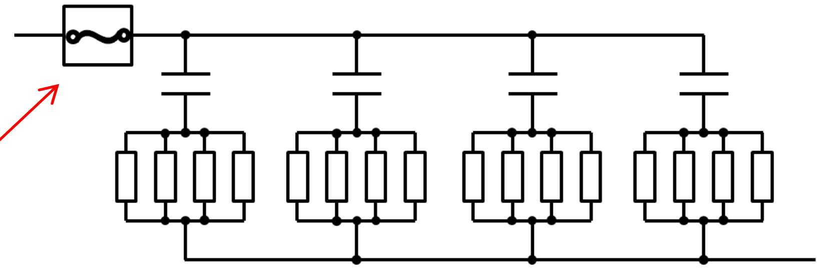
Capacitor Unit

Capacitor



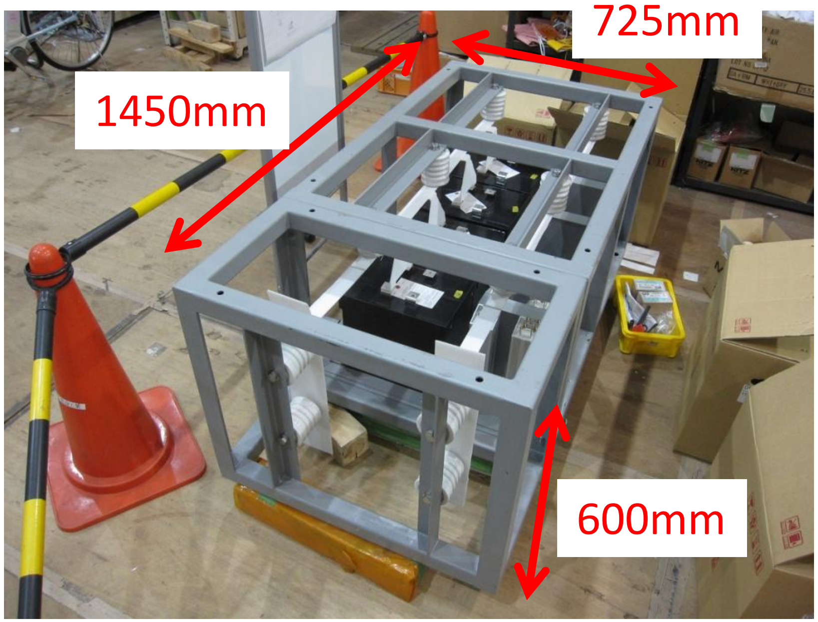
- Dry-type film capacitor
- Self-healing structure
- 5 mF, 1700 V
- 23.5 kg

Circuit diagram of capacitor unit

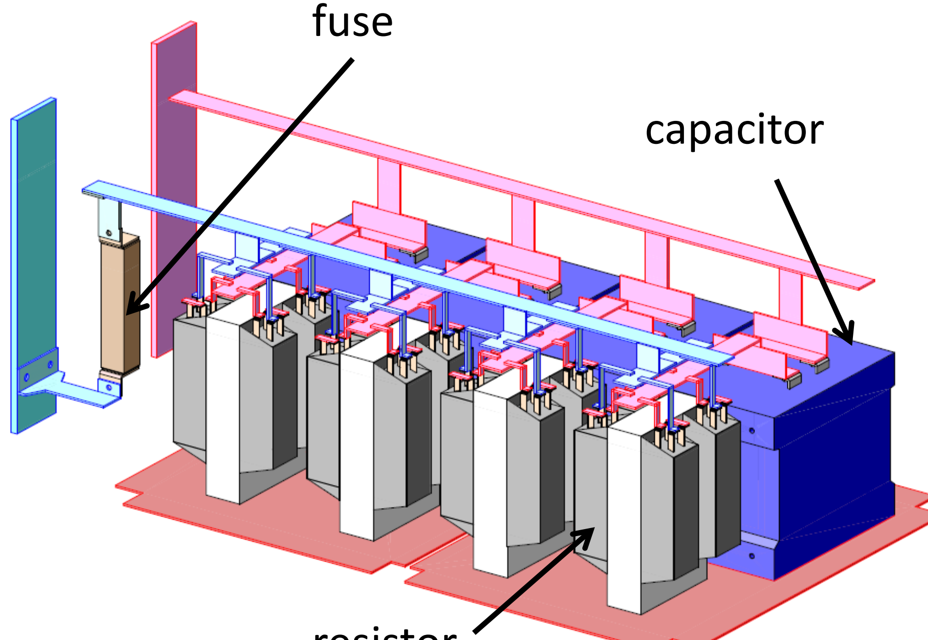


One fuse for four capacitors.

