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A SURVEY OF BEAM-BEAM LIMITATIONS *

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I. INTRODUCTION

The effect of beam-beam interaction is not normally felt in the ISR and will probably not be a serious problem for ISABELLE, at least at high energy. However, it is known to limit the luminosity of electron-positron storage rings and will, no doubt, limit the proton-antiproton collision scheme for the SPS. While theorists are struggling to explain this phenomenon it is more instructive to list their failures than their rather limited successes, in the hope that experiments may emerge which will direct their endeavors.

The search for a description of a nonlinear system as it approaches the limit in which ordered motion breaks down, is the nub of the problem. It has engaged many fine mathematical intellects for decades and will no doubt continue to do so long after ISABELLE, the $p\bar{p}$ and LEP are past achievements.

Empirical scaling laws are emerging which relate electron machines to each other but their extrapolation to proton machines remain a very speculative exercise. Experimental data on proton limits is confined to one machine, the ISR, which does not normally suffer the beam-beam effect and where it must be artificially induced or simulated. This machine is also very different in important ways from the $p\bar{p}$ collider.

The gloomy picture which has emerged recently is that the fixed limits which were conventionally assumed for proton and electron machines can only be said to be valid for the machines which engendered them - the best guess that could be made at the time. They are very difficult to extrapolate to other sets of parameters.

II. THE CONVENTIONAL LIMITS

First it should be said that the beam-beam limit as seen in electron machines appears as a phenomenon which increases the beam size of one or other of the beams as soon as they collide. Luminosity and lifetime suffer and above a critical current the situation becomes rapidly worse. In proton machines the beam-beam forces cause a steady dilation of emittance and beam loss over many hours.

A year ago it was commonly held that the maximum values for the linear $\Delta\nu$ (used as an index for the nonlinear forces which cause the phenomenon) were different for electron and proton machines but independent of design energy and other machine parameters. The conventional limit for e^+e^- machine was taken to be between $\Delta\nu = 0.03$ and 0.06. Designers, hoping for improvements in understanding as their machines were built, took the higher figure for future projects.

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The corresponding limit for proton machines was assumed to be an order of magnitude smaller ($\Delta\nu = 0.005$). Estimates had been made of how the limit depended upon the growth time to which one was sensitive. This suggested that if at $\Delta\nu = 0.05$ the growth time is a few milliseconds and sufficient to overcome the radiation damping of an electron machine it would extend to many hours at a lower limit of $\Delta\nu = 0.005$ and then be tolerable for an undamped proton machine.

Analysis of ISR behavior in situations where a nonlinear lens, intrabeam scattering and partial neutralization were severally thought to simulate features of the beam-beam interaction seemed to confirm the order of magnitude of $\Delta\nu = 0.005$. Further confirmation came when the beam-beam limit was induced in the ISR by running at low energy and with a high beta configuration on one of the beams to enhance $\Delta\nu$.

Later we shall show how experimental evidence from electron machines leads one to believe the electron limit is not fixed but energy and machine dependent, while the ensuing deeper examination of the beam-beam mechanism gives good reasons for believing the ISR proton limit may be too optimistic for the bunched beams of the $p\bar{p}$ collider.[1]

III. CLASSIFICATION OF MACHINES AND EFFECTS

Before embarking on this classification a few very qualitative words about the dynamical model of the effect are in order for those who are not conversant with the theory. It is believed that the diffusion or beam dilation occurs when nonlinear forces are strong enough to produce a chaotic motion which we shall for the moment refer to as stochastic. Since the beam-beam force is linear for small betatron displacements the chaotic motion characteristic of the stochastic limit will occur only for particles whose betatron amplitudes are above some lower limit. We can think of the beam-beam interaction as defining a "stochastic boundary" in the betatron phase plane such that motion "inside" the boundary is stable, and that particles which once cross this boundary enter the land of stochastic motion where they begin a random walk towards death. As the strength of the beam-beam interaction increases we expect the "radius" of the stochastic boundary to decrease and the so-called beam-beam limit will occur when the boundary begins to encroach significantly upon the phase area occupied by the stored beam. Nonlinear forces generate islands of bounded motion in phase space. One may think of the stochastic boundary as the point where these islands merge covering a majority of the available phase space.

