ALGORITHMS TO GET A CIRCULATING BEAM

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Abstract

Two algorithms based of trajectory fitting have been used to obtain rapidly a circulating beam in LEP with strong focusing lattices.

A new algorithm called "orbit closure" uses the beam positions measured at the first and the second turn. From their difference, it computes two corrector strengths per plane such that the second turn passes at the same place as the first turn at about ten BPM locations. This produces a closed orbit amplitude with an r.m.s. value close to that of the first turn trajectory.

A new 'first turn threader' has been tried. It detects places where an oscillation with an r.m.s. amplitude larger than a specified value starts, and computes two corrector strengths to cancel it. By iterating this process, it should be possible to correct by steps the first turn trajectory so that its r.m.s. amplitude is below a specified value.

The orbit closure has been applied with success to a very low emittance lattice ($135°$ in the horizontal plane) in LEP.

I. The principles

These algorithms are based on the fitting method. This method assumes that the linear optics of the machine is well known. It relies on the description of betatron oscillations with an expression like :

$$y_i = a \sqrt{\beta_i} \cos(\mu_i) + b \sqrt{\beta_i} \sin(\mu_i) + c + \eta_i$$

where y_i stands for the ith measurement of the beam position, β_i and μ_i for the corresponding TWISS parameters and η_i for a realization of a null-mean additive noise. Given this definition of η_i, we must put in the equation the average of the noise which is c. This parameter can be interpreted also as an offset of the measurements.

The values of a, b and c, are computed by means of the least-squares algorithm. In fact what is interesting is not the values of a, b or c themselves, but how relevant is the fit, i.e. whether the measurements follow a betatron oscillation or not. To answer this question, the residual F_n of the fit done with n measurements is computed. Its expression is :

$$F_n = \sqrt{\frac{1}{n-3} \sum_{i=1}^{n} (\tilde{y}_i - y_i)^2}$$

where $\tilde{y}_i$ is the estimation of y_i obtained once the constants a, b and c have been computed.

A very important feature of the fitting method is the possibility to discard the measurements considered as bad, i.e. those such that $|\tilde{y}_i - y_i|$ is larger than a certain number of standard deviations. Usually this number is between two and three as we discard measurements because they are at the edge of a normal distribution of random variables. Note that the best estimate of the standard deviation is F_n. Once the bad measurements have been discarded, the computation is remade until no measurement is considered as bad.

II. Orbit closure

A. The algorithm

The first step for operating a circular machine is to get a first turn. However this usually does not guaranty that the beam circulates because the closed orbit distortion may be too large. Furthermore, in the case of strong focusing lattices, the chromaticity sextupoles are strong because the dispersion is small and this makes large anharmonicities which can make a linear instability if one of the tunes comes close to an integer. This may well happen for a closed orbit distortion which would not prevent the beam to circulate with a weak focusing lattice. This is precisely the case where the orbit closure algorithm is the most useful.

When a first turn is obtained in a machine, the beam position can be measured at several places close to the point where it enters the machine, both during the first and the second turn. Then the fitting method is applied to the difference between these beam positions, and this difference is canceled out with two closed orbit correctors in each plane. Once it is made small enough, it is possible to obtain a circulating beam.

Practically twenty positions are measured downstream of the place where the injected beam enters LEP. After elimination of wrong measurements, only ten which are considered good from the fitting of the difference between first and second turn are kept for the computation. It is worth noting that the BPM's which suffer from a mere offset are not considered as bad usually.

B. Experience with a strong focusing lattice

An illuminating example of the efficiency of the closure algorithm is provided by a machine experiment done with a low-emittance lattice in LEP. The LEP machine at CERN is made from eight arc, each containing thirty FODO cell with dipoles and sextupoles, and eight insertions which contain only dipoles and quadrupoles. The super-periodicity is four. All the nonlinear elements (sextupoles) are in the arc cells. Low-emittance lattices have been envisaged for LEP as a mean to increase the luminosity at low current [1]. In one of these lattices, which was found to be difficult to operate, the arc FODO cells have an horizontal phase advance of $135°$ and a vertical phase advance of $60°$. The horizontal tune is 125.28 and the vertical tune is 75.18. Given the machine super-periodicity, such tunes guaranty that no problem is expected from the non-linear chromaticity [4].

