Study of Possibility of Space Charge Compensation in the Fermilab Booster with Multiple Electron Columns.

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Introduction

To achieve the Fermilab Accelerator Division Proton Plan goal [1] the number of protons from the Booster should reach $5.25\cdot10^{12}$ per batch of 81 bunches. One of the major obstacles on the road to higher intensities is the transverse space charge effect at injection which may lead to fast emittance blowup during bunching.

Using MAD program it was shown [2] that a significant (by a factor of 2 or more) transverse emittance blowup may occur in the presence of both space charge and magnetic field errors which break the optics periodicity. In the same paper the possibility of space charge compensation with a few (1-2) electron lenses was studied. It turned out that the electron lenses produce an adverse effect on particle dynamics, most likely due to beta-beat excitation.

To reduce the detrimental optics perturbations it was proposed to use a large number of "electron columns" which can be created by gas jet ionization [3]. The question arises how many such "columns" are necessary to produce a positive effect. To answer it we performed simplified analysis using the same programs as in study [2] (and even the same distribution of magnetic field errors).

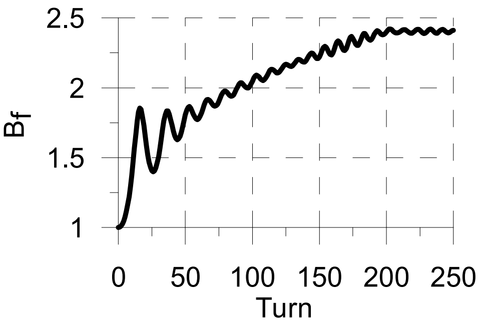

Figure 1. Bunching factor

The algorithm

The "electron columns" were represented by equidistant thin beam-beam elements with equal charges. Their transverse sizes were assumed to coincide with the beam sizes at the particular location as determined by local beta-functions and current values of emittances:

$$\sigma_x = \sqrt{\beta_x \varepsilon_x + (D_x \sigma_p)^2}, \quad \sigma_y = \sqrt{\beta_y \varepsilon_y} \tag{1}$$

where σ_p is the relative momentum spread (σ_p=0.1% after bunching) and D_x is dispersion function.

The "columns" were placed inside defocusing magnets upstream long drifts where the beta-functions are approximately equal: $\beta_x \approx 13$m, $\beta_y \approx 15$m. Time dependence of the columns charge just repeated the central bunch density as it varies during bunching (Fig.1), to achieve space charge compensation factor f with n columns the charge per column should be

$$Q_{e.c.} = -\frac{|e| h N_b B_f}{n_{columns}(\gamma^2 - 1)} f \tag{2}$$

where h=84 is the RF harmonic number and N_b is number of protons/bunch.

The space charge of the beam itself can be characterized by the space charge parameter

$$\xi_{SC} = \frac{B_f r_p h N_b}{4\pi \varepsilon_\perp \beta^2 \gamma^3} \tag{3}$$

where $r_p = 1.54\cdot10^{-18}$m is the proton classical radius, $\varepsilon_\perp$ is the r.m.s. transverse emittance. Eq.(3) gives the space charge tuneshift in a round beam with no momentum spread. For conditions we consider as nominal for Proton Plan II - $\varepsilon_\perp$=1.28mm·mrad, N_b =$6\cdot10^{10}$, γ=1.43 - the space charge parameter is as high as ξ_{SC} = 0.79.

The beam space charge was simulated with 197 beam-beam elements distributed around the ring. The charge of an element describing the space charge kick accumulated over distance L_k is [2]:

$$Q_k = \frac{|e| h N_b B_f L_k}{(\gamma^2 - 1)C} \tag{4}$$

where C = 474.25 m is the Booster circumference.

The simulations were performed using Mathematica and MAD8 according to the following scheme [2]:

- 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 the action variables from particle positions and momenta at the observation point (end of the lattice) using the stored 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 stored optics functions;
- track particles next turn with the sizes of BEAMBEAM elements (representing both space charge and electron columns) found from the previous turn and the intensity corresponding to current value of the bunching factor.

Results

Figs.2-5 present tracking results with different bunch intensity N_b, number of “electron columns” and total compensation factor f. Plots in left columns show normalized beam intensity vs turn number and plots in right columns show emittances normalized to initial values (red – horizontal, blue – vertical).

With “electron columns” placed in each of 24 Booster periods the space charge compensation drastically reduces emittance blowup and - in the case of increased intensity (Fig.4) - helps the beam to survive at all. It can be seen that even in the case of f=1 there is still noticeable effect of space charge since localized columns provide compensation only on average.

With twice smaller number of “columns” (12) the beneficial effect of compensation is less spectacular, even at the same values of the compensation factor f (Figs. 3 and 5). Still, it is big enough to pursue this idea.

