Studies of Beam Intensity Effects in Fermilab Booster Synchrotron

Part II: Beam Emittance Evolution

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Detrimental beam dynamics effects limit performance of high intensity rapid cycling synchrotrons (RCS) such as the 8 GeV Fermilab Booster. Here we report the results of comprehensive studies of various beam intensity dependent effects in the Booster (aka Summer 2019 Booster beam studies campaign).

Part I covers the dependencies of the Booster beam intensity losses on the total number of protons per pulse and on key operational parameters such as the machine tunes and chromaticities.

In Part II we cross-check two methods of the beam emittance measurements (the multi-wires proportional chambers and the ionization profile monitors), analyze the intensity dependent emittance growth effects and discuss the ultimate performance of the machine now and after foreseen and proposed upgrades.

See APT Seminar 08/25/2020
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Part I Summary: Booster Losses

• Losses due to crossing the foil
  – ~1%, scale approx \((BT+29)/2\)

• Losses out of the “three bunch gap” in the linac beam, needed for clean extraction
  – About \(1.7 \pm 0.4\%\), weak dependence on intensity \(N\)

• Losses few ms after injection (capture, etc)
  – \(1\% + 7\% (N/6e12)^3\) - space-charge \((N,Q,Q')\)

• Losses at the transition energy (5.2 GeV)
  – Small \(<1\%)\) for \(N<4.6e12\)
  – Mb as high as \(O(10\%)\) at higher intensities if not tuned up

• Losses at extraction
  – Usually small \(O(0.1\%)\)
Vertical and horizontal MWs are installed in the extraction beam line

\( \beta_x = 16.2 \text{m}, \beta_y = 25.9 \text{m}, D_x = -1.65 \text{m} \)

(one measurement per cycle at best)
(readings supposed to be intensity independent)

There are 48 wires in each instrument, spaced by 1 mm.

Statistical rms error of the MW \textbf{rms norm} emittance measurement is about 0.05 mm mrad (out of ~2 mm mrad)

NB: here and in TM-2741 we always use \textbf{rms normalized} values, unless specifically mentioned otherwise
**Emittance at Extraction vs total proton intensity $N$**

- **Transverse rms beam emittance (mm mrad)**
  - $\varepsilon_{y, \text{extr}}$ [\(\pi\) mm mrad] \(\approx 1.7 + 1.20 \cdot \left(\frac{N_p}{6 \cdot 10^{12}}\right)^{4\pm0.3}\)
  - $\varepsilon_{x, \text{extr}}$ [\(\pi\) mm mrad] \(\approx 1.8 + 1.03 \cdot \left(\frac{N_p}{6 \cdot 10^{12}}\right)^{4\pm0.3}\)

- **Operational intensity**
  - 2 mm mrad
  - $rms\ norm = 12$ mm mrad
  - 95% norm
Ionization Profile Monitors: $V$ and $H$

$V=24$ kV
$D=103$ mm
40 strips
$\Delta=1.5$ mm

$\beta_x=6.0$ m, $\beta_y=20.8$ m, $D_x=-1.8$ m in Long 04

Once per turn
Intensity dependent
IPM signals
for 4 and 20 turns injection cycles

Note:

a) Noisier at 4 turns
b) H/V differences
   • 600/650 V
c) No saturation
d) Complex dynamics
IPM Principle of Operation

Electric field \( E_{\text{ext}} = \frac{V_0}{D} \)

Detector Signal

Detector

Electrons

Ions

\(+V_0\)
Step I: Ion is born

Step II: Ion gets out of beam in time $\tau_0$

$E_{ext} = \frac{V_0}{D}$

$V_y \sim \text{Force} \cdot \tau_0 = y_0 \left( \frac{N}{\sigma^2} \right) \cdot \sqrt{\sigma} \quad \tau_0 \sim 20\text{ns}$

Step III: Ion reaches MCP “ballistically” in time $\tau_2 \sim \left( \frac{d}{E_{ext}} \right)^{1/2}$

$\tau_2 \sim 100\text{ns}$

$y = y_0 + V_y \cdot \tau_2 = y_0 \left( 1 + \alpha \frac{N}{\sigma^{3/2}} \right)$

