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Improving the Fermilab Booster Emittance*

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IMPROVING THE FERMILAB BOOSTER EMITTANCE

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Abstract

Demand of high luminosity in the Tevatron collider in Fermilab makes the small beam emittance coming out of the 8 GeV Booster a highly desirable feature. This is because Booster bunches with small emittance, when eventually coalesced into Main Ring bunches, will ensure a high luminosity in the collider. Efforts have been made to identify factors limiting the phase space density in both transverse and longitudinal dimensions. The experimental result points to space charge induced tune spread at low energy as the main factor limiting the transverse phase space density, and the space charge induced phase space dilution at transition and longitudinal coupled bunch instability as the factors limiting the longitudinal phase space density. To counteract these factors, a set of harmonic correction sextupoles and skew sextupoles were implemented to reduce the third order resonances in the transverse case. In the longitudinal case a γ_t-jump system was implemented to ease the bunch tumbling after transition, and various schemes to damp the longitudinal coupled bunch instability are either implemented or being reviewed. Future plans and efforts will be mentioned briefly at the end of this article.

Injection into the Fermilab Booster

The Fermilab Booster operates at a cycling rate of 15 Hz. H^- ions are injected at a kinetic energy of 204 MeV from the Linac. They merge with the circulating protons injected in previous turns at a straight section before entering the Booster in an attempt to increase the phase space density. The excessive electrons are stripped at a carbon foil before the beam is deflected into the Booster ring. This practice has been observed to improve the overall beam intensity transferred to the Main ring considerably compared to direct proton injection from the Linac. Relevant parameters of the Fermilab Booster are listed in Table 1. For a more detailed account, see reference [1].

Limitation on the phase space density

a. Transverse phase space

In this article the transverse emittance ϵ will be understood as the normalized emittance encompassing 95% of the beam. The limitation on the transverse phase space density is set mainly by the space charge induced tune spread after injection. In the absence of momentum spread, this is governed by

$$\Delta\nu = \frac{3rN}{2B\epsilon\beta\gamma^2} \quad (1)$$

where N is the total number of protons in the accelerator, r is the classical radius of the proton (1.5×10^{-18} meter), B is the bunching factor ,ϵ is the normalized 95% emittance and $\beta\gamma^2$ is the relativistic factor. Experimental evidence supports this relation between Booster emittance limit and the other parameters in (1). Figures 1,2 and 3 show the measured transverse emittances and momentum spread vs. total beam intensity as deduced from multiwire profiles taken on the Booster beam when it is being transferred to the Main ring at 8 GeV. The transverse emittances as shown display the following behavior

$$\begin{aligned} \epsilon_x/\pi &= \max(9.0, 6.0 \times (N_p - 0.6)) \\ \epsilon_y/\pi &= \max(7.0, 6.0 \times N_p) \end{aligned} \quad (2)$$

In the above, ϵ/π is in mm-mrad and N_p is in 10^{12} protons for the whole machine. The fact that we are able to parametrize as in (2) strongly suggests that the transverse emittance is limited by N_p as in (1) above a certain threshold value of N_p. Below this threshold value the Booster transverse emittance has to be limited from below by that coming in from the Linac. The limitations on the transverse emittance set by the other factors in (1), namely $\beta\gamma^2$ and B, have been qualitatively established too. Flying wire measurements of the circulating beam size indicates that within its resolution of about 2 msec the high intensity transverse beam blowup happens at injection when $\beta\gamma^2$ is the lowest. The bunching factor in fact also decreases rapidly at the beginning of the Booster cycle leading to increase in $\Delta\nu$ in (1). The competition between the decreasing bunching factor and the increasing relativistic factor is actually reflected in the Booster beam intensity decay in the beginning of the cycle. Finally resonance scans which track the second and third order resonances show a correlation between the widths of these resonances and both the intensity and the bunching factor consistent with (1). The dashed lines of Figures 1 and 2 are actually contours of constant $\Delta\nu$ described by (1). They correspond to a space charge induced tune spread of 0.37. The dashed line in the horizontal plot does not pass through the origin because in the actual measurement non-zero momentum spread contributes to the horizontal beam size too.

