PRESENT STATUS AND FUTURE PLANS FOR THE ISR

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Summary

The CERN Intersecting Storage Rings (ISR) are in routine operation for about 3000 hours per year on the average. Of this time 75% is for colliding-beam physics or preparations for such runs, the rest for machine development. The starting luminosity for long physics runs, with acceptable background conditions, has been up to 5.4×10^{30} cm^{-2} s^{-1}. The longest run without refilling lasted 58 hours. During one of the last development runs in 1973, with the booster used as an injector for the CPS, a luminosity of 6.6×10^{30} cm^{-2} s^{-1} was achieved. It is hoped to reach still higher luminosities by further improvements in the vacuum, further developments of means to suppress instabilities and the effects of resonances, by improved phase space densities now available from the CPS, and by the insertions of low-β sections.

Introduction

The ISR has been in operation for three years with a heavy experimental programme and with rather little unscheduled down-time. As an example, it can be mentioned that in 1973 we had 3100 operating hours of which 2360 hours were for colliding-beam physics (including time for setting up and optimizing beams, luminosity measurements, etc.), and 740 hours were for developing the performance of the machine.

Luminosities for physics runs have reached somewhat over 5×10^{30} cm^{-2} s^{-1}, and, recently, with very good background conditions up to the highest luminosities. Long periods for taking physics data have been available, with several runs of 35 to 40 hours and one of 58 hours. During machine development currents of over 20 A have been obtained in each of the two rings.

During the same year, twelve experiments have been taking data at six of the ISR's intersection regions. A large spectrometer facility, the so-called Split-Field Magnet, has been put into operation without detrimental effects on the beams.

Acceleration of ISR beams has provided another standard operating momentum for physics at 31.4 GeV/c (equivalent to 2000 GeV on a fixed target) at luminosities up to 4×10^{29} cm^{-2} s^{-1}.

The machine is, however, not only a very exciting high-energy physics facility, but provides us also with the most fascinating experimental tool for studying particle beam behaviour under a variety of conditions. Such studies go on continuously in parallel with the high-energy physics programme and have given handsome rewards in the form of continuous improvement of the performance, a trend to which we do not see, as yet, the end.

I will, in what follows, sum up various effects we have met which have temporarily limited the performance and indicate some of the remedies that have been applied as well as their results. I will concentrate mainly on the latest developments.

Recent development of the performance

Recently, the performance of the ISR has mainly been influenced by the following effects:

- resistive wall instability
- non-linear resonances and coupling resonance
- space charge Q-shifts
- beam induced pressure bumps

Although the three first effects are of completely different nature, they influence each other so much, in particular through the remedies used against them, that it seems convenient to describe them together. The fourth effect will be dealt with separately. Finally, short remarks will be made about certain effects outside the above list.

Working line gymnastics *)

The main remedy against the resistive wall effect is Landau damping. The only practical way of creating this in the ISR, is to make $dQ_{v,h}/dp$ everywhere in the vacuum chamber larger than a critical value given by the current density in the stack, i.e. we must establish certain predescribed working lines across the machine aperture. Working lines can be conveniently classed as static or dynamic. The former are either made with a disregard for the space charge deformations, e.g. "FP" in Figure 1, or with a pre-stress that gives the line an ideal shape for a given space charge load, e.g. "5C" in Figure 1. These two lines have been extensively used for ISR operation and "FP" is still the principal low intensity line.

The philosophy of dynamic lines is to progressively correct the space charge deformations during the stacking so that the working line never departs very far from its ideal form. Operationally this is far more complicated and is only made possible by the very considerable flexibility of the poleface windings under computer control, but the results are amply rewarding.

Pre-stressed static lines require a lot of space in the tune diagram. This arises because the overall tune-spread has to be large enough to ensure that the local values inside the stack are sufficient for stabilization by Landau damping and secondly because the whole line sweeps across the tune diagram. For these reasons it was not possible to avoid the 5th order non-linear resonances which cross the stacking region on the "5C" line in Figure 1. These particular

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*) For more details see Ref. 1).

resonances exhibit a somewhat variable excitation and can cause decay rates of up to 200 parts per million per minute, causing background so high that the experimentalists prefer lower luminosities. A feature with this working condition was also that the loss rates were very variable and unpredictable from run to run. This puzzled us at the beginning, but later we have found that since the excitation of the 5th order resonance comes mainly from the beam-beam effects, the losses became very sensitive to beam steering. A change in vertical beam position of a small fraction of a millimetre (having an insignificant effect on the luminosity) would change the background rather drastically [2]. Therefore, we try hard to avoid having a stack sitting across a 5th order resonance.

