Transverse echo measurements in RHIC

Wolfram Fischer

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RHIC overview
Luminosity lifetime of colliding Au$^{79+}$ beams
Motivation

• Luminosity lifetime for heavy ions dominated by IBS
  – Effort to implement stochastic cooling
    here: M. Brennan, M. Blaskiewicz
  – RHIC II upgrade based on e-cooling
    here: I. Ben-Zvi, A. Fedotov, G. Wang

• Main emittance growth mechanism working against cooling is IBS

→ Good knowledge of IBS growth rates needed to predict cooling times and equilibrium beam sizes

→ Cooling times of order 1 hour, cannot afford error larger than about factor 2
Motivation

- IBS growth rate measurements usually done by observing the free expansion of bunches
  - Must be on time scale of interest [15min at injection, hrs at store]
  - Need precise emittance measurement [not easy transversely]

- Echo measurements are
  - Much faster (~1000 turns), allow parameter scans
  - Potentially very sensitive
  - Do not rely on precise emittance measurement
Transverse echoes

• Echoes well known in plasma physics

• Sensitive method to measure diffusion rates

• Theoretical accelerator papers by Stupakov, Kauffmann (SSC)

• Longitudinal echoes observed at
  – FNAL AA [Spenzouris, Colestock et al.]
  – CERN SPS [Brüning et al.]
  – BNL AGS [Kewisch, Brennan]
Transverse echoes – phase space simulation

- 1-turn quadrupole kick is difficult
- echo-like signal was also observed with 2 dipole kicks of different strength (F. Ruggiero, SPS)

![Phase space plots showing dipole kick, filamentation, quadrupole kick, and echo.](image-url)
Transverse echoes – dipole moment simulation

Figure 3: Left: The dipole moment of the distribution versus time after a dipole kick. Right: The same signal with an additional quadrupole kick at 500 turns after the dipole kick.

Transverse echoes – echo amplitude formulae

- Approximate echo signal for one-turn quadrupole kick, small dipole kick, constants diffusion coefficient $D_0$ (Stupakov, PAC97 and Handbook)

\[
A_{\text{echo}} = \frac{\eta^{\text{max}}}{a} = \frac{Q}{\tau_d \left( 1 + 8D_0 \mu^2 \omega_0^2 \tau^3 / 3 \varepsilon \right)}
\]

- $\eta^{\text{max}}$ echo amplitude, $a$ dipole kick,
- $Q = \beta / f$ at quad
- $\tau_d = T_0 / 4 \pi \mu$ decoherence time, $T_0$ rev. time, $\omega_0 = 2 \pi / T_0$
- $\tau$ time between dipole and quadrupole kick
- $\mu$ detuning ($\Delta Q$ at $1\sigma$ amplitude), $\varepsilon$ distribution rms
- $D_0$ diffusion coefficient

→ not applicable for RHIC experiments (due to parameter range)
### Pulsed quadrupole in RHIC

#### Air core magnet

(Tevatron slow extraction)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length ( l )</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Transfer ( B/I )</td>
<td>3.6 T/kA</td>
</tr>
<tr>
<td>Inductance ( L )</td>
<td>105 ( \mu )H</td>
</tr>
<tr>
<td>Current ( I )</td>
<td>50 A</td>
</tr>
<tr>
<td>Voltage ( U )</td>
<td>2 kV</td>
</tr>
<tr>
<td>Rise and fall time</td>
<td>13 ( \mu )s (1 turn)</td>
</tr>
</tbody>
</table>

Parameter set is for a quadrupole strength of \( k = 0.002/m \) (\( f = 500m \)).

