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

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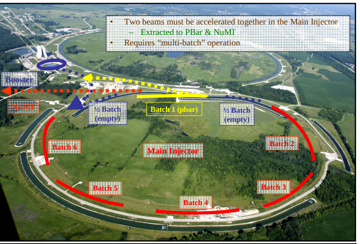
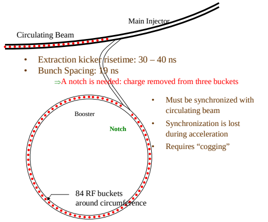
Abstract

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.



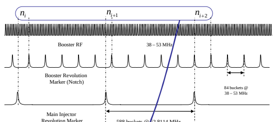
	Booster		Main Injector	
Circumference (m)	474		3319	
Harmonic Number	84		588	
Kinetic Energy (GeV)	Injection	Extraction ⇒ Injection		Extraction
	0.4	8		119
Momentum (GeV/c)	.954	8.9		120
Frequency (MHz)	37.8	52.8		53.1
Acceleration Time (s)	0.033		0.7	
Transition γ_T	5.45		21.8	



- Extraction kicker risetime: 30 – 40 ns
- Bunch Spacing: 19 ns
  - ⇒A notch is needed: charge removed from three buckets
- Must be synchronized with circulating beam
- Synchronization is lost during acceleration
- Requires "cogging"

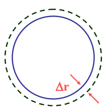
Measuring Slippage

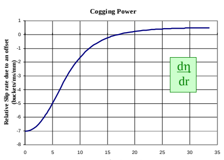
- Monitor Notch position throughout the cycle
- Use Main Injector RF as a standard clock
- Start counting on Main Injector revolution marker
- Stop Counting on Booster revolution marker
- Make a table of positions

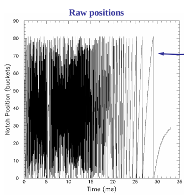


Radial Feedback Concept

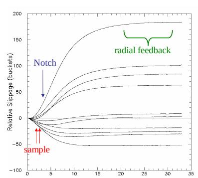
- Slippage can be induced by changing the radial position of the beam
  - Changes the feedback of the Low Level RF systems
  - Changes the circumference
  - Changes velocity
  - Active feedback corrects error toward zero







- RF buckets slip at a rate $f_{MI} - f_B$
  - Initially 15 MHz
- We consider only the relative, cycle-to-cycle slippage

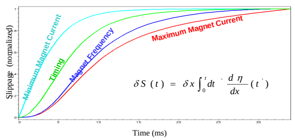


Notch Prediction

- Use the early part of the cycle to predict net slippage before extraction
- Place the notch anticipating further slippage (few ms into cycle)

Sources of Slippage

- Any change in the difference of frequencies (f_{MI}, f_B) will cause slippage
- Some errors in the Booster can be parameterized as a change in p(t)
  - Each has a particularly shaped slippage curve $\delta S(t)$
- Several possible errors shown below:
  - Timing: 1 μs ⇒ 15 bucket slip
  - Magnet Frequency: 1 mHz ⇒ 6 bucket slip
  - Minimum Magnet current (δp_1): 1/10,000 ⇒ 10 bucket slip
  - Maximum Magnet current (δp_2): 1/10,000 ⇒ 7 bucket slip
- Slip rate: h (buckets/ time)
  - 15 MHZ → 0
    - (inj. → ext.)
- Total slippage: S (buckets)
  - $S_{tot} \approx 100{,}000$ buckets
  - Only (S_{tot} mod 84) is relevant
  - 1 part in 1000 ⇒ 1 turn!



$$\delta S(t) = \delta x \int_0^t dt' \, \frac{d\eta}{dx}(t')$$

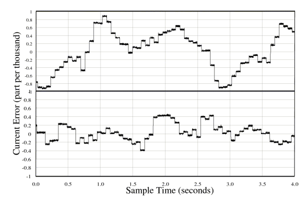
$$\eta = f_{MI} - f_B = f_{MI}\left[\frac{1}{\beta_{MI}} - \frac{1}{\sqrt{1+\frac{(mc)^2}{p^2}}}\right]$$

$$S(t) = \int_0^t dt' \, \eta(t')$$

$$p(t) = p_0 - p_1 \cos(2\pi f t)$$
$$p_1 = \tfrac{1}{2}(p_e - p_i) = 3.9666 \text{ GeV/c}$$
$$p_0 = \tfrac{1}{2}(p_e + p_i) = 4.9223 \text{ GeV/c}$$

