OPTIMIZATION OF THE HELICAL ORBITS IN THE TEVATRON*

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Abstract

To avoid multiple head-on collisions the proton and antiproton beams in the Tevatron move along separate helical orbits created by 7 horizontal and 8 vertical electrostatic separators. Still the residual long-range beam-beam interactions can adversely affect particle motion at all stages from injection to collision. With increased intensity of the beams it became necessary to modify the orbits in order to mitigate the beam-beam effect on both antiprotons and protons. This report summarizes the work done on optimization of the Tevatron helical orbits, outlines the applied criteria and presents the achieved results.

INTRODUCTION

Each of the proton and antiproton beams in the Tevatron consist of 3 trains by 12 bunches so that there are 72 interaction points (IPs) for each bunch. However, the total number of IPs is 138: around IPs in the middle of 6 straight sections (denoted as A0, B0, … , F0; B0 and D0 being the detector locations) where the leading bunches interact with collision cogging there are 2×11 IPs for bunches in the same pair of trains. Hence the total number is 6×23=138.

To separate the beams everywhere in the ring except for the two nominal IPs (B0 and D0) an ingenious scheme of helical separation was designed [1]. In the collision regime electrostatic separators create closed bumps in both planes in the arcs between IPs (so-called short arc from B0 to D0 and long arc from D0 to B0 via A0). Presently there are 3 horizontal and 4 vertical separators in the short arc and by 4 separators of each orientation in the long arc [2].

Despite that large number of separators there are peculiar factors which limit the attainable separation at each stage from injection to collision. As a result both beams at the start of the Tevatron Run II suffered high losses even at moderate initial intensities (Fig.1). To achieve the Run II luminosity goal a deeper understanding of the long-range beam-beam interaction and more careful helix design were necessary.

FIGURE OF MERIT

To comparing different helix designs some simple figure of merit would be helpful. The conventional choice is the *minimum* value over the parasitic crossings of the *radial separation in respective sigmas*:

$$S_r = \sqrt{(d_x/\sigma_{x\beta})^2 + (d_y/\sigma_{y\beta})^2} \qquad (1)$$

where $d_{x,y}$ is distance between the beams in x and y direction respectively, $\sigma_{x,y\beta}=(\beta_{x,y}\ \varepsilon_{x,y})^{1/2}$ are the r.m.s. betatron beam sizes. It is believed that in hadron colliders this value should be $S_r > 6$.

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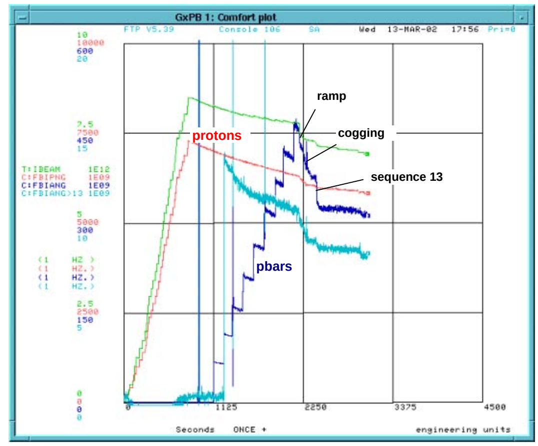

Figure 1: Beam transmission in the beginning of Run I.I

There is no agreement, however, if the beam sizes entering eq.(1) should include contribution from the energy spread σ_E in the case of finite dispersion D_x at a parasitic IP. The confusion originates from false analogy with head-on interactions where the total beam size determines the non-linearity of the beam-beam force.

At the parasitic IPs it is not the actual beam size but the beta-function that matters. Synchrotron oscillations do affect the long-range beam-beam interaction, but only through modulation of the distance between the beams, $d_x^{(\mathrm{eff})} = (d_x^2 - 3D_x^2\sigma_E^2/2)^{1/2}$, which is completely negligible in most cases.

In any case formula (1) is a completely artificial construction; its use for more than a rough assessment may be quite misleading.

The ultimate criterion is the long-range beam-beam tuneshift which may drive particle tunes onto a resonance and the beam-beam contribution to the strength of the resonance. For large separations one can use simplified formulas for the tuneshift:

$$\Delta Q^{(bb)}_{x,y} \approx \frac{r_p N \beta_{x,y}}{2\pi\gamma}\,\frac{d^2_{y,x} - d^2_{x,y}}{(d_x^2 + d_y^2)^2} \qquad (2)$$

where N is number of particles in the opposing bunch, $r_p = 1.535\cdot 10^{-18}$m is the proton classical radius, and for the $m_xQ_x + m_yQ_y = n$ resonance driving term (RDT):

$$|R^{(m,n)}_{bb}| \approx \frac{r_p N}{\pi\gamma}\,\frac{(m-1)!}{2^{m/2}\, m_x!\, m_y!}\,\frac{\sigma_{x\beta}^{m_x}\sigma_{y\beta}^{m_y}}{(d_y^2 + d_x^2)^{m/2}}\times I_x^{\frac{m_x}{2}}\, I_y^{\frac{m_y}{2}}\ \left|\begin{Bmatrix}\sin\\ \cos\end{Bmatrix}\left(m\arctan\frac{d_y}{d_x}\right)\right| \qquad (3)$$

where $I_{x,y}$ are action variables in units of the respective emittances $\varepsilon_{x,y}$, $m = |m_x| + |m_y|$ is the order of the resonance. $m_{x,y}$ in the r.h.s. of eq.(3) should be understood as the absolute values, the sine function should be chosen for odd m_y and the cosine for even m_y.

