EXPERIENCES DURING THE EARLY RUNNING-IN PHASE OF THE ISR

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Summary

The CERN Intersecting Storage Rings (ISR) produced the first proton-proton collisions at 15 GeV on January 27, 1971. These tests and other earlier ones with beam in only one ring are described. Further data and observations during the continuing running-in period are included.

1. Introduction

Protons at an energy of 15 GeV were made to collide head-on for the first time, on January 27, in the Intersecting Storage Rings (ISR) at CERN. This was the culmination of a five-year construction programme and a few hectic weeks of running-in tests. I shall try to give a short description of how it happened, and also give a summary of the results obtained. However, for the benefit of those of you who have not participated in earlier conferences of this kind, I shall start by repeating a short general description.

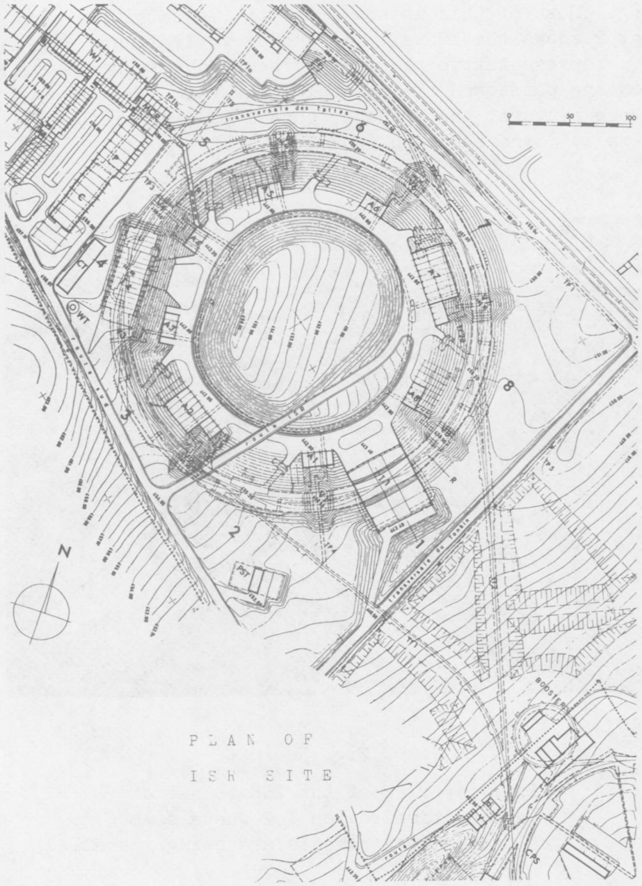

Fig. 1

Plan of the ISR site

2. General Description

A general plan of the CERN Intersecting Storage Rings facility is shown in Fig. 1. Two concentric rings of magnets, 300 m in diameter, are interlaced and somewhat distorted in order to intersect at eight locations where the beams cross each other at an angle of about 15°. The protons are first accelerated in the CERN Proton Synchrotron (CPS) to the desired energy which can be from 10 to 28 GeV and may be different for each of the storage rings. They are ejected from the CPS into a transfer channel, containing many magnets for steering and focusing the beams and, at the fork, a switching magnet allows them to go either right or left into one or other of the rings.

To obtain sufficient intensity for colliding-beam experiments, it is planned to fill each of the rings with about 4×10^{14} protons, equivalent to a circulating current of 20 A. To attain this intensity, many successive pulses from the CPS are stacked in the storage rings and a radio-frequency system is needed to do this. A pulse from the CPS enters one of the storage rings at the inner side of its vacuum chamber, the RF system then accelerates it to an orbit near the outer side where it remains while the next pulse enters and is accelerated to a position very close to the previous one. At the present intensity levels of the CPS, about 400 pulses would be required to be stacked in each ring. This beam would then be about 7 cm wide and 1 cm high, with a momentum spread of about 2%.

