J-PARC Heavy-Ion Acceleration

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J-PARC Center
Neutrino experiment (NU)

Materials & Life Science Facility (MLF)

3 GeV Rapid Cycling Synchrotron (RCS)

400 MeV H- Linac

Transmutation Experimental Facility (TEF)

50 GeV Main Ring Synchrotron (MR) [30 GeV at present]

Hadron Experimental Hall (HD)
J-PARC is a multi-purpose research facility consists of 3 accelerators and several experimental facilities that make use of high intensity proton beams. RCS already achieved acceleration of designed 1 MW-eqv. beam power. MR also approaching towards the designed beam power.

In response to the interesting HI physics program, we are considering to adapt new accelerator scheme for HI in J-PARC.

Studies of HI acceleration in the RCS is the main topic in this talk.

Outline:

1. Overview of J-PARC HI physics program
2. HI acceleration strategy and accelerator scheme
3. Overview of 3-GeV RCS and latest performances
4. Simulation results of U^{86+} acceleration in the RCS
5. Summary and Outlook
HI physics goal at J-PARC

- To study QCD phase structures (critical point and phase boundary) in high baryon density regime of $8-10\rho_0$ (U+U system).
- Study the properties of high baryon density matter.
- Fixed target collision by using slowly extracted HI beam of $1E11$/cycle (6s) from the MR.
- The HD programs should also have advantages by using HI beam.
  - Hypernuclear production rate
  - $S=-3$ sector (only possible by HI collisions)

- Beam energy: 1-20 GeV/u (U) beam from the MR
- Beam intensity: $1E11$/cycle (~6s)

To adapt such a high intensity HI scheme in the already running proton machines and moreover without intercepting any the of existing programs with proton beam is surely a big challenge!
HI Acceleration strategy in J-PARC

- We plan to use existing and high performance RCS and the MR for HI acceleration in addition to proton.
- The RCS can be a suitable HI injector for MR for the final acceleration up to ~20 GeV/u (@50 GeV for p).

**RCS:** Already achieved designed 1 MW-eq. beam power.
**MR:** Achieved up to ~5E13 protons/cycle for HD operation.

- Well understood and optimized accelerator performances.
  --- Enable realistic discussion on beam dynamics issues and measures for high intensity HI beam.
- Use existing building and devices.
  -- Reduction of space and budget to accelerate up to ~GeV/u (U) for MR injection.
- RCS has Large acceptance
  -- transverse \((\varepsilon_{tr}) > 486\pi \text{ mm mrad}\), longitudinal \((\Delta p/p) > \pm 1\%\)
HI Accelerator scheme in J-PARC
(Yet unofficial!)

- **HI Linac**: 0.4 GeV
- **H^- Linac**: 0.4 GeV
- **U^{35+}** → **U^{66+}**: 20 AMeV
- **U^{35+}** → **U^{66+}**: 61.8 AMeV
- **RCS (H^- → p)**: 0.4 → 3 GeV
- **MLF**
- **MR**: 3 → 30 GeV (p)
- **p/Hi to HD**
- **U^{86+} → U^{92+}**: 0.727 AGeV
- **U^{92+}**: 0.727 → 11.15 AGeV
- **U^{86+} → U^{92+}**: 61.8 → 735.4 AMeV
- **p** → **NU**
- **HI (under planning)**
- **Figures: Not to scale**

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HIWS-2016
Key issues to realize HI acceleration

We should meet the goal without intercepting any of the existing/planned programs with proton beam.

Four following serious issues, particularly with RCS must be cleared.

- Simultaneous operation with proton for MLF and HI for MR must be done.
- Most of the machine parameters fixed for p must be used for HI (At present, no choice for changing most of the parameters between cycles).
- Vacuum pressure level: $\sim 10^{-8}$ Torr (no problem for p). Not satisfied for HI w/ lower charge states ($U^{86+}$ is thus considered).

- New HI injection system

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HIWS-2016
How HI scheme works in RCS

RCS beam delivery pattern

5.52s (MR for HD)

40ms
MLF (p)
1 2 3 4 5 ... 134
MR (p/HI)
1 2 3 4
MLF (p)
1 2 3 ...

PB pattern

MR operates for either NU or HD
When MR operates for HD (5.52s), No. of RCS cycles: $25 \times 5.52 = 138$
$\rightarrow$ 134 RCS cycles to MLF, 4 to MR

◎ Only when MR runs HI, RCS injects HI in the MR cycle.
$\rightarrow$ No conflict with MLF/NU
HI injection system in the RCS

**Place**: At the end of extraction section.

- Only available space.

