BEAM-BEAM SIMULATIONS WITH CROSSING ANGLE IN TEV33

V. D. Shiltsev, FNAL[*], M.S.345, P.O. Box 500, Batavia, IL 60510, USA

Abstract

We consider effects of finite crossing angle at collision point on beam dynamics in the Tevatron collider upgrade (TEV33). Impact of the beam-beam interaction on beam sizes, particles diffusion and luminosity is studied with use of computer simulations. Parameter space for better collider performance is proposed.

1   INTRODUCTION

The Tevatron collider upgrade (TEV33) [1] intends to operate with some hundred bunches in each beam. Large number of bunches N_b results in small bunch spacing of 132 ns and, therefore, collisions occur more frequently. The colliding beams share the same vacuum chamber that leads to $2(N_b-1)$ parasitic collisions besides specially designed interaction points (IPs). Detrimental effects of the parasitics collisions of high current beams can be reduced by separation of the orbits of p and $\bar{p}$ beams everywhere except the IPs. However, due to limited space available and limited strength of electrostatic separators several crossing points around the IPs can not be effectively treated in such a way. Collision with half-crossing angle of $\phi = 0.2$ mrad will allow to increase the separation up to a safe value of 3 rms beam size at the first parasitic crossing [2].
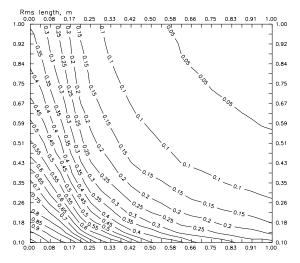

Figure 1: Contour plot of the geometrical luminosity reduction factor R due to tilt effect vs. bunch length σ_z and crossing half-angle ϕ, $\beta^* = 25$ cm.

Collisions with a crossing angle result in geometrical luminosity reduction. Then, in the case of strong electromagnetic interaction between beams, characterized by the beam-beam parameter $\xi = \frac{r_p N_p}{4\pi\varepsilon_n}N_{IP}$, (here $r_p = 1.53\cdot10^{-18}$m is the classical proton radius, N_p is the number of particles in opposing bunch, ε_n is the transverse normalized emittance of round beam, and N_{IP} is the number of IPs), the harmful impact of non-linear force due to the opposing beam tends to enhance for particles off the bunch center (at the tail and head). Finally, there is a coupling between longitudinal and transverse degrees of particle motion that causes synchrobetatron (SB) resonances at frequencies of $n\nu_x + m\nu_y + l\nu_z = $ integer, where ν_x, ν_y, ν_z are horizontal, vertical and synchrotron tunes, respectively.

2   SIMULATIONS WITH CROSSING ANGLE

BBC code and beam parameters   We employ the BBC code Ver. 3.3 developed by K.Hirata [3] for beam-beam simulations in "weak-strong regime" which is close to the TEV33 conditions where proton bunch population is about 6 times the antiproton one. The "weak" (antiproton) bunch is presented by number of test particles, while the "strong" (proton) bunch appeared as an external force of Gaussian bunch. Typically we tracked 100 (maximum 300) test particles through five slices of strong bunch for $(10-50)\cdot10^3$ turns. Typical number of 30,000 turns corresponds to about 0.6 s in TeV'33, it is some 100 synchrotron oscillation periods. No damping due to radiation or cooling is assumed to play role in the beam dynamics. Further increase of the number of particles as well as number of slices gave almost identical results. The code assumes one-plane crossing angle (e.g. horizontal) and one IP.

The code outputs of greatest practical utility are luminosity, rms beam sizes and maximum betatron amplitudes which any of the test particles attained during tracking. These outputs are given with respect to unperturbed values, e.g. sizes and amplitudes are divided by their design rms values $\sigma_{x,y}/\sigma_{x,y}^0$ and $A_{x,y}^{max}/\sigma_{x,y}^0$, the luminosity is presented by the reduction factor of $R = L/L_0$ where the bare design luminosity $L_0 = f_0 N_p N_{\bar{p}}/(4\pi\sigma_x^0\sigma_y^0)$ and f_0 is the rate of collisions.

The relevant parameters of the simulations were chosen close to the TeV33 design ones, [1], namely: energy E=1000 GeV; p, $\bar{p}$/bunch $(N_p, N_{\bar{p}})$=(30, 6) $\cdot10^{10}$; the rms energy spread of $\sigma_E = \Delta E/E$=2.2$\cdot10^{-4}$ σ_z=15 cm rms bunch length; synchrotron tune ν_z=0.0045; rms transverse emittance $\varepsilon_{x,y}$=3 $\cdot 10^{-9}$ m·rad; beta-function at IP $\beta_{x,y}^*$=25 cm; nominal $\bar{p}$ beam-beam parameter ξ=0.025 (in TEV33 this tune shift is accumulated over two IPs). These parameters correspond to beginning of the collision store.