Table I

Main Parameters of the ISR

Number of rings	2
Circumference of rings	942.66 m
Number of intersections	8
Length of long straight section	16.8 m
Intersection angle at crossing points	14.7885°
Maximum energy of each beam	28 GeV
Magnet (one ring)	
Maximum field at equilibrium orbit	12 kG
Maximum current to magnet coils	3750 A
Maximum power dissipation	7.04 MW
Number of magnet periods	48
Number of superperiods	4
Total weight of steel	5000 ton
Total weight of copper	560 ton
R.F. system (one ring)	
Number of r.f. cavities	6
Harmonic number	30
Centre frequency of r.f.	9.53 MHz
Maximum peak r.f. voltage per turn	20 kV
Vacuum System	
Vacuum chamber material	low carbon stainless steel
Vacuum chamber inside dimensions	160×52 mm²
Design pressure outside intersection regions	10^{-9} torr
Design pressure inside intersection regions	10^{-10} to 10^{-11} torr

Some of the chief parameters of the CERN-ISR are shown in Table I. The main magnets combine the functions of bending and focusing as in present-day high-energy synchrotrons; poleface windings and auxiliary magnets are included for correction and beam manipulation. Because the beams must remain circulating in the rings for several hours without appreciable loss from scattering, the vacuum requirements are very stringent. The main parts of the machine were designed to be at pressures of 10^{-9} torr and are actually now at ~ 10^{-10} torr. At the intersection regions, pressures of 10^{-11} torr are needed to reduce background from gas scattering that would be deleterious to the experiments, and these pressures have also been achieved.

Table II

SOME CHARACTERISTICS OF THE INTERSECTION REGIONS
IN THE CERN INTERSECTING STORAGE RINGS

Intersection Region 1	Centre-of-mass motion - outwards. Experimental hall, 50 m long, 55 m wide; pit 12 m long, 55 m wide, 3 m deep. Ring surrounded by demountable shielding. Cranes, 40 ton and 30 ton.
Intersection Region 2	Centre-of-mass motion - inwards. Ring tunnel (15 m wide) widened on inside by 3 m; pit 33 m long, 18 m wide, 2.4 m deep. Crane, 30 ton.
Intersection Region 3	Centre-of-mass motion - outwards. Not particularly suitable for experiments - beam dumps in area, injection upstream.
Intersection Region 4	Centre-of-mass motion - inwards. Experimental hall, 70 m long, 25 m wide; pit 33 m long, 25 m wide, 3.6 m deep. Annex for counting room and assembly. Cranes, 60 ton and 30 ton. Large magnetic-analysis system to be installed at this region.
Intersection Region 5	Centre-of-mass motion - outwards. Ring tunnel, 15 m wide; not pit. Crane, 30 ton.
Intersection Region 6	Centre-of-mass motion - inwards. Ring tunnel, 15 m wide; no pit. Crane, 30 ton.
Intersection Region 7	Centre-of-mass motion - outwards. Not suitable for experiments - beam dumps in area, injection upstream, ejection to West Experimental area.
Intersection Region 8	Centre-of-mass motion - inwards. Ring tunnel (15 m wide) widened on inside by 3 m; pit 33 m long, 18 m wide, 2.4 m deep. Crane, 30 ton.

The interaction regions are numbered consecutively in a clockwise direction, starting from the one nearest the CPS. Some of the characteristics of these regions are listed in Table II. The regions numbered 1 and 4 are enclosed by fairly large experimental halls where the beam height above the floor has been increased by means of pits built below the crossing points. The hall at region 4 also has an annex that can be used as a counting room and assembly area for experimental equipment. At region 1, where the width of the hall will accommodate experiments at large angles, considerable flexibility in arrangement is possible through surrounding the beams with demountable shielding. At regions 2 and 8, the tunnel's normal width of 15 m has been extended an extra 3 m on the inside and there are also pits below the beams.

