

OPERATING RESULTS FROM ISR

W. Schnell
CERN
Geneva, Switzerland

Summary

The CERN Intersecting Storage Rings are now in routine operation for colliding-beam physics. In 1972 more than 75% of the total operating time was used for physics or preparation for physics runs. The machine's performance has increased substantially. The original design aim for luminosity has been reached and decay rates and background radiation with intense beams have been further reduced.

Some operational aspects and the main performance limitations are described.

1. Operations

During 1972 the ISR were in operation for about 3000 hours. Of this time 60% was used for colliding-beam physics, 23% for development and 17% for start-up, filling, adjustments and luminosity measurements in preparation of physics runs.

The typical cycle of operation for physics consisted of daily fills followed by about 15 to 20 hours of circulating beams, but there also were regular runs with beams circulating for about 36 hours. In the preparations for physics runs the ISR used protons from only one acceleration cycle in three of its injector, the CERN PS. Similar arrangements were made for some of the time spent for development. Thus, the overall ISR usage was roughly 10% of the total number of protons accelerated in the PS in 1972.

The normal range of operating momenta was from 11.5 to 26 GeV/c, the equivalent of 300 to 1500 GeV/c on a fixed target. On a few occasions beams were accelerated in the ISR to 31.4 GeV/c and provided for colliding-beam physics at a momentum equivalent to just over 2000 GeV/c.

The complexity of the vacuum system and the demands on this system's performance have increased further during 1972. Many more machine components have been installed during the year and the chambers around the beam intersections have all been rebuilt - some of them more than once - and become much more complex. There have been, in total, 60 bakeouts. The bakeout has been hardened to 24 h at 300°C and the average pressure lowered to about 3×10^{-11} torr. In spite of all this, only a few scheduled runs were lost due to leaks or other vacuum problems.

On two occasions we failed to prevent high intensity beams from going astray and burning holes in thin wall parts of the chamber. Even this did not result in more than a few days' interruption. We have, however, sharpened our protective measures, such as automatic dumping, protecting the chamber by suitably placed scrapers and limiting potential damage by means of fast-acting sector valves.

The luminosity suitable for physics has increased by about an order of magnitude during the year. During the last three months the average value taken over the full duration of all runs was above

$10^{30} \text{cm}^{-2} \text{s}^{-1}$. In December the original design figure of $4 \times 10^{30} \text{cm}^{-2} \text{s}^{-1}$ was surpassed for the first time, with currents in the two rings of 11 and 12 A. Some physics data were immediately obtained during the four hours these beams were left circulating.

During the year five experiments were completed and nine other groups were taking data in the five colliding beam areas equipped for that purpose. A sixth area is now being opened, and preparations are under way for four new experiments in addition to the seven experiments approved for the Split Field magnet facility which is scheduled for operation in 1973. Details of the interaction between high-energy experiments and ISR operation are given in ref. 1.

As an example Fig. 1 shows the layout and vacuum chamber in Intersection 6, which was specially arranged for small-angle scattering experiments. In this place two large liquid-helium cryopumps have been in operation, creating pressures below 10^{-12} torr.

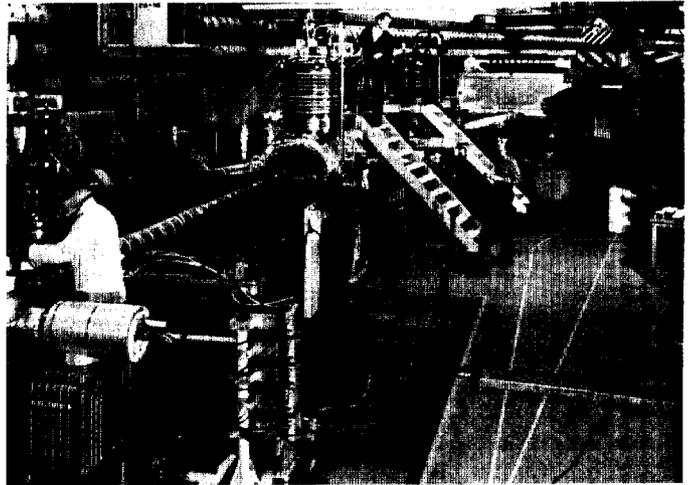


Fig. 1. Intersection I6, equipped with cryopumps.

