About Early Beam Loss in the Booster

W. Chou, February 13, 2003

From what we know now, we may have a coherent picture to explain the beam loss observed at the early stage of the cycle (0-3 ms, about 30% loss) when the Booster operates at high intensities.

- Longitudinal loss:
  - The Booster momentum acceptance is small (~ ±0.15-0.2%). It is about the same as the linac beam momentum spread (±0.13%).
  - When the RF is up and the beam is being bunched, the momentum spread will increase and exceeds the acceptance, resulting in loss.

- Transverse loss:
  - The good field region of the magnets is small (~ ±1 inch).
  - Due to edge focusing of the orbit bumps and doglegs, the beta-functions and dispersion are larger than the design value. This reduces the maximum allowable beam emittance to about only ~8 π, while the linac beam emittance is about 7 π.
  - The situation is worsened by the space charge. It blows up the emittance during multi-turn injection. The beam is scraped transversely, resulting in loss.

- The situation improves rapidly when energy $E\uparrow$:
  - Longitudinal:
    - $\Delta E/E \downarrow$
    - $1/\beta^2 \downarrow$
    - $\Delta p/p = (1/\beta^2) \times \Delta E/E \downarrow\downarrow$
  - Transverse:
    - Dogleg focusing strength: $1/f = \theta^2 / 2L \propto 1/p^2 \downarrow\downarrow$
    - Beam size due to adiabatic damping: $\varepsilon = \varepsilon_N/\beta\gamma \downarrow$
    - Space charge effect $\propto 1/\beta\gamma^2 \downarrow\downarrow$
  - Therefore, the acceptance limit will be lifted when energy goes up.
  - The loss in the middle and late stage of the cycle is due to some other mechanisms (transition crossing, head-tail instability, coupled bunch instability, etc.).

- Fast and slow loss:
  - When the acceptance limit comes from physical aperture, the loss is instantaneous.
  - When it comes from dynamic aperture (poor field quality), the loss is slow.

- Additional info needed in this study:
  - Measurement - Transverse acceptance at 24 long and 24 short straights (first need to remove the r.m.s. current limit of the steering magnets)
  - Simulation - Dynamic aperture tracking with body and chromaticity sextupoles
  - Simulation - ESME for dynamic process with RF on (moving bucket)

- Possible measures to reduce losses:
  - To enlarge aperture:
    - RF: from 2-1/4 inch to 5 inch (an action item)
    - Kicker: (?)
  - To compensate dogleg effects:
    - Increase distances between doglegs (Sasha)
    - Relocate DOG13 (global correction) (Weiren)
    - Local correction using wedge magnets (Weiren)
    - Local correction using quads (Chuck, Weiren)
    - Correction using solenoid? (Francois)
  - To reduce space charge effects:
    - Painting
      - Using falling side of the orbit bump pulse
      - Using falling or rising side of $B(t)$
    - Trade-off between linac current and injection turns
    - Install inductive inserts (an action item)
    - Install a 2nd harmonic RF system (expensive!)
  - To chop the beam at 38 MHz:
    - Laser chopping at 750 keV (Ray, Xi)

Longitudinal Calculation before and after Bunching

- Before bunching:

  Beam momentum spread:

  $\Delta p/p = \pm 0.13\%$ (measured)

  Beam energy spread:

  $\Delta E/E = \beta^2 \times \Delta p/p = \pm 0.066\%$ ($\beta = 0.713$)

  $E = 1.338$ GeV

  $\Delta E = 1.77$ MeV $= \pm 0.88$ MeV

  Beam length (1/84 of the circumference):

  $L_b = 26.4$ ns

  Beam emittance (1/84 of the total injected beam):

  $\varepsilon_L = \Delta E \times L_b = 0.047$ eV-s

- After bunching:

RF voltage:	$V_{rf} = 800$ kV (console RF curve)
RF frequency:	$f_{rf} = 37.87$ MHz
Revolution frequency:	$f_0 = 450.8$ kHz
Harmonic number:	$h = 84$
Average machine radius:	$R = 75.47$ m
Slip factor:	$\eta = 0.458$
Bunch emittance:	$\varepsilon_L = 0.047$ eV-s

  (assuming no blowup during rf capture!)

Bunch length:

$$L_b = \{\beta\, \varepsilon_L\, c^2 / f_0\}^{1/2} \times \{\eta / 2\pi h E V_{rf}\}^{1/4}$$
$$= 11.5 \text{ ns}$$

Bunch enerygy spread:

$$\Delta E = 4.1 \text{ MeV} = \pm 2.05 \text{ MeV}$$
$$\Delta E/E = \pm 0.15\%$$

Bunch momentum spread:

$$\Delta p/p = (1/\beta^2) \times \Delta E/E = \pm 0.3\%$$

→ More than a factor of 2 increase in Δp/p due to bunching (even without assuming any emittance dilution). This value exceeds the momentum acceptance of the Booster (~ ±0.15-0.2%), resulting in beam loss.

- Bonus results:

Bucket area:

$$A_{rf} = (8R/c)\, \{2EV_{rf} / \pi h^3 \eta\}^{1/2} = 0.1 \text{ eV-s}$$

Bucket height:

$$H_{rf} = \pm A_{rf} \times 2\pi f_{rf} / 8 = \pm 3 \text{ MeV}$$

Synchrotron tune:

$$\nu_s = f_s / f_0 = \{h \eta V_{rf} / 2\pi\, \beta^2 E\}^{1/2} = 0.085$$

Synchrotron period:

$$1/\nu_s = 12 \text{ turns}$$

i.e., 3 turns for 1/4 rotation.

Transverse Calculation

- Acceptance is reduced due to orbit bumps and doglegs:

  $$A = \{\beta_{max} \times \varepsilon_N/\beta\gamma\}^{-1/2} + D_{max} \times \Delta p/p + \text{c.o.d.}$$

  At injection (400 MeV):

  Good field region (horizontal) = ± 1.2 inch (TM-405)
  $\beta\gamma = 1.0$
  $\Delta p/p = \pm 0.13\%$ (measured)
  c.o.d. = closed orbit distortion = 3 mm (optimal)

  Without orbit bumps and doglegs:

  $\beta(x)_{max} = 33.7$ m, $D_{max} = 3.19$ m
  Max allowable beam emittance: $\varepsilon_N(x) = 16\ \pi$ mm-mrad

  With orbit bumps and doglegs:

  $\beta(x)_{max} = 48.7$ m, $D_{max} = 6.84$ m
  Max allowable beam emittance: $\varepsilon_N(x) = 8\ \pi$ mm-mrad
  → a factor of 2 reduction in acceptance due to large β and D!

- Beam emittance is increased during multi-turn injection due to space charge:
  - Linac beam emittance is about 7 π (Elliott, PD2 report, Ch. 8)
  - At 43 mA × 10 turns, the emittance is blown up by about 50% (Ray's IPM data)

- Put these two effects together, the beam is scraped in transverse plane, resulting in beam loss.