Magnet Sag Correction

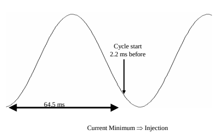
- Pulsing of RF Anode causes injection current to sag
- Causes slippage variation by cycle in a cycle train
- Counter with feed-forward compensation
  - Half-sine wave generated with clock



Timing Errors

Clock Error

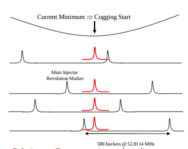
- Timing cycle start is predicted from previous cycle
- Small variation in 15 Hz frequency can lead to ms errors



- Solution ⇒ Trigger software off of magnet current level crossing instead of the cycle start

Discrete Error

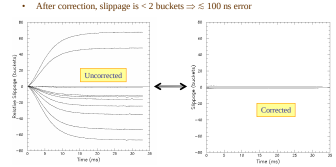
- Cogging program starts on magnet minimum
- However, measurements are taken at MI markers
- MI markers come at arbitrary times w.r.t. minimum
- Leads to a timing error of as much as 11 μs



- Solution ⇒ Generate an internal marker synchronized to the cogging start

Timing Correction

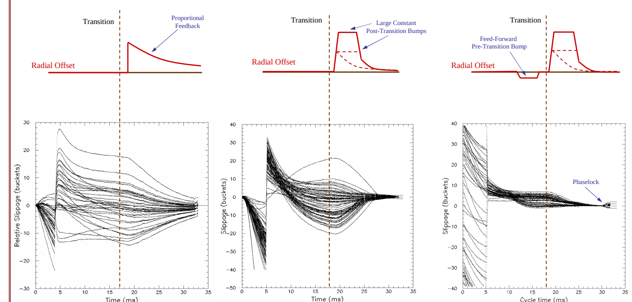
- Timing can be tested on cycles with no beam
  - RF is generated by DDS and is identical cycle-to-cycle
- Slippage was consistent with a combined error of about 10 μs
- After correction, slippage is < 2 buckets ⇒ ≲ 100 ns error



Cogging Algorithms

- Algorithm has progressed to ensure cogging in the available time

- Proportional (demonstration ≲ 2003)
  - Radial feedback after transition proportional to error remaining
  - Needed to keep within maximum displacement
  - Decay time was too slow
- Flat & proportional (2004)
  - Small goes to proportional feedback
    - Constant larger than above
  - 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
    - Needs to use a prediction algorithm – like notching
    - Reduces post-trans. cogging necessary
  - Flat feedback is the same as before
  - Proportional feedback is doubled when error is ± 1

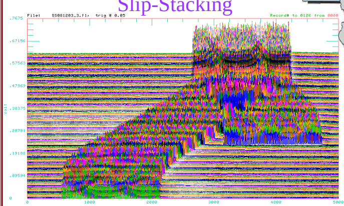


Current Performance & Outlook

- Cogging reduces extraction losses by 85-90 %
  - Ultimate performance: 90-95 % reduction
- Remaining Issue - Phaselock
  - Ruins cogging during synch to MI over last few ms
    - Irreducible error until new digital phaselock system is designed & implemented
  - Stopgap: Move extraction by 1-2 buckets cycle-to-cycle
    - Beams moves in MI, but probably okay

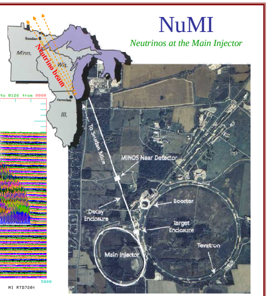
Multi-Batch Applications

Slip-Stacking

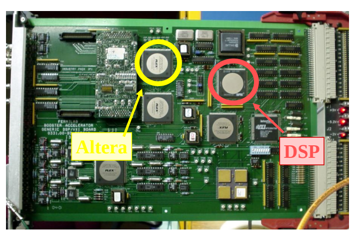


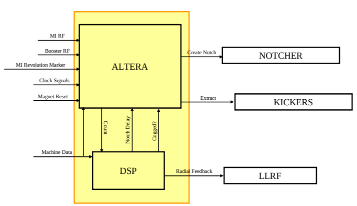
NuMI

Neutrinos at the Main Injector



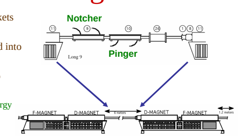
Cogging Electronics

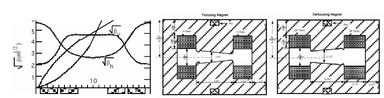




Notching

- Kicker magnet knocks 3 buckets out
- Most of the beam is deposited into collimators
- Kick must be large enough to scrape off beam
  - Beam is stiffer at higher energy
- Stronger PS needed





- Losses on cogged cycles show improvement with greater kick
  - Better cleans out notch
  - Reduces satellite bunches