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by

A. Hofmann, L. Vos, B. Zotter

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A. Hofmann, L. Vos, B. Zotter

CERN, Geneva, Switzerland

ABSTRACT

A series of experiments on the beam-beam effect has been performed at the CERN Intersecting Storage Rings colliding a bunched test beam with a strong continuous beam. The beam-beam tune-shift was increased by various means to a maximum value of about 3.5×10^{-3} per intersection (for 8 crossings). When the beams were colliding well-centered, the blow-up of the effective height of the test beam was still very slow at this value. However, the blow-up rate increased sharply when the beams were off-centered at the intersections by approximately one standard deviation, and decreased again when the test beam was debunched.

1. INTRODUCTION

The beam-beam limit for colliding charged particle beams appears as the ultimate limitation of the luminosity which can be reached in high-energy storage rings. While it is essentially caused by non-linear effects, the linear beam-beam tune-shift ΔQ_{bb} is usually taken as a measure of its strength. More correctly one should use the parameter ξ , which is related to ΔQ_{bb} by ¹⁾

$$2\pi\xi = \sin 2\pi\Delta Q_{bb} \left[1 + \frac{\tan \pi\Delta Q_{bb}}{\tan \mu} \right]$$

where μ is the phase-shift between crossing points. For small values of $\Delta Q_{bb} \ll 1$ and phase-shifts not too close to a multiple of π , ξ and ΔQ_{bb} are approximately equal.

For electrons (or positrons) a large body of experimental evidence exists ²⁾ which shows that the beam-beam limit lies in the neighbourhood of $\Delta Q_{bb} \approx 0.06$, its exact value depending on the particular storage ring. For protons, however, the only experimental evidence for a beam-beam effect comes from the CERN Intersecting Storage Rings (ISR), where experiments with continuous beams ³⁾ have shown an exponential increase of the blow-up rate in the range of $\Delta Q_{bb} = 0.01 - 0.02$.

At present, two colliding $p\bar{p}$ facilities are under construction at FNAL and CERN which will operate with tightly bunched beams colliding under very small crossing angles or head-on. These conditions differ substantially from the ISR, where continuous beams of long bunches collide under a large crossing angle. Non-linear theory predicts a region of stability below the "stochastic limit" only for the one-dimensional case, i.e. when the tune-shift is large only in one transverse direction as in the ISR. For the two-dimensional case, i.e. when the tune-shifts are comparable in both transverse directions - as is the case for most electron machines or the $p\bar{p}$ colliders - a more or less rapid diffusion is predicted for any value of ΔQ_{bb} . Since the actual situation is much too complex for analysis, several computer programs have been written to simulate the behaviour of particles in a weak "test"-beam colliding with a strong beam. For electrons one needs to follow the particles only for the damping time, and results can be obtained with a reasonable effort. For protons, however, the damping times are much too long and one should follow the particles for the full storage time, which is impractical even with the fastest existing computers.

Recent experimental evidence of the dependence of the beam-beam limit on the damping time in an e^+e^- storage ring, if extrapolated to the desired storage times of 24 hours for $p\bar{p}$ colliders, led to extremely low predictions of the beam-beam limit for bunched proton beams colliding head-on. A series of experiments with bunched proton beams was therefore performed at the ISR in the autumn of 1979, in addition to experiments with the "non-linear lens" at the CERN-SPS which are reported elsewhere in this Conference ⁴⁾.

Although the beam-conditions are quite different in the ISR compared to the $p\bar{p}$ colliders, these experiments indicated that beam-beam tune-shifts in the required range can be supported by bunched beams without catastrophic effects and the worst fears were thus dispelled. However, the final answer to the problem of the beam-beam limit of bunched proton beams can only become available when the $p\bar{p}$ colliders are operating and specific experiments are performed under controlled conditions.

