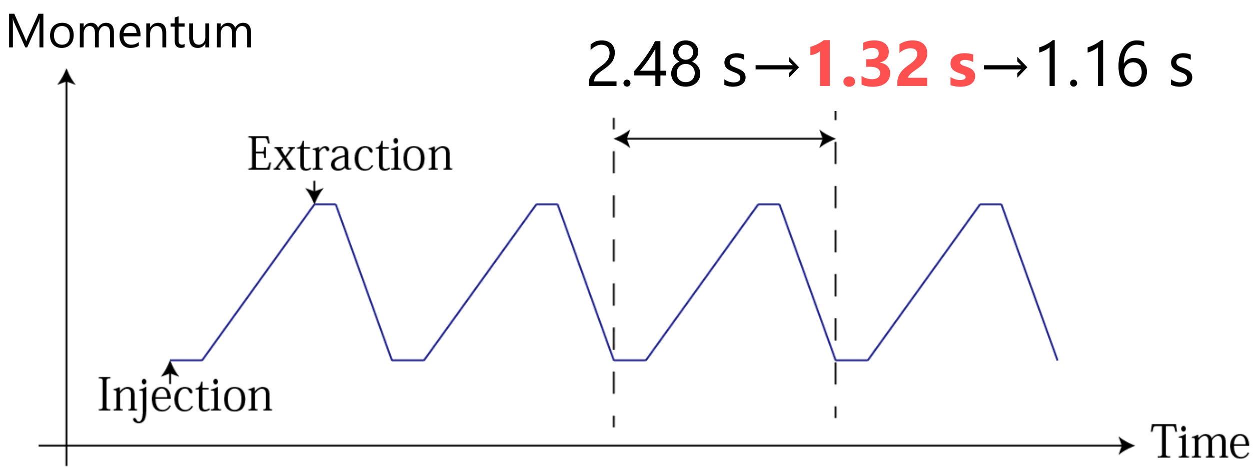
J-PARC Main Ring Upgrade toward High Repetition Rate Operation

Yoshinori Kurimoto, Yuichi Morita, Tetsushi Shimogawa
Ryu Sagawa and Kazuki Miura

Contents

Upgrade for Higher Repetition Rate

J-PARC MR　Acceleration Cycle



- **Effective beam power will be increased by shorten the period between the extractions**
- **Need new power supplies (PSs) which can drive magnets faster. (higher output voltage)**

$$V = L_{mag}\frac{dI_{mag}}{dt} + R_{mag}I_{mag}$$

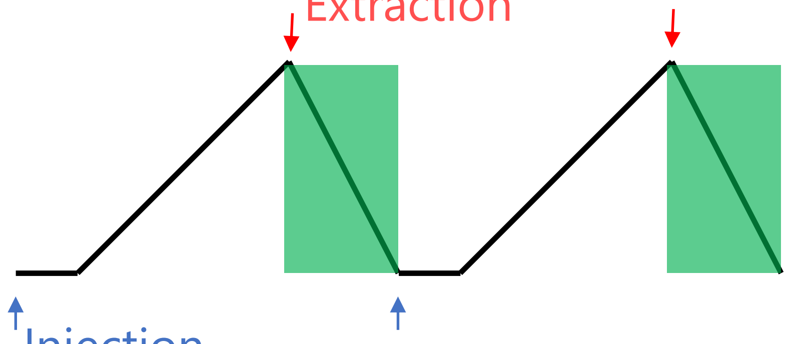
- **Replacement will be scheduled in FY2021**

Specification of Power Supplies (PS) for T_s~1.3 s

Large PS (Dipole, Quadruples @ ARC) : 6000 V, 800-1500 A　Small PS (Quadruples @ INS) : 1500 V, 800 A-1000 A

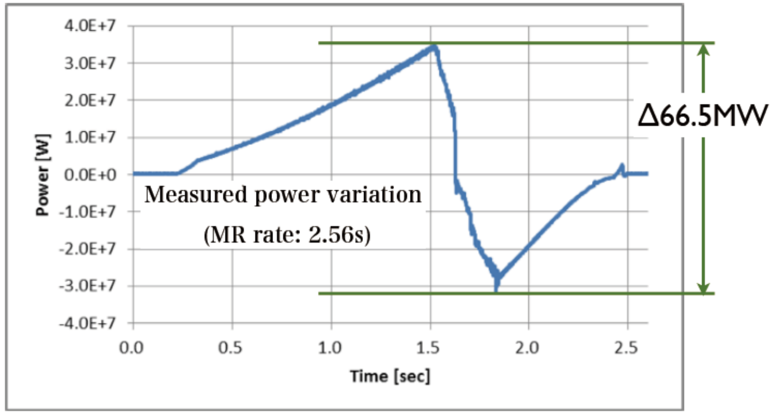
Input Power Variation

Magnetic Field



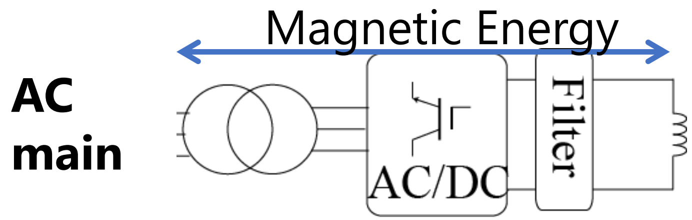
magnetic energy must be reduced for the next injection

Present Input Power Variation



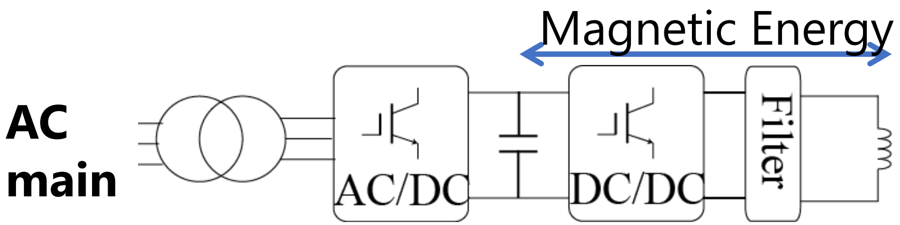
Required to be maintained at the present level even after the upgrade by the electricity company

