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THE FIRST HIGH-LUMINOSITY INSERTION IN THE ISR

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Summary

One of the means proposed to increase the luminosity in storage rings, a so-called low-β insertion, has been put successfully into operation in the Intersecting Storage Rings (ISR). By installing five quadrupoles in each ring around one intersection, a reduction of beam height by a factor 2.3 has been measured, and, with proper matching, the perturbation to the rest of the machine was found to be negligible. With circulating beams of 20 A and 24 A a luminosity of 2.11×10^{31} cm^{-2}s^{-1} has been achieved. This paper reports the results of tests conducted, compares them with the theoretical forecasts, and gives a short description of the hardware used.

Introduction

Since it is becoming more difficult to increase the luminosity by simply stacking more current in the ISR, mainly because of vacuum limitations, the alternative of reducing the effective beam height by lowering the amplitude parameter β_v in one or several intersections appears correspondingly more attractive. Feasibility studies[1,2] were made for installing a low-β insertion using conventional quadrupoles which would give an increase in luminosity by more than a factor of 2 without seriously disturbing the rest of the ISR. These studies were directed towards a scheme which would use quadrupoles available at CERN or from other laboratories in order to facilitate the scheme's realization, even at the price of a certain limitation in performance. Indeed, a better performance would have been possible with specially designed lenses.

The installation of the insertion in intersection I7 took place in autumn 1974. The tests performed during the last ISR running period before the long Christmas shut-down confirmed the theoretical prediction. The luminosity was increased by a factor 2.3 with respect to intersection I5, where the beam height was not reduced, and a record figure of 2.1×10^{31} cm^{-2}s^{-1} was obtained with currents of 19.8 A × 24.0 A. Although rather limited, the results concerning the decay rates appear consistent with those observed under similar conditions without the insertion and give confidence for the future utilization of these new facilities for colliding beam physics.

Lattice and Parameters

In order not to reduce the physics capability in the other intersections, the low-β insertion must be reasonably well matched to the rest of the machine. This means that the perturbation of the existing beam parameters, i.e. the momentum compaction function $\alpha_p(s)$ and the horizontal and vertical betatron amplitude functions $\beta_h(s)$, $\beta_v(s)$ must be as small as possible outside the insertion when it is switched on. The matching of α_p is the most important as it directly governs the momentum spread and, therefore, the maximum current which can be stored in the aperture of the ISR. The β_v matching is also of importance since it directly affects the luminosity in the other intersections and the level of background in the machine. The least important parameter is β_h which contributes by only 20 % (at 26 GeV/c) to the beam width.

To obtain a minimum β_v at the intersection together with a perfect match of α_p, a basic lattice of two doublets of quadrupoles DF and FD placed in this order symmetrically about the intersection was adopted as a starting point. The inconvenience of a large α_p at the intersection was proved not to be important for a low-β insertion of a moderate strength[3]. Additional quadrupoles were then added to this basic scheme in order to control the betatron matching. The optimization of schemes of five and six quadrupoles was carried out using the matching routine in the AGS program. This program allows weights to be applied to the α_p, β_h and β_v matching depending on their importance. The variables were the strengths and the positions of the quadrupoles with constraints of maximum strength and available space in the ISR. A scheme of five quadrupoles was finally retained with the optics parameters of Table 1. The mismatch of 2 % for α_p and 14 % for $\beta_{h,max}$ on the extreme orbit causes a reduction of about 5 % in the maximum beam intensity.

TABLE 1

Beam Optics Parameters with the Low-β Insertion on

	Parameters	At central orbit $\Delta p/p = 0$ (m)	At extreme orbit $\Delta p/p = +0.021$ (m)
outside the insertion	α_p^{max} (or x^{max} for $\frac{\Delta p}{p} \neq 0$)	2.284 (2.238)	0.0618 (0.0602)
	β_v^{max}	57.91 (52.14)	62.94 (52.96)
	β_h^{max}	45.67 (41.00)	47.39 (41.53)
	β_v^{max} at any intersection	15.66 (14.25)	17.11 (14.07)
	β_v^{min} " " " "	12.80 (14.25)	12.80 (14.07)
at low-β intersection	β_v	2.75 (14.25)	2.90 (14.07)
	β_h	46.70 (20.85)	44.79 (14.07)
	α_p (or x for $\frac{\Delta p}{p} \neq 0$)	3.179 (2.184)	0.0791 (0.0602)
	Q_h	8.878 (8.892)	8.938 (8.957)
	Q_v	8.859 (8.663)	8.914 (8.726)

The values in brackets correspond to the basic machine with the insertion switched off. The difference between these two sets of figures gives a measure of the mismatch.

