EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ISR-TH/67-47

Manuscript for the Proceedings of the VI International
Conference on High Energy Accelerators

IMPROVEMENT POSSIBILITIES IN THE PERFORMANCE OF THE CERN INTERSECTING STORAGE RINGS

by

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Geneva - 22nd August, 1967

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Abstract

A combination of stacking in betatron and synchrotron phase space increases the luminosity and the flexibility in operation of the CERN Intersecting Storage Rings (ISR).

Maximum luminosity is obtained by stacking such that 2/3 of the horizontal aperture is occupied by betatron oscillations and 1/3 by momentum spread.

For experiments which require a smaller momentum spread, optimum luminosity is achieved by synchrotron stacking up to that limit, and by filling the remaining aperture using betatron stacking.

In practice, this goal can be reached by betatron stacking (multi-turn injection) from the PS booster into the PS, and from the PS into the ISR, and by synchrotron stacking in the ISR.

With an 800 MeV four-ring booster it is possible to inject two turns into the PS, and two turns into the ISR. Using realistic figures for beam emittances in the booster, for the efficiency of two-turn injection and for transfer errors, we get the following optimistic estimates for the improved ISR performance:

(i) Maximum luminosity mode: stacked current $I = 400$ to 500 A, luminosity $L = 10^{33}$ cm^{-2} s^{-1} in each intersection region.

(ii) Mode where $\Delta E_{CM} = \frac{1}{2} m_\pi c^2$: stacked current $I = 50$ A, luminosity $L = 2 \times 10^{31}$ cm^{-2} s^{-1} in each intersection region.

Beam-beam interactions, the negative mass instability, and the transverse resistive instability, all limit the ISR performance at currents well above those quoted. The image dominated transverse coherent and incoherent limits are at about the above value.

1. INTRODUCTION

We investigated the consequences of changes in two assumptions upon which the performance estimate for the CERN Intersecting Storage Rings (ISR) given in 1) is based:

i) the beam properties of the present CERN Proton Synchrotron (PS), both in transverse and longitudinal phase space,

ii) the accumulation of protons in the ISR by RF stacking.

By an appropriate choice of a new intermediate injector for the PS (the PS booster 2)) it appears possible to achieve a substantial increase in the phase space density of the PS beam. Further, phase space considerations to be given below show that a substantial additional increase in ISR performance is possible by filling more aperture with betatron oscillations (multi-turn injection) and less aperture with momentum spread (RF stacking).

Under assumption i) and ii), above, the stored current in the ISR is just proportional to the momentum spread, and the luminosity is proportional to its square. At the maximum permissible momentum spread ($\Delta p/p = 2\%$) the stacked current is 20 A, and the luminosity is $L = 4 \times 10^{30}$ cm^{-2} s^{-1}. With the new PS booster, employing a combination of betatron and synchrotron stacking, we look forward to increases in luminosity and flexibility in the operation of the ISR; in particular, as will be detailed in the remainder of this paper, we envisage a maximum luminosity $L = 10^{33}$ cm^{-2} s^{-1}; while, in a different mode of operation, the design luminosity $\left(4 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}\right)$ may be attained with a momentum uncertainty of only $\Delta p/p = 0.5‰$ (centre of mass energy uncertainty less than 25 MeV).

1.1 Outline.

These very interesting improvement possibilities have stimulated considerable effort on the part of the accelerator development staff in CERN. It is neither possible nor appropriate for us to present all this material; instead, we shall describe the fundamental concepts. More detailed descriptions of particular items may be found in numerous CERN reports to which we shall give reference.

Section 2 is devoted to phase space considerations, and in particular, to an analysis of the relative merits of betatron and synchrotron stacking.

In Section 3, we describe two ways by which betatron stacking can be accomplished : combining beams in the transfer line between two machines, and multi-turn injection.

Section 4 is devoted to problems arising from the new modes of operation proposed for the ISR. Some of these have already been studied at length, others need further research and/or development before the improvement possibilities can be realized in practice.

