

## REPORT ON THE ISR

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### Summary of Operation and Results

During 1974, the period covered by this report, the ISR were in operation for 3500 h, of which 80% were for physics runs and their preparation. 20 physics experiments took data at six of the beam intersections. Ten of these experiments were completed. Several new ones will start this year, after the annual shut-down ending March 1st. Again six intersections will be used for physics, including one (I 7) that has now been equipped with a high luminosity insertion.

Operational performance throughout the year has profited from the regular application of the methods developed at the end of 1973, viz. gradual compensation of the space-charge tune shift during stacking<sup>1</sup> followed by fine tune corrections with the help of Schottky diagnostics<sup>2</sup>. Circulating currents above 15 A and luminosities around  $5 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$  became routine performance, while the beams remained confined to the space of the tune diagram marked 8C in Fig. 1. This space is free of non-linear resonances below the order 8.

In addition, a further improvement of the pressure to values well below  $10^{-11}$  torr average around the two rings, has led to improved clearing of ionization electrons. As a result, decay rates as low as  $3 \times 10^{-5}$  fractional loss of current per hour have often been observed. More than half of this decay is due to beam-beam collisions, the rest to nuclear collisions with the residual gas. These conditions permitted running at the highest luminosity while all experiments could take data, undisturbed by excessive background.

Higher luminosities up to a maximum of  $1.4 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$  (in all intersections) have been reached with the working line marked 5V on Fig. 1, straddling 5th order resonances. The resulting decay rates are typically 100 times higher than the figure given above. The background is acceptable for some experiments, but not all, which explains why these conditions have not often been used in practice.

Towards the end of the year a new working line marked ELSA in Fig. 2 was introduced for routine physics runs. Currents above 20 A and luminosities around  $10^{31} \text{ cm}^{-2} \text{ s}^{-1}$  were obtained, while resonances below the order 8 were still avoided and the background conditions remained good for all experiments.

The same working line is also used for running with the high luminosity insertion<sup>3</sup> which has, so far, given a record luminosity of  $2.1 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$  in intersection 7, but has not yet been used for physics.

Luminosities have also improved at the top momentum of 31.4 GeV/c which we reach by phase displacement acceleration<sup>4</sup>. The maximum obtained so far is  $2.4 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$  with over 9 A circulating in both rings.

Details of performance developments and of our studies of beam behaviour are given below.

### Performance Limits and Beam Behaviour

#### Beam Current

The circulating beam current is limited by three classes of effects.

The first and most serious limitation is still the beam-induced pressure rise, i.e. the desorption of gas by ions hitting the chamber walls after acceleration in the beam's electrostatic potential. This leads to a critical current, above which pressure runaway occurs. The critical current depends on the local pumping speed and on the ion desorption coefficient  $\eta$ , defined as the net number of molecules released from the adsorbed surface layers per incident ion. We are gaining confidence that values of  $\eta$  close to zero can be reliably obtained - and hence that the problem can be eliminated - by glow-discharge cleaning<sup>5</sup> of the vacuum chamber prior to installation. Unfortunately we have so far not been in a position to apply this remedy to more than a fraction of the 2 km of total circumference. Other remedies that have been applied to certain sections are bake-out at increased temperature (350° C) and insertion of titanium sleeves which have been found to present a surface with near zero desorption coefficient.

The main remedy so far has been an increase of the pumping speed by means of a large number of titanium sublimation pumps. As a result, the critical current has increased to over 20 A. Record currents of over 30 A have been achieved in each of the rings, but not with stable pressure. Additional pumps are still being installed, now even inside the short magnet units.

The second problem is transverse coherent instability due to resistance and inductance of the chamber walls. The four lowest potentially unstable modes are stabilized by feedback systems<sup>6</sup>, but the main remedy is Landau damping via a large tune spread. This spread is limited, however, by the requirement of avoiding low-order resonances.

Although 5th order resonances are sometimes acceptable - and were accepted during most of 1973 - it was finally realized that clean background conditions for all experiments could not be obtained in this way. Instead, the space-charge compensated line 8C was developed<sup>1</sup>. The current distribution in the pole-face windings is changed in steps during stacking. Final corrections of tune and chromaticity are made on the coasting beams, after measurements of the working line by transverse Schottky scans. In order to go as close to the transverse stability limit as possible, the current density in momentum is monitored in intervals during stacking by longitudinal Schottky scans, which are now automatically calibrated by the controls computer. The density is controlled by varying the degree of vertical shaving at injection.