**Scheme**: One turn injection from the HI booster.

- By using 1 or 2 kickers. Simple injection system.
Overview of the RCS and latest performance with proton beam
Overview of 3-GeV RCS

Design parameters:

**Particle**
- Particle: \( p \)
- Circumference: 348.333 m
- Superperiodicity: 3
- Harmonic number: 2
- No of bunch: 2

**Injection energy**
- Injection energy: 400 MeV

**Extraction energy**
- Extraction energy: 3 GeV

**Repetition rate**
- Repetition rate: 25 Hz

**Particles per pulse**
- Particles per pulse: \( 8.3 \times 10^{13} \)

**Output beam power**
- Output beam power: 1 MW

**Transition gamma**
- Transition gamma: 9.14 GeV

**Collimator Limit**
- Collimator Limit: 4 kW (3% @ inj. beam power)

Extracted 3 GeV protons are simultaneously delivered to the neutron and muon production targets in the MLF (97%) as well as to the MR (3% @HD opr.).
**RCS scheme for proton**

- **Fast Extraction**
- **Injection**
- **Acceleration**

**Time (ms):**
- 0
- 20
- 40

**B (T):**
- 0.28
- 1.13

**Intermediate pulses**
- 456ns
- 814ns

**Multi-turn H- stripping injection**

**Longitudinal painting**

**Closed orbit variation for painting**

**Painting area**

**Transverse painting** (H plane). Done in the V plane too.

**Large acceptance:**
\[ \varepsilon_{tr} > 486\pi \text{ mm mrad, } \Delta p/p > \pm 1\% \]
RCS 1 MW beam study results

- Successfully demonstrated acceleration and extraction of 1 MW-equivalent beam power.
- Beam loss at 1 MW: <0.2% and only at injection energy -- mostly due to the foil scattering.

Experimental results:
Circulating beam intensity measured by a CT

- $8.41 \times 10^{13}$ ppp: 1.01 MW-eq.
- $7.86 \times 10^{13}$ ppp: 0.944 MW-eq.
- $6.87 \times 10^{13}$ ppp: 0.825 MW-eq.
- $5.80 \times 10^{13}$ ppp: 0.696 MW-eq.
- $4.73 \times 10^{13}$ ppp: 0.568 MW-eq.

\[ \rightarrow \] Demonstrates RCS potential to achieve a rather high intensity HI beam too.
### RCS proton beam power capability

--- Space charge limitation

Laslett tune shift at injection energy:

\[
\Delta \nu = - \frac{r_p n_t}{2\pi \beta^2 \gamma^3 \varepsilon B_f}
\]

- \( r_p \): classical radius of proton
- \( n_t \): no. of protons in the ring
- \( \beta, \gamma \): relativistic parameters
- \( \varepsilon \): transverse painting emittance
  
  \((100\pi \text{ mm mrad})\)
- \( B_f \): Bunching factor (0.4)

<table>
<thead>
<tr>
<th>( E_{\text{inj}} ) (MeV)</th>
<th>ppp (x10(^{13}))</th>
<th>Beam power at ( E_{\text{ext}} ) (MW)</th>
<th>( \Delta \nu )</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>181</td>
<td>4.5</td>
<td>0.54</td>
<td>-0.53</td>
<td>Achieved</td>
</tr>
<tr>
<td>400</td>
<td>8.33</td>
<td>1</td>
<td>-0.33</td>
<td>Achieved</td>
</tr>
<tr>
<td>400</td>
<td>11.0</td>
<td>1.3</td>
<td>-0.43</td>
<td>Reasonable</td>
</tr>
<tr>
<td>400</td>
<td>13.3</td>
<td>1.6</td>
<td>-0.53</td>
<td>Reasonable</td>
</tr>
</tbody>
</table>
Tune footprint (Simulation)

Trans. painting ($\varepsilon_{tr}$) = 100\(\pi\) mm mrad
Longitudinal painting: Full ($B_1=0.4$)
$V2/V1 = 0.8\%$, $\Delta p$ offset = -0.2%
$\phi 2 = -100$deg.

**Black:** 181 MeV injection
4.5E13/pulse (0.54 MW)

**Red:** 400 MeV injection
12.5E13/pulse (1.5 MW)
Simulation for $U^{86+}$ acceleration in the RCS

Code: ORBIT-3D

Steps:
1. Single particle w/o SC
2. Multi-particle w/ SC

- BM, QM, Sextuples are kept unchanged as optimized for 1MW proton (for MLF).
  → Those can’t be changed pulse-to-pulse.

- rf patterns are differently used.
  → Upgrades might be necessary.
  (may not be a big issue!)