Electric field $E_{ext} = \frac{V_0}{D}$
Main Equation and Solutions – Uniform Beam

\[ d^2 y / dt^2 = \frac{1}{\tau_1^2} y \quad r < a \]
\[ d^2 y / dt^2 = \frac{1}{\tau_1^2} y \frac{a^2}{y^2 + x^2} \quad r > a \]
\[ x(t) = \frac{ZeE_{ext}}{2M} t^2 = \frac{ZeV_0}{2MD} t^2 \]

\[ y(t) = y_0 h(t) \]

\[ y(t) = y_0 \frac{t}{\tau_0} \left[ \text{ch}(\alpha)(\text{ch}(\tilde{\alpha}) - \frac{\text{sh}(\tilde{\alpha})}{\alpha}) + \text{sh}(\alpha)\text{sh}(\tilde{\alpha}) \right] \]
where \( \alpha = \tau_0 / \tau_1 \) and \( \tilde{\alpha} = \alpha(1 - \tau_0 / t) \)

\[ h(t = \tau_2) \approx 1 + \frac{4 \tau_2 \tau_0}{3 \tau_1^2} = 1 + \frac{16U_{SC}D}{3V_0a} \sqrt{\frac{d}{a}} \]

\[ U_{SC} = \frac{30I_p}{\beta_p} \approx [18.3 \, V] \frac{N_p}{6 \cdot 10^{12}} \]

Characteristic SC blowup time \( \sim 50 \, \text{ns} \)

Time to get out of beam \( \sim 20 \, \text{ns} \)

Time to reach MCP \( (d \approx 50 \, \text{mm}) \) \( \sim 100 \, \text{ns} \)
... if the beam consists of short bunches space by $t_b$, extra correction factor is applied:

$$y_{[1]}(t) = y_0 \cdot \left[ 1 + \frac{\tau_0^2}{\tau_1^2} \left( \frac{t}{3\tau_0} (\Gamma\left(\frac{1}{4}\right) - \Gamma\left(\frac{1}{4}, \frac{t^4}{\tau_0^4}\right)) - \frac{1}{2}\sqrt{\pi}\text{erf}\left(\frac{t^2}{\tau_0^2}\right) + \frac{\tau_0^2}{6t^2}(1 - \exp(-\frac{t^4}{\tau_0^4})) \right) \right]$$

$$\sigma_m = \sigma_0 \cdot h \approx \sigma_0 \cdot \left[ 1 + \frac{2U_{SC}}{E_{ext}\sigma_0} \left( \frac{\Gamma\left(\frac{1}{4}\right)}{3}\sqrt{\frac{d}{\sigma_0}} - \frac{\sqrt{\pi}}{2} \right) \right]$$

$$h = 1 + \frac{2U_{SC}}{E_{ext}\sigma_0} \left( \frac{\Gamma\left(\frac{1}{4}\right)}{3}\sqrt{\frac{d}{\sigma_0}} - \frac{\sqrt{\pi}}{2} \right) \cdot \left[ 1 + \frac{t_b}{\tau_0} \right]$$

$\Gamma\left(\frac{1}{4}\right) \approx 3.625$
That’s not All: “Zero Intensity” Correction

There are also intensity independent effects leading to the IPM profile smearing:

a) the initial velocities of the ions;
b) IPM charge collection strips distance 1.5 mm;
c) angular misalignment of the IPM long and narrow strips with respect to the high energy proton beam orbit;
d) charging of dielectric material in between the strips or strip-to-stripe capacitive cross talk;
e) non-uniformity of the extraction electric field in the operational IPM aperture….

They all add in quadrature… eg, initial kinetic energy $E_i$ results in

$$\sigma_m^2 = \sigma_0^2 h^2 (U_{SC}, \sigma_0, E_{ext}, d) + \left( \frac{4E_i d}{ZeE_{ext}} \right)$$
Let’s start with the latter effect: MW vs IPM at $N=0$.
Same “Smearing” Effect in Horiz and Vert IPMs

\[ \sigma^2_{IPM} - \sigma^2_{MW} (\text{mm}^2) \]

\[ \sigma^2_T = 2.8 \pm 0.1 \text{ mm}^2 \]
Vertical mean squared IPM size $\sigma^*$ as measured at extraction ($V=24$ kV, $D=103$ mm, black squares) vs the total proton beam intensity $N_p$. The theoretical prediction of Eq.(3) (with $d=D/2=52$ mm, red line) is calculated using the initial beam sizes $\sigma_0$ as measured by the Multi-Wires monitor (blue line). The measured IPM rms sizes $\sigma_{m,IPM}^2$ are corrected for the intensity independent smearing as $\sigma^* = \left(\sigma_{m,IPM}^2(N_p) - \sigma^2_T\right)^{1/2}$ with $\sigma_T^2=2.7$ mm$^2$. 
Finding the Original $\sigma_0$ from the IPM $\sigma_m$