It must be noted that the presented results are obtained by 2D simulations, the synchrotron motion was taken into account only as precalculated bunching factor. The space charge gradient modulation along the bunch may introduce synchro-betatron coupling and produce an adverse affect on particle stability.

References

[1] B.Baller, E.J.Prebys, W.J.Spalding, “Proton Plan”, Beams-doc-1441.

[2] Y.Alexahin, A.Drozhdin, N.Kazarinov, Xi Yang, PAC07-THPAN105, FERMILAB-CONF-07-225-AD, Jun 2007.

[3] V.Shiltsev, “On Possibility of Using Electron Columns for Controlled Space Charge Compensation” (unpublished).

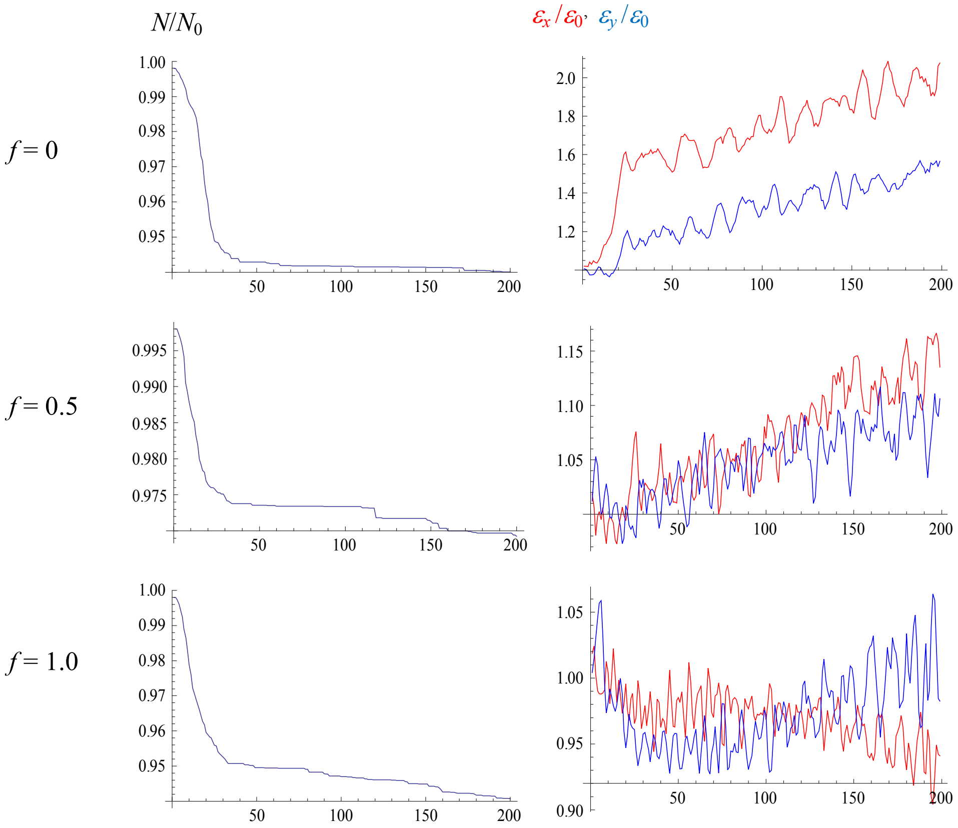

Figure 2. Normalized beam intensity and emittances vs turn number at $N_b=6\cdot10^{10}$, $n_{columns}$=24 and indicated values of the compensation factor *f*.

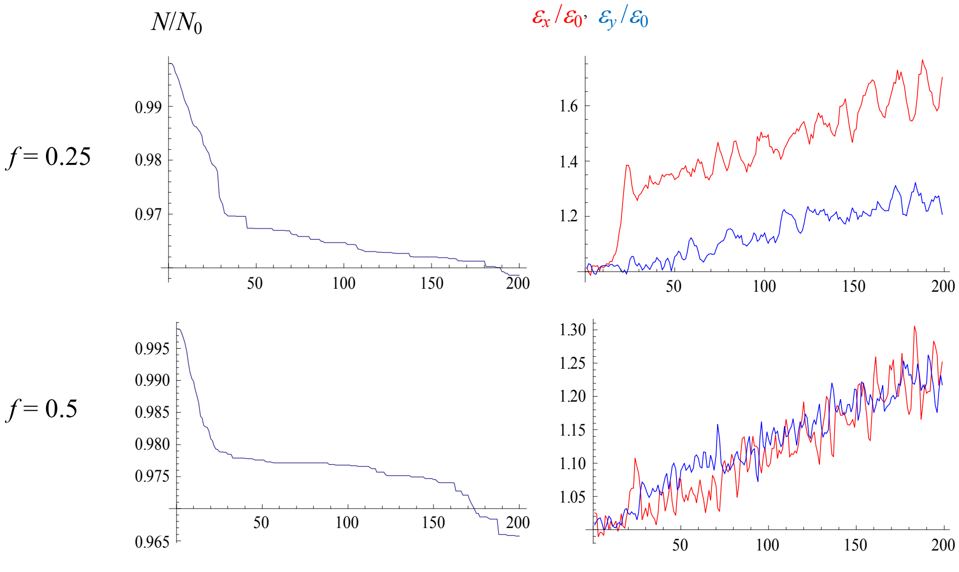

Figure 3. Normalized beam intensity and emittances vs turn number at $N_b=6\cdot10^{10}$, $n_{columns}$=12 and indicated values of the compensation factor *f*.

