

## ON-LINE CONTROL OF THE CERN PROTON SYNCHROTRON CLOSED ORBIT AT INJECTION

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### Abstract

The computerized acquisition and control system installed on the CERN proton synchrotron (CPS) has been used to implement an optimization loop acting on the beam closed orbit. A global method acting on the whole trajectory and a local one on about half a betatronic wavelength are described.

### Introduction

Manipulating the beam trajectory is a difficult task, often hampering studies of the influence of the closed orbit on the accelerator performance. The use of an IBM 1800 on-line computer<sup>1,2)</sup> gave us the opportunity to provide a tool for this purpose.

Each of the 100 magnets of the CPS is equipped with back-leg windings (BLW) providing a horizontal dipolar correction. Twenty-four power supplies are directly connected to 24 of the BLW's and four others to a multiplexer which allows their connection to any of the other BLW's belonging to the same group (one group starts every 12 magnets and comprises 24 consecutive BLW's). Two different approaches have been tried: one acts on the entire closed orbit and is able to optimize the circulating beam intensity or minimize the orbit radial excursions; the other acts on a restricted area (about half a betatronic wavelength).

### On-line Optimization of the CPS Closed Orbit at Injection

#### The Strategy

A search is made for a beam trajectory giving a maximum number of protons ( $I_p$ ) at the end of acceleration. The closed orbit is corrected by working in on its harmonic components and correction of the inflection (position and angle at injection point) accordingly. The harmonic orbit corrections are created in a biased manner by adding appropriate sets of currents to the existing ones in each of the 24 BLW's<sup>3)</sup>. In principle, a harmonic orbit correction of any order could be created this way, within the range limited by the number and distribution of the BLW's. We chose the sixth and seventh order components, which are predominant, as the betatronic oscillation frequency ( $Q_R$ ) of the synchrotron is around 6.25.

The sets of currents which are to create harmonic corrections are calculated as follows: first a set of currents is estimated, equal to the amplitudes of a space harmonic of a given order around the synchrotron. This yields a set of discrete functions which can be expanded in a series of trigonometric functions (Fourier analysis) in order to calculate the amount of undesired harmonic components. This results in a square matrix provided the Fourier

analysis is carried out in terms of the same and all the harmonic components as those estimated. In particular, the resulting matrix is proved to be symmetric positive definite (SPD)<sup>4)</sup>. Therefore, one can always compute an elementary transformation matrix which transforms the SPD matrix into a diagonal one. After multiplying the sets of estimated currents by the transformation matrix, currents are obtained which create pure harmonic orbit corrections. However, it is also proved<sup>4)</sup> that if one widens the spectrum of harmonic components, hence increasing the order of the SPD matrix, the amplitudes of the currents which create pure harmonic corrections are also increased. Moreover, the amplitude of the harmonics which are always embedded within the estimated sets of currents but not included in the spectrum for diagonalization, will grow considerably. If one wants, for example, to create only 6th and 7th harmonic corrections, a very pure effect on the orbit is obtained. If, however, one wants to create in this way a full spectrum ranging from the 0th to the 12th harmonic, the resulting harmonic orbit corrections will include a large amount of 13th, 14th, etc., order components. This method of creating harmonic corrections is very flexible as new sets of currents can always be computed on-line if the distribution of the BLW supplies changes during optimization, for instance due to hardware failures.

The optimization strategy uses 6 control vectors: the 6th and 7th harmonic orbit correction (cos and sin); the radial and angular displacement of the injected beam at injection point.

The strategy itself is a combination of a modified steepest ascent method (on the first four control vectors) and a cyclic exchange method (on the last two control vectors) with the proton intensity as optimization criterion. However, this combination of classical strategies had to be modified so that it is fast and can run in parallel with the normal operation of the synchrotron, which is pulsed at a slow rate. In particular, great care was taken during measurements of the proton intensity. The number of measurements depends upon the current stability of the CPS and is self-adaptive. Unexpected events (bad pulses) had to be discarded and noise filtered out. Therefore a statistical filter was developed with good results. Further, as the synchrotron period is fairly long, the process is likely to undergo drifts of settings which are detected by the strategy<sup>3)</sup>.

#### Results

The strategy has been used successfully to increase the proton intensity at different instants of the acceleration cycle. Full optimization takes on average 15 minutes (CPS cycle 2 secs).