The mismatch of β_v results in luminosity fluctuations of $\pm$ 7 % between the intersections outside the insertion. The reduction factor of β_v in the insertion varies from 5.18 on central orbit to 4.85 on the extreme orbit. Using an average value of 5 and a loss of 5 % in the maximum intensity, the absolute gain in luminosity can be estimated to be $0.95\sqrt{5} = 2.15$.

The recently developed ELSA-type working line (Figure 1) was chosen for use with this insertion for two reasons:

- First, this line provides large Q-spreads in a region of the Q-diagram free of non-linear resonances up to the 7th order, and to the 8th order for the stacking region of the aperture; thus, the maximum ISR intensities can be stacked with a minimum of background[4]. Indeed, to have background at the nuclear scattering level, uncorrected resonances in the stacking aperture must be of the 8th or higher order; this requirement becomes more stringent in the case of a low-β insertion since the superperiodicity of 4 is suppressed and all resonances are excited by the magnetic defects and the beam-beam electromagnetic interaction.
- The second reason is a consequence of the Q-shift ($\Delta Q_h = -0.014$, $\Delta Q_v = 0.196$) introduced by the low-β insertion itself which moves the working line of the bare machine towards the region of ELSA in the Q-diagram; thus, only a small correction from the poleface windings and sextupoles is required to create the ELSA line.

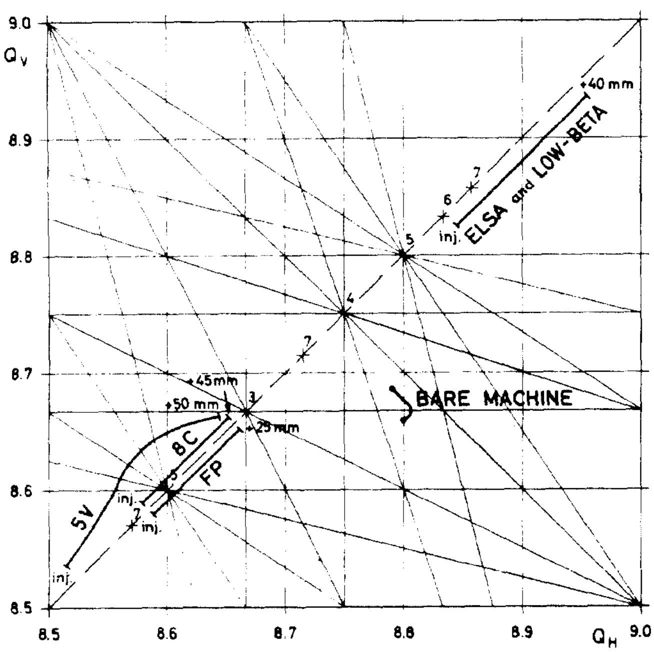

FIGURE 1

ISR Working Lines

When using pure quadrupole lenses in an insertion, the matching for off-momentum particles is perturbed for three reasons: to maintain constant Q-values across the aperture, all the focusing strengths of the machine must vary across the aperture proportionally to $(1 + \frac{\Delta p}{p})$; to obtain a given $Q' = \frac{\partial Q}{\partial(\frac{\Delta p}{p})}$, an additional variation by $(1 + \frac{Q'}{Q}\frac{\Delta p}{p})$ must be added; and finally, the orbit parameters are slightly different for off-momentum particles whether the distributed poleface windings or the small number of localized sextupoles are used to produce the sextupole Q-correction. For off-momentum particles, the absence of a sextupole correction in the quadrupoles introduces orbit and β-modulations larger than would be expected from the mismatch on central orbit (Table 1). In the future, a correction is foreseen for the main harmonics of these distortions using the four independently powered sextupoles which were installed for resonance compensation. In the last run with the low-β insertion, an attempt was made to reduce the orbit distortions by a dipole correction which removed the distortions for the extreme $\Delta p/p$ at the detriment of the central orbit for which the distortions are of less importance. Lastly, the use of pure quadrupoles in the insertion adversely affects the Q-shifts which became proportional to $(1 - \Delta p/p)$. This effect is of little importance and is taken into account in the tuning.