Fuse to avoid the concentration of energy from ~100 capacitors (if a capacitor is shorted.)

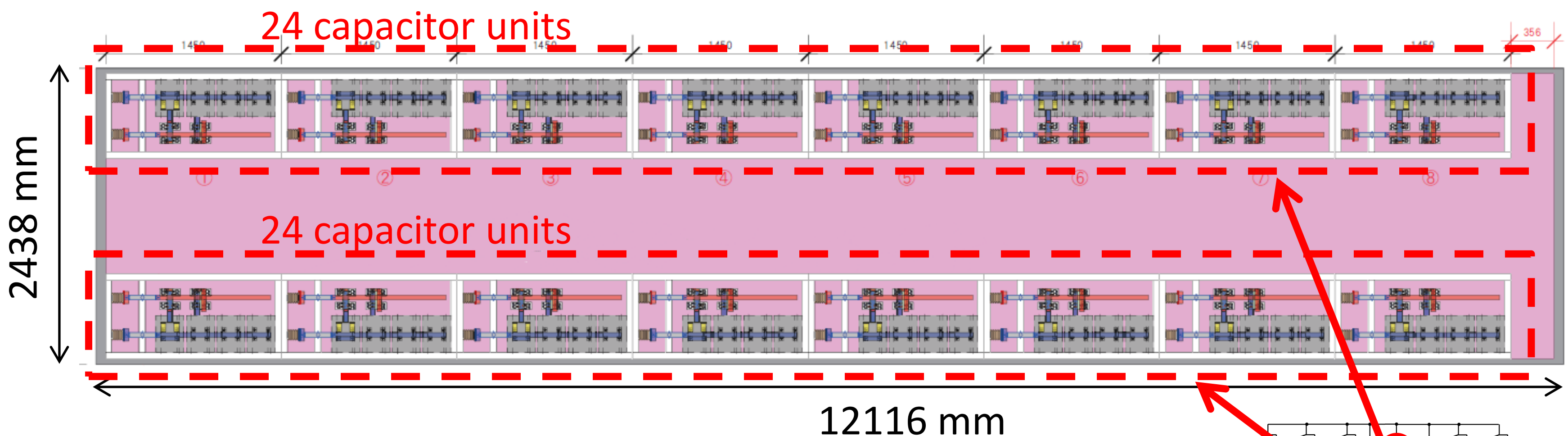


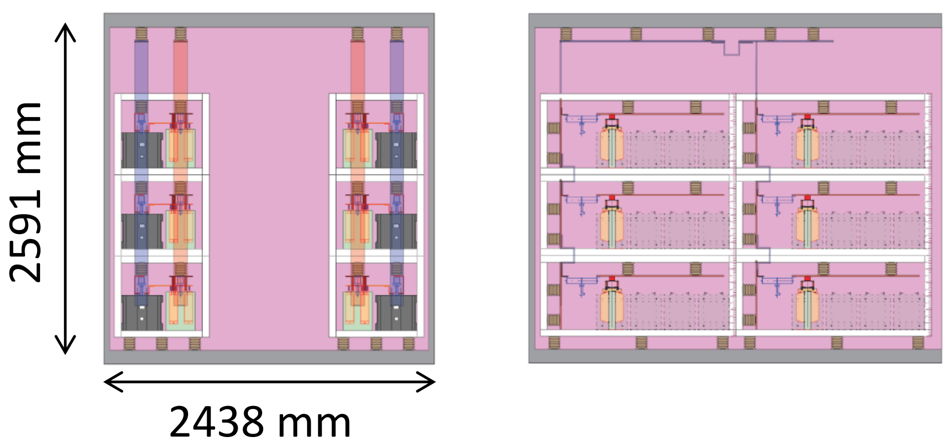
prototype

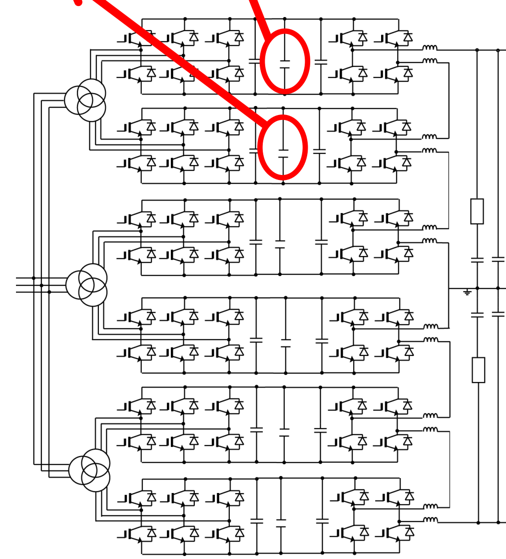


Design of Capacitor Bank

- Single capacitor bank consists of 24 capacitor units (96 capacitors) connected in parallel.
- 2 capacitor banks are installed in a 40 ft container.







Capacitor bank specifications for a single BMPS

Number of 40 ft containers	Number of capacitors	Weight of capacitor banks
