EXPERIMENTAL OBSERVATION OF BEAM BEHAVIOUR IN THE ISR

W. Schnell

CERN, Geneva, Switzerland

1. Introduction

The ISR are usually operated with the full number of 20 bunches injected from the CPS, or with 4 bunches for low intensity work and sharing with other CPS users. The injection momenta have been 15, 22 and 26 GeV/c, plus three runs at 10.5 GeV/c.

As far as single particle dynamics is concerned, there have never been any difficulties.

Injection near the inner edge of the vacuum chamber presented no basic difficulties. Closed orbit distortions have been small from the beginning and since then very satisfactory correction schemes [1] have become available. We have, therefore, always had enough horizontal aperture to accomodate at least the design value of 2 % momentum spread for stacked beams.

Since r.f. stacking - at the top or at the bottom - also works well, with phase space efficiencies of about 70 %, we are not, at present, limited by available longitudinal phase plane area, although the longitudinal density of the injected beam approaches only marginally the ISR design value. Fig. 1a shows the build-up of a stack. Fig. 2a, obtained by r.f. scanning (empty buckets) shows the particle distribution versus momentum of an unsaturated stack.

We have very good control [2] as well as monitoring [3] of working points and working lines in the Q_V, Q_H plane, enabling us to avoid low order non-linear resonances and to choose well defined amounts of pure sextupole field, which will be quoted below in terms of $Q' = dQ/(dp/p)$.

With non aperture-limited beams of up to 2.5 A intensity we have occasionally observed decay rates equal or close to the rate of nuclear collisions against the residual gas only. Since the average pressure at low intensities is very low (less than 10^{-10} torr of nuclear scattering equivalent N_2) these rates are exceedingly low (a few times 10^{-4} per hour). It is perhaps not surprising, therefore, that we cannot always reproduce the nuclear collision rate reliably. Nevertheless, 12 hour colliding beam runs with less than 10 % total loss are not unusual, and 2.5 % total loss after 19 hours at 2.5 A has once been observed. These loss rates could be explained by multiple Coulomb scattering, assuming that the beams were aperture limited.

At higher intensities decay rates generally tend to increase. Other conspicuous high intensity phenomena are sudden partial loss and vacuum effects produced by the beam.

Present (beginning of September, 1971) record intensities are 6.9 A in Ring 1 and 5.6 A in Ring 2.

The rest of this paper describes the principal high intensity effects we have encountered so far. Paragraph (2) deals with the single (bunched) beam pulse injected from the CPS. The remainder deals with stacked beams.

2. Bunched beam instability

When the radio frequency is on, the bunched beam (about 1.5×10^{12} protons) injected from the CPS suffers a horizontal blow-up by roughly a factor two. This blow-up is independent of the number of bunches, and accompanied by a coherent oscillation at the lowest azimuthal frequency (9 - Q). A positive value of Q' of about one is sufficient to suppress the effect.

We believe that we encountered the "head tail"[4] effect. It is of little consequence to us, since larger values of Q' are required anyhow to suppress the resistive wall instability described below.

3. Non-linear resonances

Most of our standard working lines in the Q_H, Q_V diagram are chosen such that a low intensity test beam, moved slowly across the horizontal aperture (3 mm/s speed) does not show any loss inside the region occupied by the stack. This excludes resonances below the order 6, although 4th and 5th order resonances have to be admitted between the injection orbit and the stack whenever we want to generate enough sextupole field to prevent transverse instability at high current.

It has been observed on a few occasions - but not always confirmed - that admitting lower order resonances in the stack (Fig. 2b) leads to enhanced loss rates.

We have tried to detect transport mechanisms which might continuously feed particles into higher order, "invisible" resonances (or resonances close to the stack), thereby creating - or contributing to - the anomalous decay rates observed at higher currents.

Intra-beam scattering [5] may be one such transport mechanism. However, no clear evidence has yet been found.

Another transport mechanism could be longitudinal instability at microwave frequencies. Such an instability could develop at the sharp edges of the dip which a resonance may create in the particle distribution [6]. As will be explained in paragraph (5), there is no clear evidence of this either.

