J-PARC Main Ring Magnet Power Supplies

Tetsushi SHIMOGAWA (KEK/J-PARC)
for the J-PARC accelerator group

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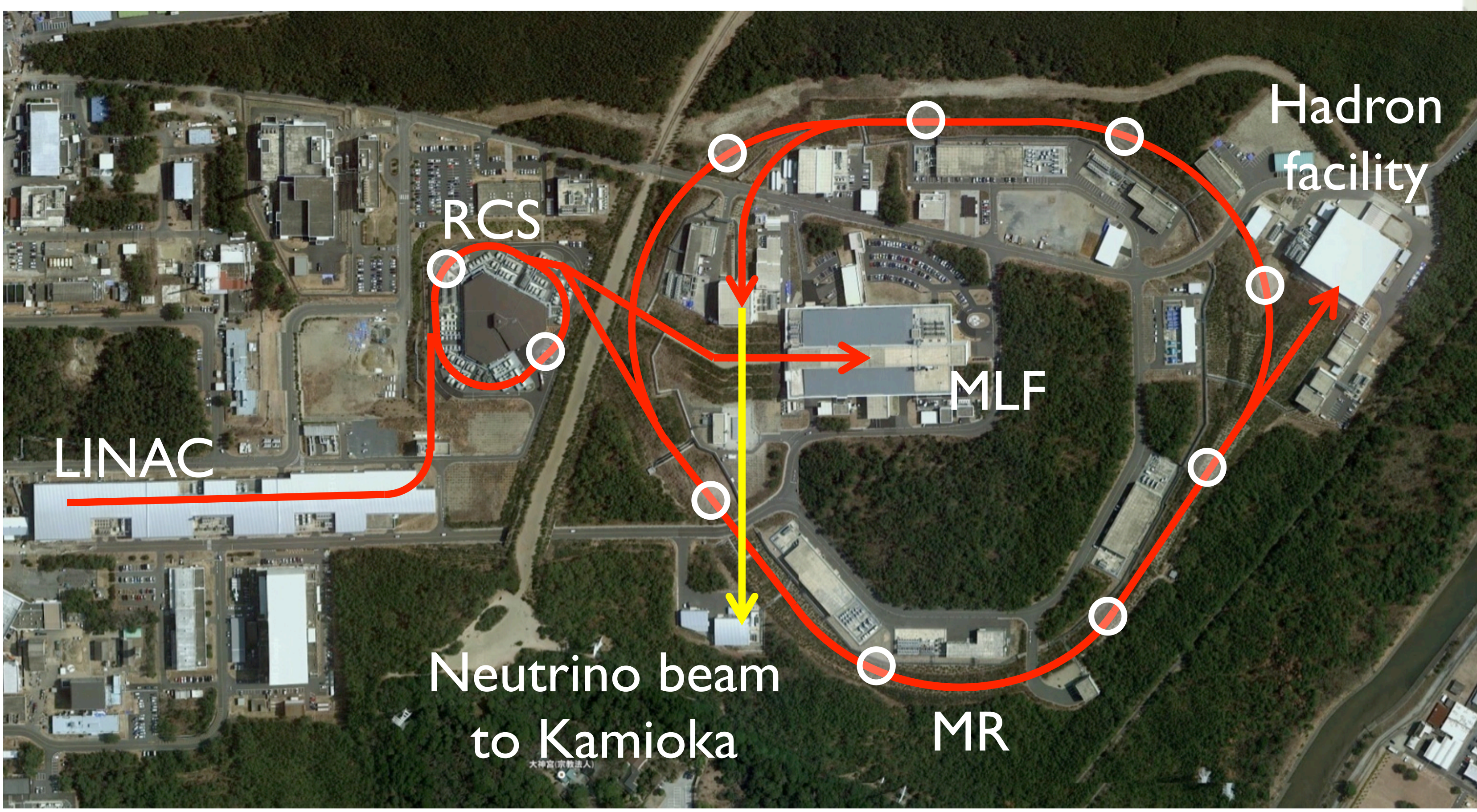
- ✦Summary

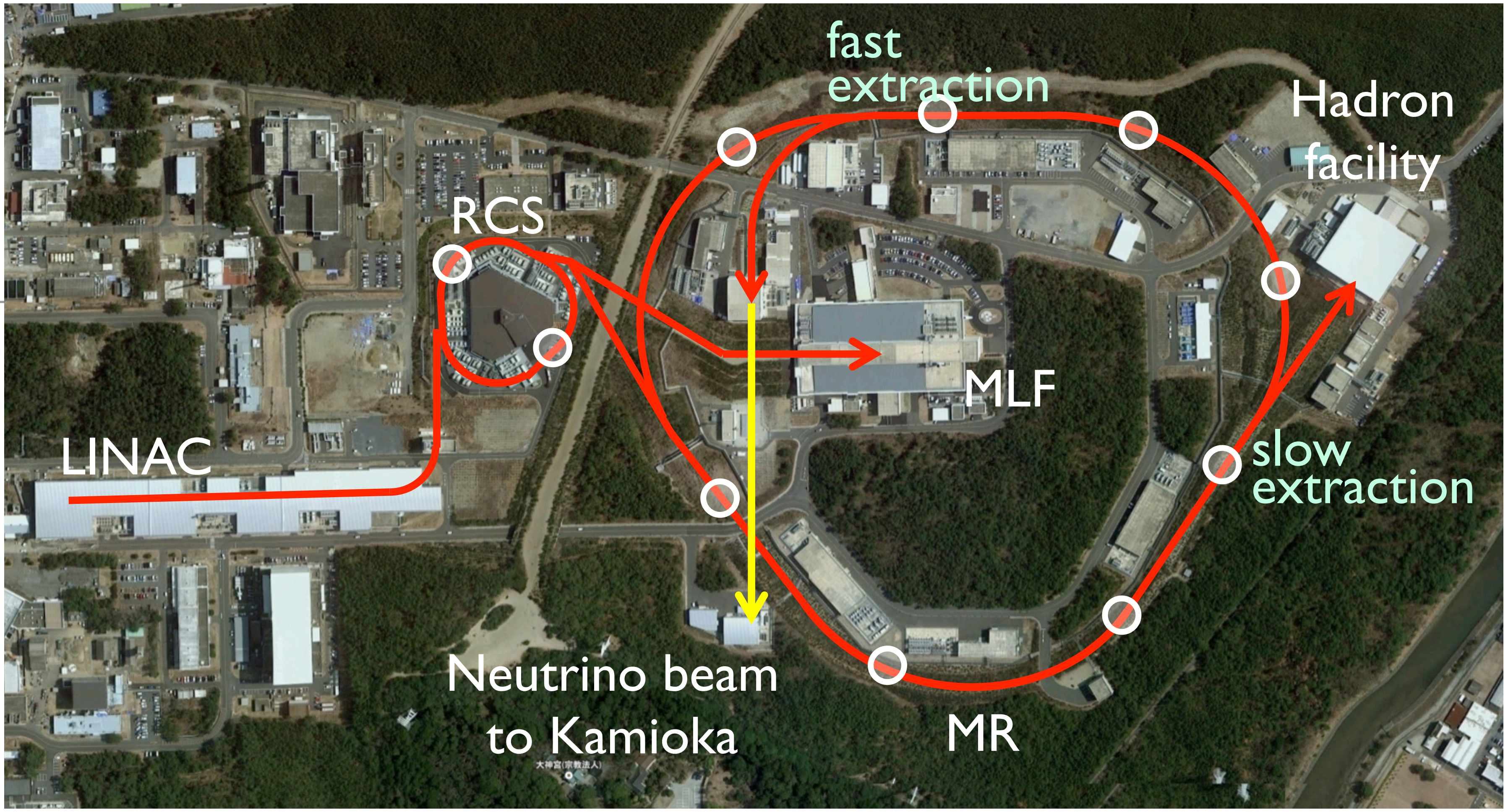
J-PARC
(Japan Proton Accelerator Research Complex)

- 3 accelerators in J-PARC
  - LINAC
  - 3 GeV rapid cycle synchrotron (RCS)
  - 30 (50) GeV main ring (MR)



~130 km north east from TOKYO.

J-PARC MR



✦Feature of MR

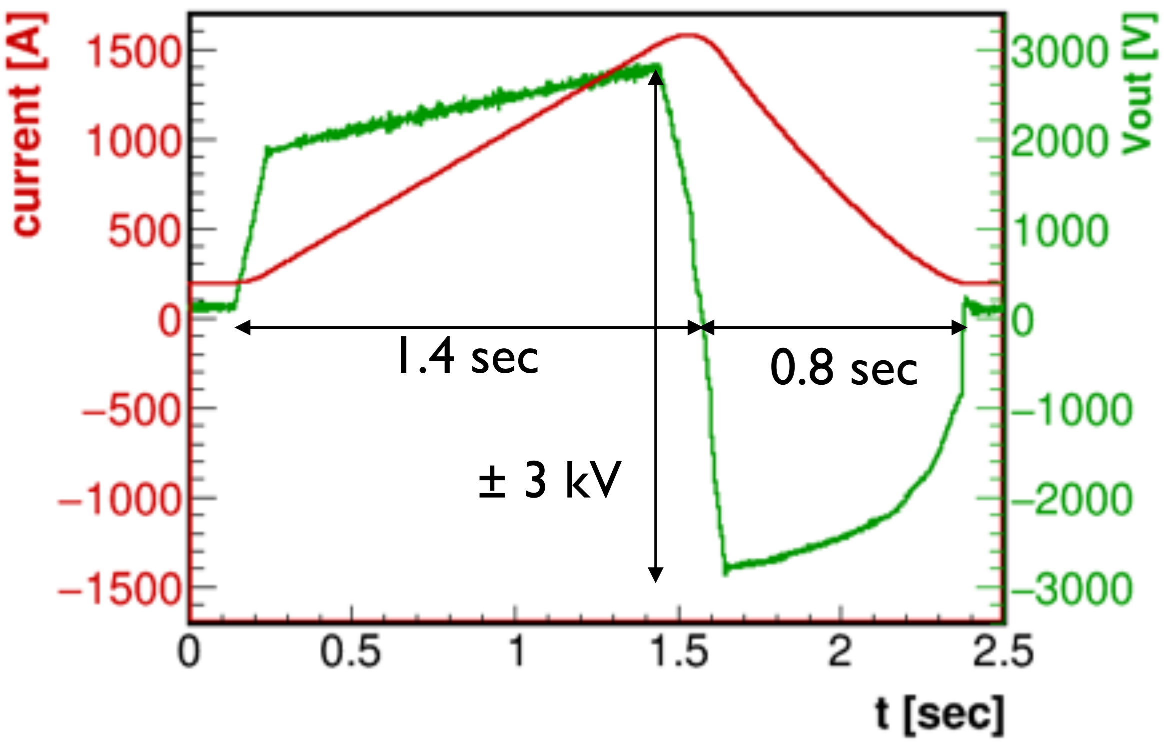
- circumference : 1568 [m]
- Injection / extraction Energy : 3 / 30 [GeV]
- Two extraction mode : Fast (FX) / Slow extraction (SX)
- Harmonic number : 9
- N bunches : 8
- Repetition rate : 0.4 (FX)/ 0.18 (SX) [Hz]
- Betatron tune : 22.40, 20.75 (FX) / 22.275 , 20.30 (SX)
- RF frequency : 1.67 ~ 1.72 [MHz]

MR is currently operated at a beam intensity of 420 (FX)/45 (SX) kW.

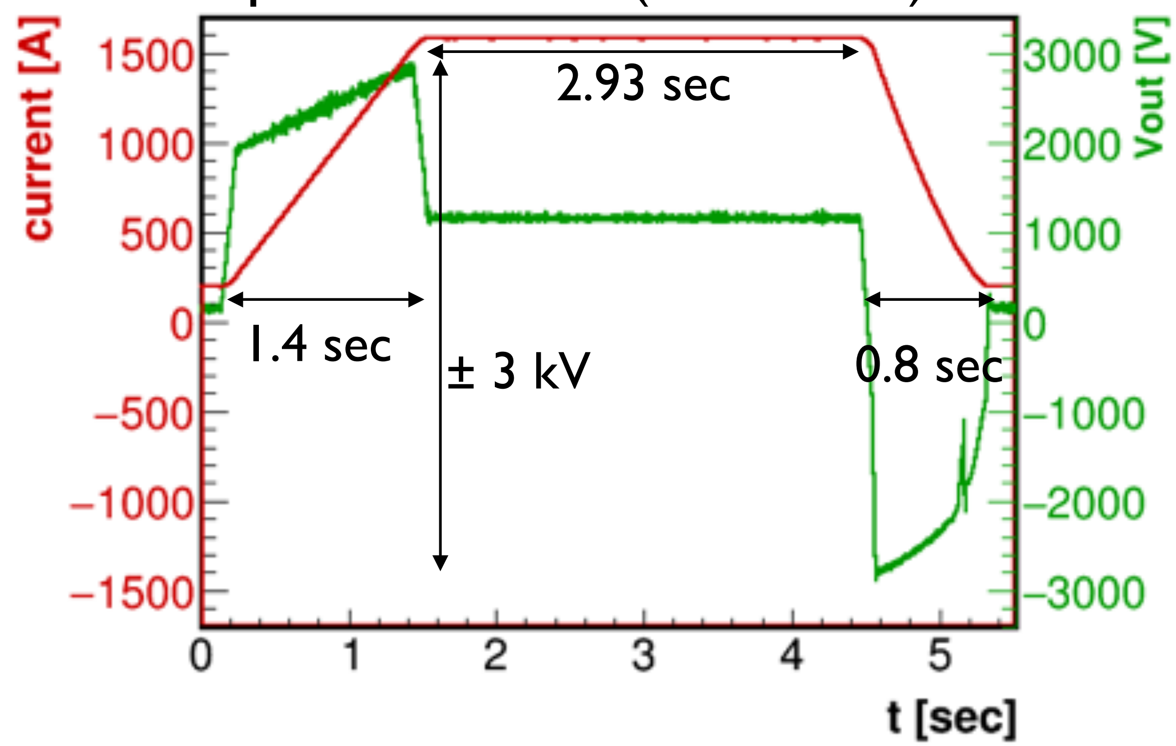
Contents

Power supplies & current pattern

current pattern in FX (PS for BM)



current pattern in SX (PS for BM)

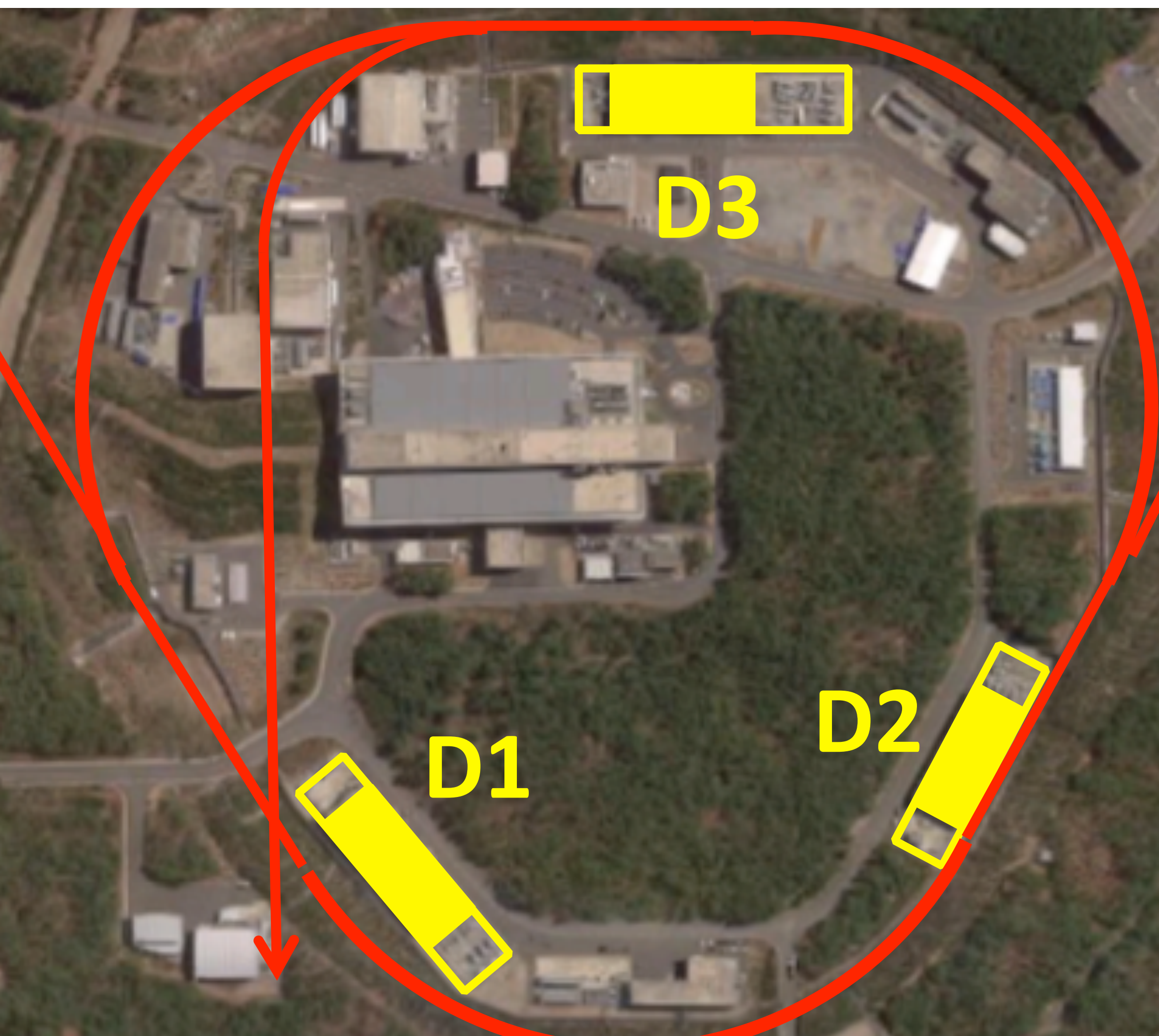


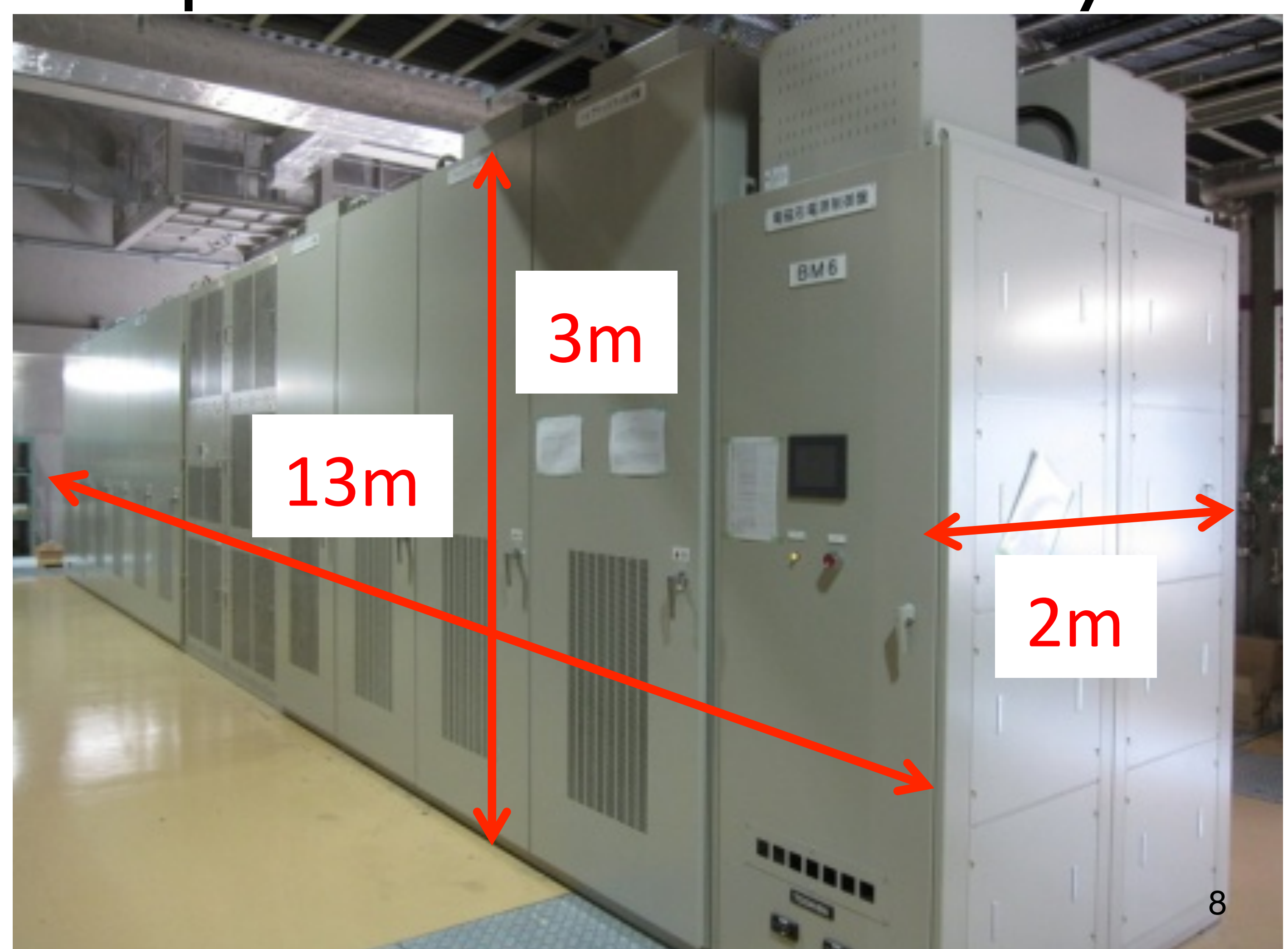
PS	#. of PS	I_{Max}	Vout [V]	#. of magnet / PS	L [H]	R [Ω]
BM	6	1570	± 3 kV	16	1.7	0.75
Arc. Q	4	~800	± 3 kV	27 or 48	1.7 ~ 3.4	1.1 ~ 2.2
Ins. Q	7	~900	± 800 V	6 or 9	0.2 ~ 1.7	0.2 ~ 0.4
SM	3	200	± 400 V	24	0.4	1.2

