An automatic finder of field defects in a large A.G. machine

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Abstract

A series of program modules has been written in C, which can perform various tasks to analyze closed orbit measurements. They have been grouped into a software package which can be used by an operator to find field defects from orbit measurements. The basic algorithms used are well known and simple, based on fitting betatron oscillations. The effort has been put in the execution speed and ease of use.

New algorithms have been introduced to detect wrong measurements and check the relevance of the kick calculation, which are a decisive step towards automatization. It is presently possible to localize all relevant dipole field defects in a machine as large as LEP within less than one hour, including the check of the orbit readings.

I. THE PRINCIPLES

The essential part of the orbit treatment is the so-called fitting method. In a defect-free region, the on-momentum orbit measurements are expected to follow a betatron oscillation like :

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

where y_i stands for the i^{th} measurement of the orbit, 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 method. 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, we compute the residual $F_{n,j}$ of the fit :

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

where $\tilde{y}_i$ is the estimation of y_i on the interval $[j, j+n-1]$. In practice the fitting width n varies between 4 (the minimum width since we fit 3 parameters) and a given maximum

fitting width we will call M . j denotes the position of the current measurement. The sums are here expressed from j to $j+n-1$ for sake of clarity. In practice we do not take into account the measurements considered as bad, so that the sums are done over n "good" measurements starting from position j (which can go further than $j+n-1$ if bad measurements are in between). The bad measurements are merely skipped.

Since $F_{n,j}$ is obviously related with the r.m.s. of η , we decided to normalize it in order to deal with numbers of the order of unity :

$$F_{n,j} = \sqrt{\frac{1}{n-3} \sum_{i=j}^{j+n-1} \left(\frac{\tilde{y}_i - y_i}{\sigma} \right)^2}$$

with σ the r.m.s. of η . So a large value of $F_{n,j}$ indicates a bad fit, i.e. a defect inside the fitting range, whereas a value around unity indicates a good fit, i.e. a piece of closed orbit behaving like a betatron oscillation.

Thus if there is a defect between $i-1$ and i , all the values $F_{n,i-n+1}, \dots, F_{n,i}$ will be large. If the $F_{n,j}$ values are displayed in array tables, n being the column index and j the line index, we observe typical patterns associated with defects. To a single measurement wrong at position j correspond n large values of $F_{n,j}$ at positions $j-n, j-n+1, \dots, j$. To a discontinuity in the orbit between positions $j-1$ and j , correspond $n-1$ large values of $F_{n,j}$ at positions $j-n, j-n+1, \dots, j-1$. As it is easy to recognize such patterns in a residue table, they were called "signature" in previous studies [2]. A common feature of the two examples above is the appearance of large values of $F_{n,j-n}$ following small values of $F_{n-1,j-n+1}$. This looks like a stair in the table and can be easily detected. This is what is used to locate defects.

II. NEW ALGORITHMS

A. Defect searching

The defect detection in A.G. machines was previously done by looking at the above defined signatures. But it appeared, after many orbit treatments, that simple signatures are not frequent and that it is much more efficient to look for "stairslike pattern" to find the defects. There-

fore this was the criterion chosen to be implemented in the automatic system. The algorithm to find a defect is the following : We compute the fit residues for the current measurement -let us say j - for different width : $F_{4,j}, \dots, F_{M,j}$, where M stands for the maximum fitting width. If $F_{4,j}$ is "large" (with respect to a given threshold experimentally set to 1.1), the algorithm begins to search for a stair, i.e. it looks if $F_{5,p(j)} > F_{4,p(j)}$ where $p(j)$ is the previous measurement strictly before j which is not disabled (usually $j-1$). The algorithm carries on until it reaches the maximum fitting width M : for a current width n it tests whether $F_{n,p^{n-4}(j)} > F_{n-1,p^{n-4}(j)}$. If it as been the case for all n from 4 to M , then a defect is detected between measurement $j+3$ (excluded) and $j+4$ (included).

When such a defect has been detected, a penalty parameter is computed in order to evaluate its importance. Since a defect between pick-up $i-1$ (excluded) and pick-up i (included) affects $N-1$ fits earlier (i.e. from measurement $i-N+1$ to measurement $i-1$ at least), N being the fitting-width, we decided to introduce :

$$f(i) = \sqrt{\frac{1}{(M-1) \cdot (M-3)} \sum_{n=4}^M \sum_{k=i-M+1}^{i-1} F_{n,k}^2} \quad (1)$$

The smaller (or at least the closer to 1) this number is the better all the concerned fits are and then the less important is the detected defect.

B. Relevance of an action performed on orbit measurements

In order to test the relevance of actions made on orbit measurements (like deletion of one measurement, addition of a field defect or their opposite), we introduce a measure of its efficiency as follows :

$$efficiency = 100 \cdot \frac{f(i) - \bar{f}(i)}{f(i)} \quad (in \%)$$

where $\bar{f}$ denote the value of f , defined in (1), after the action has been performed. So if this action is relevant, the fits will be better after it and therefore $\bar{f}$ will be smaller than f and the above efficiency will be positive. If the action performed is not relevant the efficiency will be around 0 or even worse : negative.

C. The automatic system

With the detection and evaluation of defects and with the measure of the efficiency of a performed action, we now have the tools to built up an automatic treatment of orbit measurements. The algorithm we developed is described by figure 1. At first the expected noise r.m.s. is adjusted in order to deal with fit residues around 1. To this end the

Figure 1: Automatic orbit treatment algorithm

fit residues are computed for the whole machine and for all fitting width from 4 to M . Since those residues must be around 1 if no defect occurs and if the noise r.m.s. is the one expected, this r.m.s. is set to a value such that the mean of all residues is 1.

