THE CREATION OF SMALL INTERACTION DIAMONDS IN THE CERN INTERSECTING STORAGE RINGS (ISR)

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Summary

The original ISR design included the possibility of superposing equilibrium orbits in four of the eight intersection regions by means of supplementary quadrupoles. This scheme has two advantages. Firstly, the beam density is increased so improving the ratio of beam-beam to beam-gas counts and secondly, the size of the interaction diamond is greatly reduced. The closed orbit modulation was measured and the effects of this scheme on the betatron frequencies was studied. Since the scheme is applied with the stacks already circulating, dynamic computer control of the correcting elements is required to maintain the correct tuning in the ISR. In total, 31 power supplies are progressively changed. Since the machine is strongly perturbed by this scheme, nearly all aspects of operation are affected. This particularity applies to the excitation of localized bumps in the closed orbits. Fully satisfactory operation for physics experiments has been achieved with beams of typically 6 A, a luminosity of 1.4×10^{30} $cm^{-2}s^{-1}$ and a diamond size corresponding to a single injected pulse.

Introduction

The use of a harmonic gradient perturbation for the superposition of equilibrium orbits of particles of different momenta in storage rings was described by K.M. Terwilliger[1]. By this means, very small interaction diamonds can be formed and, as a consequence of the higher beam current densities achieved, the ratio of beam-beam to beam-gas counts is improved. For the ISR, the reduction in beam-gas counts is considered to be of less importance than the simple reduction in beam size, since pressures in the intersection regions are often below 10^{-11} mmHg.

Some advantages and disadvantages of the small size of the interaction diamond are:

a) The source of an event can be estimated more accurately which is important for small angle scattering experiments.

b) All the equilibrium orbits pass through the diamond with the zero angle, as well as zero position, with respect to the central orbit.

c) Spectrometer arms with a small angular acceptance see more of the diamond.

d) All momentum resolution with radial position is lost.

e) The orbit perturbations reduce the maximum current for any given aperture.

General Description of the ISR Superposition Scheme

The original ISR design included 24 supplementary quadrupoles, which are powered in three groups: TF, TD1 and TD2, where F and D signify that the quadrupoles are horizontally focusing or defocusing, respectively. The magnet layout for one octant is shown in Figure 1. The quadrupole groups TD1 and TD2 are distributed so as to preferentially excite an 8th order gradient harmonic. This is sufficient, in fact, to reduce the momentum compaction function (α_p) to zero at eight regularly spaced points around the machine. Here the beam width is reduced and depends only on the amplitude of the betatron oscillations. The shift in the horizontal and vertical machine tunes (Q_H, Q_V), due to the additional gradient is then compensated by the TF quadrupoles which are placed at the zero points in α_p. Unfortunately, the outer and inner arcs in the ISR are not equivalent (see Figure 1) and the intersection regions do not correspond to an 8th order harmonic. For this reason, only four intersections (the even numbered) can benefit from the reduced beam width. The unfavoured intersections are positioned such that the beam characteristics are only marginally changed.

The exact quadrupole excitations and the detailed effects of the scheme are calculated with a computer program[2]. The program minimizes the α_p and its radial derivative (α_p') in the four even numbered intersections while maintaining the additional integrated gradient

