MEASUREMENT AND COMPENSATION OF SPACE CHARGE INDUCED Q-SHIFTS IN THE CERN INTERSECTING STORAGE RINGS (ISR)

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Summary

The space charge induced Q-shifts were measured either by comparing the radial positions of a given non-linear resonance with and without a stack, or by means of RF deflecting fields. The first consequence of these Q-shifts is a displacement of the working line in the stability diagram towards low order non-linear resonances. A secondary effect is a progressive reduction of the radial derivatives of the Q's at the edges of the stack with increasing intensity, which makes the stack unstable in these regions. These results were used to derive "prestressed" working lines which are suited to high intensity stacks.

Introduction

The effect of the space charge on the betatron frequencies (Q_H, Q_V) of a beam consists of a progressive shift and curvature of the original Q-distribution or working line in the stability diagram Q_H-Q_V as further protons are added to the beam. Owing to this shift, low order non-linear resonances or the coupling resonance $Q_H = Q_V$ may penetrate into the stack and adversely affect the beam's lifetime, the background conditions or the luminosity. In addition, the local Q-shifts are not uniform across the whole aperture. The resulting change in curvature of the working line can locally reduce the Q-spread. At these positions, the beam becomes vulnerable to transverse instabilities. It was, therefore, important to measure the Q-shifts inside a stack. These results were used to design a working line which, under the influence of the stacked beam, becomes straightened and moves into a region in the stability diagram suitable for physics experiments.

1. Q-Measurements inside a Stack

The first method used in the ISR was proposed by W. Schnell[1]. It consists of comparing the positions of a given non-linear resonance in the presence of a small beam of some tens of milliampere and of a stack of several ampere. In both cases, the position of the resonance is detected by the loss of particles which are excited to amplitudes greater than the aperture. This loss is localized by recording the radio frequency (RF) signal generated on a pick-up electrode by scanning a stack with empty buckets (RF scans). Figure 1 shows the principle of measurement and how the Q-shift (ΔQ) is deduced from the positional change (Δx) and the slope $Q' = p dQ/dp$ of the working line for the third order resonance $3\,Q_H = 26$. For intensities (I) as high as 5 A, Q at the centre of a stack varies linearly with I and follows the relationship:

$$\Delta Q_H \;=\; 0.002\ I \;;\quad \Delta Q_V \;=\; -0.0025\ I$$

for a current density across the aperture, $\rho = 0.17$ A/mm and a momentum of 22 GeV/c. This method becomes intractable when the complete Q-distribution is needed since it demands as many stacks and magnetic settings as points of measurement.

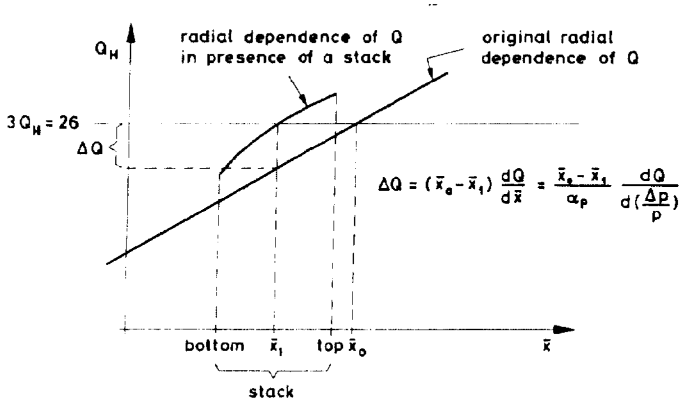

Figure 1. Measurement of incoherent Q-shift

A second method which provides the Q-shift at several positions inside a stack of protons has been developed. It is based on the technique of RF knock-out in which a pulsed RF electric field of frequency f_β excites a growing coherent oscillation in a thin slice of the beam in either the horizontal or the vertical plane according to the direction of the field. The width of the slice is a function of the average deflection angle per turn (δ) and of the duration of the pulse (τ). The values chosen were 3.10^{-8} rad for δ and 50 ms for τ. The Q-value is deduced from f_β via the relationship:

$$f_\beta \;=\; |n - Q|\ \ f_r$$

where the mode number n is equal to either 8 or 9 and the revolution frequency is 317.8 kHz. The positions of the localized blow-ups in the beam can be detected as previously mentioned. The oscillogram of the RF scan shows that the dips are sufficiently narrow to make these measurements comparable to those using a non-linear resonance.