2. EXPERIMENTS AT THE CERN INTERSECTING STORAGE RINGS

The vertical beam-beam tune-shift ΔQ_{bb} per intersection for small amplitude particles in a test-beam, colliding horizontally with a strong beam under a large crossing angle α can be written

$$\Delta Q_{bb} = \frac{60\sqrt{2}}{\alpha} \left[\frac{\beta_v^*}{\frac{pc}{e}} \right]_t \left(\frac{I}{h_{eff}} \right)_s \quad (2)$$

where β_v^* is the betafunction at the intersection and p the momentum of the test beam, while I is the current and $h_{eff} = 2\sqrt{\pi} \sigma$ the effective height of the strong beam. For the ISR, the crossing angle is 258 mrad, and we get approximately

$$\Delta Q_{bb} = \frac{10^{-3}}{3} \left[\frac{\beta_{v/m}^*}{\frac{pc}{e/GV}} \right]_t \left(\frac{I/A}{h_{eff/mm}} \right)_s \quad (3)$$

Under regular operating conditions for storing large currents $pc/e \approx 26.5$ GV and $\beta_v^* \approx 12.5$ m. For a current of 30A one can get effective heights down to about 4 mm, which leads to $\Delta Q_{bb} \approx 1.2 \times 10^{-3}$. Measured values of the beam-beam tune-shift agree quite well with these calculations if a reduction of about 30% is taken into account which is due to the finite amplitudes of the particles in the test beam. However, for comparison it is customary to use the theoretical value of ΔQ_{bb} valid for zero-amplitude particles.

Large currents can be obtained in the ISR only with continuous beams, while bunched beams are limited to less than about 3A by the RF system which was only designed for stacking. Hence only very small values of ΔQ_{bb} could be obtained by colliding two bunched beams. However, by colliding a bunched test beam with a large continuous beam interesting values of ΔQ in the 10^{-3} range can be reached, especially if one or several of the factors in Eq(3) can be improved over their regular values. Such a situation had occurred in an earlier experiment at the ISR dating back to 1973, where a bunched beam had been collided with a coasting beam for other reasons. However, the current in the "strong" beam was only 5A, and thus the beam-beam tune-shift only a few times 10^{-4} . In order to reach

higher values of ΔQ_{bb} under well-controlled conditions, a series of 5 experiments was performed at the ISR in the autumn of 1979. Due to the complexity of the operations these experiments were extremely time consuming, and only a part of the planned measurements could be performed within the scheduled MD-runs.

The first experiment consisted of a straight-forward increase of the current in the strong beam while keeping the effective height small by heavy "shaving" during stacking. An energy of 26.5 GeV was chosen as being the best for obtaining high currents. Nevertheless, only 25A were reached in this experiment but with an effective height of 4.2 mm on average, corresponding to $\Delta Q_{bb} = 10^{-3}$. A bunched test-beam of about 100 mA was injected in the other ring and again kept small by shaving. The working point of the test-beam was carefully adjusted to a region free of resonances below 13th order ($Q_V = 8.612$, $Q_H = 8.622$, $Q_{H,V} \approx 0.5$). The beams were steered to obtain maximum luminosity in all 8 intersections, and the luminosity decay was monitored for over one hour. Its value of $2.4 \pm 2.6\%/hr$ is much larger than usually obtained with coasting beams under these conditions, but it remained essentially unchanged when the beams were displaced by ± 1 mm in alternate intersections (corresponding to about one standard deviation) (see fig.1). Since the non-linear forces should become much stronger when the beams are off-centered by $1-2\sigma$, the observed luminosity decay was considered not to be caused by the beam-beam effect, but possibly by RF noise or instabilities of the bunched beam. A somewhat larger decay rate was found when the beams were displaced by ± 2 mm ($7.2 \pm 7.3\%/hr$), but the result is still compatible with the earlier measurements when the error-bars are included, which were larger due to a shorter measurement time.

In a second experiment we attempted to increase the beam-beam tune shift by lowering the energy of the test-beam to the lowest standard energy of the ISR of 11.5 GeV. However, since the installation of a reduced-aperture vacuum-chamber in the split-field magnet, unequal energy operation of the ISR has become rather difficult and requires threading the beams through the chamber with special beam-bumps. Although the energy of the strong beam was also reduced to 22 GeV, only 20 A could be stacked and a somewhat larger effective height of 5.8 mm was obtained, corresponding to ΔQ_{bb} of 1.5×10^{-3} only. Also the current decay of the test beam was quite rapid (4%/hr) and remained so when the strong beam was dumped. The luminosity decay rate of $7.3 \pm 8.7 \%/hr$ was compatible with the current decay.