The contribution of the gradient errors measured in the quadrupoles can be analyzed in two ways:

- On one side, these errors produce orbit and β-modulations. Table 2 gives the field and gradient errors integrated along the most external closed orbit (for $\Delta p/p = \pm 0.025$ including an eventual orbit distortion of 24 mm peak-to-peak at $\beta_{h,max}$). The resulting orbit and β-modulations appear much smaller than those resulting from the sextupole effect.
- On the other hand, for the part of the aperture beyond this limit, the gradient errors increase up to a maximum value of 3 % at the chamber wall. This region is crossed by particles of large betatron amplitudes resulting in an even stronger resonance excitation.

TABLE 2

Influence of Gradient and Field Errors

Quad. No.	$\frac{G\ell(x)-G\ell(0)}{G\ell(0)}$ (%)	$\frac{B\ell(x)-xG\ell(0)}{xG\ell(0)}$ (%)	$(\Delta x)_{max}$ (mm)	$\left(\frac{\Delta\beta_v}{\beta_v}\right)_{max}$ (%)	$\left(\frac{\Delta\beta_h}{\beta_h}\right)_{max}$ (%)
Q1	-0.1	0.0			
Q2	-0.2	0.0			
Q3	-1.7	-0.2	0.7	0.3	0.3
Q4	-0.7	-0.1			
Q5	-0.6	-0.1			

The errors with respect to a perfect quadrupole of the integrated gradient and field are given for the most external orbit ($x = \alpha_p(\text{local}) \times 0.025$ plus an orbit distortion of 12 mm peak at $\beta_h = 41$ m). The influence of these errors on the main optics parameters is also given.

Installation

The 10 quadrupoles were made available quickly through loans from Daresbury and Desy Laboratories and from spares in the ISR and PS Departments of CERN. The insertion was installed during the October shut-down in intersection 7. Figure 2 gives the layout and Figure 3 a general picture of the insertion.

Since it was decided at the outset to operate the low-β insertion with equal momenta in both rings, the corresponding quadrupoles could be connected in series which reduced the number of power supplies. The type of

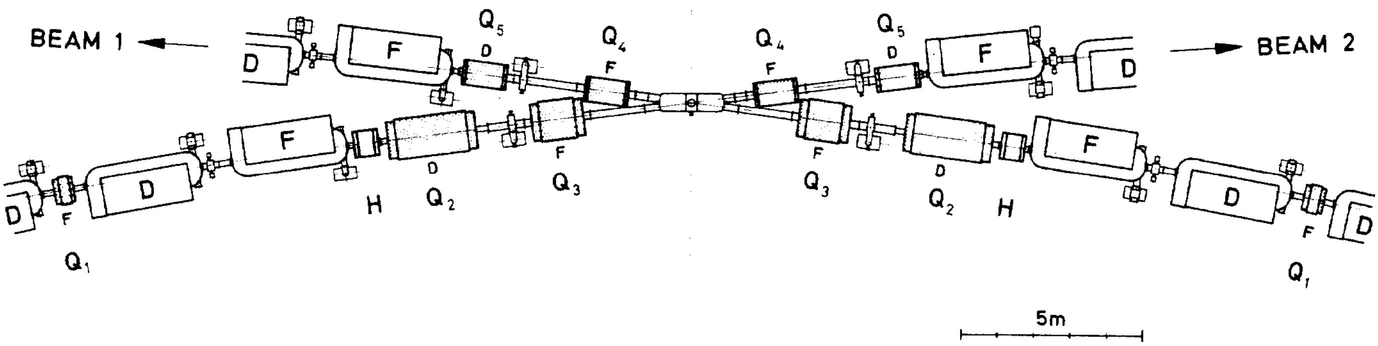

FIGURE 2

Layout of the Low-β Insertion

the quadrupoles and their main characteristics are given in Table 3. For comparison, the currents for operation at 26 GeV/c are listed as well. The quadrupoles have been adapted for their installation in the ISR, and remeasured over the entire useful aperture to determine the gradient and higher multipole components for beam optics calculations.

