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SUMMARY OF THE WORKING GROUP ON BEAM–BEAM EFFECTS

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The main purpose of the Working Group on Beam–Beam effects was to review the operational aspects and side effects of the beam–beam interaction. SPS, TEVATRON and HERA experience was compared and an extrapolation to the LHC attempted.

KEY WORDS: Collective effects, linear accelerators: superconducting, synchrotrons: superconducting

1 OVERVIEW

The working group's main concern was operational aspects and side effects of the beam–beam interaction. Whenever possible, experience from the SPS, the TEVATRON and from HERA has been compared and an extrapolation to the LHC attempted. The following topics were discussed: Effect of unmatched cross-sections; beam halo and diffusion; modelling; sensitivity to resonances; effects of linear coupling; parasitic crossing effects; crossing angle effects.

The participants in the Beam–Beam Working Group were: O. Brüning, M. Furman, W. Herr, K. Hirata, E. Keil, J.-P. Koutchouk, J. Marriner, W. Scandale, R. Schmidt and F. Willeke (Chairman).

2 THE EFFECT OF UNMATCHED CROSS-SECTIONS

In p–p̄ operation in the SPS collider, a blow-up of the strong proton beam has been observed if the $\bar{p}$-beam has a smaller emittance than the proton beam.[1]

From the TEVATRON such an effect has never been reported, but the SPS experience has been confirmed by observations made at HERA. The e–p collider HERA is a double ring machine where the collision parameters, and in particular the cross-section of the beams at the interaction point, are not automatically matched. In HERA matched cross-sections are most important for the stability of the proton beam, as can be seen from Table 1, which summarizes the conditions under which HERA has been operated. The stability of the proton beam is here characterized by the beam lifetime. The effect is evident if one compares line

TABLE 1: HERA Collision Parameters.

	Protons				Electrons			
	E [GeV]	$\Delta\nu_x, \Delta\nu_y$ $[10^{-3}]$	σ_x, σ_y [mm]	τ Date [h]	E [GeV]	$\Delta\nu_x, \Delta\nu_y$ $[10^{-2}]$	σ_x, σ_y [mm]	σ_y^p/σ_y^e
10-91	480	3.1,2.0	0.32,0.10	1	12.0	0.3,0.3	0.13,0.02	5
10-91	480	0.7,0.4	0.32,0.10	10	26.5	0.3,0.4	0.28,0.04	2
11–91	480	0.7,0.2	0.32,0.10	50	26.5	0.3,0.6	0.28,0.05	1.6
10–92	820	0.8,0.6	0.21,0.07	100	26.5	0.6,1.1	0.28,0.05	1.4
1993	820	0.7,0.4	0.19,0.06	200	26.5	0.8,1.8	0.28,0.06	1
1994	820	0.4,0.3	0.19,0.06	300	27.5	1.3,1.8	0.30,0.05	1.2

two with line five in Table 1. The beam–beam tune-shifts are the same but the lifetimes in the two cases differ by a factor of 20.

Another manifestation of the effect is the emittance growth. The proton beam in HERA exhibits with beam–beam interaction an emittance growth of $3 \times 10^{-4}\pi$ mrad mm h^{-1} which is about two to three times larger than the growth without beam–beam interaction. This growth is accelerating while the beams are colliding since the beam sizes become unmatched.

Since such an effect was never observed in the TEVATRON, a comparison of the collision parameters of SPS, the TEVATRON and HERA has been performed in the working group. The result of this comparison is that the TEVATRON experience is not in contradiction with the SPS and HERA experience. In Table 2 the main operational parameters of the three machines are listed. Table 3 compares beam cross-section ratios.

The effect of unmatched cross-sections is thus experimentally well established. The theoretical understanding is still poor. One of the open questions discussed in the working group was why unmatched cross-sections are very detrimental whereas a relative separation of the two beams, which also enhances the degree of nonlinearity, seems to be not nearly as harmful, as we know from experience at all three accelerators. O. Brüning pointed out that this behaviour is consistent with a strong threshold-like increase in the driving

TABLE 2: TEVATRON and HERA Main Parameters.