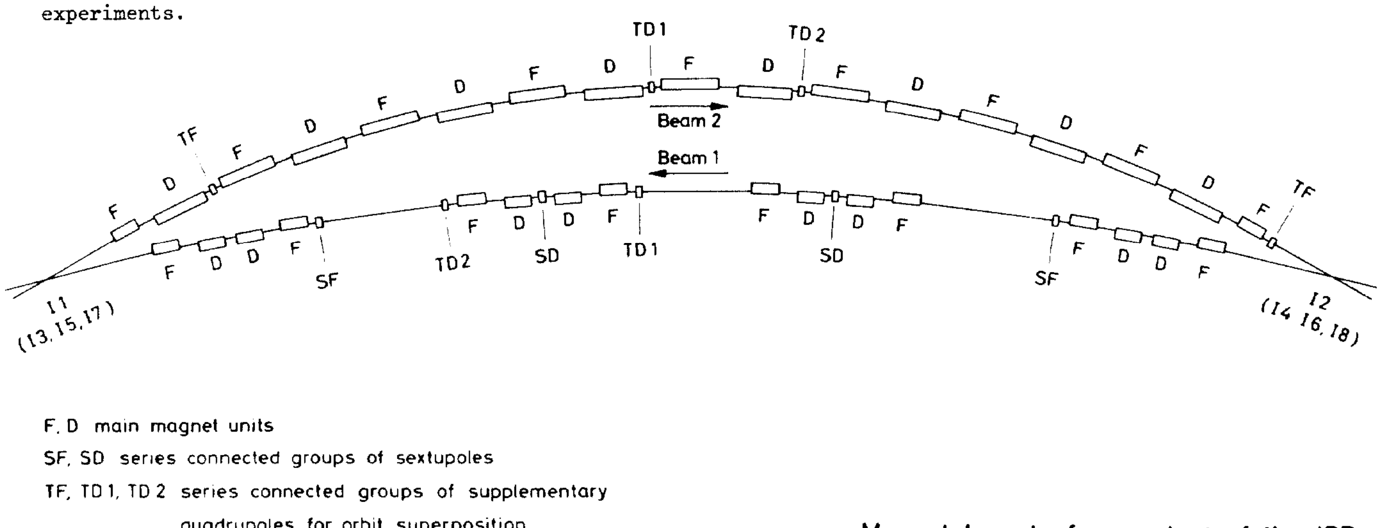
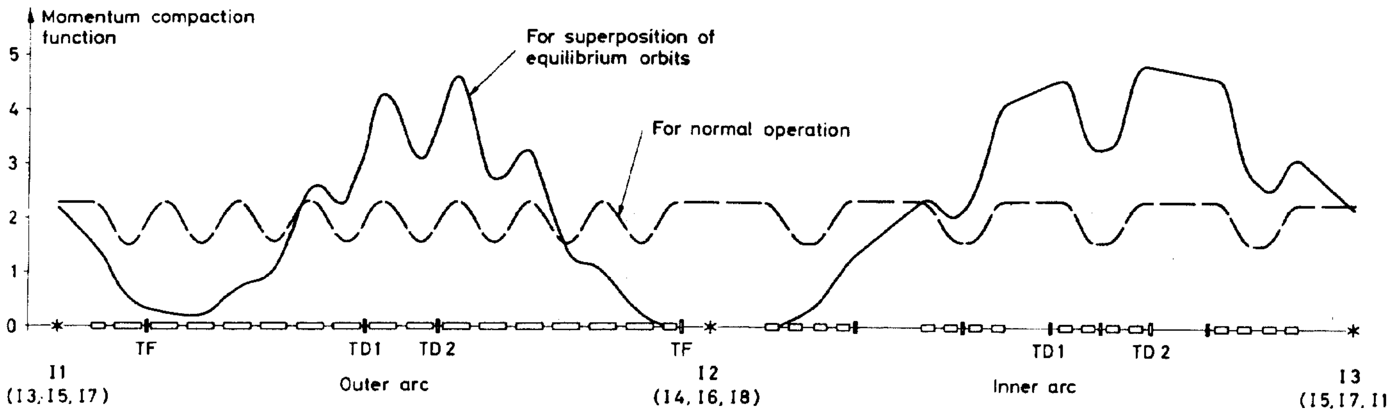


FIGURE 1



The momentum compaction function through one superperiod for normal operation and for the superposition of equilibrium orbits

FIGURE 2

at zero. At the remaining four null points, α_p and α_p' are reduced to nearly zero. Figure 2 shows α_p through one superperiod both with and without the supplementary quadrupoles excited. Table 1 lists the principal parameters for the two cases. The luminosity is largely unaffected, since it is independent of beam width and the increases in β_V are very small. In the superposition scheme, the fluctuations in α_p have maxima twice as large as those in the normal machine. Thus, the beam will be a series of tightly waisted bulges. Unfortunately, this increase in α_p limits the maximum current that can be stacked compared to that of the normal machine. However, there is still space for at least 10 A in the ISR with the scheme applied, but at present, other factors are limiting the current. The maximum achieved to date is 7.2 A during machine development time. The values in Table 1 show that the odd numbered intersections in fact lose very little. One problem, however, which is not directly evident, is the vulnerability of the odd numbered intersections to background noise. This arises from the adjacent α_p maximum being only 20 m upstream of the intersection and any beam halo or tail is preferentially swept against the chamber walls at these points. By scraping the beam edges, this problem can usually be solved.

