PROSPECTS FOR TUNES NEAR THE INTEGER AT THE FERMILAB PBAR-P COLLIDER

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Abstract

A series of experiments with the Tevatron Collider has been made which has as a goal the operation of the machine with betatron tunes near 19.05. Experiments near the integer working point are described, including closed orbit control, and emittance growth due to power supply noise. Results from a pbar-p store with large pbar tune shifts and tunes near the integer are described.

History

The beam-beam interaction in a collider causes the working point to be smeared over some region of tune space. This tune spread is a particular problem when the tunes overlap resonances. The non-linear part of the beam-beam force also drives these resonances leading to emittance growth and shortened luminosity lifetime.

One effective solution to this situation has been to use electrostatic separators to reduce the number of crossing points and thus the magnitude of the tune shift and spread. An additional technique is to find the area in tune space with the most space free of lower order resonances. An examination of the tune diagram quickly shows that the largest resonance free area is near the integer stopbands.

Working Diagram Near an Integer Tune

Machine resonances of the form $m\nu_x + n\nu_y = p$, where $|m| + |n|$ is the order of the resonance, define the tune space for a synchrotron. The working point for the Tevatron Collider is normally near 19.41 in both planes, hence the 5th and 7th order resonance lines border the region of stable operation.

For a sum resonance of order n, the closest resonance line is separated by $1/n$ from the integer. For example, the nearest 7th order resonance for a tune of 19.05 is at $1/7 = 0.143$, leaving a 0.09 betatron tune space for stable operation. By operating at a tune near the integer, the largest region of betatron tune space is available, as shown in Figure 1.

Previous Colliders

Electron-positron colliders are not likely to operate with tunes near the integer because of complications from synchrotron sidebands. Namely, the synchrotron radiation must be compensated with large rf voltages. These high voltages in turn lead to large synchrotron tunes. If the betatron tune were near an integer, the synchrotron sidebands of the betatron frequency would overlap the integer resonance and cause the beam to blow up.

Bunched-beam hadron colliders have low synchrotron frequencies, sometimes less than 50 Hz, and it is possible to move much closer to integer tunes than in e^+e^- machines. Although the ISR had successful high luminosity operation with tunes near the integer, the two bunched-beam hadron colliders, the SPS and Tevatron, have chosen not to explore this region of tune space. This is in part due to the historical development of these colliders.

Since both were designed and operated as fixed target machines before being used as colliders, there was a certain predisposition towards using tried and true working points. For example, the early experiments to investigate coasting beam behavior were done between fixed target runs. It was easier to leave the machine tunes as they were found rather than change them. Also, there was really no reason to change them for the detrimental effect of the beam- beam interaction in conjunction with low-order resonances was not fully appreciated at that time.

There are other problems than lack of experience with working near the integer tunes. Below we describe experiments with the Tevatron which were to address these problems. The first worry was the control of the closed orbit. This turned out to be easily solved; stable orbits with acceptable distortions were made using standard equipment and algorithms.

Closed Orbit Control

Closed orbit control presents some difficulties in operating near the integer tune. Small steering errors in magnets can cause large closed orbit distortions, $x(s)$, which are given by

$$x(s) = \frac{\delta(B'l)\sqrt{\beta(s)\beta}}{B\rho\ 2\sin(\pi\nu)}\cos(\phi(s) - \pi\nu) \qquad (1)$$

where $\delta(B'l)$ is the dipole magnet steering error, $B\rho$ is the magnetic rigidity, β is the beta function at the dipole, $\beta(s)$ is the beta function and $\phi(s)$ is the phase advance at the point of calculation. For a fractional tune close to 0.41, $1/sin(\pi\nu)$ is

