THE CERN INTERSECTING STORAGE RINGS

K. Johnsen

CERN, Geneva, Switzerland

Abstract

The present status of the CERN Intersecting Storage Rings is described together with details of the performance during the first few months of operation. Maximum currents of 6.9 A have been achieved to date and the present limitations appear to be due to gas desorption from ion bombardment of vacuum-chamber walls. At present, about 30 h/week (average) is devoted to colliding-beam physics under good background conditions and very low losses at currents up to about 4 A in each ring.

I. Introduction

When we started planning this Conference we hoped that this could be the first occasion for you to learn about the early successful tests of the ISR. Events have turned out differently though, and to us in a very happy way. Probably all of you have known for some time that the ISR has been successfully started up and, therefore, this information is not news to you. In fact, we were able to announce to the June meeting of the CERN Council that 1st March this year could be considered as the end of the construction. This was four months earlier than assumed in our early plans of a 5½ year construction period. The cost of the project also came out slightly below the estimated figure of 332 MSF (in 1965 value of the Swiss franc).

It is almost exactly one year ago that we started tests with beams in the transfer tunnels, although by then most components had already been tested individually. On October 29 we injected for the first time into one of the rings, obtained at once a circulating beam, made our first lifetime measurements over a period of about half an hour and stacked with the RF system. The first results were very encouraging and still more encouraging things happended during the weeks that followed, in particular during January when we observed, for the first time, lifetimes of days and weeks with quite decent intensities. Quantitative results are given later.

At the end of January Ring II was also put smoothly into operation, and on January 27 beams at momenta of 15 GeV/c were stacked in both rings and first collisions (corresponding to a 500 GeV beam hitting a fixed target) were observed by detectors placed at two of the intersection regions. On February 17, the first collisions between two beams of 22.5 GeV/c were observed and on May 18, the first collisions between two beams of 26.5 GeV/c occurred. The first pilot run, under conditions suitable for colliding-beam physics, was successfully carried out during the night of February 24/25, when beams of about 700 mA were left circulating in each ring for 6 hours. At the end of this time, the loss had been 1 mA in one ring and 11 mA in the other, and we had proven that we were actually ready to receive the first experimental teams on the floor.

Consequently, as stated earlier, we considered 1st March as the end of the construction period.

I could continue to tell the story in the sequence things happened. I believe, however, that it is more logical and efficient to give the main results out of their historical context and to discuss various aspects separately.

II. Equipment Behaviour

The various components of the ISR have been described at earlier conferences and the construction proceeded along these lines with only minor changes. Therefore, I shall assume that you are reasonably familiar with our equipment, but some comments on the behaviour of this equipment may be of interest.

First a few words about equipment reliability, as experienced during the period since we started. Of course, we have had equipment failure occasionally. We have so far, however, had no major failure anywhere (touch wood!). One might say that nowadays enough should be known about standard accelerator magnets that one would not expect serious difficulties. However, we have in our system a very large number of power supplies for adjustment magnets, correcting windings and poleface windings, but even on these the troubles have been minor, although noticeable. Of equal importance is the fact that these systems have also met our specifications, which in many cases had to be rather severe. The closed orbit gives an example of performance in this res-

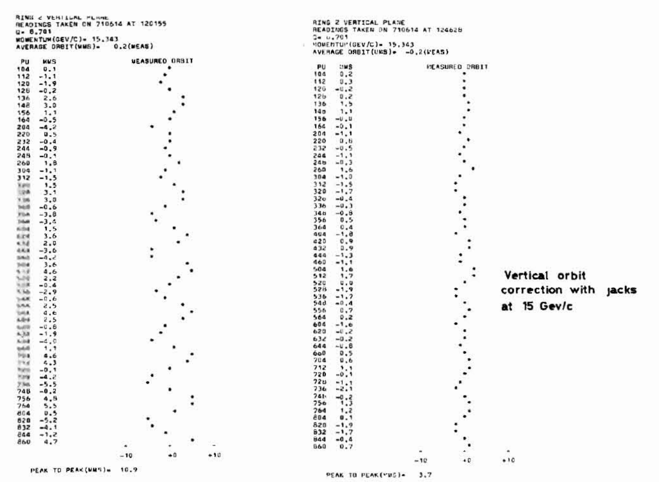

Fig. 1

Vertical closed orbit at 15 GeV
Left: Uncorrected
Right: Corrected with jacks

pect. The first reliable closed orbit measurements have peak-to-peak deviations of 8 mm vertically and 16 mm horizontally whereas the design figures specified that they should be below 22 mm and 33 mm, respectively.

