A NEW TEVATRON COLLIDER WORKING POINT NEAR THE INTEGER

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Abstract

It is well established that in hadron colliders the beam-beam interaction is more harmful in the presence of machine resonances of the form $m\nu_x+n\nu_y=p$, where $|m|+|n|$ is the order of the resonance.[1] Since the closest a resonance line can be to the integer stopband is 1/order, the closer the working point is to the integer, the fewer lower order resonances there are to enhance the beam-beam effects. A shift of the working point of the Tevatron from 19.4 to values near 19 and 20 has been studied. Problems with closed orbit control, dispersion matching, and matched low β insertions were considered. An excellent solution for the B0 insertion was found which has an improved β^*. A new injection optics allows a transition to the low β optics which is much easier than the one now used. Results from the first machine studies demonstrate the ability to control the orbit with tunes of 19.03 horizontal and 20.03 vertical. Further studies require the activation of additional quadrupole compensation circuits.

Introduction

The Tevatron Collider working point in betatron tune space near 19.41 in both planes is presently bounded by the 2/5 and 3/7 stopbands (separated by .029). For normal collider operation, this area is completely filled by a combination of the tune spreads caused by the beam-beam interaction and by the chromaticity of the machine. The beam-beam interaction is particularly important because the 6 proton and 6 antiproton bunches have 12 crossings per revolution. In practice, the proton bunch intensities are intentionally reduced and the emittances are increased until the beam-beam tune spread of the pbar bunches does not exceed the available area. Typically, the proton bunches have intensities of 7E10 and transverse 95% emittances of 24 π. The maximum luminosity under these conditions is 2E30 cm^{-2} s^{-1}.

A significant contribution to the tune spread is due to the chromaticity of the machine and the large momentum spread of the beam. The momentum spread ($\Delta p/p$=1.4E-4 rms at 900 GeV) is a consequence of the bunch coalescing in the Main Ring, necessary to achieve large bunch intensities. The chromaticity must be kept above 3 units to be safe from temporal variations in the sextupole components of the superconducting dipoles in the ring.

It is an obvious suggestion that the working point be moved to provide a larger area which is free of lowest order resonances.

Tunes Near Integer Stopbands

In principle, a much greater area of tune space is available near an integer stopband. This follows from the observation that for a sum resonance of order n, the closest line is 1/n away from the integer stopband. For example, with a fractional tune of 0.04, the nearest 7th order resonance is at 1/7 = 0.143, leaving space for tune spreads of over 0.10 free of all resonances through 7th order. Fig. 1a shows the present operating point on the working diagram and fig. 1b shows the proposed scheme. All resonances through 9th order are shown.

Experience with tunes near the integer is rather limited in colliding beam machines. Electron-positron machines are usually limited because of high synchrotron tunes which create an effective tune spread that prohibits operating near an integer stopband. There are few examples of hadron colliders. The ISR had a high luminosity working point in which the fractional tune extended to 0.955 [2].

Since the proton-pbar beam-beam tune shift only increases the tunes, the machine tune above the integer can be set as close to the integer stopband as the width of the stopband and the perturbations to the lattice will allow. The lattice seems quite acceptable for the (19.04,20.04) solution. The width of the integer stopband may be determined by the beam-beam interaction itself and is a question to be answered by experiment.

The choice of the 19.04, 20.04 working point is a combination guided by theoretical expectations and practical limitations. To be above the integer rather than below is suggested for two reasons. The first is that the beam-beam tune shift is largest for particles with the smallest betatron amplitude. Since the susceptibility to resonance effects goes as a power of the betatron amplitude, one expects that it is better to have the small amplitude particles nearest the resonances. The second reason is to avoid the "sawtooth resonances", beam-beam interactions between bunches leading to dipole and quadrupole oscillations.[3]

Practical Considerations

The major practical consideration was that the ability to try the integer tunes during the 1988-89 collider run required a solution which could be implemented without physically changing any of the magnetic elements of the Tevatron. The choice of which integer tune to be near and whether to be above or below has been investigated in some detail primarily using SYNCH. All horizontal tunes near 20 lead to dispersion functions which are quite large. Not only does the large dispersion at E0 cause emittance growth in the transfer of the beam from the MR to the Tevatron, but the beam size in the region of the maximum horizontal beta function near the IR becomes uncomfortably large. The difficulty with the dispersion might be due to the denominator in the dispersion expression[4]:

$$D(s) = \frac{\sqrt{\beta(s)}}{2\sin(\pi\nu)} \int_s^{s+C} \frac{\sqrt{\beta(t)}}{\rho(t)} \cos(|\phi(t)-\phi(s)|-\pi\nu)\ dt \quad (1)$$

where the integral is done around the circumference of the machine, ρ is the bending radius, and β and ϕ are the usual betatron amplitude and phase advance.