2. Performance and beam behaviour

2.1 Luminosity

The luminosity provided by two beams crossing horizontally under an angle α is given by

$$\frac{I_1 I_2}{c e^2 n_e \tan^2 \frac{\alpha}{2}}$$

where I_1 , I_2 are the circulating beam currents, n_e the effective beam height at the crossing and $\alpha = 15^\circ$ in the ISR. Originally we expected to obtain

a luminosity of $4 \times 10^{30} \text{cm}^{-2} \text{s}^{-1}$ with 20 A beam current and $h_e = 10 \text{ mm}$. Since the vertical emittance of our injector and the transfer errors are smaller than assumed, we obtain smaller values of h_e and require somewhat smaller currents.

Ever since the start we have found our luminosity limited by two main effects: a third one is likely to become important in the near future.

The most important one of these effects is a beam-induced deterioration of the vacuum. Ions originating from collisions with the residual gas are driven into the chamber walls by the beam's electrostatic potential, which is about 1.5 kV at 10 A beam current. The ions liberate gas molecules from the surface layers adsorbed at the walls. It is easy to show that with such a process, where the pressure rise is proportional to the product of beam current and pressure, one has a critical current, above which the equilibrium pressure rises to infinity.

This effect has been thoroughly studied by now.² One remedy applied is to reduce the surface coverage by adsorbed molecules. As a first step we have adopted baking at 300°C for 24 h everywhere and every time a sector has been exposed to atmospheric pressure, instead of only 6 h at 200°C as used earlier. Surface treatment with ions from a glow discharge is applied to parts of the chamber where the pumping speed is small and difficult to increase. This is done in the laboratory, prior to installation. The beneficial effect seems to survive a few hours at atmospheric pressure. Keeping the entire system in the 10^{-11} torr range of pressures also contributes to reducing the amount of beam-induced outgassing. In clean parts of the vacuum system we actually observe beam-induced pumping, i.e. the number of molecules desorbed per incident ion is smaller than one.

The other, more universal, remedy is to increase the distributed pumping speed by means of a large number of additional titanium sublimation pumps. A program of installing a total of about 500 such pumps has been pursued throughout the year. By the end of the year about 2/3 of these pumps were in operation. As a result, the critical current had increased from about 4 A around the middle of 1971 to nearly 14 A in both rings (Fig. 2).

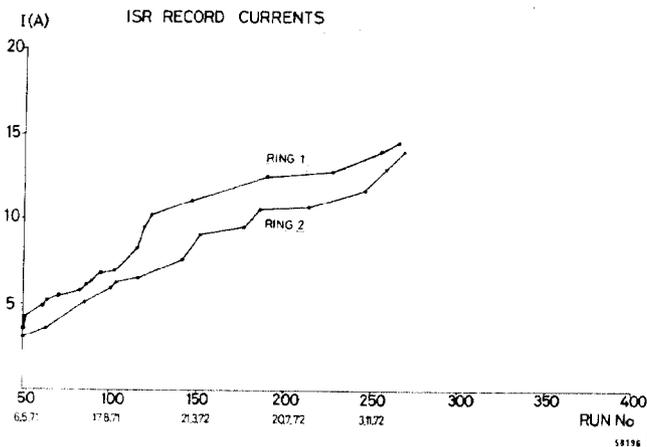


Fig. 2. ISR record currents.

Most of the sublimation pumps still being installed this year go to the centres of our long magnet units, where the pumping speed, without pumps is strongly conductance limited. Installing additional pumps there is not difficult since all our magnets are of the open C configuration, having been made like that precisely to keep the vacuum chamber accessible.

The second limitation is transverse instability due to the resistivity and inductance of the chamber walls.³ The observed instability threshold is in good agreement with calculations. Stability is provided by Landau damping via the spread in betatron frequencies. To make this spread large enough we have to apply a rather large sextupole component to the magnetic field. This remedy is limited, however, by the necessity of keeping low order non-linear resonances outside the momentum range occupied by the stacked beam. Fig. 3 shows a few typical working lines in the plane of horizontal and vertical betatron wave numbers, Q_v , Q_h , measured at low beam intensity. As a refinement, some of these lines are curved to counteract the influence of the beam's space charge.⁴ This is obtained by a suitable distribution of the currents in the poleface windings. Since it is the local value of dQ/dp that determines stability, the threshold is somewhat increased by keeping the working line straight at high intensity. Reference 4 also describes our methods of measuring the local values of betatron frequencies in a stacked beam.