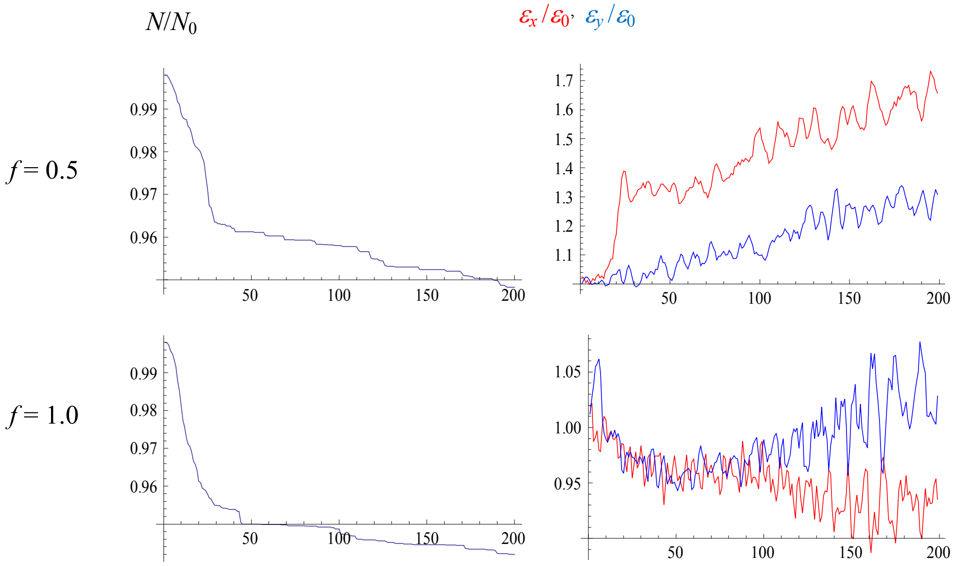

Figure 4. Normalized beam intensity and emittances vs turn number at $N_b = 9 \cdot 10^{10}$, $n_{columns} = 24$ and indicated values of the compensation factor *f*.

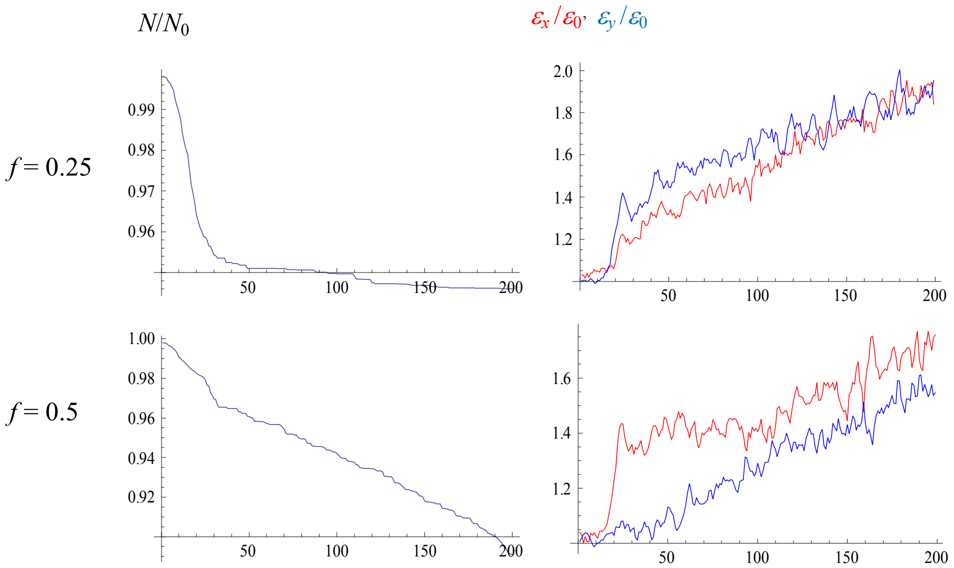

Figure 5. Normalized beam intensity and emittances vs turn number at $N_b = 9 \cdot 10^{10}$, $n_{columns} = 12$ and indicated values of the compensation factor *f*.