Preliminary measurements of the incoherent space-charge Q-shift have been made by observing the shift in momentum at which a resonance occurs in a stack, at different current levels. The result is $dQ_V/dI \sim 0.0025\ A^{-1}$ at 22 GeV/c, in rough agreement with expectations.

4. Transverse instabilities at low frequencies

A combination of beam loss and coherent oscillation at the lowest azimuthal mode (i.e., with $(9 - Q)f_{rev}$ appearing at a position sensitive pick-up) can occur during stacking. If stacking is continued, a characteristic sawtooth of loss and build-up occurs, (Fig. 1b). The loss and oscillation can also be initiated by a small transverse kick or by horizontal displacements of the whole stack.

The measured oscillation frequency always falls within the range of Q values occupied by the stack, as measured with low intensity test beams. On several occasions we could verify that the frequency of the instability corresponded to that part of the stack with the lowest local value of Q' or the highest density. The effect can be vertical or horizontal or both simultaneously.

Beam loss and coherent oscillations can be suppressed by applying sextuple fields. The value of Q' needed for stabilisation increases with increasing stack density, up to about 2 for the highest densities available at present. This is in good agreement with the theoretical value [7] required to suppress instabilities due to the calculated resistivity and inductivity of the chamber walls. The predominance of the lowest mode, and the observation that the required sextupole fields tend to increase with decreasing frequency (i.e., when Q is made to approach 9), make us conclude that there is an appreciable contribution of wall resistivity, as expected.

If - at a few amperes current - one observes the pick-up signal with a spectrum analyser one sees lines, or groups of lines, in the 30 to 70 MHz frequency range. These oscillations, which can be observed even in stable beams, are believed to be due to electrons oscillating in the beam's potential. More details are given in [8] and [9].

5. Microwave instabilities

During the construction of the ISR we became concerned about microwave instabilities - predominately longitudinal ones - due to electromagnetic interaction between the beam and resonant structures formed by the vacuum envelope. Considerable theoretical and experimental work led to the conclusion that damping resistors were required in numerous places inside the vacuum chamber in order to suppress local resonances. However, due to lack of time, hardly any of these resistors had actually been installed when we started to run the ISR.

In spite of this, no "macroscopic" microwave instabilities (i.e., involving at least one entire edge of the particle distribution) have occurred. Not only did we never pick up any signals, but we also never found an increase of momentum spread which could be ascribed to such an instability.

Instabilities, originating at the edges of non-linear resonances, as mentioned under (3) are more difficult to detect, since no macroscopic blow-up needs to occur. In the absence of conclusive evidence, we installed damping resistors in Ring 1, and not in Ring 2, during the Easter shut-down. After this, Ring 1 showed a marked improvement of decay rate at intermediate currents, while Ring 2 did not. Meanwhile, however, Ring 2 has also improved (perhaps in connection with vacuum effects) and we have failed to observe unambiguous microwave signals in either ring, although we have lowered the detection threshold below 1 mA of equivalent beam current modulation in the range of 1 to 2 GHz, where the strongest resonances are expected.

6. Beam-beam interaction

We have never observed any interaction between stable beams.

We have observed enhanced decay rate of an aperture limited beam in one ring when heavy beam loss, stacking, or beam dumping, occurs in the other ring.

We have also observed the occurrence of the transverse instability described in (4) in one ring, triggered by the same instability occuring in the other. This requires the Q-spreads to be small, so as to have potential danger of instability anyhow, and the two Q-values to be close together.

7. Clearing fields, anomalous decay and blow-up

Clearing electrodes, designed to prevent space-charge neutralisation by extracting all electrons, are placed at each end of each magnet [10].

Last year, when these electrodes were not yet operational and when we still had pressures above 10^{-8} torr locally and above 10^{-9} torr on average, we observed decay rates above the gas scattering rate for all currents above 0.1 A. At 1 A the decay rate was of the order of 0.3 min^{-1}.