3	576	~30 ton (exclude containers)

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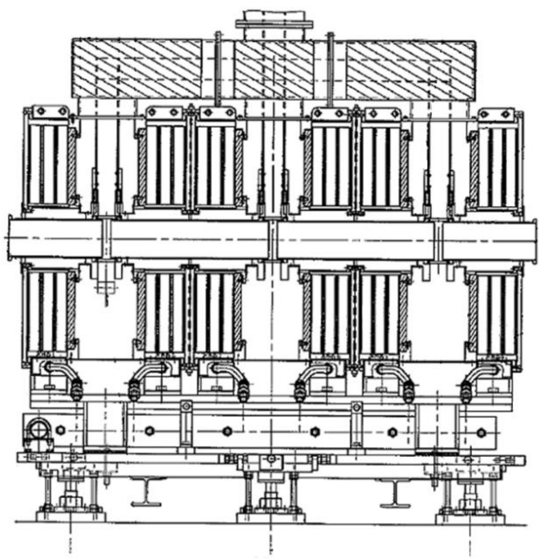
Present cavity

Core material	FT-3M
Voltage / gap [kV]	~15
Gaps / cavity	3
Accelerating gradient [kV/m]	~25
Resonance frequency [MHz]	1.72
Cooling	Water
Power Loss [kW]	~220

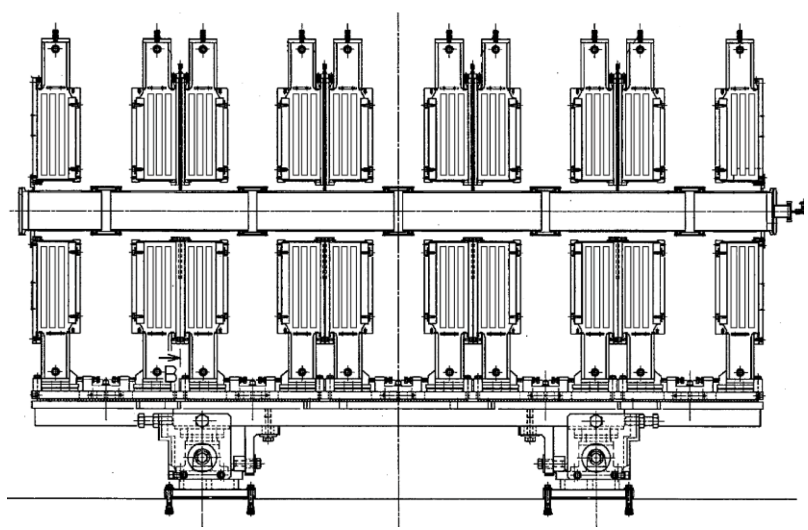
1846 mm



High gradient cavity

Core material	FT-3L
Voltage / gap [kV]	~15
Gaps / cavity	5, 4
Accelerating gradient [kV/m]	~30
Resonance frequency [MHz]	1.72
Cooling	Water
Power Loss [kW]	~180 (5-GAP), ~140 (4-GAP)

