A Novel Beam Injection Scheme in the Fermilab Booster for Intensity Upgrade

Chandra Bhat
Fermi National Accelerator Laboratory

BE/ABP
ACCELERATOR PHYSICS FORUM
CERN, Geneva, Switzerland
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Proton Delivery Scenario from the Booster (approximate)

- Expected protons from Booster
- Preparing for PIP II (Booster at 20Hz)
- Summer shutdown (we are here)
- # of Protons during the last quarter with rep rate of ≈6/sec

From Bill Pellico

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Record $1.25 \times 10^{17}$ protons/hour on July 24, 2015
(previous record $1.1 \times 10^{17}$ protons/hour)

Base Design

Efficiency ($\approx 90\%$)

Average rep. Rate
# Upgrade Path for Power on Target

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PIP Completed</th>
<th>PIP-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection Energy (KE) (GeV)</td>
<td>0.4</td>
<td>0.8</td>
</tr>
<tr>
<td>Extraction Energy KE (GeV)</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Injection Intensity (p/pulse)</td>
<td>4.52E12</td>
<td>6.63E12</td>
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<td>Extraction Intensity (p/pulse)</td>
<td>4.3E12</td>
<td>6.44E12</td>
</tr>
<tr>
<td>Bunch Removed</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>95</td>
<td>97</td>
</tr>
<tr>
<td>Booster repetition rate (Hz)</td>
<td>15</td>
<td>20</td>
</tr>
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<td>Booster Beam Power at Exit (kW)</td>
<td>94</td>
<td>184</td>
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<tr>
<td>MI batches</td>
<td>12 per 1.33 sec</td>
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<td>NOvA beam power (kW)</td>
<td>700</td>
<td>1200</td>
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<td>Rate availability for other users (Hz)</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>Booster flux capability (protons/hr)</td>
<td>~2.3E17</td>
<td>~3.5E17</td>
</tr>
<tr>
<td>Laslett Tune shift at Injection</td>
<td>≈0.227</td>
<td>≈0.263</td>
</tr>
<tr>
<td>Longitudinal energy spread</td>
<td>&lt;6 MeV</td>
<td>&lt;6 MeV</td>
</tr>
<tr>
<td>Transverse emittances (p-mm-mrad)</td>
<td>&lt;14</td>
<td>18</td>
</tr>
<tr>
<td>Booster uptime</td>
<td>&gt;85%</td>
<td>&gt;85%</td>
</tr>
</tbody>
</table>
Are there innovative ways to increase the Booster beam before the PIP-II era?

- Introduction
- Beam Simulations
- Experimental Demonstrations
  - Beam studies and Findings
- Summary and Future Plans
Layout of the Fermilab Booster

Booster Lattice Parameter

- Circumference: \(2\pi \times 74.47\) meters
- Injection energy: 400 Mev (kinetic)
- Extraction energy: 8 Gev (kinetic)
- Cycle time: \(\frac{1}{15}\) sec
- Harmonic number, \(h\): 84
- Transition gamma: 5.45
- Injection Frequency: 37.77 Mhz
- Extraction Frequency: 52.81 Mhz
- Maximum RF voltage: 0.86 MV
- Longitudinal emittance: 0.25 eV sec
- Horizontal \(\beta\) max: 33.7 meters
- Vertical \(\beta\) max: 20.5 meters
- Maximum dispersion: 3.2 meters
- Tune \(u_x = v_y\): 6.7
- Transverse emittance (normalized): 12\(\pi\) mm rad
- Bend magnet length: 2.9 meters
- Standard cell length: 19.76 meters
- Bend magnets per cell: 4
- Bend magnets total: 96
- Typical bunch intensity: 3 \times 10^{10}
- Phase advance per cell: 96 degs
- Cell type: \text{FOFOODD (DOODFOF)}
Beam Injection into the Booster

1. When injecting, ORBMP is ramped up, bending any incoming H- ions and any circulating protons into the same orbit which passes through a stripping foil.
2. Once beam injected, ORBMP is ramped back so that the circulating beam is sufficiently away from the stripping foil.
Fermilab Booster is the 2nd oldest RCS in the world & its magnets ramp at the rate of 15 Hz.

Historically it was assumed that one has to inject beam very close to $\dot{B} = 0$.