Nevertheless, we have tried out our system for closed-orbit corrections. A particular example is illustrated in Figure 1, where we have reduced the vertical peak-to-peak deviation from 11 mm to 4 mm. When we make corrections like this, we may move motorised jacks or excite auxiliary windings, or magnets; the pick-up electrodes supply the required information, the control computer is essential both in processing the information and in setting the power supplies in question. This kind of closed-orbit correction has made it possible to run the ISR without realignment since October last year although the magnets have moved 0.9 mm downwards, on the average, and the r.m.s. spread of their vertical positions has increased to 0.6 mm.

Altogether, the flexibility built into our system has been extremely useful. Another example may be quoted: it is very important to keep the aperture free of resonances up to such high orders that it is impossible to rely upon just setting fields and gradients to calculated values (although this was very successful for the early runs). This, coupled with the fact that a certain amount of sextupole components must be present in the field to avoid coherent instabilities, has made it necessary to go through a fine and very interesting empirical field-correction procedure to get good working lines.

As you all know, the RF system in a proton storage ring plays quite a different role from that in a an accelerator proper. It has a difficult amplitude and frequency programme and tight requirements on precision whereas the voltages actually applied are not very high. The stacking process has come out as predicted and we have stacked with up to 70% efficiency. This means that the phase-space density in the stack is up to 70% of what is theoretically possible with the phase-space densities delivered by the CPS. Let me also mention that the refinement of stacking with suppressed buckets, as described at the Cambridge Conference in 1967, has also been successfully tested.

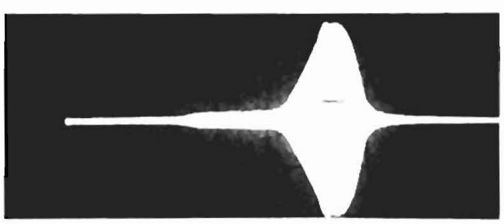

Fig. 2

Empty bucket scan of a 2 A stack, 20 bunches, stacking at the bottom

A typical stack is illustrated in Figure 2. Such a picture is obtained by scanning through a stack with empty RF buckets and the signal observed on the electrostatic pick-up electrodes is then proportional to dI/dp.

The vacuum that we have achieved is of particular interest. In our original design we did not dare to rely upon getting better than 10^{-9} torr average and 10^{-10} torr in the crossing regions, and even that was considered optimistic taking into account the complexity and size of the system and the reliability required. We have actually achieved pressures an order of magnitude lower than this. As I will mention later, we still have some vacuum difficulties associated with high stacked currents, but the trouble would most likely have been much more severe if we had only reached our design pressures. Here also, reliability and flexibility have gone beyond expectations. Vacuum failures have not hampered our work, and the extraordinarily flexible way in which the people responsible for the vacuum system can open up sections to air, put in modifications, rebake and still be back in operation within rather short shut-downs has been quite remarkable. This is very important for the experimental set-ups in the crossing regions.

I have mentioned diagnostics a few times but, of course, there is much more. In both the beam-transfer lines and the main rings the properties of beams have been measured with high accuracy and their positions to fractions of millimeters through the use of fluorescent screens, secondary emission grids, electrostatic pick-ups (mentioned before), scrapers, beam probes, etc. The total stacked currents are measured by current transformers.

The control functions are largely centralised in the main control room. A particular feature of our control system is the very extensive use of a control computer both for the processing of data and for setting machine parameters. (An example was given earlier.)

With the equipment working as expected, it is obvious that beam behaviour has also turned out as expected for stacked currents low enough that single particle dynamics apply. I have already mentioned closed orbits and stacking. Q-values are at the design values, within the tolerances, and can be measured to an accuracy of ± 0.001.

III. Performance

Since a colliding beam device is basically a low-intensity device seen from the point of view of the experimentalists, the performance limitations at intensities well beyond where single particle dynamics apply are of greatest interest. You will hear more about this in other contributions to the Conference and I will only mention the main points.