PS & PS building

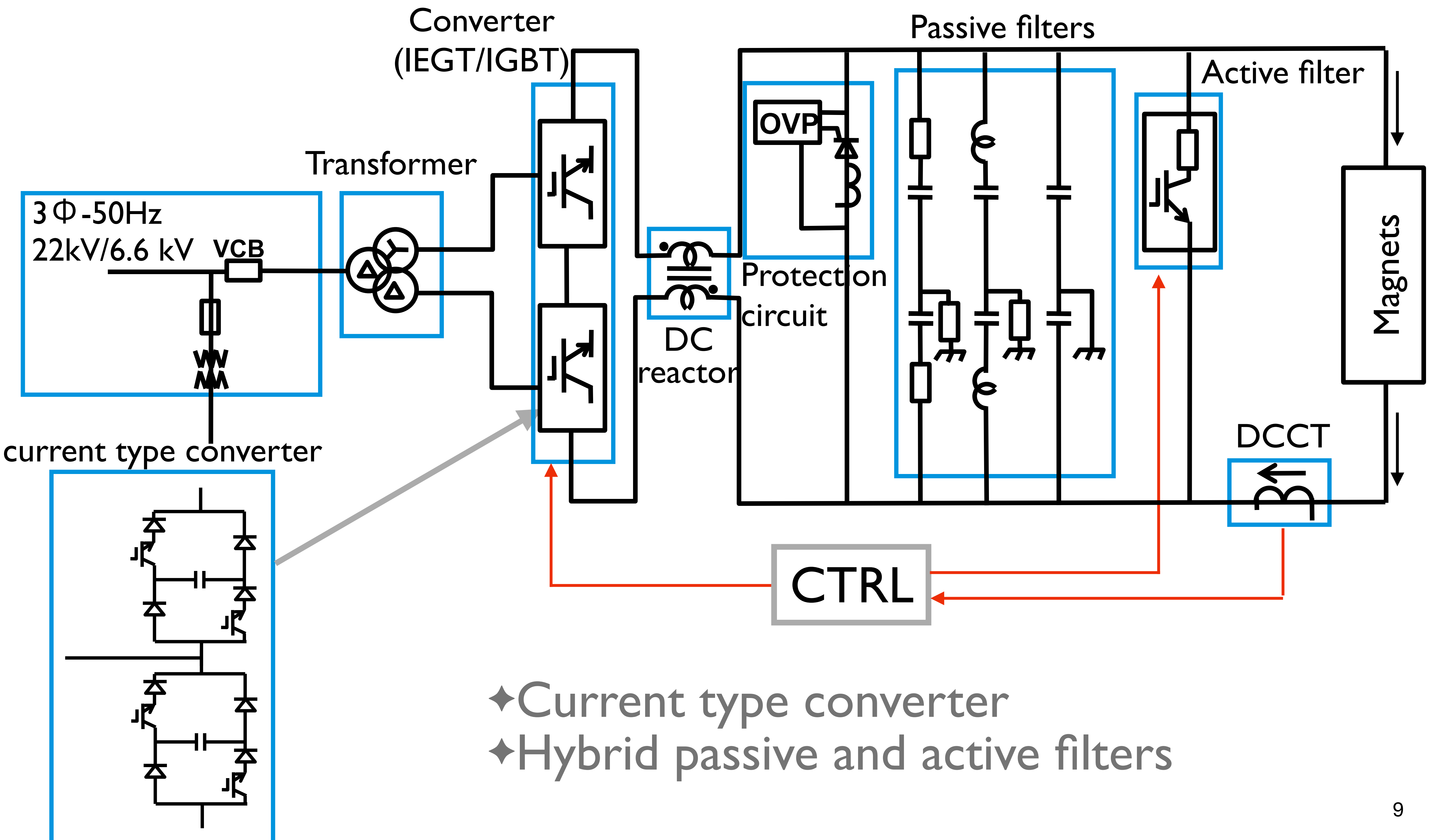
- ✦3 PS buildings in MR
  - D1 : BMx2, Ins. Qx7, SMx3
  - D2 : BMx2, Arc. Qx2
  - D3 : BMx2, Arc. Qx2

present PS for 1 BM family





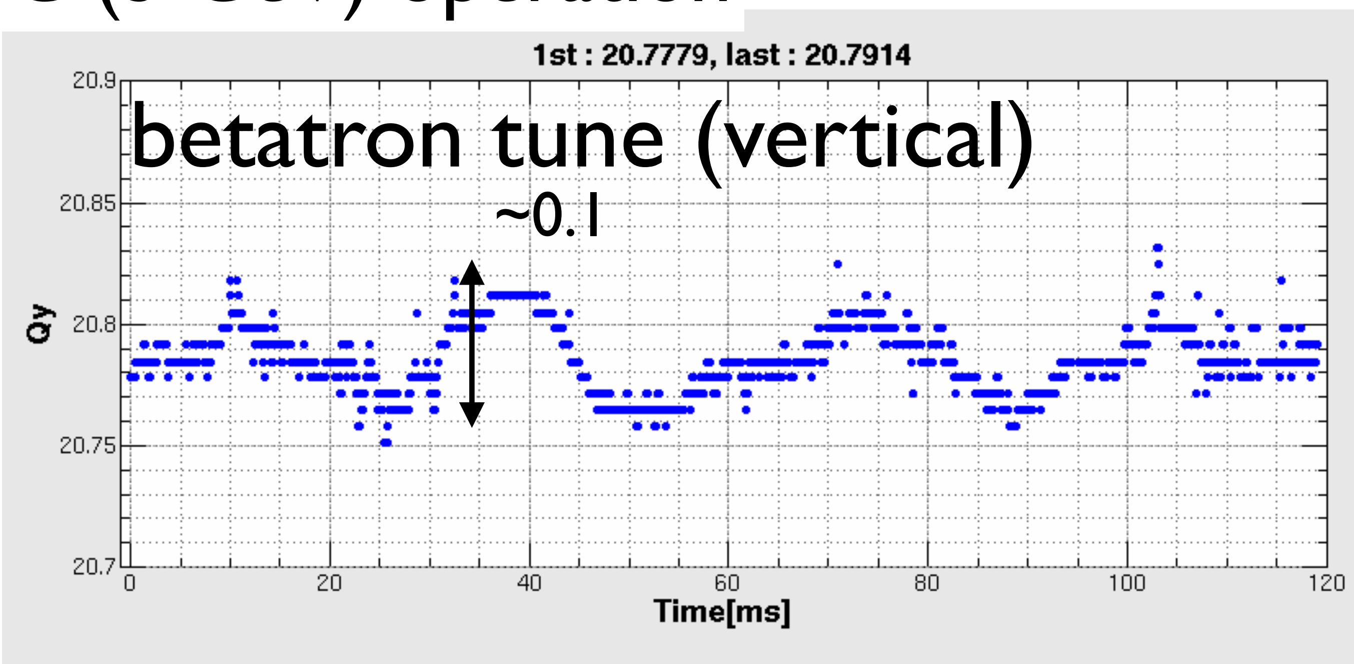
Main circuit Present power supplies

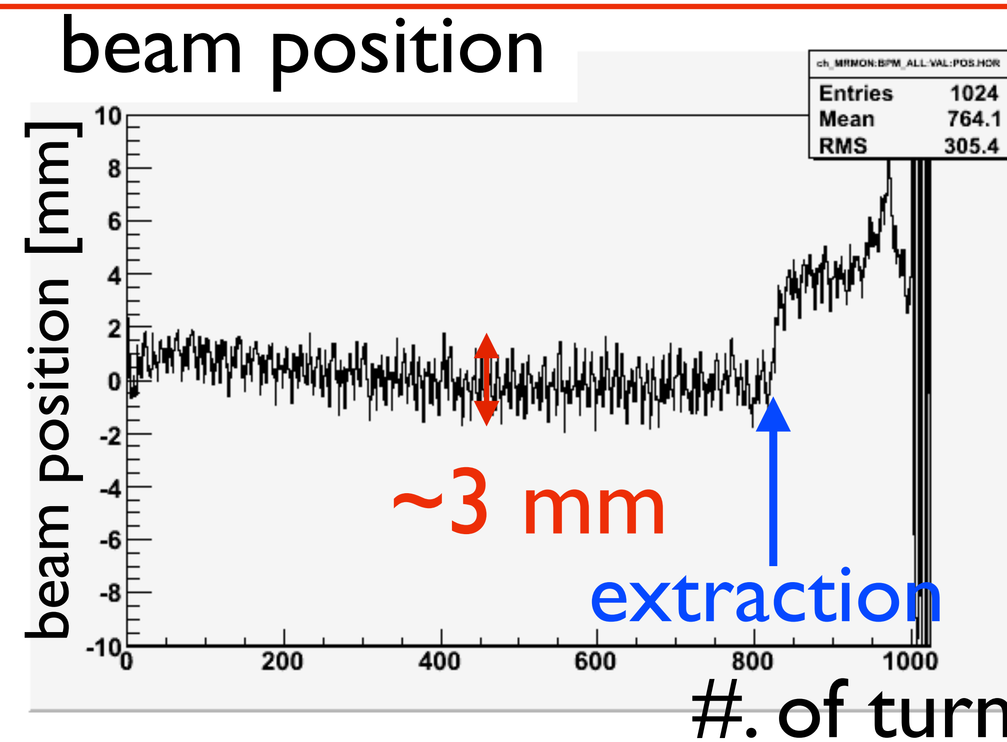


✦Current type converter
✦Hybrid passive and active filters

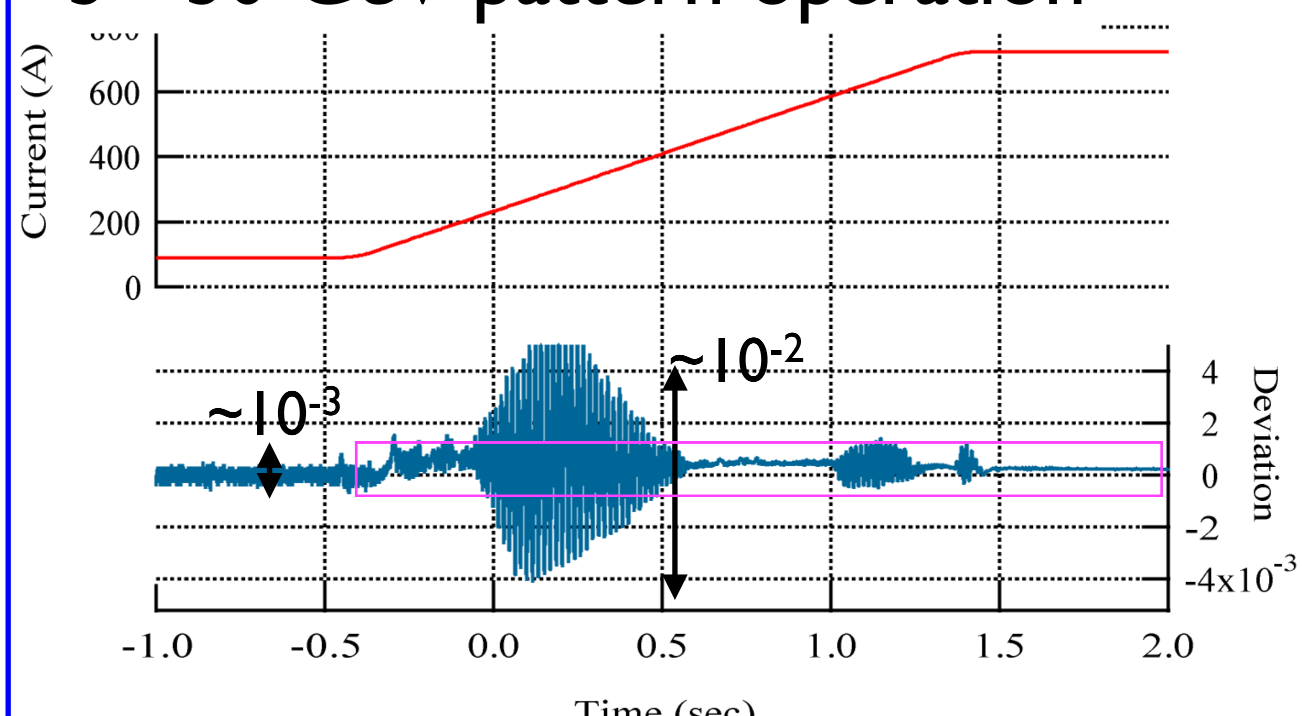
First beam commissioning in 2008

DC (3 GeV) operation





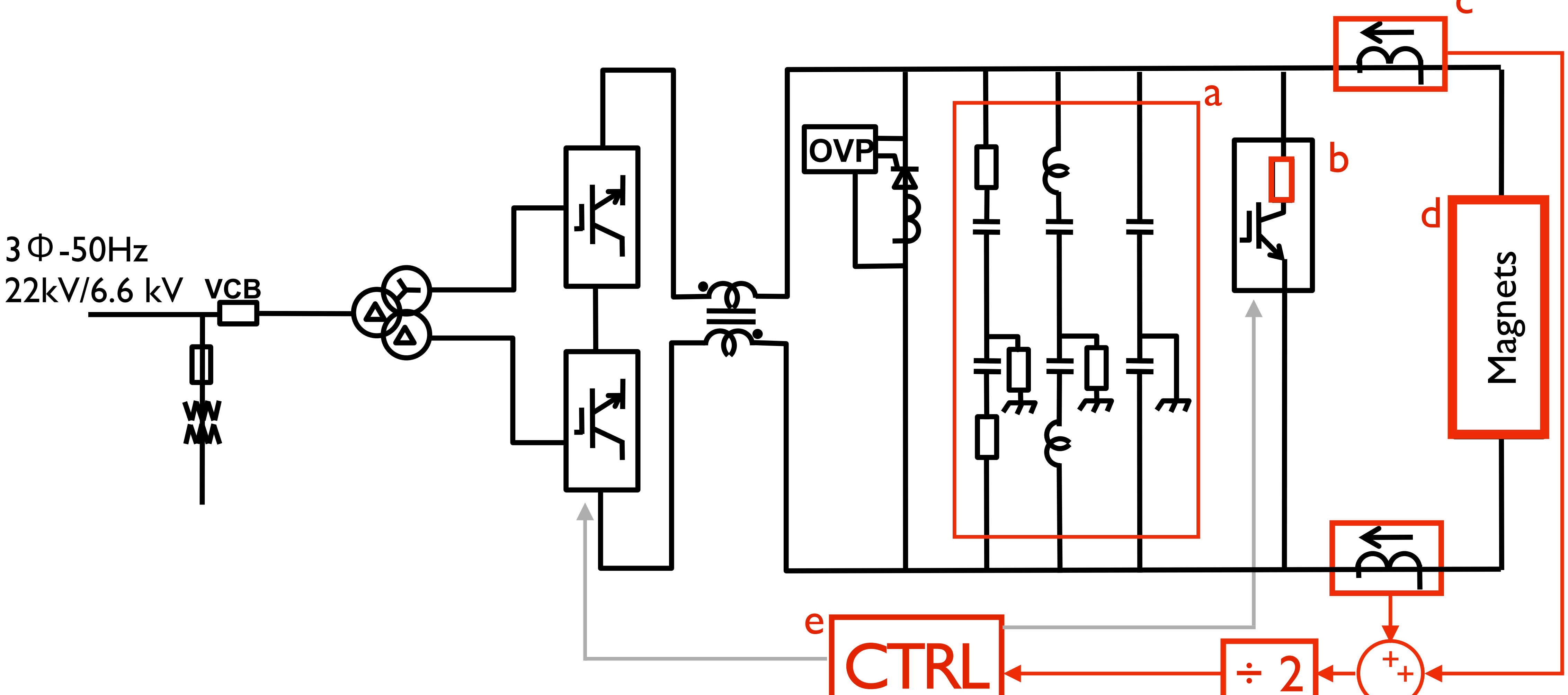
3 - 30 GeV pattern operation



- Large current deviation (~10^{-3})
  - Large error in betatron tune and beam position.
  - Large tracking error of current deviation in acceleration start

For improving large current regulation...

