EFFECTS OF SPACE CHARGE AND MAGNET NONLINEARITIES ON BEAM DYNAMICS IN THE FERMILAB BOOSTER*

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Abstract

Presently the Fermilab Booster can accommodate about half the maximum proton beam intensity which the Linac can deliver. One of the limitations is related to large vertical tuneshift produced by space-charge forces at injection energy. In the present report we study the nonlinear beam dynamics in the presence of space charge and magnet imperfections and analyze the possibility of space charge compensation with electron lenses.

INTRODUCTION

To achieve the Fermilab Accelerator Division Proton Plan goal [1] the number of protons from the Booster should reach 5.25×10^{12} per batch of 81 bunches - almost twice the present number. One of the major obstacles on the road to this goal is the transverse space charge effect at injection leading to fast emittance blowup during bunching. The bunching takes about 200 turns causing fast build-up of the transverse space charge tuneshift which is difficult to compensate with conventional magnets, therefore it was proposed to use electron lenses for this purpose [2]. The objective of this report is to study the feasibility of space charge compensation with electron lenses and fast quadrupoles. There is a number of programs for the space charge simulations; however, for the initial evaluation we decided to use MAD [3] since it has various tools for nonlinear dynamic analysis. Though limited to 2D space charge simulation, MAD allows study of its joint effect with magnet nonlinearities and optics perturbations. It will be shown that with a small number of electron lenses (1-2) which can be installed in the Booster the space charge compensation produces an adverse effect on particle dynamics. Another possibility considered in this report is shifting the horizontal tune with the help of fast γ-transition quadrupoles so as to avoid crossing half-integer stopband during bunching. This attempt gave promising yet inconclusive results.

BOOSTER LATTICE

Fig. 1 shows optics functions in the Booster lattice. The lattice consists of 24 FOFDOOD cells with combined function magnets. During injection the orbit is displaced onto the stripping foil with fast orbit bump magnets which have strong nonlinear field components and adversely affect particle dynamics. In simulations we use measured multipoles up to the 14th-pole. We assume the orbit bump magnets current to be linearly switched off in 30 turns after injection.

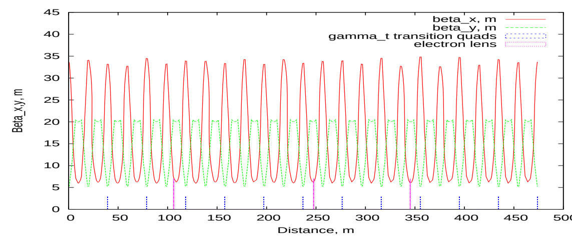

Figure 1: Booster lattice.

After completion of the multi-turn injection the RF voltage is turned on capturing the protons into 84 bunches of which 3 bunches are kicked out to create a gap for extraction. The charge density increase during the bunching is shown in Fig. 2.

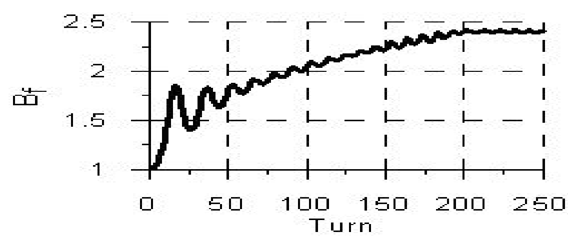

Figure 2: Bunching factor.

The Booster bare lattice tunes are close to $Q_x \approx$6.75, $Q_y \approx$6.85. In the ideal lattice the space charge gradient of a matched beam has the same 24-fold periodicity so it practically can not excite resonances of order lower than 7. The real situation is quite different due to random optics perturbations. They were simulated by gradient errors with r.m.s. spread $\sigma_{K1}/K1 = 5\times10^{-4}$ distributed in accordance with the Gauss law. The phase advance errors corresponding to a particular seed of distribution used in simulations is shown in Fig. 3.

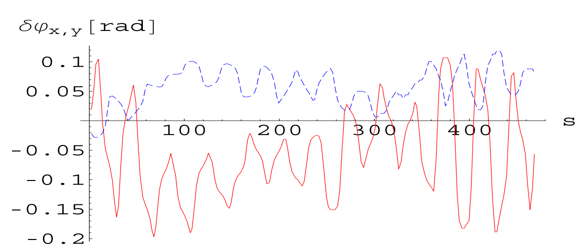

Figure 3: Horizontal (red) and vertical (dashed blue) random phase advance errors used in simulations vs distance from HP24S monitor.

We also take into account the nonlinearities in regular magnets but their effect is small compared to the effect of the space charge and the orbit bump magnets nonlinearities.