To make further progress, it has been tried to stack on both sides of 5th order resonances, to cancel their excitation (predominantly due to beam-beam forces) by careful steering of the beams' relative position at the crossing <sup>7</sup>, to cancel the excitation of 4th order resonances by octupoles <sup>8</sup> or, on the contrary, to clean out the particles near these resonances by strong excitation and scraping. So far, none of these methods have become operational, although all showed signs of success and some are being pursued.

Practical progress has been made by adopting a working line (ELSA on Fig. 2) close to  $Q_v = Q_h = 9$  where the available space between low-order resonances is maximum. The careful compensation of space-charge is, of course, maintained. As the lowest modes of transverse oscillation are stabilized by electronic feedback, the increase of the resistive wall effect due to the low oscillation frequency (down to about 15 kHz) does not influence the stability threshold. We did have to modify the feedback system to cope with the low frequencies. Increased electronic noise at these frequencies is a potential problem. Closed orbit distortion is another obvious one. So far, the closest distance to the integral resonance has been about 0.045 in horizontal tune, for the high energy edge of the stack. Experience will show how much closer we may go, but six physics runs have proven already that this working line yields clean background conditions with currents around 20 A and luminosities around  $10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ . Landau damping should be sufficient for another factor 1.5 in current, which is above our present vacuum limit.

Another approach which we are trying, is to extend the bandwidth of the transverse feedback stabilizers to 50 MHz. This should yield a factor of about two in stable current. The main problems are electronic noise, output power to cope with injection errors without overload, and proper roll-off of the frequency response to avoid instability by parasitic electronic phase-shifts.

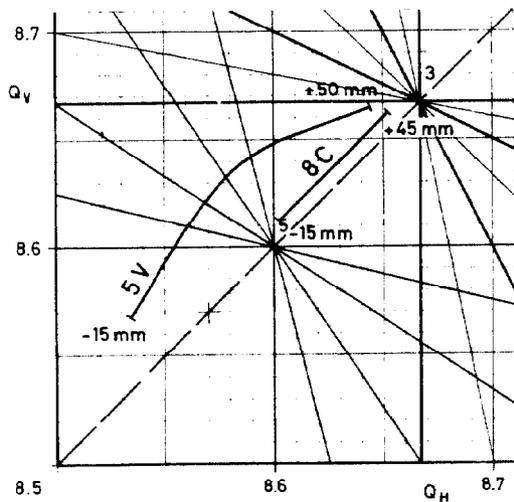


Fig. 1 - Part of the tune diagram with working lines 8C and 5V.

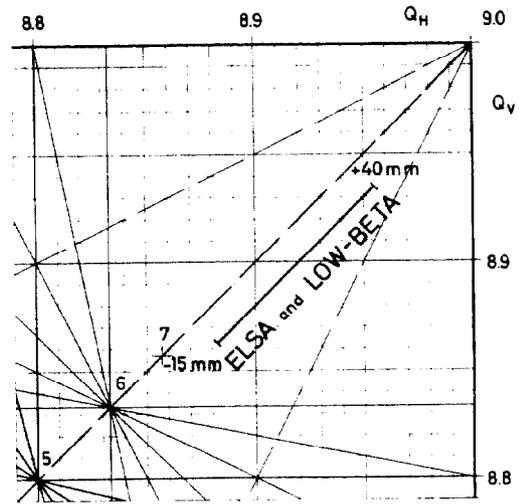


Fig. 2 - A working line near the integral resonances.

A third limit - so far only a potential one - to the current obtainable within a given radial aperture is the available longitudinal phase-plane density. The PS, with its Booster injector, already yields maximum densities of the incoming bunches about a factor 2.5 above the original ISR design assumption, but substantial dilution occurs during stacking. This dilution is not fully explained, but much progress has been made <sup>9</sup> in finding the reasons. The influence of wall impedances on RF bucket parameters is understood and can be compensated. Threshold behaviour of bunch area blow-up has been observed. Microwave structure developing on injected bunches can be seen under certain conditions (Fig. 3).