- ✦Optimization of passive and active filters
  - ▸ Capacitance in common mode filter (a)
  - ▸ Resistance in active filter (b)
- ✦Add DCCT to cancel common mode noise (c)
- ✦Re-cabling between PS and magnets (d)
- ✦More sophisticated algorithm into the control system (e)

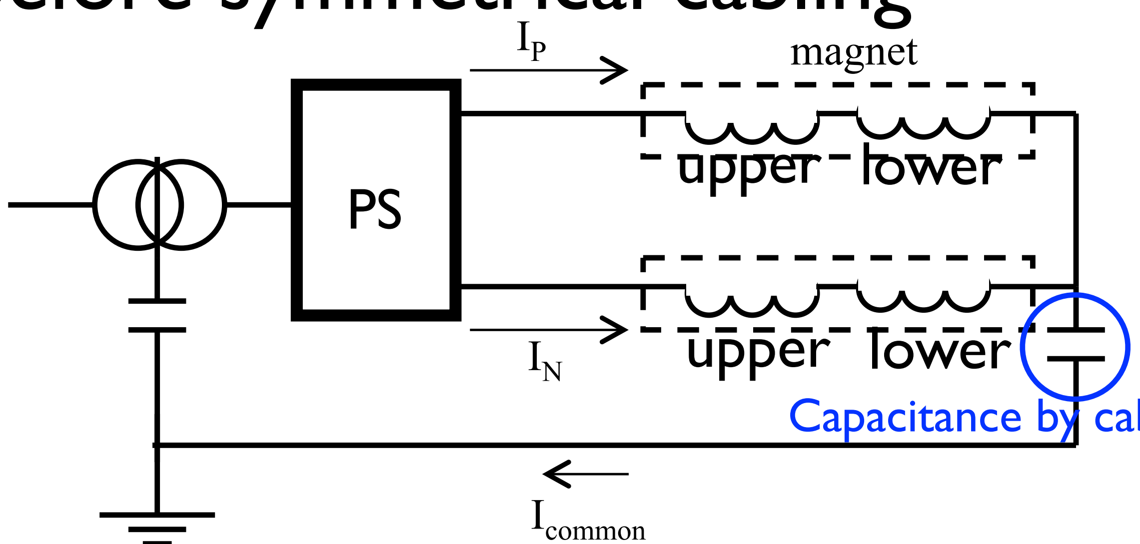


Re-cabling between PS and magnets

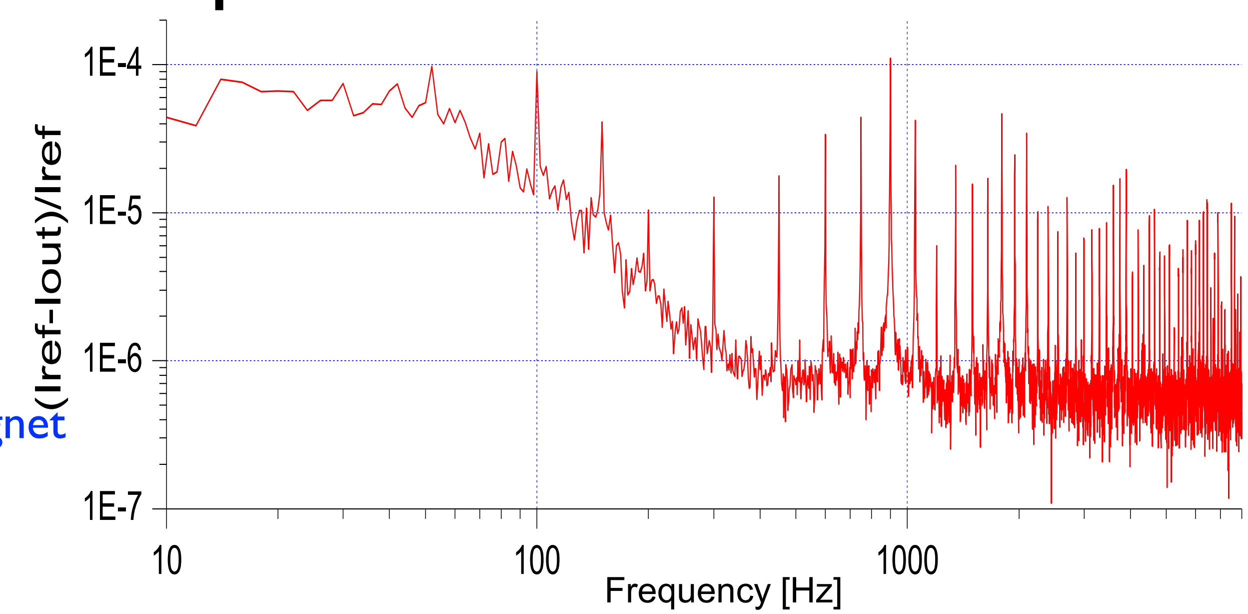
✦Cancel the common mode by symmetrical cabling

$I_P = I + I_{normal} + I_{common}$
$I_N = -I - I_{normal} + I_{common}$

before symmetrical cabling

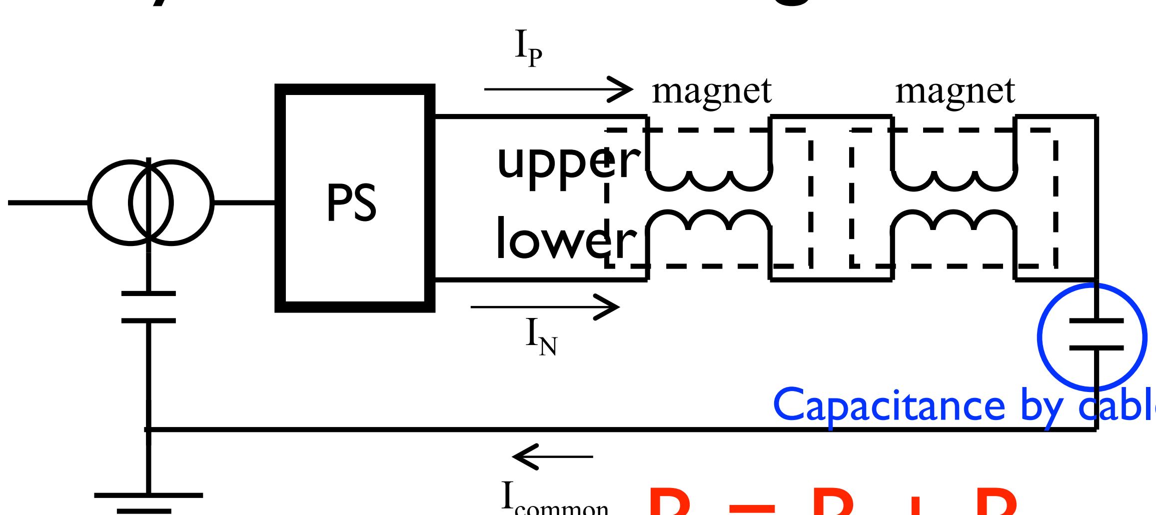


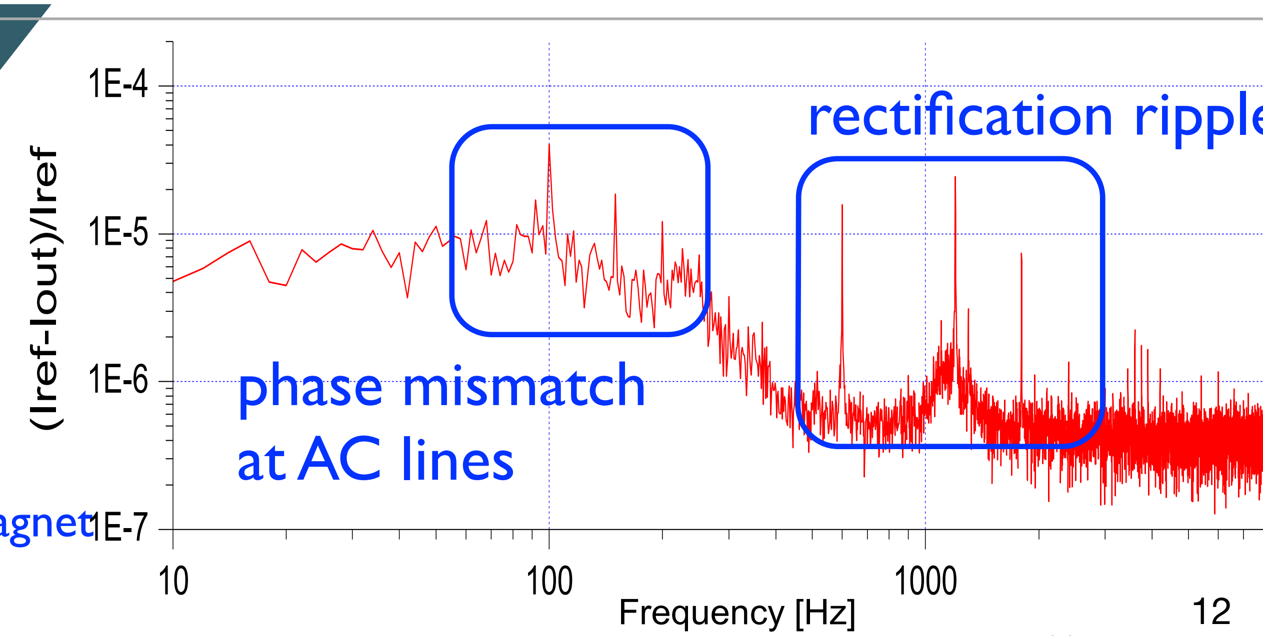
FFT spectrum of current deviation



$B = B + B_{normal} \pm B_{common}$

after symmetrical cabling





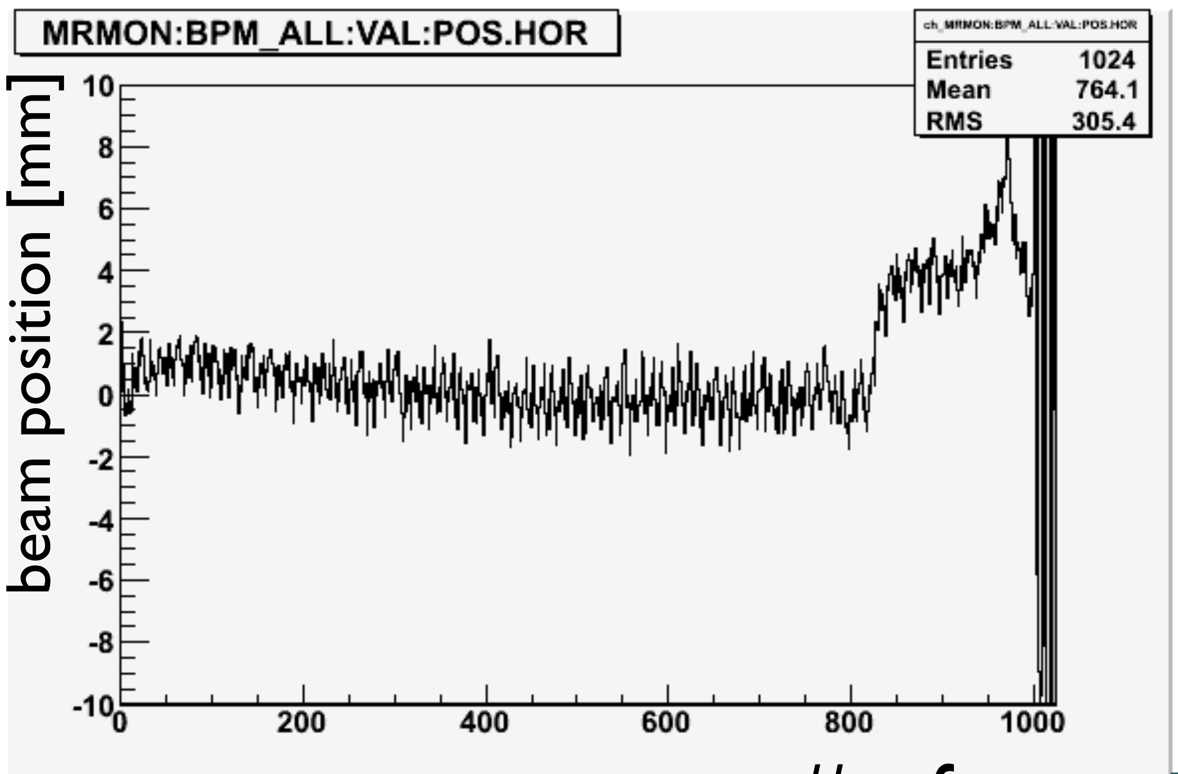
$B = B + B_{normal}$

only normal mode ripple !!

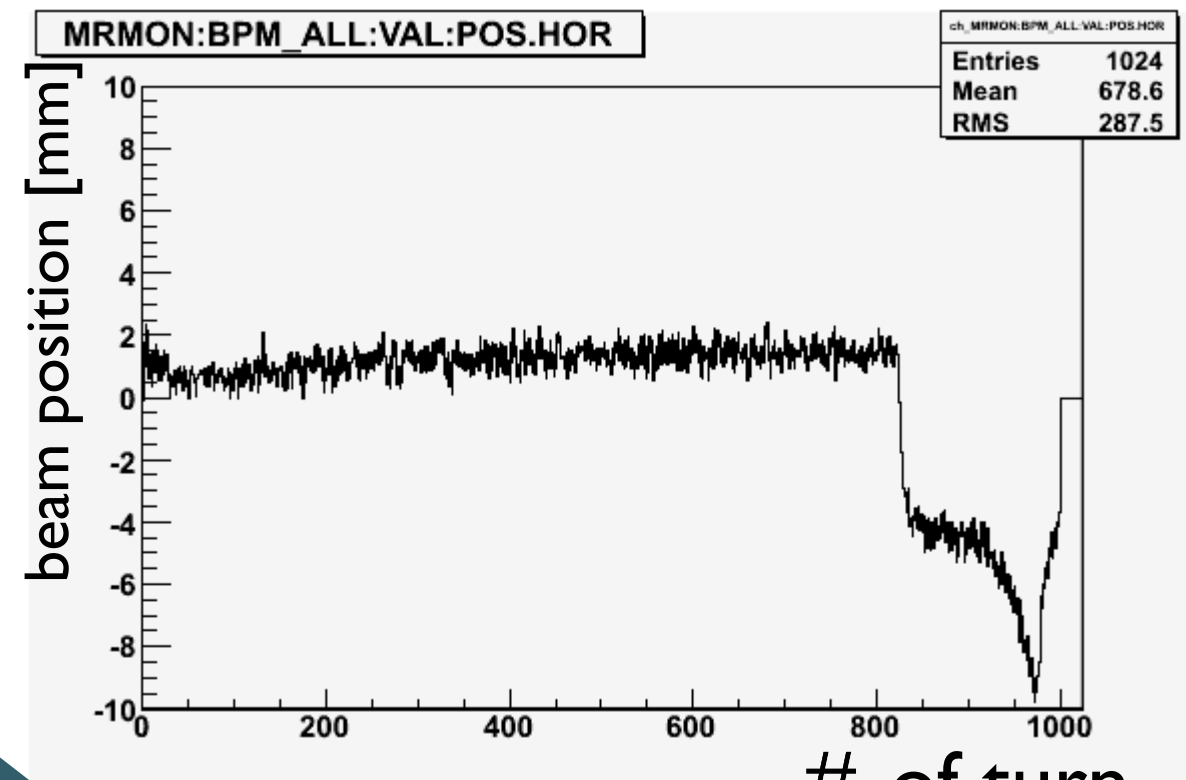
Comparison of before/after PS improvement

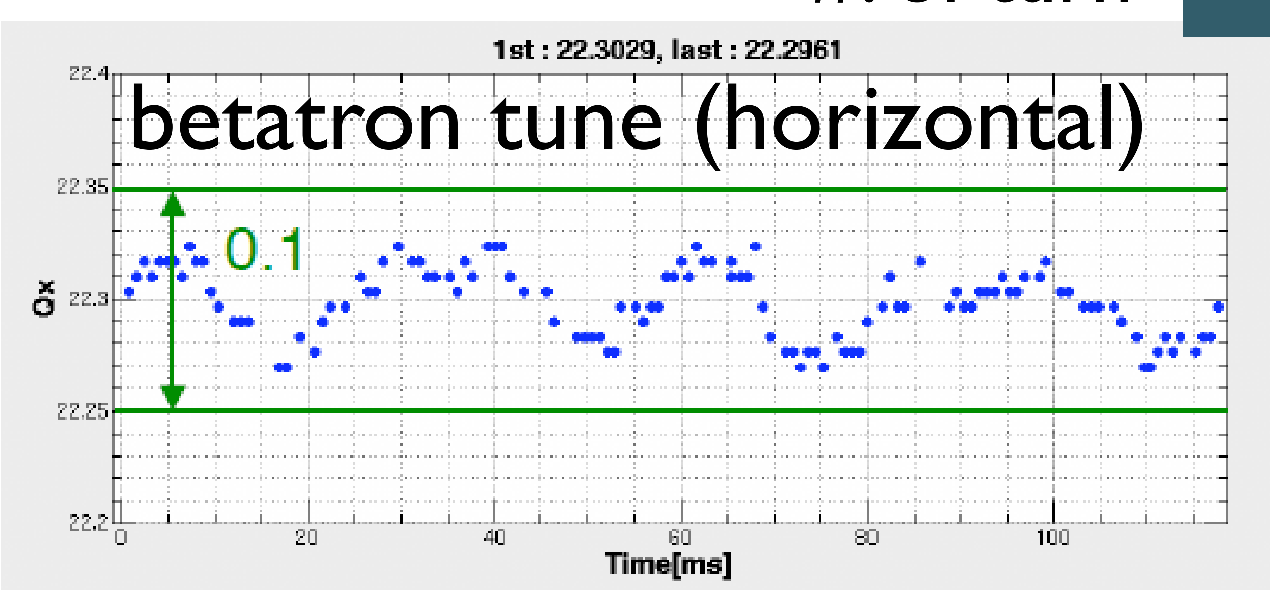
✦Also the beam parameters are improved.

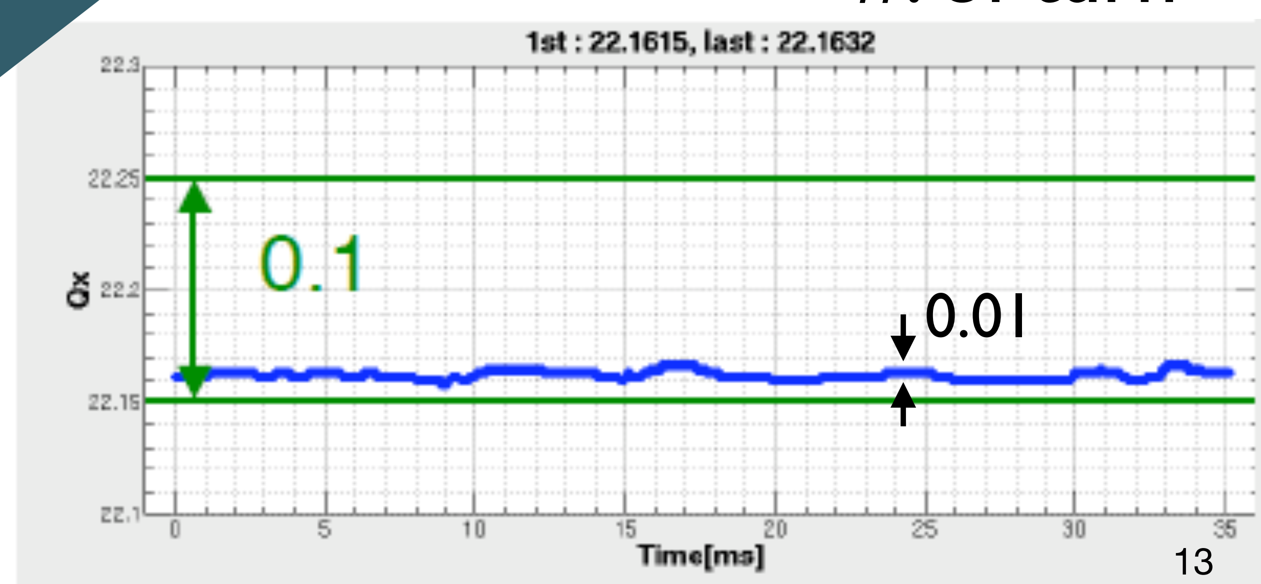
before



after

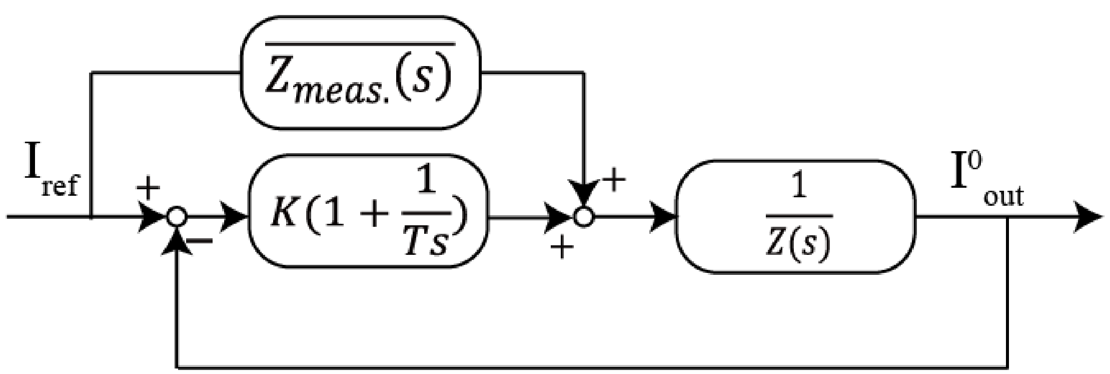






Correction of tracking error

- Tracking error correction by “feed forward” technique.
  - The impedance is measured reference current pattern and output current in driving.
  - Adding the feed-forward voltage using the measured impedance.



