# ACCELERATING A POLARIZED BEAM IN THE TEVATRON

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We examine herein the feasibility of accelerating a polarized proton beam in the Tevatron to the top energy. We start with a brief discussion of the general features of the spin dynamics in a synchrotron or a storage ring and then apply the results to the different rings in the Tevatron complex.

## A. Spin Dynamics

In a magnet ring, along with the ideal closed orbit (distance coordinate s) and the betatron tune one can define a closed spin-axis $\hat{n}(s)$ and a precession tune $\nu_p$ ($2\pi\nu_p$ = precession angle per revolution). At any given s, there are two eigen-spin orientations $\hat{n}$ and $-\hat{n}$ with eigen-spin tunes $\nu_p$ and $-\nu_p$. For a particle traveling in the closed orbit of an ideal machine, if the spin is injected in an eigen-orientation, it will remain in the orientation. Generally, both $\hat{n}$ and $\nu_p$ vary with the energy $\gamma$.

A particle traveling off the ideal closed orbit feels an incremental field which is oscillatory with tunes.

$$\nu_r = \begin{cases} k = \text{integer} & \text{(imperfection term - due to closed orbit distortions)} \\ kP \pm \nu_x \pm \nu_z & \text{(intrinsic term - due to lattice periodicity P and betatron oscillations with tunes } \nu_x \text{ and } \nu_z\text{)} \end{cases}$$

The oscillatory incremental field couples the two spin eigenstates and when in resonance ($\nu_p = \nu_r$), can cause transitions (spin flips). The eigen-spin tune $\nu_p$ generally increases monotonically with $\gamma$ and hence, sweeps across many resonant values $\nu_r$ when the particle is accelerated. The coupling strength $\epsilon$ depends on the specific magnet lattice and on the magnitudes of the closed orbit distortions and betatron oscillation amplitudes. It is generally larger at higher energies.

A spin rotator (Siberian snake) is a series of dipoles inserted in the ring lattice (presumably in a straight section) such that:

1. It does not affect the closed orbit outside the rotator. The closed orbit within the dipoles is unavoidably deflected and makes an excursion about the original orbit.
2. It drastically modifies the precession tune $\nu_p$ such that the modified tune has a fixed non-resonant value independent of $\gamma$.

Thus, all resonances are effectively eliminated by the use of the spin rotator. The action of the spin rotator can be understood from the analog of a one-dimensional linear oscillation. When driven resonantly by a periodic force its amplitude will grow. But if the phase of the oscillation is shifted at equal intervals by, say, $\pi$, the resonant force will alternately excite and damp the oscillation and the resonance becomes ineffective. By analogy the effect of the spin rotator should be equivalent to shifting the phase by $\pi$. It can be seen that a spin rotator located at s should rotate the spin 180° about any given axis lying in the plane perpendicular to $\hat{n}(s)$. There are, therefore, two different types of spin rotators with orthogonal rotation axes.

In a planar (horizontal) machine, the ideal closed orbit is planar and $\nu_p = \gamma G$ (G = anomalous gyromagnetic ratio = 1.793 for protons). The closed spin-axis $\hat{n}$ is everywhere vertical and the rotation axis of a spin rotator should lie in the horizontal plane. The two standard types of spin rotators are the longitudinal (type 1) with rotation axis along the closed orbit and the transverse (type 2) with rotation axis perpendicular to the closed orbit. These spin rotators and their parameters are shown in Figs. 2 and 3.

Not demonstrable by the crude one-dimensional analog is the fact that between rotators ($\pi$-phase shifters) the amplitude growth due to the excitation must be limited. With one spin rotator in the ring the maximum coupling strength $\epsilon$ that can be controlled is only 0.5.

We now discuss each of the rings in the Tevatron complex individually.