b. Longitudinal phase space

If we translate the momentum spread in Figure 3 into longitudinal bunch area, we get a relation

$$\epsilon_L = 0.05 + 0.028N_p^2 \quad (3)$$

ϵ_L is in eV-sec and N_p again in 10^{12} protons in the whole machine. This relation is good from low intensity up to about 3.6×10^{10} protons/bunch (3×10^{12} total). The longitudinal phase space density is mainly limited by two adverse effects: The longitudinal space charge force causes a mismatch into the bucket after transition, resulting in bunch tumbling and phase space dilution. Coupled bunch instability driven by parasitic modes in the RF cavities aggravates the situation. The threshold for this instability is about 10^{12} circulating protons. Figure 4 shows a "mountain range" picture of one bunch taken from 24 ms to 25 ms into the cycle (transition time is about 19.5 ms). This shows a combination of dipole oscillation mainly due to the coupled bunch instability, and a quadrupole oscillation due to the space charge induced bunch tumbling. The coupled bunch mode 16 (at ~115 MHz $\cong (f_0 \cdot (2 + 16/h))$, where f_0=52.5 MHz is the RF frequency at crossing and h=84 is the harmonic number) is identified as the major contributor to the longitudinal coupled bunch instability. Figure 5 shows another mountain range picture taken under the same condition as Figure 4 but with the γ_t-jump system turned on. The dipole mode of the longitudinal coupled bunch instability is more pronounced. The beam spectrum is shown in Figure 6 when the instability is present.

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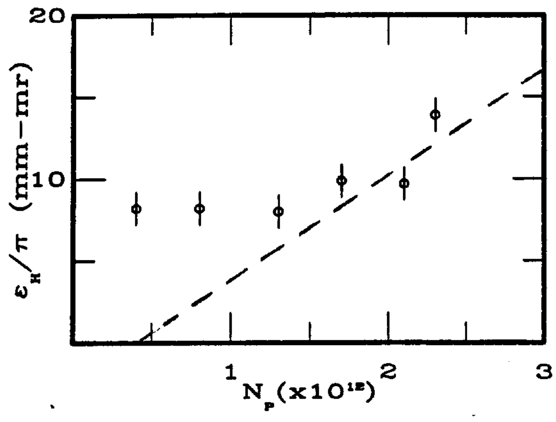

Figure 1: Normalized 95% horizontal emittance at 8 GeV vs. Booster beam intensity

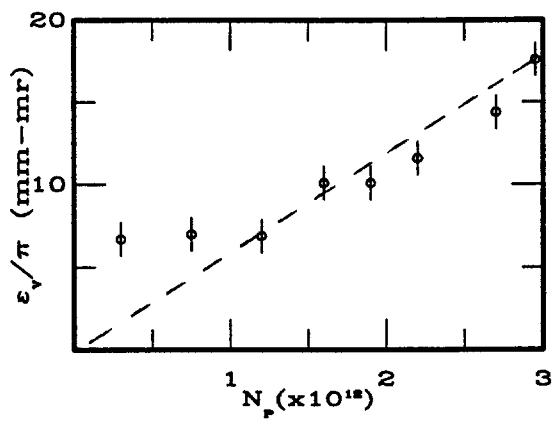

Figure 2: Normalized 95% vertical emittance at 8 GeV vs. Booster beam intensity

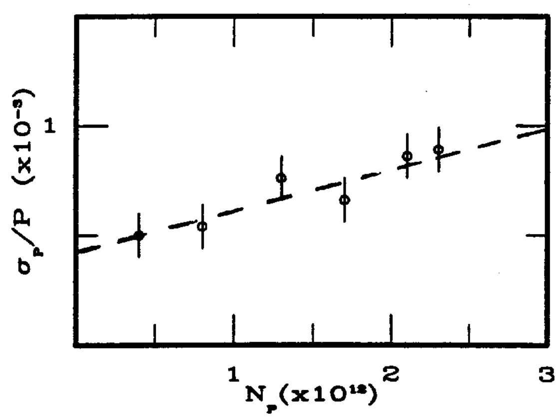

Figure 3: Momentum spread at 8 GeV vs. Booster beam intensity. The above three figures reflect data obtained from the 8 GeV transfer line multiwire measurements. The transverse rms beam size σ is related to the transverse emittance ϵ via $\sigma^2 = (\epsilon\beta_L/6\pi\beta\gamma)$ when momentum spread is neglected. β_L is the lattice beta function and $\beta\gamma$ is the relativistic factor