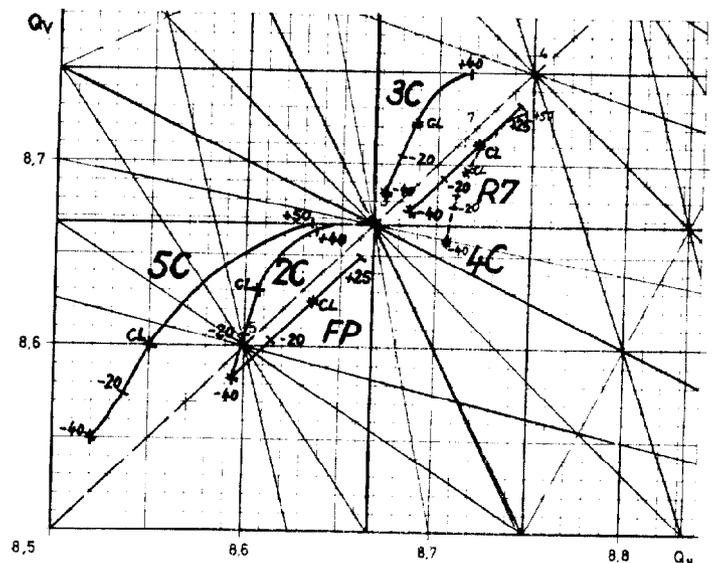


Fig. 3. Typical working lines. The figures on the curves give the radial position of the closed orbit, measured from the centre (CL) of the aperture, in millimetres.

At the highest intensities the line marked 5C, providing $\Delta Q \sim 0.1$ across the stack, is required for stability with a reasonable safety margin. This line includes a number of 5th order resonances. Their effect is noticeable but quite acceptable.

The third problem, which is not a serious limitation yet, is longitudinal instability of the injected beam, leading to dilution by roughly a factor of two, in phase plane density.⁵

Since we have horizontal aperture to spare, we are able to alleviate all three effects by scraping away vertically a fraction of the injected beam⁶ so as to obtain a given current at reduced effective beam height and reduced particle density in momentum space. We call it "shaving". About 50% in luminosity was gained in this way. As already mentioned, we have reached, so far, a luminosity of $4.4 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ with $h_e = 3.2 \text{ mm}$, and perfectly acceptable decay rates and background.

Fig. 4 shows the development of ISR luminosity since the start of regular operation in the spring of 1971.

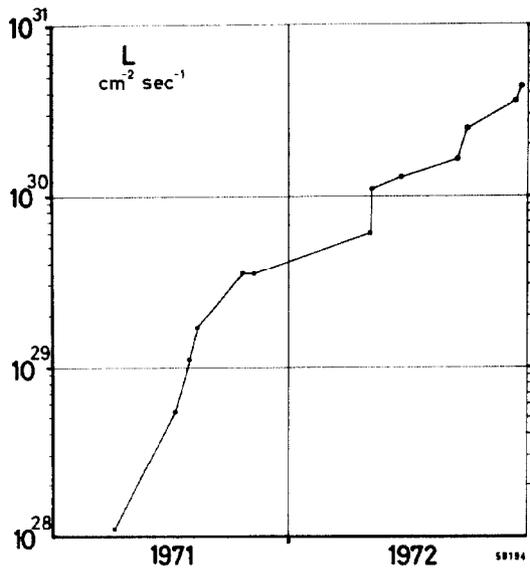


Fig. 4. Development of ISR luminosity.

In the near future, we intend to put into operation an active feedback system to improve transverse stability.⁷ This, together with continued vacuum improvements and the expected increase of PS intensity, should enable us to gain another factor of two, at least, in luminosity.

As the beam-beam Q-shift is still very small (about 2×10^{-4} at 20 A) in our machine, a substantial increase beyond $10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ should be possible by inserting magnet structures for low β , or low-angle crossing, or both, in one of the intersection regions. This is being studied at present.

2.2 Beam decay and background radiation

Ideally the beams should decay because of gas scattering only. Nuclear collisions lead to loss of intensity. Multiple Coulomb scattering leads to gradual blow-up of the effective beam height, h_e . As a by-product of the vacuum improvements mentioned above, the average pressure is now about 3 to $4 \times 10^{-11} \text{ torr}$ (Fig. 5). The corresponding loss rate due to nuclear scattering is exceedingly low, near 10^{-4} h^{-1} , and the half-life of luminosity, due to the increase of h_e , should be about two weeks.