## B. Tevatron Ring

The Tevatron ring is horizontal planar. Thus only vertical displacements of the beam from the midplane contributes to coupling. The strengths of the resonances have been calculated using the program DEPOL and are plotted in Fig. 1. The vertical betatron oscillation is assumed to correspond to a normalized emittance of $10\pi$ mm-mrad, and the vertical alignment and gradient errors are taken to be $\Delta z = 0.1$ mm and $\Delta B'/B' = 10^{-3}$. The strongest resonance at the top energy has $\epsilon \sim 0.8$. Thus at least two spin rotators: one longitudinal, one transverse, are needed. This arrangement has the further advantage that with the double spin rotators the modified closed spin-axis $\hat{n}$ is $+\hat{z}$ for one half turn and $-\hat{z}$ for the other half, whereas that with a single rotator of either type is in the horizontal plane and rotates rapidly with s. It is easier to maintain and inject a vertically polarized beam.

Using 5.5 T dipoles each rotator is no longer than 5 m and can be accommodated in diametrically opposite short (8 m) straight sections at station 48. The orbit excursion in the transverse rotator (the larger of the two) at the low energy end of 150 GeV is only 5.5 mm which puts very little demand on the dipole aperture.

## C. Main Ring

With the overpasses at B0 and D0 the main ring is non-planar. The case of non-planar closed orbit has never been studied in any detail, but from the discussions in section A, it is evident that the general features and ranges of parameters of the resonances should not be too different from those of the original planar main ring without the overpasses which, in turn, should not be too different from those of the Tevatron ring extrapolated down to 8 GeV. We conclude, therefore, that the maximum coupling at the top energy of 150 GeV is $\epsilon \sim 0.25$ and, hence, one single spin rotator will do. (One may still want to use a double rotator for the reason of wanting to keep $\hat{n}$ vertical.)

The orbit excursion for the longitudinal rotator at 8 GeV is ~ 12 cm for 1.8 T conventional dipoles and ~ 4 cm for 5.5 T superconducting dipoles. The apertures required to accommodate these excursions are rather large but definitely not impossible.

Detailed studies of the design for the non-planar case should be carried out. But one stage of the Tevatron up-grade program is to replace the main ring by a planar 150 GeV ring in a tunnel separate from the Tevatron tunnel. After the main ring is replaced, there will be no need to deal with a non-planar machine. In addition, studies are in progress to investigate the effectiveness of partial spin rotators which rotate the spin less than 180°. The idea is that for eliminating weak resonances ($\epsilon << 0.5$) partial rotators may be sufficient and that the orbit excursions in a partial rotator will be smaller, thereby putting less demand on the aperture.

## D. Booster Ring

The Booster, with $P = 24$ and $\nu_z = 6.8$ has only one intrinsic resonance at $\nu_r = 0 + \nu_z = 6.8$ and 15 imperfection resonances at $\nu_r = 3$ to 17. Because the booster is a rapid cycling machine, it is likely that the rather rapid crossing of these resonances will not cause much depolarization. Whatever small depolarization there is can certainly be eliminated or at least greatly reduced by the procedures used on the ZGS and the AGS, namely orbit corrections to reduce the strengths of the imperfection resonances and pulsed quadrupoles to produce even faster crossing of the intrinsic resonance.

Furthermore, if the partial rotator performs as well as indicated by the preliminary analysis, one should be able to use it effectively on the Booster. The straight sections in the Booster are only 6 meters long. Depending on the design, it is likely that superconducting dipoles must be used in the partial rotator. In this case, we will have a passive all-rotator or all-Siberian snake scheme for the acceleration of polarized protons in the Tevatron.

## E. Further R and D Work Required

In addition to further analytical studies of the non-planar ring and the partial rotator, we need experimental tests and measurements of the performance of Siberian snakes in general. Efforts to improve the current of polarized sources, and the speed and precision of polarimeters will all help in making accelerated polarized beam projects easier and more useful.