With average pressures around 2×10^{-10} torr decay rates are considerably lower and one has to exceed 4 A in order to reach the order of 0.1 min^{-1}.

Turning on all clearing fields brings about another striking improvement (Fig. 3). Only with all electrodes turned on, can we obtain decay rates such as :

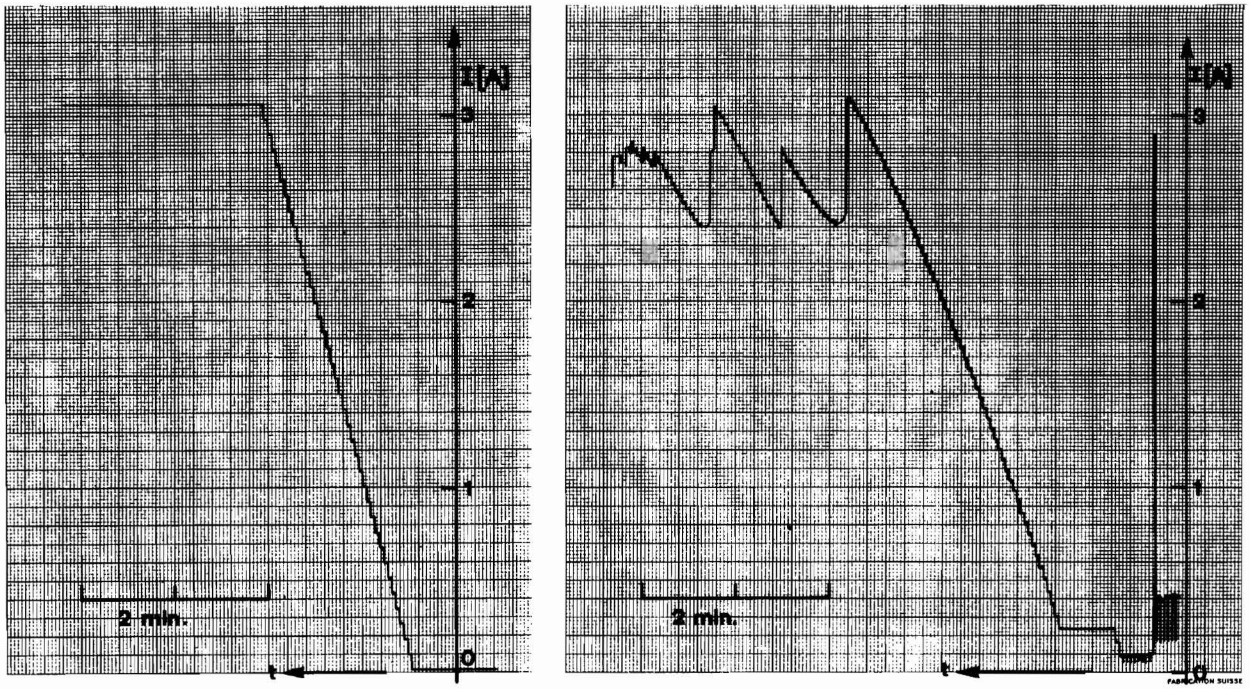
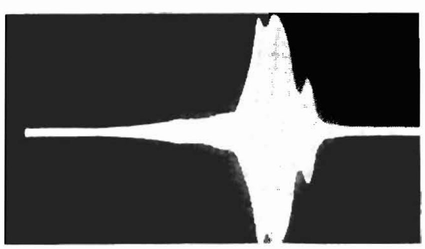


Figure 1

a. Normal stacking

b. Sawtooth intensity limitation due to transverse instability

a. normal stack 4.15 A



b. stack containing non-linear resonances, 1.77 A

Figure 2
Particle density (ordinate) versus momentum (abscissa) obtained by r.f. scanning. Injection on the left, outer radial aperture limit on the right.