The strength of the nonlinear forces necessary to cause the islands to merge depends on the number of degrees of freedom of the system. If there are more degrees of freedom the number of islands and possible resonant conditions is increased. They need not therefore be as strong before they merge. It is instructive to classify the various machines in terms of the number of degrees of freedom.

At first sight ISR and ISABELLE appear to have only one degree of freedom. Their beams are unbunched and are cross at a finite angle where they are wide and flat. The interaction should be almost entirely in the vertical plane. Any small horizontal forces tend to cancel as the beams cross. However, if one calculates the $\Delta\nu$ limit for one degree of freedom it turns out to be 0.2 and much larger than the empirical 0.005 for these machines. To reconcile theory with experiment one must believe there is after all some coupling into a second degree of freedom and, in addition, that other processes like intrabeam scattering hasten the journey of particles to the stochastic region. This situation is at best unsatisfactory.

Electron-positron machines and the $p\bar{p}$ collider are clearly machines in which the beam-beam forces act in two coupled degrees of freedom (vertical and radial) as their beams clash head on. The $\Delta\nu$ which produces the stochastic limit is lower for the more numerous resonant conditions of a coupled system and has been calculated to be $\Delta\nu = 0.05$. Moreover in contrast to one degree systems, Arnold diffusion is possible. This is a nonlinear diffusive process which promotes the migration of particles even well within the stochastic boundary and effectively lowers the $\Delta\nu$ limit.

The bunched beam machines, e^+e^- and $p\bar{p}$ also have a third degree of freedom; the longitudinal plane, which must aggravate the situation still further. Synchro-betatron resonances are possible adding further to the number of islands so that one would expect the $p\bar{p}$ or hypothetical undamped e^+e^- machine to have a lower $\Delta\nu$ limit than the ISR's $\Delta\nu = 0.005$. Another way of convincing ourselves that this is the case is to remember that switching on the rf speeds beam loss if nonlinear resonances are near enough to be crossed in the course of synchrotron motion.

Electron machines of course have synchrotron radiation damping which takes care of beam-beam diffusion if it is lower than the few milliseconds damping time constant. However they have two other (perhaps related effects) which give us hope that they are worse than the $p\bar{p}$ collector. The noise induced by quantum emission probably makes the stochastic diffusion worse and in an electron machine, particles are continually sampling the edges of phase space. In a proton machine betatron and synchrotron amplitudes remain invariable for a given particle and there are no quantum jumps.

There have been extensive attempts to simulate electron machines with computers (e.g. Close at Berkeley) and these confirm that synchrotron motion is an essential ingredient in simulating their beam-beam effects.

While it seems reasonably safe to extrapolate ISR experience to a similar machine like ISABELLE and while as we shall see electron machines are beginning to fit into a pattern, the $p\bar{p}$ is so dissimilar from existing machines and the theory so incomplete that it is difficult to say more than its $\Delta\nu$ limit will be lower than the ISR and higher than an electron machine with a damping constant of many hours. However since it bears more similarity to the electron machines let us explore what one may learn from them.

IV. EXPERIMENTAL EVIDENCE FROM ELECTRON POSITRON MACHINES

Very recent and yet unpublished measurements from the SPEAR Group, clearly confirm the energy dependence of the small amplitude beam-beam tune shift $\Delta\nu$ (previously observed at ACO, ADONE and SPEAR itself) down to energies as low as 0.6 GeV.

Data from existing electron machines now extend to damping times as long as ~ 1 s, a small but significant step in the direction of undamped proton machines.

Although the dynamics of the beam-beam interaction is far from being understood, existing data on the maximum tolerable $\Delta\nu$ exibit common distinctive features.