Present PS



Currently, all magnetic energy are returned to the AC main grid

Proposal of a new PS with capacitor bank

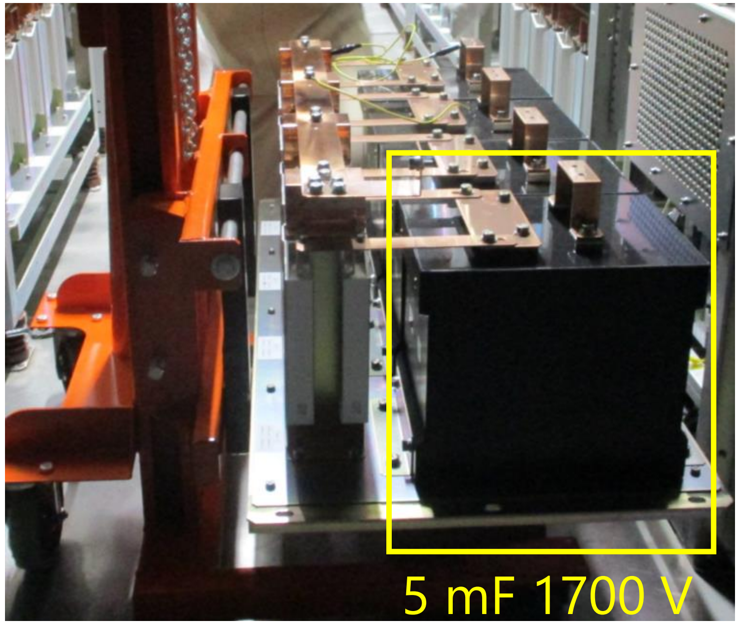


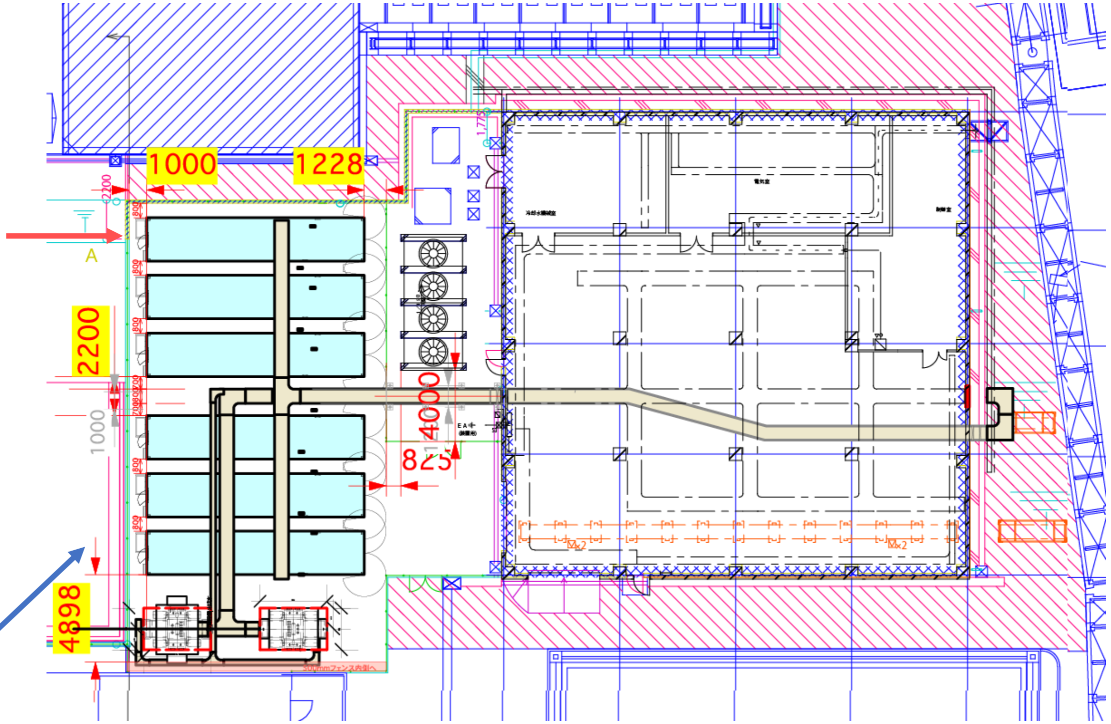
All magnetic energy is recovered to capacitor bank

Hardware Requirement and Design

Capacitor Bank

- High Energy Density 300 J /kg, Dry Type, Self Healing
- Limited Space → 4 MJ/a Large PS





Reserved Area
For Capacitor Bank
(2 Large PSs)

Voltage on Capacitors

- Simple IGBT bridge for current regulation

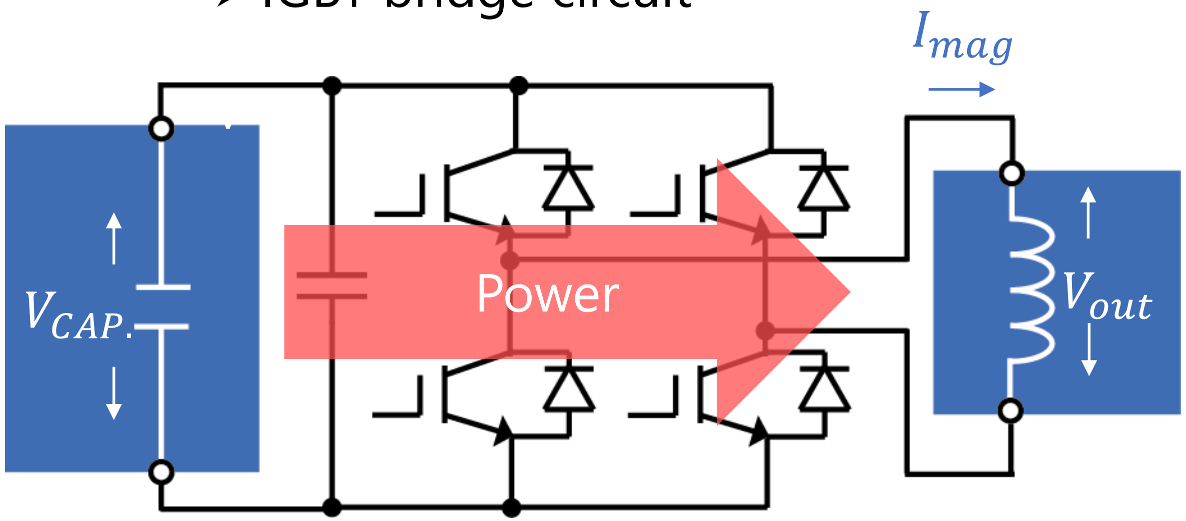
→ $V_{CAP.} > V_{out} = 6000\ V$

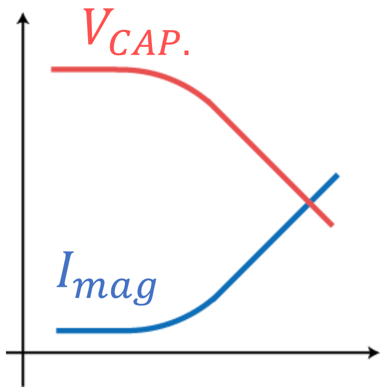
- $V_{CAP.}$ decreases for exciting magnets

$$\frac{V_{CAP.MIN.}}{V_{CAP.MAX.}} = \sqrt{1 - \frac{\frac{1}{2} L_{mag} I_{MAX.}{}^{2}}{4\ [\mathrm{MJ}]}} \sim 0.67$$