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SPACE CHARGE SIMULATIONS WITH MAD

Though there is no special option in MAD for the space charge calculation, it can be modeled with a number (up to 200 in MAD8) of BEAMBEAM elements with Gaussian transverse profile. In order to represent the space charge kick accumulated over distance L_k the number of particles N_k in a fictitious colliding beam must be set as:

$$N_k = B_f \frac{N \cdot L_k}{C \cdot (\gamma^2 - 1)} \quad (1)$$

where $B_f > 1$ is the bunching factor (see Fig. 2), N is the total number of particles in the beam, C=474.2 m is the machine circumference, γ is the relativistic mass factor ($\gamma \approx 1.43$ at injection). Also, the beam sizes should be specified for the BEAMBEAM elements which are not known in advance exactly since the space charge modifies optics functions. They can be found by iterative procedure, we use Mathematica to run MAD and recompute the beam sizes at each iteration. Fig. 4 shows tunes found with this method as functions of the space charge parameter

$$\xi_{SC} = \frac{B_f \cdot r_p \cdot N}{4\pi \cdot \epsilon_\perp \cdot \beta^2 \cdot \gamma^3} \quad (2)$$

where $r_p = 1.5 \times 10^{-18}$m is the proton classical radius, $\varepsilon_\perp$ is the r.m.s. transverse emittance. Eq.(2) gives the tuneshift in a round beam with no momentum spread. For calculations shown in Fig. 4 the relative momentum spread was set at $\sigma_p = 0.001$ which is the final value after bunching.

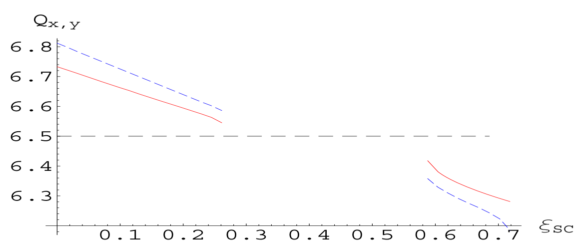

Figure 4: Horizontal (red) and vertical (dashed blue) tunes vs space charge parameter.

Table 1: Initial beam parameters.

Number of protons	5×10^{12}
Kinetic energy, MeV	400
R.m.s. emittance, mm·mrad	1.28
Momentum spread,%	0.0275

The equilibrium solution does not exist at some beam intensities: there is a wide gap corresponding to the stopband of the half-integer resonance. For initial beam parameters shown Table 1 the final value is $\xi_{SC} = 0.8$. The question arises what will happen with the beam when ξ_{SC} crosses the half-integer stopband during bunching. To answer this question we performed tracking simulations using the following simplified scheme using Mathematica and MAD in the master-slave mode: - find stationary self-consistent solution for optics with initial ξ_{SC}, store these optics functions for emittance and beam size calculations during tracking (there is no stable optics when ξ_{SC} crosses the stopband); - after each turn calculate of the action variables from particle positions and momenta at the observation point (end of the lattice) using the initial optics functions; - find transverse emittances by fitting the obtained distribution in the action variables with Gaussian distribution (exponential in the action variables); - calculate the beam sizes from thus found emittances and initial optics functions; - track particles next turn with the BEAMBEAM element sizes found from the previous turn and the intensity corresponding to current value of the bunching factor. Fig. 5. shows emittance growth with initial beam parameters from Table 1 with and without random optics perturbations discussed in the previous section. One can see that even moderate perturbations cause fast emittance blowup. It should be noted that at twice smaller N (present Booster operation) there is no appreciable emittance growth even in presence of perturbations.

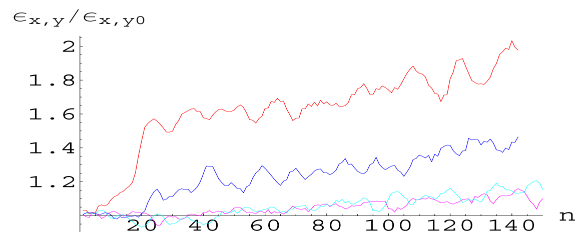

Figure 5: Horizontal and vertical emittance vs. turn number at nominal beam intensity with (red and blue) and without (magenta and cyan) random optics errors.

MITIGATION OF THE SPACE CHARGE EFFECT

Space Charge Compensation with Electron Lenses

There are several reasons making the electron lenses extremely attractive, among them: - electron current can be varied fast to follow the bunch peak current during bunching - electron lenses with sufficiently small beam size reduce not only the tuneshift but tunespread as well. Unfortunately there is few free regions in the Booster where the electron lenses can be installed. At all these locations the horizontal beta-function is much smaller than the vertical one ($\beta_x \approx 6m$, $\beta_y \approx 21m$) so that only the vertical tuneshift can be effectively compensated. To avoid strong horizontal emittance blowup seen in Fig. 5 the lattice tunes can be flipped so that the horizontal tune reach the half-integer later. The first attempt was to use just one electron lense with the current repeating the bunching factor time dependence (Fig. 2) and providing 50% tuneshift compensation. The electron beam size of 7mm was chosen to be sufficiently close to the initial vertical beam size of 5mm in order to provide the footprint compression as well. This attempt resulted in almost total loss of the beam (see Fig.

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6), supposedly due to strong beta-beat excited by the lens.