III.1. Lifetime

At low currents the loss rates of a stacked beam is $I^{-1}dI/dt = 5 \times 10^{-6}\ min^{-1}$ and quite consistent with nuclear scattering. By low currents, I mean currents up to a little more than 1 A in the circulating proton beams (which is not so low after all). At 3 A the best lifetime observed is still very good, with loss rates $I^{-1}dI/dt \approx 10^{-5}\ min^{-1}$, but at such currents we do start noticing a departure from nuclear scattering, and it is quite noticeable at 4 A with $I^{-1}dI/dt \approx 3 \times 10^{-5}\ min^{-1}$. Above this current, the loss rate increases rather fast to reach about $3 \times 10^{-4}\ min^{-1}$ at 5 A and goes at present to infinity at 6 - 7 A. This is, however, associated with a vacuum deterioration which will be described in more detail in the next section. Nevertheless, it should be said here that the rates observed are still inconsistent with expected rates due to nuclear scattering and even with multiple coulomb scattering, if we take into account the speed at which a stack reaches the quoted loss rates. Other mechanisms must therefore be found to explain the observations. Details about these phenomena and speculations about the causes I leave to the specialized sessions and the associated discussions. It should only be noted that although the figures quoted above are about the best ones observed, they have normally been observed several times. However, there is a considerable spread in the data.

III.2. Intensity limitations

Let us now come to some phenomena related to high intensity stacks.

a) Transverse coherent instability

Most of you have heard that during the early runs, we found an intensity limitation appearing around 3 A, a value perhaps a little lower than expected. The frequency of coherent signals induced in pick-up stations, and the fact that the instability can be influenced by sextupole fields, show that it is a low frequency instability which is driven by the resistivity and inductivity of the vacuum chambers.

After we started applying appropriate sextupole components to the magnetic field, this transverse coherent instability has hardly been seen again although we have provoked it artificially in order to study it. The sextupole component required agrees within a factor of two or so with predicted values.

b) Another intensity limitation

Another intensity limitation occurred, however, an example of which is shown by the curve marked I in Figure 3. It differed from the previous one mainly by the fact that it did not seem to be associated with coherent oscillations. Further, it seemed to be rather insensitive to field shape, energy and stacking conditions (beam shape, density, etc.). But the most striking feature seems to be that it is always associated with a severe vacuum deterioration that follows the beam current rather than the losses. Figure 3 also shows a typical recording of the pressure in a long straight section, and one notices the relation between this pressure and the beam intensity. The places where these pressure bumps occur are more or less fixed. We have tried baking parts of the vacuum system to 300° C instead of the usual 200° C and some of these pressure bumps have disappeared. During the present shutdown we are baking the rest of the vacuum system.

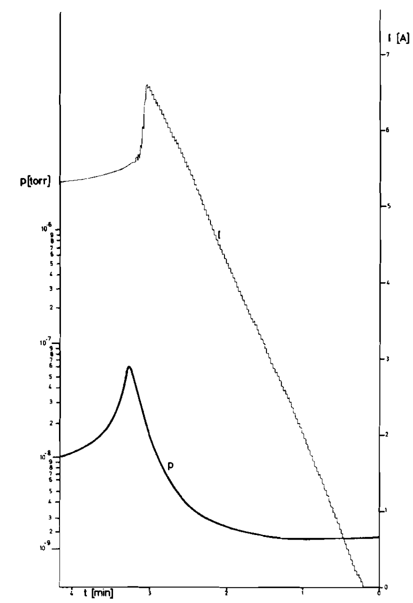

Fig. 3

Anti-stacking and pressure bump
The p curve is shifted to the left by 12 sec.

The mechanism creating these pressure bumps is not fully understood but it seems most likely that the cause is gas desorption from the chamber walls due to bombardment of the ions created in the residual gas inside the beam. The first bombardment releases gas which creates more ions, thus increasing the bombardment further and so on. Beyond a certain critical beam current this results in an avalanche of pressure increase.

Under such conditions, a stacked beam seems to behave in the following way: For currents below say 4.5 A the beam size is rather small - in fact smaller than anticipated during the construction of the ISR. Above this value of current, the beam size is observed to be much bigger, and it is believed that this is somehow due to the pressure bumps. The growth can only continue until the beam hits the scrapers, from which moment large losses occur. At high currents, the losses from one CPS pulse to another may become larger than the injected pulse, thus causing the "stacking downward"; this situation is illustrated in Figure 3.

It still needs to be explained what causes the beam growth, as it is faster than it would be from multiple scattering with the observed average pressures. It is likely that the growth of the beam size is related to the fact that the beam is probably completely neutralised in the pressure bumps, as the clearing electrodes cannot cope with the high rate at which electrons are being created in these regions. This means that the space-charge forces are a few orders of magnitude stronger in these regions than in a normal deneutralised beam. No final conclusion has yet been reached on the details of the blow-up mechanism, although there are theories which I believe will be discussed in later sessions.