Fig. 1 : Luminosity versus time (experiment 1)

Fig. 2 : Working region for high- β experiment

A final means to obtain larger values of ΔQ_{bb} is an increase of β_V^* by changing the focussing in one ring. In earlier experiments on the beam-beam limit of continuous beams²⁾ this had been achieved by using the independently powered quadrupoles of the low- β insertion in the ISR. While quite high values of β_V^* had been obtained in this manner (100-200 m) in one intersection, the machine was then completely mismatched and the values of β_V^* in the other 7 intersections varied wildly (between 6 and 60 m). In order to obtain smaller fluctuations, the lattice functions were rematched with the help of the "tuning quadrupoles" of which 4 are available in each octant. Together with the pole-face windings of the main magnets this permitted us to find computer solutions with $\beta_V^* \approx 60$ m in all eight intersections. Unfortunately, the vertical beta function becomes much larger in the lattice (almost 200 m), and the working points fall into an unfavourable region between a third and fourth order resonance ($Q_V = 8.09$, $Q_H = 8.77$, see fig.2). However, an increase of ΔQ_{bb} of up to a factor 5 appeared possible.

The next two experiments were performed under these working conditions: In the first run, a stack of over 30A was obtained and an incredibly small effective height of 4 mm was measured in spite of the increased value of β_V^* , which was found to be of the order of 50 m. This would yield a theoretical ΔQ_{bb} of over 5×10^{-3} , but the total measured tune-shift of 0.014 when the strong beam was dumped corresponds only to 1.7×10^{-3} per intersection. This discrepancy cannot be explained by the usual reduction due to finite amplitude of particles in the test beam, and we suspect that the beam-height measured was incorrect. In addition, the test beam decayed quite rapidly (12%/hr), probably due to the large values of β_V in the lattice. The luminosity decay could only be measured for about 30 minutes, and no time was left for displacing the beams. However, the observed decay of $19.2 \pm 7\%$ /hr. warranted a repeat of the experiment. In the next run, the effective height was found to be much larger (8.2 mm) for a 32A stack at 22 GeV. The corresponding value of $\Delta Q_{bb} = 3.5 \times 10^{-3}$ agreed fairly well with the measured 2.4×10^{-3} per intersection when the 30% reduction is applied. Because of the rather rapid current decay, we monitored the blow-up of the effective height rather than the luminosity decay. For centrally colliding-beams, the lifetime was found to be over 30 hours, but came down to about $1\frac{1}{2}$ hours when the beams were displaced by about one standard deviation in alternate intersections (see fig. 3). Finally the test beam was debunched, and for the rather short remaining time (< 10 min) the effective height appeared to remain essentially constant.

Fig. 3 : Luminosity, current + effective height in high β experiment

5. CONCLUSIONS

The beam-beam tune-shift of a weak bunched proton beam colliding with a strong coasting beam in the ISR has been gradually increased to over 3×10^{-3} per intersection, without observing catastrophic beam-loss or blow-up when the beams were colliding well-centered. For beams off-centered by about one standard deviation, the blow-up rate of the bunched test beam increased dramatically, but fell again to very low values when the beam was debunched. While these results can be interpreted as having reached the beam-beam limit when the bunched beams were displaced, it cannot be excluded that the displacement changed the tunes sufficiently to drive the beam into a single isolated resonance. The blow-up rate of the beam height could then have been enhanced by the noise of the RF system, which also explains the reduction of the blow-up when the RF was switched off and the beam debunched.

In either case, the main objective of the series of experiments was achieved by showing that a bunched beam could be subjected to a beam-beam tune shift of over 3×10^{-3} per intersection in the ISR without catastrophic beam loss or blow-up when the collisions were well centered.

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