Current Scheme (CIS)

Capture & Acceleration using 37-52 MHz RF system in $\approx 360\mu s$

$\sim 60\mu s$ - $200\mu s$ debunching

$1/15\text{Hz} \approx 0.0666\text{ s}$

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Simulations for CIS

Mimic Operational Beam: injection at ~35us before BDOT=0

Issues: A limited time for Beam Capture. RF manipulations are non-adiabatic at capture ⇐ ~50% emittance dilution, ≈10% beam loss
Beam Transmission in the Current Booster and Intensity Limit

Observations:
1. Beam loss as a function of beam intensity
2. <50% emittance dilution at injection
3. Large Vrf power

I believe that the longitudinal beam dynamics at injection is the problem.
Schematic of the Early Injection Scheme for the Booster (EIS)

- Begin Injection
- Impose Beam Capture in Stationary rf Buckets ($\hat{P}=0$)
- Beam Acceleration using 37-52 MHz RF system

- Change in $E_s < 0.24\text{MeV}$
- $\approx 40\mu s$ injection
- $150\mu s$
- $1/15\text{Hz} \approx 0.0666\text{s}$
- Energy Acceptance $> 4\text{MeV}$
- Beam $\Delta E \approx 1.3\text{MeV}$
- $f_{sy} = 8\text{kHz}-27\text{kHz} @ V_{rf}=0.035-0.4\text{MV}$
- Beam capture for $>260\mu s$ (no debunching)

C. M. Bhat, IPAC2015
Early Injection Scheme

What is spooky about this method

- The beam is injected on the deceleration part of the magnetic ramp.
- Beam capture takes place while magnetic field is changing.

Historically, it was believed that the capture and acceleration efficiencies in the Booster will be optimal if beam is injected close to $\dot{B} = 0$.

What is Innovative about this Method?

- Beam capture should be carried out by imposing $\dot{P} = 0$ even though $\ddot{B} \neq 0$.
- Since the $fs \approx 8$-$27$kHz for $V_{rf}=0.034$-$0.34$MV, nearly adiabatic capture of the beam needs only $\approx 260\mu$s.
- Preserving the longitudinal emittance at capture means less rf voltage through the acceleration cycle $\iff$ Lesser RF power.
- Better beam for slip-stacking. $\iff$ Main Injector/RR demand smaller $dp/p$ beam for improving slip-stacking.
Beam Simulations with ESME

Inj. @ at ≈ -150μs w.r.t. $\dot{B} = 0$ for 40μs. Start beam capture immediately after 10 μs for next 250 μs.

Since we impose $\dot{P}=0$, one demands $\Delta B/B = γ_f^2 Δf/f$ during beam capture.

RF manipulations are more adiabatic at capture $\leftarrow$ ~0% emittance dilution and no beam particle losses
Beam Simulations from Injection → Extraction (Evolution of Phase space Distribution)

**Inj. @ at -100μs w.r.t. \( \dot{B} = 0 \), Capture from -64 μs to 135μs, with a phase kick of ~ 6 deg after transition crossing.

Because of small emittance at capture acceleration needs less rf voltage
Beam Simulations from Injection → Extraction

with $2 \times 10^{10} - 12 \times 10^{10}$ protons/bunch

- $E_s = 1.339$ GeV, $V_r f = 0.035$ MV
- $E_s = 1.339$ GeV, $V_r f = 0.41$ MV
- $E_s = 4.42$ GeV, $V_r f = 0.76$ MV
- $E_s = 5.37$ GeV, $V_r f = 0.75$ MV
- $E_s = 8.94$ GeV, $V_r f = 0.13$ MV

Around the Extraction

Time (deg)
(Revolution Period=360°)

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“Proof of Principle” Experiment

- Beam injection at 144 μs earlier than $\dot{B} = 0$.

- Simulated Vrf curve is used
- Transition crossing needed additional tuning
Samples of Transverse Beam Sizes for the First 2 ms (Nothing Unusual)

5E12 p/ Booster Batch

IPM Data: Horizontal Beam size

IPM Data: Vertical Beam Size
These experiments proved that

1) One can inject the beam much earlier than $\dot{B} = 0$.
2) Can achieve beam transmission efficiency comparable to the current operation.
3) There is ample of room to increase beam intensity in the Booster by a factor more than 1.5.