The first peak to the right of the second RF harmonic line corresponds to the 115 MHz mode 16. Further measurements with higher resolution in the frequency domain have determined this to be dominantly a dipole mode.

Current status and improvements

a. Transverse

A set of harmonic correction sextupoles (2 normal and 2 skew) has been installed to counteract the natural third order resonance driving force in the Booster. The excitations of these sextupoles are adjusted empirically to best reduce the beam loss due to resonance early in the cycle. Figures 7 and 8 show the resonance scan of beam intensity vs. correction quadrupole excitation, which can be translated into tune values, at 1.5 ms after injection with and without the harmonic correction sextupoles turned on. It is clear that the loss in Figure 7 due to a third order driving term is considerably reduced by the harmonic correction sextupole. The phase space density is estimated to improve by 5% with this system.

b. Longitudinal

We already saw in Figures 4 and 5 the reduction in bunch tumbling with the γ_t-jump system. This system consists of 12 pulsed quadrupole magnets of alternating polarity[2], capable of changing the value of γ_t by one unit in 100 μsec. For comparison, The normal transition crossing rate is $d\gamma/dt = 0.406$/msec near transition. The adverse effects, mainly bunch dilution, are in a large part avoided through this system. The consequent reduction in the longitudinal emittance after transition resulted in more pronounced longitudinal coupled bunch instability when the major resonance crossings occur. This is being handled by both resistive dampers installed in each RF cavity and an active longitudinal damper aimed at reducing overall longitudinal dipole oscillations. The resistive dampers are observed to reduce specific modes including mode 16. The active damper is effective in responding to longitudinal dipole modes and reducing its amplitude. But towards the end of the cycle the instability displays gradually more quadrupole motion in the bunch and becomes more immune to the active damper. So far the combination of γ_t-jump and the dampers gives us the best beam quality in the longitudinal dimension.

Further improvements

a. Transverse

i) The completion of Fermilab Linac upgrade expected in 1992 will see increased injection energy at 400 MeV into the Booster (presently at 200 MeV). This should improve the phase space density by a factor of 1.75, with perhaps twice as much total beam delivered.

ii) A plan to pulse the existing group of chromaticity correcting sextupoles individually as a harmonic correction system is being studied.

b. Longitudinal

i) Study is being carried out on the feasibility of implementing a higher RF harmonic (Landau) cavity[3] to introduce greater intrabunch tune spread to discourage growth of instability.

ii) Experiments have been done on running two RF cavities at the harmonic number 77, which is 7 below the normal harmonic number of 84, in order to introduce interbunch tune spread. The effect is visible but not conclusive. More effort will be devoted to addressing this possibility.

iii) The possibility of doubling the active damper voltage is being considered.

iv) We are also considering upgrading the Booster cavity to double the voltage and thereby eliminating half of them.

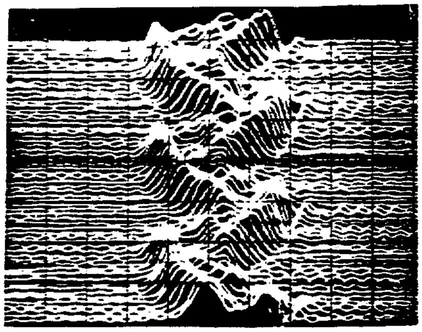

Figure 4: Mountain range plots of the booster single bunch profile. This is taken from 24 msec to 25 msec. The γ_t-jump system is off