During year 1993, two eight hours shifts had been done where no circulating beam was obtained. This led us to an extensive analysis of the problems associated with this lattice in order to understand why it was so difficult. A report on this study is available [2] and some of the results concerning this lattice can be found at this conference [1]. One interesting outcome of this

study was that it is not possible to correct both third order resonances and horizontal anharmonicity. It was felt that it was easier to try to cope with the anharmonicity than with the third order resonances. The horizontal anharmonicity, i.e. the derivative of the horizontal tune with respect to the horizontal emittance, has a value of $- 1.6 \times 10^5 m^{-1}$ for the lattice under consideration. For an r.m.s. closed orbit amplitude of 4mm at the BPM's where β_x is about 10m, the associated emittance is about 1.6μrad.m, which makes an associated horizontal tune-shift is -0.26. As the fractional part of the horizontal tune of our machine is 0.28, we see that a badly corrected closed orbit can easily lead to an horizontal instability due to the fact that the horizontal tune becomes an integer. In practice it can be observed that the horizontal tune, estimated from a Fourier analysis of several turns measurements, wanders considerably depending on the corrections applied to the first turn trajectory.

In the successful experiment, a great care was taken first to correct the first turn trajectory so that its r.m.s. value was between 3 and 2mm. This took about five hours and this is why a more powerful algorithm, described in the next section, was studied. When the first turn was corrected, the orbit closure algorithm was applied but no circulating beam was obtained although the goal was not far, according to the signal of the RF pick-up indicating that some particles were trapped in the RF buckets for several turns. It took us some time to realize that in fact corrector increments of the order of 10μrad **had to be applied**. Indeed usually closed orbit corrections of this importance are not vital as a kick of 10μrad at a place where β_x is 10m makes a closed orbit distortion of less than 0.1mm if the fractional part of the tune is close to 0.3. In the present case, if the first turn trajectory has an r.m.s. amplitude above 3mm, the horizontal anharmonicity brings the horizontal tune close to an integer, which in turn amplifies the closed orbit distortion due to this small kick an makes the betatron oscillations unstable.

III. First turn threader

A. Why a new threader?

A new algorithm is in the process of being developed. In fact there is already a usable facility in LEP, but it is extremely lengthy to make a small r.m.s. oscillation amplitude. In order to develop more easily strong focusing lattices, a faster automatic algorithm, which produces a first turn trajectory with an r.m.s. deviation as small as possible, is needed as mentioned above.

Before a first turn is done, the injected beam is steered as well as possible, so that its oscillation amplitude just after its entrance in the machine can be reduced to some tenths of millimeters. However as soon as it encounters field defects, the oscillation amplitude increases and the beam is eventually lost.

The idea underlying the new threader was to detect these growing oscillations and to correct them one after the other using a single trajectory measurement. In this process, after a correction is computed, its contribution is subtracted from the trajectory measurement and the next correction is computed with the corrected trajectory. It is clear that, if the beam is lost in the first turn, this can only be partially applied and this algorithm is not valid close to the places where the beam is lost. The aim was in fact to improve a first turn trajectory from a full turn measurement.

B. What has been achieved

The first part of the new process was to establish a simple algorithm to detect field defects. The algorithm is similar to that used for the defect search from a closed orbit measurement [3], but simpler. A fit of the measured trajectory was done from the injection point starting at each BPM and the residue of each fit was computed. A threshold was set for these residues, above which it was considered that a defect must be there.

This looks simple minded but in practice, it is not possible to determine the location of discontinuities in the measured trajectory by merely looking at the first large residue and deciding that the defect lies close to the last BPM used to do the fit. It was noticed that, instead of this, the detected defect was close to the first BPM used to do the fit. As ten BPM's are used, this can make quite a difference in the location! Once the location of a defect is found, even approximately, two closed orbit correctors upstream of the detected defect are chosen to cancel the downstream oscillation. This complete procedure which consists of identifying defects and making corrections was the main outcome of the first study of the algorithm in the LEP control system.

The next step of the algorithm was to compute a correction for several successive defects. After a first defect has been found, a correction is computed and its contribution to the oscillation is subtracted from the measurements. Then the next defect is sought and the process is iterated. Applying this in practice shown us that it was not possible to go further than about four defects because the algorithm is linear and the machine is not. Another complication came from the existence of the experimental solenoids which make a coupling between the two oscillation planes. Although this can be handled with a formalism based on 4×4 transfer matrices, this is not yet available in the LEP control system. Thus the only possibility is to enter the coupled sections with very low oscillation amplitudes. This was not done in the program we used, therefore the algorithm was not successful.

Nevertheless the two above conclusions are already extremely useful to carry on a study on a fast threader for strong focusing lattices.

IV. Conclusion

The orbit closure algorithm, which was already recommended for the LEP startup in 1989, proved to be extremely useful to obtain a circulating beam with a very strongly focusing lattice.

Devising a fast threader algorithm is far from being an easy task. In fact our study is only at its starting stage and we arrived already at useful recommendations to develop it.

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