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DETERMINATION OF THE SEXTUPOLE COMPONENTS FOR THE SUPERCONDUCTING
LOW- β_v INSERTION OF THE CERN INTERSECTING STORAGE RINGS

by

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Introduction

In the Intersecting Storage Rings (ISR) at CERN the production rate of events in intersection 8 has been made larger by a factor 7, compared to the standard intersections, thanks to the installation of a superconducting low- β_v insertion¹.

The production rate of events with a cross-section σ , at an intersection where the effective height of the beams is h , is given by²:

$$\frac{dn}{dt} = \sigma \cdot L = \frac{\sigma}{c^2} \frac{I_1 I_2}{h \tan \theta / 2} \quad (1)$$

L is called the luminosity. I_1 and I_2 are the intensities of the beams, e the charge of the proton, c the speed of light, θ the crossing angle of the beams.

Thus a low- β_v scheme, which reduces h , only makes sense if it does not lead to a reduction of the stored intensities I_1 and I_2 , and if the h 's at the other seven intersections of the ISR are not increased. These conditions are almost fulfilled by a good matching of the betatron functions and the dispersion, which constitutes the linear optics design of the insertion.

However the accumulation of protons in the ISR is made by "stacking in the synchrotron phase space"². Therefore the intensity of the stored beam depends on the momentum acceptance of the machine. As the positions of the closed orbits as a function of momentum determine this acceptance, sextupole components have been added to the superconducting low- β_v scheme in order to maintain the acceptance as close as possible to that of the standard machine, which has a conventional low- β_v insertion in intersection 1.

On the other hand if the height h of the beam is momentum dependent, an average of $1/h$ has to be made for obtaining the luminosity in analogy with equation (1). Sextupoles help avoiding an increase of h with momentum which would lead to a reduction of the luminosity.

Before going into the principles for the computation of the sextupoles, let us rapidly recall how protons are accumulated in the ISR and what the consequences of the linear design³ are for our present problem.

1. Accumulation of protons in the ISR, stability of a stack

Protons sent by the synchrotron injector are picked up by the ISR RF system and released on stacking orbits. The maximum and minimum momentum deviations with respect to the central momentum, with which protons can circulate in the ISR, define respectively "the top and the bottom of the proton stack". Their difference is the momentum acceptance which equals about 2.6% in the standard machine. The details of the stacking process can be found in ref. 2.

The stability of a stack is guaranteed by "Landau damping"² arising from a spread of the betatron fre-

quencies with momentum. For a given frequency spread per unit of momentum, the stability condition is equivalent to a limit on the density of the proton current per unit of momentum. Therefore the maximum stored current is just proportional to the momentum acceptance

Under these conditions a closed orbit distortion or a horizontal blow-up of the proton pulses, which lower the extreme momenta with which the pulses can circulate, reduce the momentum acceptance and by that the stack intensity. The closed orbit distortions can be important in the ISR because the tunes are kept close to 9, as shown in Fig. 1; this is necessary for placing the large tune interval ($\Delta Q \sim 0.065$), required by the Landau damping, in a region of the Q_v - Q_h -plane free from non-linear resonances of an order higher than 6 (see Fig. 1).

Fig. 1 "Working line", i.e. tune values in a stack of the ISR. The numbers above the diagonal indicate the order of the fan of non-linear resonances.

2. Linear matching of the superconducting insertion³

Maintaining the momentum acceptance while making an insertion is realised to a first approximation by a matching of the dispersion function and the horizontal envelope function β_h .

The β_v function must also be matched in order not to perturb the other intersections and not to introduce background due to a vertical blow-up of the beam.

The space limitations in the ISR hindered the realization of a perfect matching of the superconducting insertion, and the horizontal betatron matching had to be sacrificed³. This resulted in a large modulation of β_h .

In spite of this poor matching, the theoretical momentum acceptance of the ISR with the superconducting insertion in I8 is practically equal to that of the ISR with the conventional low- β insertion in I1, which is the standard machine used for high intensity runs, provided that sextupole components are introduced in the superconducting quadrupoles.