Finally, let us look at the intensity records as they have occurred as a function of time. (Figure 4) It seems to be a very steady trend upwards, and we believe that this may be the result of some selfcuring of the vacuum and some vacuum improvements due to special bake-outs during this period. The maximum current we have reached is 6.9 A.

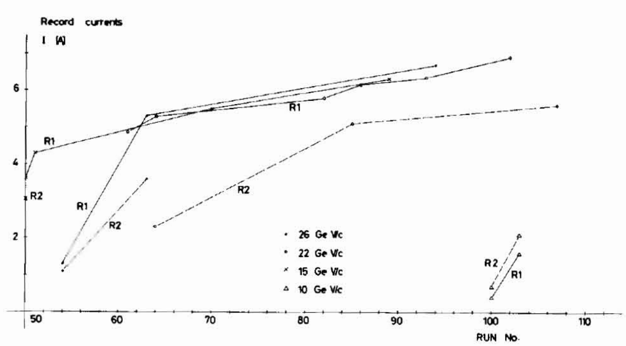

Fig. 4

History of record current

c) Longitudinal instabilities

It is well known that one of the effects that we were afraid would occur in the ISR was very-high-frequency interactions between the beam and various components surrounding the beam. Therefore, we took special precautions to avoid this with the result that we have, so far, had no conclusive experimental evidence of the existence of such instabilities.

However, we do observe consistently that Ring I is better in loss rate and maximum current than Ring II. The main difference between the rings is that Ring I has resistors installed to damp high-frequency oscillations, whereas Ring II has no such resistors. We do not know whether or not this is significant for the observed difference in beam behaviour. It may just be that Ring I has been more closely studied than Ring II since we have had a tendency of putting more priority on Ring I.

d) Beam-beam interactions

No beam-beam interaction has been observed under quiet beam conditions, although we have seen a very small amount of "cross-talk" at sudden intensity changes in one of the beams.

IV. The ISR as a Facility for Experiments

As mentioned in the introduction, the ISR was ready to receive the first experimental teams from 1st March this year. Since that date, almost 400 hours have been devoted to data taking, and eight different experiments have been involved. Some results from four of these experiments have already been published both at conferences and in scientific journals. Figure 5 indicates types of experiments and their location. In addition to those being able to take data, the figure also shows some under active preparation.

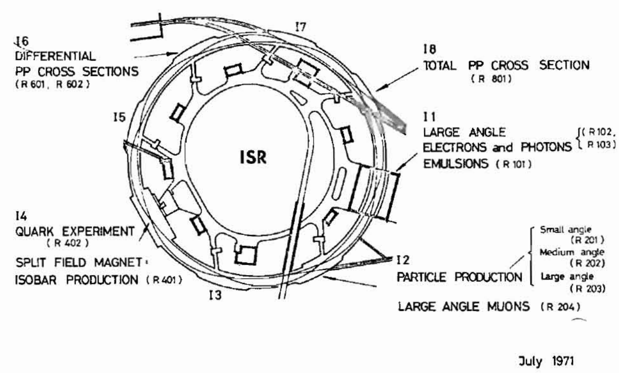

Fig. 5

ISR experiments

Let us have a brief look at the machine conditions that can be provided for experiments at this time.

IV.1. Background

I should like to characterise the background conditions during physics runs in the following general terms:

Up to 1.5 A in each ring, the background conditions are very good unless there has been a mishap with the stack.

Up to 2.5 A, the background is still good, but some experiments that are very sensitive to background (emulsions in particular) start having difficulties.

Between 3 to 4 A, background is still acceptable for many experiments.

Above 4 A, we have so far not created acceptable background conditions. It should be emphasised, however, that we have not tried very hard, as there has been little demand for this up to now.

IV.2. Luminosity

The beams can be steered vertically very accurately in the crossing regions and this is used, through an optimisation procedure, during the preparation for physics runs. One optimises both on luminosity and on background. This procedure also gives good measurements of the effective height of the beams (the height entering the luminosity formula). Typical results lie between 5 - 7 mm, whereas the original design assumed 10 mm. The highest luminosity we have had during a long physics run was

$$L \simeq 1.8 \times 10^{29}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

which was obtained with $I_1 = 3.8$ A and $I_2 = 3.4$ A. If we would put into the luminosity formula the highest figures ever achieved for the intensities in the two rings, we should get

$$L \simeq 0.5 \times 10^{30}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

But this value is of no interest for physics until we have improved on the background at these high intensities.