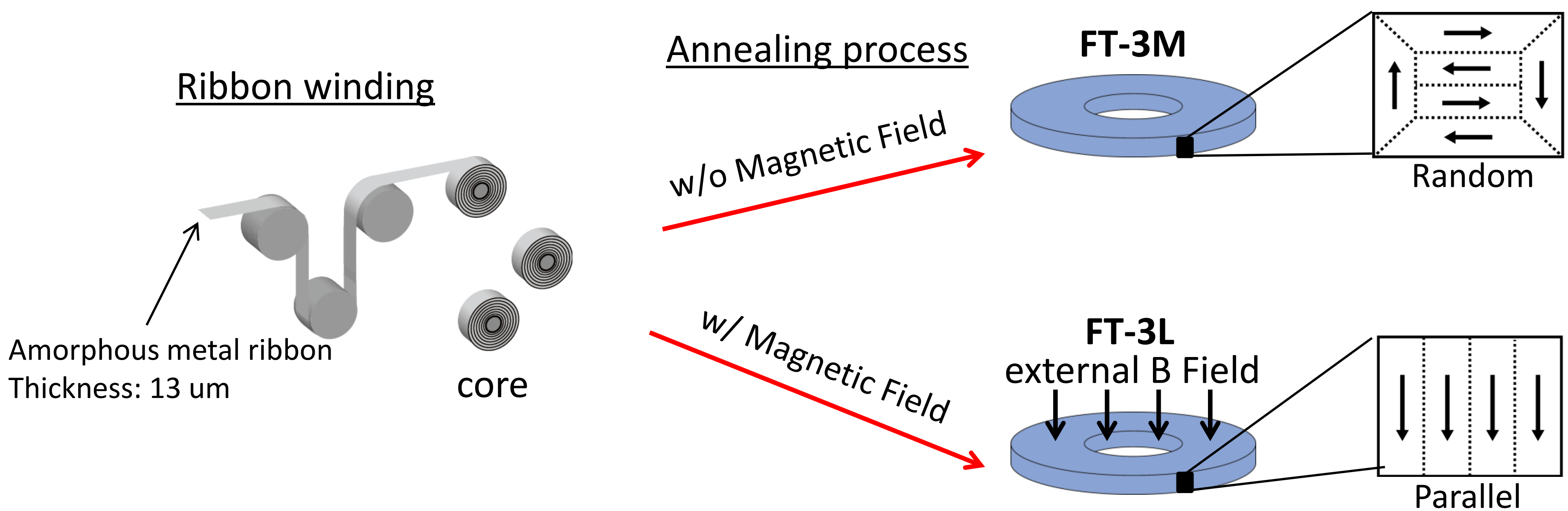
2591 mm



FINEMET (Nanocrystalline Fe-based Soft Magnetic Material)

Hitachi Metals, Ltd.

FINEMET Core Production



Core Loss Reduction		
	Shunt impedance [Ω/gap]	Loss per gap [kW/gap]
Cavity with FT-3M	1100	~72
Cavity with FT-3L	2000	~36

