EXPERIMENTAL INVESTIGATION OF THE BEAM-BEAM LIMIT OF PROTON BEAMS

B. Zotter

CERN, Geneva, Switzerland

(presented by E.Keil)

1. Introduction

A severe limitation for increasing luminosity in colliding, high-energy storage rings is the reduced lifetime of particles due to the beam-beam effect. This limitation is usually expressed by the maximum beam-beam tune shift, which is caused by the linear part of the interaction forces, although the effect is essentially caused by the nonlinear parts, for which the linear part is only a rough measure. While this effect has been studied extensively in electron-positron storage rings, only few experimental data are available for proton-proton interactions. Even at the highest beam currents and densities, the beam-beam tune shift at the CERN Intersecting Storage Rings (ISR) is only about 10^{-3} and remains well below the theoretically expected limit of 5×10^{-3}.

In the ISR geometry with crossing angles of about 15°, the beam-beam tune shift depends essentially on four factors. In the mksA-system we obtain

$$\Delta Q_{bb} = -3.5 \times 10^{-7} \left(\frac{\beta_v^*}{\gamma}\right)_1 \left(\frac{I}{h}\right)_2$$

where β_v^* is the vertical β-function at the intersection, and γ the energy factor for beam 1 (the test beam), while I and h are the current and effective height of beam 2. Besides working with large currents of small height for beam 2, the obvious choice for increasing the beam-beam tune shift is to reduce the energy of the test beam.

A series of experiments /1/ has been performed some time ago with test beams at only 2 GeV/c. The maximum achieved tune shift was about 4×10^{-3}, and the lifetime measurements were over-shadowed by the rapid decay of the test beam due to intra-beam scattering even in the absence of a second beam.

A second series of experiments /2/ was made with a "nonlinear lens" which should simulate a second beam when brought into the neighbourhood of the test beam. Very large tune shifts could be obtained with this device, but it is questionable whether the nonlinear content of the forces due to the lens bears any resemblance to that of another beam. It was found that the lifetime of the test beam was strongly reduced, but depended critically on the exact working point.

With the installation of a low-β insertion in the ISR in 1975, it became attractive to consider a scheme using these quadrupoles to increase the vertical β-functions.

2. Retuning of the ISR

The proper combination of all focusing elements to obtain large values of the vertical β-function in one intersection was first investigated by computer. The program AGS permits insertion matching and finds β-functions and dispersion of complete rings. It was soon discovered that the five "low-β quads" were not sufficient to obtain high β-values in one intersection without getting excessive values of the β-functions and/or dispersion in the rest of the ring. The three existing families of Terwilliger quadrupoles and the pole-face windings had to be included for matching, and modification of the beam parameters had to be accepted in the rest of the ring.

Solutions were obtained which had vertical β-values well in excess of 100 m, and reasonable values of the β-functions over the whole ring. The dispersion exceeded locally 4 m but remained small at the injection kicker. This meant that injection had to be moved close to central orbit in order to avoid excessive beam loss by aperture limitations. Therefore the current in the test beam was limited by this effect. While the horizontal tune remained almost unchanged, the vertical tune was found to be about 8.45. Thus, the high-β working line and the normal ISR working lines (8.6 - 8.9) lie on opposite sides of the half-integer resonance, and one could hardly attempt to change the quadrupole settings gradually, but would have to inject directly into the properly tuned lattice.

The chromaticity and curvature of the working line were adjusted with existing sextupoles, octupoles, and pole-face windings to yield the working line shown in Fig. 1. A "data-base" was created which permits on-line correction of the tune and of the closed orbit with the control computer.

The experiment required careful preparation, as corresponding low-β quads in both rings were powered in series, and thus one set had to be short-circuited. Furthermore, the polarity of the power supplies had to be inverted manually. The power supplies also had to be adjusted to obtain good regulation at current levels much smaller than their design values. For normal ISR operation with the low-β insertion, most of these modifications had to be removed, and the experiments thus needed careful planning. In practice, injection close to central orbit turned out to be quite difficult, but was successful. Both the horizontal and vertical tunes