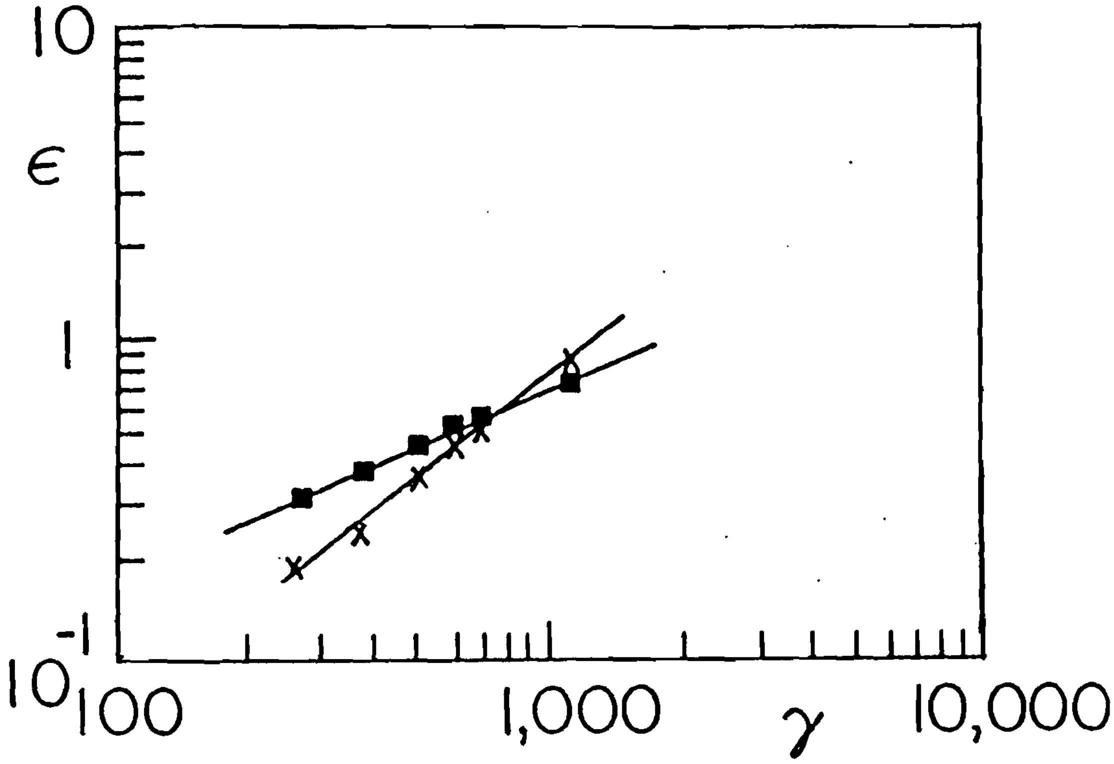
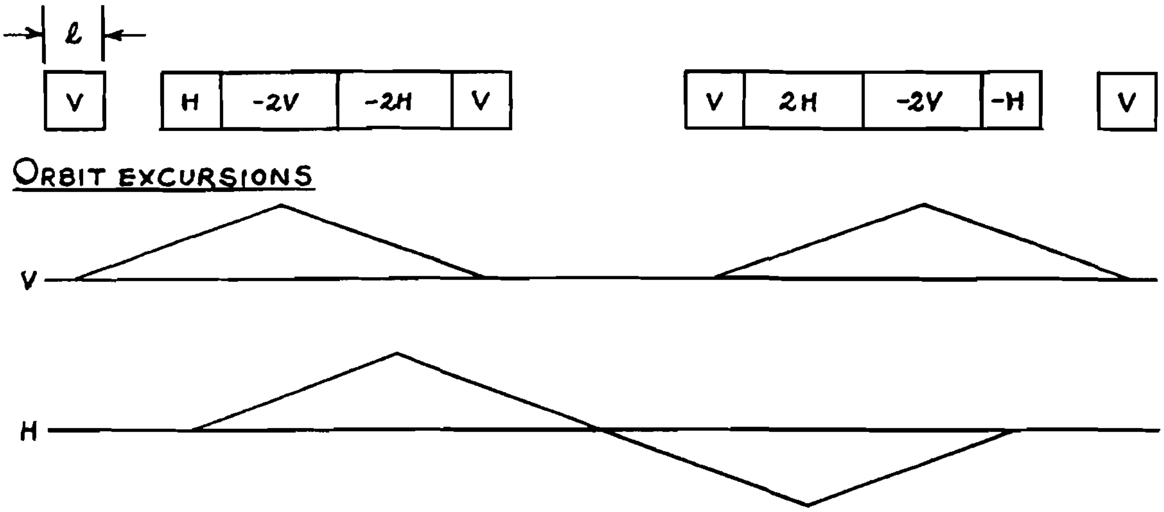
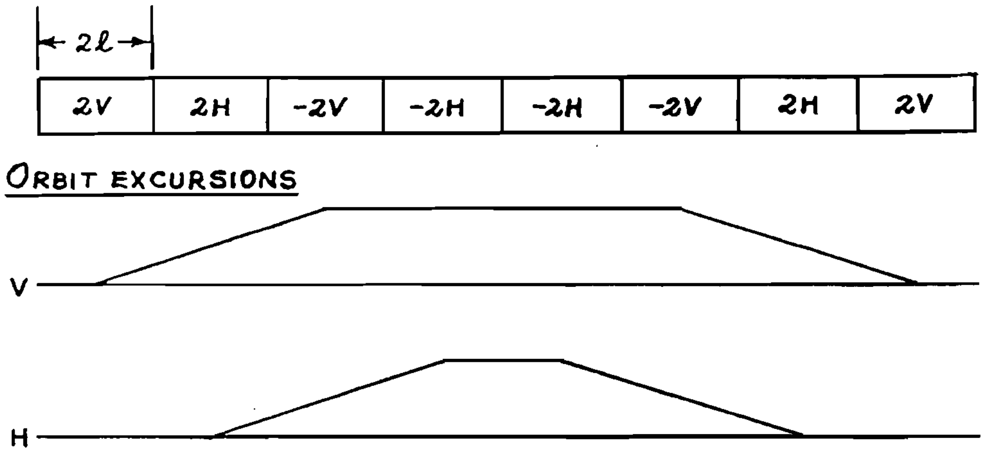