➡ $V_{CAP.MAX.}$ is chosen to be **10000 V**

➢ IGBT bridge circuit





Power Converter with IGBT Units

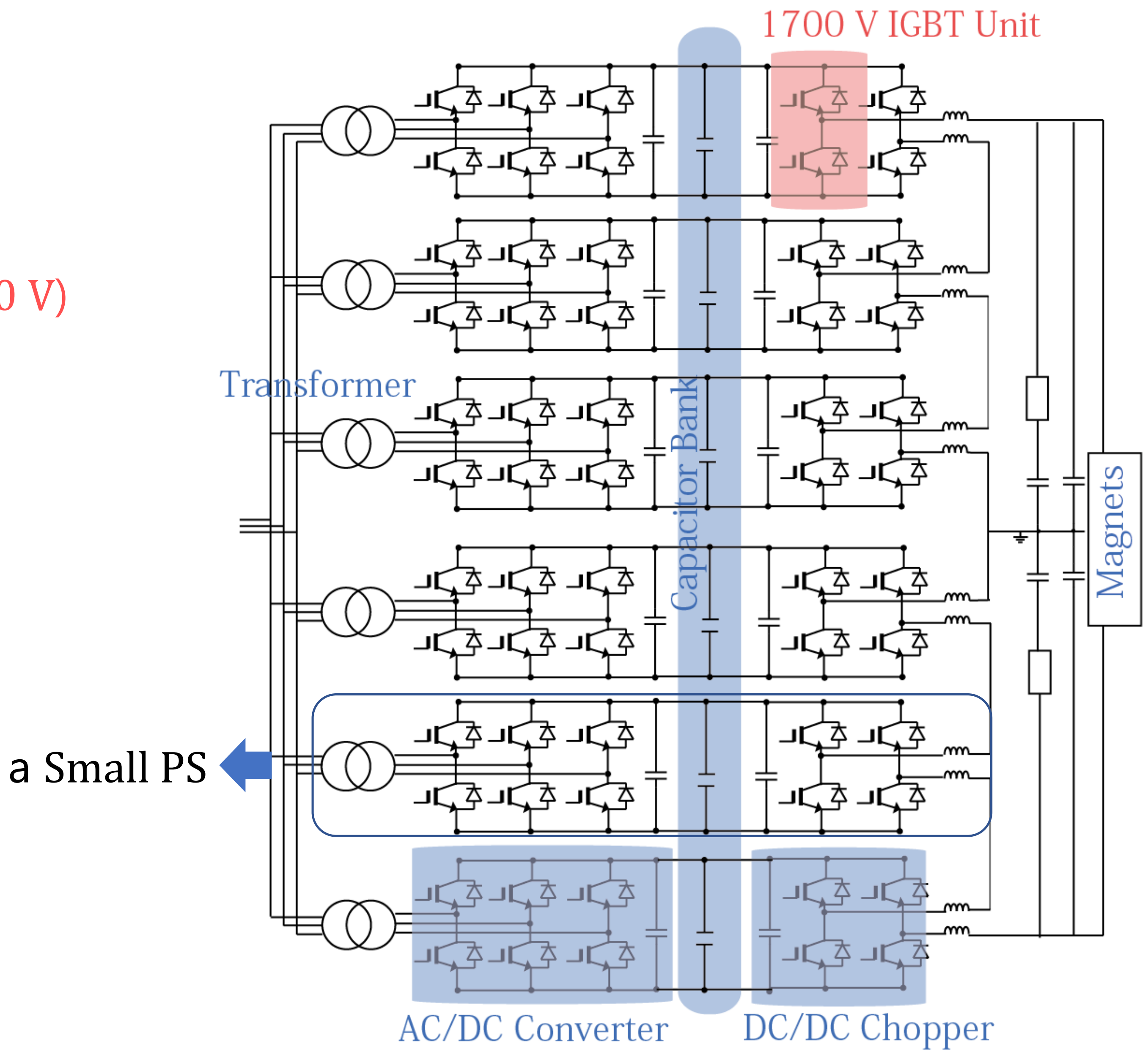
➢ Newly developed a 1700 V IGBT Unit.

6s for Large PS (1700 × 6 > 10000 V)

1s for Small PS (1700 V > 1500 V)

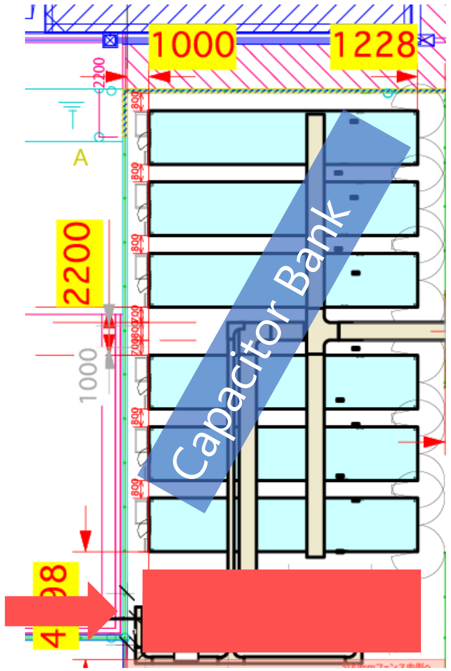
◆ Save R&D resources
◆ Common Spares

Original Design of a Large PS



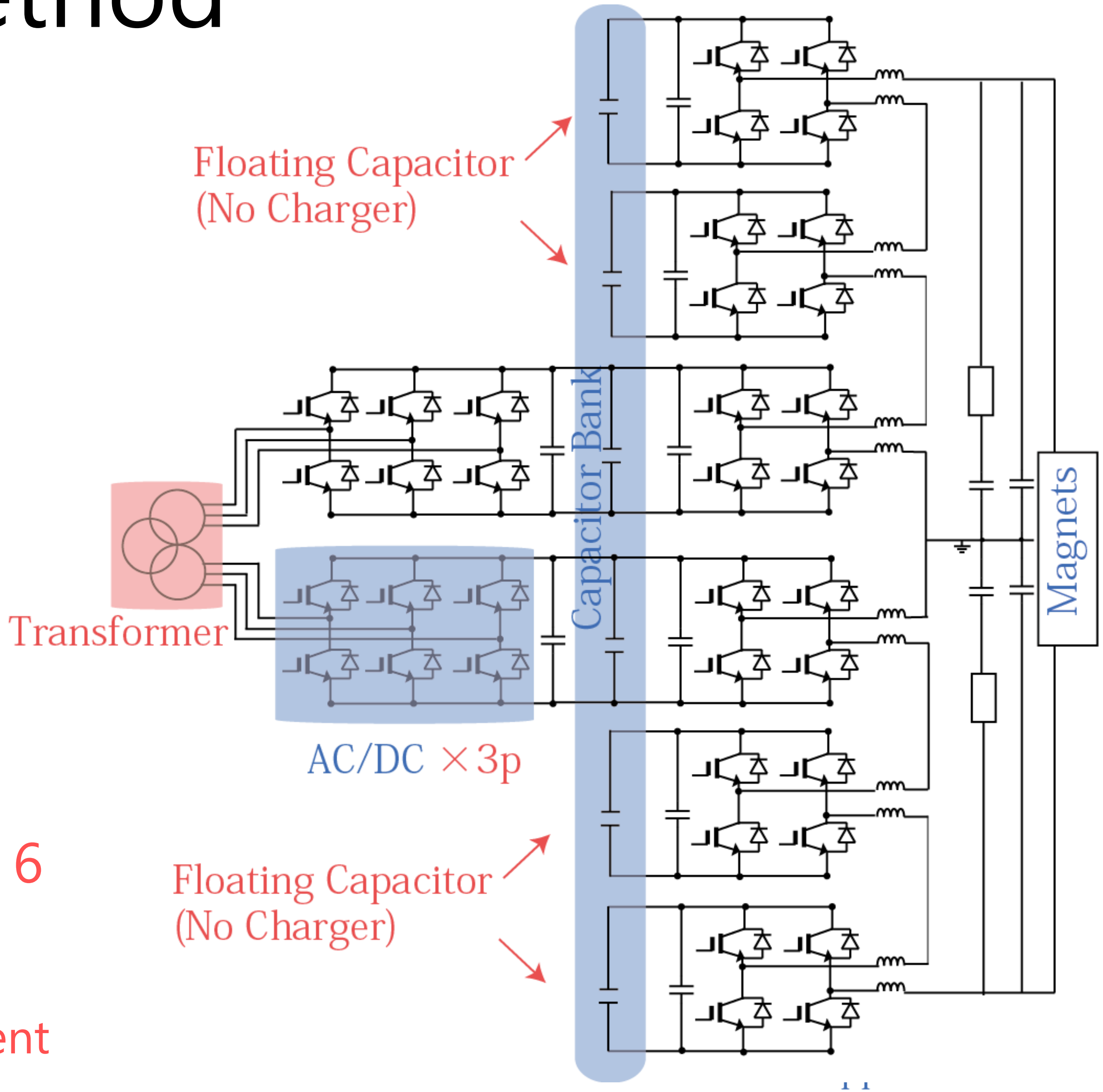
Floating Capacitor Method

No space for 6 power transformers



Reserved area for transformers (2 Large PSs)