$\Delta\nu$ is a function of energy below a certain threshold energy E_o, depending on the particular machine and exibits the expected energy independent behavior above threshold.

The energy dependence is of the form E^{α} with α in between 1 and 2.[2]

It has been suggested, on the basis of simple models postulating the effect of beam-beam interaction to be equivalent to a random excitation in the betatron phase space,[3-5] that the energy dependence comes in through the scaling parameter

$$\sqrt{\dot{n}\,\tau_D} \propto \sqrt{\frac{b\rho}{E^3}} \qquad \begin{array}{l} b = \text{bunch number} \\ \rho = \text{bending radius} \end{array}$$

the number of interactions in a damping time.

The square root dependence on the number of bunches is well established for those machines (ACO and ADONE) capable of operating with different bunch numbers (b). Experiments with many bunches have also been performed at the CEA,[6] where this type of behavior was not observed. However the $\Delta\nu$ was extremely small and the beam configuration so different from that of the other space charge limited rings that we do not think they fall in the same class as the others. The prediction of the "threshold" energy is still not entirely satisfactory but some degree of success has been obtained by a number of authors[3,4,7] in trying to unify the data from different machines. If the picture should prove to be essentially correct, it is somewhat alarming to find the $\Delta\nu$ limit for SPEAR when the damping time is as short as 1 second, is already as low as that assumed for $p\bar{p}$ which must preserve emittance for many hours.

If one can extrapolate the existing data from electron machines to the number of crossings corresponding to a 24 h life-time in the SPS, one would predict the tolerable $\Delta\nu$ for $p\bar{p}$ to be much lower than 10^{-3}.

Such an extrapolation over two orders of magnitude in $\sqrt{\dot{n}\tau}$ is, of course, very questionable and almost certainly pessimistic since it ignores the points mentioned above in favor of proton machines.

V. CONCLUSIONS ON $p\bar{p}$ COLLIDER

It would be unwise to close ones eyes to the reasons for now suspecting that the $\Delta\nu$ limit is lower than that derived from ISR experience with an unbunched beam. However there is encouraging evidence from the ISR that at $\Delta\nu = 0.0005$ per crossing the dynamics resolve into ordered motion again.[8] Beam-beam induced resonances up to eighth order can be clearly seen at discrete momenta in the ISR stack with a transverse Schottky scan. If these resonances are the major destructive mechanism of the beam-beam effect one can hope to steer the much smaller $\Delta p/p$ of the SPS between them. Should this prove to be the case it will still be possible to reach the lower end ($L = 10^{29}$) of the range of luminosities expected from the p-$\bar{p}$ scheme. Provided one is prepared to inflate transverse beam dimensions rather than reduce bunch intensity, the $\Delta\nu$ per encounter could then be as low as 0.0004 for 6×10^{11} particles in each beam.

How far one may expect to progress in the direction of higher luminosity must depend on the application of ingenuity to the problems of beam separation and exploration of the working diagram. To improve our understanding of these phenomena before we come to meet them face to face we suggest a number of experiments which are relevant to p$\bar{p}$ and future e^+e^- projects.

VI. PROJECTED EXPERIMENTS

Clearly, of the machines studied, the p$\bar{p}$ is the one most sensitive to the uncertainties in the theory because no comparable bunched proton collider exists. Experiments to find $\Delta\nu$ for bunched beams might be carried out in the ISR to narrow the considerable window of uncertainty between the conventional limit to that extrapolated directly from electron machines. Experiments simulating nonlinear behavior with the SPS proton beam and the ISR nonlinear lens could also throw some light on the harmful effect of synchrotron motion.

Electron machines encouraged by the emergence of a semi-empirical fit will no doubt extend the measurements of energy dependence. This is especially urgent at the long damping time end for p$\bar{p}$ and at the high energy end for LEP. PETRA and PEP can provide valuable information on this and on the bunch number dependence.

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