Results   Luminosity reduction due to geometrical "hourglass" and beam tilt effects depends on two parameters: the bunch length to beta function ratio $S = \sigma_z/\beta^*$ and normalized angle $\Phi = \phi\sigma_z/\sigma^*$ (also known as Piwinski angle). For TeV'33 $S = 0.6$ at the injection and about 1.0 after 12 hours of beam life time; the normalized angle of

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$\Phi = 1.0$ corresponds to $\phi = 0.183$ mrad. The simulations of the geometrical luminosity reduction shows the R goes down with either decrease of S or increase of Φ as shown in Fig.1. The approximate formulae $R \approx 0.96/\sqrt{1 + \Phi^2}$ can be used for the parameter of $S = 0.6$. At some particular tunes and the total luminosity degradation is about the pure geometrical one as in Fig.1, e.g. no signs of the degradation due to SBRs are seen after 30,000 turns with "good" tunes of $\nu_x = 0.57$, $\nu_y = 0.58$, $\xi = 0.025$ [4].
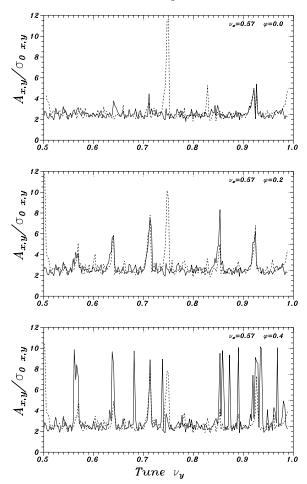

Figure 2: Maximum horizontal (A_x/σ_x^0 - solid) and vertical ($A_y\sigma_y^0$ - dashed) amplitudes vs. ν_y. $\nu_x = 0.57$, $\xi = 0.025$, $S = 0.6$, crossing angle $\phi = 0$ mrad (top), 0.2 mrad (center, $\Phi \simeq 1$), and 0.4 mrad (bottom).

Our simulations show that the resonances due to SB coupling distinctly manifest itself in the growth of the maximum betatron amplitude. The later is an indicator of transverse particle diffusion which forms a halo and concludes in particles losses. Performing scan over the vertical tune $\nu_y = 0.5....1.0$ with $\nu_x = 0.57$, we have found the resonance picture qualitatively changes with increase of the half-angle ϕ. Fig.2 presents the values of A_x/σ_x^0 (solid curves) and A_y/σ_y^0 (dashed curves) after 10,000 turns vs. ν_y without the crossing angle $\phi = 0$ (upper plot), and with crossing angle of $\phi = 0.2$ mrad (center plot) and $\phi = 0.4$ mrad (bottom plot). First of all, the number resonances grows with ϕ: five of them are seen without the angle, while
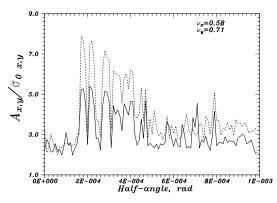

Figure 3: Maximum horizontal (A_x - solid) and vertical (A_y - dashed) amplitudes vs ϕ ($\nu_x = 0.58$, $\nu_y = 0.71$, $\xi = 0.025$, $\Phi = 0...5$, $S = 1$).

about ten and twenty at ϕ=0.2 mrad and 0.4 mrad, respectively, leaving not too much tune space for the collider operation. The synchrotron tune is comparatively small - at the particular case presented in Fig.2 $\nu_z = 0.0046$, therefore, the SBRs – at the tunes $\nu_{x,y,z}$ of $n\nu_x + m\nu_y + l\nu_z = q$, where (n, m, l) and q are integer – look like closely spaced sidebands of (n, m) resonances (line "splitting").

The major resonances at $\phi = 0$ are (4,-2); (2,4); (0,4); (0,6); (2,2); while a number of new SBRs appears at $\phi = 0.4$ mrad – split line of (1,-1,$\pm$1) at $\nu_y = 0.57$, (4,-2,0) and (4,-2,-2) at ν_y=0.64, (4,4,0) at 0.68, the line of (2,4) resonance becomes wider and lager; the (0,4,-2) sideband of the 3/4 resonance appears at 0.74; then one can see (2,1,0) at 0.86 and (2,1,2) at 0.87; split (2,2) lines at 0.93 and (1,-2,$\pm$1) at 0.97; higher order resonances are seen at ν_x =0.89 and 0.98. The degradation is also seen in the rms beam sizes but not as drastic as for the maximum amplitudes in Fig.2.