For the intersection, a completely new vacuum chamber had to be designed and built. The vertical and horizontal aperture requirements are given in Table 3 for the different quadrupoles. As can be seen, for Q4 and Q5 an elliptical vacuum chamber had to be built which fitted tightly between the two adjacent poles. Two scrapers were provided at the beams' crossing point for beam diagnostics. This scraper system and its use for luminosity measurements are reported elsewhere at this Conference[5].

To meet the requirements of current setting precision and ripple, the spare ISR power supplies, which were designed for different purposes, had to be modified. For the ripple, passive filters were added and a copper sheet tightly fitting the pole contours gave and additional reduction by a factor 50 at 600 Hz as well as acting as heat shield during the bake-out.

Performance and Tests[6]

The tests of the low-β insertion and the development of the ELSA-type working line were carried out at the same time. For the first two tests, the working line was shifted by $\Delta Q_h \simeq \Delta Q_v = -0.025$ to attenuate the effect of the proximity of the 9th integers. Table 4 gives the closed orbit measurements made outside the insertion with the quadrupoles switched on

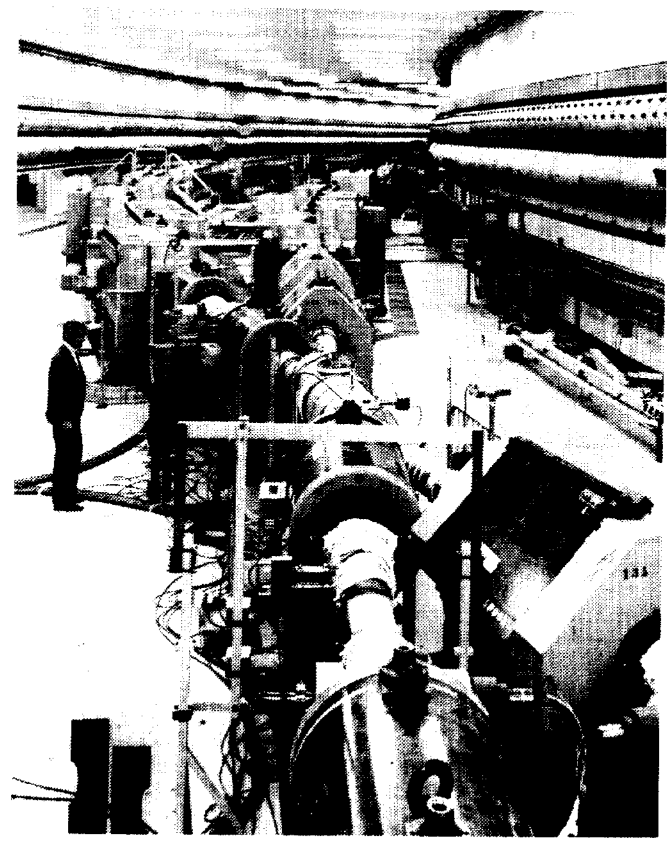

FIGURE 3

General View of the Insertion in Intersection 7

TABLE 3

Nominal and Operating Characteristics of the Quadrupoles

Quadrupoles	Nominal charcteristics					Operating characteristics at 26 GeV/c		
	Pole distance (mm)	steel length (mm)	gradient (kG/cm)	current (A)	power (kW)	current (A)	beam width (mm)	beam height (mm)
Q1 ISR Terwilliger	184	300	0.53	150	6	141.9	103	47
Q2 MPS Q 2 m	200	2000	1.05	625	115	466.0	134	39
Q3 MPS Q 1 m	200	1000	1.05	750	80	433.0	184	23
Q4 Desy QB	161	1047	1.30	1000	200	660.0	182	17
Q5 Daresbury Q16	161	1047	1.30	1000	200	875.0	132	32

and off. The effect of the insertion on an off-momentum orbit is quite small ($\Delta x_{p\text{-to-}p} = 1.3$ mm for $\Delta p/p = 0.021$) and compares well with the values given in Table 1. The slight variations of the vertical closed orbit distortions are explained by deviations of the orbits from the median plane of the quadrupoles. These deviations can result either from small misalignments or from initial orbit distortions. The same reasoning applies to the horizontal closed orbit for $\Delta p/p = 0$.