Parameters	SPS	TEVATRON	HERA
Energy/GeV	350	920	820
$N_p/10^{11}$	1	2	0.4
$\Delta\nu/10^{-3}$	3	3	1
$\varepsilon\cdot\gamma/\pi$ mrad mm	6	3	4
Bunchlength/ns	1	1.8	0.6
Synchrotron Frequency/Hz	178	47	30

TABLE 3: SPS, TEVATRON and HERA Ratio of Beam Cross-Section.

Machine	Particles	Stability	σ_1^x/σ_2^x	σ_2^y/σ_2^y
HERA	$p(=1), e(=2)$	poor	2	1.15
HERA	$p(=1), e(=2)$	excellent	1	0.70
SPS	$p(=1), \bar{p}(=2)$	poor	1.7	1.7
SPS	$p(=1), \bar{p}(=2)$	good	1.25	1.25
TEVATRON	$p(=1), \bar{p}(=2)$	good	1.30	1.30

terms of the nonlinear resonances exited by the beam–beam forces. This threshold occurs for amplitudes larger than 2 σ of the cross-section of the opposite beam.[2] On the other hand, in case of partly separated beams, the driving terms of even-order resonances are little affected. Indeed, there are additional odd-order resonance driving terms generated, but their strength is a smooth function of the separation. No threshold-like behaviour can be found.

The working group concluded that the unmatched cross-section effect is an important one for double ring colliders. There should be sufficient flexibility in the optics design to compensate for possible deviations in the cross-sections of the two beams.

3 DIFFUSION, HALO

The conventional wisdom on halo formation and population of the tails of the distribution function in the presence of beam–beam interaction is that it is caused by diffusion-like behaviour of the particle amplitudes. If the amplitudes exceed about 2 σ of the size of the opposite beam, the quasi-diffusion becomes particularly strong and exhibits a strong amplitude dependence. The theory of nonlinear dynamics tells us that the reason for this quasi-stochastic motion is that the trajectories of the particles in phase space become infinitely complicated near nonlinear resonances. A modulation of the particle tunes creates additional resonances, sidebands, which surround each nonlinear resonance. This enhances the probability for quasi-stochastic behaviour.

Recently, new experimental evidence on the influence of modulation on particle losses in the presence of the beam–beam effect was obtained from HERA[3] and discussed in the working group.

A tune modulation with a depth of $\Delta Q_{\text{mod}} \simeq 10^{-4}$ in the frequency range between 100 Hz–200 Hz was applied. At modulation frequencies of around 1100 Hz, a pronounced maximum of beam losses occurred. For these modulation frequencies, the tunes coincided with the first modulation sideband of the 7th-order resonance driven by beam–beam effect (if the beams collide with a small offset). Observing the losses by moving in and retracting a beam scraper allowed a diffusion constant to be determined[4] which characterizes the beam dynamics in this situation. This was accomplished by using the solution of the diffusion equation as a fit function ('local diffusion model'). The diffusion constant determined in this way agrees within a factor of ten with an analytical calculation of modulational diffusion.[5]

The frequency content of the losses was analyzed. It turned out that for multiples of the line frequency up to 1200 Hz and for other distinguished frequencies such as vibrations induced by the rotating vacuum pumps, one observes enhanced beam loss rates. In a further step, a 150 Hz tune modulation phase locked to the line frequency was applied by modulating the current of a quadrupole magnet supply. Amplitude and phase could be adjusted such that the original loss at 150 Hz was compensated.

The members of the working group agreed that it would be worthwhile to continue these type of experiments. It was suggested that the frequency spectrum of beam losses should be regularly stored and made available for post processing.