Final Design of a Large PS



One large transformer instead of 6

- Save space
- Successfully operated at CERN-PS
- Need complicated power management

Power Management with Capacitor Bank

Output Voltage Division

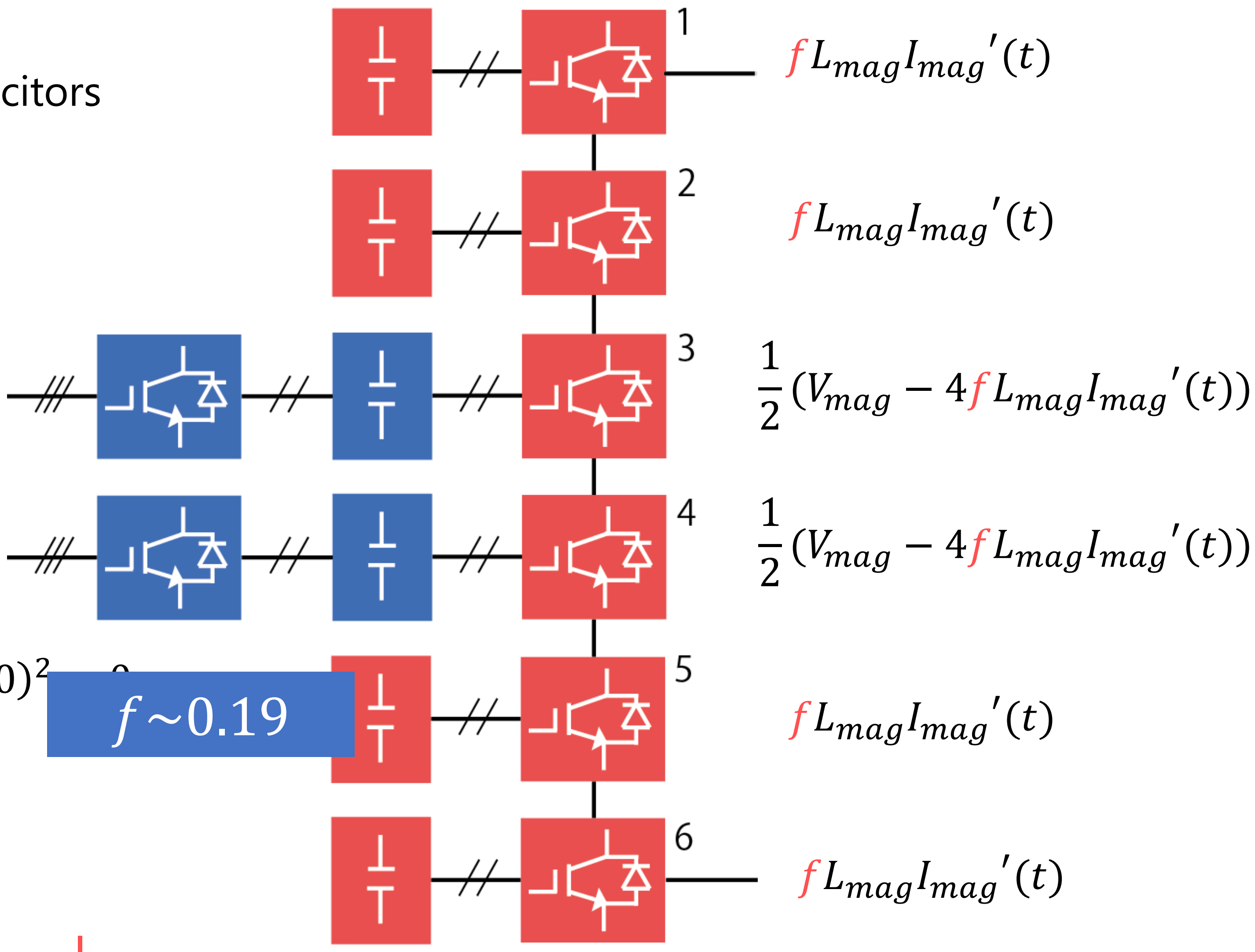
To maintain the cyclic operation of floating capacitors

$$\int_0^{T_{cycle}} dt\, I_{mag}(t) V_{out1,2,5,6}(t) = 0$$

This is easily satisfied when

$$V_{out1,2,5,6}(t) = f L_{mag} \frac{dI_{mag}(t)}{dt}$$

$$\int_0^{T_{cycle}} dt\, I_{mag}(t) I_{mag}'(t) = I_{mag}(T_{cycle})^2 - I_{mag}(0)^2 = 0$$



Since the other twos regulate $I_{mag}(t)$, they automatically drive remaining part of V_{mag}.

Choose proper f so that $V_{CAP,i} > |V_{out,i}|$

Output

- $V_{out1,2,5,6}(t) = fL_{mag}\frac{dI_{mag}(t)}{dt}$
- $V_{out3,4}(t) = \frac{1}{2}(V_{mag}(t) - 4fL_{mag}I_{mag}'(t))$