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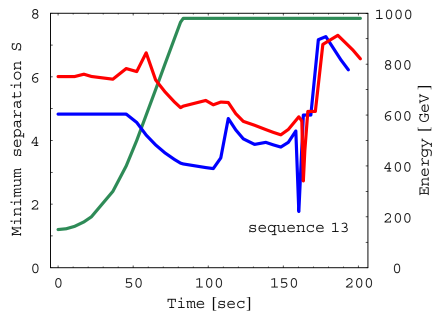

Figure 2: Beam separation during ramp and squeeze presently (red) and in the beginning of Run II (blue).

Obviously the synchrotron beam size does not enter explicitly eqs.(2, 3). Also, eq.(3) suggests that the total separation measured in the maximal of the two beam sizes

$$S_m = \sqrt{d_x^2 + d_y^2} / \max(\sigma_{x\beta}, \sigma_{y\beta}) \quad (4)$$

may be more relevant than separation in respective sigmas (1) since it determines maximum values of RDTs of any given order.

However, S_m does not retain information on the separation angle which determines the driving term (3) of a particular resonance. Therefore the helix design must be made on the basis of rigorous evaluation of the beam-beam effects, figures of merit (1) or (4) can be used only for initial guidance.

Approximations (2) and (3) work well for $S_m > 5$, at smaller separations the exact formulas must be applied. An efficient algorithm for fast and precise calculation of tuneshifts and RDTs at any value of separation has been implemented as a Mathematica notebook [3] and extensively used for the Tevatron helix improvement.

ALGORITHM FOR HELIX CORRECTION

Though there is a large number of BPMs in the Tevatron (118/plane), they do not provide information on helical orbits directly at the IP locations so some sort of interpolation is necessary. In the critical points with small separation even small errors in betatron phase advances may significantly affect the result, e.g. change the sign of separation so that the calculated correction would worsen the situation.

Therefore it is necessary to have good knowledge of the real optics. It is even more important for correct calculation of the resonance driving terms. There are different methods for optics reconstruction, e.g. using the turn-by-turn data. It can be found by either fitting the lattice to data as described in [4] or applying the perturbation theory [5].

In the result the scheme for helix correction looks as follows:

- measurement of the helical orbits at BPMs,
- optics reconstruction from either of TBT, AC dipole or ORM measurements,
- interpolation of the measured helix onto IPs,
- calculation of the beam-beam tuneshifts and RDTs,
- search for correction (usually a closed bump in the vicinity of a weak point helps).

HELICAL ORBITS AT INJECTION, RAMP AND SQUEEZE

Fig.2 shows the minimum radial separation S_r calculated with the design optics as a function of time during acceleration and squeeze with the initial Run II helix (blue, circa January 2002) and the improved helix (red). Still there are specific difficulties in the helix design at these stages which we consider in the following subsections.

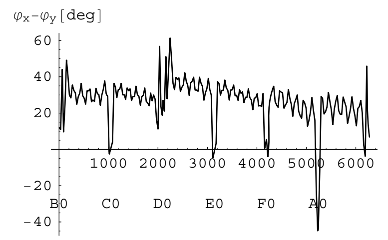

Figure 3: Phase advance difference around the ring starting from B0 with injection optics.

Injection Helix

Ideally the horizontal and vertical orbits would advance with shift in phase by π/2, but in practice this is precluded by: i) irregularities in betatron phase advance over the straight sections, especially A0 (see Fig.3); ii) aperture restrictions (geometrical as well as dynamic).

The most severe aperture restriction (±1/2" vertically) was imposed by C0 Lambertson magnets inherited from the fixed target operation. The injection helix design introduced in May 2002 managed to comply with this restriction while increasing the minimum separation in respective sigmas up to $S_r \approx 6$. It remained in use for a long time after the C0 Lambertson magnets removal. Further improvement became possible after installation of a number of new separators [2] and was necessitated by increased proton losses due to larger number of pbars (up to 10^{11}/bunch) coming from the Recycler.

Fig.4 shows separation in maximal sigmas S_m at all 138 IPs starting form the one 53.6m downstream B0 (there is a shift in IP positions with injection cogging). With May 2002 helix (red) the separation had the minimum at the second IP (112.9m downstream B0). Though it was just slightly smaller than in a number of other IPs, the separation angle at this point was conducive to excitation of the $7Q_y$ resonance close to the Tevatron working point (Fig.5).

Employing new separators (whose primary goal was to assist to the main separators at B0 and D0 in the collision mode [2]) it was possible to increase separation at this and some other points without increasing it in the remaining places of tight aperture restrictions. Separation and contribution to the $7Q_y$ RDT with the latest version of the injection helix introduced in May 2007 is shown in Figs. 4 and 5 in blue.