But we did not have all beam controls during these beam experiments established by simulations.
Tasks under Development

- Beam capture soon after the completion of the beam injection,
- A frequency synchronization between the LLRF and changing magnetic field on the down ramp.
- Implement phase corrections/jump at transition crossing.
- Fast bunch rotation $\leftrightarrow$ Gives lower beam energy spread at extraction. Hence, is better for slip-stacking in RR.
- Beam loading compensation
Implications of EIS

- One can increase the Booster beam power at extraction, because more number of Booster turns can be accommodated.
- Higher brightness beam to the downstream machines.
- Booster can be run with nearly 30% less RF power per cycle – This is a great bonus.
Acknowledgements

W. Pellico, C. Drennan, K. Triplett, S. Chaurize, B. Hendrick, T. Sullivan and A. Waller
### Summary

Expected by adopting Early Injection Scheme

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<td>(~6E12)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.44E12</td>
</tr>
<tr>
<td>Number of Booster Turns</td>
<td>13</td>
<td>(18)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>300</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>95</td>
<td>(≥97)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>97</td>
</tr>
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<td></td>
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Backup
# Beam Simulations from Injection → Extraction

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
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<tbody>
<tr>
<td>Booster circumference $(2\pi R)$ [m]</td>
<td>473.8</td>
</tr>
<tr>
<td>Injection KE [MeV]</td>
<td>400</td>
</tr>
<tr>
<td>Extraction KE [MeV]</td>
<td>8000</td>
</tr>
<tr>
<td>Cycle Time [sec]</td>
<td>1/15</td>
</tr>
<tr>
<td>Beam injection w.r.t. $\dot{B} = 0$ [µsec]</td>
<td>0, -90, -144</td>
</tr>
<tr>
<td>Harmonic Number</td>
<td>84</td>
</tr>
<tr>
<td>Transition Gamma $\gamma_T$</td>
<td>5.478</td>
</tr>
<tr>
<td>$\Delta E$ at Injection [MeV]</td>
<td>1.6</td>
</tr>
<tr>
<td>Longitudinal Emittance [eV sec]</td>
<td>0.04</td>
</tr>
<tr>
<td>Beam Structure at Injection</td>
<td>201MHz</td>
</tr>
<tr>
<td>Number of BT</td>
<td>1-17</td>
</tr>
<tr>
<td>Bunch Intensity [protons/bunch]</td>
<td>2E10-12E10</td>
</tr>
<tr>
<td>Beam transverse radius [cm]</td>
<td>1.2*</td>
</tr>
<tr>
<td>Beam pipe (RF) radius [cm]</td>
<td>2.86*</td>
</tr>
</tbody>
</table>

*Used in simulations with space charge effects
Laslett SC tune shift

\[ \Delta \nu_{SC} = - \frac{N_{tot} r_c B_f}{4 \pi \varepsilon_n \beta_p \gamma_p^2}, \]

where \( N_{tot} \) is total number of particles in the ring, \( r_c = 1.53 \cdot 10^{-18} \text{m} \) for protons, \( \varepsilon_n \) is rms normalized emittance, \( \beta_p = v_p/c \) and \( \gamma_p \) are usual relativistic parameters, and \( B_f \geq 1 \) is a peak to average current ratio. Normally, for proton low-energy synchrotrons the tune shift lays in range of \(-0.1\ldots-0.5\) (see, e.g.,[4]). Above the threshold, the beam emittance dilute and particles are lost. Due to the acceleration, the short time at low energy is enough for developing only the lowest order resonances.
Studies with Different Intensities

Early Injection: Beam Injection at -144 µsec w.r.t. $B_{\text{min}}$

- 15-Booster Turns (90% eff.)
- 14-Booster Turns (92% eff.)
- 13-Booster Turns (92% eff.)
- 8-Booster Turns (91% eff.)
- 4-Booster Turns (95% eff.)
Beam Emittance

Near Extraction

\[ \text{LE(95\%)} \approx 0.13 \pm 0.01 \text{ eV s (10\%)} \]

Data

\[ \text{LE(95\%)} \approx 0.13 \pm 0.01 \text{ eV s (10\%)} \]

Simulation

\[ \text{LE(95\%)} \approx 0.13 \pm 0.01 \text{ eV s (10\%)} \]

Simulation

\[ 1/30s \approx 0.0333s \]

RF Voltage

\[ 14BT, dE=+/-0.81\text{MeV}@400\text{ MeV}, \text{Inj@-35us wrt Bdot=0, M} \]

\[ \text{EV(1) VS TIME} \]

\[ 5.5\text{E10 ppb} \]

LE(95\%) = 0.14 eV s

\[ \theta_{\text{rms}} = 5.5 \text{E4} \text{rad} \]