To maintain the cy

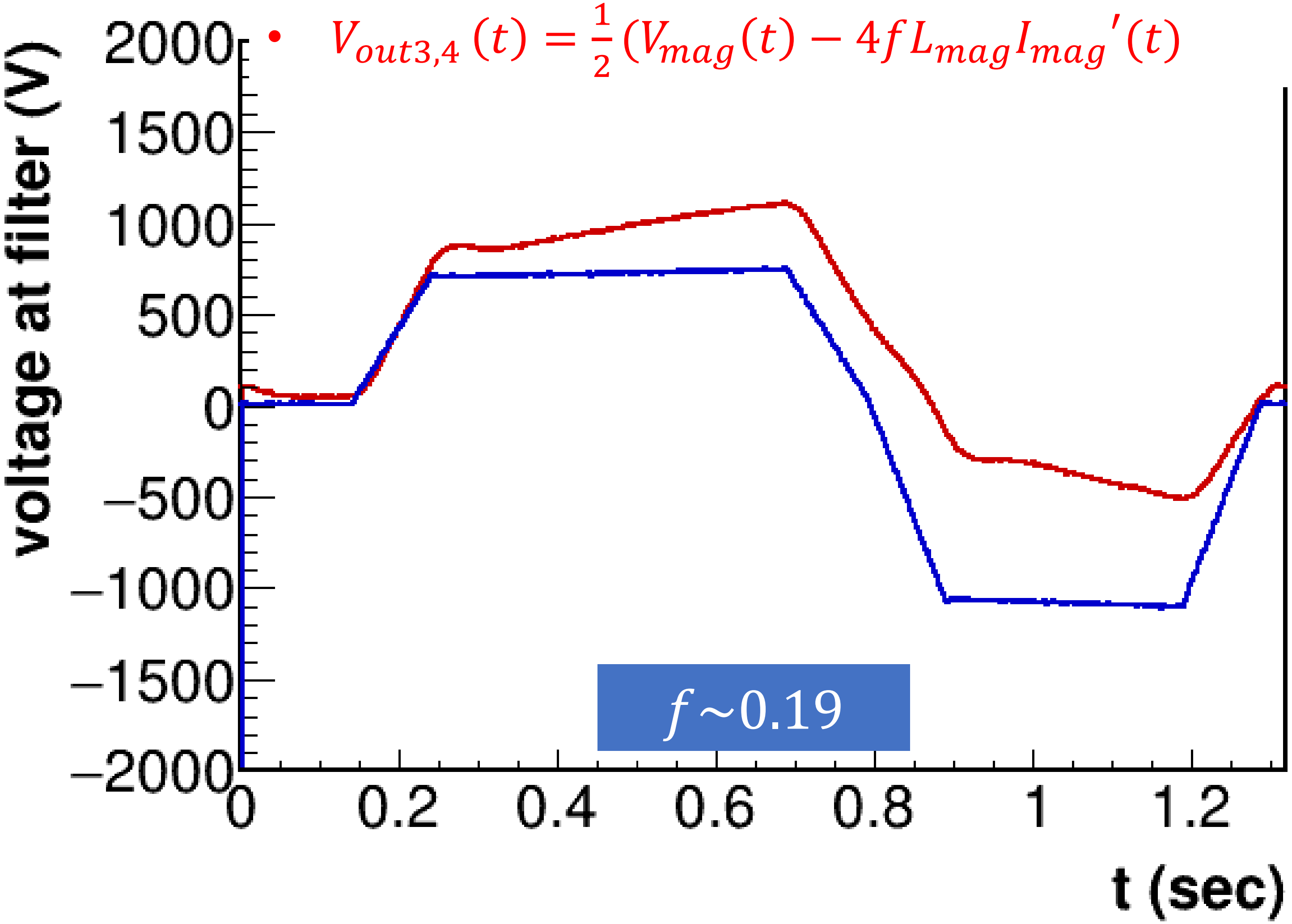
$\int_0^{T_{cycle}} dt\, I_{mag}($

This is easily satisfi

$V_{out1,2,5,6}(t) =$

$\int_0^{T_{cycle}} dt\, I_{mag}(t)I_{m}$

Since the other tw
automatically drive



$ag'(t)$

$ag'(t)$

$4fL_{mag}I_{mag}'(t))$

$4fL_{mag}I_{mag}'(t))$

$ag'(t)$

$ag'(t)$

Choose proper f so that $V_{CAP,i} > |V_{out,i}|$

Input Power Control

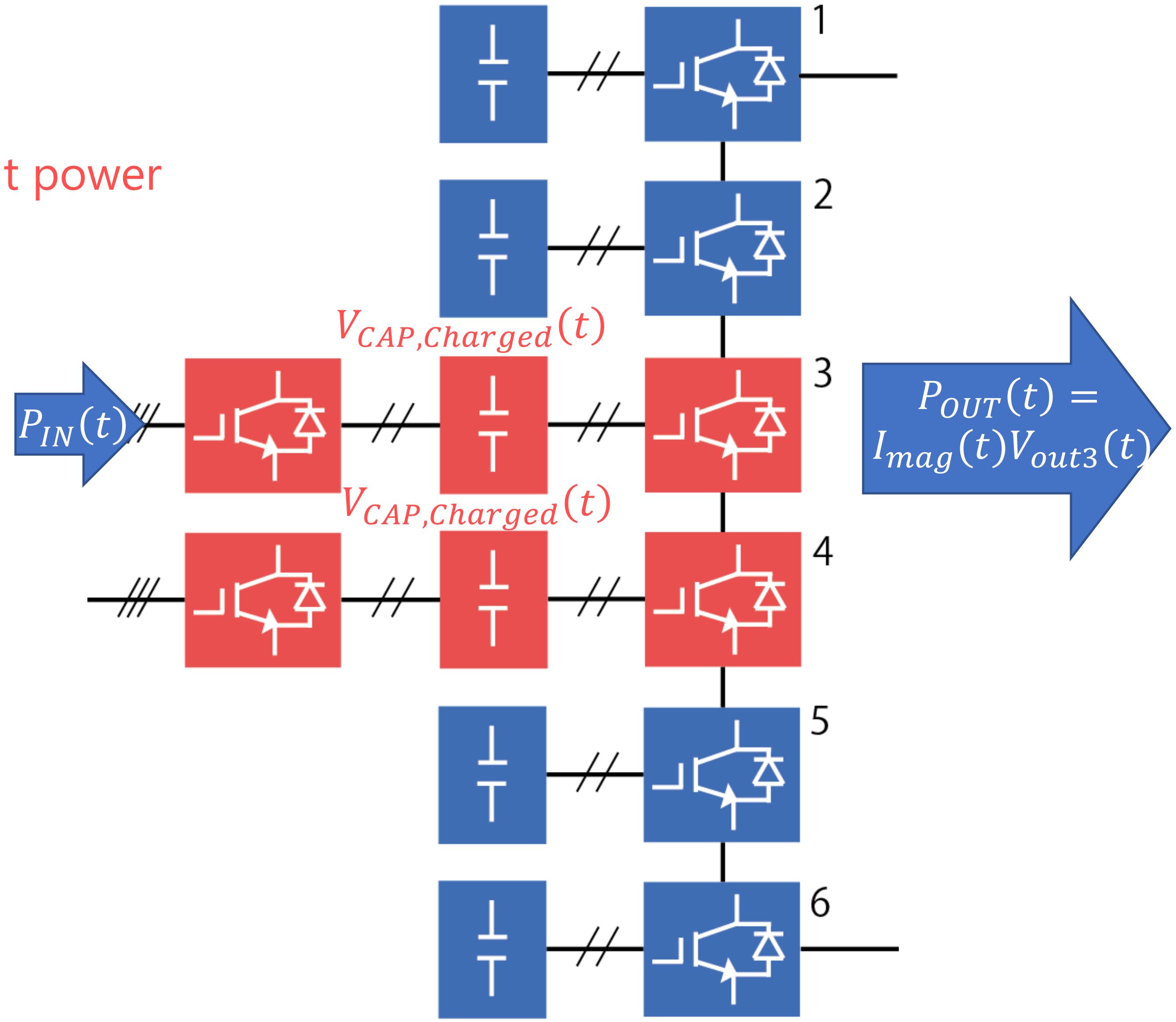
Controlling $V_{CAP,Charged}(t)$= controlling the input power

The Stored Energy of a Charged Capacitor

$$\frac{1}{2}C\left(V_{CAP}{}^{2}(t) - V_{CAP}{}^{2}(0)\right) =$$

$$\int_0^t dt\, P_{IN}(t)$$

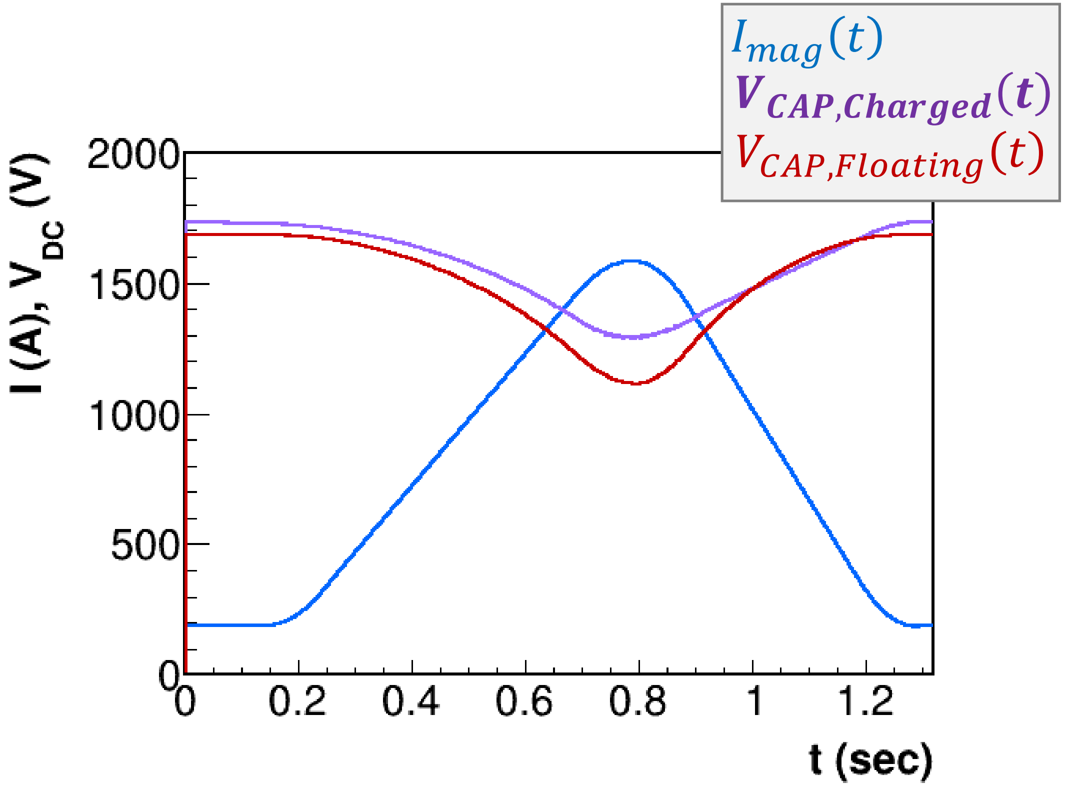
$$-\int_0^t dt\left[\frac{I_{mag}(t)\frac{1}{2}(V_{mag}(t) - 4fL_{mag}I_{mag}{}'(t))}{V_{out3}(t)}\right]$$