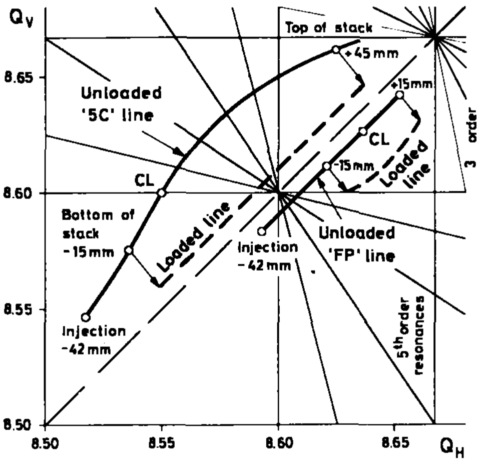

Fig. 1 - The static working lines "5C" and "FP" shown with and without a stack.

A dynamically compensated line can be much shorter, since the local tune-spreads inside the stack are maintained close to the maximum value and the line's excursions are very limited. Using the dynamically compensated line "8C", shown in Figure 2, full-aperture stacks of 17.6 A at 26 GeV/c can be made in the region between the 5th and 3rd order resonances, which is free of all resonances up to the 8th order. Compared to "5C", this line is shortened by a factor of 1.5 and the avoidance of the resonances lower than 8th order reliably gives excellent physics conditions.

When setting up a dynamically compensated line, the base line is first created and recorded in a file specifying all the relevant power supply currents. Re-alignment of the ISR and other changes make it necessary to periodically update this basic file. The pre-stresses, however, need no updating as they are in the form of small changes of tune derivatives, referred to the base line and are, therefore, invariant. When applying the pre-stresses, the ISR control computer changes all the power supplies in ratio so that the circulating beam sees a smooth transformation which takes only a few seconds. The stack does not show any sign of disturbance. The "8C" stack is built up in five steps. Prior to each step the line is pre-stressed (see Figure 2) and then the space charge is added bringing the line back to its ideal form. This procedure is controlled interactively by the ISR computer and it takes about one hour to fill both rings at 26 GeV/c to the maximum current of 17.6 A. At no time does the "8C" working line wander outside the limits shown and the stack always maintains a respectful distance from the diagonal ($Q_h = Q_v$), the 3rd order resonances and the 5th order resonances. If the full space charge pre-stress were applied in a single step, the stack would be swept across the 3rd and 5th order resonances and would be blown up and partially destroyed.

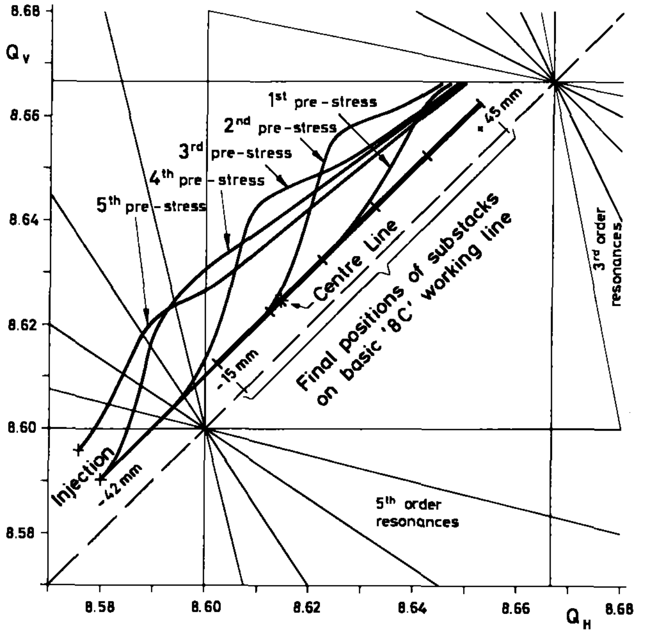

Fig. 2 - The "8C" family of pre-stressed working lines used at 26 GeV/c to stack 17.6 A in five steps of 3.52 A across the chamber from + 45 mm to - 15 mm (α_p average).

The "8C" line when loaded to its limit, is sufficiently stabilized by Landau damping to survive under very quiet conditions, but the slightest disturbance will cause the stack to be lost. The active transverse feed-back system is, therefore, used to ensure the stack's stability [3].