IV.3. Length of runs

A typical mode of operating the ISR is as follows: We start up in the morning and have a day of machine studies, using either 4 bunches per pulse from the CPS or the full 20-bunch CPS pulses. Near the end of the day, there is a period of two to three hours preparation for physics during which we stack to the desired intensities, go through the optimisation procedure, check on background, etc. possibly restack if first stacks are not acceptable. The stacks are then left quietly circulating, normally for the next 11 hours, and the experimental teams take their data. During this period there are only three people left on the ISR. If by some mishap the beams are lost, we do not refill, but abandon the rest of that run. This does not happen often. Normally, the beams are about as good at the end of such runs as at the beginning, although the average loss rates may be somewhat higher than the best ones quoted earlier in this paper. We have also had a few runs lasting considerably longer than 11 hours, up to 34 hours, of course with considerably reduced luminosity at the end, but still with quite acceptable conditions.

At present we give on the average 30 hours/week of running time for taking physics data. This will be increased somewhat over the next few months. The aim is to give about 2000 hours/year to physics in the future.

V. Thoughts for the Future

Our immediate tasks are obviously to increase the luminosity and to improve the background conditions for the maximum luminosities we can achieve. Although, up to now, we have not encountered any fundamental limitations, we cannot predict that this will not occur perhaps even just beyond our present maximum of 6.9 A. Nevertheless, we are optimistic about the possibility of achieving our design aims, and perhaps going somewhat beyond them with good tuning of both the CPS and the ISR. When the PS Booster comes into operation, we should be able to increase the luminosity further and we may also follow up the suggestions made some years ago by Keil and Sessler for multiple injection.

There are many possibilities for the more distant future but, although we have discussed them, there are no definite plans for their implementation. On the use of other particles than protons, we could accept deuterons if they were provided by the CPS; the future use of antiprotons has been considered but we are eagerly awaiting results on the cooling experiments at Novosibirsk before further planning; for electron-proton collisions, we would need an electron injector and the possibilities for interesting physics at these high energies might well be worth the capital investment.

An obvious future improvement is, of course, the replacement of the ISR magnets by superconducting ones. A possible first step might be to introduce superconducting magnets at the crossing points to enlarge these areas and to give greater flexibility for experiments; we could also find out how superconducting magnets perform under such strict tolerances. Beyond this, it can be seen from the paper presented by J.B. Adams at this Conference that the 300 GeV accelerator is well placed to send protons to the ISR, for colliding beams at energies in each ring of 100 to 150 GeV. The energy would be dependent not only on the maximum useful field that could be obtained in the superconducting magnets but also on the lengths of straight sections, particularly those at the crossing points. But we would hope that the experience gained with our physics programme in the next few years would be able to provide guidance for making suitable decisions on such straight sections.

VI. Conclusion

The whole ISR Department is very happy that we are able to report in this way on the finishing of the construction of the ISR and the beginning of operation. I think it was recognized back in 1965 that CERN was taking a daring road when it embarked on this project. All the questions raised at that time have not yet been answered and we still have challenging problems ahead, both on the machine and on the physics programme. However, the interest shown in the project from the entire high-energy community of the world has been, and still is, the most encouraging one for the tasks ahead.

DISCUSSION

F. AMMAN : Have you any indication of dilution in phase space in the beam transfer from the PS to the ISR ?

K. JOHNSEN : Under good conditions, the dilution of longitudinal phase space between the CPS and the ISR is negligible. It is more difficult to avoid dilution in the ISR, but under the best conditions, the phase-space density even after stacking is as high as 70 % of what is theoretically possible with the phase-space densities delivered by the CPS.

M. GOLDHABER : Have you any plans to study the background by looking at secondary particles ? This could teach one something about vacuum contamination.

K. JOHNSEN : Perhaps Bonaudi would answer this question.

F. BONAUDI : When the rings are set up properly, and at moderate intensities, the background is compatible with rates predicted by beam interactions with the residual gas. However, in worse conditions, the background can increase by as much as 3 orders of magnitude. It is delicate to set up properly many intersections simultaneously.

W. HARDT : Did you succeed in improving the background conditions by scraping the beam ?

F. BONAUDI : This has been tried, but the results are not very conclusive. More work will have to be done.