$$\overline{Z_{means}(s)} = K\left(1+\frac{1}{Ts}\right)\frac{1}{N}\sum_{i=i}^{N}\frac{I_{ref}-I^i_{out}}{I^i_{out}}$$

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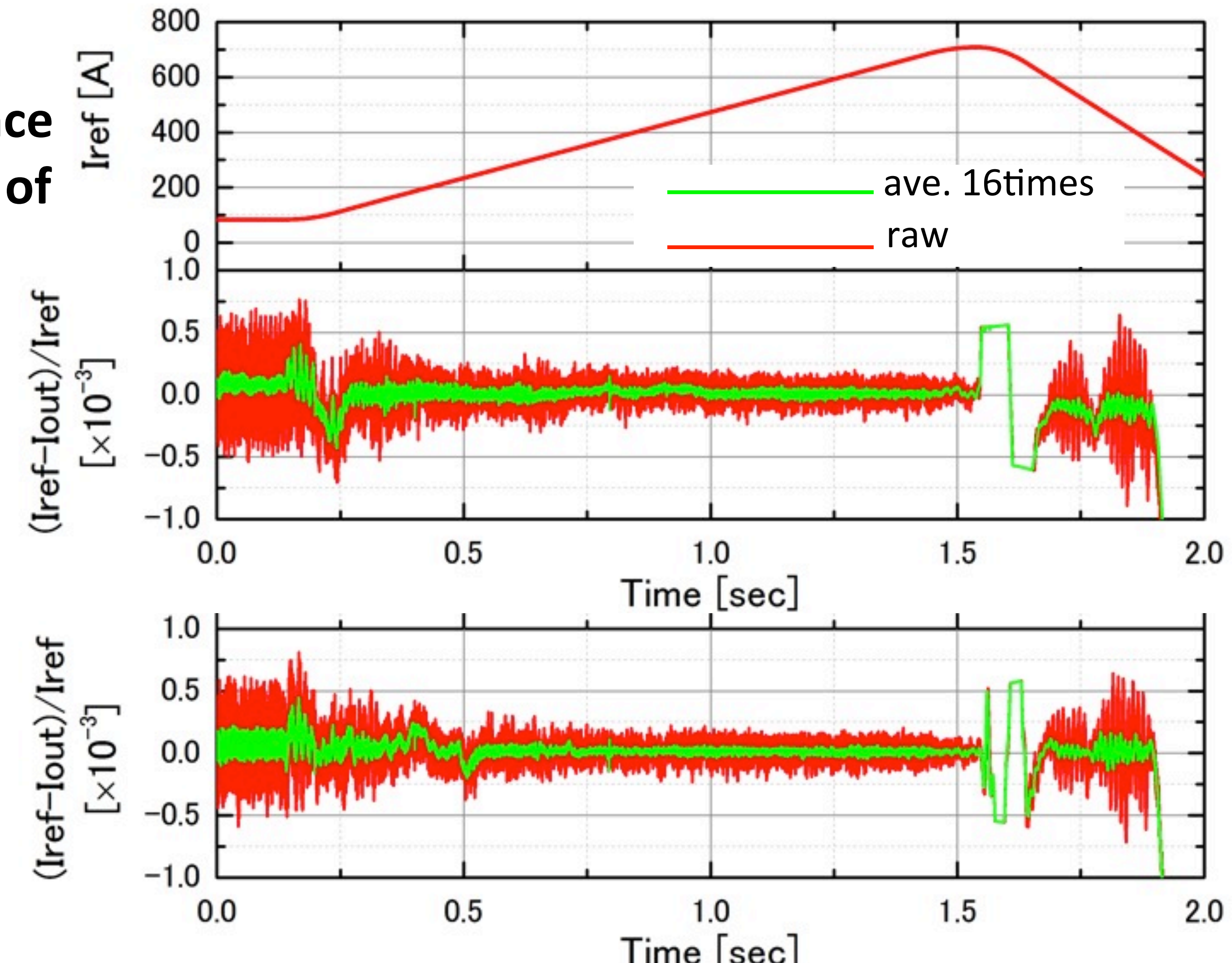
Reference pattern of current

V_{ref} OFF

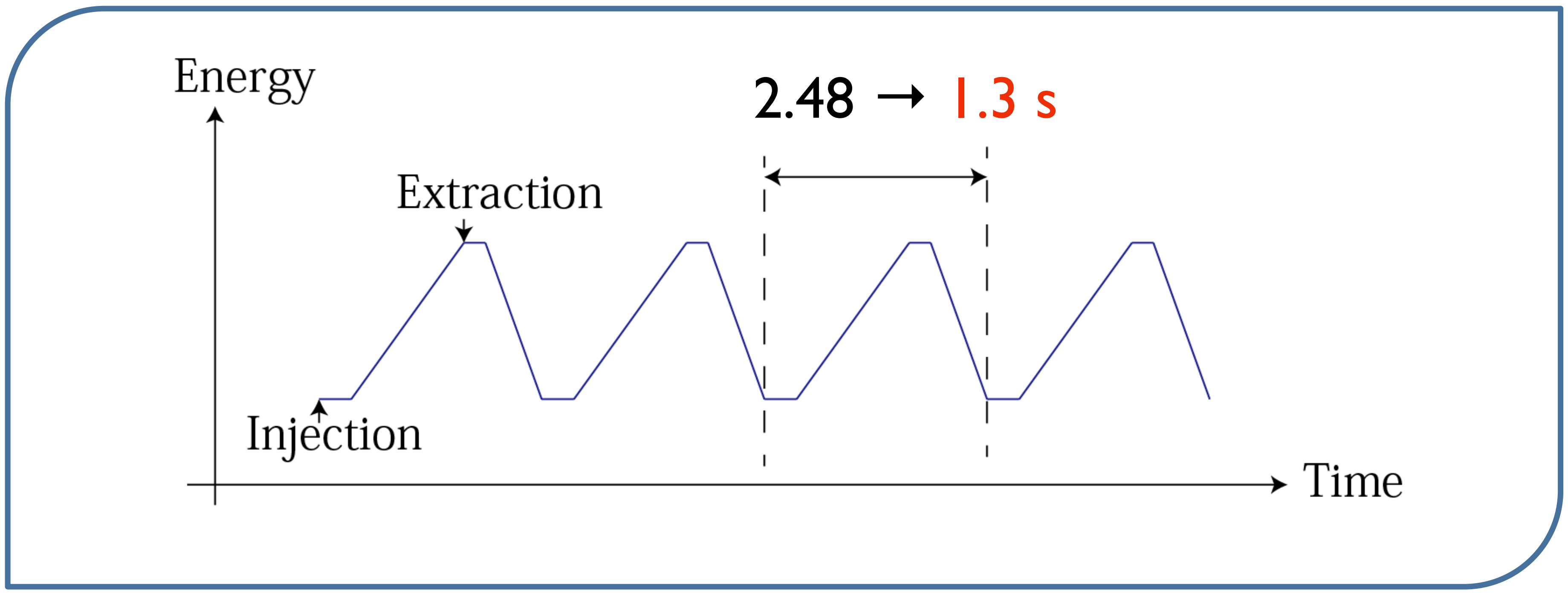
V_{ref} ON



Contents

MR upgrades toward 750 kW of beam power

✦Increasing repetition rate from 0.4 Hz → 0.8 Hz

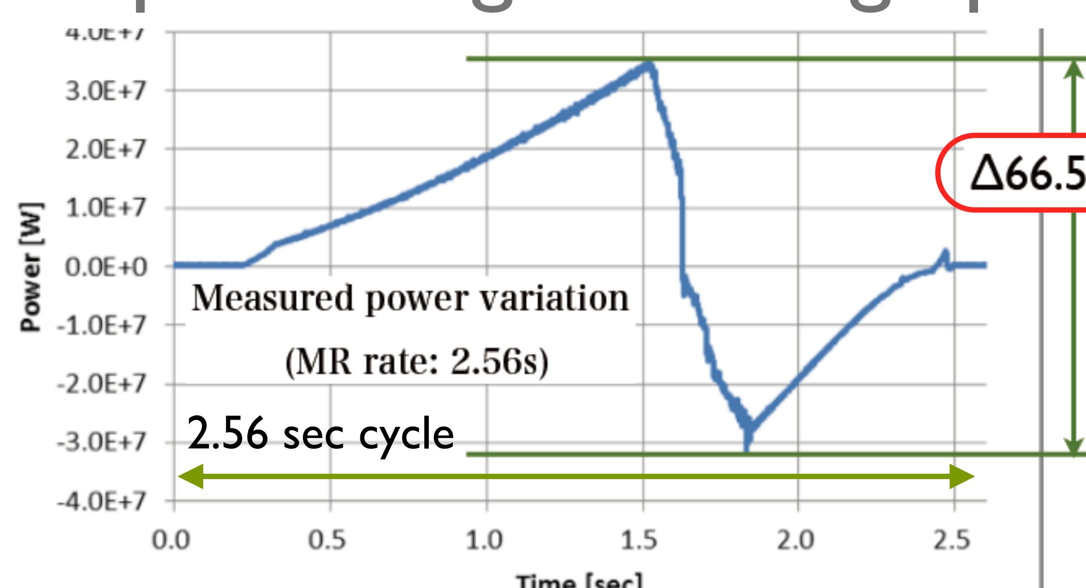


✦Issues of main magnet power supply are
high output voltage and large power variation.

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

Higher output voltage
by shorten repetition cycle

⇒ PS consists of
several PS units in series



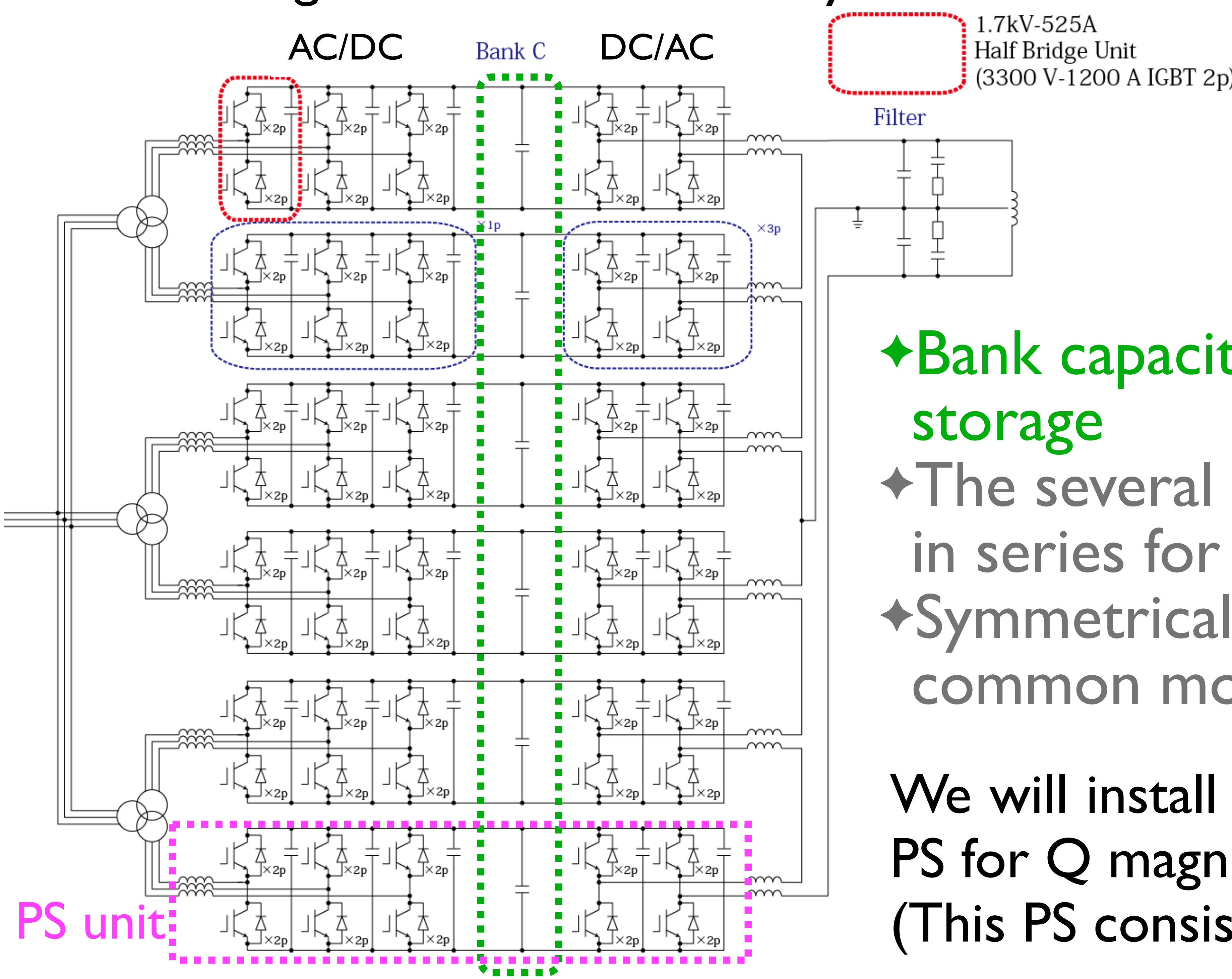
Δ66.5MW → ~~~Δ140MW~~ (~~1sec cycle~~)

Not allowed
by Electric Power Company

⇒ Energy storage
with capacitor bank

Design of new power supplies

design of PS for 1 BM family



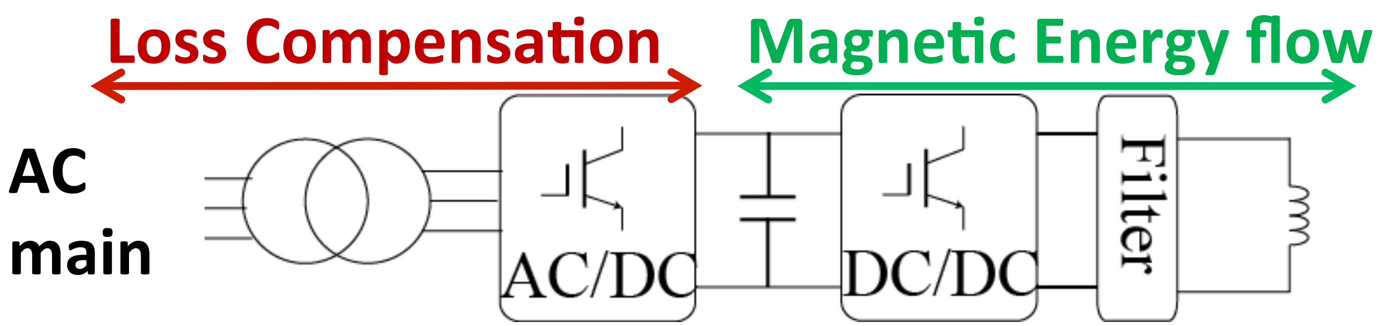
- ✦Bank capacitors for energy storage
- ✦The several PS unit connecting in series for high output voltage.
- ✦Symmetrical circuit for rejecting common mode noise.

We will install the first model of new PS for Q magnet in this summer. (This PS consist single PS unit.)

R&D status

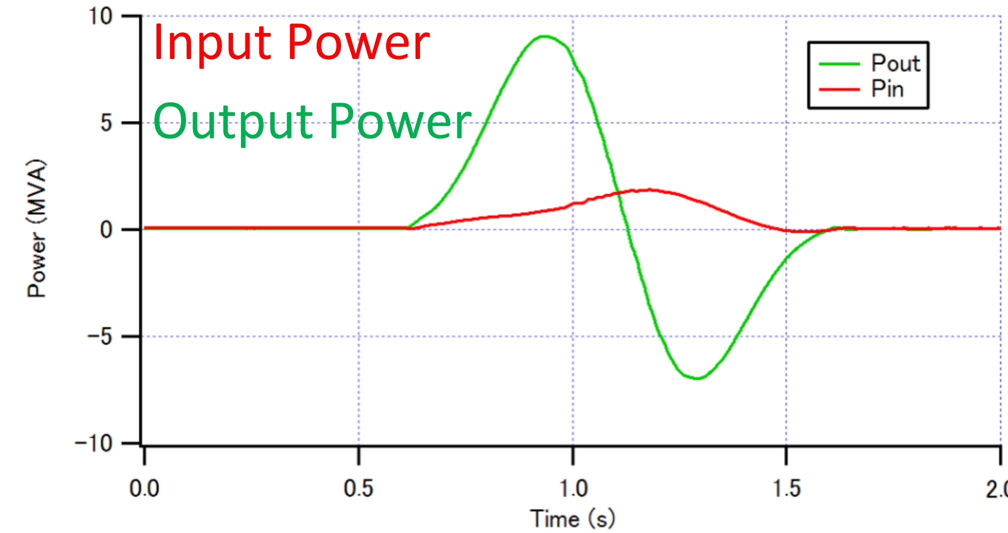
Capacitive energy storage

Conceptual Schematics



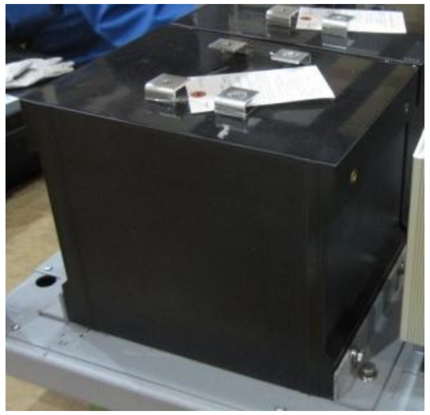
- ✦All magnetic energy is provided from the capacitive energy storage.
- ✦Only energy loss is compensated from main grid.

Input and Output Power for one power supply



- ✦Input power can be reduced 30 % of output power.