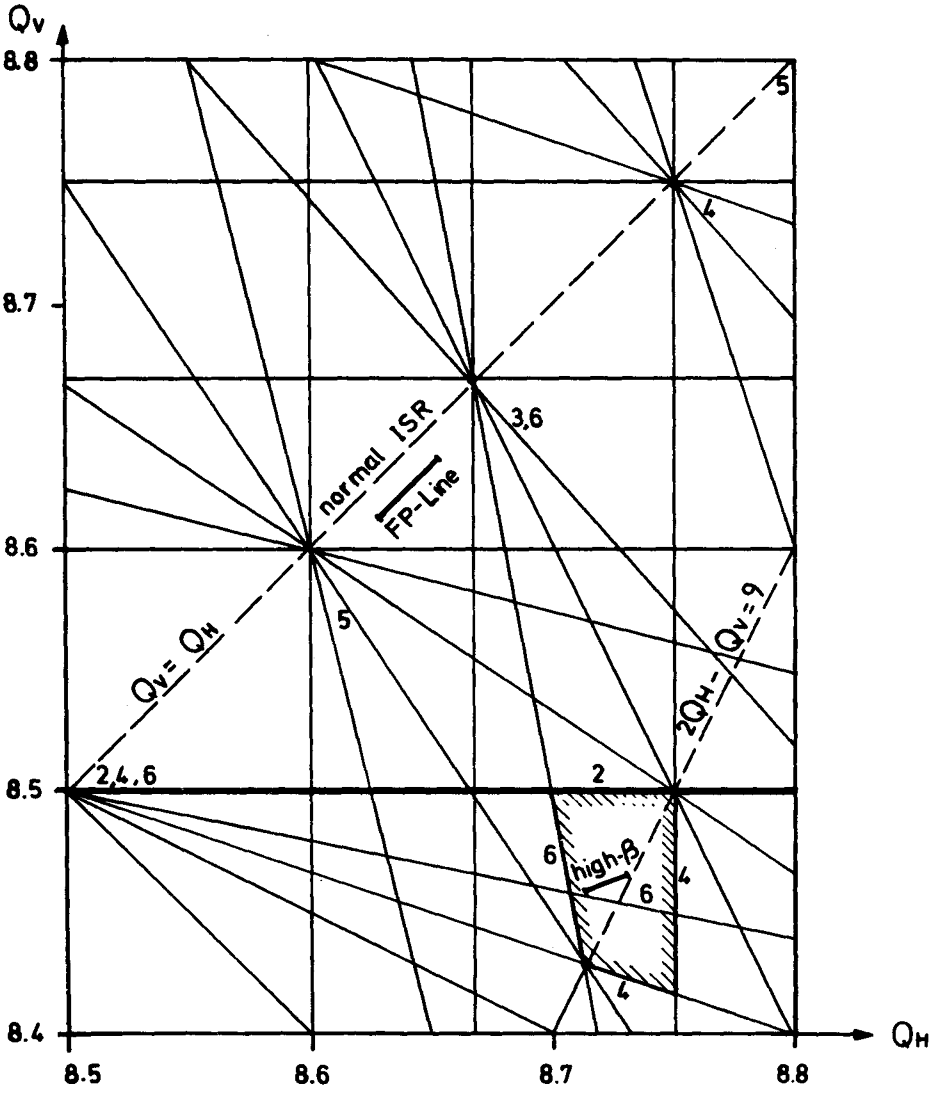

Fig. 1. Working diagram Q_v vs. Q_h, showing a normal ISR working line (FP) and the region where high-β solutions were found.

were measured at injection and for various positions of the beam in the free aperture. Only small corrections of the working line appeared to be necessary.

The value of the vertical β-function at the high-β intersection was measured by changing the excitation of the two nearest quadrupoles. For small changes, the β-value in a quadrupole is given by

$$\beta = -\frac{4\pi}{L}\frac{\Delta Q}{\Delta K}$$

where L is the length of the lens, and ΔQ the measured tune shift for a change ΔK in quadrupole strength, which is directly proportional to the change in current. Hysteresis effects could be avoided by making the current change only in one direction. The agreement of measured β-values and those calculated by computer was within a few per cent.

3. Experiment

The test beam was at the lowest standard ISR energy of 11 GeV/c in order to avoid the excessive intra-beam scattering at even lower energies. However, the best high-current, high-density beams are obtained at 26 GeV/c. Thus the ejection energy of the injection synchrotron has to be changed during the experiment for maximum beam-beam Q-shift. Two experiments were made with 11 GeV in both rings, which limited the tune shift to about 5×10^{-3}.

After stacking in both rings, the beams were brought to best coincidence by monitoring the luminosity at the intersections as the beams were displaced vertically by local bumps. However, due to low current in the test beam, long measurement times were required, and only a few intersections (with the highest β-values) could be corrected carefully. However, since the closed orbits were adjusted beforehand in both rings, the required corrections were always very small.

The test beam was scraped down vertically in order not to exceed the height of the strong beam in the high-β intersection. Since also the strong beam was scraped during stacking in order to keep its height small, and since the β-function in the test beam was about 10 times larger, this left very little current in the test beam. The beam height was monitored with the "beam finder", a probe that stops automatically when a preset charge is intercepted.

When the scraper was retracted, the decay rate of the test beam was zero in all runs for the observation period (about 10 minutes). By retracting the scraper only a small distance (about 0.3 mm) the beam remained aperture limited, and the decay rate started climbing after a short quiet period (of at most a few minutes). The average values of the final decay rates are shown in Table I and plotted in Fig. 2.