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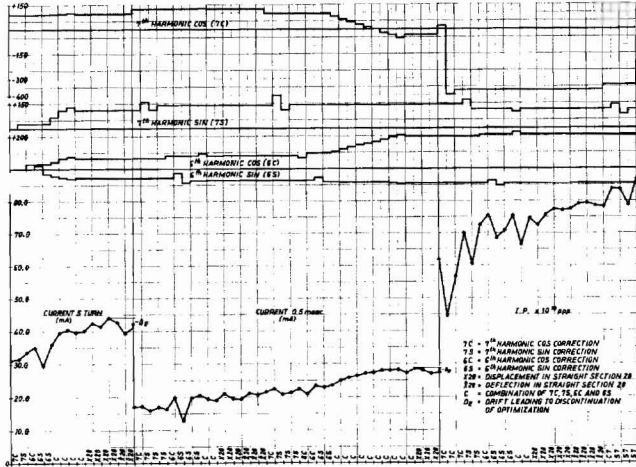


Fig. 1 Automatic start-up of the synchrotron

a) Automatic on-line start-up of the synchrotron (fig. 1). This experiment was carried out on the CPS at a proton intensity of  $80 \times 10^{10}$  protons per pulse. All dipolar corrections were switched off and as a result the proton intensity fell to zero. Next the synchrotron was regulated manually so that the proton beam could be injected and a part maintained for about 30 revolutions. Under such conditions, the on-line strategy was started on the proton current after 5 turns until the intensity after 500  $\mu$ sec reached a threshold, and then switched over to the optimization of the current after 500  $\mu$ sec, during which the proton beam was suddenly accelerated. Eventually the strategy switched over to the optimization of the proton intensity at the end of acceleration and brought it up to  $96 \cdot 10^{10}$  ppp. Fig. 1 shows the start-up process.

b) Optimization during normal CPS operation. During normal operation the strategy works on a generally well-tuned machine. Furthermore, manual operation has access to many more control elements so a dazzling performance cannot be expected from the strategy. Nevertheless, a few percent increase of the proton intensity was generally obtained.

On-line Minimization of the Closed Orbit Distortions

The same strategy with the same control vectors was used to minimize the standard deviation of the orbit position measured by pick-up electrodes. This on-line facility was created to permit systematic studies of orbit-focalization interaction at low energy. The program ran during normal CPS operation and each time minimization was possible

Experiment	Before/after minimization	$I_p$ $10^{10}$ ppp	Max. peak-to-peak at injection mm	Standard deviation at injection mm
1	before	150	27	18
	after	112	17	8.8
2	before	170	30	22.3
	after	120	23	9.7

Table I

it resulted in a significant decrease in the number of protons at the end of acceleration. Typical results are shown in Table I. During other experiments minimization was not even possible (neither 6th nor 7th harmonics in the closed orbit).

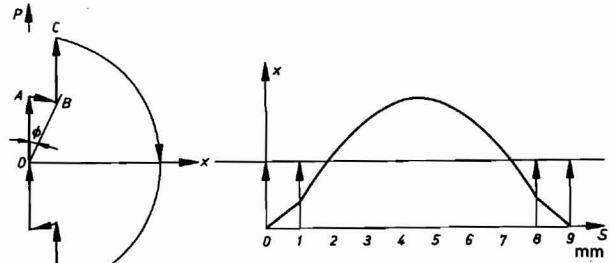


Fig. 2  $p(x)$  and  $x(s)$  for  $Q_R = 6.25$

Local Beam Bump Method

A local closed orbit deformation (bump) is obtained over a pseudo-half betatronic wavelength by means of a set of 4 multiplexed power supplies. As indicated on fig. 2, the maximum amplitude is reached in the straight section (ss) between magnets 4 and 5. In terms of "smoothed normalized variables"<sup>5)</sup>, the radial displacement  $\bar{x}$  and the transverse momentum  $\bar{p}$  are both dimensioned in "equivalent millimetres". For a given perturbation of  $\bar{x}$  mm eq at a given energy, the currents are equal in the 4 BLW's if the CPS  $Q_R$  is just 6.25 for this energy (16 magnets per wavelength). If it is not, the residual oscillation outside the bump can be compensated by a different set of currents between BLW's 0 - 9 and 1 - 8<sup>6)</sup>. Given the number of the straight section where the bump will be maximum, the value of this bump for a certain energy and  $Q_R$ , a computer program produces the desired bump with no significant oscillation outside.

By varying the bump amplitude in a given straight section, one can check the pick-up electrode calibration (the computed bump must be equal to the measured one) and measure an apparent vacuum chamber aperture as it is seen by the proton beam (fig. 3). This aperture is defined as a function of the ratio between the accelerated proton beam and the linac beam at the CPS input. First this ratio is measured over 5 CPS cycles: the average gives a non-bump reference value of 100% within a confidence interval