400 revolutions after injection

500 revolutions

800 revolutions

1000 revolutions  
2 x vertical scale

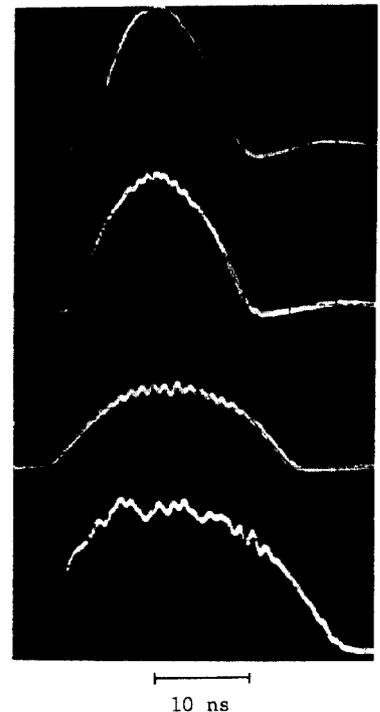


Fig. 3 - Bunches at different times after injection, with the RF turned off. Microwave structure can be seen to develop. The bandwidth of the pick-up is about 700 MHz.

Another curious phenomenon is the formation - a fraction of a second after injection - of small noisy clusters of particles. These clusters, representing an unknown small fraction of the injected beam, are decelerated, apparently by self-induced fields, with an energy loss of a few kilovolts per turn (Fig. 4).

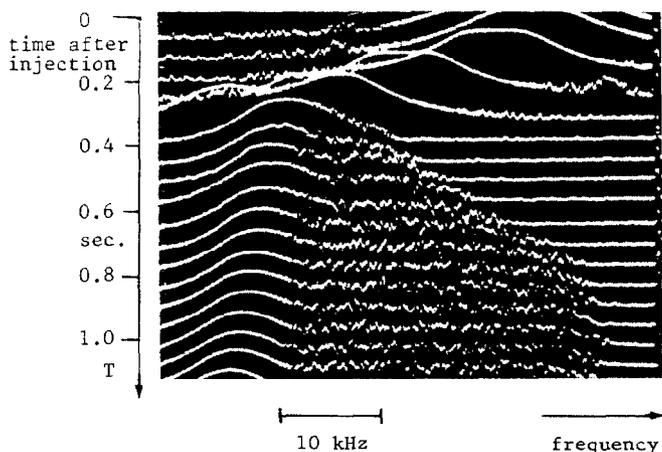


Fig. 4 - A series of spectrum analyser scans of the signal from a longitudinal pick-up, showing the presence of particles at different momenta and different times after injection in the ISR. The injection momentum is to the right. The top traces show the regular acceleration of the injected beam towards the stacking momentum. After about 0.4 s noisy clusters of particles can be seen to emerge from the main beam and to be decelerated back towards the inner aperture limit. The slope formed by the front edges of the noisy bands gives the energy loss per turn, about 2 keV in this case.

None of these longitudinal effects have limited performance so far. A maximum of 30 A has been stacked within about 3% momentum spread. Larger densities have been obtained experimentally in smaller stacks.

#### Transverse Emittance

As the luminosity is proportional to the inverse of the effective beam height  $h_e$ , and as we have a limited maximum current, and intensity to spare at injection, we apply vertical shaving<sup>10</sup> of the injected beam. The resulting value of  $h_e$  is typically 3 to 4 mm at the highest energies and the ratio of horizontal to vertical emittance is about 3. Heavier shaving does not produce values of  $h_e$  much below 3 mm. This can probably be explained by coupling effects and is being studied.

A gradual blow-up of  $h_e$  occurs during the 20 to 40 h of typical beam life. In general, this blow-up is the only noticeable contribution to the decay of luminosity. Typical rates are now about  $10^{-2} \text{ h}^{-1}$ ; a value which is reasonably consistent with explanations by intra-beam scattering<sup>11</sup>.

Studies have continued on the reduction of the vertical beam size by stochastic cooling and resulted in a successful demonstration of basic feasibility<sup>12</sup>. Fig. 5 shows the development of  $h_e$  during a period of 13 h when the cooling system was alternately on and off.

More development is needed, however, before one can be certain of any practical interest of this method.