4 MODELLING

The working group has attempted to summarize the experience with simulations of beam stability in the case of weak–strong beam–beam interactions by drawing up a list of features which have to be included in a particle tracking code:

(a) Motion in six dimensions of phase space

(b) Beam–beam interaction taking into account exact treatment of the crossing angle and finite bunch length (see below)

(c) Parasitic crossings

(d) Tilt of flat beams

(e) Tune modulation from power supply ripple, ground motion, relative motion of the two beams, and shape oscillations of the opposing beam

(f) Lattice nonlinearities — most important is to add the amplitude dependence of the tunes generated by the lattice nonlinearities; for tail studies it is necessary to take into account a detailed description of the fields even if they do not compete with the beam–beam force for small amplitudes

(g) Linear coupling — it might be important to model the local residual coupling in case the coupling is globally corrected

(h) Noise effects in rf amplitude and phase, multiple and intra beam scattering are important for the study of tail population.

5 BEAM–BEAM DRIVEN RESONANCES

The working group made a comparison of the sensitivity to nonlinear resonances in beam–beam operation in the three colliders SPS, TEVATRON and HERA. The operational experience is that all three machines are sensitive to resonances up to order 17. If the tunes are placed in the vicinity of these resonances, one observes enhanced beam losses and a reduction of the beam lifetime. In all three machines, the working point has been chosen for this reason near the main coupling resonance. Here is a list of the working points:

(a) SPS: $Qx = 26.69$, $Q_y = 27.685$

(b) TEVATRON: $Q_x = 19.56$, $Q_y = 20.57$

(c) HERA: $Q_x = 31.294$, $Q_y = 32.298$.

It should be noted here that the TEVATRON experiment for operating with the tunes close to integer values failed. The main reason for this failure was the sensitivity to orbit distortions at these tunes which caused a serious operational problem.

Another remark is that HERA cannot be operated at the SPS tunes. For tunes above $Q_x = 31.3$, $Q_y = 32.3$ the backgrounds are strongly enhanced and the beam lifetime drops from 100 h to 10 h or less. The reason is a strong 1/3-integer resonance, caused by the fact that the field quality of the superconducting dipole magnets have a nonsystematic sextupole component with rms values of $\int B_3 dl / \int B_1 dl = 3 \times 10^{-4}$ measured at $r = 25$ mm. This produces a width of the $3Q_x = 94$ resonance of $\Delta = 0.01$ for an amplitude of 6 σ of the beam size.

6 COUPLING EFFECTS

The working group discussed the interference of linear coupling and the nonlinear beam–beam force. The appropriate way to include coupling in the description of nonlinear resonances is, as in Reference 6, to describe the nonlinear fields in terms of the eigencoordinates of the coupled system. If one proceeds in this way one recognizes that the coupling changes the dynamics of the system by the generation of so-called skew resonances characterized by $n_1 \cdot Q_1 + n_2 \cdot Q_2 = p$ where n_1, n_2, p are integers and n_2 is odd. In the absence of linear coupling, skew resonances are usually small, since all the fields in an accelerator are designed with midplane symmetry. One finds that the strength of the normal resonances (n_2 even) is little affected by coupling. Therefore, the density of resonances for strong coupling is enhanced by a factor of about two. Strong coupling is always present on or close to the main diagonal in the tune diagram, near the coupling resonance $Q_x - Q_y =$ integer. The strength of the skew resonance is, in good approximation, proportional to the strength of normal resonances and to the ratio of the driving term of the coupling resonance (which determines the minimum distance of the eigentunes $|Q_1 - Q_2|_{\min}$) and the distance of the tunes from the coupling resonance, $|Q_1 - Q_2|_{\min}/|Q_1 - Q_2|$. One can conclude that linear coupling causes operational difficulties and loss of stability by a combination of a limitation of the choice of the working point and an enhanced density of resonances.

The sensitivity to coupling effects in all three machines is about the same. In order to assure tolerable background conditions, one must reduce the width of the coupling resonance to $|Q_1 - Q_2|_{\min} \leq 0.005$ (global coupling compensation) and the tunes must be chosen outside the vicinity of the residual coupling resonance $|Q_1 - Q_2| \geq |Q_1 - Q_2|_{\min}$.

