Cooling of Ion Beam by a Bunched Electron Beam in Storage Ring

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Outline

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Scientific motivation

All electron coolers are operated based on the DC electrostatic accelerators, energy up to 4.3 MeV electron beam (Recycler, Fermilab).

First electron cooler @ BINP Russia

Powerful high energy electron cooling method is required for EICs.
Scientific motivation

All electron coolers are operated based on the DC electrostatic accelerators energy up to 4.3 MeV electron beam (Recycler, Fermilab).

- Powerful high energy electron cooling method is required for EICs.
- Electrostatic accelerators are NOT available and RF accelerator is needed.

First electron cooler @ BINP Russia

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Scientific motivation

all electron coolers are operated base on the **DC electrostatic accelerators**
energy up to **4.3 MeV** electron beam (Recycler, Fermilab)

**First electron cooler @ BINP Russia**

◆ **Electron beam is bunched**
To investigate the bunched electron beam cooling process on the classical electron cooler @ CSRm, IMP Lanzhou
Experimental setup and conditions

New high voltage system is used to produce pulsed electron beam

- High voltage platform closed to the gun
- 35 kV electron cooler @ CSRm
Basic idea: Switch on/off electron beam by the grid electrode

Experimental setup and conditions

Grid voltage from a pulse generator

Grid electrode is used to control the electric field at the cathode
Experimental setup and conditions

Pulsed electron beam is obtained with:

- The pulse width from 70 ns to DC
- The peak current up to 70 mA
- The repetition frequency up to 450 kHz

![5us electron pulse](image1)

![70ns electron pulse](image2)
### The main parameters of the experiments

<table>
<thead>
<tr>
<th>Item</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion</td>
<td>$^{86}\text{Kr}^{25+}$</td>
</tr>
<tr>
<td>Energy</td>
<td>4.98 MeV/u</td>
</tr>
<tr>
<td>Revolution frequency</td>
<td>191.4 kHz</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>2</td>
</tr>
<tr>
<td>RF voltage</td>
<td>600 V</td>
</tr>
<tr>
<td>Stored particle number</td>
<td>$\sim 10^8$</td>
</tr>
<tr>
<td>Electron energy</td>
<td>2734.5 V</td>
</tr>
<tr>
<td>Electron current (DC)</td>
<td>$\sim 30$ mA or even less</td>
</tr>
<tr>
<td>Ion bunch width</td>
<td>$\sim 1000$ ns (RMS value)</td>
</tr>
<tr>
<td>Pulse width</td>
<td>300 ns to 1200 ns for bunched ion beam</td>
</tr>
<tr>
<td></td>
<td>500 ns to 4000 ns for coasting ion beam</td>
</tr>
</tbody>
</table>
Experimental setup and conditions

The total measurement cycle is 50 seconds in the experiment

1. Beam stacking with DC cooling, around 10 seconds
2. Continuously DC cooling, to improve the beam quality, around 2 seconds
3. Switch off the DC electron beam (without cooling), beam blows up, around 4 seconds
4. Switch on the detectors, including BPM, Schottky and IPM
5. Switch on RF system, after 500 ms, switch on the pulsed electron beam.

The ion beam current in the experiment
Experiment and simulation results

- **Synchronization**

The repetition frequency of electron pulse **must be matched to** the ion beam revolution frequency.

![Graph showing the relationship between electron pulse frequency and lifetime.](image)

- Ion beam revolution frequency $f_\text{o} = 191.4 \text{kHz}$
- Electron pulse width $\Delta t = 2.0 \mu s$
- Electron beam current $I_{\text{avg}} = 5.0 \text{mA}$

- Peak frequency $f_{\text{peak}} = 191.338 \text{kHz}$
- Standard deviation $\sigma = 0.84 \text{kHz}$
**Experiment and simulation results**

- **Grouping effects**

- The coasting ion beam (no RF in the ring) can be cooled and captured in the electron pulse.
- Finally the ion pulse length **is equal to** the electron pulse length

![Graphs showing pulse width vs time for different electron pulse lengths: 500ns, 1000ns, and 1500ns.](image)

- **500ns electron pulse**
- **1000ns electron pulse**
- **1500ns electron pulse**
Experiment and simulation results

A “barrier bucket” is produced by the space charge field of the pulsed electron beam. The ions (with the energy spread smaller than the bucket height) will be captured in the bucket.
Experiment and simulation results

A simulation shows the cooling process of coasting ion beam by a pulsed e-beam.
Experiment and simulation results

- Bunched ion beam cooling by pulsed electron beam

- The ion bunches can be cooled by pulsed electron beam
- Even the electron pulse width is shorter than the initial ion beam bunch length
Experiment and simulation results

The cooling process with different electron pulse length

- It is observed that the cooling is faster with larger e-beam pulse length (the electron peak current is a constant)
It is also observed that the cooling is faster with high e-beam peak current (the electron pulse length is a constant).

**Experiment and simulation results**

The cooling process with different electron peak current.
Experiment and simulation results

The measured longitudinal beam shape can be fitted by Bi-Gaussian distribution

\[ y = \frac{\Gamma_c}{\sqrt{2\pi} \sigma_c} \exp\left(\frac{(t - t_0)^2}{2\sigma_c^2}\right) + \frac{\Gamma_t}{\sqrt{2\pi} \sigma_t} \exp\left(\frac{(t - t_0)^2}{2\sigma_t^2}\right) + \delta \]

\[ \sigma = \frac{S_c \sigma_c + S_t \sigma_t}{S_c + S_t} \]
Experiment and simulation results

- The cooling rate increases with increasing of the electron pulse length and the e-beam peak current.

\[ \lambda_{cooling} = \frac{1}{\tau_{cooling}} = \frac{1}{\frac{d}{\sigma_b} \frac{d}{dt} \sigma_b} \]

![Graph showing cooling rate vs. Delta T (µs) with data points for different peak currents.](image)
Experiment and simulation results

- The transverse beam cooling effect was observed by IPM detector.

<table>
<thead>
<tr>
<th>le</th>
<th>e-pulsewidth</th>
<th>IPM intensity (relative)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.4mA</td>
<td>400ns</td>
<td><img src="#" alt="Graph 1" /></td>
</tr>
<tr>
<td>29.6mA</td>
<td>400ns</td>
<td><img src="#" alt="Graph 2" /></td>
</tr>
</tbody>
</table>
Summary

- Both coasting and bunched ion beam can be cooled by pulsed electron beam in transverse and longitudinal phase space;
- The electron pulse and ions should be synchronized;
- A group effect is observed while the coasting ion beam cooled by pulsed electron beam.
- A dependence of cooling rate on different pulse electron beam parameters is summarized preliminary;
- A cooling effect was observed while the electron bunch length is shorter than the ion bunches.
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Thanks very much for your attention!