1/2

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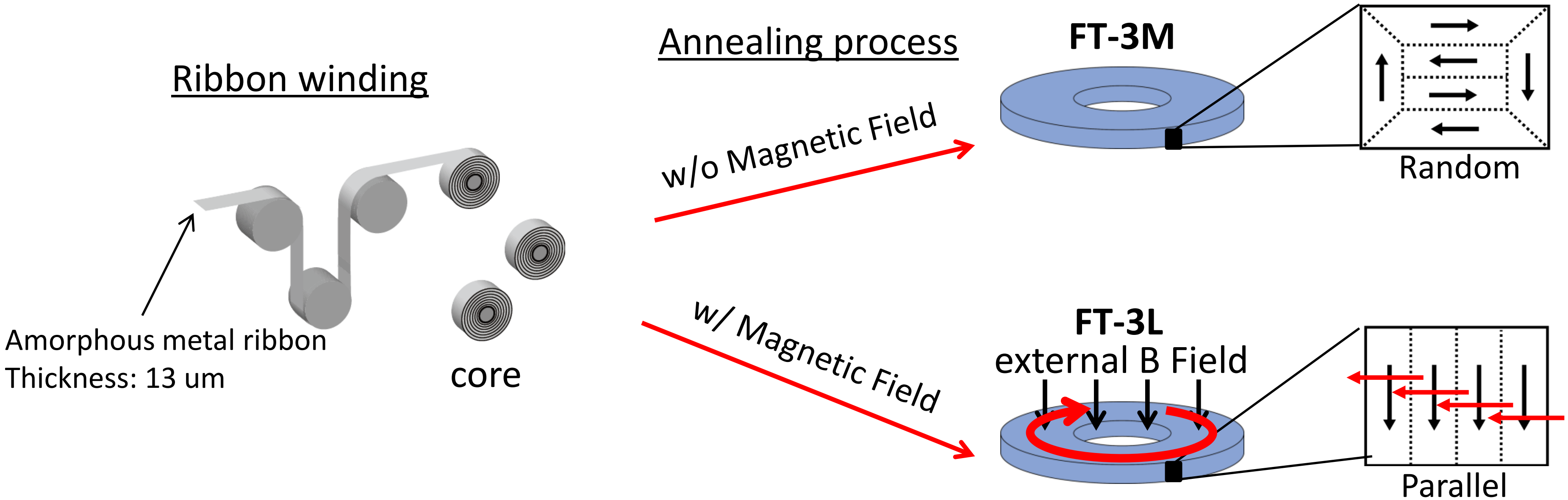

Core Loss Reduction		
	Shunt impedance [Ω/gap]	Loss per gap [kW/gap]
Cavity with FT-3M	1100	~72
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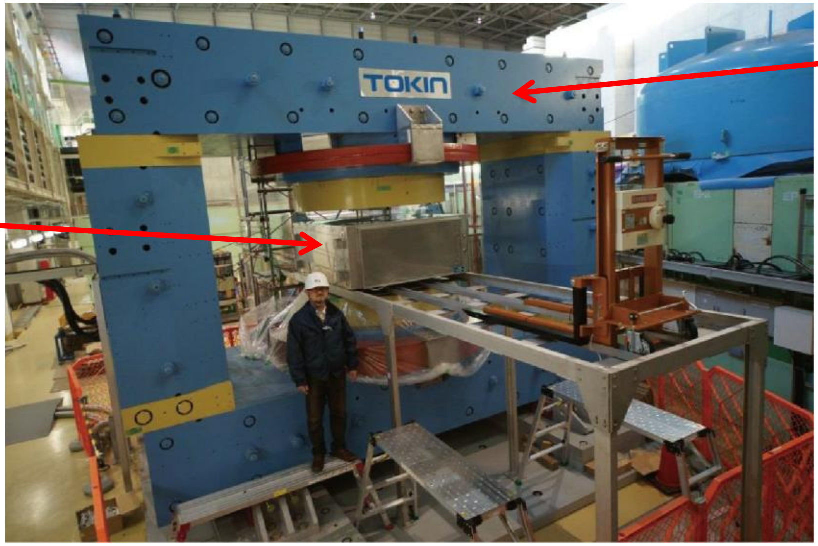
1/2