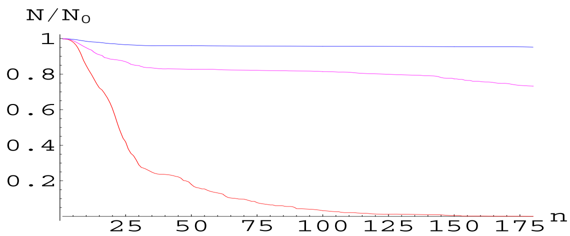

Figure 6: Intensity vs. turn number without SC compensation (blue), with one (red) and two (magenta) electron lenses.

It is possible to reduce the beta-beat by using two electron lenses $\pi/2$ apart in the betatron phase. Two lenses were installed 238.6m apart (which is close to C/2=237.1m): one 4.3m upstream the HP06L monitor and the other 2.85m upstream the HP18L monitor. In bare lattice the vertical phase advance between these points is $3.4 \times 2\pi$, however, with account of the space charge it will be close to $3.25 \times 2\pi$ by the time the tune reaches the half-integer. The current in the lenses was reduced by half compared to the single lens case so as to provide the same 50% tuneshift compensation. Fig. 7 shows some reduction in the emittance growth but at the price of quite high losses (Fig. 6).

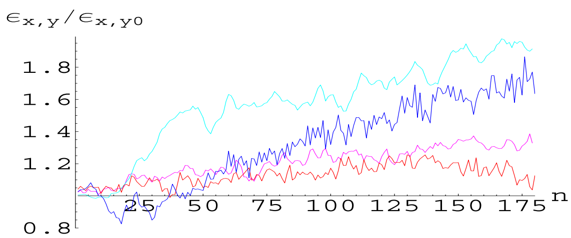

Figure 7: Horizontal and vertical emittance vs. turn number with 2 electron lenses (red and blue) and without lenses (magenta and cyan).

It is obvious that if successful space charge compensation is possible it requires many more electron lenses than the present Booster can accommodate.

Tuneshift Stabilization with γ-Transition Quadrupoles

During bunching the half-integer stopband is crossed in unfavorable direction: the emittance growth locks the tune onto the resonance value increasing the harmful effect. This suggests the idea of shifting the tune in advance below half-integer with the help of fast quadrupoles and reducing their current in the course of bunching so as to keep the total tune in the safe range $6 < Q < 6.5$. There are two families of fast γ-transition quadrupoles in the Booster which primary goal was to create α-jump at critical energy transition. When powered with the same polarity these families consisting of 6 quadrupoles each can produce large horizontal tuneshift, $\Delta Q_x \approx 2.7 \times 10^{-3} I_{QGT}[A]$ at injection energy, so that less than 150A is necessary to push the horizontal tune below half-integer. The results of simulations for the initial current $I_{QGT} = -135A$ decaying exponentially with time constant of 100turns are shown in Fig. 8 and Fig. 9. There is no horizontal emittance growth at all while the vertical emittance behaves the same way as in absence of any compensation (compare with Fig. 5). However, after ~ 60 turns there is an onset of losses which can be probably fixed with a more sophisticated time dependence of currents in fast quadrupoles.

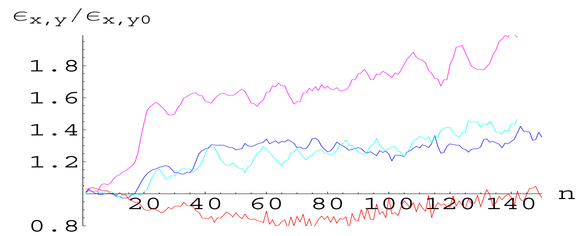

Figure 8: Horizontal and vertical emittance vs. turn number with (red and blue) and without (magenta and cyan) tuneshift stabilization.

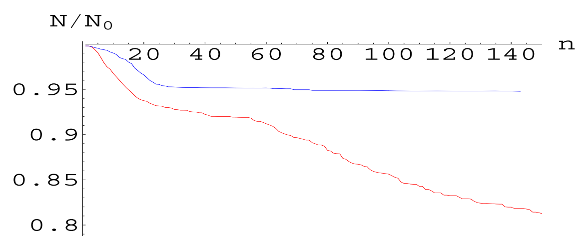

Figure 9: Intensity vs. turn number with (red) and without (blue) tuneshift stabilization.

SUMMARY

- MAD program can be successfully used for preliminary analysis of the transverse space charge effect and its compensation. - In absence of random optics perturbations space charge tuneshifts as high as 0.7 are possible. - Space charge compensation with electron lenses requires a large number of lenses to be distributed around the ring; simulations with fast quadrupoles suggest that 12 lenses would be barely enough. - Attempt to stabilize the horizontal tune with fast γ-transition quadrupoles gave encouraging results eliminating fast initial emittance blowup, however, there are high losses at a later stage.

REFERENCES

[1] B.Baller, E.J.Prebys, W.J.Spalding, Proton Plan, Beams-doc-1441, `http://beamdocs.fnal.gov/AD-public/DocDB/DocumentDatabase`.

[2] A.V.Burov,G.W.Foster,V.D.Shiltsev, FERMILAB-Conf-01/130-T, 2001.

[3] MAD Manual, `http://mad.web.cern.ch/mad/`.

[4] W.Merz, C. Ankenbrandt, K. Koepke, FERMILAB-TM-1473, 1987.