7 EFFECTS OF PARASITIC CROSSINGS

Parasitic crossings are a subject of concern in every multibunch collider and this is also true for the LHC. The fact that not all the bunches experience the same parasitic crossings might be particularly harmful. This has been called the 'Pacman Effect'. A train of bunches must have gaps — for example, for injection and abort kickers — unless one is willing to accept that the risetime of the fields in these elements limits the luminosity. The bunches at the edges of the trains obviously see fewer parasitic crossings than the central bunches. Since the operational parameters such as tune and orbit have to be optimized for the majority of bunches, the edge bunches might suffer bad lifetime and in an extreme case might even be lost so that the next bunch takes over the part of the lost one.

For the LHC, an increase of the beam–beam-induced tune spread over the bunches by a factor of two to three has been calculated[7] by taking into account the effect of edge bunches. The bunch-to-bunch spread can, however, be reduced in case of an even number of interaction regions if the beams are separated alternately in the horizontal and the vertical plane. Then the parasitic beam–beam tune-shifts cancel within a pair of interaction regions. There is a small concern arising from this scenario. Whereas the tuneshift from parasitic crossings cancels, this does not happen for the orbit distortions induced by the parasitic crossings. If there is also separation in the vertical plane, there will be a vertical closed orbit error inside the sextupoles for edge bunches which might increase the linear coupling. The contribution to the tune split has been estimated by the working group and found to be in the order of $|Q_1 - Q_2|_{\min} \simeq 0.002 \ldots 0.006$, which is at the edge of being significant.

The fact that the supersymmetry for edge bunches will be broken is not considered to be of great importance since the symmetry breaking effect from field imperfections is expected to be of the same magnitude.

As mentioned above, edge bunches will suffer from closed orbit distortions due to missing parasitic crossings. It has been estimated that these distortions will cause the edge bunches to be separated at the main collision point by, at most, $1\ \sigma$ of the beam size. This, however, is not expected to cause a serious reduction in the lifetime of these bunches, being infered from experience with slightly separated beams at the SPS, the TEVATRON and HERA.

Nevertheless, the problem of distorted orbit for edge bunches was deemed serious enough for the working group to discuss possible cures. It seems quite obvious that a correction system with fast and strong kickers is not feasible. Whereas the required bandwidth of 5 MHz is not outrageously large, the required power exceeds the power of existing systems (for example the HERA multibunch feedback) by four orders of magnitude. In addition, a distributed system is required, since the orbit distortion has to be corrected locally. It might be possible to tailor the bunch intensity along the bunchtrain in such a way as to minimize the distorted orbit. However, the price to pay is a considerable reduction in luminosity ($\simeq$(25–50)%).

Another way to deal with the problem is to reduce the parasitic crossing effect in the first place by choosing a larger crossing angle. This point will be discussed below.

Unfortunately, there is little that one can learn from HERA on edge bunch effects. The bunch spacing in HERA, 96 ns, is not limited by the interaction region layout and by parasitic crossing but by the achievable longitudinal density of proton bunches in the accelerator chain. Therefore, there are only two parasitic crossings in HERA which induce a tune shift in the order of $\Delta Q \simeq 10^{-5}$.

8 CROSSING ANGLE EFFECTS

Hirata presented a new way of calculating the beam–beam forces acting on a particle in a bunch which crosses the opposing bunch under an angle.[8] The main features of the new method are:

(a) A transformation into a frame which moves with respect to the collision point. The velocity vector of the frame is given by the sum of the velocity vectors of the two beams ($\vec{v}_{\text{frame}} = \vec{v}_{\text{beam1}} + \vec{v}_{\text{beam2}}$). In this frame the two beams collide head-on but the bunches are tilted around an axis perpendicular to the crossing plane.

(b) The beam–beam forces in the moving frame are represented by several transverse kicks. Each kick contains the contribution of the forces from a slice of the bunch.