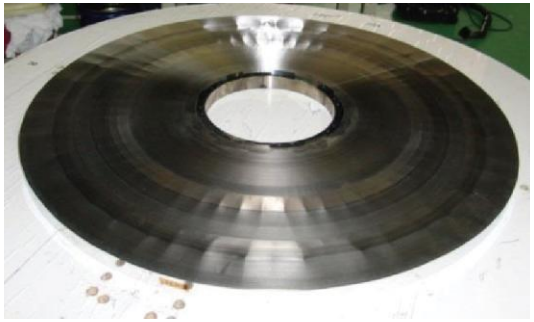
oven



Magnet to produce external B field

C. Ohmori, IPAC2015

FT-3L core



800 mm

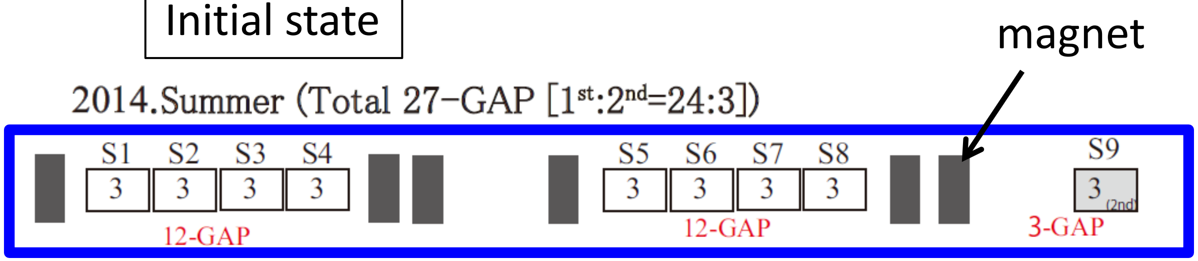
5-GAP accelerating cavity

Upgrade of RF system

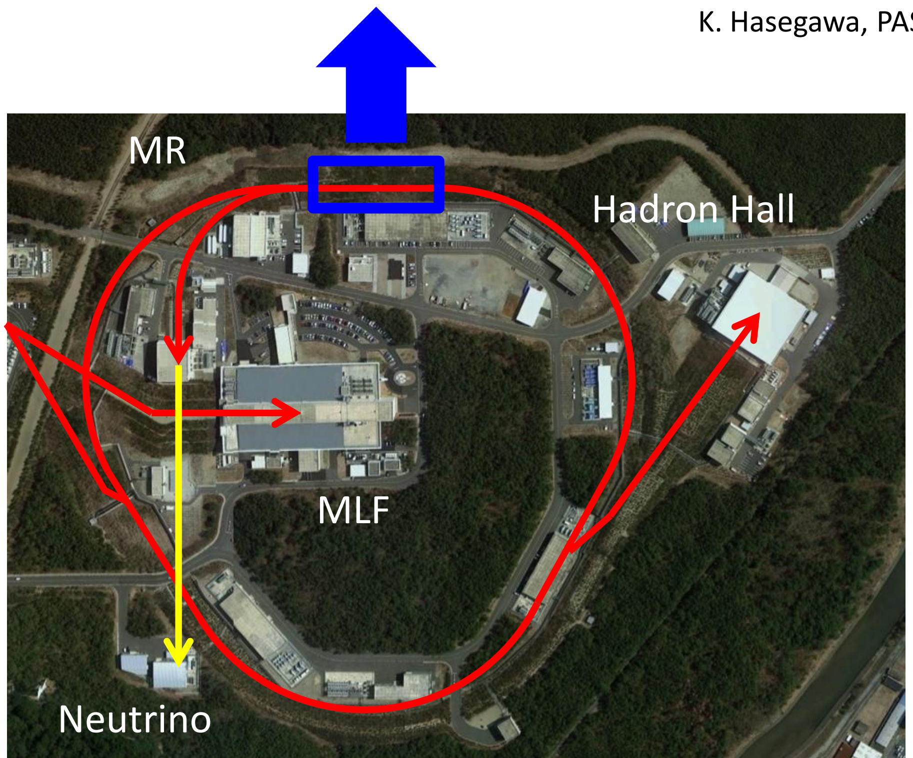
Maximum accelerating voltage per turn will be increased from 280 kV to 560 kV.

Increase the number of cavities in the limited space.