Fig. 2

ISR site, February, 1971

3. Progress of Construction

Construction on the ISR began in 1966 and was scheduled for completion in 1971. By the end of 1970 all major components were in place and had gone through systems tests. Major work remaining for completion were the bake-out of the vacuum chamber in Ring II, some parts of the controls and a certain amount of cabling. Most of this is now complete (March, 1971). Fig. 2 shows the ISR site in February, 1971, and Fig. 3 is a representative photo from inside the tunnel, with a crossing point and the pit below the beam. To the right on the picture, the transfer tunnel is also visible, where it joins the main tunnel.

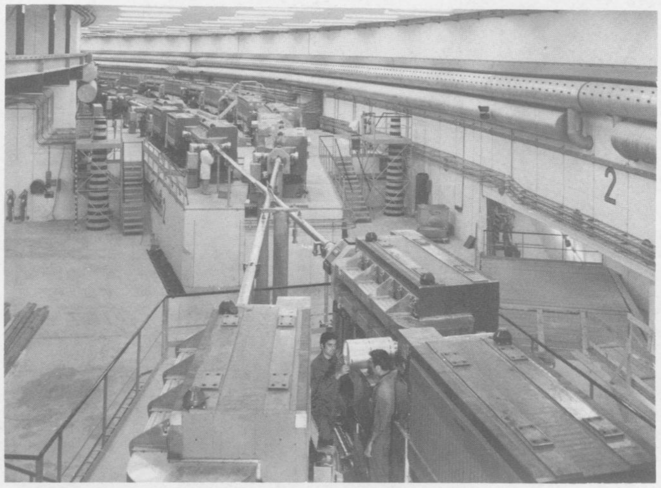

Fig. 3

Interior view of the ISR tunnel at
intersection region I 2 where some
of the initial experiments are being installed

4. Beam Tests in the ISR

a) Early tests in the Beam-Transfer System

Protons were first ejected from the CPS on April 23, 1970 and were stopped on a dump situated only 30 m downstream from the point of ejection. A number of tests were made to measure beam characteristics and to check diagnostic equipment. On September 3, the first pulse passed through the full 400 m length of one of the transfer lines to a temporary stop. With all magnets set to the calculated values the beam was observed to be within 5 mm of the centre of the last monitor. On September 24, the beam passed successfully through the other transfer line.

Extensive measurements showed good agreement between the observed and computed beam-optics properties. The beam loss along the channels was very small.

b) Tests on ISR Ring I

During last summer, the state of construction of the ISR was sufficiently far advanced that, if priority was then given to one ring over the other, there might be a good chance to try for a circulating beam in it before the start of the scheduled long shut-down of the CPS. Accordingly, emphasis was placed on Ring I and a first trial with beam was scheduled for October 29. At this time, part of the vacuum system was still unbaked, so conditions were not optimum. Nevertheless, the pressure was a few times 10^{-9}torr.

In all the early test runs, the momentum was 15 GeV/c and, for most of them, only a fraction of each CPS pulse was sent to the ISR. These conditions were imposed by a desire to have minimum interference with the CPS operation and its experimental programme.

In the first run, most of the beam-transfer system's magnets were set to optimal values found in the previous tests. Then, with its final magnets, the injection system and the main ISR magnets set to calculated values, the first pulse to enter Ring I circulated successfully, with more than 50% injection efficiency. Minor adjustments to the injection system quickly increased the efficiency to 100%. But, before these adjustments were made, the beam was allowed to circulate and it remained in the ring for over 20 minutes, when it was successfully dumped after a loss of only 20%.

Also during the first run, the RF system was turned on with calculated settings. The beam was trapped, accelerated across the aperture and a stacked beam of 350 mA was achieved. Measurements were also made of the betatron frequencies; the values $Q_H = 8.81$ and $Q_V = 8.67$ are very close to predicted values.

In the second run, the closed orbit was measured, with no corrections to the magnet; peak deviations were, vertically ± 4 mm, and horizontally ± 10 mm, both well within tolerance. After some preliminary adjustments to the RF system, stacking with full injected CPS beam achieved a circulating beam in the ISR of 1.5 A, the maximum allowed without the emergency dumping system, as yet incomplete.