It is interesting to note that separation in respective sigmas (1) failed to predict the trouble with IP #2 being significantly larger there than the minimum value with May 2002 helix (6.7 vs 5.6).

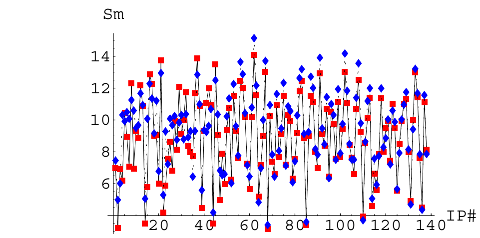

Figure 4: Beam separation at injection vs IP number with present (blue) and May 2002 (red) helices.

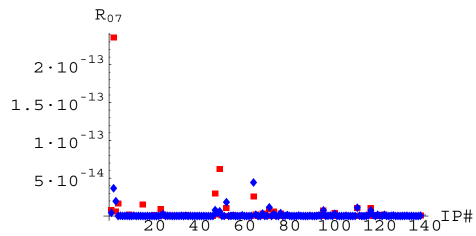

Figure 5: IPs contribution to the $7Q_y$ RDT with beam separation shown in Fig. 4

Separation During Acceleration

There are several complications with the helical orbits at the ramp. First, the maximum voltage limitation of 50 kV/cm (separator sparking) leads to a faster drop in separation $d\sim 1/E$ than in the beam size $\sigma\sim 1/E^{1/2}$ during the second part of the ramp above E = 500GeV. Second, since there is no fast orbit feedback it is difficult to control the orbits and avoid particle losses in unprotected areas which may result in SC magnet quench. Also, due to orbit drifts from ramp to ramp it is not possible to measure the helix (which is the difference between the closed orbits with separators on and off) so one has to rely on calculations.
With the initial Run II helix design there were high losses during the second part of the ramp when the C17V and B17H voltage was reaching the limit. By employing a larger number of separators it was possible to completely eliminate these losses. Unfortunately, due to mentioned above difficulty with the orbit control it was not possible to use this solution at energies below 500GeV. As a consequence now, with increased intensity of the beams, especially of the antiprotons, there are noticeable losses in the beginning of the ramp (up to 5%). Therefore a further improvement is needed.

Low-beta Squeeze

The major difficulty with separation during the squeeze is associated with the flip of polarity of the B17H separator (to satisfy needs of HEP experiments) which leads to a momentary collapse of the helix (formerly at sequence 13 of the squeeze).

In the beginning of Run II antiproton losses at this step reached ~20% and rapidly increased with proton intensity limiting the achievable luminosity.

It was possible to attain a 50% increase in the minimum separation S_r at sequence 13 - from 1.8 to 2.7 - by adding additional break points into the squeeze table and appropriately tailoring the time dependence of separator voltages around the moment when B17H changes its polarity. In order not to increase the total time spent in this dangerous region the time interval between the new break points was reduced form 5s to 2s. All this resulted in a drastic improvement of the pbar transfer efficiency through the squeeze. With increased number of antiprotons it is the protons that suffer most at this step.

Now that the “Roman pot” detectors were removed there is no need in the B17H polarity flip and it is possible to eliminate the “sequence 13” problem altogether.

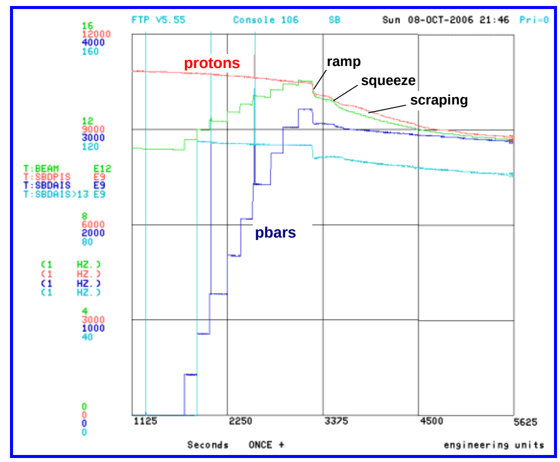

Figure 6: Beam transmission in October 2006. Please note different scale compared to Fig.1.

SUMMARY

Careful design of helical orbits in the Tevatron allowed to significantly reduce particle losses during injection, acceleration and squeeze (see Fig.6) and helped to achieve the Run II luminosity goal. Still the particle transmission from injection to collision is not perfect, a further helix optimization may be necessary to accommodate ever increasing beam intensities.

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REFERENCES

[1] Tevatron Run II Handbook, http://www-ad.fnal.gov/runII/index.html
[2] R.S. Moore, Y. Alexahin, J. Johnstone, T. Sen, PAC-2005-TPAP026, Knoxville, TN (2005)
[3] Y. Alexahin, FERMILAB-PUB-00-120-T (2000).
[4] Y. Alexahin et al. THPAN104, this Conference.
[5] Y. Alexahin, E.Gianfelice-Wendt, FERMILAB-PUB-06-093-AD (2006)