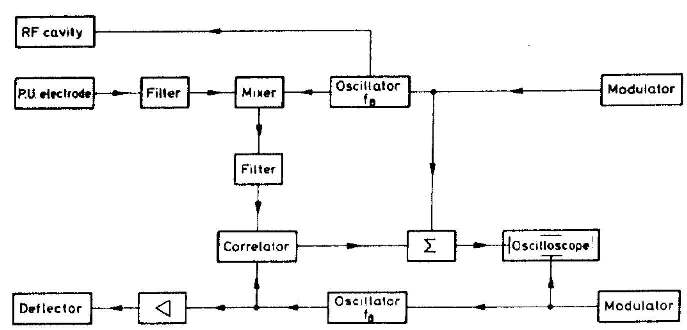

Figure 2. Diagram of the RF knock-out system

Based on the RF knock-out principle, a system was developed to measure the distribution of Q_H and Q_V across the entire beam with practically no losses (Fig. 2). The beam is simultaneously modulated in the longitudinal phase space by RF empty buckets at the thirtieth harmonic f_B of the revolution frequency and kicked vertically or horizontally at frequency f_β. As the empty buckets cross the oscillating part of the beam, a signal at the beating frequency of f_B and f_β is picked up at an observation electrode, filtered and mixed with the master oscillator signal of frequency f_B. A correlation is then made with the signal of frequency f_β which drives the coherent transverse oscillation in the beam. The analogue voltage of f_B is superimposed on the output signal of the correlator, which acts as a marker, and is applied to the vertical plates of an oscilloscope while the analogue voltage of f_β is applied to the horizontal plates. The number of measuring points is determined by the ratio of the modulation frequency of f_β to the modulation frequency of f_B, e.g. 20 in the present case. A typical oscillogram of Q-values at the position of the markers is displayed in Figure 3. The Q-shifts $\Delta Q_H(\bar{x})$ and $\Delta Q_V(\bar{x})$ measured in this way for a 22 GeV/c stack of 8 A extending from -16 mm to +40 mm about central orbit are given in Figure 4.

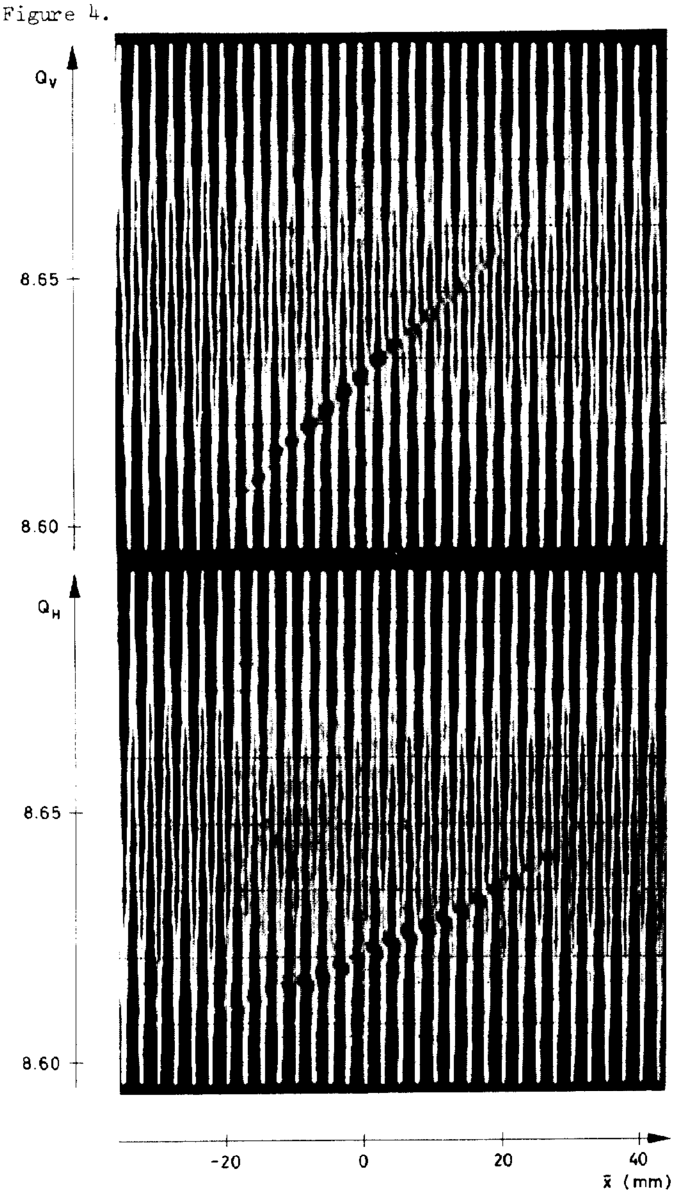

Figure 3. Q-distribution in a proton beam
(p = 22 GeV/c, I = 8 A, ρ = 0.17 A/mm)