The space available for the "8C" line is very limited. It has been found prudent not to allow the tune-separation, $\Delta = Q_h - Q_v$, to fall below 0.01. For example, at $\Delta = 0.005$ the betatron coupling strongly perturbs the tune-values and an appreciable percentage (∿ 17%) of the larger horizontal emittance is coupled into the vertical emittance. This is serious for the luminosity as we apply heavy beam shaving to reduce the effective beam height, and thus the horizontal to vertical emittance ratio is normally large in the stack. Once the tune-separation for the baseline is fixed, the size of a substack and the top and bottom of the main stack are fixed by the space between the base line and the 3rd and 5th order resonances. The tolerances aimed for on the positioning of these lines is ± 0.001. In order to maintain the tight tolerances on the stack's position in the tune-diagram, the current density has to be carefully controlled to give the correct space charge loading. The radial positions of the substacks are maintained to ± 1 mm to avoid the resonances. The basic "8C" scheme can be converted to any energy and to different beam current densities.

It has also become normal practice to correct working line shifts during physics runs. This has been made possible by a method for measuring tunes based on the Schottky noise from the stack [4].

At 22 and 26 GeV/c, "8C" has been extensively used with the full five substacks. Typically, the starting luminosities were 5×10^{30} cm^{-2} s^{-1}. More recently, "8C" has been used at 26 GeV/c with the top and bottom substacks omitted giving 10.6 A and with the base line moved further from the diagonal ($Q_h = Q_v$). The most recent of these runs had a starting luminosity of 3.8×10^{30} cm^{-2} s^{-1} with a beam decay rate of 0.8×10^{-6} min^{-1}. During this 27-hour run, the luminosity fell to 2.7×10^{30} cm^{-2} s^{-1} and the decay rate rose to 1.1×10^{-6} min^{-1}. Approximately 40% of the decay rate can be attributed to beam-beam interactions and the remainder to scattering on the residual gas. Although it is not a proven fact, it appears that the increased tune-separation improves injection optimization and the quality of the stacks. The maximum luminosity so far achieved in the ISR under physics conditions, 6.6×10^{30} cm^{-2} s^{-1}, has also been obtained on the "8C" line.

In order to stack still higher currents, an increased tune-spread is required. At present, an expanded "8C" line is being developed which extends across the 5th order non-linear resonances. At the crossing point, the tune-spread is locally increased so that the resonances are traversed more quickly in momentum space. By making separate stacks either side of the 5th order resonances, it is hoped that higher intensities can be reached.

RF knock-out of that part of the stack which is sitting across resonances has also been tried with encouraging results. A combination of these methods may make it possible to reach $L = 10^{31}$ cm^{-2} s^{-1}.

Beam induced pressure bumps

The difficulties we have had with beam induced pressure bumps ever since we reached the 4 A level, are probably by now well known to everybody. The mechanism is briefly as follows:

Ions originating from collisions with the residual gas are driven into the chamber walls by the beam's electrostatic potential, which is about 1 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 [5]. One remedy applied is to reduce the surface coverage of adsorbed molecules. As a first step we have adopted baking at 300° C for 24 hours everywhere and every time a sector has been exposed to atmospheric pressure, instead of only 6 hours 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 survives 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. Figure 3 shows an example of this beam pumping effect observed in a glow discharge cleaned section.

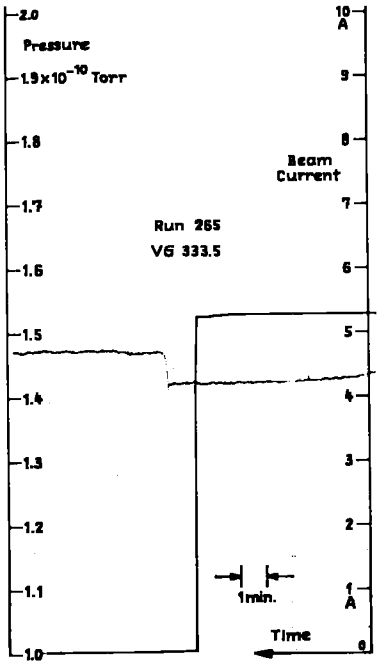

Fig. 3 - Beam pumping in a section which has been cleaned by glow discharge.