This conservation of the momentum acceptance results from the control of the off-momentum closed orbits:

- the maximum of the dispersion function associated with the superconducting scheme is smaller than that associated with the conventional low- β scheme,
- the sextupole components of the low- β scheme maintain the regularity of the extrema of the off-momentum closed orbits associated with the superconducting scheme while the off-momentum closed orbits associated with the conventional low- β scheme have a large modulation of the extrema.

3. Sextupole scheme for the superconducting low- β insertion

In the ISR the variation of the tunes with momentum, as shown in Fig. 1, is realised by means of sextupole and high order multipole components sitting in the combined function main magnets. This compensation "in situ" of the variation with momentum of the focusing power of the quadrupoles guarantees a cancellation of the first derivative of β with respect to momentum at least and a cancellation of the derivative of the dispersion with respect to momentum⁴. Then introducing an insertion with pure quadrupoles, breaks down this compensation "in situ". This means that a first derivative of β with respect to momentum appears, as well as a derivative of the dispersion.

The sextupole component K' sufficient to maintain the focusing power constant to the first order in momentum deviation $\Delta p/p$, in a quadrupole of gradient K is:

$$K' = K/D$$

where D is the average dispersion in the quadrupole. The components calculated this way, for the superconducting scheme, are listed in Table 1. Due to the low dispersion in the vertically focusing quadrupoles SL3 and SL5³ the sextupole strength for maintaining their focusing power constant with momentum is large. As the sextupole windings have to be mounted on cylinders inside the quadrupole⁵, it was found that the forces exercised on these windings prevented reaching such high strengths. Therefore the sextupole strengths necessary to match the off-momentum closed orbits were taken as design values.

Table 1 Normalised gradients and derivatives for the superconducting quadrupoles in ring 1

Quadrupole names	SL1	SL3	SL5	SL7
Quadrupole effective length L_q (m)	0.65	1.15	1.15	0.65
$K_v = \frac{1}{B\rho} \frac{dB_x}{dy}$ (m ⁻²)	-0.3836	0.4100	0.3650	-0.3672
Sextupole effective lengths L_s (m)	0.74	1.24	1.24	0.74
$K'_v = KL_q/DL_s$ (m ⁻³) for compensation to the first order in $\Delta p/p$	-0.153	0.336	0.302	-0.164
$K'_v = \frac{1}{B\rho} \frac{d^2B_x}{dy^2}$ for closed orbit matching (m ⁻³)	-0.162	0.179	0.202	-0.202

3.1 Principle of the calculation of the sextupoles for off-momentum closed orbit matching

As the horizontal tune at the top of the stack is closer to an integer value by more than a factor 2 compared to the tune at injection (see Fig. 1), it is essential that the off-momentum closed orbit at the top of the stack looks like that of the basic ISR (as described in ref.2), which guarantees the maximum momentum acceptance.

Therefore the sextupole components of the horizontally focusing quadrupoles SL1 and SL7 (see Fig. 2) have been adjusted so that the off-momentum closed orbits at the top of the stack with and without the insertion are identical outside the insertion location.

Fig. 2 Sketch of the low- β scheme and off-momentum horizontal closed orbits, with and without insertion. The non-referenced magnets are ISR combined function main magnets. SL1 and SL7 are horizontally focusing and superconducting quadrupoles. SL3 and SL5 are vertically focusing and superconducting quadrupoles. SL9 is a horizontally focusing conventional quadrupole, without embedded sextupole component.