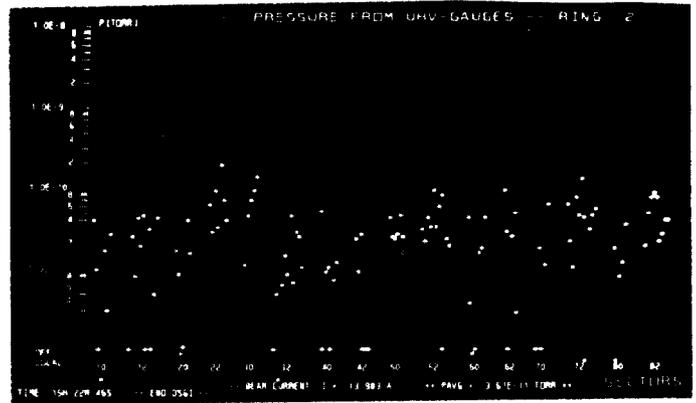


Fig. 5. CRT display of pressures around the ISR.

Instead, when we started in 1970, we observed alarming loss rates, such as 0.5 minute^{-1} at 1 A beam current, not compatible with gas scattering even at the higher pressures we had then. We soon found that this anomalous decay did depend on vacuum after all, and on the clearing of space charge produced by electrons that are created by ionization and tend to be trapped in the beam's potential. Dramatic improvements were obtained by lowering the pressure and by installing more electrostatic clearing electrodes in addition to the large number already present from the beginning.⁸ The explanation seems to be instability of the coupled oscillation of protons and electrons.^{9 10} Since, in this instability, the electrons gain amplitude much faster than the protons, they are shaken out to the wall, or out of resonance with the protons, while the protons suffer only small blow-up. But the process repeats itself at a few seconds' interval, leading to gradual blow-up of the proton beam. We have, in fact, observed bursts of proton oscillations at the right frequency (about 100 MHz at 10 A beam current) and repetition rate. As the vacuum and clearing were gradually improved, these oscillations became weaker, and their repetition period longer, until we have reached the point where the effect is mostly undetectable.

The present status is that decay rates compatible with nuclear scattering have occasionally been observed with beams as high as 8 A. It is true that most of the time decay rates are higher and the blow-up of h_e is always faster than compatible with Coulomb scattering by about an order of magnitude. This is not yet explained, but it does not present a serious problem. In practice the half life of luminosity is about 30 h.

Background radiation due to beam-gas and beam-wall collisions has improved together with the beam life and is, in general, very low. Indeed, our motivation for trying to reduce beam decay has nearly always been reduced background rather than increased beam life. The "shaving" of the injected beam has been found to lead to an additional improvement. At best, the background is compatible with the local pressure - about 10^{-11} torr - in the intersection regions.

On the other hand, it has turned out that it would be difficult to reconcile high decay rates with low background by means of periodic scraping. The difficulties with heavy scraping of stacked beams are not fully understood. Secondary electrons generated by lost protons may be a possible explanation. We do remove low density halos from the beam by scraping. This usually improves the background by a small factor for several hours.⁶

Much of the remaining decay and background may be explained by diffusion processes which can gradually change the momentum of particles and drive them into high-order non-linear resonances, where they suffer excitation of transverse oscillation or loss. One such diffusion process can be multiple Coulomb scattering between the protons of the same beam ("intra beam scattering" 11). Fig. 6 shows particle density versus momentum of a fresh beam and the same beam 15 h later. The smoothing of the edges is in reasonable agreement with calculations of intra beam scattering.

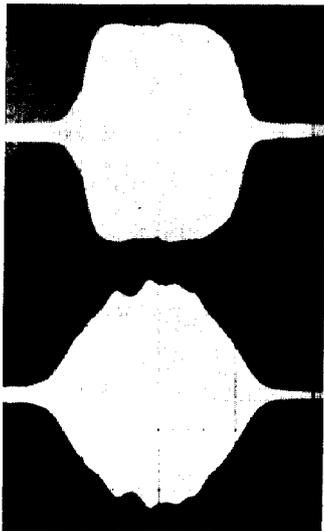


Fig. 6. RF scan (by empty buckets) yielding particle density (ordinate) versus momentum of a fresh beam (above) and of the same beam 15 h later. Beam current: 5.5 A.

