Booster Modeling and Space Charge Study

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Fermilab
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Booster Study Group

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- **Universities:** L. Coney, C. Jacobs, L. Klamp, S. Kopp, D. Michael, H. Zhang, R. Zwaska

Study Goals

- To establish a realistic and useful Booster model
  - Inherited a bare FODO lattice model
  - Now it includes the correction package (steering magnets and trim quads), sextupoles, octupoles, gamma-t jump quads, injection orbit bump, doglegs, septa, BEX magnet, etc.

- To understand the beam loss and emittance blowup mechanism, and the roles of space charge and other associated effects

- To carry out both simulations and measurements

- To investigate possible measures for performance improvement
Outline of the Talk

- Introduction
  - Booster – the bottleneck
  - Parameter list
- Linear optics modeling - the dogleg effect
- Space charge study
- The first 3 milliseconds in the Booster
- Space charge reduction
- 2nd order optics modeling - chromaticity
- Gamma-t jump modeling
- Power supply experiments at E4R
Fermilab Accelerator Complex

Fermilab Tevatron Accelerator With Main Injector

Diagram showing the layout of the Fermilab Tevatron Accelerator with main injector, including the main injector, recycler, accumulator, and other components.
Booster – the Bottleneck

- The Booster is a 30 years old machine and has never been upgraded.
- The 400-MeV Linac can provide $25 \times 10^{12}$ particles per Booster cycle.
- The 120-GeV Main Injector can accept $25 \times 10^{12}$ protons per Booster cycle.
- However, the 8-GeV Booster can only deliver $5 \times 10^{12}$ particles per cycle.
Booster Beam Loss
(courtesy R. Webber)

For 0, 2, 4, 6, 8, 10, 12, 14 Injected Turns
How Do Particles Get Lost?

- The Booster up-ramp cycle is 33.3 ms
- The first 3 ms – big loss (~30%):
  - The dogleg effect – reducing machine acceptance
  - Space charge – diluting beam emittance
- Transition crossing: several percent loss
- After transition - coupled bunch instability: a few percent loss
### Booster Parameter List

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference (m)</td>
<td>474.2</td>
</tr>
<tr>
<td>Average machine radius (m)</td>
<td>75.47</td>
</tr>
<tr>
<td>Injection kinetic energy (MeV)</td>
<td>400</td>
</tr>
<tr>
<td>Extraction kinetic energy (GeV)</td>
<td>8</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>15</td>
</tr>
<tr>
<td>RF frequency (MHz)</td>
<td>37.87 – 52.81</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>84</td>
</tr>
<tr>
<td>Protons per bunch</td>
<td>$6 \times 10^{10}$</td>
</tr>
<tr>
<td>Protons per cycle</td>
<td>$5 \times 10^{12}$</td>
</tr>
<tr>
<td>Protons per second*</td>
<td>$2.5 \times 10^{13}$</td>
</tr>
<tr>
<td>Protons per hour*</td>
<td>$9 \times 10^{16}$</td>
</tr>
<tr>
<td>Average beam current* (µA)</td>
<td>4</td>
</tr>
<tr>
<td>Average beam power* (kW)</td>
<td>32</td>
</tr>
<tr>
<td>(*): MiniBooNE continuous operation at 5 Hz</td>
<td></td>
</tr>
<tr>
<td>Lattice</td>
<td>FOFODODO</td>
</tr>
<tr>
<td>Super-periodicity</td>
<td>24</td>
</tr>
<tr>
<td>Cell length (m)</td>
<td>19.758</td>
</tr>
<tr>
<td>Length of combined function magnet (m)</td>
<td>2.889612</td>
</tr>
<tr>
<td>Magnet per cell</td>
<td>4</td>
</tr>
<tr>
<td>Magnet total</td>
<td>96</td>
</tr>
<tr>
<td>Number of straight sections</td>
<td>24 Long, 24 Short, 48 Mini</td>
</tr>
</tbody>
</table>
Booster Parameter List (cont...)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of each straight section (m)</td>
<td>6(Long), 1.2(Short), 0.5(Mini)</td>
</tr>
<tr>
<td>Max/Min $\beta_x$ (m)</td>
<td>33.67 (Short)/6.12 (Long)</td>
</tr>
<tr>
<td>Max/Min $\beta_y$ (m)</td>
<td>20.46 (Long)/5.27 (Short)</td>
</tr>
<tr>
<td>Max/Min $D_x$ (m)</td>
<td>3.19 (Long)/1.84 (Short)</td>
</tr>
<tr>
<td>Phase advance per cell $\varphi_x, \varphi_y$ (degree)</td>
<td>100.5, 102</td>
</tr>
<tr>
<td>Horizontal, vertical tune $\nu_x, \nu_y$</td>
<td>6.7, 6.8</td>
</tr>
<tr>
<td>Natural chromaticity $\xi_x, \xi_y$</td>
<td>-9.2, -7.0</td>
</tr>
<tr>
<td>Transition $\gamma_t$</td>
<td>5.45</td>
</tr>
<tr>
<td>Transition momentum (GeV/c)</td>
<td>5.03</td>
</tr>
<tr>
<td>Transition crossing moment (ms)</td>
<td>17</td>
</tr>
<tr>
<td>$\beta$ at injection, extraction</td>
<td>0.713, 0.994</td>
</tr>
<tr>
<td>$\gamma$ at injection, extraction</td>
<td>1.426, 9.526</td>
</tr>
<tr>
<td>$\eta$ at injection, extraction</td>
<td>-0.458, 0.0227</td>
</tr>
<tr>
<td>Revolution frequency at injection, extraction (kHz)</td>
<td>450.8, 628.7</td>
</tr>
<tr>
<td>Revolution time at injection, extraction (µs)</td>
<td>2.22, 1.59</td>
</tr>
<tr>
<td>Injection turns (typical)</td>
<td>11</td>
</tr>
<tr>
<td>Injection time (typical, µs)</td>
<td>24.4</td>
</tr>
<tr>
<td>Injection linac peak current (typical, mA)</td>
<td>40</td>
</tr>
<tr>
<td>Maximum Laslett tune shift</td>
<td>0.4</td>
</tr>
<tr>
<td>Normalized transverse emittance $\varepsilon_N$ (95%, mm-mrad)</td>
<td>12 $\pi$</td>
</tr>
<tr>
<td>Longitudinal emittance (95%, eV-s)</td>
<td>0.1</td>
</tr>
</tbody>
</table>
The Dogleg Effect