2. Influence of the Space Charge on the Design of Working Lines

In the ISR, the working lines were initially designed[2] with constant Q-spreads (Q_H' and Q_V'). These straight lines were located in the Q-diagram in such a way as not to cross low order resonances, especially in the stacking region for reasons of background, but also in the regions between injection and the bottom of the stack where such resonances produce blow-up of the injected beam and a consequent reduction in luminosity. In Figure 5, 22FB is an example of these lines for

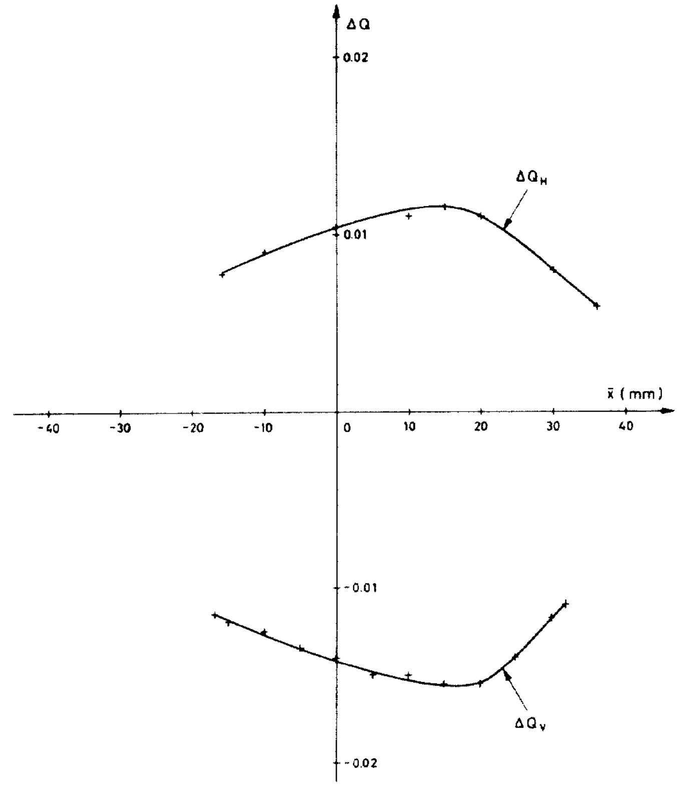

Figure 4. Q-shifts in a proton beam
(p = 22 GeV/c, I = 8 A, ρ = 0.17 A/mm)

which the stacking region was kept free of resonances up to the eighth order.

The space charge Q-shifts displace this working line causing the resonances 3 Q_H = 26 and 5 Q_V = 43 to enter into the edges of the stack. The variation in Q-shift across the aperture (Fig. 4) gives a reduction of the Q-spreads Q_V' at the stack's bottom and Q_H' at the stack's top.

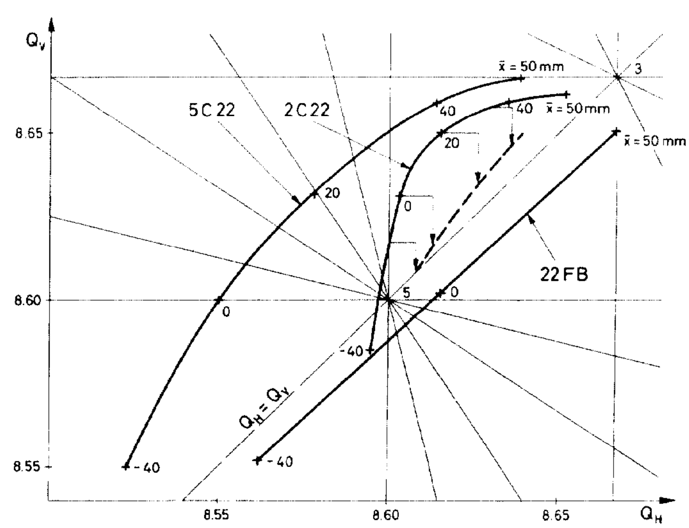

Figure 5. Working lines in the Q-diagram.
The dotted line shows the deformation of the line 2C22 in the presence of a stack of 8 A located between $\bar{x}$ = -16 mm and $\bar{x}$ = +40 mm

Coherent transverse instabilities due to the resistivity of the vacuum chamber wall first appear for the small parts of the beam situated in these regions, as illustrated in Figure 6. To prevent these instabilities, it is necessary to increase the Q-spreads of the initial working line accordingly. However, the large increase in the maximum beam current and the technique for shaving stacks[3], which requires the whole available aperture for stacking, has made it impossible to build a straight working line with large enough Q-spreads and for which the stack would contain only eighth order resonances.