Dry-type film Capacitor

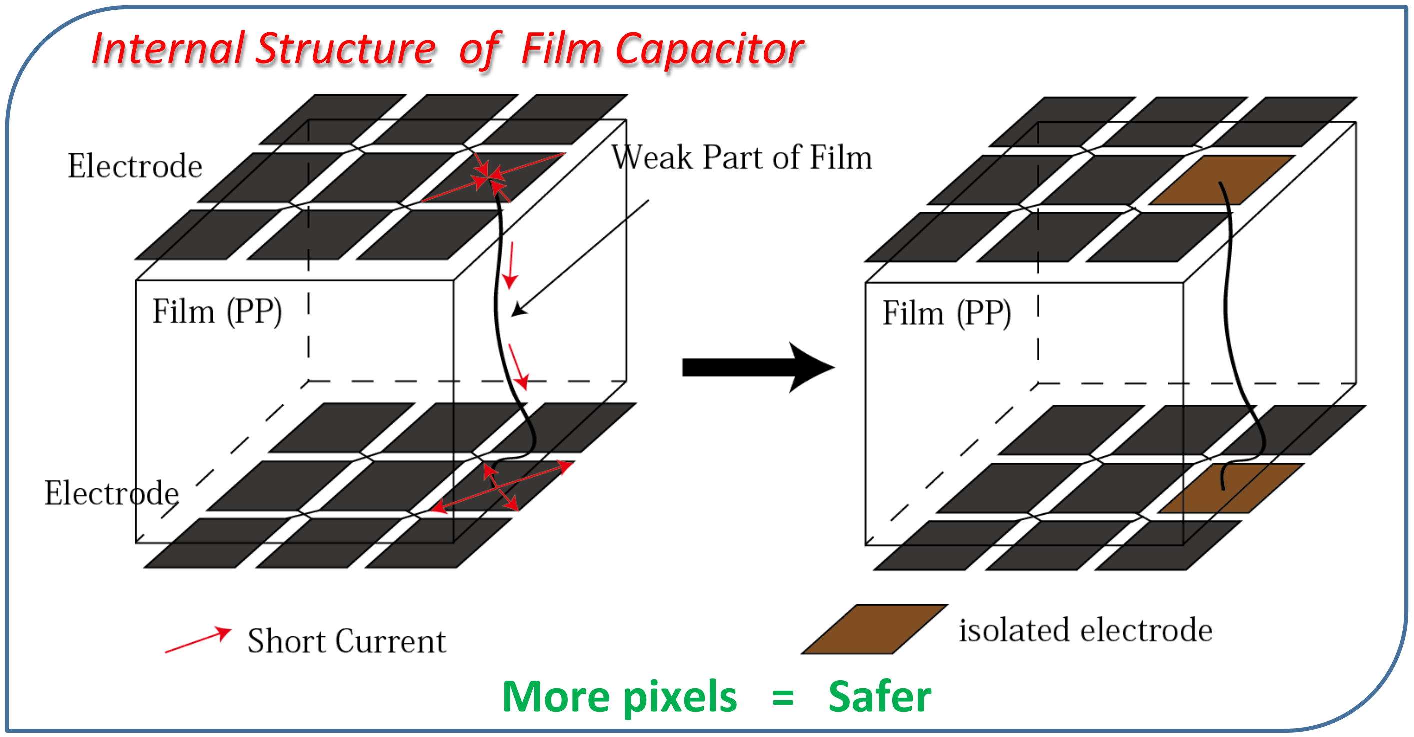


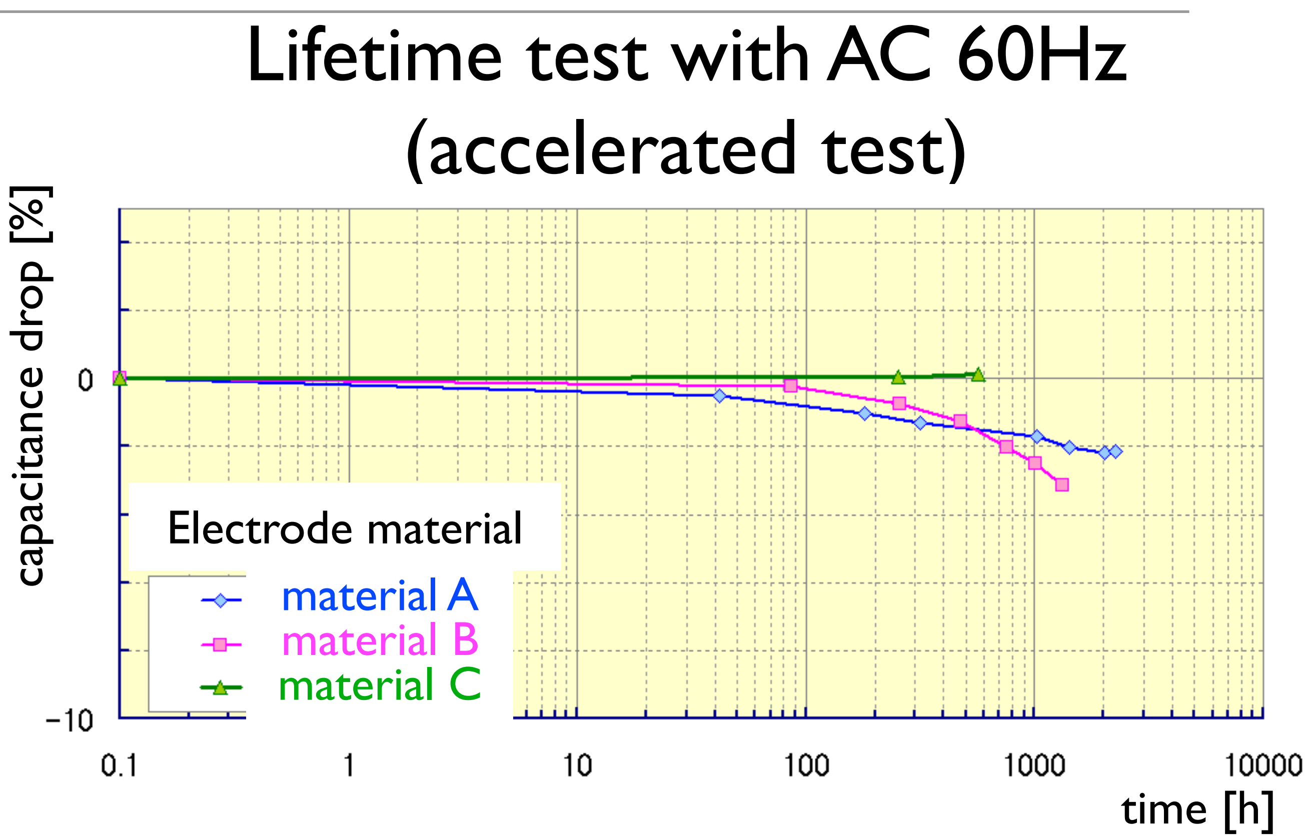
- ✦The capacitor should
  - have longer than 10 years lifetime ($\sim 10^8$ charge-discharge cycle).
  - not be short internally for safety.

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

⇒ Then, we develop capacitor based on Dry-type film capacitor.

Development of capacitor





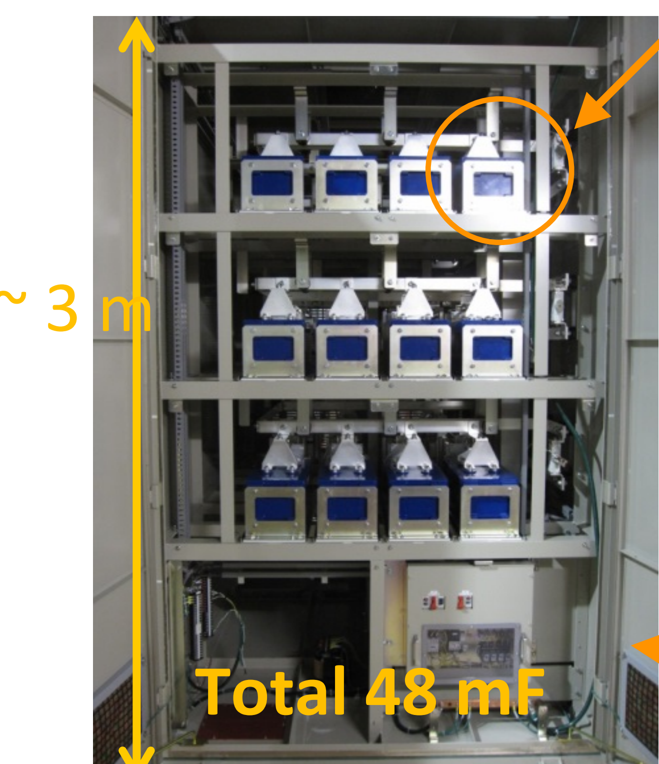
- ✦Internal structure of the film capacitor
  - ▸ Many small pixel capacitor connected each other.
  - ▸ A pixel capacitor with weak part is isolated by over current.
  - ▸ As a result, the capacitance decreases by 1/10000.
- ✦The lifetime is defined as the time until capacitance drop by 5 %.
- ✦Material C is adopted: Extrapolated lifetime = 4.5×10^8 pulse.

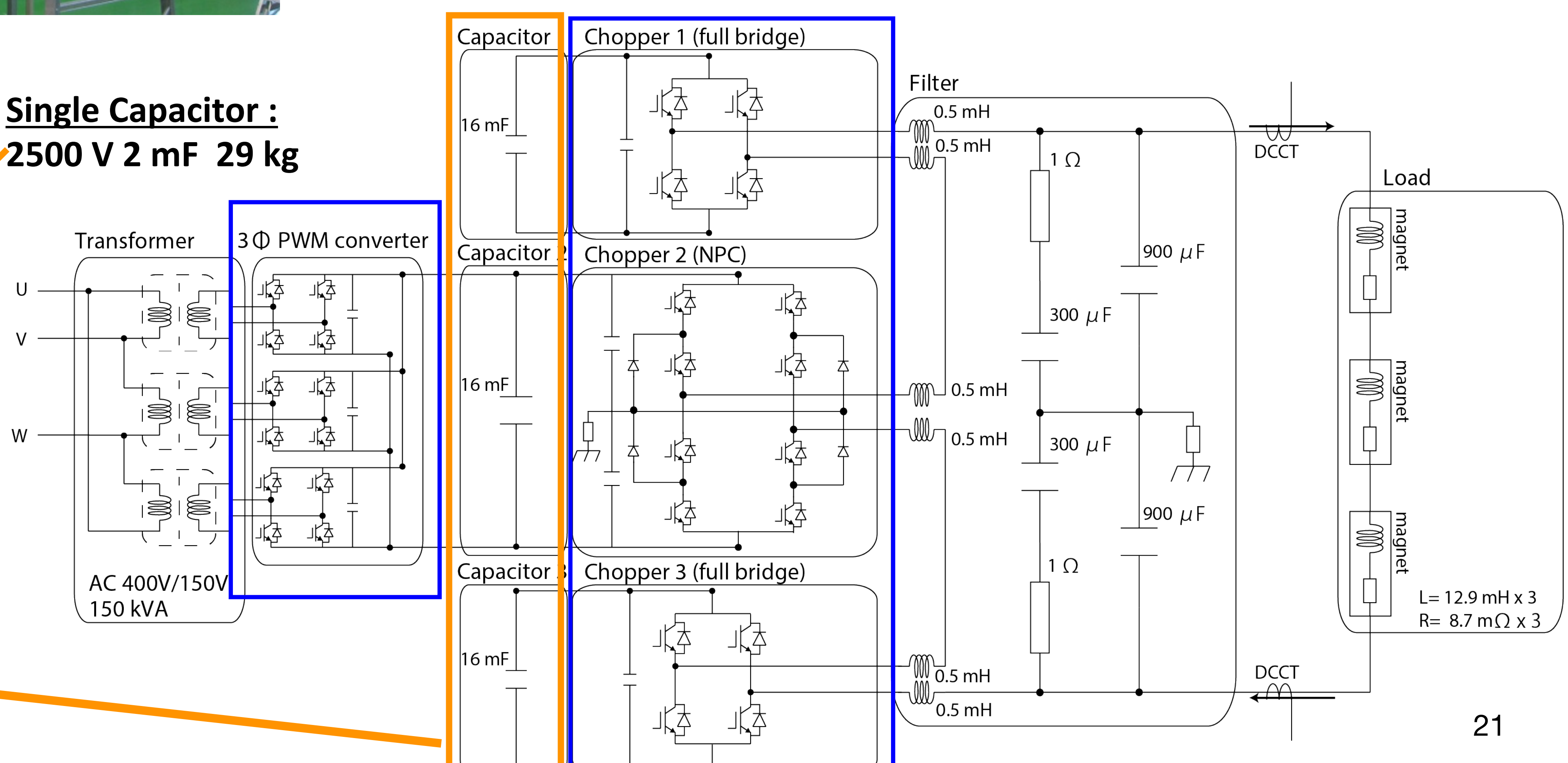
Capacitor design was fixed !!

Test with real scale components

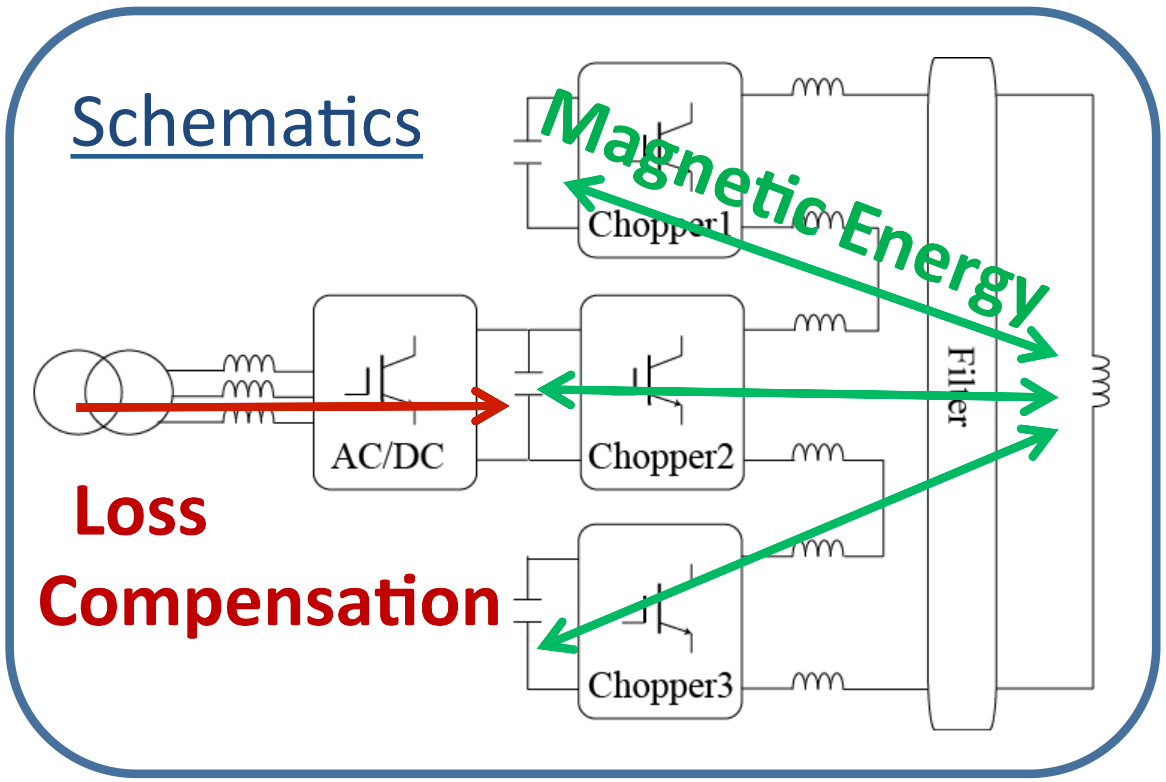
- ✦Combined test of Minimum hardware and our developed control system.
- ✦Switching components are real scales.

Single Capacitor :
2500 V 2 mF 29 kg

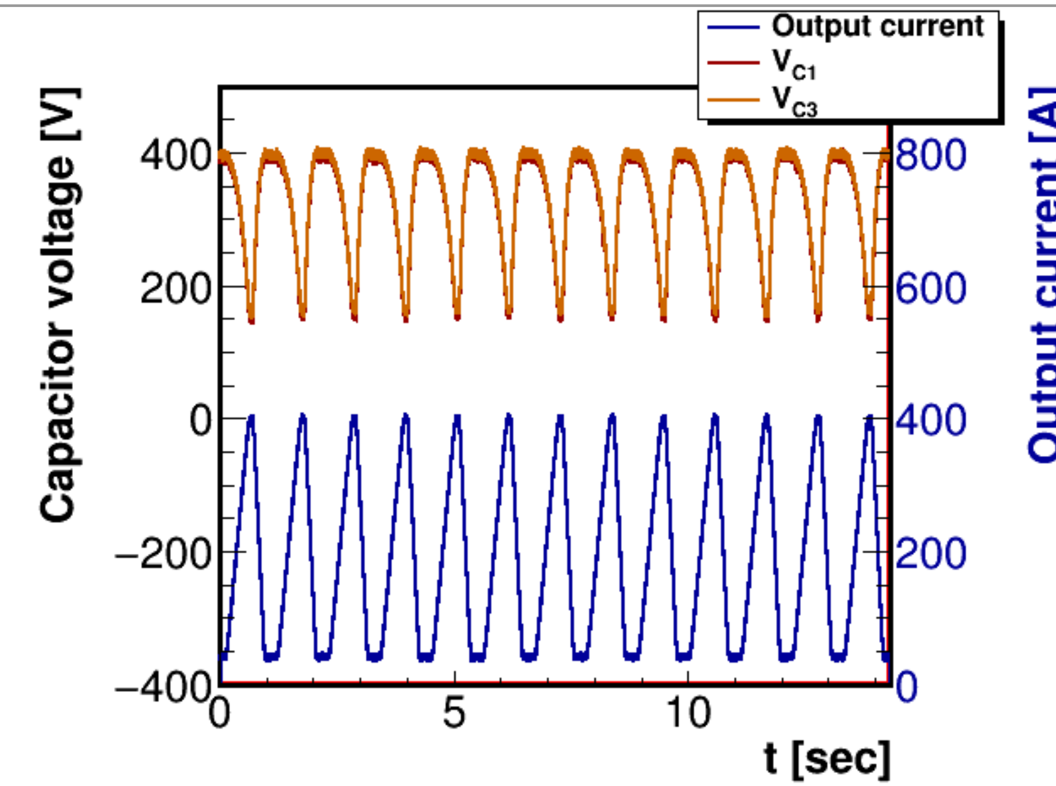




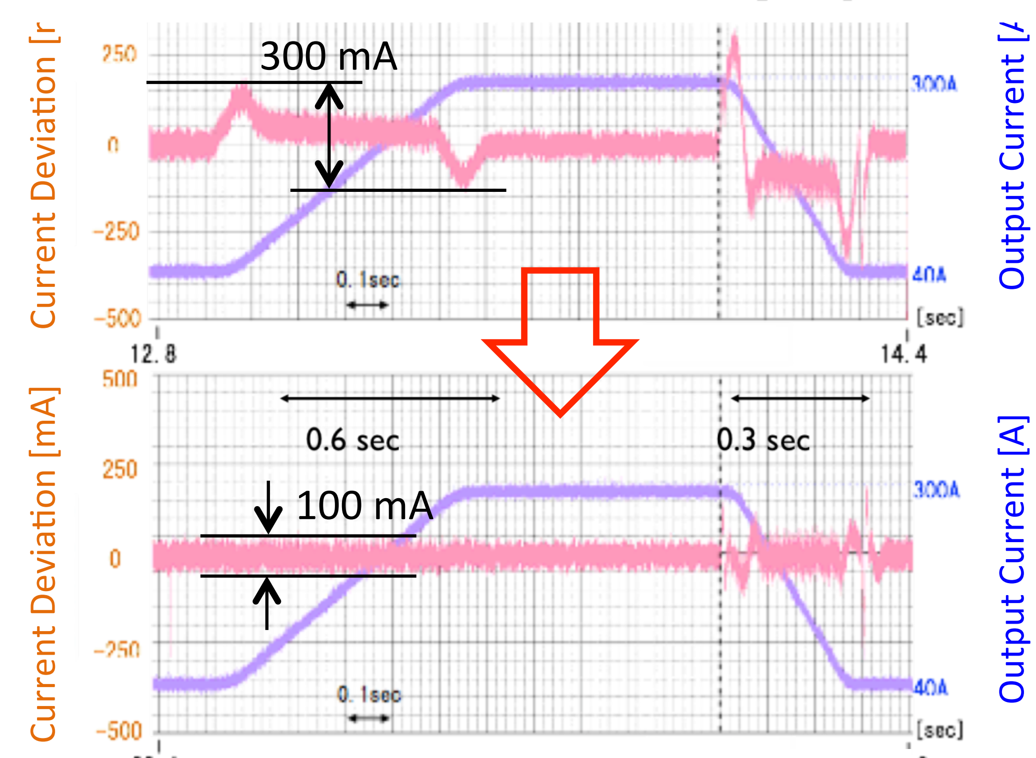
Test result with real scale components



A)



B)



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

We have succeeded

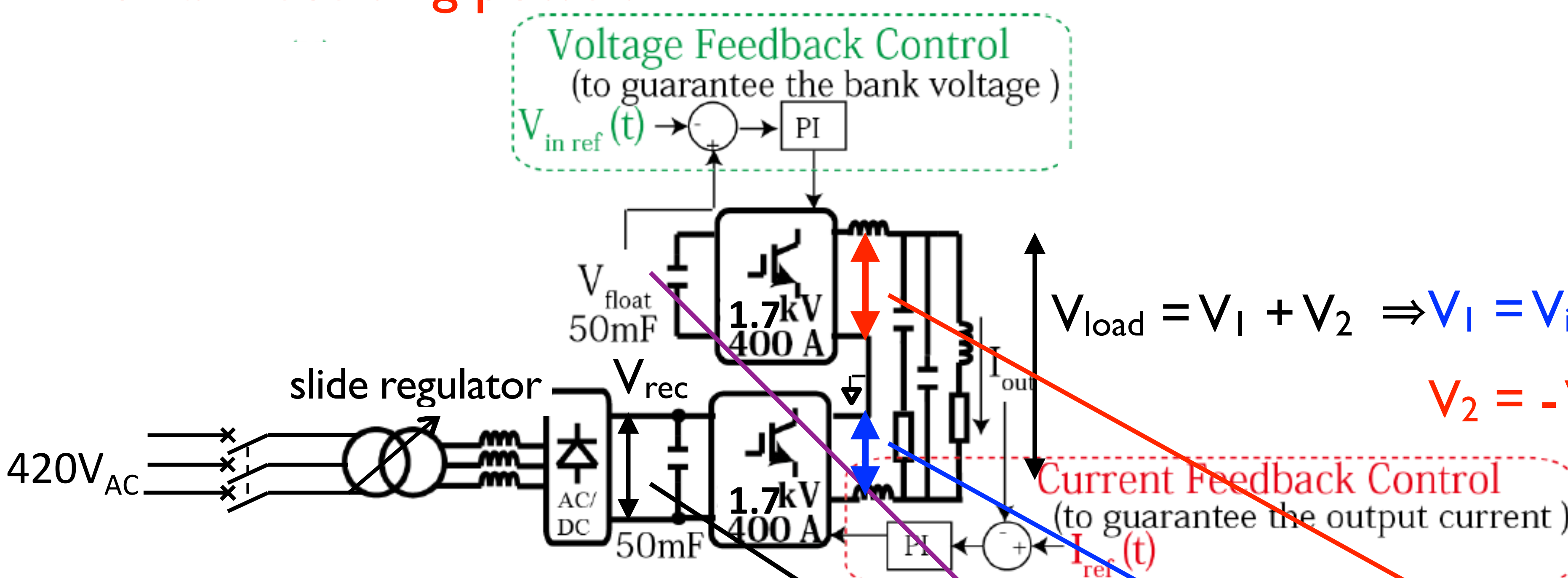
A) Energy transfer control between capacitor bank and magnets.