Anticipating that all the problems raised in Section 4 can be overcome, Section 5 gives an outline of a possible ISR improvement programme with estimates of the performance associated with each step (Table 1).

2. PHASE SPACE CONSIDERATIONS

The luminosity clearly increases with the cube of the beam height. Hence, vertical betatron stacking should be used in the ISR up to the limit of the vertical aperture.

In the horizontal plane, we have the choice of any combination of betatron and synchrotron stacking, with a consequent flexibility in ISR operation.

In the unrestricted optimisation of the luminosity -- under the assumption of a fixed and uniform particle phase space density, and of a beam size which is the same for all momenta in the stack -- we find 3) that it is best to betatron stack up to a beam size equal to 2/3 of the available horizontal aperture, and to fill the remaining 1/3 by synchrotron stacking. Allowing for a beam size which reaches the edge of the horizontal aperture for all momenta would increase the luminosity by a factor $(9/4)^2$. However, we shall not exploit this possibility in this paper.

In some cases, the centre of mass energy uncertainty is limited by experimental requirements. It is due to the momentum spread in the beams and to the variation of crossing angle arising from betatron oscillations. A formula is given in 4); for the ISR, the uncertainty is simply the sum of the energy spreads in the beams. Consequently, the maximum luminosity is attained by synchrotron stacking up to the permissible energy spread, and by filling the remaining horizontal aperture with betatron stacking.

3. BETATRON STACKING

Detailed discussions of betatron stacking in the PS and ISR may be found in 3), 5), 6).

3.1 Techniques for multi-turn injection into the PS.

Because of the vertical stacking of the booster rings it is natural to propose the combination of two beams in the vertical plane, as it has been suggested by Bovet 7). This can conveniently be done in a double septum magnet with opposite fields on either side of the septum. Two advantages of this scheme are:

i) There are no magnetic forces acting on the septum which can therefore be made just thick enough to carry the required current.

ii) Since the septum magnet is installed in a transfer tunnel the vertical beam size can be made large compared to the septum thickness by an appropriate choice of the vertical β-function. This is in contrast to multiturn injection where the β-function usually is determined by the magnet lattice.

For these two reasons the combination of beams outside the PS is very efficient, in fact, more efficient than multiturn injection. However, the process cannot be repeated because the resulting beam size would be too large for injection. Instead, further betatron stacking into the PS can be accomplished by multiturn injection. This process is in principle the same as, in practice simpler than, and only differs in detail from multiturn injection into the ISR. We will not discuss it further. It should be noticed that more efficient filling of the PS aperture results if the combined beam is rotated by 90° 8) before multiturn injection into the PS.

3.2 Two-turn injection into the ISR.

The ratio of the circumferences of the ISR and the PS is 3/2. Hence, when the RF frequencies are locked together, opposite bunches in the PS can be transferred into the same ISR bucket by a suitable injection/ejection scheme, if the time interval between the transfers is an odd number of ISR revolutions. In order to achieve the efficient phase space filling shown in Fig. 1, we require appropriate phase space shaping and proper choice of the horizontal tune. (For transfer on the third revolution, $Q = 8\ 5/6$ is an acceptable choice).

The fast ejection kicker magnet required for this transfer scheme must be pulsed twice within nine microseconds.

In the ISR, the incoming beam is made parallel to the injection orbit by a magnet with a thin septum. The injection orbit is positioned by a programmed half wavelength bump excited by two rapid bump magnets a quarter wavelength upstream and downstream from the septum, resulting in the phase space configuration shown in Fig. 2.

Maximum use of the available aperture can be accomplished by using full-aperture kicker magnets to excite the closed orbit bump. Consequently, the whole stack is repeatedly displaced; we assume, that this can be done without losing the stack.

After the injection of a PS pulse there are some full and some empty buckets circulating on the ISR injection orbit. We propose to RF stack every pulse separately. Intolerable dilution of the stack is avoided by suppressing those buckets which do not contain particles before they reach the stack, as has been suggested by Schnell 9), and has been tested on CESAR 10). This has the advantages that the injection system must only handle buckets which are empty or being filled (and no full ones from previous PS pulses), and that the tolerance on the magnetic field is relaxed.