- A dogleg is a set of 4 orbit bump magnets located in the injection and/or extraction areas.
  - Injection area: to create orbit bump for H⁺ injection. (pulse length ~60 µs)
  - Extraction area: to increase the aperture at the septum. (dc)
- The **dogleg effect** is referred to the edge focusing of these orbit bump magnets.
- In the past 30 years, this dogleg effect was ignored in the Fermilab Booster, because it was considered to be “small perturbation.” However, it is not small at all. (first pointed out by A. Drozhdin)
- The edge focusing strength is:
  \[ 1/f = \tan \theta / \rho \cong \theta^2 / L \]
  \( \theta \) - bend angle (60 mrad), \( \rho \) - bend radius, \( L \) – magnet length (26 cm).
- The sum of edge focusing of the two extraction doglegs (0.1152 m⁻¹) almost equals to that of one main quadrupole (0.1567 m⁻¹), thus causing large perturbation to the lattice.
The Dogleg Effect (cont...)

- The doglegs are R-bends (horizontal or vertical). Their edge focusing gives large perturbation in the non-deflecting plane (vertical or horizontal):
  \[ \beta(x)_{\text{max}}: 33 \text{ m} \rightarrow 47 \text{ m} \]
  \[ \beta(y)_{\text{max}}: 20 \text{ m} \rightarrow 26 \text{ m} \]
  \[ D(x)_{\text{max}}: 3 \text{ m} \rightarrow 6 \text{ m} \]
  
  Machine acceptance: \( 16\pi \rightarrow 8\pi \), reduced by 50%!

- Beam measurement agreed with the model.

- Removal of one of the two doglegs led to immediate improvement:
  - Beam loss cut to half
  - A milestone of the MiniBooNE experiment reached (5e16 protons per hour)
  - \( \rightarrow \) champagne celebration
Edge Focusing of a Wedge Magnet

\[ L = \text{magnet length} \]
\[ \theta = \text{bend angle} \]
\[ \eta = \text{edge angle} \]

Sector magnet (Sbend): \( \eta = 0 \)
Rectangular magnet (Rbend): \( \eta = -\theta/2 \)

Focusing strength as a function of edge angle \( \eta \)

Non-deflecting plane: \( 1/f = 2\eta\theta/L + \theta^2/L \)
Deflecting plane: \( 1/f = -2\eta\theta/L \)
Sum = \( \theta^2/L \) (always focusing!)