Comparison of the vertical (left) and horizontal (right) rms beam sizes at extraction for a range of total proton beam intensities $N_p$. Red and blue dots are as measured by MWs and recalculated for the IPM location. Black squares with error bars are for the rms beam sizes reconstructed from the IPM data correction for $\sigma^2_T$ and for the space-charge expansion $h(N_p, V, D, d )$

$$\sigma_0 \approx \frac{\sigma^*}{\left(1+\left(\frac{\frac{c}{\sigma^*}}{\frac{3}{2}}\right)\left(1+\alpha\frac{c^2}{\sigma^*}\right)\right)}$$
Apply the Method to the Entire Booster Cycle

![Graph showing vertical rms beam size (σ_mm) vs. turn number. The graph compares raw IPM data, data corrected for σ_r, and data corrected for SC and σ_r. The y-axis represents vertical rms beam size in millimeters (σ_mm), and the x-axis represents turn number. The graph includes three lines: red for raw IPM data, black with a dashed line for data corrected for σ_r, and blue with a dashed line for data corrected for SC and σ_r. The data shows a decrease in vertical rms beam size as the turn number increases, with the corrected data lines showing a smaller decrease compared to the raw data.]
1) Obits move while the space-charge expansion depends on the distance $d$ from the beam orbit to the IPM collection plate. $O(10\%)$

2) Beta-functions at the IPM locations vary in the cycle – see Fig. – as well as the space-charge forces which somewhat distort the optical focusing lattice functions $O(10\%)$

3) Bunching varies (smaller effect) $O(5\%)$
Method: Assume no Emittance growth at $N=0$

Vertical rms proton beam size and emittance at low intensity $N_p=0.5 \times 10^{12}$: black – raw IPM data; green – 100 turn window average of the raw IPM data; pink and white – vertical rms normalized emittances calculated from the raw IPM data, blue and red – same, but corrected for intensity independent smearing; brown – same with additional fudge factor $G(t)$.

$$G(t)=1/(1+0.14 \cdot t/T +0.018 \cdot (1-T/2)^2/(T/2)^2)$$
Emittance Arguments to Account for $\beta$–function Variations

1) to avoid appearance of emittance growth at low intensity (2 turns injection)
2) to avoid decrease of emittance in the cycle
3) still to be matched to MW sizes at extraction

\[ F(t) = (0.86 + 0.14 \frac{t}{T} + 0.18 \times 4 \times (1 - \frac{t - T}{2})^2 \times \frac{1}{T^2}) \]
Emittance in Cycle (With All the Corrections In)

Vertical emittance at $N_p = 4.6 \cdot 10^{12}$

![Graph showing emittance over turn number](image-url)
Space-Charge Tune Shift Parameter $dQ_{SC} \sim N B_i / \varepsilon \beta \gamma^2$

at nominal intensity $N_p = 4.5e12$

For measured bunch length and beam emittances

Shaded area for beam emittances $2\pi$ to $3\pi$
Emittance Evolution at Various Intensities $N$
Emittance Increase over 0-3000 turns

averaged over five hundred turns 3000-3500 minus averaged over 0-500

Presumably due to space-charge effects
Emittance Increase over 3000-19000 turns

averaged over five hundred turns 19000-19500 minus averaged over 3000-35000

WHY?

1) Incoherent noise excitation? Multi-pacting/e-cloud?
2) Coherent effect?
3) Instrumental?
Can IPM/MW info shed extra light on the Booster losses?

Losses depend on apertures, beam sizes and orbit position

Figure 16: Cross Sectional View of a "F" magnet (left) and a "D" magnet [5] overlapped by apertures of some typical Booster elements implying possible aperture restrictions on the beam: a) RF-cavities (Diam. 2.25"); b) regular beam pipes (Diam. 3.25"); c) corrector package (Diam. 4.5"); d) special aperture in short straight 12 (Diam. 5.23" shifted horizontally by 2 cm outwards); e) 0.5 meter pipes between F and magnets (Diam. 6.00"); f) flanges of combined-function magnets (Diam. 7.25") – from Ref. [6].
Beam sizes over the Booster cycle

Losses depend on apertures, beam sizes and orbit position

Figure 15: Vertical and horizontal rms IPM beam sizes’ evolution over the Booster cycle at \( N_p = 6.2 \times 10^{12} \) (raw data – black line).
Losses depend on apertures, beam sizes and orbit position.