4. SOME SOLVED AND SOME UNSOLVED PROBLEMS

4.1 Magnet technology

To accomplish the complicated injection and ejection schemes we require the development of several types of magnet, some of which may go beyond present practice:

i) Magnets to distort closed orbits locally in the PS and the ISR. The amplitude of the closed orbit distortion should be one to two centimetres, varying with time in a few microseconds. In order to limit the perturbation of the stacked beam, tight tolerances have to be imposed on the pulse length, timing and amplitude of these magnets in the ISR.

ii) Fast kicker magnets, capable of selecting one or more specified bunches. These kicker magnets must have rise-times of a few tens of nanoseconds, and be capable of being pulsed several times in a few microseconds. Since recharging of the storage lines is excluded because of the short time interval we need independent storage lines with hard-tube switches or a whole string of storage lines with spark gaps between them which are triggered in the correct sequence, as suggested by W.C. Middelkoop 11).

iii) An ultra-high vacuum thin septum magnet for two-turn injection into the ISR.

4.2 RF bucket suppression

In some of our schemes, most of the 30 ISR buckets have to be suppressed, which imposes tighter tolerances on the residual RF voltage than in the original proposal 9).

4.3 Stack shaping

RF stacking of only a few pulses is an inefficient process resulting in a rather poorly defined momentum distribution of the stack. In order to have a small energy spread in the beam, it is necessary to remove from the stack particles with energies too far from the average value. Recent experiments on CESAR 10) have already confirmed the feasibility of a proposed method for achieving stacks with small energy spread.

4.4 Transverse space-charge effects in the booster and the PS

Assuming that the PS is space-charge limited at 50 MeV, and that the usual space-charge formula 12) is valid, the emittances required in a booster which contains the PS circumference in four separate rings can be calculated 2). It turns out that the increase in emittance is much smaller than the increase in intensity: due to the multiple rings there is a net gain in phase density by about a factor of 4.

For two-turn and four-turn injection into the PS the peak line density in the PS is increased by a factor 20 or 40, respectively, beyond the present value; the average line density is always 10 times the present value. In order to avoid space-charge problems at injection from the booster into the PS, the transfer energy must be chosen appropriately 6). With the present choice of 800 MeV, two-turn injection can certainly be done, four-turn injection is just at the limit.

4.5 Longitudinal space-charge effects in the PS.

Operation of the PS with a booster, and with multi-turn injection, involves the acceleration, with passage through transition, of beams whose local charge density per unit length is an order of magnitude or more greater than in the PS at present. To accomplish this without loss in phase density requires compensation of the effects of longitudinal space-charge forces at transition 13). Computations by Sørenssen 14) on the "Triple Switch" method suggested by Schnell show that it is adequate for single-turn injection into the PS. An RF system which continuously matches the buckets to the bunch shape, and a simultaneous reduction of the tune when passing through transition, will handle the line density associated with two-turn injection 15).

The very high line density resulting from four-turn injection can probably be handled by extensions of the Triple Switch method (e.g. quintuple etc. switches), or by wall modifications as proposed in the 300 GeV design study 16), and discussed in detail by Briggs and Neil 17), and Sessler and Vaccaro 18).

4.6 Space-Charge phenomena in the ISR.

The injection method proposed here, which leads to the highest luminosity has a circulating current of about 500 A; somewhat in excess of the theoretical transverse space-charge limit which is about 200 A 19). The beam has no longitudinal structure and a fixed energy, and the space-charge effect is dominated by image currents in the vacuum chamber wall (the direct space-charge limit is 10.000 A).

For these reasons, the incoherent space-charge limit may be readily increased by a variation of the focusing strength of the ISR as a function of the stacked current. In this way one is limited by the difference between the coherent and incoherent tune shifts, resulting in a current of about 500 A. Another way of increasing the space-charge limit is modifications of the electrical properties of the vacuum chamber wall, as recently suggested by Laslett 20).