To be more precise, this sum is from the **body focusing** in the deflecting plane. The sum of the edges in the two planes is zero.
Dogleg Layout Sketch
(courtesy A. Drozdhin)
Present Dogleg Layout
(courtesy J. Lackey)
Dogleg Perturbation on Linear Lattice: MAD Simulation
(courtesy A. Drozhdin)

Horizontal beta-function

Horizontal dispersion
Dogleg Perturbation on Dispersion: Simulation vs. Measurement
(courtesy E. McCrory)
Beam Experiment: Removing One of the Two Doglegs

After, beam loss cut by half

Injected beam intensity (x 10^{12})

(Courtesy J. Lackey)
New Dogleg Layout
(courtesy J. Lackey)

Edge focusing reduced by 80% by increasing dogleg spacing

Septum

Dogleg

Edge focusing reduced by 80% by increasing dogleg spacing

Septum

Dogleg

Edge focusing reduced by 80% by increasing dogleg spacing
Application to Other Machines - KEK Booster

- KEK Booster has four horizontal bump magnets for $H^+$ injection:
  - $\theta$ (mrad): 140, -180, -100, 140
  - $L$ (m): 0.349, 0.449, 0.249, 0.349
  - Total edge focusing strength: $\sum \frac{\theta^2}{L} = 0.2246 \text{ m}^{-1}$
- KEK Booster main quadrupole strength: $\frac{1}{f} = 0.6987 \text{ m}^{-1}$
- So the additional focusing is about 1/3 of a main quadrupole and is in the vertical plane.
- SYNCH shows about 30% increase in $\beta(y)_{\text{max}}$ with the dogleg effect.
- How about AGS Booster or CERN PS Booster?
Space Charge Study

Simulation code development:

- **1-D ESME** (P. Lucas, J. MacLachlan)
- **2-1/2-D ORBIT** (F. Ostiguy, L. Michelotti, W. Chou)
  - Original parallelized code obtained from SNS (J. Holmes, J. Galambos)
  - Add in map generation using Mxyzptlk/beamline C++ class libraries
  - MAD parser (FNAL Lex/Yacc based parser)
  - Replace (the now obsolete) Supercode shell with Python
  - Improvements in code efficiency; support for acceleration (work in progress)
  - Numerous bug fixes
Space Charge Study (cont…)

- **3-D Synergia** (P. Spentzouris, J. Amundson, in collaboration with L. Michelotti, F. Ostiguy)
  - Modification of the linac space charge code IMPACT for circular machines
  - Split operator technique
  - Parallel PIC code
  - Use the same MAD parser
  - Use the same Mxyzptlk/beamline C++ class libraries to compute map coefficients; propagation handled by IMPACT
  - Linear map (could use higher order)
  - Up to 5M particles on 65x65x65 grid
  - Funded by the DOE SciDAC project
  - References: Fermilab-Conf-03-126-E, Fermilab-Conf-03-127
  - Web: [http://cepa.fnal.gov/psm/aas/Advanced_Accelerator_Simulation.html](http://cepa.fnal.gov/psm/aas/Advanced_Accelerator_Simulation.html)
Linac 805 MHz Microbunches
(ESME, courtesy P. Lucas)

One microbunch with $\Delta p/p = \pm 0.13\%$

Multi-turn injection
Tune Footprint
(ORBIT, varying beam intensity)

Laslett tune shift: $\Delta v \approx -0.3$
Tune Footprint
(Synergia, courtesy P. Spentzouris)
Emittance Histogram (ORBIT)

- With space charge
- No space charge

![Emittance Histogram Graph](image_url)
Emittance Growth
(ORBIT, 11-turn injection, varying beam intensity)

- Fast growth during injection
- Slow growth after injection
- No space charge
IPM Measurement
(Raw data)

40 mA, 10-turn injection

20 mA, 10-turn injection

45 turns
Emittance Growth
(Synergia, processed IPM data, courtesy P. Spentzouris)
Emittance Growth (cont...)