The computation procedure is as follows:

- approximate strengths are affected to the insertion sextupoles,
- the two series of sextupole and octupole components in the main magnets of the ISR are computed by means of the routine MA in the AGS program⁶ in order to make the correct working line (as shown on Fig. 1),
- the quadrupole and sextupole components of the insertion are turned off and the closed orbit corresponding to the momentum deviation $\Delta p/p_m$ of the top of the stack is computed with AGS⁶; this off-momentum closed orbit is that of the basic ISR²,
- the quadrupole and sextupole components of the insertion are reset to their preceeding values; a trajectory starting at the beginning of the insertion, i.e. at the upstream end of SL1 in Fig. 2, with the coordinates of the closed orbit computed in c) is tracked, for the same value $\Delta p/p_m$ of the momentum deviation, through the insertion (see Fig. 2); the tracking is made with the routine TH in the AGS⁶ program,
- the sextupole components in SL1 and SL7 are incremented so that the additional kicks produced by these increments, cancel the difference between the coordinates of the trajectory computed in d) and those of the orbit computed in c) at the end of the insertion (i.e. just after SL9 in Fig. 2);

the computation is made assuming that the trajectories are betatron oscillations around the off-momentum closed orbit obtained with the insertion (it is computed in b); the computation can be made only if the horizontal phase advance between SL1 and SL7 is substantially different from 180° ; it is actually 152° at the top of the stack and as the β_h 's in these quadrupoles are of the order of 80 m, the computation can easily be made. At this point the computation can be restarted in a) with the incremented sextupole strengths.

3.2 Results

The computation explained above converges rather fast: three iterations are enough to obtain the sextupole strengths for SL1 and SL7, starting with absolute values of K' equaling 0.18 in all sextupoles. The iterative procedure is stopped when the maximum excursions of the closed orbits with and without the insertion differ by less than a tenth of a millimetre. The strengths of the sextupoles in SL3 and SL5 have been adjusted so that the product KK' is the same for these magnets and for SL7 (it is larger for SL7 than for SL1): under those conditions all the sextupole windings experience the same force and hence can be assumed to be at the same distance from the quench limit.

The complete procedure involving the sextupoles in the four SL quadrupoles has been repeated twice, leading to the values "for closed orbit matching" in Table 1. For these values of the sextupole components, the position of the closed orbit at the top of the stack (i.e. $\Delta p/p = 0.021$) is the same outside the insertion, with and without the insertion turned on. Furthermore at injection (i.e. $\Delta p/p = -0.021$) the position of the closed orbit is displaced by less than 0.3 mm at any place in the machine when the insertion is turned on. This result justifies making the analogy between the above calculation and a correction of the second order chromatic aberration of the insertion for the horizontal motion.

Experimentally it was found that the top of the stack and the injection orbit could be set at the same value of the momentum deviation as that of the standard machine.

The variation of β_y with momentum at the intersection point is given in Table 2, the associated effective height averaged over a stack is 4 % larger than that associated with a constant value of β_y equal to that of the central orbit.

Table 2

Momentum deviation	- 0.005 bottom of stack	0 central orbit	0.021 top of stack
β_y^* at the interaction point in ring 1 (m)	0.278	0.287	0.350

Removing the sextupole components of the insertion leads to:

- a decrease of 3.5 % of the momentum acceptance due to the modulation of the off-momentum closed orbits with respect to the ideal ones;
- an increase of 2 % of the average effective height due to the variation of β_y^* with momentum at the interaction point.

Conclusion

Sextupole components were introduced in the quadrupoles of the superconducting insertion of the ISR in order to maintain the momentum acceptance of the machine in spite of the large β_h modulation resulting from the horizontal betatron mismatch and to a lesser extent to correct the variation of β_y^* with momentum. The matching of the off-momentum closed orbit at the top of the stack was the procedure which made it possible. This matching is practically equivalent to a correction of the second order chromatic aberration since all the off-momentum closed orbits are almost matched once it is performed.

With the tune values used in the ISR for stacking and physics running, withdrawing the insertion sextupoles would provoke a loss of luminosity of the order of 5 % which is modest but logical. Indeed the sextupoles have to compensate at the most a decrease of about 2 % (the value of the maximum momentum deviation) of the quadrupole strength.

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