TABLE 1

Principal Parameters for Normal Machine Operation and Operation with the Superposition Scheme

	Momentum Compaction Function	Horizontal & Vertical Betatron Amplitude Functions	
	α_p	β_H	β_V
Normal Operation			
Maximum values	2.37	42.0	52.4
At even intersections	2.30	22.6	14.9
At odd intersections	2.30	22.6	14.9
Superposition Scheme			
Maximum values	4.85	51.0	62.2
At even intersections	0.0	22.5	17.3
At odd intersections	2.21	24.1	19.5

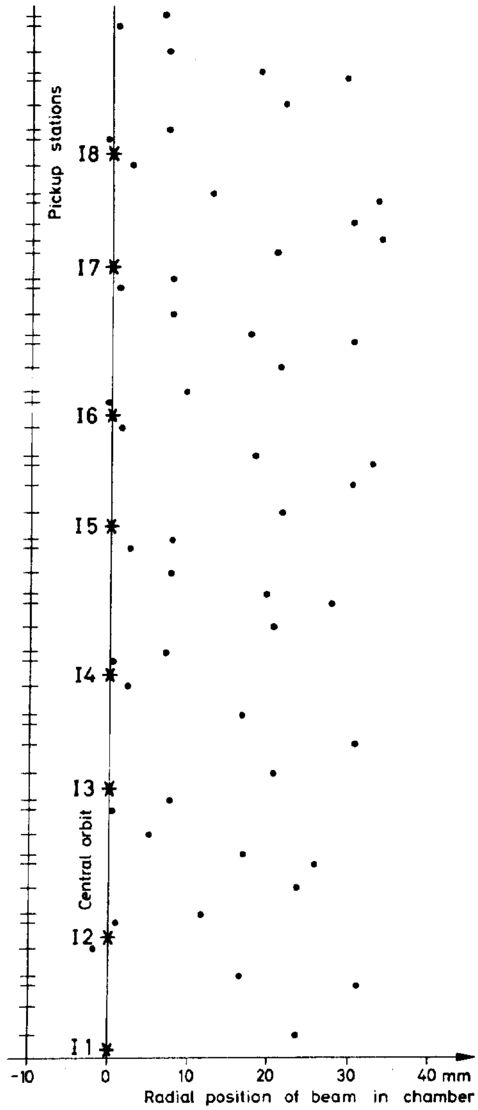
(these values are based on computer simulations of the ISR and differ slightly from the design parameters.)

Practical Development and Measurements

Figure 3 shows the first orbit measurements made to verify that α_p was azimuthally modulated by an 8th order harmonic and that it was zero in the even numbered intersections. The four quadrants are not exactly the same owing to the basic closed orbit distortion which was 5.8 mm peak-to-peak. The beam position monitors are too widely spaced to check all the characteristics shown in the computed curve in Figure 2.

It has been tacitly assumed, so far, that the supplementary quadrupoles are sufficient by themselves. In practice, the simple application of the quadrupoles causes small but unacceptable changes in Q_H and Q_V with accompanying increases in the Q-spreads across the chamber. These effects are summarized in the stability diagram shown in Figure 4. The lines 1 and 2 are called "working lines" and represent the Q-values for the equilibrium orbits with momenta differing from the central orbit in the range $\pm$ 1.5 %. This is approximately the largest momentum spread which can be accepted in the ISR for the superposition scheme. Line 1 is the working line known as FATA which is used as a base for all calculations. Line 2 shows that the simple application of the superposition scheme shifts the stack across the 5th order resonances. Before this problem had been fully evaluated, a physics run was made under precisely these conditions. The bad background observed can now be attributed to these resonances in the stack.

As has been mentioned, the TF quadrupoles are used to compensate the Q-changes caused by the TD1 and TD2 quadrupoles. Since both Q_H and Q_V have to be adjusted, this compensation is not perfect. One possibility is to create an extra degree of freedom by independently powering some of the TF quadrupoles. The alternative chosen in the ISR is to use the poleface windings to apply a correction. The increase in Q-spread in the working line comes from a different source. The sextupolar component seen by the beam is partly created by individual sextupoles and partly by the poleface windings. The latter are mounted on all the magnet units and their average effect is unchanged by this scheme but the former are localized and their effect depends on the local perturbations in the machine parameters.