- Transverse sc only
- Transverse + Longitudinal
- Longitudinal sc only
- No space charge
Emittance Growth (cont...)
(varying linac current I and injection turns together)

First 50 turns

First 200 turns

I x 11 turns

I/2 x 22 turns

Turn

Turn

I x 11 turns

I/2 x 22 turns
First 3 milliseconds in the Booster

- **Transverse loss**
  - The transverse acceptance is:
    \[
    A = \left( \frac{\beta_{\text{max}} \times \epsilon_N}{\beta \gamma} \right)^{-1/2} + D_{\text{max}} \times \Delta p/p + \text{c.o.d.}
    \]
  - The magnet good field region is about ±1.2 inch
  - For regular $\beta_{\text{max}}$ and $D_{\text{max}}$, the maximum allowable $\epsilon_N$ is about $16\pi$
  - But the doglegs blow up the lattice function and reduce $\epsilon_N$ to about $8\pi$
  - The incoming linac beam is $7\pi$
  - Space charge dilutes the emittance during the multiturn injection, resulting in loss.

- **Longitudinal loss**
  - The measured Booster momentum acceptance is small: ±0.15-0.2%
  - The measured linac beam momentum spread is about ±0.13%
  - When the beam is bunched, the momentum spread increases to ±0.3%
  - This exceeds the acceptance and results in loss
Longitudinal Measurement

Momentum acceptance

Microbunch length
First turn at L18
First 3 milliseconds in the Booster
(cont...)

When beam energy goes up, the situation improves rapidly:

- **Transverse:**
  - Dogleg focusing strength: \( 1/f = \theta^2/L \propto 1/p^2 \downarrow \downarrow \)
  - Beam size due to adiabatic damping: \( \varepsilon = \varepsilon_N/\beta\gamma \downarrow \)
  - Space charge effect \( \propto 1/\beta^2 \gamma^2 \downarrow \downarrow \)

- **Longitudinal:**
  - \( \Delta E/E \downarrow \)
  - \( 1/\beta^2 \downarrow \)
  - \( \Delta p/p = (1/\beta^2) \times \Delta E/E \downarrow \downarrow \)

In the middle and late stage of the cycle, other schemes will contribute to the beam loss (e.g., transition crossing, coupled bunch instability), but which is beyond this topic.
Space Charge Reduction

- Painting experiment
- Inductive insert experiment
- Quadrupole pickup
- IPM improvement
- ($H^-$ source and linac improvements)
- ($2^{nd}$ harmonic RF)
Painting Experiment

Adjust injection timing

Injection orbit bump

no painting

painting

start

end
Inductive Inserts Experiment

- Two Fermilab-made modules have been installed in the PSR at LANL. They help increase the PSR beam intensity significantly.
- Two same modules were installed in the Booster. But no effect on the beam (neither bad nor good).
- A possible explanation is the inductance not big enough.
- Five more modules were made and will be tested.
Inductive Inserts Experiment (cont...)

- J. Crisp’s measured lamination impedance (96 magnets):
  \[ Z(\text{lam}) = 37 \, \text{k} \Omega + j \omega \, 40 \, \mu\text{H} \]

- Space charge impedance (for \( g = 2 \)):
  \[ Z(\text{sc}) = -j \omega \, 92 \, \mu\text{H} \]

- D. Wildman’s measured inductive insert impedance:
  \[ Z(\text{ind. insert}) = j \omega \, 4 \, \mu\text{H} \]
  per module (30-in long)
Quadrupole Pickup
(Courtesy A. Jansson)

Magnetic quad pickup

A pickup installed on the CERN PS
IPM Improvement

- Present two Booster IPMs (one H, one V) collect ions with 10 kV clearing field
- Consider to increase to 30 kV by using the old MI IPM power supply
- Investigate the possibility to convert them to electron collection with an external permanent magnetic field (similar to the new ones in MI, RHIC and SPS)
Chromaticity Modeling

Chromaticity sextupole setting

[zero current @inj: $\xi(x) = -23$, $\xi(y) = +11$]
Chromaticity Modeling (cont...)

\[ \xi = \xi(\text{lat}) + \xi(\text{chrom sext}) + \xi(\text{mag sext}) + \xi(\text{dogleg}) \]

- **Goal:**
  To have a spreadsheet relating the sextupole current to the machine chromaticity throughout the cycle