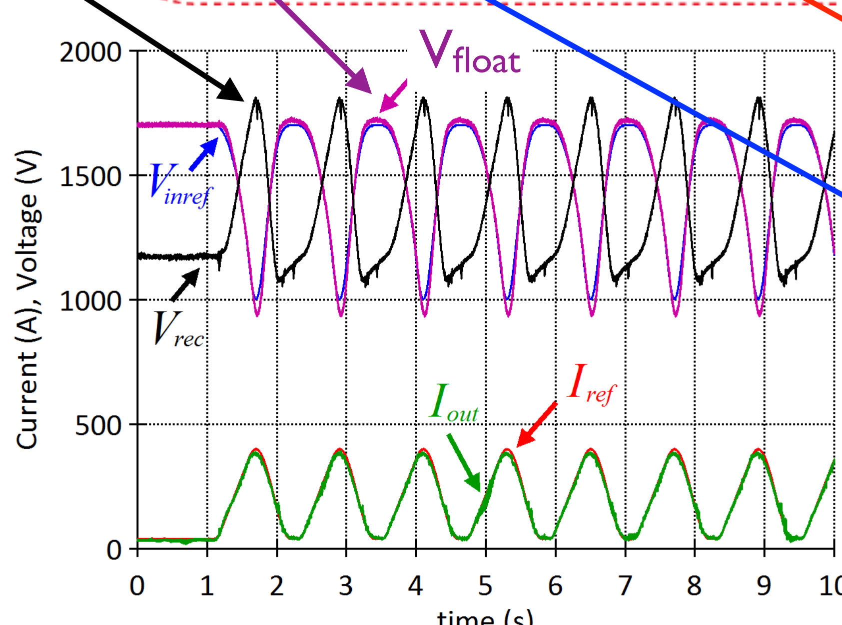
B) Correction of the current deviation.

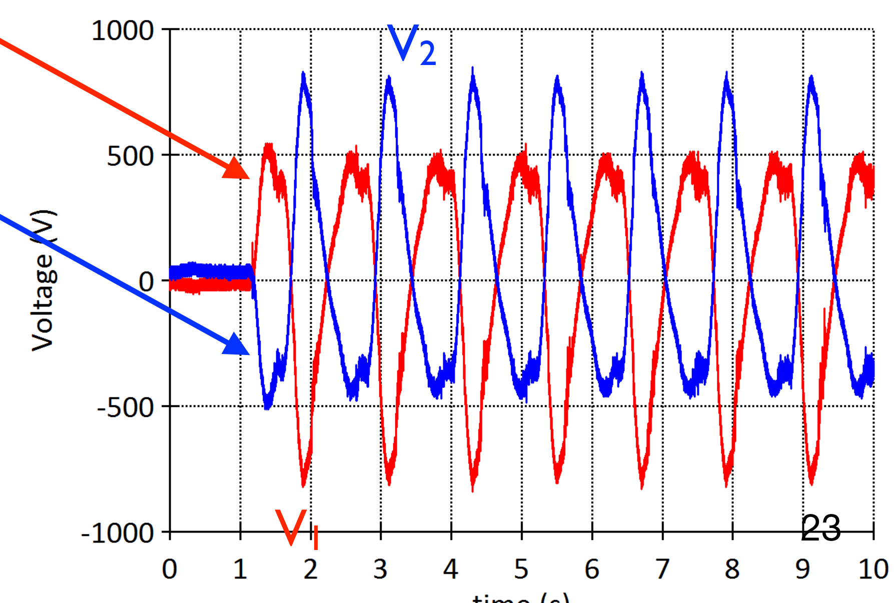
Control method has been established with real scale PS component.

How do we get high output voltage of converter in the test with small load ?

- That test is only ~200 V output with L=38 mH, R=27 mΩ of load magnets.
- However, the real load is L = 1.75 H, R = 0.25 Ω. (We don't have large load for testing.)
- Test method is developed to obtain as high as possible output voltage with small load and small receiving power.







Summary

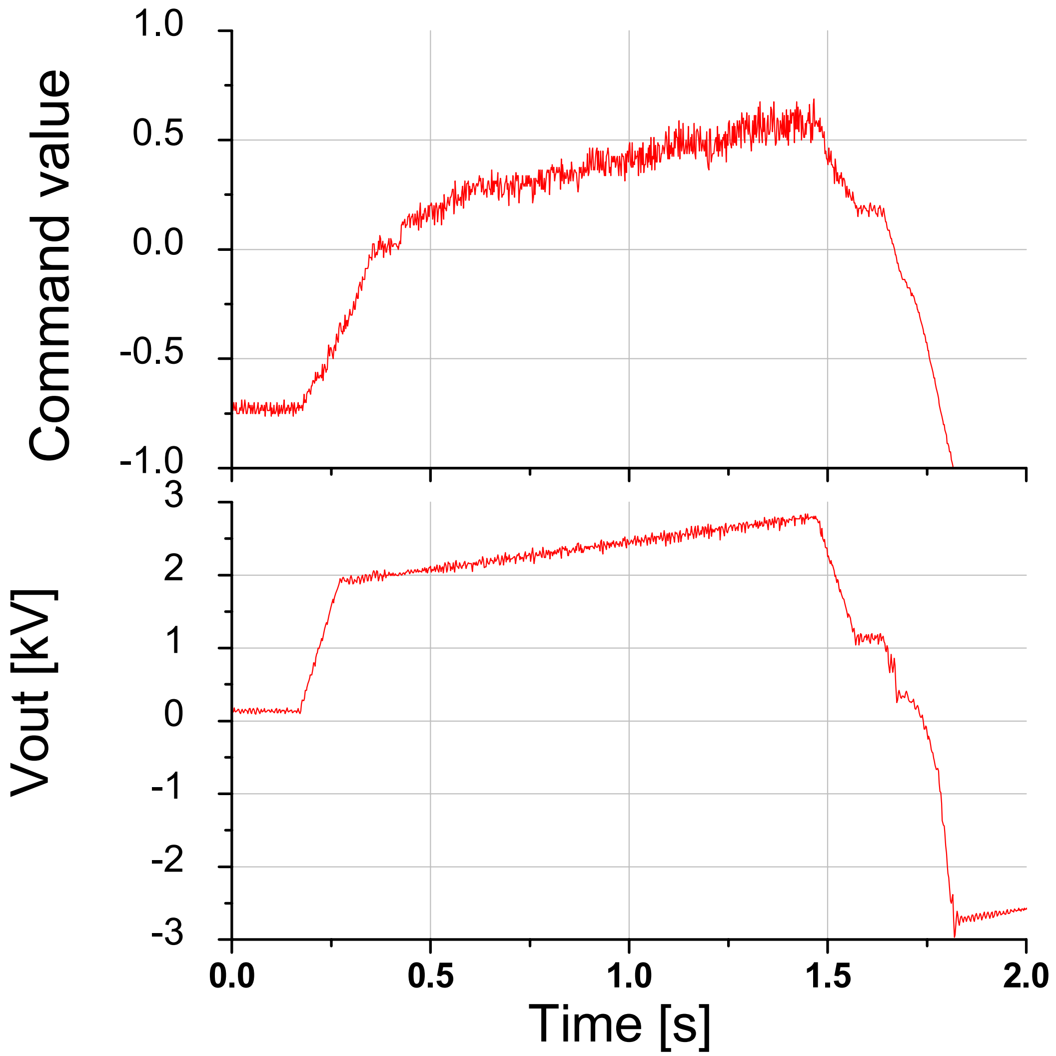
- Present power supplies of main magnet in J-PARC MR
  - In first beam commissioning, we could not precisely regulate the magnetic current using our original power supplies due to several reasons such as common-mode ripples.
    - ✓ We did re-cabling between the power supplies and magnets for the cancellation of the common-mode ripples.
    - ✓ The tracking performance was improved by "feed-forward" technique.
- New power supplies for upgrade of J-PARC MR
  - R&D was done, the production of the first model of new power supplies is on going.
  - The first model of new power supplies are installed in this summer.

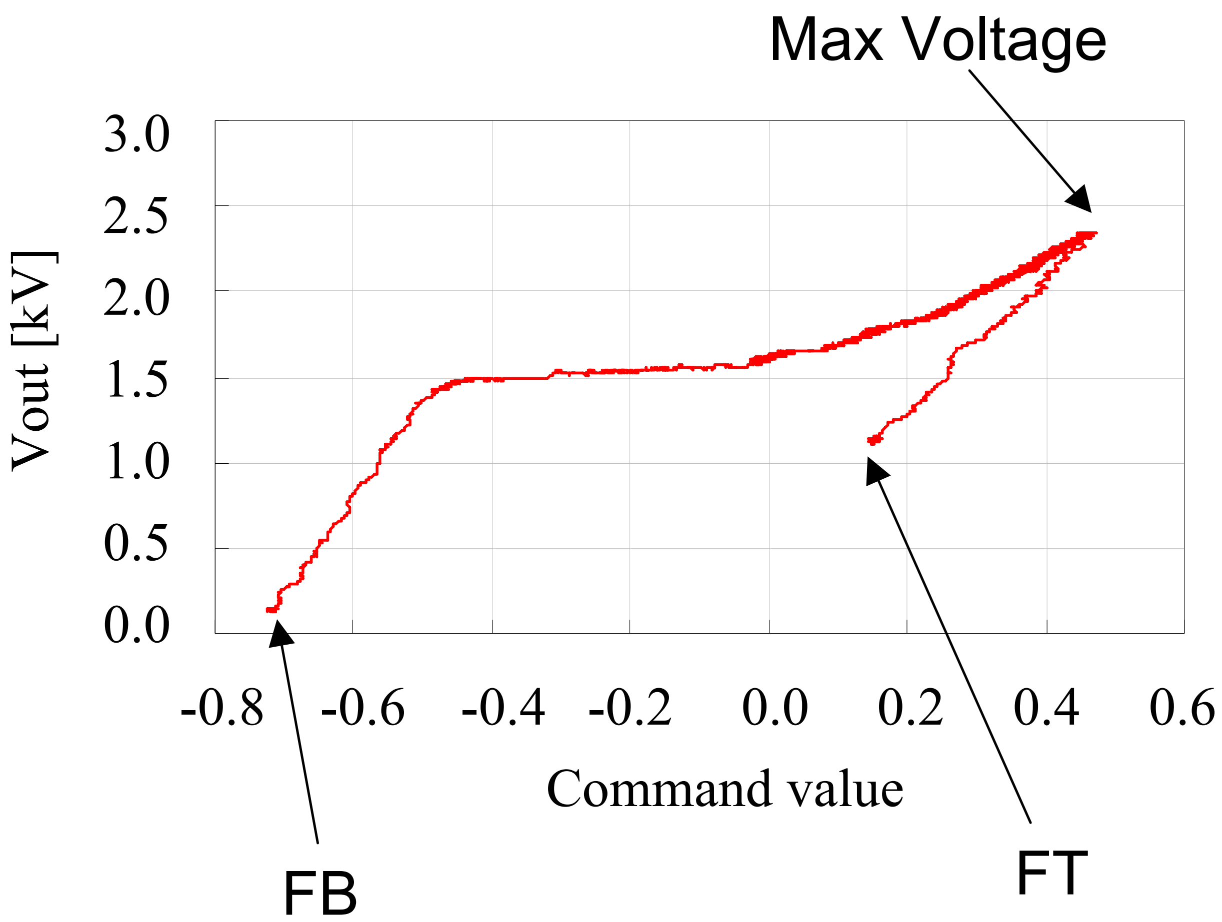
backups

MR magnet power supplies

Family	L @ 30 GeV [H]	current @ F.B. [A]	current @ F.T. [A]
BM	1.47	190	1570
QFN	2.93	86	710
QDN	3.46	86	710
QFX	2.39	86	710
QDX	1.75	86	710
QFP	0.57	77	640
QFR	0.44	77	640
QDR	0.20	75	620
QFS	0.30	81	670
QDS	0.35	110	890
QFT	0.32	95	780
QDT	0.37	90	750
SFA	0.42	20	200
SDA	0.41	20	200
SDB	0.41	20	200

Nonlinear gain on the converter



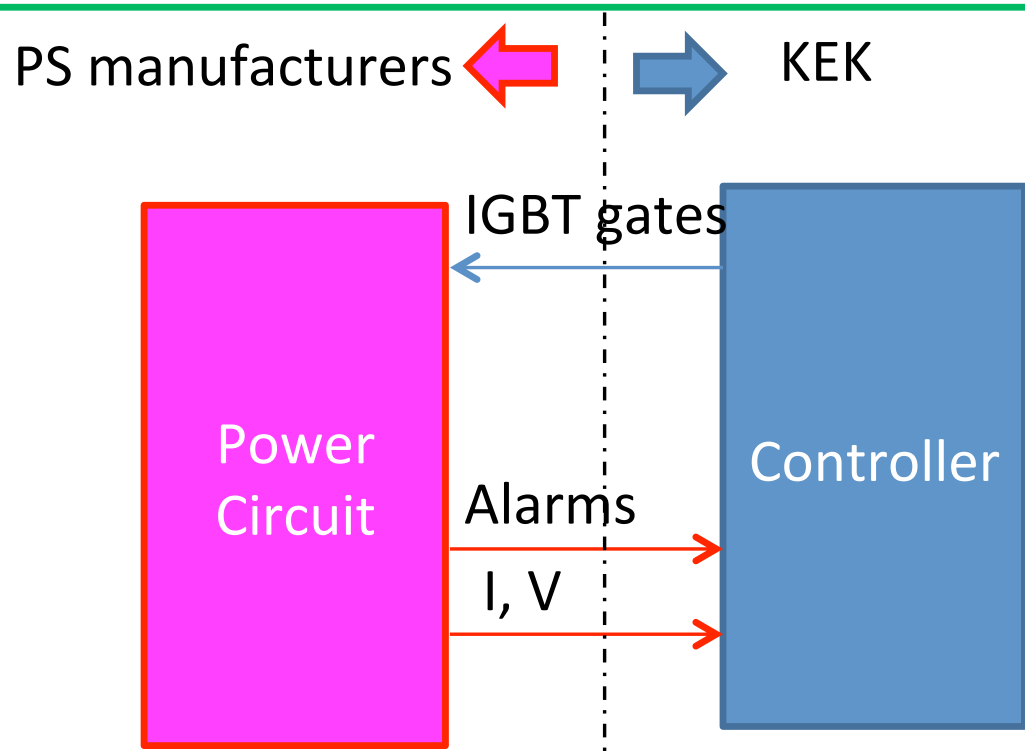


This nonlinearity makes the tracking error.

7

Approach toward production

Controllers and power circuits are separately considered.



Power Circuits

By manufacturers

Controllers

- The control algorithm is already developed and tested.
- Electrical design and software design are done by the KEK stuffs.
- Just asking local factories for the production

This approach was also adopted for new injection septum PS and now is under testing

- For companies, this expands possibilities to join our project
- PS manufacturers can concentrate on power circuits

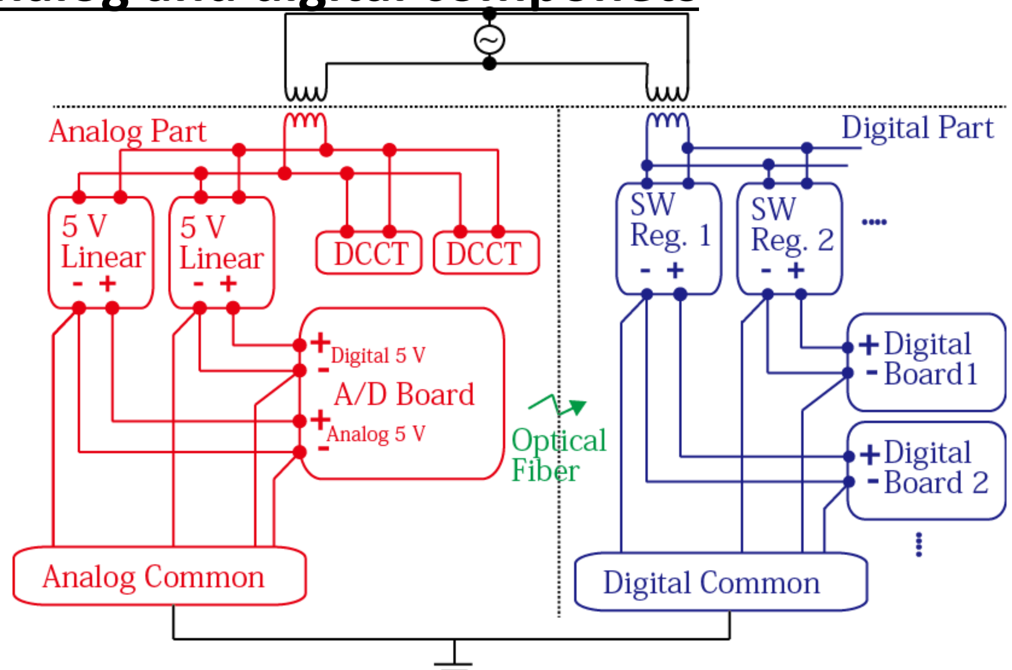
→ **Cost Reduction**

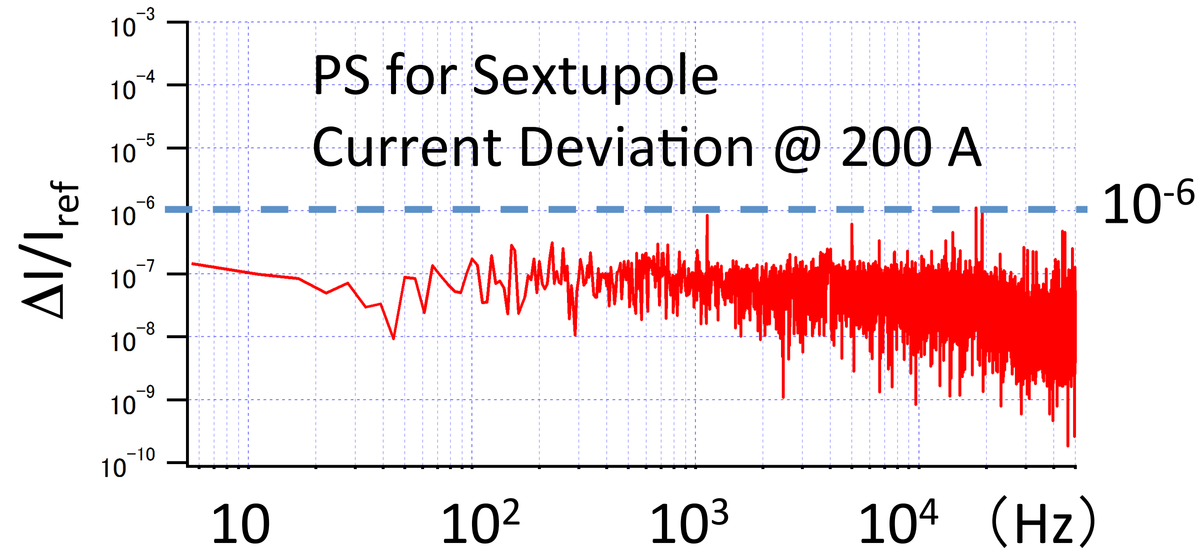
- Enable us to easily modify and upgrade our control scheme
- However, close communication between KEK and PS manufacturers is mandatory

↔ at least one KEK stuff stays in the manufacturer.