During the subsequent runs the positions of resonances in the aperture were determined by observing losses in a circulating beam as it was moved back and forth, radially, by small changes in the main magnetic field. Preliminary measurements on stacking efficiency gave an overall figure of 70%. With low-intensity beam from the CPS, the equivalent of 80 pulses (650 mA) was stacked.

Extensive studies of beam lifetime in these tests indicated a fairly strong dependence on intensity. Low-intensity beams showed losses of less than 0.1% per minute whereas losses of one or two orders of magnitude greater were observed with higher intensities.

When, on January 11, the test runs could be resumed, Ring I had undergone important improvements in two respects: the whole ring had been baked, and the average pressure had dropped to a few times 10^{-10} torr. Further, the clearing electrodes were now operational. The effect was spectacular. On January 11, when we first stacked beam to about 0.5 A, the loss rate was 2×10^{-3} min^{-1}, which was already an improvement compared with two months earlier. However, when the clearing electrodes were switched on (± 3 kV) the loss rate became unmeasureably small ($< 10^{-4}$ min^{-1}). In later runs, we stacked to currents in the few ampere range. The left part of Fig. 4 shows a typical stacking. Again we found an intensity dependent loss rate, but still encouragingly low, typically 10^{-3} min^{-1} at 2 A.

We discovered another phenomenon during the January runs: when the stack reached about 3 A, and without any apparent saturation in the stacking process, the stack intensity dropped by a considerable fraction (the right part of Fig. 4). If we continued to stack, the current increased again to the value before the first drop and then produced a second drop, and so on. This current limitation was named the "Brick Wall" (BW).

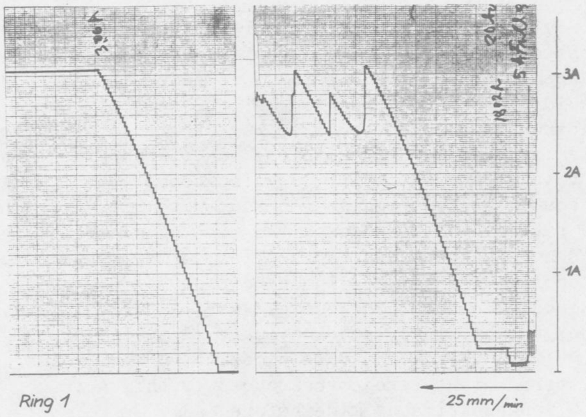

Fig. 4

Left: Typical stacking
Right: A stacking hitting the Brick Wall

c) Tests on Ring II

By the end of January, Ring II was as far advanced as Ring I had been in October, and it was decided to put it into operation on January 25, again mainly to search for hardware trouble at the earliest possible moment. It started operation as smoothly as Ring I, and showed very much the same behaviour; in particular, the loss rate of small circulating currents (≲ 100 mA) was very low, which was of importance for the next series of tests.

d) Collisions

Both rings were now capable of being operated together. We felt that it would be interesting to observe, for the first time, collisions between protons in the two beams. But it was perhaps of equal importance to see if the lifetime of one beam would be influenced in any way by the presence of the other one. It was decided to try this on January 27. The momentum was again chosen at 15 GeV/c in both rings. The schedule of the CPS allowed us just 12 hours of beam time but, during the first half of this, only 20% of the CPS beam (4 out of 20 bunches) would be available.

A stack of 586.6 mA was created in Ring I, again with unmeasurable loss rate. (The last digit did not change during more than one hour.) A single shot of 4 bunches was then sent into Ring II, giving a circulating beam of 14.7 mA. No measurable loss could be observed in this second beam, and it could soon be concluded that a half-ampere beam in one ring had no significant influence on the lifetime of a weak beam in the other ring.

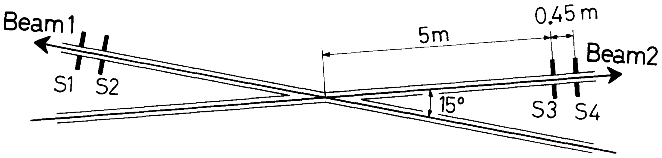

Fig. 5

Layout of scintillators of the colliding beam monitor in crossing point I 5.