- **The task is complicated by two factors:**
  - The dogleg effect, which perturbs the local lattice function and has an energy dependence *(calculable)*
  - The main magnets have large sextupole component, which comes from both the body part and the end packs *(need measurement)*
The doglegs' direct contribution to the chromaticity is small. But their impact on the chromaticity is significant because of the big change of local $\beta$ and $D$ at the chromaticity sextupoles.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$\xi(x)$</th>
<th>$\xi(y)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare lattice (Lat)</td>
<td>-9.16679</td>
<td>-7.03638</td>
</tr>
<tr>
<td>Lat + dogleg</td>
<td>-9.57427</td>
<td>-7.01265</td>
</tr>
<tr>
<td>Lat + body sext</td>
<td>-23.55770</td>
<td>11.65977</td>
</tr>
<tr>
<td>Lat + body sext + dogleg</td>
<td>-23.40371</td>
<td>11.00271</td>
</tr>
<tr>
<td>Lat + body sext + chrom sext + dogleg</td>
<td>0.04399</td>
<td>-0.18496</td>
</tr>
<tr>
<td>Lat + body sext + chrom sext (no dogleg)</td>
<td>3.67119</td>
<td>-11.11968</td>
</tr>
</tbody>
</table>
Field Measurement at E4R

A mole used for dc field measurement
Main Magnet Sextupole Component

- Two independent measurements:
  - Field measurement at the E4R
  - Chromaticity measurement at the Main Control Room
- The two teams did not talk to each other on purpose (a blind check)
- The results are found to be in good agreement at 400 MeV
- Work in progress for ac measurement

<table>
<thead>
<tr>
<th>Magnet type</th>
<th>Body only</th>
<th>Body + Ends field measurement</th>
<th>Body + Ends chromaticity measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>0.0242</td>
<td>0.004</td>
<td>-0.003</td>
</tr>
<tr>
<td>D</td>
<td>-0.0306</td>
<td>-0.0413</td>
<td>-0.0454</td>
</tr>
</tbody>
</table>
Main Magnet Sextupole Measurements (cont...)

F magnet

Comparison of ssd Values

-0.05
-0.04
-0.03
-0.02
-0.01
0

Time (ms)

ssd (1/m^3)

E4R data (body) ▲ E4R data (integral) ✗ MCR data (zero setting)

Body only

Body+ends

Chrom meas.

D magnet

Comparison of ssf Values

-0.01
0
0.01
0.02
0.03
0.04
0.05

Time (ms)

ssf (1/m^3)

E4R data (body) ▲ E4R data (integral) ✗ MCR data (zero setting)

Body only

Body+ends

Chrom meas.
Gamma-t Jump Modeling

- Gamma-t quad location:
  - 6 QF: Short 4, 8, 12, 16, 20 and 24
  - 6 QD: Short 2, 6, 10, 14, 18 and 22

- Length:
  - QF = 21.6 cm
  - QD = 24.6 cm

- Stength:
  - B' = 480 Gauss/in @ 2000A
Gamma-t Jump Modeling (cont...)
Power Supply Experiments at E4R

- Motivation: To make the existing RF system capable to accelerate more particles
- Experiment 1: Reduce the repetition rate from 15 Hz to 12 Hz
  - Test successful
  - But rejected by the Control Dept because of its large impact on the clock system
- Experiment 2: Dual harmonic resonant (15 Hz + 12.5% 30 Hz)
  - Purpose: To reduce the peak RF power by 25%
  - Design and fabrication of the 2nd harmonic choke is under way
Booster Cell with 2\textsuperscript{nd} Harmonic

Single harmonic

\[ L_m = 20.4 \text{ mH} \]
\[ L_{ch} = 40 \text{ mH} \]
\[ C = 8341 \ \mu\text{F} \]
\[ f_0 = 15 \text{ Hz} \]

Dual harmonic

\[ L_m = 20.4 \text{ mH} \]
\[ L_{ch} = 40 \text{ mH} \]
\[ C_1 = 6110 \ \mu\text{F} \]
\[ L_2 = 26 \text{ mH} \]
\[ C_2 = 1480 \ \mu\text{F} \]
\[ f_1 = 15 \text{ Hz} \]
\[ f_2 = 30 \text{ Hz} \]
Dual Harmonic Current and dI/dt
(3 cases: dual 0%, 9%, 18%; courtesy D. Wolff)
Two 2\textsuperscript{nd} Harmonic Choke Designs
(Courtesy V. Kashikhin)

\textbf{H-magnet type} \hspace{2cm} \textbf{Toroidal transformer type}
Summary

- Thanks to many people’s commitment and a good collaboration among several departments, divisions and universities, the Booster study is making steady progress.

- This study is making the Booster a better machine.
Questions?