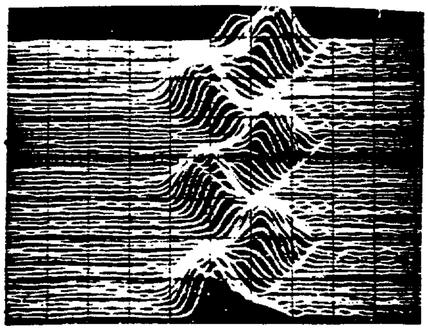

Figure 5: Same picture as Figure 4 except that the γ_t-jump system is turned on. The coupled bunch mode seen here is mode 16

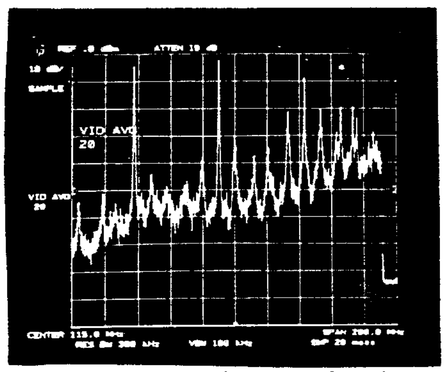

Figure 6: Spectrum of the Booster beam signal at a longitudinal pickup showing modes corresponding to longitudinal coupled bunch instability.

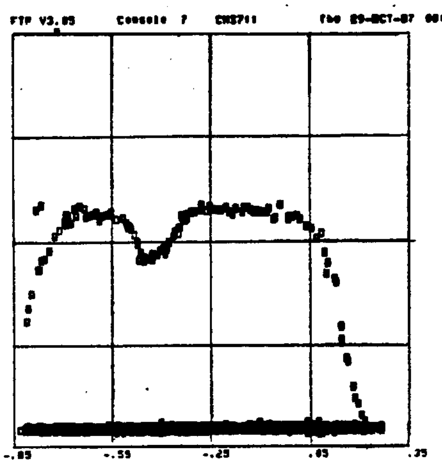

Figure 7: A plot of the Booster beam intensity near injection vs. the excitation of the correction quadrupoles. This plot indicates that the beam is suffering from a harmonic resonance.

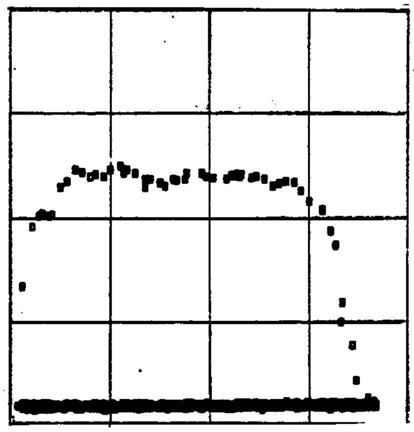

Figure 8: The beam loss in Figure 7 is neutralized by the correction sextupole, showing it was a 3rd. order resonance.

References

1. E. Hubbard et al., "Booster Synchrotron", Fermilab Technical Memo TM-405, (1973)

C. Ankenbrandt and S. Holmes, 1987 IEEE Particle Accelerator Conference Proceedings Vol.2, p1066

C. Ankenbrandt et al., Proceedings of the 11th International High Energy Accelerators, 1980, p260

2. W. Merz et al., 1987 IEEE Particle Accelerator Conference Proceedings Vol.2, p1343

3. Y. Chao and K.-Y. Ng, Fermilab Physics Note FN-470, also these Proceedings.

S.Stahl and S. Bogacz, Fermilab Physics Note FN-460

Injection Energy (Kinetic)	204 MeV
Extraction Energy (Kinetic)	8 GeV
Circumference	474.20 meters
Cycle Rate	15 Hz
Number of Bunches	84
RF harmonic number	84
Max. Beam Intensity	3×10^{12}
Horz. Tune ν_x	6.7
Vert. Tune ν_y	6.8
Transition Gamma γ_t	5.4
RF frequency(Inj.)	30.31 MHz
RF frequency(Ext.)	52.81 MHz
RF voltage (Maximum)	950 KV

Table 1: Booster parameters