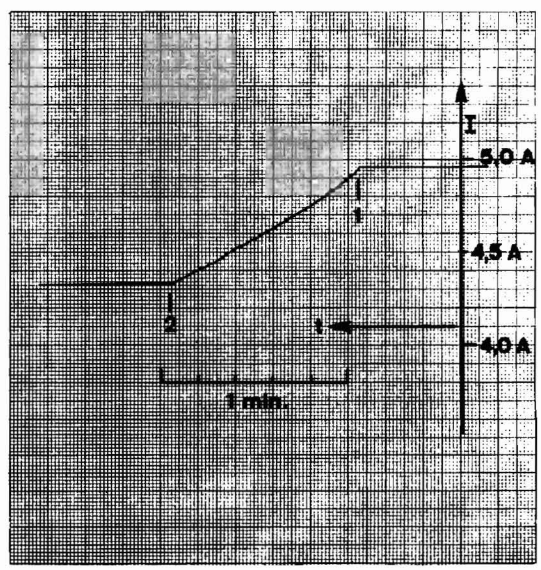


Figure 3
Effect on beam decay of turning clearing fields off (1) and on again (2) in one octant.

$\leqslant 7 \times 10^{-6}$ minute^{-1} at $\leqslant$ 2.5 A
3×10^{-5} minute^{-1} at 4.0 A
3×10^{-4} minute^{-1} at 5.0 A

There is theoretical and experimental evidence[10], however, that longitudinal variations of the chamber cross-section create longitudinal potential wells which keep electrons from flowing to clearing electrodes. Thus pockets of neutralisation appear still to exist. More electrodes are being installed to improve this.

We do not know the mechanism by which neutralisation enhances beam decay. A slow non-linear stochastic instability, called Arnold diffusion, due to azimuthal variation of neutralisation and space-charge, is a possibility [5].

Between 4 and 5 A a substantial (by about a factor of two) but finite blow-up of radial betatron amplitudes occurs. In this current range the vacuum effect described below is already noticeable but the blow-up cannot be explained by gas scattering alone.

Our present current limit, at 6 to 7 A in Ring 1, seems to be caused by a similar, but much more violent blow-up. It seems very likely that this is provoked by the pressure rise, which becomes catastrophic within the same current range. However, the blow-up and resulting decay rate is faster at any level of current and pressure than gas scattering at the measured average pressure can explain.

8. Vacuum effects

Above a few hundred milliamperes of beam current multipactoring occurred in the r.f. cavities. This has been completely suppressed by means of d.c. biasing electrodes installed in the gap area of the cavities.

At currents above 3.5 A a widespread and steep rise of pressure occurs. It is limited to local areas of 10 to 30 m length, but these areas are numerous and their position varies from run to run. The pressure rise depends on the beam current rather than the loss rate. The equilibrium pressure is a steeply rising function of current and tends towards infinity at the approach of a rather well defined "critical current". There has been a slow but continuous, week to week improvement, leading to a gradual increase of the critical current from 4 A to 6 A in about 3 months. Strong bake-out (to about 300°C) removes the effect from the regions baked. However, until we have baked to that temperature in all places, we do not know at which current the pressure rise may reappear. Catastrophic beam loss (about 1 min^{-1}) sets in when the pressure peaks approach 10^{-6} torr. The fact that we can accumulate more than the critical current is only due to a few tens of seconds delay between pressure and current.

Measuring the rate of beam-induced gas liberation (e.g., by dumping the beam and observing the initial rate of decrease of pressure) we find that the number of excess molecules liberated per primary ionising collision is of the order of unity.

The observed behaviour can be explained by ions (more likely than electrons) created in the residual gas, liberating more gas when striking the walls. Reducing the surface layers of adsorbed gas by strong bake-out is the main remedy envisaged at present.

Another possible explanation could be that microscopic dust particles are charged by electrons (from ionisation of the residual gas) and then lifted into the beam by its electrostatic attraction. By subjecting the chamber wall to mechanical vibration we have, indeed, demonstrated that this can happen, especially when the clearing fields are turned off, so that electrons become available for charging dust along an entire straight section. However, this does not seem to be the main effect under normal conditions.

9. Acknowledgement

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10. References

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