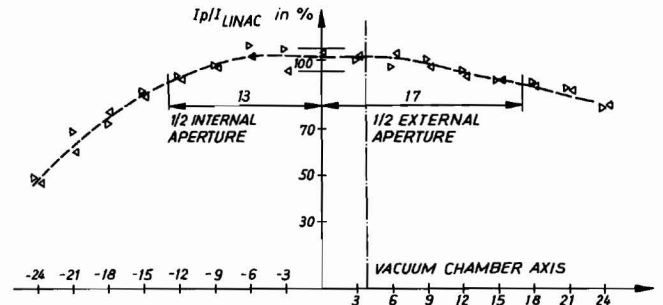
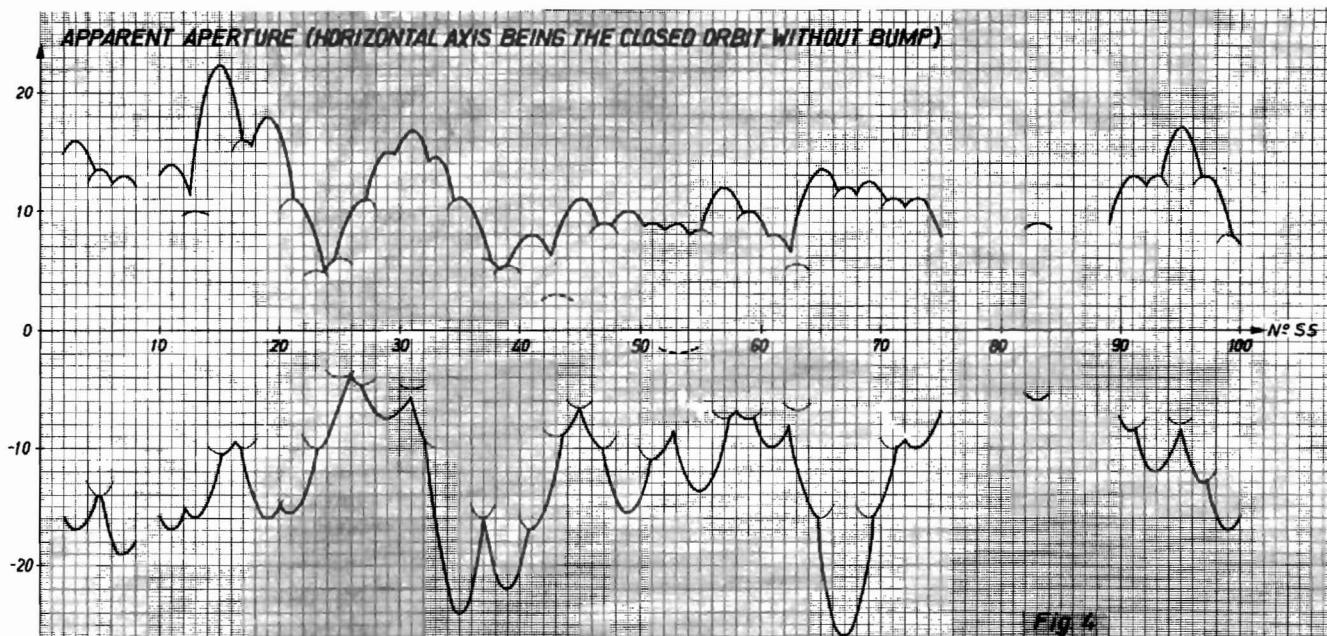


Fig. 3



of  $\pm 2$  times the standard deviation. Next a bump is scanned in both senses (inside and outside) with in the vacuum chamber until this ratio drops to 85% (with this value as a threshold the program can be used in parallel with normal operation) or until the currents in the BLW's reach their maximum. The apparent aperture for a given energy is defined as the value in mm eq between the two points of the curve where this ratio is at 90% of its encountered maximum.

On repeating this procedure for each focusing straight section, the profile of the CPS apparent aperture over the whole synchrotron length is obtained<sup>7)</sup>. Of course, this bump method has no meaning in the synchrotron portion where the RF beam control keeps the beam position constant (as measured with PU 78 + 87) and in the injection portion (ss 26) where the beam is injected between the perturbed BLW's and prevents a local bump by creating betatron oscillations all around the CPS. Outside these portions the apparent aperture profile (fig. 4) shows the locus of throttle points (e.g. in ss 62).

Several tests performed with different CPS operating conditions showed that some of these throttle apertures are constant though the orbit optimum positions have changed. It is then possible to distinguish between a mechanical throttle and another effect such as a magnetic defect. Because a multipolar perturbation creates a modulation of the beam size, the apparent aperture would be modulated with the opposite phase if the vacuum chamber were perfectly cylindrical. Fourier analysis of the apparent aperture reveals the presence of quadrupolar and sextupolar effects.

The local bump method which has been developed as a tool for beam diagnostics could be used in several ways:

- as an aid for the operation to localize throttle points,
- as a beam optimization method moving the beam locally at its position of maximum intensity,
- as an aid to measure and correct the effects of multipolar defects. This on-line facility will be really significant as soon as pulsed power supplies are connected to the multiplexer.

#### Conclusion

The results obtained confirm the following facts: the use of the computer allows studies which would have been practically impossible with conventional control systems; a fully automatic and on-line closed loop control system of a large process in continuous evolution (as is the case with most particle accelerators) costs too much in manpower to be fully completed. The ideal aim seems to be to give enough assistance to the operating staff to face problems encountered efficiently. The two strategies outlined above are an illustration of possible facilities.

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