Low noise measurement and digital control

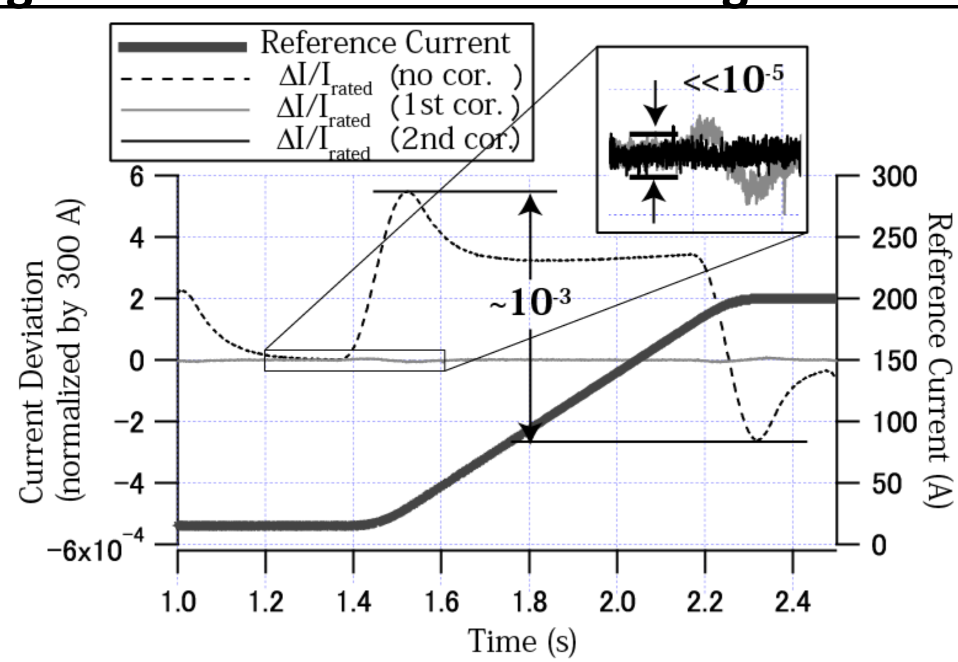
- **24 bit A/D board and Isolation between analog and digital componets**



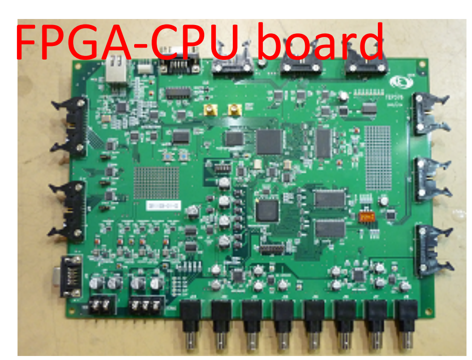


Succeed to measure current at ppm level

- **Digital Control Board for Tracking Error Correction**



Tracking error can be reduced down to 10^{-5}



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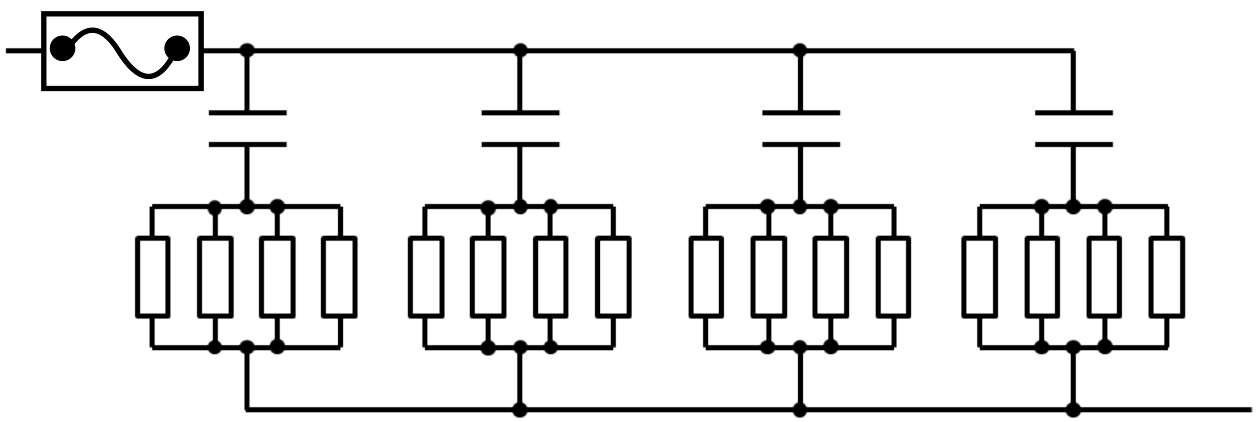
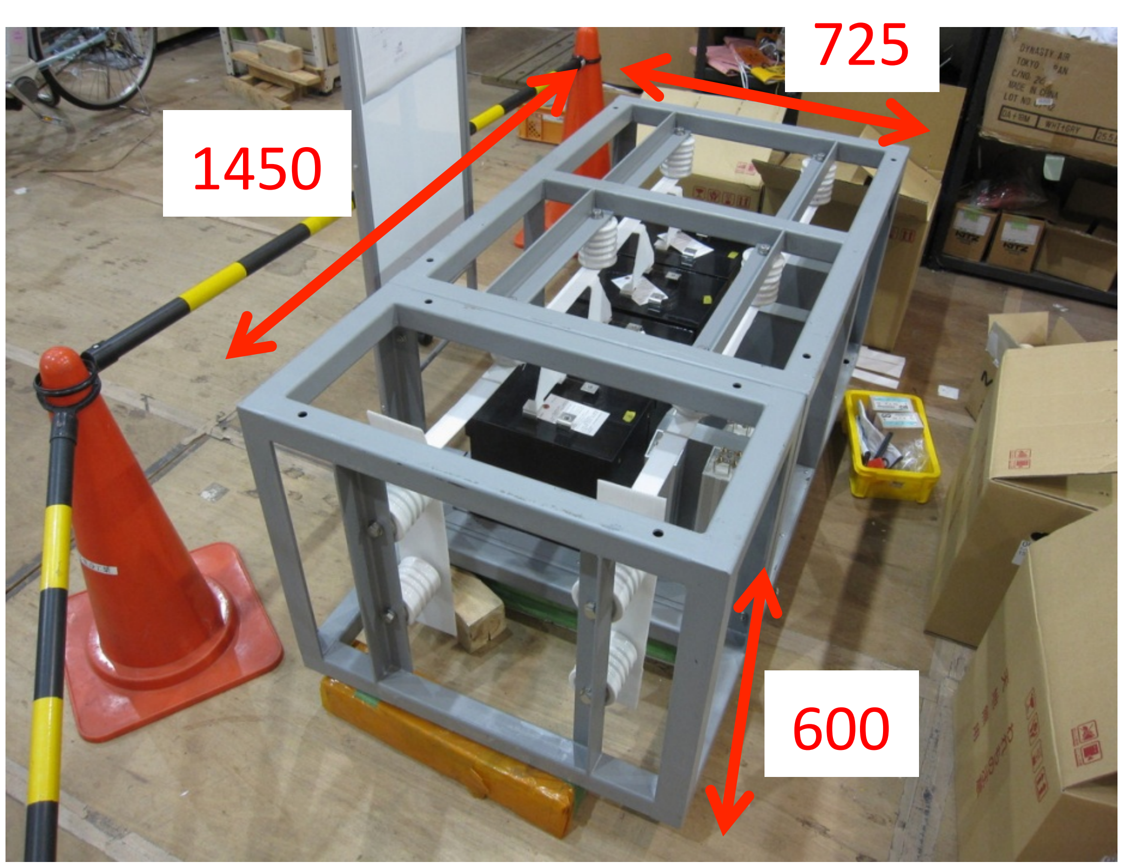
Unit of bank capacitor

Schematic circuit of capacitor unit

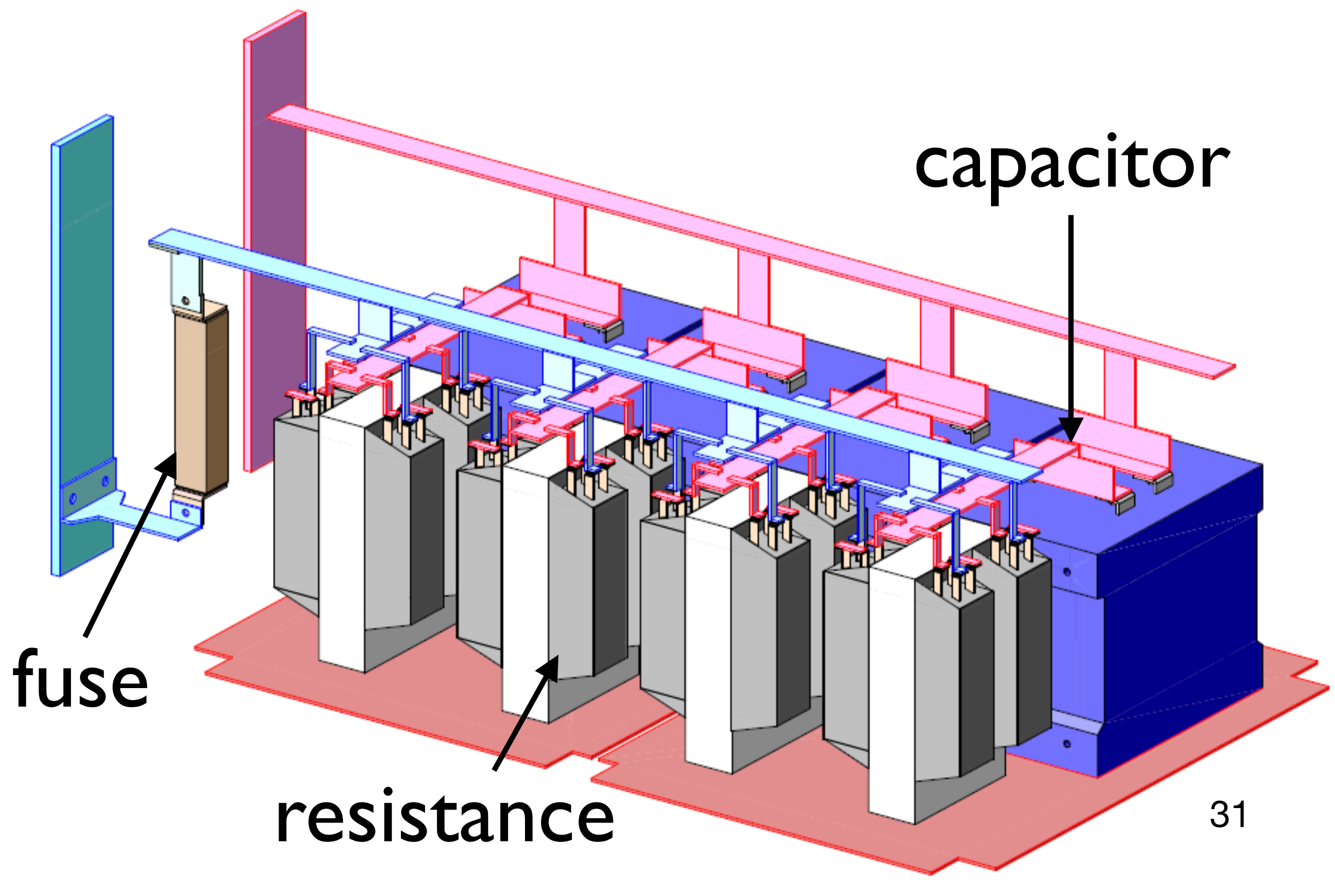


✦Fuse to avoid the concentration of energy from ~100 capacitors. (If a capacitor is shorted.)

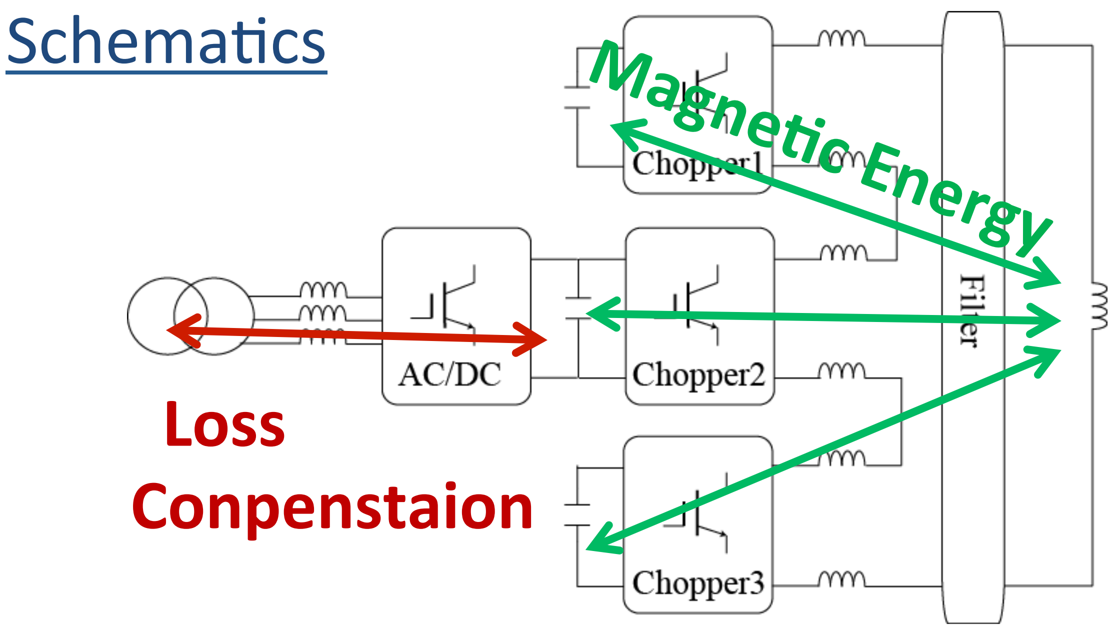
✦One fuse for 4 capacitors.