The working group tried to understand the difference between the old and the new methods of calculating crossing angle effects. Unfortunately, the new method does not provide compact formulae which would allow a straight-forward comparison of crossing parameters such as Piwinski's normalized crossing angle.[9] The result of the discussion is a qualitative comparison of several aspects and effects of beam–beam interaction under a crossing angle as follows:

(a) Longitudinal Fields resulting from the crossing geometry: The new model provides a rigorous treatment of the geometrical effect. The conventional method is a good approximation.

(b) Dependence of the transverse kick from the longitudinal position in the bunch: This is taken into account in the new method by 'slicing'. The conventional method is a fairly good approximation.

(c) Individual Particles collide under individual angles with the opposite bunch: This is not a crossing angle effect. It also occurs for head-on collisions. The new method takes this effect into account since the moving frame is calculated for each particle individually. This effect is not taken into account in the conventional picture.

(d) Enhancement of crossing angle in the head and the tail: If the longitudinal centre of the bunch is at the collision point, where the slope of the beam envelope function is zero ($\alpha = 0$), head and tail are in a region with $\alpha \neq 0$. Therefore, the average slope of head or tail is different from zero (for example, for a uniform distribution $0 < \varepsilon < \varepsilon_{\text{max}}$ one has $< x'(x) >= 2\alpha \cdot x/(\sqrt{\varepsilon_{\text{max}}\beta} + x))$ Thus this effect increases the normalized crossing angles for the head and the tail. This effect is particularly strong if the beams collide under a crossing angle. Then, the particles in head and tail have a systematic offset with respect to the centre of the opposite beam. This effect is taken into account only in the new method.

(e) The hourglass effect: If the β-functions at the collision point are not the same in both planes $\beta_x^* \neq \beta_y^*$, then the beam–beam tune shift is enhanced in head and tail. The enhancement factor can be as large as $\simeq 1/2 \cdot \sqrt{\beta_x^*/\beta_y^*}$ (for equal beam emittance in both planes). This effect is also taken into account only in the new method. It is, however, not a crossing angle effect, but also occurs for head-on collisions.

(f) Tracking Studies: Hirata reported on tracking studies made for the KEK B-factory. A normalized crossing angle of $1/2\Phi\sigma_s/\sigma_x = 0.5$ turned out to be tolerable. It is believed that in DORIS-I, where the normalized crossing angle was close to unity, crossing angle effects have been the reason for perfomance limitations. Unfortunately a direct comparison of the results of calculations with the conventional and the new method are not yet available. It is considered very worthwhile to carry out such a comparison.

(g) Experimental Evidence: Experimental experience was reported by the working group from the SPS, the TEVATRON and from HERA. In a test in the SPS, a normalized crossing angle of $1/2\Phi\sigma_s/\sigma_x = 0.45$ between the p- and the $\bar{p}$-beam was installed using electrostatic separators. No detrimental effects could be detected under these operating conditions. In the TEVATRON, no tests have so far been made. However, a normalized angle of $1/2\Phi\sigma_s/\sigma_x = 1.8$ would be possible. A crossing angle experiment in the TEVATRON therefore would be very beneficial. In HERA, under normal operation a normalized crossing angle of 0.12 is possible, and HERA was occasionally operated under such circumstances. There is no clear evidence that this produces problems.

(h) Conclusions for the LHC: For the LHC, the working group has concluded that a crossing angle larger than 200 μrad might provide a more favourable solution for the layout of the interaction region. The LHC designers are encouraged by the group to investigate this option using the new tools for investigating beam–beam interactions under a crossing angle.

9 CONCLUSION

Small changes in the operational parameters such as tune chromaticity, coupling, and tune modulation can make a large difference in performance, and we are still far from a quantitative understanding.

It is very difficult to predict beam lifetime, halo and tail forming, or backgrounds by particle tracking. The models which have been used so far are incomplete.

The working group did not identify exceedingly critical issues in the beam–beam interaction with parameters as envisioned for the LHC.

There might be room for further improvements of the the LHC collision scenario. In particular, a larger crossing angle might lead to a better solution.

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