Injection energy: 61.8 MeV/u
Extraction energy: 735 MeV/u
→ (1) Successfully confirmed by the single particle simulation.
(2) Multi-particle simulations w/ SC

Space charge limit:

Laslett tune shift:

$$\Delta \nu \approx -\frac{q^2}{A} \frac{r_p n_t}{2\pi \beta^2 \gamma^3 \varepsilon B_f}$$

For 1 MW proton: $8.33 \times 10^{13}/2b$

$\rightarrow 4.2 \times 10^{13}/b$

<table>
<thead>
<tr>
<th>Particle</th>
<th>ppb</th>
<th>$\Delta \nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>$4.2 \times 10^{13}$</td>
<td>-0.33</td>
</tr>
<tr>
<td>$U^{86+}$</td>
<td>$1.1 \times 10^{11}$</td>
<td>-0.33</td>
</tr>
</tbody>
</table>

Consistent with numerical estimation!
(2) Transverse and longitudinal beam distributions

Inj. beam parameters:

<table>
<thead>
<tr>
<th>Inj. turn</th>
<th>No of bunch</th>
<th>Intensity ($\times 10^{11}$)</th>
<th>Beam shape</th>
<th>$\Delta s$ (ns)</th>
<th>$\Delta p/p$ (%)</th>
<th>$\varepsilon_{tr}$ ($\pi$ mm mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1.1</td>
<td>Gaussian</td>
<td>1180</td>
<td>$\pm 0.9$</td>
<td>100</td>
</tr>
</tbody>
</table>

Black: injection
Red: extraction

$>99.9\%$ transverse emittances of the extracted beam are within 3-50BT collimator aperture.

✓ Collimated beam power $<<$ Collimator limit
✓ Satisfy very strict beam quality for MR injection.
(2) **Beam survival**

- No any unexpected beam losses.
- Beam survival > 99.95% even for $1.1 \times 10^{11}$/b of U$^{86+}$ ions
- Beam loss localizes at ring collimator.
- However, intensity dependence beam loss is slightly non linear.
  - Further improvement is possible by optimizing injected beam shape and/or rf patterns.
- Gives bottom line for the new booster parameters.

U$^{86+}$: $1.1 \times 10^{11}$ → stripping at 3-50BT → U$^{92+}$: $\sim 1 \times 10^{11}$/RCS cycle
4 RCS cycles injection in the MR: $4 \times 10^{11}$/MR cycle!
Summary

In order to realize HI physics program in J-PARC, a new HI accelerator scheme by utilizing most of the existing facilities are proposed.

RCS plays the most important role to realize HI program in J-PARC. Possibilities of HI acceleration in the RCS are reported.

Studies are done within the designed and fixed frame for proton in the RCS.

- More than $10^{11} \text{U}^{86+}$ ions can be achieved without any significant beam losses.
- No serious beam dynamics issues even up to such an intensity.

→ Gives $4 \times 10^{11} \text{U}^{92+}$ ions/cycle (5.52s) in the MR and quite more than experimental requirement at present.

Design studies of new HI Booster is in good progress.

→ Harada-san (Tomorrow)

The RCS including proposed new HI accelerator scheme has no interference/conflict with existing programs that make use of proton beams.
Thank you for your attention!

May be in near future
Backup slides
HI Accelerator Scheme

**Diagram:**
- **H⁻ LINAC** to **RCS** to **MR**
- **HI LINAC** to **New HI Booster** to **RCS** to **MR**
- **GAS stripper**:
  - U³⁵⁺ → U⁶⁶⁺
- **Foil stripper**:
  - U⁶⁶⁺ → U⁸⁶⁺ (61.8 MeV/u)
  - U⁸⁶⁺ → U⁹²⁺ (727 MeV/u)

**Table:**

<table>
<thead>
<tr>
<th>E (MeV/u)</th>
<th>LINAC out</th>
<th>Booster out</th>
<th>Stripper 2 Carbon</th>
<th>RCS out</th>
<th>Stripper 3 Cu&lt;Zₜ&lt;Tₐ</th>
<th>MR out</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>67.0</td>
<td>61.8</td>
<td>735.4</td>
<td>727.0</td>
<td>11.15 GeV/u</td>
<td></td>
</tr>
<tr>
<td>Q 35</td>
<td>66+-2</td>
<td>86</td>
<td>86</td>
<td>92</td>
<td>92</td>
<td></td>
</tr>
</tbody>
</table>
Present simulation background

Tool: ORBIT 3-D space charge code:

➔ Originally developed at the SNS in Oak Ridge.
➔ Successfully adopted in the RCS, especially for beam instability simulation.
(Ext. kicker impedance is a significant beam instability source in the RCS.)

● *Space charge effect is strongly connected to the beam instability.*
-- First an accurate space charge simulation was demonstrated.

Beam instability at 1 MW: Simulation vs. Measurement

The next step was to determine optimum parameters to avoid beam instability at 1 MW.

Even DC chromatic correction gives beam instability at 1 MW!
➔ Confirmed by measurements!!

ORBIT can be used HI beam simulation in the RCS