Scintillator counters had been installed in two of the crossing regions to observe p-p collisions; the arrangement in crossing point 5 is shown in Fig. 5. A coincidence $S_1 + S_2$ occurring at the same time as a coincidence in $S_3 + S_4$ would be registered as a possible colliding-beam event. With the conditions given above for this very first trial, a coincidence counting rate of about 1 s^{-1} was registered and, with the very small loss rate of the two beams, the rate of accidental coincidences was a factor 20 smaller. There was no doubt that collisions between 15 GeV/c protons were being registered. In fact, the energy was a little higher than 15 GeV in the rings, and the equivalent accelerator energy was, therefore, very close to 500 GeV. The registered event rate corresponded, within a factor of 2, to rough estimates made beforehand.

Later the same day, rates up to 100 s^{-1} were registered with considerably higher currents in the rings. More detailed results are reported in the next chapter. The main conclusion of the day was that the ISR can provide an effective facility for research at the highest centre-of-mass energies available anywhere in the world.

On February 17, the energy was raised for the first time to 22.4 GeV/c in both rings, and collisions were observed under good back-ground conditions. Again, in terms of equivalent accelerator energy, this would be about 1.1 TeV.

5. Summary of Main Results and some Conclusions

By February 23 the ISR had run a total of 150 hours, most of the time only with Ring I. In this time, there has been very little equipment failure, and almost all the equipment has worked as predicted.

It is impossible to give more than a fraction of the results obtained, therefore, the following is only a summary. Many of the results quoted are the best ones, because it is believed that they can be reproduced and have, in most cases, been actually reproduced several times.

a) Life time

$I^{-1}\, dI/dt$ = unmeasurable at < 0.6 A and 15.3 GeV/c
= ~ 0.5 x 10^{-3} min^{-1} at ~ 2 A and 15.3 GeV/c
= ~ 10^{-3} min^{-1} at 2.7 A and 15.3 GeV/c
= ~ 10^{-4} min^{-1} at 2.2 A and 22.5 GeV/c

There seems to be little doubt that the decay rate increases with increasing circulating current. There is an indication that it decreases with increasing energy. In all the cases quoted, the average equivalent nitrogen pressure was ~ 2 x 10^{-10} torr, and the clearing electrodes were on.

b) Current limitations

When we try to stack to high currents we often meet the phenomenon that in section 4 b) was called the Brick Wall and illustrated in Fig. 4. A similar phenomenon occurs when we stack to a current near the BW value, without reaching it, and then try to move the stack a little inwards by reducing the magnetic field slightly. The losses seem to be associated with severe transverse oscillations. The BW has been found sensitive to the sextupole component in the machine. The highest current (4 A) was reached with an average $pdQ_V/dp = 3.3$ and $pdQ_H/dp = 3.8$. The machine was in this case adjusted to $Q_V = 8.85$ and $Q_H = 8.90$ on the central orbit. We tend to believe that the BW is a transverse instability due to a beam/wall interaction.

c) Beam-beam interactions

i) A beam of 2.7 A in Ring I had no influence on the loss rate of a 25 mA beam in Ring II. The loss rate of the weak beam during the experiment was 1.6 x 10^{-4} min^{-1}, and the experiment lasted 50 minutes.

ii) Stacking to 1.9 A in Ring II had no effect on a 1.7 A beam circulating simultaneously in Ring I.

d) Conditions for observing p-p collisions

After the first observations of p-p collisions described in section 4 d), further data were taken the same day under various conditions of beam in the two rings. Because background rises rapidly with the rate of loss of beam, and since Ring II still had high loss rates for high currents, the best conditions for observing collisions were with relatively small currents in this ring. Fig. 6 shows the counting rate as a function of the product of the stacked beam currents $I_1 I_2$ in the two rings. The highest value of 110 counts/sec.

was obtained with I_1 = 2.19 A and I_2 = 0.33 A, but with a background of about 10%. For points lower down on the curve, the accidentals were only a few percent. Scraping the edges of the beam in Ring I reduced the background, but the best conditions were obtained when the beam dump, which limits the vertical aperture, was moved in so that it just started touching the beam and then left in this position to act as a shadow against stray particles.