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RHIC transverse echoes (1)

First RHIC echoes

- Au\(^{79+}\) at injection
- single bunch
- dipole kick by injecting with angle
- 1-turn quad kick

[W. Fischer, R. Tomas, T. Satogata, PAC05]

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RHIC transverse echoes (2)

Can observe echoes only

- With dipole kick of a few $\sigma$
- Nonlinear detuning an order of magnitude larger than natural one
- Quadrupole kick times no larger than a few 100 turns
**RHIC transverse echoes (3)**

**TABLE 1.** Typical parameters for transverse echo measurement in RHIC with beams of gold and copper ions, and protons.

<table>
<thead>
<tr>
<th>parameter</th>
<th>unit</th>
<th>Au</th>
<th>Cu</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass and charge number $A, Z$</td>
<td>...</td>
<td>197, 79</td>
<td>63, 29</td>
<td>1.1</td>
</tr>
<tr>
<td>relativistic $\gamma$</td>
<td>...</td>
<td>10.5</td>
<td>12.1</td>
<td>25.9</td>
</tr>
<tr>
<td>revolution time $T_0$</td>
<td>$\mu s$</td>
<td>12.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>rms emittance, unnorm. $\varepsilon$</td>
<td>mm·mrad</td>
<td>0.16</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>detuning $\mu$</td>
<td>...</td>
<td></td>
<td>0.0014</td>
<td></td>
</tr>
<tr>
<td>decoherence time $\tau_d$</td>
<td>turns</td>
<td>57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>dipole kick $a$</td>
<td>mm / $\sigma$</td>
<td>10 / $\approx$ 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>normalized quadrupole kick $Q$</td>
<td>...</td>
<td>0.025</td>
<td></td>
<td></td>
</tr>
<tr>
<td>time $\tau_0$</td>
<td>turns</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>quadrupole kick time $\tau$</td>
<td>turns</td>
<td>450</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>synchrotron period $T_s$</td>
<td>turns</td>
<td>450</td>
<td>540</td>
<td>3900</td>
</tr>
<tr>
<td>bunch intensity $N_b$</td>
<td>$10^9$</td>
<td>0.1–1.0</td>
<td>0.1–1.3</td>
<td>65–95</td>
</tr>
</tbody>
</table>
RHIC transverse echoes (4)

Scan of nonlinear detuning $\mu$ (octupoles)

- no echo without detuning, no echo with large detuning
- very weak proton echoes (unexpected)
RHIC transverse echoes (5)

Scan of quadrupole kick time $\tau$

- no echo small $\tau$, no echo with large $\tau$
- very weak proton echoes (unexpected)
RHIC transverse echoes (6)

Scan of bunch intensity $N_b$ (increasing diffusion from IBS)

All measurements with $\mu = 0.0014$, $\tau = 450$ turns

- echo decreases with increasing bunch intensity (like IBS)
- no proton data over sufficiently large range of $N_b$
Simulations (1)

- only 1D
- linear transfer matrixes
- octupoles to adjust $\mu$
- typically 10000 particles
- diffusion introduced through random kicks from Gaussian distribution (adjustable width, constant for all amplitudes)
Simulations (2)

Can find diffusion coefficient in simulation that approximately reproduces detuning scan for gold ions.

Particles trapped in islands

2 orders of magnitude in $D_0$

- $D_0 = 1.3 \times 10^{-7} \text{(mm.mrad)}^2/\text{s}$
- $D_0 = 3.4 \times 10^{-6} \text{(mm.mrad)}^2/\text{s}$
- $D_0 = 1.3 \times 10^{-5} \text{(mm.mrad)}^2/\text{s}$

Relative echo amplitude $A_{\text{echo}}$ against detuning $\mu$.

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Simulation can reproduce experimental main features of experimental quadrupole kick time scan.
Can find proportionality coefficient $D_0/N_b$ so that simulation fits experimental intensity dependency (→ extracts measured $D_0$)

- Fitted $D_0$ corresponds to emittance growth time of about 100 h, consistent with free expansion measurements (not very accurate)

Expect IBS growth rates for Cu about factor 2 smaller than those for Au
Summary – Transverse Echoes in RHIC

- Transverse echoes observed in RHIC with Au\textsuperscript{79+}, Cu\textsuperscript{29+}, p\textsuperscript{+}
  - Dipole kick with injection under angle
  - Air core quadrupole provides 1-turn kick
- Diffusion with p\textsuperscript{+} stronger than with heavier ions (unexpected)
- Observed intensity dependent echoes with Au\textsuperscript{79+}, Cu\textsuperscript{29+},
  → were fitted to simulation results to extract diffusion rates