No problems are expected in any of the modes of ISR operation proposed in this paper from the negative mass instability, transverse and longitudinal resistive instabilities, the Touschek effect, and coherent or incoherent beam-beam effects 19).

4.7 Bunching of the ISR beam

Bunching of the ISR beam was considered several times 21) as a method to improve the ratio of interaction rate to background, or to turn off the beam-beam interactions without modifications of the transverse beam geometry. However, bunching a beam with a momentum spread equal to a substantial fraction of the permissible maximum ($\Delta p/p = 2\%$) requires a very powerful RF system 22).

With the improvements discussed before very substantial currents can be accumulated in the momentum spread handled by a much more moderate RF system which, however, has to be appropriately designed to cope with the beam loading. Hence, bunching the ISR beam becomes a very practical proposal.

5. A POSSIBLE ISR IMPROVEMENT PROGRAMME

Employing the concepts outlined in Section 3, and having overcome the problems mentioned in Section 4, we can look forward to a long period of ISR improvement during which new pieces of equipment are brought into operation, resulting in an ever increasing ISR performance capability. The improvement factors associated with each step were evaluated in detail by Bovet and Keil 6). In Table 1, we give, in a possible chronological sequence, stages of ISR improvement. Two figures are shown in each line. The first is the increase in luminosity over the present operating conditions, when the energy spread in the beam is restricted to very small values, and when betatron stacking is exploited to the extreme. The second figure is simply the maximum increase in luminosity which can be reached by the optimum combination of betatron and synchrotron stacking in that particular mode of operation.

ACKNOWLEDGEMENTS

While the ideas described in this report were evolving we enjoyed continued discussions with many of our colleagues. We are indebted to them for the stimulating environment which was necessary for this work.

TABLE 1 - ISR IMPROVEMENT POSSIBILITIES

Method	Interaction Rate Improvement Factor	
	Low Δp/p	Maximum
Present PS and ISR	1	1
Present PS; two turns into ISR	4	5
PS with booster; one turn into ISR	80	70
PS with booster; two turns into ISR	330	270
PS with booster; two turns into PS and into ISR	1300	450
PS with booster; four turns into PS and two turns into ISR	2000	300

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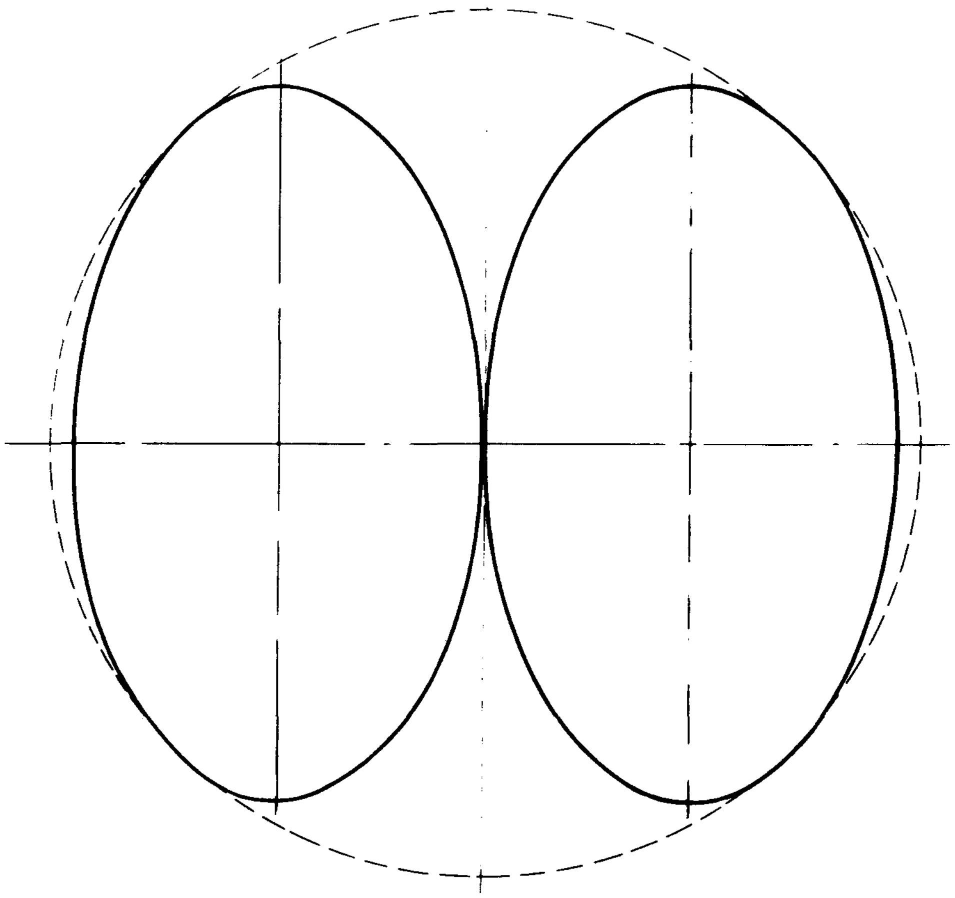