An alternative way of reducing the desorption coefficient involves the use of other, cleaner materials to replace the traditional stainless steel chamber. We are actively investigating such possibilities and to date we have obtained the best results from titanium which has been given an 800° C vacuum bakeout prior to installation in the ISR. This has given consistently negative desorption coefficients and is comparable with the best results from glow discharged stainless steel.

The other, more universal, remedy is to increase the distributed pumping by means of a large number of additional titanium sublimation pumps. About 500 such pumps have been installed. As a result of these various remedies, the critical current had increased from about 4 A around the middle of 1971 to about 20 A in both rings. For most of this period this particular problem was the main performance limitation in the ISR and consequently a strain on our vacuum group. It was therefore quite a relief when they recently succeeded in bringing the critical beam current high enough that the other problems previously described came in the forefront of interest. We have good hopes in bringing the critical current still higher by the methods mentioned, say to 30 A, so that the vacuum system can keep pace with the improvements expected in the other problems.

Behaviour of bunched beams

Bunched beams have a tendency of behaving differently from unbunched beams, and in general not in a beneficial way. For instance, the injected beam exibits a longitudinal instability that leads to a considerable dilution of the longitudinal phase plane density. This is not yet a serious problem but in order to cope with the instability at the higher intensities that we expect in the future, possible cures have been investigated and tried with encouraging results. These will be reported on in a separate paper [6].

Another problem is that of lifetime and background. Bunched beams normally exibit orders of magnitude larger loss rates than unbunched beams. This is of no consequence to the ISR, but possibly of importance to future machines, and we are studying this effect. The indications are strong that it is the effect of non-linear resonances that is being enhanced by the bunching, and therefore we sometimes use even bunched beams for the specific purpose of studying non-linear resonance excitation. However, more studies are needed to understand these problems.

Acceleration to 31.4 GeV/c

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. The maximum luminosity achieved was 4×10^{29} cm^{-2} s^{-1}. Phase displacement acceleration was used for this [7].

During the acceleration process 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. Serious beam losses due to beam-beam effects occur during the acceleration process. Only a small fraction of the stacked current is left after acceleration to 31 GeV/c if a beam is circulating in the other ring. When the beams are separated vertically by several beam heights in all intersections, these current losses can be avoided. This is another example of the importance of the non-linear resonances.

Some possible future developments of the ISR

Emittance exchanges in the transfer line

A new method of reducing the beam height was proposed by Schnell [8]. This can be done by a series of septum magnets in the beam transfer line. The vertical emittance ellipse is sliced into n parts which are then superimposed. The horizontal emittance is divided into n separate ellipses, which are placed side by side. With the choice of n = 4, a worthwhile increase in luminosity can be obtained with a beam that still passes the horizontal aperture of the existing injection magnets. Altogether four septum magnets would be needed, otherwise no new elements.

The disadvantage of this method is the increased ratio of horizontal to vertical emittances. Although there may be space within the horizontal aperture, the coupling may become very serious, pushing us even further away from the diagonal in the working diagram. However, this means that the working lines have to be made shorter (Figures 1 and 2), and the corresponding, increased difficulty with instabilities may make it difficult to take advantage of this method.

Stochastic cooling of betatron oscillations

An even more speculative method of reducing the vertical beam height has been proposed by Van der Meer and has become known as "stochastic cooling" [9]. The method consists in observing, with a wide band pick-up, small statistical deviations of the centre of gravity from the closed orbit of a short longitudinal beam sample, containing a finite number of protons, and reducing the error 5/4 λ downstream with a fast kicker. New deviations of the centre of gravity are continuously created by the proton migration into and out of the sample, so that successive application of this correction leads to a progressive reduction of the rms betatron oscillation amplitude. The theory shows that it is marginal whether we shall, in practice, be able to reduce the beam height through this method. We feel that the idea is exciting and have therefore started an experiment. However, no conclusive results have been obtained yet.

High luminosity insertions

The most realistic way to increase the luminosity is, however, to change beam geometries by inserting and modifying beam optics elements near the crossing regions.

The simplest is to insert a system of quadrupoles that will reduce β_v, otherwise leaving the machine essentially unchanged. The first such system will consist of existing beam transport quadrupoles (partly borrowed from outside CERN), which will be installed this year. This system was analysed by Keil [10]. He arrived at $\beta_{min} \simeq 2.5$ m as compared with about 14 m in an unperturbed crossing region. This should therefore give a luminosity improvement of 2.3. The obstruction-free space is ± 1.7 m which is just sufficient for the installation of a solenoid magnet, proposed by one of the experimental teams. The layout is shown in Figure 4.