Figure 1. Strengths $\epsilon$ of depolarizing resonances in the Tevatron ring plotted against energy $\gamma$. For intrinsic resonances (black squares) the normalized vertical emittance is taken to be $10\pi$ mm-mrad. For imperfection resonances (crosses) the maximum alignment and gradient errors are assumed to be $\Delta z = 0.1$ mm and $\Delta B'/B' = 10^{-3}$.



| | Conventional dipole | Superconducting dipole |
|---|---|---|
| Field B | 1.83 T | 5.48 T |
| Unit length ℓ | 0.75 m | 0.25 m |
| Total length 19 ℓ | 14.25 m | 4.75 m |
| Orbit excursion $\Delta x = \Delta z$ | 1.15 m/$\beta\gamma$ | 0.38 m/$\beta\gamma$ |

Figure 2. Longitudinal rotator (Type 1 Siberian snake) precesses the spin 180° about the longitudinal ($\hat{y}$) axis. For the proton each unit has $B\ell$ = 1.37 Tm and precesses the spin 45°. H and V denote horizontal and vertical orbital deflections.



| | Conventional dipole | Superconducting dipole |
|---|---|---|
| Field B | 1.83 T | 5.48 T |
| Unit length ℓ | 0.75 m | 0.25 m |
| Total length 16 ℓ | 12 m | 4 m |
| Orbit excursion $\Delta x = \Delta z$ | 2.63 $m/\beta\gamma$ | 0.88 $m/\beta\gamma$ |

Figure 3. Transverse rotator (Type 2 Siberian snake) precesses the spin 180° about the transverse ($\hat{x}$) axis. For the proton each unit has $B\ell$ = 1.37 Tm and precesses the spin 45°. H and V denote horizontal and vertical orbit deflections.