Similar results have been obtained by studying the rate of particles being lost on to a scraper. On Fig. 7, again showing density versus momentum, one can see dips, due to the 5th order resonances of working line 5C (cf. Fig. 3).

Single beam Arnold diffusion, driven by azimuthal variation of neutralisation,¹¹ had been invoked in the past, to explain beam decay. We have not observed any positive evidence for this. We plan, however, to provoke and study it by means of a non-linear lens (a current bar near the beam).

Fig. 6 has been obtained by scanning with empty RF buckets. Fig. 7 is due to a new diagnostic method which we call Schottky scans, and which seems worth mentioning. The finite number of particles in the

beam leads to statistical fluctuations in azimuthal charge density. These are given by Schottky's formula for noise in a particle beam. An electromagnetic pick-up yields a corresponding voltage. Scanning the frequency spectrum of this voltage, and integrating the result of many scans in a digital memory unit, one obtains an output proportional to the square root of density versus momentum. Several minutes' integration time is needed, but the method has the advantage of being completely non-destructive, so that the evolution of particle distribution in momentum can be followed throughout a run. The figure caption gives a few more details.

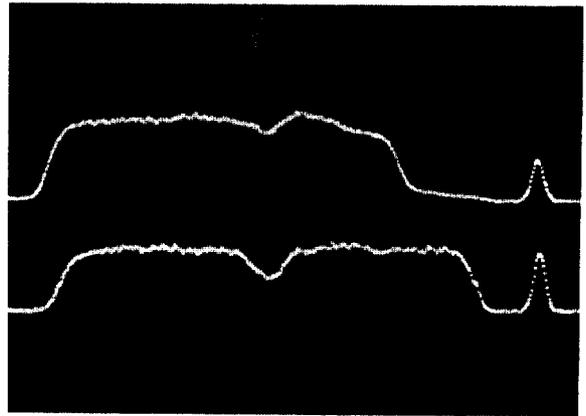


Fig. 7. Schottky scan yielding square root of particle density (ordinate) versus momentum. Dips due to 5th order resonances are visible. The scan was made on the 1110th harmonic of the revolution frequency (350 MHz). The peak on the right is a marker. Upper trace: ring 1, lower trace: ring 2. Beam currents 11.5 A and 13.2 A.

2.3 Special features

Our magnet structure contains a set of quadrupoles which enable us to superimpose, in every other intersection, the closed orbits of different momenta. This reduces the size of the interaction diamond by about a factor 5 in linear dimensions, to about 6 cm (length) x 0.8 cm (width). Our experience with this scheme is described in ref. 12.

The luminosity is measured, routinely, by Van der Meer's method, i.e. by vertically displacing the crossing beams with respect to each other and measuring beam-beam counting rate as a function of relative position. There are special steering magnets for this purpose. Much effort has been devoted to improving the accuracy of this measurement and to decreasing the time needed to perform it. As a result, we can measure luminosity in all experimental intersections simultaneously under computer control with a reproducibility of about $\pm 2\%$.

The maximum particle momentum currently available from the PS is 26 GeV/c. At the price of much reduced luminosity, we have accelerated stacked beams from about 26 GeV/c to 31.4 GeV/c, the maximum our magnet power supplies can provide.¹³ One way of doing this is to rebunch part of a beam which has been stacked at the lower energy and to accelerate it bunched. This is done by means of the same RF system as used for stacking. Up to 0.65 A per ring has been accelerated by this method. The bunches are perfectly stable, in spite of their high intensity, apparently because they are kept in tight-fitting RF buckets. So far all our colliding beams at 31.4 GeV/c have been obtained in this way. The maximum luminosity achieved was $5 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$.

More current can be accelerated by phase displacement, i.e. by pulling empty buckets through the stack, again using our normal RF system. Up to now we have tried this only once, in one ring, bringing 1.3 A to the top energy.

In both cases the shape and location of the magnetic working line must be kept constant while the field increases and saturation worsens. This is done by means of the poleface windings, the currents of which are continuously regulated by the controls computer.

3. Conclusion

We have still not found any new or fundamental limitation to the performance of our machine. The limitations we have require time and effort to be gradually removed, but they are well understood and a development program dealing with them is under way. We believe, therefore, that there is ample room for future growth, first with the machine as it is, later with some local modifications of the magnet structure. One may also conclude in a more general way that future projects of colliding beam facilities involving protons can now be put on a rather safe basis.

References

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