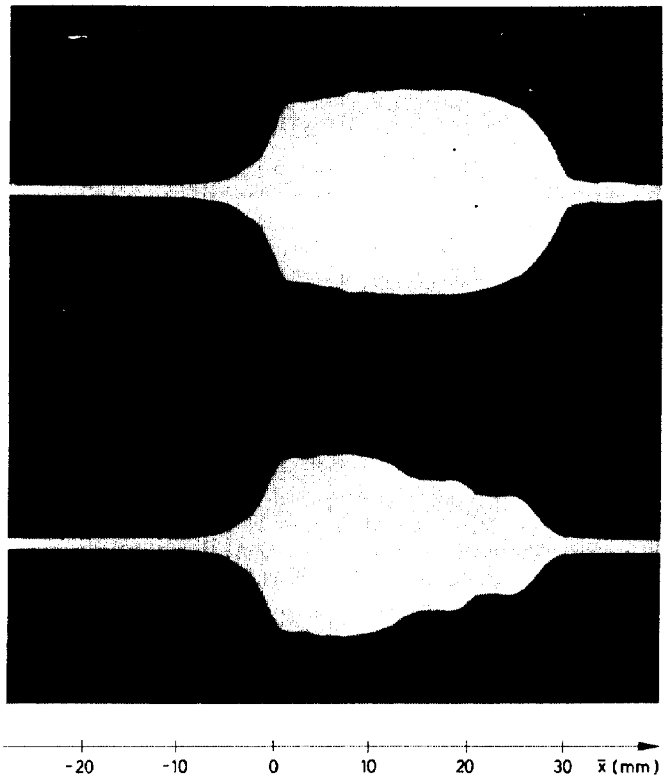

Figure 6. Beam loss resulting from a horizontal transverse instability. When reducing the horizontal Q-spread in the presence of a stack of 6.8 A, the instability affects mainly the top part of the stack. The two RF scans were taken before and after the instability occurred and show the resulting beam loss.

A solution was found by using "prestressed" working lines which save space in the Q-diagram. For these lines, Q'_H and Q'_V vary in the aperture according to linear laws, and they have their maximum values only where the reduction introduced by the space charge effect is maximum, i.e. the top of the stack for Q'_H and the bottom for Q'_V. 2C22 is an example of these lines which was established experimentally at 22 GeV/c with Q'_H max = 3.1 and Q'_V max = 2.2. During stacking, this line is progressively straightened but the stack remains free of resonances up to the eighth order. The behaviour with respect to the transverse instabilities was found as expected. For low and normal stack densities (ρ < 0.17 A/mm), the beam is fully stable during stacking and external kicks do not trigger any instability. These lines were extensively used during the last months of 1972. With shaved stacks of 8.3 A and 8.6 A in Rings 1 and 2, respectively, a luminosity of 2.3 x 10^{30} $cm^{-2}s^{-1}$ was reached.

For high density stacks (ρ > 0.35 A/mm) it was found necessary to make a prestressed working line with larger Q-spreads and to accept fifth order resonances in the stack. However, it was possible to shift this new line 5C22 (Fig. 5) away from the coupling resonance $Q_H = Q_V$, which improved the luminosity; when the injected beam crosses the diagonal, there is an interchange of horizontal and vertical emittance which gives, for shaved stacks, a 20 % reduction in luminosity. The line 5C22 gave acceptable physics conditions and was used to achieve the record luminosity of 4.4 x 10^{30} $cm^{-2}s^{-1}$. Experiments will continue to determine the influence of fifth order resonances on the background.

3. Further Developments

With increasing intensity, the space charge effects will play a more and more important role in the performance of the ISR. The Q-shifts which result from the integrated effect over the whole circumference have been measured and used to derive a special working line. Another aspect of the space charge effects is connected with their azimuthal repartition around the ring; this mainly concerns the excitation of non-linear resonances and will affect the choice of the final position of the working line in the Q-diagram. At present, this line is located across fifth order resonances. In the future, an alternative will be to take the line nearer to the natural operating point (Q_H = 8.8 and Q_V = 8.7) , to compensate for the excitation of third and fourth order resonances by means of azimuthally distributed sextupoles and octupoles and to take advantage of the new feedback damping system.

Acknowledgement

The circuitry used for the RF knock-out measurements was built by A. Vaughan.

References

1) W. Schnell - Q-Shift Measurements in a Stack - Internal ISR Running-in Report, 6th September 1971

2) J.P. Gourber and K.N. Henrichsen - Adjustment of the Working Lines in the ISR - Proc. Int.Conf. on High Energy Acc., CERN, Geneva (1971) - p. 518

3) P.J. Bryant et al. - Improvement in Luminosity, Background and Chamber Protection with Beam Scrapers in the ISR - Paper presented to this Conference.