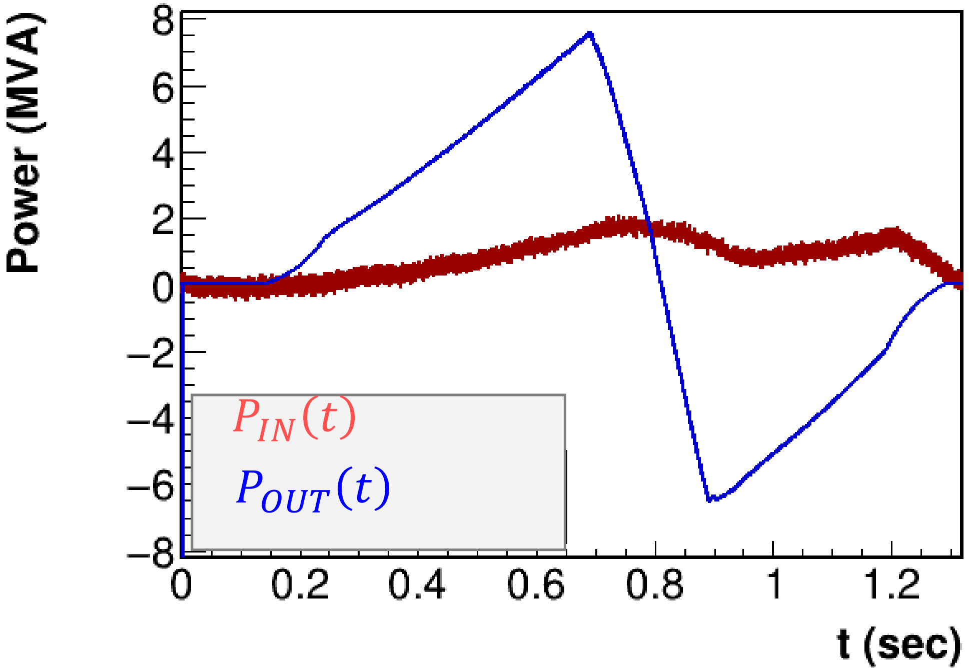


The voltage pattern $V_{CAP,Charged}(t)$ fixes the input power $P_{IN}(t)$

Result of $V_{CAP,Charged}(t)$ Optimization

~TEST with Real Bending Magnets~





- The peak input power is successfully reduced (almost ¼ of the peak output power)

R&D is complete and Mass production is on going

Summary

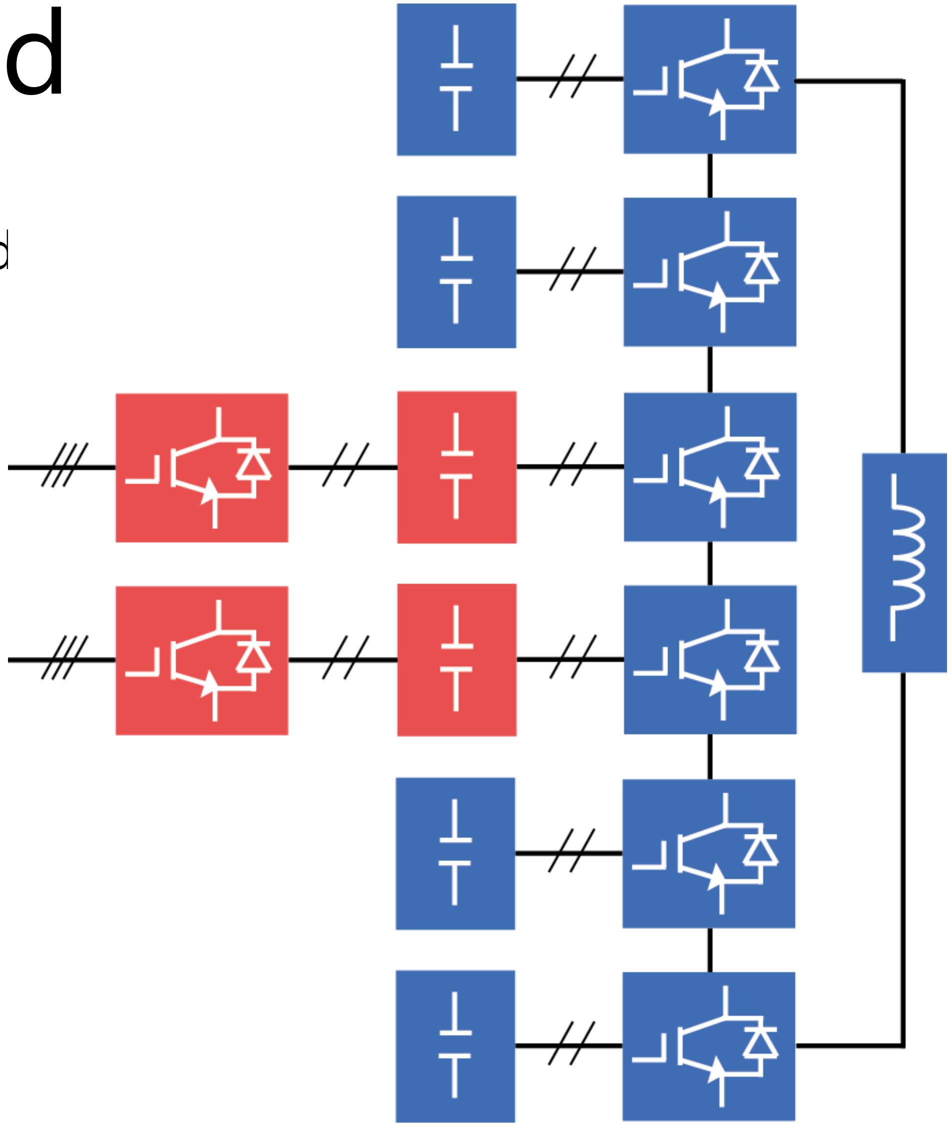
- Need new magnet PSs which can drive magnets faster to increase repetition rate of J-PARC MR
- The new PSs must have energy storage to reduce the input power variation
- A new PS with capacitor bank and its power management scheme had been developed.
- Test operation with the real bending magnets are successfully done
- Mass production is on going and all installation will be complete by the end of FY2021

