AUTOMATED INJECTION PROCEDURE FOR THE CERN INTERSECTING STORAGE RINGS (ISR)

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Summary

The performance of the ISR is critically dependent on the conservation of the transverse beam size. One important source of transverse blow-up for proton beams is injection errors. A two-phase injection procedure is designed to limit these errors to negligible proportions. The first phase, based on the analysis of the first turn beam trajectory, reduces the errors sufficiently to ensure that nearly all of the particles ejected by the CERN-PS will circulate on the ISR injection orbit. The remaining errors are reduced in a second phase based on the accurate measurement of the injection error amplitude, i.e. the amplitude of the coherent betatron oscillation of the injected beam. The residual error causes a blow-up not exceeding a few per cent. The two phases are fully automated using the ISR control computer.

Introduction

The injection procedures for the ISR have been considerably improved over the last years from a point of view of speed, ease of operation and quality. The process of injection tuning can be split into two phases :

- pre-optimisation of injection
- fine tuning of injection

These two phases are discussed in the following paragraphs.

Pre-optimisation

The problem to be solved in the injection procedure can be described as follows: find a fast and an efficient way to match the beam trajectory in a beam transfer channel to the closed orbit of the machine. The issue is complicated by the fact that the closed orbit is not necessarily known, and cannot always be measured. This can be caused by starting conditions that are such that the beam only makes a few turns after injection before being completely lost owing to excessive injection errors in one or both transverse planes.

Pre-optimisation based on single turn trajectory only

The beam observation method on which decisions are based regarding changes in transfer channel trajectory is the measurement of the beam position during the first turn.[1]

The resulting position depends on the following factors :

(i) the closed orbit
(ii) the betatron oscillation due to the injection error
(iii) the momentum of the beam with respect to the momentum at central orbit (horizontal plane only).

If these factors can be separated, then the injection error can be determined fully in a given reference frame and it can be cancelled by applying suitable corrections to the trajectory in the beam transfer channel.

The separation of the 2 (3) components of the first turn trajectory is performed as follows :

(i) The beam momentum $\Delta p/p$ can easily be computed by minimising in the horizontal plane the relation [2]

$$\sum_{j=1}^{N} (P_i - \alpha_{p_i} \frac{\Delta p}{p})^2$$

P_i = beam position at pick-up station i

α_{p_i} = momentum compaction function at station i

(ii) The residual horizontal and the vertical trajectory can be described as follows :

$$P_i = \sum_{j=1}^{M} \frac{\sqrt{\beta_i}}{2\sin\pi q} C_j \cos(|\mu_j-\mu_i|-\pi Q)+\sqrt{\beta_i}E\cos(\mu_i+\emptyset) \qquad (1)$$

$$= \sum_{j=1}^{M} \frac{\sqrt{\beta_i}}{2\sin\pi q} C_j \cos(|\mu_j-\mu_i|-\pi Q) + \sqrt{\beta_i}E_1\cos\mu_i - \sqrt{\beta_i}E_2\sin\mu_i \qquad (2)$$

The summation term describes the closed orbit whilst the last term describes the betatron oscillation caused by the injection error. The symbols have the following meaning :

C_j : the normalised dipole error causing a closed orbit deformation

μ_i : phase at the pick-up station

μ_j : phase of the dipole error

β_i : the beta function at the pick-up station

E : the normalised amplitude of the injection error, units $\sqrt{\mu\text{radm}}$

$\emptyset$: the phase of the injection error

Q,q: the tune and the non-integral part of the tune of the machine

The unknowns are C_j, μ_j, E and $\emptyset(E_1,E_2)$. A classical least square minimisation cannot be executed since μ_j appears as an argument of cosines. The way around this is to filter out a sine function from the ensemble of the beam positions and to consider the residual part as an approximation of the closed orbit. In this way, the azimuth of C_j (i.e. the phase jumps of the closed orbit vector) are left unchanged whilst the resulting amplitudes of C_j are incorrect. A fine search is launched on this approximate orbit which yields the correct values for μ_j. These values are then substituted in formula 2 and a classical least square minimisation is calculated which yields C_j, E_1 and E_2. This calculation is very time consuming in view of the large number of pick-up measurements to be treated (50). Experiments have shown that the closed orbit is sufficiently described in this application by a single C value. An increasing number of C's did not improve the quality of the calculation which is determined by the difference between the measured beam position and the sum of the calculated closed orbit and betatron oscillation. This procedure has been implemented in an Argus computer program for optimisation of steering called OPST.

The precision of the procedure is limited essentially by two factors :

(i) the errors of the computation which remains an approximation.

(ii) the limited precision of the first turn trajectory measurement.

The figures for resolution and accuracy quoted in ref. 1 are in the range of 0.7 - 3 mm and 1 - 3% respectively. The residual error after application of this procedure is a measure of the overall quality and is smaller than 0.5 $\sqrt{\mu radm}$ and 1 $\sqrt{\mu radm}$ for the vertical and horizontal planes respectively which is certainly adequate in a half aperture at normal injection orbits of about 1.5 $\sqrt{\mu radm}$ (V) and 2 $\sqrt{\mu radm}$ (H).

