Recent Improvement of Slow-Extraction at HIMAC Synchrotron


National Institute of Radiological Sciences
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Bird’s eye view of HIMAC

HIMAC
(Heavy Ion Medical Accelerator in Chiba)
Requirement to slow-extraction at HIMAC

Requirements from scanning irradiation:

- Fast beam ON/OFF
- Time structure control
- Intensity control
- Precise beam size control

RF-knockout slow-extraction (RF-KO extraction)

Scanning irradiation
RF-knockout extraction (1)

Diffusion by **transverse RF-field**

- Constant separatrix
- Fast response of beam on/off
- Easy operation

Frequency modulation (FM)

Amplitude modulation (AM)
RF-knockout extraction (2)

Before this study

- Fast beam ON/OFF
- Time structure control
- Intensity control
- Precise beam size control

Too slow!!

Too huge!!

Mismatch!!

200 μs/di

200ms/div
Particles can be spilled out from the separatrix by diffusion of RF-KO.

Longitudinal motion contributes to extraction through horizontal chromaticity.
Fast response of beam on/off

By turning on/off both transverse and longitudinal RF-fields, cut-off time of 50 μs is achieved.
NIRS

HIMAC

**kHz order ripple reduction**

- A mono frequency RF-field is applied to increase the extraction speed near the separatrix boundary.
- kHz order of ripple is sufficiently suppressed.
- Increase extraction speed!!

**RF-KO spectrum**

- 50kHz order of ripple is sufficiently suppressed.
- Separate function method
  - Ripple $\leq \pm 20\%$

- Spill
  - 500 $\mu$s/div
Effect of synchrotron oscillation

Ripple spectrum

Synchrotron sideband

Coherent longitudinal oscillation brings fs ripple to spill!

However, fs ripple was not removed.
Reduction of fs ripple

Synchrotron sideband

Ripple spectrum

fs = 1.45 kHz

After debunch-recapture process, fs ripple was suppressed!!
In the RF-KO slow-extraction, global time-structure can be controlled by the amplitude modulation (AM) of transverse RF-field. Originally, we have used linear AM function to expand the spill length.

In order to obtain square shaped spill, suitable AM function is necessary!!
To obtain suitable AM function analytically, we used simple 1-D model. The radial distribution of particles is assumed to be Rayleigh distribution under diffusion of RF-KO.
Global spill control (3)

Using model, new AM function can be calculated analytically to keep the extracted intensity constant.

\[
\theta(n) = \left[ \frac{d}{dn} \left( \frac{\sigma^2(n)}{k} \right) \right]^{1/2}
\]

\[
\sigma^2(n) = -r_0^2 \left[ \ln \left( \frac{n}{f_{rev} \cdot \tau_{ext}} \right) \cdot \left\{ 1 - \exp\left( -\frac{r_0^2}{\sigma_0^2} \right) \right\} + \exp\left( -\frac{r_0^2}{\sigma_0^2} \right) \right]^{-1}
\]
1) Without feedback: the result is in good agreement with the simulation one.
2) With feedback system: square shaped spill is realized.
Now, we develop intensity control system during a single flattop. Based on simple model, AM function is analytically calculated to control intensity. **Dynamic range of more than 10 is expected.**
In order to control beam size at HEB1, it is necessary to define optical parameters of extracted beam at the extraction channel as initial condition of HEB1. Measurement method of outgoing separatrix was proposed and verified. In mismatched case, we cannot control optics!!

\[
\text{Beam size [mm]} \quad \text{s [m]}
\]

Optics before this study

Calculation doesn’t support measurement!!

Measurement method of outgoing separatrix was proposed and verified.
1) Inserted and fix rod1 at $x = x_1$.

2) Search a shadow of rod1 at $s_2$ by changing the horizontal position of the rod2 every operation cycle of the synchrotron.

\[ x'_1 = \frac{x_2 - x_1}{\Delta L} \]

In this way, outgoing separatrix can be measured owing to constant separatrix.
Separatrix at s2 under rod1 inserted

Shadow of rod1 at s2

Angle at s1 can be calculated.
Comparing simulation with measurement, twiss parameters was defined.

<table>
<thead>
<tr>
<th>Twiss parameters</th>
<th>Design</th>
<th>Estimated</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_x$</td>
<td>5 m</td>
<td>15 m</td>
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<tr>
<td>$\alpha_x$</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$D_x$</td>
<td>-0.5</td>
<td>-0.5</td>
</tr>
<tr>
<td>$D'_x$</td>
<td>0.0</td>
<td>0.2</td>
</tr>
<tr>
<td>$\varepsilon_x$</td>
<td>10 [π mm mrad]</td>
<td>1.5 [π mm mrad]</td>
</tr>
</tbody>
</table>

Optics was redesigned to match the extracted beam.
Matching with transport system

Beam envelope at HEBT

Beam profile can be estimated at each monitor.

Measured beam sizes were in good agreement with calculated envelope at each monitor in HEBT.
Summary

Toward requirements from scanning irradiation…

• Fast beam on/off NIM-A 489, p.59, 503, p.485.
  very fast cut-off time of $50 \mu s$ is achieved.

• Time structure control NIM-A 522, p.196.
  kHz order ripple of $\pm 20\%$ is achieved by separate function method.
  fs ripple is suppressed by debunch-recapture process.
  10Hz order ripple of $\pm 5\%$ is achieved by new AM function.

• Intensity control
  dynamic range of 10 is expected. (in progress)

• Beam size control NIM-A 515, p.863
  outgoing separatrix measurement made it possible to control beam size.

Thank you for your attention!!