Backup

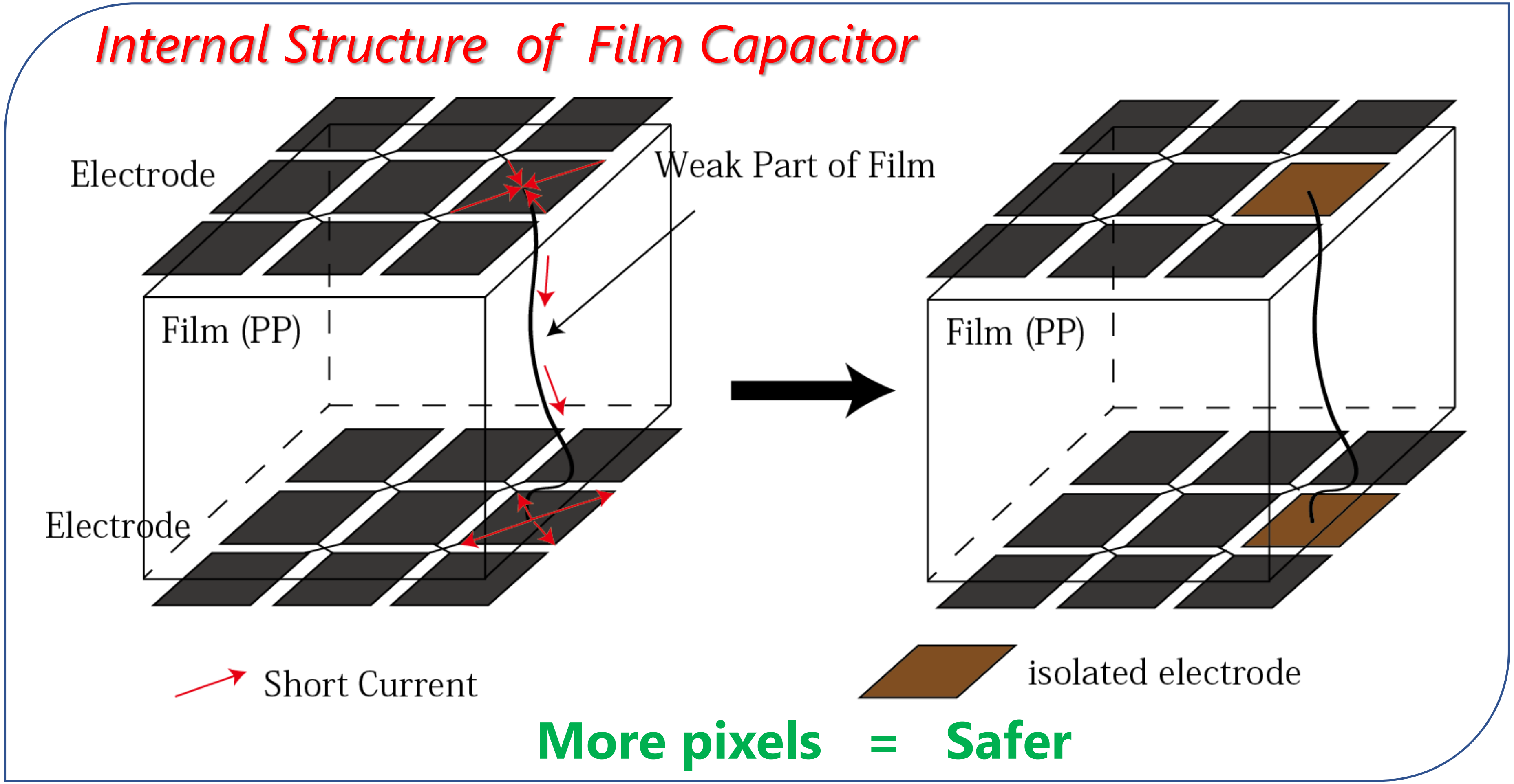
Parameters to be controlled

➢ Capacitor Voltage and Magnet Current need to be controlled

1. Floating Capacitor Voltage ← connected DC/DC Choppers
2. Magnet Current ← other DC/DC Choppers
3. Charged Capacitor Voltage ← AC/DC Converters



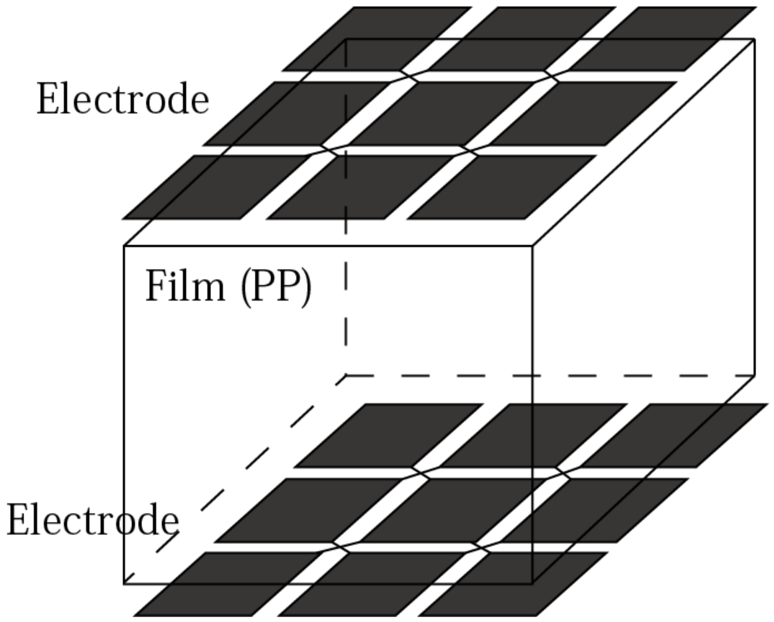
Self-Healing Structure



- Many small pixel capacitors connect with 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 decreases by 5 %**

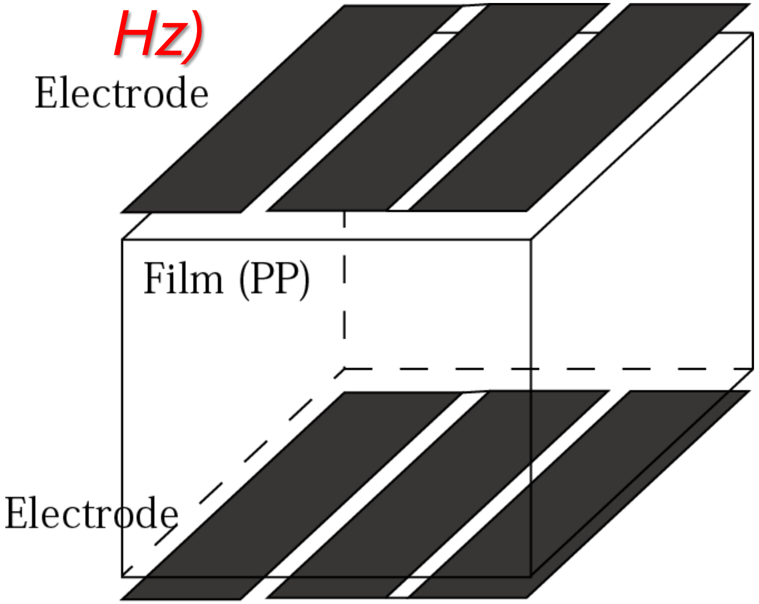
AC or DC ?