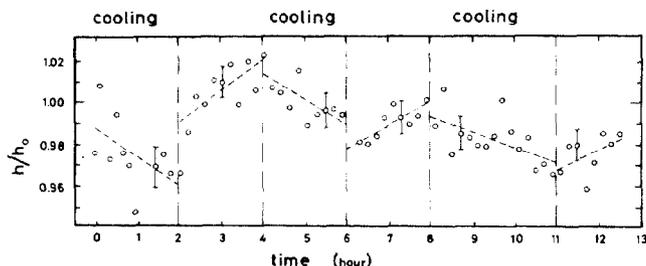


Fig. 5 - The effective beam height as a function of time, under the influence of stochastic cooling, turned on and off at regular intervals.

In intersection 7 a system of steel-copper quadrupoles, modifying the local beta function, has been installed and tested<sup>3</sup>. This insertion produces a decrease of the local beam height by a factor 2.3. So far, a maximum luminosity of  $2.1 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$  has been achieved, with circulating currents of 19.8 A in one ring and 24.1 A in the other.

Even at the highest attainable luminosity the linear beam-beam tune shift is only about  $10^{-3}$  per intersection. No indication of stochastic behaviour or of Arnold diffusion has ever been observed. Beam-beam effects at much higher current have, however, been simulated by a strongly non-linear lens. Results are given in ref. 13.

#### Background Radiation and Beam Decay

Background radiation caused by protons lost from the circulating beams has always been a problem. Attempts to control the beam loss in time or space, so as to keep stray particles from reaching the experimenters' equipment, have never led to more than partial success. We do occasionally remove halos from the beam by periodic scraping (a few times at most, during a beam's life) and we are installing a system of secondary collimators to prevent particles scattered on the beam dump block - the main aperture limit - from reaching the down-stream intersections.

In general, however, the only reliable way to eliminate background problems was to reduce the rate of beam loss to values several orders of magnitude below what would be required from the point of view of beam life.

During the first years of ISR operation we had beam decay that was intensity dependent and much faster than what could be explained by beam-gas collisions only. It is clear now that the reasons for this anomalous decay fall into two classes, viz.

- a) non-linear resonance excitation,
- b) the effect of electrons produced by ionization and trapped in the beam's potential in spite of the action of the clearing system.

The resonance excitation <sup>7,8</sup> is predominantly due to beam-beam forces; much less due to magnet imperfections. The following practical conclusion seems firmly established; sum resonances of up to and including 5th order have a drastic influence on beam decay and background. Their compensation is possible in principle, but difficult in practice because of the very tight tolerances - below 0.1 mm - on vertical beam position in the intersections. Resonances of order 8 or higher have little effect on beam loss, although the incoherent blow-up of amplitudes around 8th order and 11th order resonances has often been seen on Schottky scans. Our efforts have, therefore, been concentrated on avoiding low-order resonances, more than on making them acceptable.

The effects of trapped electrons seem to be multiple and complicated. They seem to become noticeable at electron concentrations of the order of a few parts per thousand and drastic at ten times higher concentrations. The improved clearing and vacuum have all but eliminated these effects by now. A brief summary of our observations seems nevertheless appropriate.

The predominant effect of trapped electrons - though possibly not the only one - is to provoke electron-proton transverse instability <sup>14,15</sup>. The observed dipole moments of transverse oscillation are extremely small, equivalent to proton barycentre amplitudes of a few times  $10^{-7}$  m. Fig. 6 gives an example. It shows the output of a spectrum analyser scanning the signal from a pick-up electrode which is sensitive both to vertical oscillations and to variations of longitudinal charge density. The centre frequency is about 100 MHz. The peaks, forming a regular comb of spectral lines at all revolution harmonics are due to the longitudinal Schottky noise of the circulating protons. The lines at  $(n - Q)f_r$  in between (where  $Q$  is the betatron wave number and  $f_r$  the revolution frequency) are due to electron-proton instability. The instability may remain stationary at constant macroscopic dipole moment for minutes, or it may be periodic with regular repetition periods ranging from tens of milliseconds to seconds. The width of the observed spectral lines is small compared with the spread of proton oscillation frequencies (the widths seen in Fig. 6 are purely instrumental). This, and the correlation of the end of a burst of instability with a burst of background radiation suggest that a very small fraction of the protons is driven to large amplitudes until some of them strike the chamber wall.