Initial state



K. Hasegawa, PASJ2015



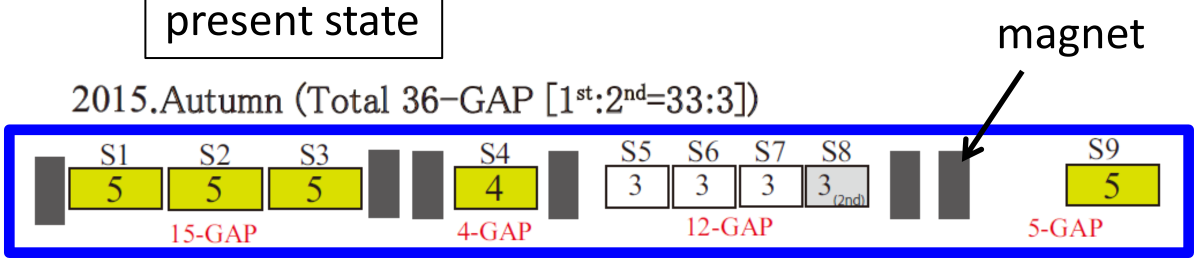
Normal operation:
13 kV/gap x 21 gaps = 280 kV

Upgrade of RF system

Maximum accelerating voltage per turn will be increased from 280 kV to 560 kV.

Increase the number of cavities in the limited space.

present state



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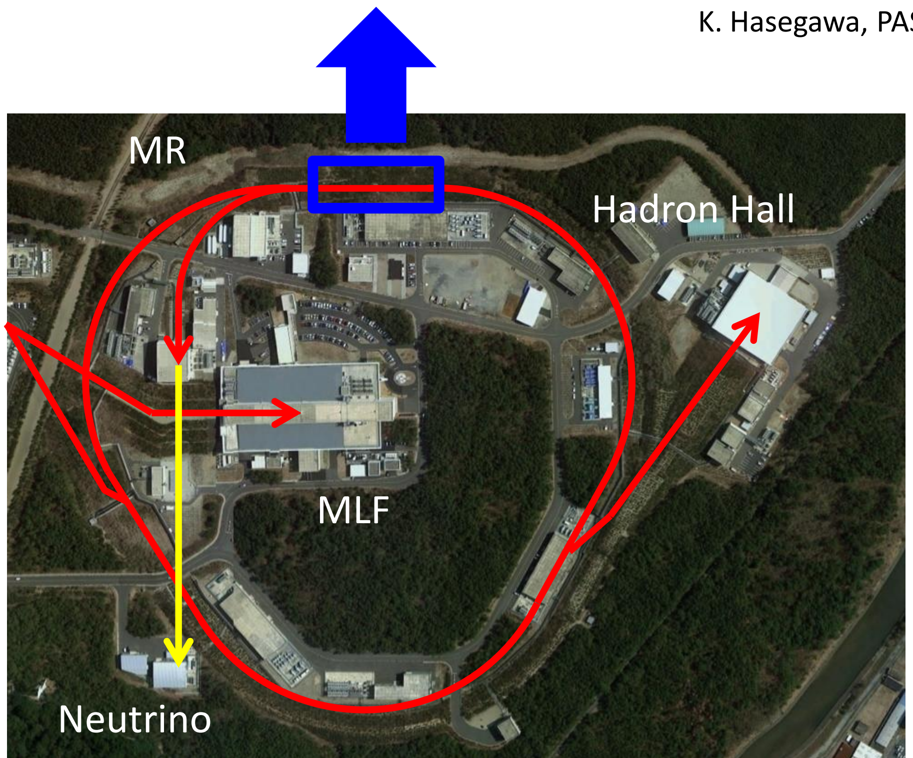


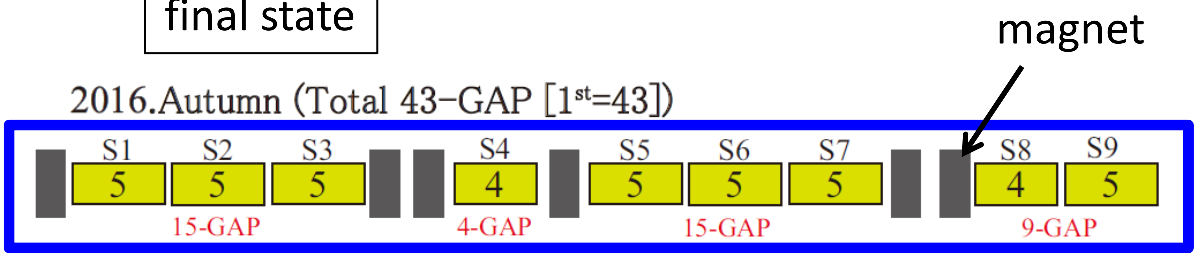
Normal operation:
14 kV/gap x 20 gaps = 280 kV

