Cycle-to-Cycle Extraction Synchronization of the Fermilab Booster for Multiple Batch Injection to the Main Injector

We report on a system to ensure cycle-to-cycle synchronization of beam extraction from the Fermilab Booster accelerator to the Main Injector. Such synchronization is necessary for multiple batch operation of the Main Injector for the Run II upgrade of anti-proton production using slipstacking in the Main Injector, and for the NuMI (Neutrinos at the Main Injector) neutrino beam. To perform this task a system of fast measurements and feedback controls the longitudinal progress of the Booster beam throughout its acceleration period by manipulation of the transverse position maintained by the LLRF (Low-level Radio Frequency) system.

Sources of Slippage
- Any change in the difference in frequencies $f_{MI} - f_{B}$ will cause slippage
- Some errors in the Beam will be parameterized as a change in $f_{MI}$
- We use a periodic signal to detect slippage

Cogging Power
- Cogging reduces extraction losses by 85-90 %
- Ultimate performance: 90-95 % reduction

Current Performance & Outlook
- Cogging reduces extraction losses by 85-90 %
  - Ultimate performance: 90-95 % reduction
  - Remaining Issue - Phaselock
  - Rate cogging firing event to ME over last two ms
  - Invaluable error until new digital phaselock system is designed & implemented
  - Slippage: Move extraction by 1-2 buckets cycle-to-cycle
  - Beam choice at ME, but probability okay

Cogging Electronics
- Kicker magnet knocks 3 buckets out
- Most of the beam is depleted into collimators
- Kick magnets large enough to strip off beams
- Beam is utilized at higher energy
- Stronger FS needed

Notching
- Only cogged cycles show improvement with greater kick
  - Better bunch overlap
  - Needle-like beams

Table: Measuring Slippage

<table>
<thead>
<tr>
<th>Slippage source</th>
<th>Slippage type</th>
<th>Slippage measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection</td>
<td>Slippage</td>
<td>Slippage measurement</td>
</tr>
<tr>
<td>Kinetic Energy</td>
<td>Slippage</td>
<td>Slippage measurement</td>
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<tr>
<td>Charging Voltage</td>
<td>Slippage</td>
<td>Slippage measurement</td>
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</tbody>
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Abstract

Cogging Algorithms
- Algorithm has progressed to ensure cogging in the available time
- Flat & proportional (2003)
  - Small goes to proportional feedback
  - Needs to use a prediction algorithm – like notching
  - Reduces post-trans. cogging necessary
- Proportional (demonstration 2004)
  - Larger errors go to a large constant value of feedback
  - Stay there until error is small
  - Return to proportional mode
- Pre-trans, flat, & enhanced proportional (2005)
  - Small pre-transition bump
  - Flat & proportional (2004)
  - Timing: 1 µs
  - 1 part in 1000
  - 1 turn!
- Flat & proportional (2003)
  - Timing: 1 µs
  - 1 part in 1000
  - 1 turn!

Slippage can be induced by
- Changing the circumference
- Changing velocity
- Active feedback corrects error toward zero

Timing Errors
- RF buckets slip at some $\omega = \frac{f_{MI}}{f_{B}}$ times
- We consider only the relation, cycle to cycle slippage

Sources of Slippage
- Timing cycle start and beam extraction processes
- Small variation in 15 Hz frequency can lead to ms errors
- Slippage was consistent with a combined error of about 10 µs

Radial Feedback Concept
- Slippage can be induced by changing the radial position of the beam
- Changing the beam radius during revolution
- Changing the beam radius across different beams

Ground positions
- Use the early part of the cycle to predict and slippage for injection
- Place the notch anticipating further slippage (few ms into cycle)

Notch Prediction
- Timing error of the cycle with the beam
- Timing error of the cycle with the beam
- Timing error of the cycle with the beam

Timing Correction
- Timing error of the cycle with the beam
- Timing error of the cycle with the beam
- Timing error of the cycle with the beam

Multi-Batch Applications
- Slip-Stacking
- NuMI (Neutrinos at the Main Injector)