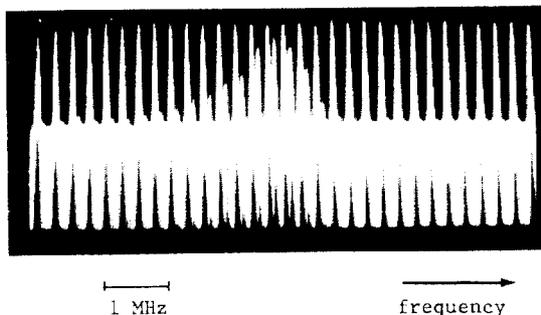


Fig. 6 - Spectrum analyser scan of the signal from a single-plate pick-up electrode showing a family of spectral lines due to electron-proton instability. The regular comb of lines - spaced at 318 kHz - is the longitudinal Schottky noise. The centre frequency is 100 MHz.

Among the unexplained observations is an apparent correlation between the presence of non-linear resonances in the beam and the appearance of a spectrum of transverse oscillations resembling electron-proton instability. Equally unexplained is the occasional observation of spectral lines outside the ranges of proton dipole frequencies, or grossly outside the range of plausible electron frequencies.

The clearing of electrons has been gradually improved by installing additional clearing electrodes in all places where one could expect electrons to be trapped in electrostatic potential wells, created by variations of chamber cross-section or by the crossing beams. In addition, the general increase of pumping speed has led to a reduction of pressure to about  $0.7 \times 10^{-11}$  torr averaged around each ring. At this pressure the rate of electron production by ionization is so low that collisions between electrons and protons contribute substantially to the clearing.

As a result, signs of electron-proton instability are only rarely seen now and decay rates compatible with beam-beam and beam-gas scattering are often approached or reached.

The threshold value of beam neutralization for the onset of anomalous decay seems to be around a few parts per thousand. Precise measurements of such small degrees of neutralization are obviously difficult. One method employed <sup>16</sup> to study neutralization behaviour is to observe - with a pick-up electrode - the Schottky noise emitted from trapped electrons, outside the frequencies occupied by circulating and oscillating protons. Fig. 7 shows the build-up of this noise, and hence of electron concentration, after a sudden reversal of the voltage on the clearing plates. The time-constant of the build-up is about ten seconds.

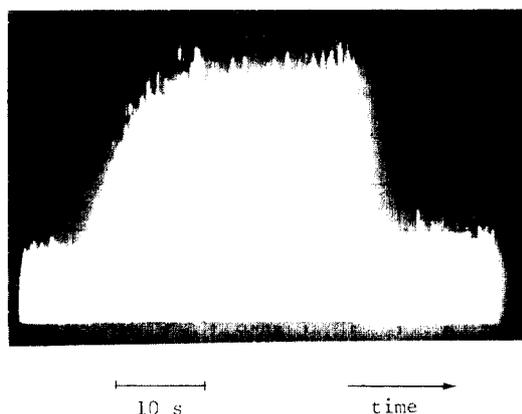


Fig. 7 - Schottky noise emitted by trapped electrons as a function of time while clearing is turned off and on again 30 s later. The pick-up signal has passed a narrow-band receiver tuned to a frequency not occupied by protons.

The clearing system now permits the remote measurement of the total clearing current for each octant of each ring. As the existing vacuum gauges are inadequate for pressures around and below  $10^{-11}$  torr, the clearing current at known beam current is our only direct information about average pressure. A system for remote measurement of the individual current in each electrode (about  $10^{-9}$  A for a 20 A beam and  $5 \times 10^{-12}$  torr) is under development.

### Conclusions

With a peak luminosity five times above the original design aim we still do not seem to have reached any fundamental limit. Continued progress can, therefore, be expected and a luminosity of  $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$  does not seem unrealistic as an ultimate goal. Progress will be only gradual, however, as the main obstacle - the beam-induced pressure rise - depends on pumping speed and surface conditions in two kilometres of vacuum chamber, accessible to piecemeal modification only.

The studies of beam behaviour and the resulting developments will certainly continue. An increasing fraction of this work is likely to be concerned with fundamental problems, related to possible future projects as well as to the ISR. We are aware of the responsibility of running the world's first proton storage rings. We do hope they will not remain the only ones.

### References

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