For DC voltage



- Many (small) pixels
- Higher voltage (200 V/μm)

For AC voltage (50/60 Hz)



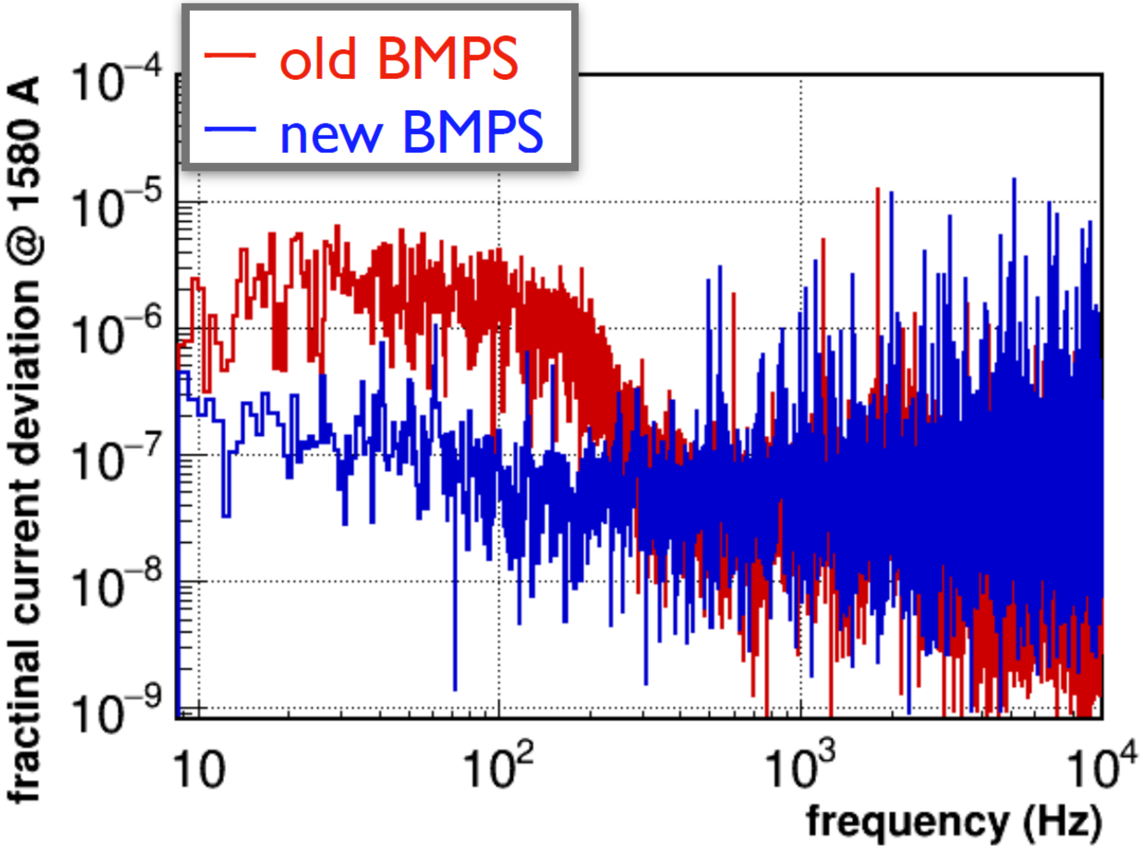
- fewer (Large) pixels to reduce discharge at the surroundings of pixels due to voltage change
- Lower voltage (<100 V/μm)

→ **Bigger**

Our application (Not 50/60 Hz but only 1 Hz) is the middle of DC and AC

→ **DC Capacitor- based development !!**

Current Deviation of the new and old PS



Definition

$$\frac{I_{measured} - I_{reference}}{I_{reference}} \text{ @30 GeV}$$

- Current deviation can directly affect on the flatness of slowly extracted beam. D. Naito et al, Phys. Rev. Accel. Beams **22**, 072802 (2019)

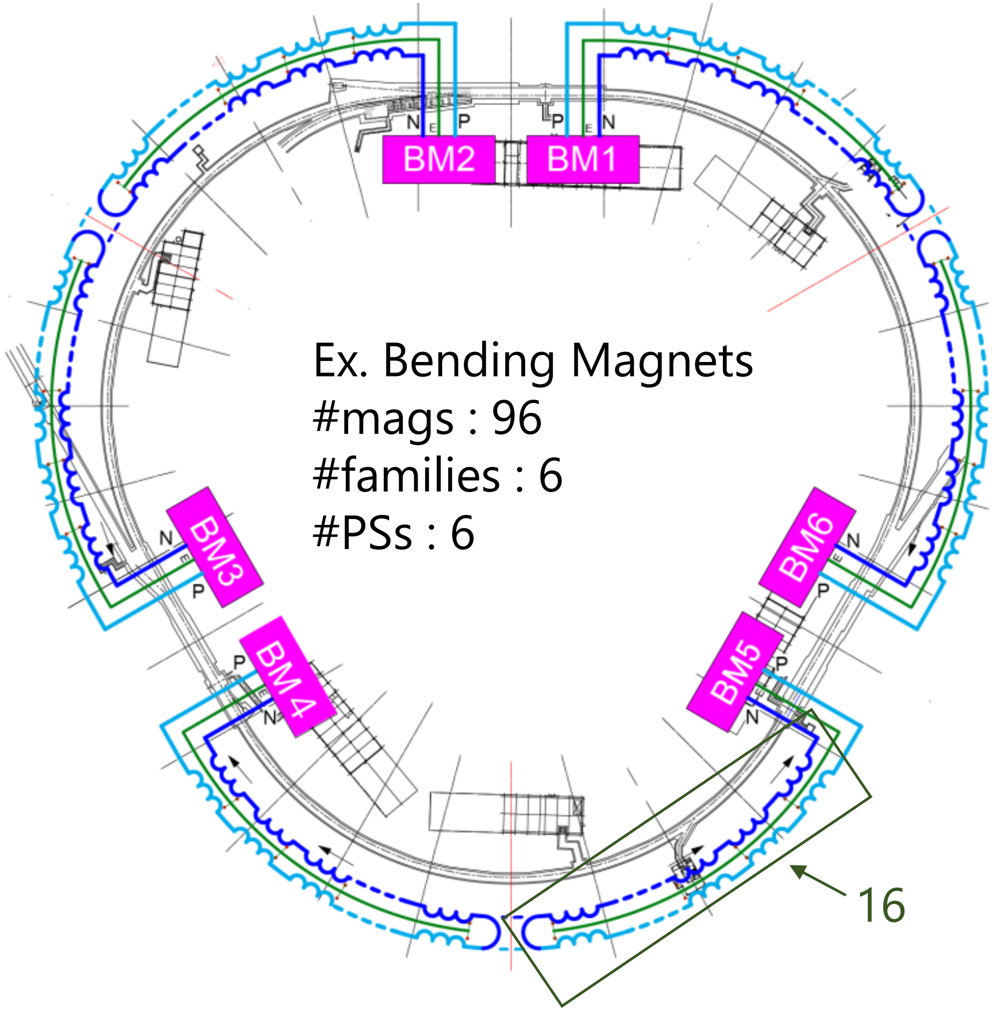
Families and Power Supplies

One PS drives several magnets connected in series. These several magnets are collectively called "a Family"

➡ #Families = #PSs = 20

<u>Magnet Families in J-PARC MR</u>

Family	Type	#mags	PS
BM1,BM2,BM3,BM4,BM5,BM6	B	16	Large
QFN,QDN,QFX	Q	48	Large
QDX	Q	27	Large
QFR	Q	9	Small
QFP,QFS,QFT,QDR,QDS,QDT	Q	6	Small
SFA,SDA,SDB	S	27	Small



<u>Specification of PSs for $T_s \sim 1.3\ s$</u>

Large PS: 6000 V, 800-1500 A Small PS : 1500 V, 800 A-1000 A