![Table I: Booster beam sizes and half-apertures without collimators.](image)

@ **injection**: losses on vertical aperture

@ **transition**: losses on horizontal aperture
How do losses affect IPM profiles (1)

at $N_p=6.2\cdot10^{12}$ (uncorrected, raw IPM data)
How do losses affect IPM profiles (2)

at $N_p = 6.2 \cdot 10^{12}$ (uncorrected, raw IPM data)

Why?

Nonlinear optics?
Nonlinear IPM?
Coherent motion?
IPM Profiles at Transition

NB: raw data (upper curves V, H), corrected data (lower); peak at turn #9664
IPM Profiles Before-At-After #9664

NB: skewed H peak at turn #9664
Part II Summary: Booster Emittances

• Linac $H$-beam comes with small emittance
  - ~$0.7-1\,\pi \text{ mm mrad}$ (i.e., up to 6 pi “95%”)

• Scattering while crossing the foil
  - $+(0.2_H - 0.6_V)\,\pi \text{ mm mrad}$, scales approx $(BT+29)/2$

• Growth few ms after injection
  - $\Delta \varepsilon_{y,3000} \approx 0.2 + 0.4 \cdot (N_p/6 \times 10^{12})^2$ … space-charge ($N,Q'$)

• “Steady” growth thru the rest of the cycle
  - $\Delta \varepsilon_{y,3000-19000} \approx 0.97 \cdot (N_p/6 \times 10^{12})^3$ … why?
  - there other minor features $O(0.2\,\pi)$ – mb instrumental?

• All that results in $(MW/IPM)$ extraction values of
  - $\varepsilon_{y,\text{extr}} [\pi \text{ mm mrad}] \approx 1.7 + 1.20 \cdot (N_p/6 \times 10^{12})^4 \pm 0.3$
  - $\varepsilon_{x,\text{extr}} [\pi \text{ mm mrad}] \approx 1.8 + 1.03 \cdot (N_p/6 \times 10^{12})^4 \pm 0.3$
Booster *Ionization Profile Monitors* are extremely valuable tools for fast beam size diagnostics:

- operate in the ion collection mode without external magnetic field
- there are strong systematic space-charge effects in the IPMs leading to significant, factor of 2 or more, expansion of the rms beam size reported by the IPMs w.r.t. to the original proton beam size.

We accounted these effects following theoretical recipes arXiv:2003.09072

- Resulting in acceptable systematic error $O(10\text{-}20\%)$
- Corrections can be/should be implemented online
- Some subtle effects, e.g. those due to variable bunching factor need further exploration and experimental studies, e.g.
Vertical mean squared beam size as reported by the Booster IPM with voltages $V=12$, 18 and 24 kV at nominal $N_p = 4.5 \cdot 10^{12}$, red and blue dots – MW and 24 kV IPM data taken in 2019 S09

**Theory scaling:**

$$h \sim \left( \frac{2U_{sc} D}{\sigma_0 V} \right) \left[ \frac{\Gamma(1/4)}{3} \left( \frac{d}{\sigma_0} \right)^{1/2} - \frac{\sqrt{\pi}}{2} \right]$$

Data courtesy V. Kapin
Seminar #2 : Discussion/Conclusions (2)

• Further IPM studies/improvements:
  – the differential IPM profile measurements at several values of $V$ may allow to estimate the actual proton beam size $\sigma_0$ as approximation for $V$ going to infinity using theory Eq.
  – arrival times from the beam to the MCP plate depend on the ion species $\tau_0 = (2MD\sigma_0/ZeV)^{1/2}$ - so, IPM signals at ~10ns resolution can allow quantitative analysis of the Booster vacuum

• Beam effects to study further
  – *Origin of the “steady emittance growth” over the cycle*
    • Exclude instrumental explanation
    • See signs of e-cloud (simulate Booster …like RR/MI)
    • Special tests with extra gap in the Booster beam
    • Detect coherent motion (why there is no instability?)
  – *Why IPM profiles are skewed at the times of losses?*
Thank You for Your Attention!

(Also Angela, David, Jon, and many key Fermilab participants.)
Backup Slides and Slides from Seminar #1