Pre-optimisation based on single turn trajectory and closed orbit

The pre-optimisation can very easily be refined after the previous correction since the closed orbit measurement is available together with the first turn trajectory. The rather complicated calculation to separate the closed orbit, $\Delta p/p$ and betatron oscillation is replaced by a simple substraction between the first turn trajectory and the closed orbit. [3] The residual error is now further reduced to less than 0.25 $\sqrt{\mu radm}$ vertical and 0.5 $\sqrt{\mu radm}$ horizontal which are essentially due to the errors of the first turn trajectory since the resolution and precision of the closed orbit measurements are far superior to the ones of the first turn. These figures fit quite well with the quoted inaccuracies of the measuring system.

Fine optimisation of injection

The task of the fine optimisation is to reduce the injection errors to such small values that the injected beam size is essentially conserved. It has been shown[4] that an injection error d modifies the emittance as follows :

$$E = E_o + 2d^2 \quad \text{(d in normalised units)}$$

The standard momenta for injection in the ISR are 11.5, 15, 22 and 26 GeV/c. The latter is by far the most frequently used. The following table shows the effect of typical residual errors of the pre-optimisation on the beam size at 26 GeV/c. This beam is smaller than at the other standard momenta.

	E_o	d	E	$\Delta E/E_o$	$\Delta r/r$
	$\mu radm$	$\sqrt{\mu radm}$	$\mu radm$	%	%
V	0.3	0.23	0.41	35	17
H	0.45	0.38	0.74	64	32

r : beam radius

From these figures it is evident that there is room for substantial improvement. To achieve this another procedure is used. An important element in this procedure is the observation station used to measure the amplitude of the betatron amplitude. This is done by a device known as the beta detector[5] which makes the amplitude of the injection errors available to the ISR control computer. The only unknown factor to be determined is the phase of the injection error whilst its amplitude can be measured with a precision of a few .01 $\sqrt{\mu radm}$. This is done by adding a known vector to the original one and measuring the resultant amplitude. Repeating this with a second vector produces a number of relations which are sufficient and necessary to calculate the unknown phase. This calculation is given in the appendix. The fine optimisation procedure has been implemented via an Argus computer program for optimisation of injection called OPIN. The residual errors are reduced to less than 0.04 $\sqrt{\mu radm}$ vertically and 0.2 $\sqrt{\mu radm}$ horizontally which causes emittance increases of 1% and 18% respectively. In this procedure it is often necessary to treat the two transverse planes separately since on many occasions an influence was observed of the error condition of one plane on the error measurement of the other due to beta coupling between the two planes. The computer program automatically checks whether the coupling is important or not and decides whether to proceed with a parallel or sequential treatment of the two transverse planes. This phenomenon is not apparent in the pre-optimisation observation of first turn trajectories and closed orbit.

Conclusion

The two main injection procedures for the ISR have been described. They have been operational since 1976 and have been used successfully for various machine conditions where a good injection was always obtained in a very short time. The main impact on the operation of the ISR is that the injection into the ISR has ceased to be a specialist activity and has become a routine activity.

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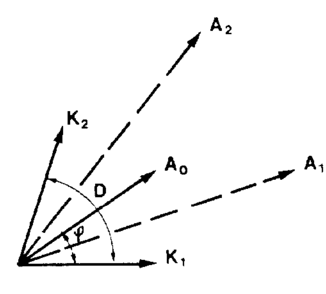
Appendix

Calculation of the injection error vector based on amplitude measurements

Given a vector A_o with amplitude a_o and with phase ϕ and vectors K_1, K_2 with amplitudes k_1 and k_2 and with phases 0 and D, one can write the following relationship:

$$a^2 = a_o{}^2+k_1{}^2+k_2{}^2+2a_ok_1\cos\phi+2k_1k_2\cos D+2a_ok_2\cos(\phi-D) \quad \text{(A1)}$$



In fact the vectors K_1 and K_2 constitute the reference frame as shown in the above figure.

From equation (A1) the whole method can be derived.

$k_1 = k_2 = 0$ measure $a = a_o$

$k_2 = 0$, K_1 is a known vector

measure $$a_1^2 = a_o^2 + k_1^2 + 2a_o k_1 \cos(\phi) \tag{A2}$$

$k_1 = 0$, K_2 is a known vector

Measure $$a_2^2 = a_o^2 + k_2^2 + 2a_o k_2 \cos(\phi+D) \tag{A3}$$

Equation (A2) yields

$$\cos\phi = r = \frac{a_1^2 - a_o^2 - k_1^2}{2a_o k_1} \tag{A4}$$

Equation (A3) yields

$$\sin = \frac{r\cos D - s}{\sin D} \tag{A5}$$

with

$$s = \cos(\phi+D) = \frac{a_2^2 - a_o^2 - k_2^2}{2a_o k_2}$$

From equations (A4) and (A5) one can calculate ϕ.

A correction can now be calculated for A_o with components along K_1 and K_2.

$$\left.\begin{aligned} k_{1c} &= a_o \frac{s\cos D - r}{\sin^2 D} \\ k_{2c} &= a_o \frac{r\cos D - s}{\sin^2 D} \end{aligned}\right\} \tag{A6}$$

If K_1 and K_2 are orthogonal, equations (A6) become :

$$\left.\begin{aligned} k_{1c} &= -a_o r \\ k_{2c} &= -a_o s \end{aligned}\right\}$$

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