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An acceptable solution at tunes of 19.05 in both planes was found, however the required current in the correction quadrupole circuits was too large for the available power supplies. The correction quads are needed to compensate the increased phase advance of the low β insertion (about 0.5 in tune). Splitting the tunes (19.04,20.04), following the suggestion by C. Ankenbrandt, allows the correction quads to operate at acceptable currents.

Fig. 2 shows a SYNCH solution with tunes of 19.04 horizontal and 20.04 vertical which is particularly interesting for two reasons: 1) the minimum B0 β functions are smaller than the present operating values (23 cm by 38 cm vs 55 cm by 55 cm, with the dispersion η_x=0.18) which increases the luminosity and shortens the luminous volume, 2) the solution requires no changes to the Tevatron itself beyond reconfiguring the electrical circuits on the 12 correction quads closest to the B0 interaction region.

In addition, a new injection lattice has been found which simplifies the transition to the low β optics, with about 8 steps (compared to 30) and no polarity reversals of any of the circuits. For this new injection optics the dispersion match between the MR and the Tevatron is quite good, with little emittance growth in the transfer (< 3 π mm-mr, horizontally).

Expected Performance

The potential improvements to the Tevatron Collider operation as a consequence of implementing the scheme outlined here can be separated into two categories. In first category are the the long range upgrade plans which follow from the "proof-of-principle" test of operation near the integer stopbands. Our present understanding of the effects of the beam-beam interaction in hadron colliders is based on the idea that emittance growth follows from resonances which are driven by the beam-beam forces. These forces exist for cases where the bunches pass by each other at some separation determined by electrostatic separators, as well as for the head on collisions. As a consequence, the operation of the machine near an integer, where many resonances can be avoided, may allow more flexibility in operating parameters such as numbers of bunches, interaction regions, and strengths of electrostatic separators.

A second category is the potential improvement to the present collider run. (One assumes that the next run will be entirely different, with two operating low β insertions). With no assumptions about the improvements one expects due to the avoidance of resonances, the proposed low β is significantly better than the present one. The luminosity does not scale directly from the decrease in beam size at the crossing point because of the finite lengths of the bunches. Nevertheless, the increase in peak luminosity should be at least 50%. The reduced length of the luminous region at the interaction point would be a significant improvement to the CDF detector. The projective geometry of the detector and, in particular, the trigger which uses a transverse energy criterion based on the assumption that the event vertex is at the center of the IR, are much improved with a shorter luminous region.

The most interesting question is whether the beam-beam tune spread can be increased if there is more free area on the tune diagram. The Main Ring is working well, and it is not unusual to see intensities in the collider which are only one half of what the MR is capable of producing. The proton emittance is intentionally increased as a matter of course by as much as a factor of two to keep the pbar tunes from the 3/7 resonances discussed above. Whether the two factors of two can be applied to the expected increase in peak luminosity is something to be investigated experimentally. For those not desiring an increased peak luminosity, the increased luminosity/pbar would help solve some of the pbar economics problems. Fills could be made more often, keeping the average luminosity closer to the peak value.

First Beam Studies

The first study period was primarily concerned with the stability of the closed orbit and whether the dipole correction elements of the Tevatron were adequate for the necessary adjustments. This concern follows from the expression for a closed orbit distortion which has the same denominator as equation (1). At 150 GeV, the orbit did deteriorate as the tune was changed from 19.4 to 19.03, but a single orbit correction at 19.25 allowed injection and coasting beam at a tune of 19.03. The currents in the correction dipoles remained within their 50 amp limit even when scaled to 1 TeV.

The beam lifetime was only a few seconds at (19.04, 20.07), deteriorating rapidly from (19.08, 20.12) where it was tens of minutes. The reason for the short lifetime is unknown and will be the subject of further beam studies.

Resonance Compensation

For the tunes near an integer and split by an integer, new resonance compensation circuits are required. The existing Tevatron circuits are designed for tunes near the half integer and are primarily used for resonant extraction with ν_x=0.5. Coupling is primarily controlled with a zero harmonic skew quad circuit.

For the ν_x-ν_y=-1 situation two new skew quadrupole circuits are needed to provide sine and cosine-like odd harmonics. Even harmonics for the quadrupole resonances $2\nu_x$=38 and $2\nu_y$=40 are also being installed.