An Equilibrium Orbit with the Superposition Scheme

(Central orbit momentum is 22 GeV/c and plotted orbit is for a momentum error of 0.9 %, ISR - I 27th April 1972)

FIGURE 3

These effects have been fully evaluated and the corrections calculated.

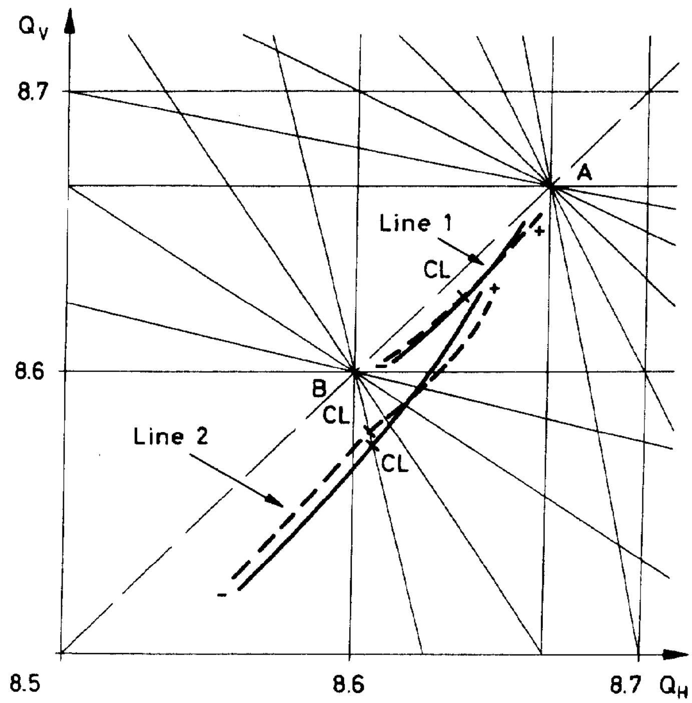
The agreement between theory and measurement can be seen in Figure 4 where the solid lines represent theoretical calculations and the broken lines measurements.

Dynamic Application of the Superposition Scheme

The standard ISR injection orbit is at an average position of 42 ± 2 mm inside the central orbit. With the superposition scheme applied, this orbit passes outside the vacuum chamber at α_p maxima, thus making it impossible to inject directly onto the standard working line. Injection can be moved closer to the central orbit but this complicates the setting up of the machine. For these reasons, an alternative approach was sought after.

It has been found possible to apply this scheme, including the working line corrections with sextupoles and poleface windings, to beams which are already circulating under normal conditions. This involves the smooth progressive powering of the quadrupoles and 28 correcting elements in each ring. The transformation is performed on-line in a few minutes by the ISR control computer ARGUS. For beam currents of a few hundred mA, the power supplies can be changed rapidly without beam loss, but for higher currents, the rate of change becomes a critical parameter. Table 2 compares the beam losses from similar 6 A stacks for different application times up to 400 s, which is now used operationally in the ISR. These beam losses are accompanied by a blow-up of the betatron oscillations. This is negligible at low beam intensities and rises to an 8 % increase in vertical beam size at 6 A for an application speed of 400 s.

Above 7 A, the beams become unstable and are liable to be lost suddenly while the power supplies are changing. This probably indicates that there is insufficient Q-spread in the working line or at some time during the transformation. Using modified working lines during machine development time, a current of 7.2 A has been reached.



——— theoretical

– – – – measured at 15 GeV/c (Ring 1)

CL center line

+, - indicate momentum spread, $\frac{\Delta p}{p} = \pm 1.3\,\%$

A, B nodes of 3rd and 5th order non-linear resonances respectively

Working lines in the Q_H-Q_V stability diagram for the useful stacking region

FIGURE 4

TABLE 2

Comparison of Beam Losses for Different Application Rates for the Superposition Scheme

Application Time s	Initial Current A	Current Loss A
40	6.14	0.85
80	6.21	0.78
200	6.16	0.41
400	6.39	0.06

