J-PARC Main Ring Upgrade toward High Repetition Rate Operation

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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)
- Replacement will be scheduled in FY2021

\[ V = L_{\text{mag}} \frac{dI_{\text{mag}}}{dt} + R_{\text{mag}} I_{\text{mag}} \]

Specification of Power Supplies (PS) for \( T_s \sim 1.3 \text{ s} \)

- 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

Injection → Extraction

Magnetic energy must be reduced for the next injection

Present Input Power Variation

Present PS

AC main

Magnetic Energy

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

Proposal of a new PS with capacitor bank

AC main

Magnetic Energy

All magnetic energy is recovered to capacitor bank

Measured power variation (MR rate: 2.568)

Required to be maintained at the present level even after the upgrade by the electricity company
Hardware Requirement and Design
Capacitor Bank

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

- Simple IGBT bridge for current regulation
  
  \[ V_{\text{CAP.}} > V_{\text{out}} = 6000 \text{ V} \]

- \( V_{\text{CAP.}} \) decreases for exciting magnets

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

\( V_{\text{CAP. MAX.}} \) is chosen to be \( 10000 \text{ V} \)
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
Floating Capacitor Method

No space for 6 power transformers

Reserved area for transformers (2 Large PSs)

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

\[ V_{out1,2,5,6}(t) = fL_{mag} \frac{dI_{mag}(t)}{dt} \]

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

To maintain the cycle

\[
\int_{0}^{T_{cycle}} dt I_{mag}
\]

This is easily satisfied when

\[
V_{out1,2,5,6}(t) = \int_{0}^{T_{cycle}} dt I_{mag}(t) I_{m}
\]

Since the other two regulate \( I_{mag} \), they automatically drive the remaining part of \( V_{mag} \).

Choose proper \( f \) so that \( V_{CAP,i} > |V_{out,i}| \)

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

\[
V_{out3,4}(t) = \frac{1}{2} (V_{mag}(t) - 4f L_{mag} I_{mag}'(t))
\]
Input Power Control

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

The Stored Energy of a Charged Capacitor

$$\frac{1}{2} C \left( V_{CAP}^2(t) - V_{CAP}^2(0) \right) = \int_0^t dt \ P_{IN}(t)$$

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

$$V_{out3}(t)$$

The voltage pattern $V_{CAP, Charged}(t)$ fixes the input power $P_{IN}(t)$
Result of $V_{CAP,\text{Charged}}(t)$ Optimization

~TEST with Real Bending Magnets~

- The peak input power is successfully reduced (almost $\frac{1}{4}$ 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 \( \frac{1}{10000} \)
- The lifetime is defined as the time until capacitance decreases by 5%

More pixels = Safer
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)

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

\[ \frac{I_{\text{measured}} - I_{\text{reference}}}{I_{\text{reference}}} \]

@30 GeV

Families and Power Supplies

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

#Families = #PSs = 20

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

Magnet Families in J-PARC MR

Ex. Bending Magnets
#mags : 96
#families : 6
#PSs : 6

Specification of PSs for $T_s \sim 1.3 \, s$

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