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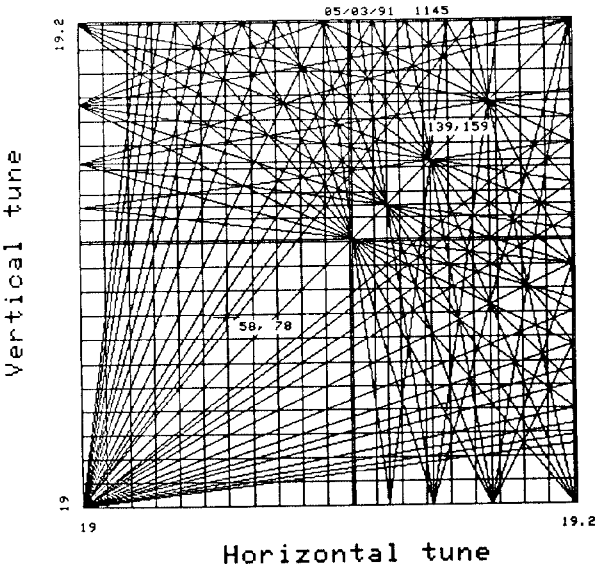

Figure 1: Resonance lines of the Tevatron pbar-p collider near the integer tune. All resonance lines through 9th order are shown. The grid spacing is .01 units. The locations of the tune coordinates for the proton (19.059, 19.079) and pbar (19.140, 19.160) beams is shown for the case with 36 proton bunches and 1 pbar bunch.

approximately 1.0. For a fractional tune near the integer, for example, $\nu = 0.05$, $1/sin(\pi\nu)$ is 6.4. Thus for a given steering error, the orbit distortion is six times greater when operating near an integer tune as compared with the normal Tevatron Collider operation.

In the Tevatron Collider studies near the integer tune, these orbit distortions were corrected by adjusting correction dipoles magnets using a standard three-bump technique. With a tune of 19.05, a rms horizontal orbit position of 1.0 mm and a rms vertical orbit position of 1.5 mm was obtained as shown in Figure 2. The store remained stable for many hours.

Emittance Growth

The second observation was that the transverse emittance growth became unacceptably large as the tunes were moved toward the integer. The first guess was that the integer stopband was larger than anticipated. Harmonic corrections were tried to compensate the quadrupole driven part of the stopband with no beneficial results.

Harmonic Corrections

The $2\nu = 39$ circuit was modified to be $2\nu = 38$ for both the horizontal and vertical planes to try to compensate this component of the horizontal integer stop band. It had no beneficial

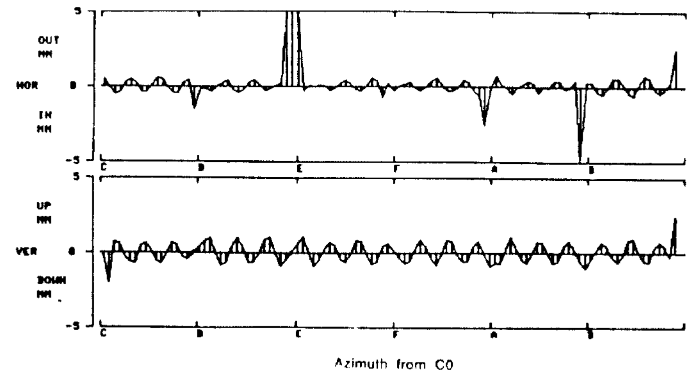

Figure 2: Closed orbit after orbit distortion corrections for a Tevatron collider store with a horizontal and vertical tune of 19.05. The upper display is the horizontal and shows the path around the injection septum magnet at E0. Anomalous readbacks at the end of each sector correspond to detectors excluded from the fit. The lower display is the vertical plane.

effect on the beam lifetime even with the tune close to 19.0.

It was concluded that the quadrupole-driven part of the stopband was not the cause of the shortened beam lifetime. Rather, the power supply ripple played a dominant role in the emittance growth.

Emittance Growth due to Power Supply Noise

However, by injecting common mode noise onto the main dipole and quadrupole bus it was possible to exacerbate the emittance growth rate. A companion paper on the details of this experiment describes the detective work needed to understand this effect. A feedback loop was constructed and added to the circuit, reducing the noise on the bus by a power of ten. The emittance growth rate was only reduced by a factor of two, indicating that the dominant source of emittance growth had been cured, but that at least one other remains to be found.

Sensitivity to noise, such as that due to power supply ripple, is also a concern at tunes near the integer because the betatron frequencies are low enough to overlap the major components of the power supply noise spectra. Emittance growth rates were reduced by a factor of two when a noise reduction circuit was connected to the power supply. Details of the power supply noise reduction are given in another paper submitted to this conference; "Common Mode Noise on the Main Tevatron Bus and Associated Beam Emittance Growth".