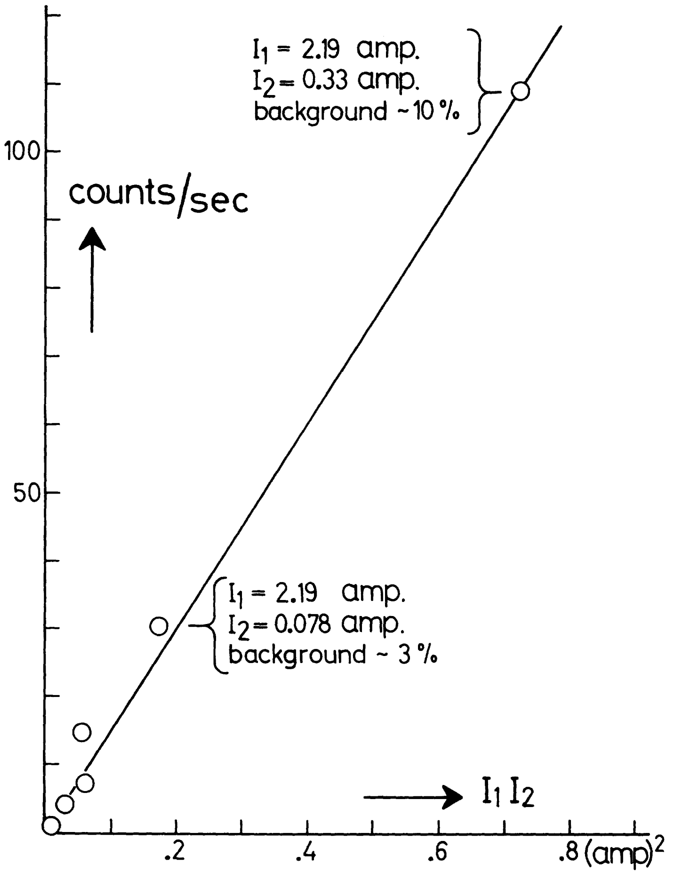

Fig. 6

Relation between the counting rate in the colliding beam monitor and the product of the circulating currents

e) Miscellaneous observations

Variations of voltage on the clearing electrodes between 3 and 6 kV do not seem to influence the loss rate or the BW. We do not know yet at what voltage the clearing electrodes start to clear, nor do we know if the whole ring is really cleared or whether there may still be uncleared pockets.

Although the vacuum seems not to deteriorate with the presence of beams of these intensities, there are large local pressure increases near the RF stations when the RF voltage is on in the presence of a beam. The pressure drops to its previous low values very quickly when the RF is switched off. Since this pressure rise depends fairly clearly on the RF voltage, as one would expect with multipactoring, it is believed that this may be the cause.

6. The Future

There have been a large number of proposals for experiments using the ISR and 11 of these have been accepted and are in active preparation. The first few of these are now being installed and should start taking some preliminary data very soon. On April 8, the ISR will stop operation for almost a month to carry out further installations for experiments.

From now until at least the middle of the year, studies on the machine will have first priority, particularly to investigate the observed intensity limitations, loss rates, and conditions affecting background. However, it is hoped that, later in the year, emphasis will shift to provide more time for the experimental programme.

7. Acknowledgement

The completion of the ISR on time, and within the cost estimate, is the result of the fine team-work of all the staff (about 300) of the ISR Construction Department of CERN. This Department is, however, also grateful for the support it has received from the rest of CERN, from the high energy physics community in Europe and elsewhere, from industry that has supplied the components, and last, but not least, from the CERN Council and its subordinate bodies who authorized the project in 1965 and have since supplied the funds needed every year.