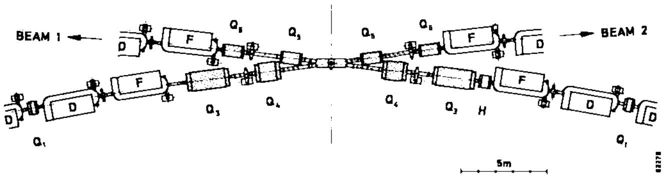

Fig. 4 - Low-β insertion with conventional quadrupoles.

Further improvements can be made with stronger lenses, which will require superconducting magnets. We have started working on plans for such a system as well, but naturally on a much longer time scale. The layout, illustrated in Figure 5, is not very different from the one with conventional lenses, but with the increased strength we hope to reach a $\beta_{min} \simeq 0.6$ m and consequently a factor of five in luminosity [11]. Prototype work has started in close collaboration with other laboratories, in particular Rutherford High Energy Laboratory.

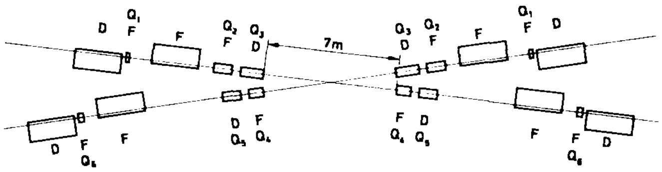

Fig. 5 - Example of low-β insertion layout with superconducting quadrupoles.

In addition to giving higher luminosity, such a superconducting low-β insertion will be a very realistic test facility of superconducting magnets under the most stringent conditions that we meet in accelerators. We therefore expect to gain an experience that will be very valuable for possible future projects.

Even more efficient insertions are possible if we attack the crossing angle as well as β. This cannot be done, however, without disturbing and modifying considerably the present ISR. This possibility has been considered by Montague and Zotter 12), and an example is illustrated in Figure 6. To achieve very small or zero crossing angle, it is necessary to displace ten magnets per ring. In addition, eight new bending magnets and 22 new quadrupoles would be required for the two rings. In this example some quadrupoles and the bending magnets would have to be superconducting to achieve the required strength. Montague and Zotter quote in their paper luminosity estimates in the neighbourhood of 10^{33} cm^{-2} s^{-1}. The main disadvantages of this kind of scheme are the modifications required in the main ISR structure, and the limited unobstructed space left along the beams from the crossing points. No decision is needed for the time being between the various schemes requiring superconducting magnets.

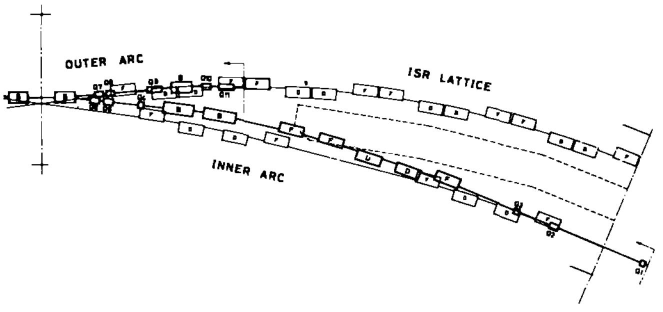

Fig. 6 - Example of high-luminosity insertion acting upon both β and crossing angle.

Superconducting ISR

A more spectacular use of superconductivity would be to replace all ISR magnets by superconducting magnets and thus being able to stack 100 - 150 GeV protons injected from the SPS. The ISR are conveniently situated for such a solution. This would, however, be a large project that would be for the far future. Its advantages and disadvantages would also have to be weighed against those of the even more ambitious project of constructing completely new 400 GeV storage rings attached to the SPS. Speculations on this is, however, outside the scope of this paper.

Concluding remarks

The ISR have fullfilled and partly surpassed all the hopes we had for this project when it was conceived. In some respect we have met problems, the difficulties of which we had not fully appreciated during the construction. However, the necessary remedies have been found and incorporated. In fact, we believe that the ISR have potentialities well beyond the present performance, in particular with respect to luminosity, where we hope that it will not be too long till we are operating in the 10^{31} - 10^{32} cm^{-2} s^{-1} range.

Our greatest hope is now that the ISR turn out to be only the first example of a series of such p-p facilities.

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