Even so, one can project the emittance growth rate that has been obtained to what might be expected for collider conditions at 900 GeV. The projected rates for tunes near 19.06 are similar to those which were observed during the earliest operation of the Tevatron Collider. That is, the situation with the feedback loop is very close to what one could try to use for operation of

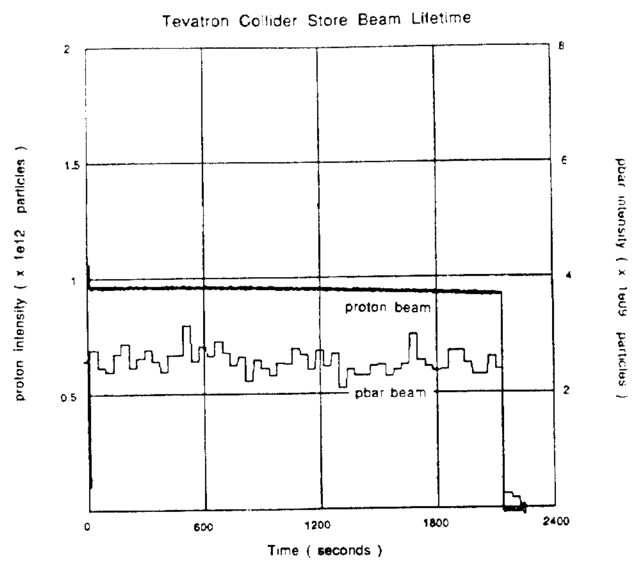

Figure 3: Tevatron Collider p-pbar intensities over time for a store with nominal tunes near $\nu = 19.07$. Intensities are averaged over six bunches for both protons and pbars.

the collider.

Unusual Storage Conditions

One store was attempted which had as its goal the demonstration that the luminosity lifetime would be long even with large tune shifts if the tunes were near enough to the integer to avoid resonances. Unfortunately the proton beam was too strong and the pbar tune shift was so large that the pbar tunes were moved into a region with many resonances. Nevertheless, the beam lifetimes were quite good, with little emittance growth.

This pbar-p store was at 150 GeV with a horizontal and vertical proton tune of 19.08 and 19.06, respectively. There were 36 proton bunches and one pbar bunch. The average proton intensity was approximately 1.0×10^{12} and the pbar intensity was 2.5×10^{9}. The proton tunes are weakly affected by the pbars. The pbar tune shift was large having passed through 36 proton bunches and the pbar tunes are calculated to be 19.16 in the horizontal plane and 19.12 in the vertical plane. This places the pbar tunes between resonance lines. The pbar tune spreads were small enough, however, due to the size of the pbar bunch that a long beam lifetime was possible. The lifetime of the pbar bunch was measured to be approximately eight hours, as extrapolated from the data in Figure 3. This beam lifetime result is unusual for a calculated tune shift of 0.08.

This long lifetime is understood as a case where the emittance of the low intensity pbar bunch was small enough to be mostly within the linear region of the strong proton beam-beam force. That is, the pbar tunes were shifted by .08 but with little tune spread. The proton beam was acting almost as a perfect quadrupole and the tunes just happened to be shifted to a region between significant resonances. While the experiment did not address our proposition that regions near the integer are more benign, it does seem to be an example of a rather unique operating mode. Namely, there is a good lifetime with a tune shift of .08 and the larger proton beam has been used effectively as a lattice quadrupole at each of the 72 pbar-p crossing points.

Conclusions

The experimental results indicate that there is no fundamental reason not to have a bunched beam hadron collider with tunes close to the integer.

Certain practical problems such as closed orbit control and the most dominant emittance growth source due to common mode power supply noise have been solved.

Future experiments at 900 GeV with tunes of 19.06 may have similar emittance growth rates as past collider runs with tunes at 19.41.

Acknowledgments

The authors are grateful to Dr. Peoples, Dugan, and Harrison for their continued support of this research project. The Beam Instrumentation Group under Dr. Jackson provided invaluable aid with the tune and emittance measurements.

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