Fig. 1

HORIZONTAL BETATRON PHASE SPACE CONFIGURATION FOR TWO-TURN INJECTION

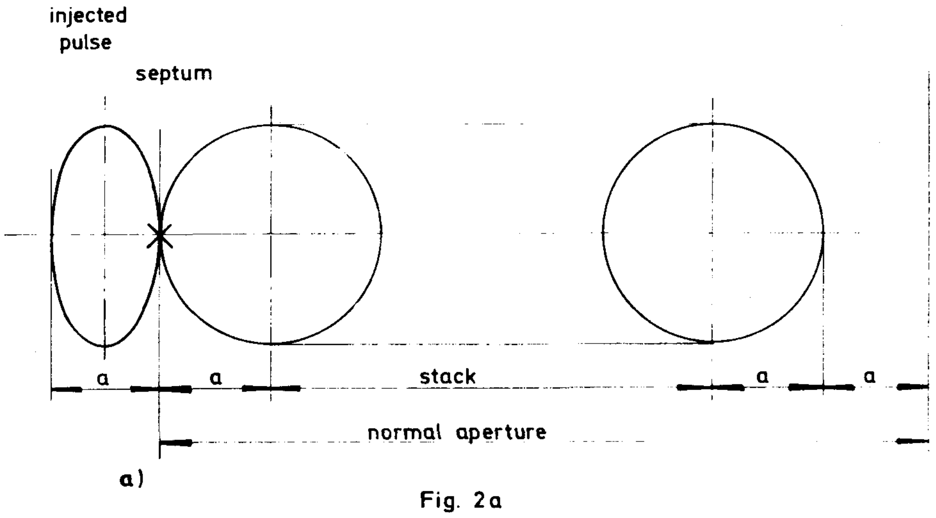

Fig. 2a

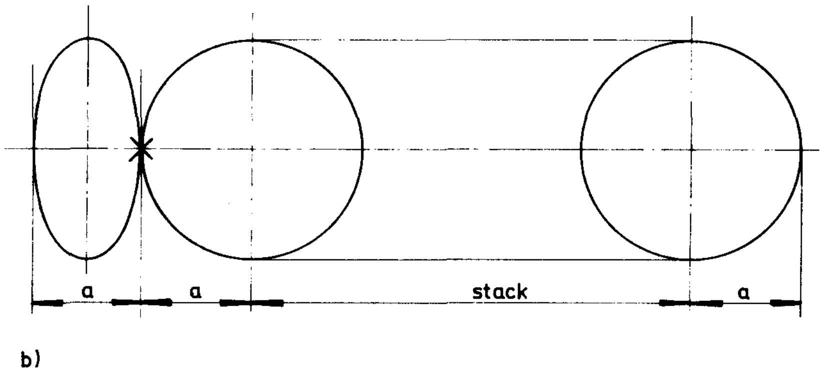

Fig. 2b

TWO-TURN INJECTION SCHEME WITH A CLOSED ORBIT BUMP EXCITED, AND (b) WITH NO CLOSED ORBIT BUMP. THE INJECTION ORBIT IS INDICATED BY X.