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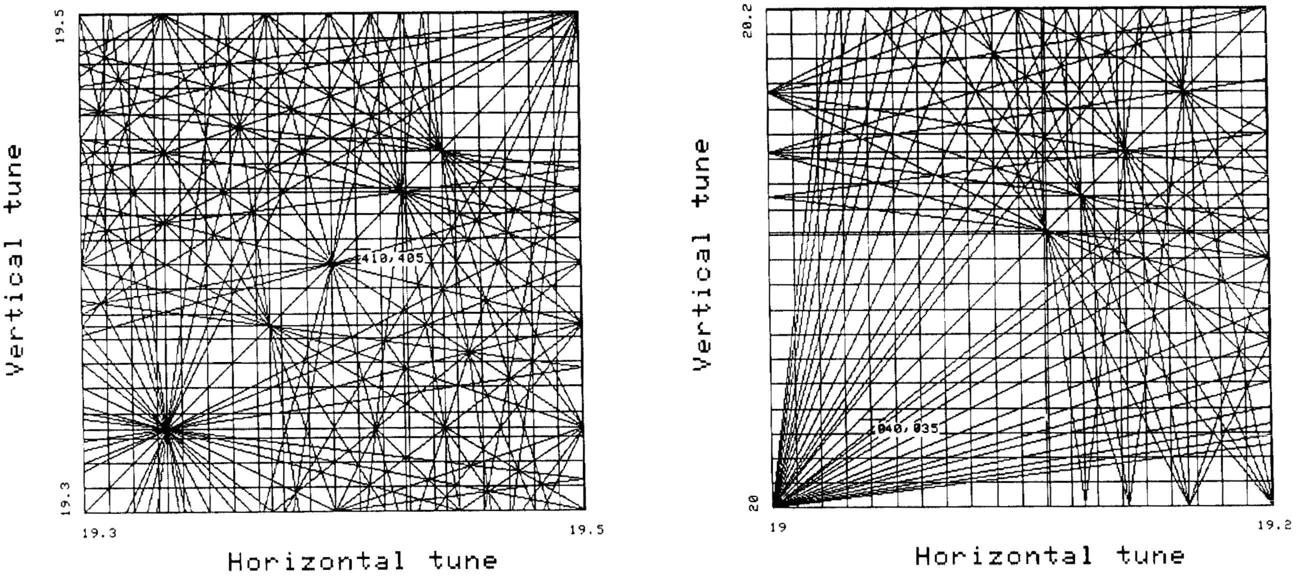

Fig.1 Comparison of a)present and b)proposed diagrams of the Tevatron pbar-p collider. All resonances through 9th order are shown. The grid spacing is 0.01 units. Present operating conditions generate a pbar tune spread which fills the area between 19.400 and 19.429.

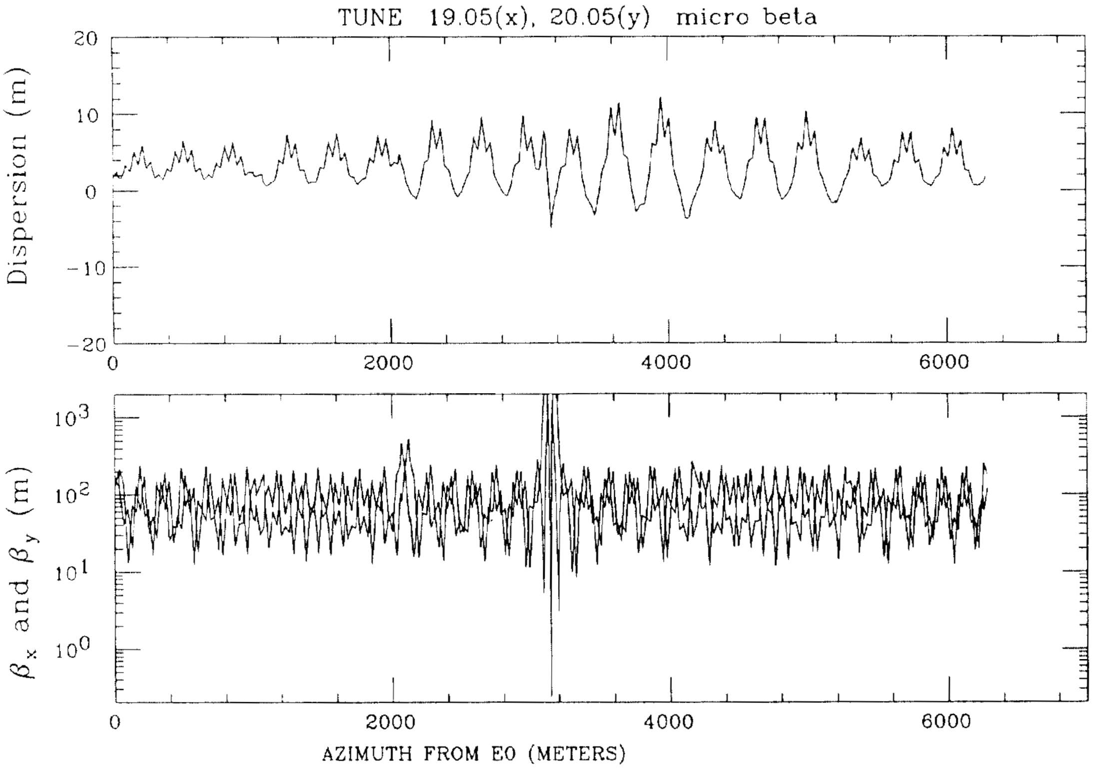

Fig.2 Lattice functions for the low β solution with split tunes near integer stopbands.