Upgrade of RF system

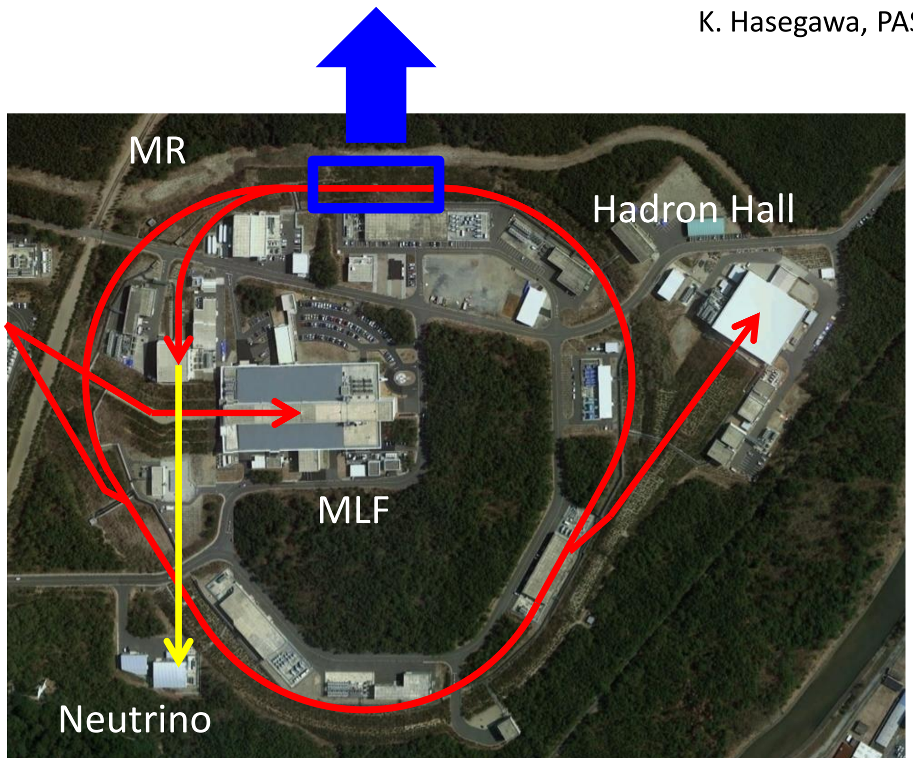
Maximum accelerating voltage per turn will be increased from 280 kV to 560 kV.

Increase the number of cavities in the limited space.

final state



K. Hasegawa, PASJ2015



Normal operation:
13 kV/gap x 43 gaps = 560 kV

Power loss of present cavity and high gradient cavity

To achieve 560 kV per turn, ~43 gaps are required.

	Present cavity	High gradient cavity
Core material	FT-3M	FT-3L
Accelerating Voltage / gap [kV]	~15	~15
Number of gaps	45 (*15 cavities)	43 (9 cavities)
Power loss / gap [kW]	~72	~36
Total power loss [kW]	~3200	~1600

1/2

*15 cavities can not be installed in the limited space.
In the case of FT-3M cavity, additional power supplies are also required.

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Summary

High repetition rate scheme is adopted to increase beam power of J-PARC MR.

2.48s → 1.3s

Magnet power supply and **RF accelerating cavity** are main components to be upgraded.

	Issues		Solutions
Magnet Power Supply	High output voltage	⇨	Several PS units connected in series
	Power variation at electrical system	⇨	Capacitive Energy Storage Scheme ↳ The power variation keeps present value even in the high repetition rate operation.
RF Accelerating Cavity	High accelerating voltage	⇨	- Increasing number of accelerating gaps - Developing FT-3L core ⇧ 1/2 power loss FT-3M core