Other Operational Aspects

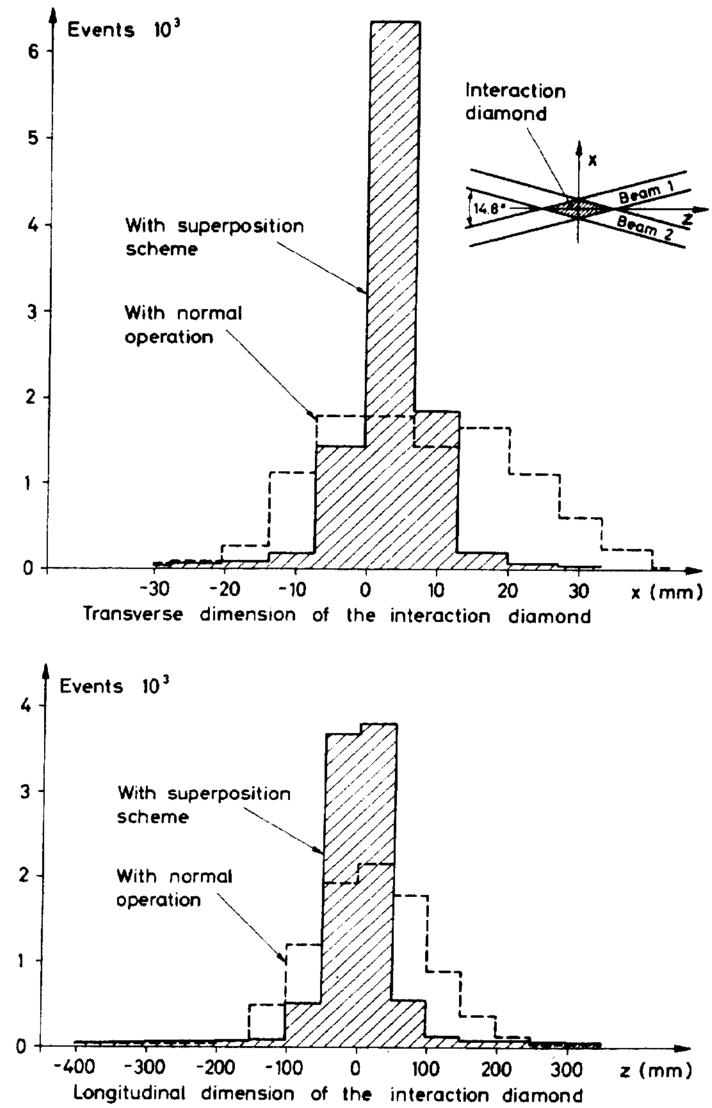
Although the working line is unchanged, the local parameters are different from those of the normal machine. Of the two closed orbit correction programs[3], the least squares method can be used without modification, since it locates the field errors and corrects them directly. The harmonic method applies a distributed correction which is susceptible to parameter changes.

In the case of closed orbit bumps, which are used for luminosity measurements and for positioning the interaction diamond, it was necessary to make new calculations. The measurement of these bumps is rather complicated. A single pulse is accelerated to the required radial position and kept trapped by the radio frequency system in order to maintain the bunched structure. This is necessary for the functioning of the beam position monitors. Once the superposition scheme is applied, the trapped pulse can be used almost indefinitely for the various orbit measurements.

At the null points in α_p, the beam's potential well is approximately four times deeper than for a normal beam of the same current. Under most conditions, the existing clearing electrode system can still remove the trapped electrons. An exceptional case, for which some difficulties have been experienced, is the use of a titanium cloud for luminosity measurements.

Operational Results

The superposition scheme was first used for physics experimentation in June 1972. Its performance has steadily improved and it is regularly scheduled at all energies. Figure 5 compares the transverse and longitudinal dimensions of the interaction diamond as seen in the normal and the superposition modes. Each pair of curves is normalized to the same total number of events. At the half height of the beam-beam count distribution, the superposition scheme reduces the diamond width to 8.5 mm, which corresponds closely to the width expected for a single pulse. This is independent of the initial beam width. Typically the scheme can be operated with 6 A in each beam with beam decay rates of 1 in 10^5 per minute and a luminosity of 1.4×10^{30} $cm^{-2}s^{-1}$. It is hoped to increase these currents to 10 A. Other possibilities, which have not yet been explored, are the partial application of the scheme to increase the currents while accepting a larger diamond size and the inverse scheme in which α_p maxima are used to increase the diamond size so giving a very large momentum resolution across the beams.



Effect of superposition quadrupoles

Data taken with small angle spectrometer CHLM collaboration (Exp. R 201)
10 k events spectr at 70 mrad

FIGURE 5

Acknowledgements

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