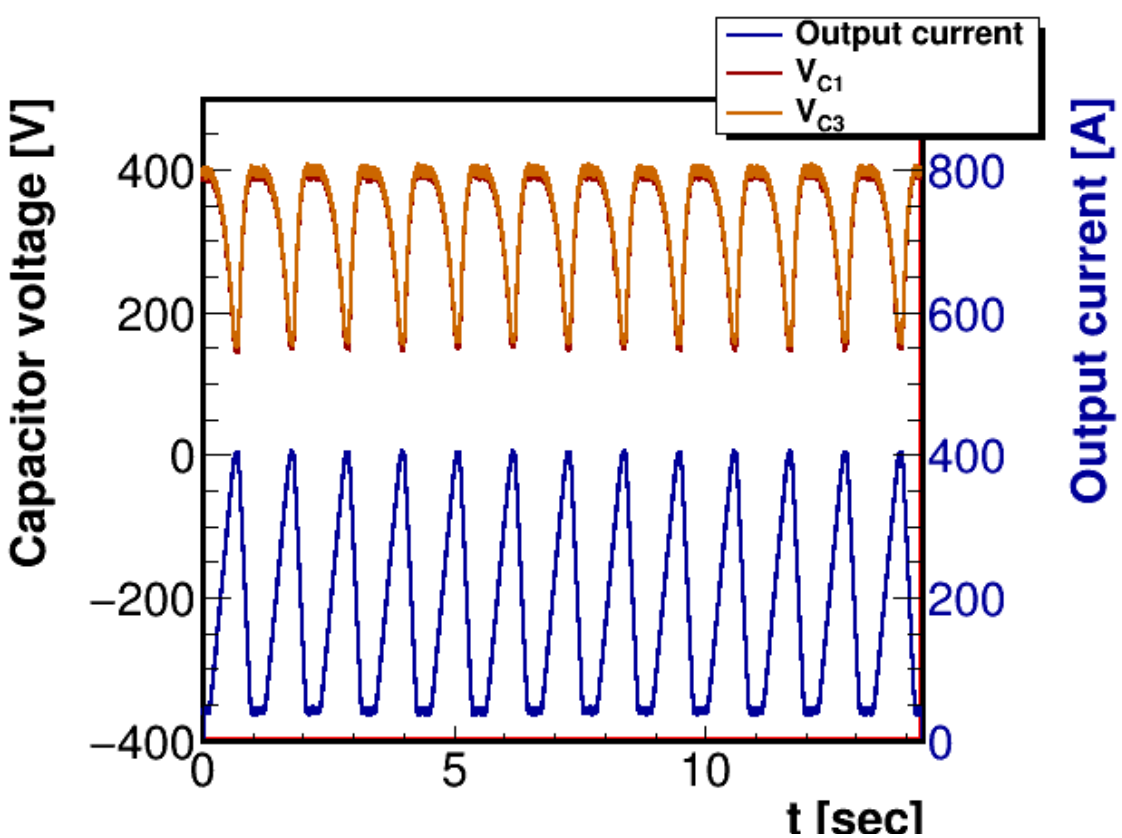


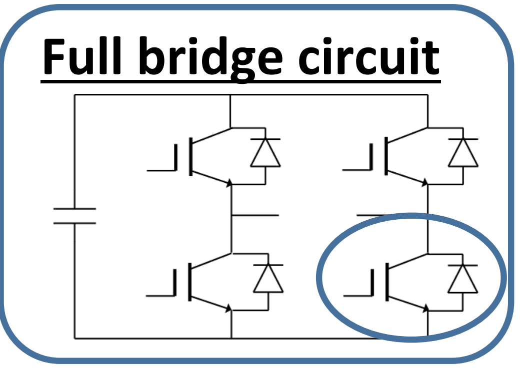
prototype of capacitor unit

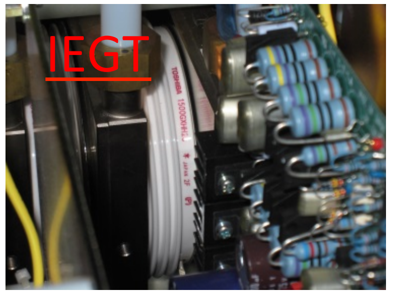


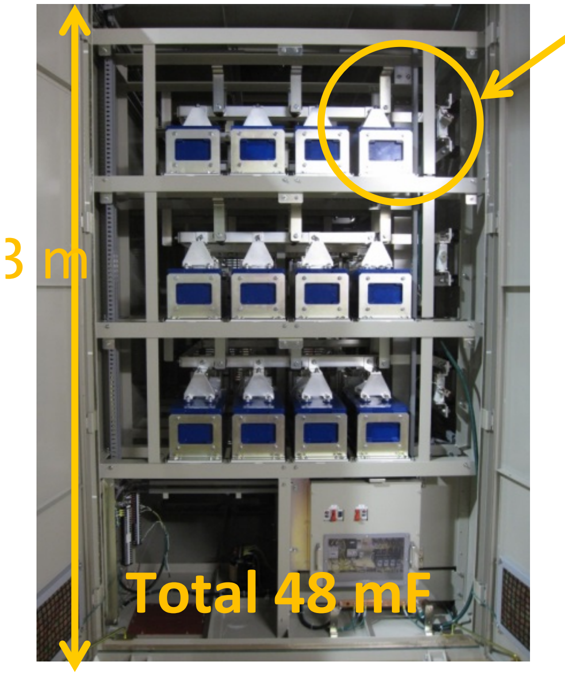
Test result with minimum hardware











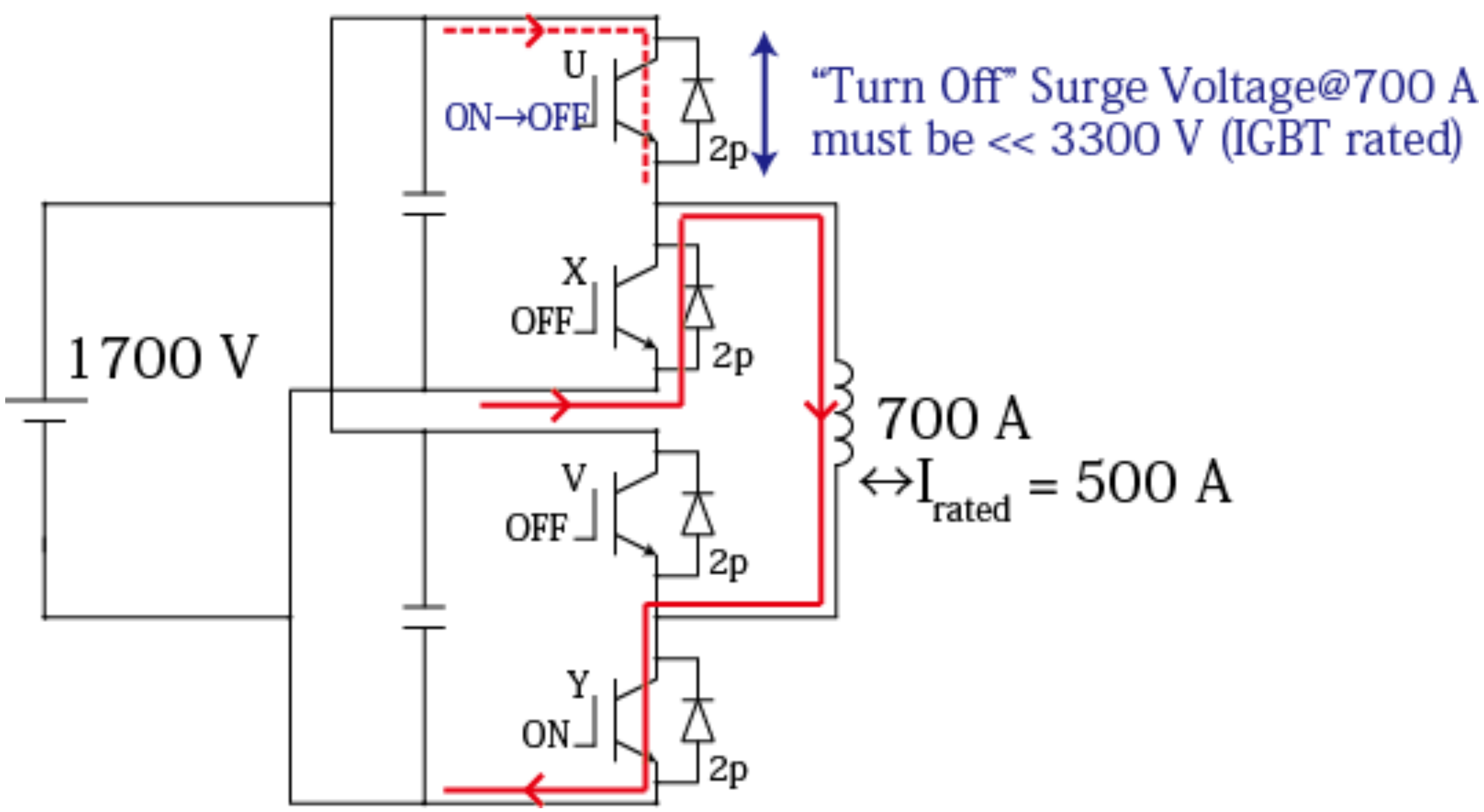
Single Capacitor :
2500 V 2 mF 29 kg

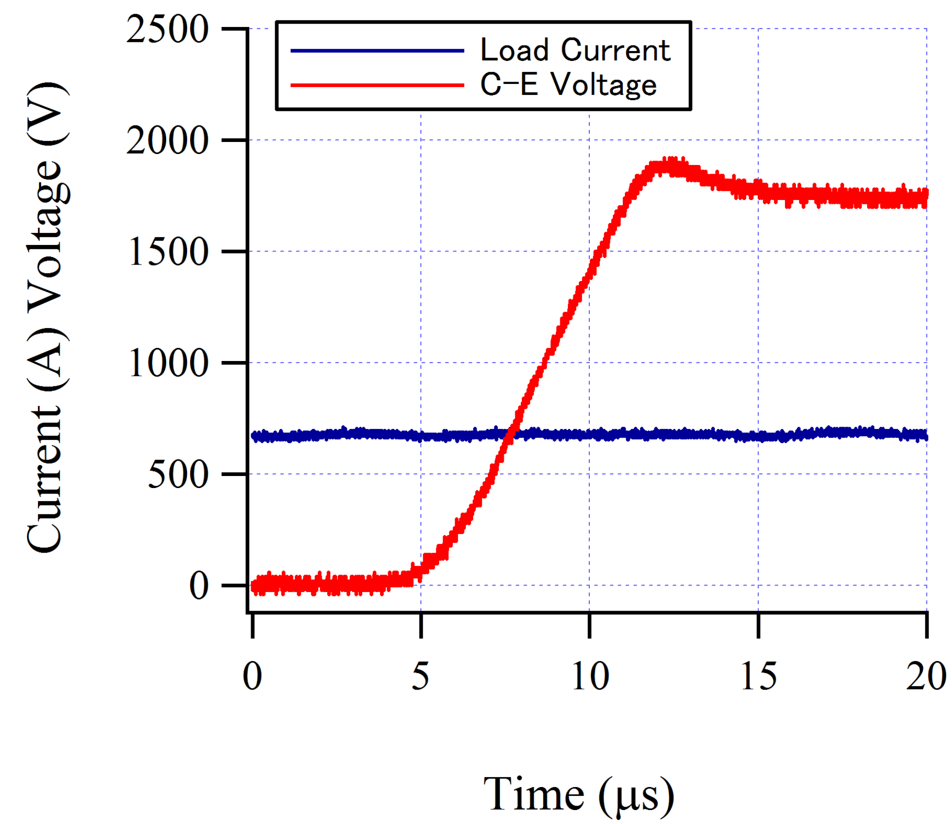
Planed area for new PSs can accommodate all capacitor banks (≈6F)

We have successfully controlled energy between the capacitor bank and magnets

Measurement of surge voltage in IGBT unit

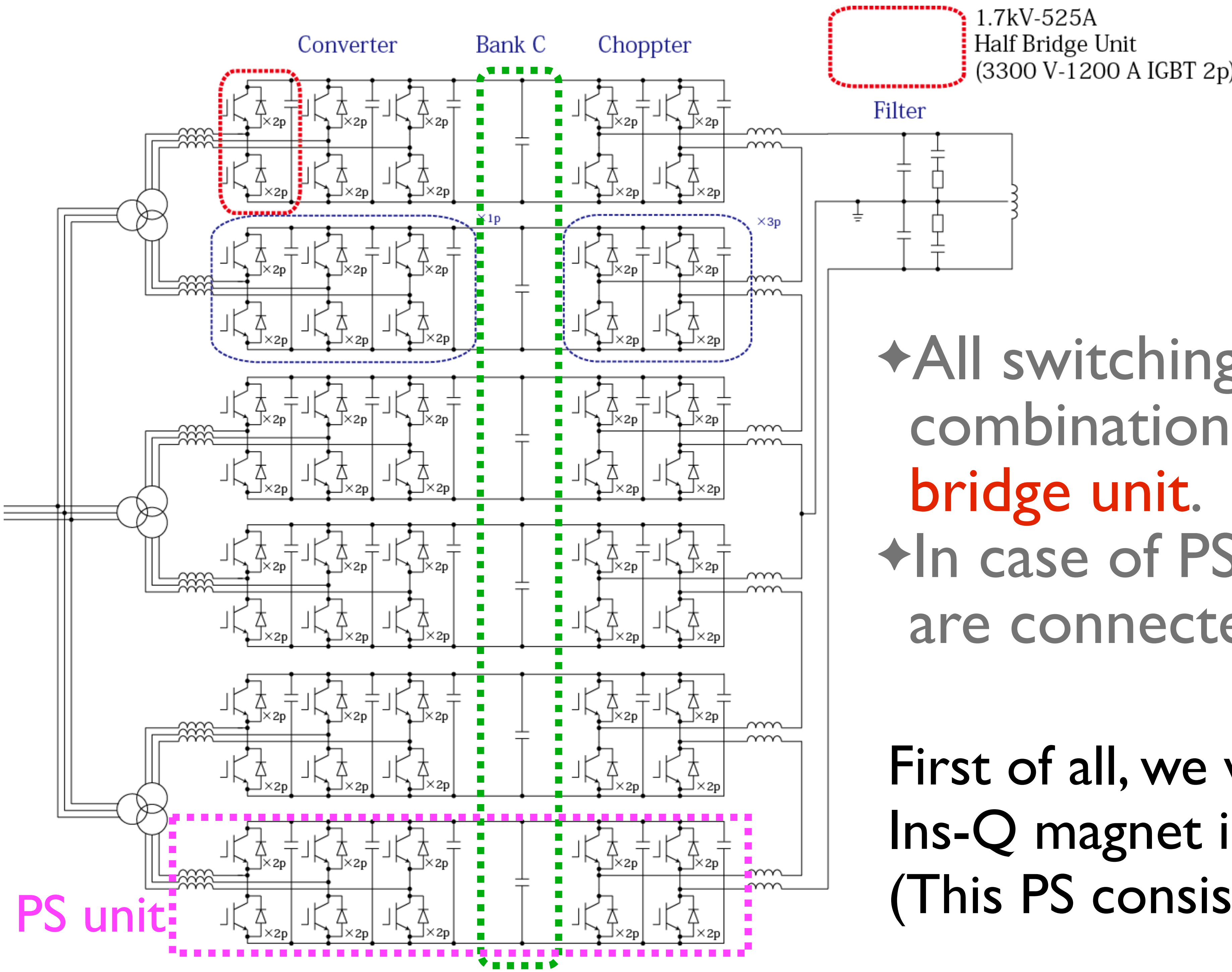
- Mechanical test of IGBT half bridge unit
  - When switch U changes ON → OFF, voltage between corrector and emitter is measured.
  - The capacitance is charged by energy stored in parasite inductance.





Design of new power supplies

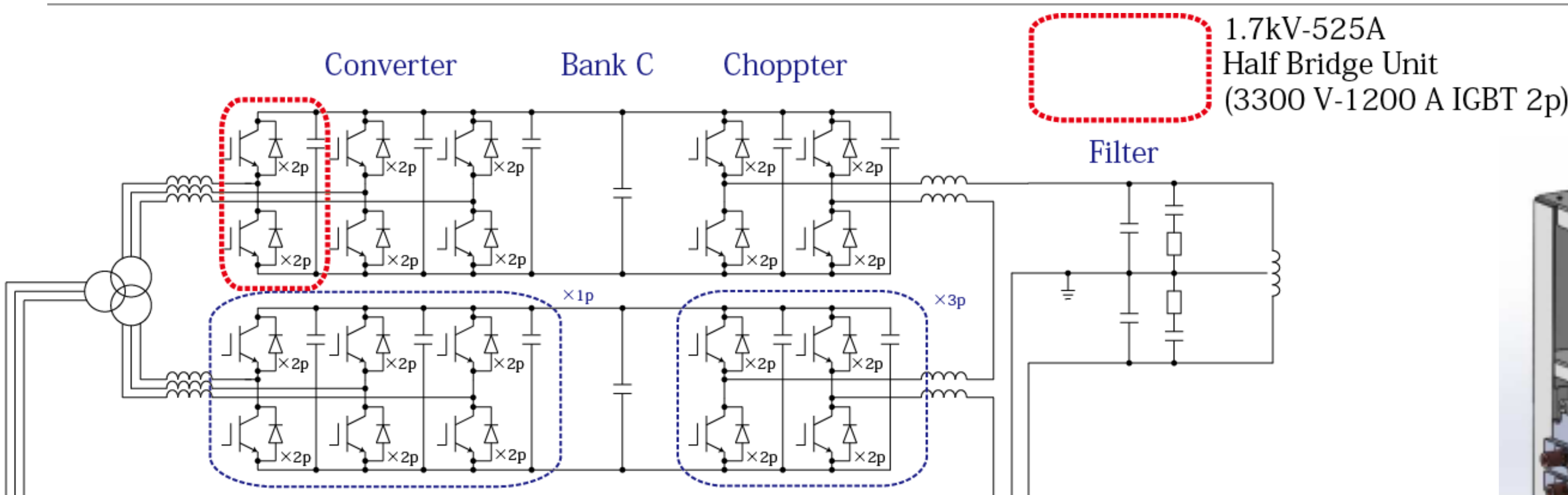
design of PS for 1 BM family

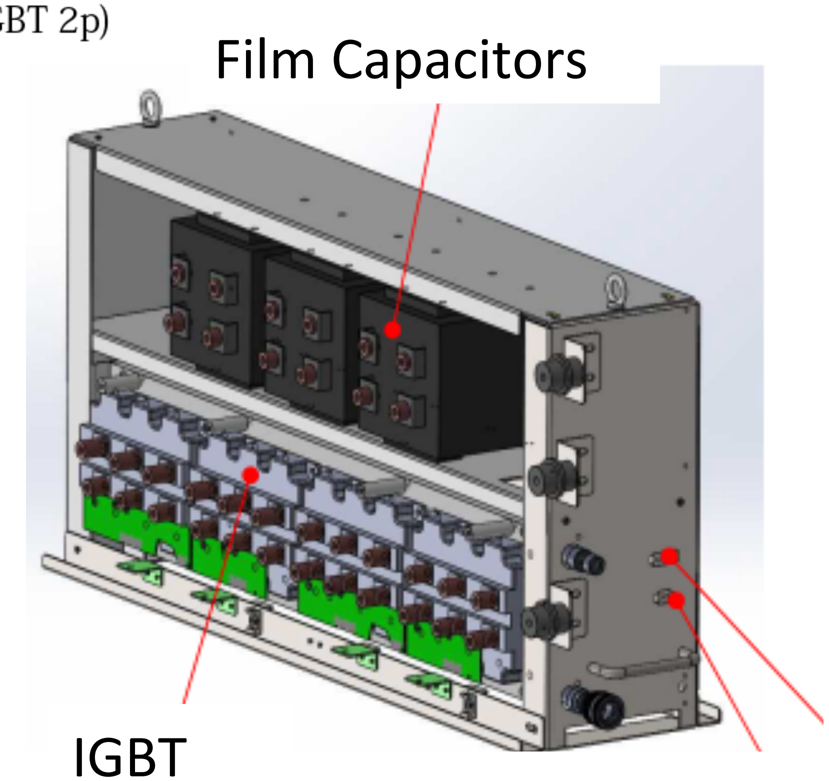


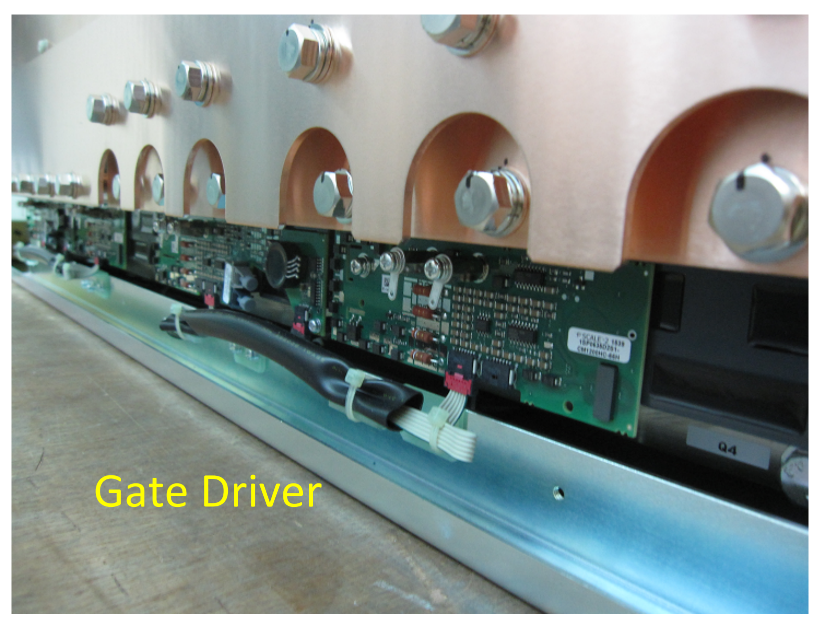
- ✦All switching devices consist of combination of the same half bridge unit.
- ✦In case of PS for BM, 6 PS units are connected in series.

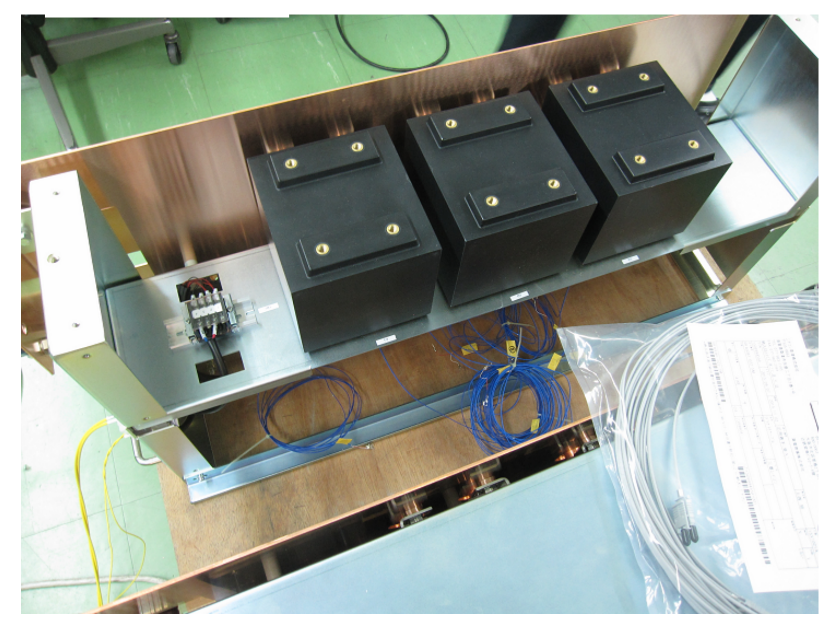
First of all, we will install the PS for a Ins-Q magnet in this summer.
(This PS consist single PS unit.)

Production of IGBT (half bridge) unit









Design of capacitor bank

- ✦A capacitor unit consists of 4 capacitor, one fuse and 16 removable resisters for adjusting the current into the capacitor.
- ✦Single capacitor bank for BM PS consists of 24 capacitor units.
- ✦2 capacitor banks are installed in a 40ft container.
- ✦240 mF capacitor bank will be made and tested in this summer.

24 capacitor units (3x8) = 480 mF