Originally, it was planned to start with the maximum tune shift, and then to scrape the strong beam down gradually and to observe the change in decay-rate of the test beam. Unfortunately, because of the presence of very sensitive experi-

Table I - Experimental Results

Run No.	β_v^* (m)	I_2 (A)	ΔQ_{bb}	decay rate ppm/min
679	120	-		
711	194	7.4 (11 GeV)	0.005	50 - 100
724	200	15 (26 GeV)	0.017	7×10^3
	200	10	0.012	5×10^3
742	103	23 (26 GeV)	0.020	12×10^3
846	110	8.4 (11 GeV)	0.0045	160

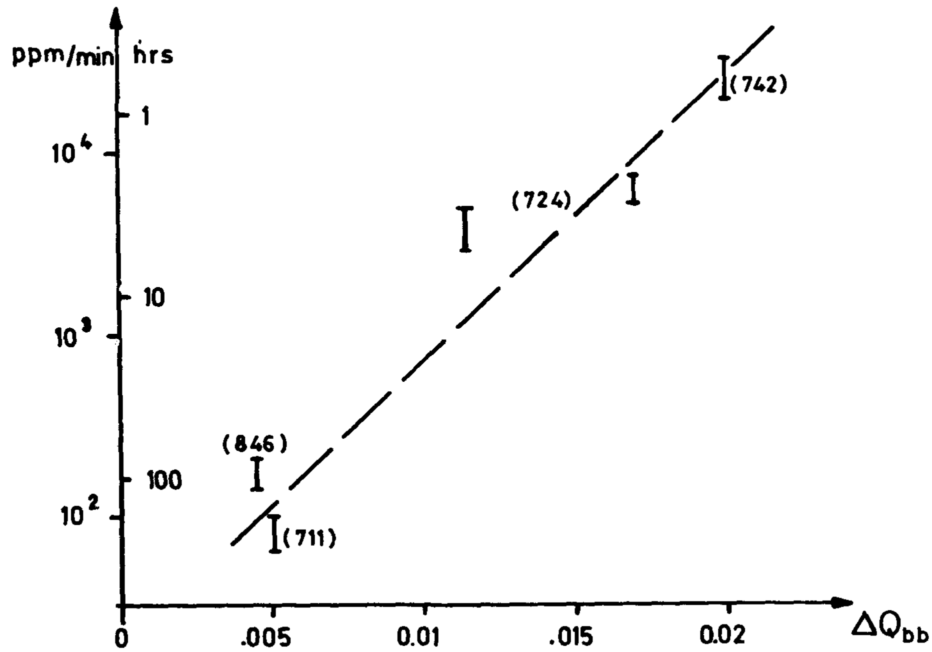

Fig. 2. Decay rate (ppm/min), resp. lifetime (hrs) versus beam-beam tune shift

mental equipment around the ISR, this could be done only once, as the scraping had to be stopped before the radiation level became too high. The beam was then dumped suddenly, which permitted a measurement of the total beam-beam tune shift due to all interaction regions. In all cases it was at least 40% below the calculated one. This may be partially due to incomplete crossing in some intersections where the test beam is small, but is certainly enhanced by the finite size of the test beam /3/ while the theoretical expression is valid for beams of infinitesimal size. However, it is customary to compare results on this latter value, as the tune shift is only a rough measure of the nonlinear effect anyhow.

4. Conclusions

The measurements of the lifetime of colliding proton beams presented in this paper are only of a preliminary nature, due to the complexity and length of the experiments. However, from the few data points shown in Fig. 2, it appears that the lifetime decreases exponentially with the beam-beam tune shift. If these data are extrapolated to the approximate beam-beam limit for electrons (0.05), the lifetime would be of the order of milliseconds. However, for electrons, the beam would become unstable only if the blow-up rate is faster than the damping rate, which is also typically of the order of milliseconds. Thus there appears to be rough agreement between the measurements of the beam-beam effect for (bunched) electrons and for (coasting) protons, and generalization of the results to electron-proton collisions may be permitted.

For proton beams it should be possible to exceed the presently accepted limit of 5×10^{-3} for the beam-beam tune shift at least for reduced periods of time. This conclusion may be important for the design of future colliding beam devices aiming for the highest luminosities.

Acknowledgements

The experiments described in this paper would not have been possible without the collaboration of a large number of people, expecially L. Vos who made the ISR operate under very unfavourable working conditions.

References

1. K. Hübner; A Search for a Beam-Beam Effect in the ISR, IXth Int. Conf. on High Energy Accelerators, Stanford, 1974, p. 63.
2. E. Keil; Effects of a Nonlinear Lens on the Stored Proton Beam in the ISR, IEEE Trans. NS-22, p. 1370 (1975).
3. A. Jejcic and J. le Duff; Non-Linear Beam-Beam Effect, VIIIth Int. Conf. on High Energy Accelerators, CERN, 1971, p. 354.

ДИСКУССИЯ

H.Widemann: At larger tune shifts do you see a blow up of the beam size?

E.Keil: The beam size is restricted by scrapers while the lifetime is being measured. Hence, an increase in betatron amplitude causes particle loss.

M.Month: What makes you think that the lifetime in electron rings is about 5 msec?

E.Keil: The beam-beam limit in electron storage rings should occur when the growth time due to beam-beam collisions and the synchrotron-radiation damping time are of the same order of magnitude. The latter is usually in the millisecond range.