Finally, from Fig.2 one can conclude that at $\xi = 0.025$, $\nu_x = 0.57$, there are "windows" in ν_y without SB resonances at 0.51–0.56, 0.58–0.62 and 0.77–0.83. The first two are preferable from the point of larger luminosity [4]. This "off-resonant" case shows no meaningful changes in particles diffusion rates with increase of the angle, while at the "bad" operation point – see maximum amplitudes vs. the crossing angle with close to resonance tunes $\nu_x = 0.58$, $\nu_y = 0.71$ in Fig.3 – the amplitude does not grow until normalized angle of $\Phi \simeq 1$ ($\phi \simeq 0.2$ mrad), then rapidly increases and slowly decreases after $\Phi \geq 3$. That weakening of the SBR at $\Phi \sim 3 - 5$ is probably due to the fact that the effective beam-beam interaction becomes smaller due to the tilt effect.

In order to determine the tune space for better performance we made a 2-D scan over the tune space of ν_x, ν_y (0.55...0.65, 0.55...0.65). Without the crossing angle, betatron amplitude has no peculiarities. The resonance "hills" are clearly seen in the plots of maximum amplitudes of horizontal and vertical betatron oscillations – see top and bottom plots in Fig.4, respectively – if the crossing angle is equal to 0.2 mrad. After only 10,000 turns the ratio of $A_{x,y}/\sigma_{x,y}^0$ could reach values of the order of 5 at some res-

onance lines, while without the angle they do not exceed 2.7. One can recognize the most valuable resonances in the tune space – they are at $\nu_x \approx 0.59$ and $2\nu_x + \nu_y$ in horizontal dynamics, and at $\nu_x + 3\nu_y$ and $\nu_x + \nu_y$ in the vertical one. Note, that if both tunes are in the area of 0.55–0.59 then both amplitudes are small.
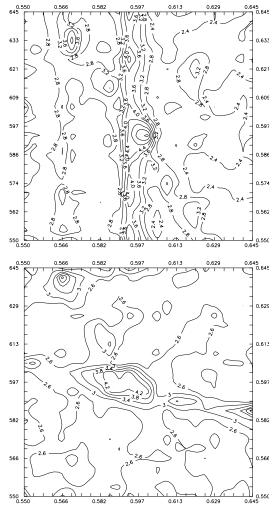

Figure 4: The A_x and A_y scan contour plots (upper and lower plots). The abscissa and ordinate are horizontal and vertical tunes, respectively;$\xi = 0.025$, $\Phi = 1$, $S = 0.6$

Fig.5 presents the luminosity reduction factor R contour plot in (ν_x, ν_y) plane. The darker areas correspond to the higher luminosities with maximum R of about 0.9. The contour spacing is 5% in luminosity reduction. One can see, that there several areas with small luminosity where the R is about 0.7. The lower left corner of the plot 0.55< ν_x <0.59, 0.55< ν_y < 0.59 is rather dark, that means better luminosity conditions.

3   DISCUSSION AND CONCLUSIONS

We found that far of resonances only geometrical luminosity degradation due to "hour-glass" and tilt takes place. We observe no enhanced particle diffusion over the tune space of $0.55 < \nu_x, \nu_y < 0.59$ with crossing angle less than
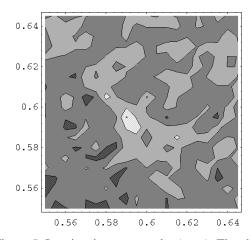

Figure 5: Luminosity contour plot (scan). The abscissa and ordinate are horizontal and vertical tunes, respectively;$\xi = 0.025$, $\Phi = 1$, $S = 0.6$.

0.2 mrad $\Phi < 1$, while other tune areas are influenced by synchrobetatron resonances, and dangerous increase of the loss rate occurs at $\Phi \geq 1$ ($\phi \geq 0.2$ mrad). The beam size or maximum betatron amplitudes do not grow monotonically with increase of Φ – instead, they rather be constant or even decrease slightly. The effects are found to be larger for larger beam-beam parameter ξ [4].

The experiments with crossing angle at the SPS(CERN) collider [6] shown no SB luminosity reduction and no substantial particle loss increase with parameters of $\Phi = 0.5$, ξ=0.02 and $\nu_z = 0.005$. We should emphasize that the TEV33 parameters are close to the SPS (except twice larger Φ), therefore, our "optimistic" conclusions about SB dynamics are consistent with the previous experience.

Nevertheless, the effects of tune ripple, coupling and sextupole fields in the rest of the lattice, two IPs instead of one, smaller synchrotron tune, beam separation at the IPs, and the crossings angle in two planes need further studies. The BBC code can also be used for investigation of the parasitic crossings effect.

4   REFERENCES

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