TABLE 4

Vertical and Horizontal Closed Orbit Distortions Measured outside the Insertion with the Quadrupoles Switched on

Orbit distortion in mm	at $\bar{x} = -40$ mm	at $\bar{x} = 0$	at $\bar{x} = 40$ mm
$\Delta x_{\text{peak-to-peak}}$	8.4 (6.3)	6.2 (6.3)	11.9 (10.6)
$\Delta y_{\text{peak-to-peak}}$	5.2 (3.3)	4.7 (3.6)	5.5 (4.5)

The values in brackets correspond to the basic machine with the insertion switched off.

The Q-shifts measured on the centre line were $\Delta Q_h = -0.014$ and $\Delta Q_v = +0.192$ to be compared to the theoretical values of -0.014 and $+0.196$, respectively. The present ISR equipment does not allow easy measurement of β values. The ratio of the β_v values between the low-β insertion and a normal intersection was calculated from profile measurements made with scrapers on small beams. Values rather independent of $\bar{x}$ were measured at the centre line:

$$\frac{\beta_v^{I7}}{\beta_v^{I5}} = 5.6 \pm 0.4$$

to be compared with the theoretical value of 5.61. In future, we intend to develop a technique of β measurements using the pick-up electrodes and the Q-kickers.

With the help of the active feedback system[7], 19.8 A and 24.0 A have been stacked in Rings 1 and 2, respectively, using the standard technique of dynamic compensation of the incoherent tune shift[8]. A record figure of luminosity of 2.11×10^{31} cm^{-2}s^{-1} was measured in I7 corresponding to an effective beam height of 2.25 mm. The ratio of the luminosities measured in I7 and I5 was:

$$\frac{2.11 \times 10^{31}\ \text{cm}^{-2}\text{s}^{-1}}{0.9 \times 10^{31}\ \text{cm}^{-2}\text{s}^{-1}} = 2.34 \ ,$$

which agrees with the β_v measurements:

$$\sqrt{\frac{\beta_v^{I7}}{\beta_v^{I5}}} = 2.37 \pm 0.1 \ .$$

With these currents, decay rates of 6 ppm min^{-1} in Ring 1 and 23 ppm min^{-1} in Ring 2 were measured. Although the difference between the two rings was not explained, a decay rate of 6 ppm min^{-1} with 7th order resonances in the middle and 6 $Q_v = 53$ on the edge of the stack is comparable with that normally obtained in the ISR without low-β insertion.

In the last two runs, the working line was shifted to its final position. A dipole correction was applied on-line to correct the orbit distortions for extreme values of $\Delta p/p$ at the expense of increasing the distortion on central orbit (Table 5). With 17.9 A in Ring 1 and 18.2 A in Ring 2, a decay rate of 1 ppm min^{-1} has been measured in Ring 2 whereas in Ring 1 it was 20 ppm min^{-1}. In contrast to the earlier run, the decay rate in Ring 1 was higher than in Ring 2. However, these results indicate that the decay rates of the order of 1 ppm min^{-1}, i.e. at the nuclear scattering limit, should be obtainable with the low-β insertion.

TABLE 5

Effect of Dipole Corrections of the Extreme Orbits

$\Delta x_{\text{peak-to-peak}}$ (mm)	at $\bar{x} = -37$ mm	at $\bar{x} = 0$	at $\bar{x} = 42$ mm
prior to correction	8.8	4.7	15.8
after correction	4.4	11.4	8.7

Conclusion

The insertion behaves as expected from the optics calculations. Studies will continue to improve the matching of off-momentum particles and to control the effect of non-linear resonances on decay rate and background. However, the first results have been sufficiently encouraging that a physics programme is already foreseen for this intersection. In the future, the insertion will be displaced to intersection 1 where it will be used in conjunction with a superconducting analyzing solenoid.

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