Then a search for defects is done all around the machine, as explained in subsection A., and the defects are classified according to their penalty parameter in order to deal we most important ones first. Treating minor defects before major ones can bring severe errors and misunderstandings of the actual defects. Defects with a penalty less than a given threshold (which can be adjust by the user) are neglected in order not to treat to many defects at the same time.

Then for each defect detected, we analyze it as follows :

- a - first test the suspected measurement by removing it and looking at the efficiency of the removal. If this efficiency is greater than 7.5%, the measurement is labeled as faulty.
- b - if the measurement is not found faulty, then search for a field defect, i.e. a kick, between i and $i-1$ (for a defect occurring in i). The kick calculation is done by minimizing the error between the downstream measurements and the upstream measurements extrapolated with the effect of the kick.
- c - if no field defect is found between i and $i-1$ test both

- adjacent measurements of $i : i - 1$ and $i + 1$ as in a)
- d - if no bad measurement is found within those neighbors, search for a field defect between $i - 1$ and $i + 1$
 - e - if nothing found, look for a field defect between $i - 2$ and i
 - f - if nothing found, search for field defect between $i - 2$ and $i + 1$
 - g - if there is still nothing found, give up here and let the problem unsolved. It will either be solvable afterwards or solved by the human user.

As described in the organigram (fig. 1) either the automatic system is run as a loop if all the detected defects have been treated, or the treatment is tried once again because the change of the situation can have made solvable problems which were not before. If after this second trial there are still remaining problems, the relevance of all the performed actions is checked by looking at the efficiency of their opposite. For example, if a measurement has been disabled, it is enabled and the efficiency of this action is tested. If the efficiency is negative the measurement is kept disabled otherwise it is enabled. The same treatment is applied to the field defects found. Then the process is stopped and the hand is given back to the user. If no problem remains after the second trial, the automatic process is run as a loop.

III. RESULTS

The automatic system was used at the end of 1992 to help the search of defects in coordination with the survey. Almost all large misalignments were found, the detailed report can be found in [3].

However the LEP machine was too much misaligned and this effort did not pay. In particular an important defect consisting of a common misalignment of seven quadrupoles was missed because it did not appear on the measurements done with a 90° optics. The pattern of the misalignment is shown on figure 2. In fact this defect was identified with the 60° optics. It was simply not considered relevant because it disappeared on the 90° optics. This experience was useful as it leads us to the right procedure, i.e. choosing the lowest possible phase advance per cell for the closed orbit analysis with the fitting method.

IV. CONCLUSION

An automatic system to find field defects in a large A.G. machine is available. It allows to locate defects in an orbit made of about 500 measurements in about one hour.

Figure 2: Misalignment missed by the fitting method. This misalignment makes a series of π -bumps if the phase advance per cell is 90° , which is the case for the named quadrupoles.

Using in the analysis of orbits for helping the LEP re-alignment in 1993, made it possible to identify problems related with its use. A positive outcome of this exercise was that the sampling of the orbit in term of betatron phase advance is critical. With one BPM at each D quadrupole, as in LEP, it is necessary to use an optics with a phase advance per cell below 60° in order not to miss defects.

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Automatic and expert systems for orbit analysis

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Abstract

In alternating gradient machines, the analysis of closed orbit or trajectory measurements in terms of betatron oscillations is useful to detect field defects. This has been used for long to help realignment.

In a large machine like LEP it is not practical to launch a survey check without making sure of the existence of the defects. In order to improve the reliability of their detection, it is extremely useful to have a fast system which makes it possible to cross-check several measurements.

For treating a large quantity of information in an empirical way, the use of an expert-system was proposed. In fact the numerical content of accelerator orbit measurements as well as the good knowledge of the modeling of such a machine makes such a system useless. The experience gained on the analysis of closed orbit measurements done at CERN shows that a simple algorithmic process is more efficient to analyze closed orbit measurements.

I. HISTORICAL INTRODUCTION

The search for field defects by fitting closed orbit measurements with betatron oscillations has been used for a long time [1]. The principle is that, in a part of a machine without any field error, the closed orbit is merely a betatron oscillation. As the modeling of these oscillations is well known, it is easy to determine whether a given closed orbit measurement behaves like a betatron oscillation or not by means of the very common technique of the least-squares fits. If the fit residue is large with respect to the expected r.m.s error of the measurements, a defect has been detected.

What is useful for a circular machine is to detect field defects and especially to distinguish them from orbit measurement errors. This last point is very important as it avoids a displacement of persons towards a place without any interest. For this analysis many tests have to be done. As we wanted to make an automatic system to perform those tests for LEP, a first feasibility study was done on the accumulation ring EPA at CERN [2]. It made it possible to determine exactly the location of the main dipole error in this machine.

At this time a Fortran program was written to compute the fits. The test of measurement relevance was done by looking for special patterns on the printout constituted of tables of residues associated with fit done with four to eight or more measurements downstream each Beam Position Monitor (BPM). Then removing the effect of detected field defects and disabling bad measurements was done by editing the input of the Fortran program. Thus the feasibility of the method was shown but the procedure was very much time consuming. Therefore it was decided to launch a further study to make a faster system.

It was felt that the patterns observed by printing tables of fit residues [3, 7] were symbolic quantities and that many rules were applied systematically in the course of the analysis. As we thought that we could do a more efficient analysis by increasing the number of rules, the approach of expert-system was attempted [4]. About half a man-year was spent on this. We obtained a system which was able to analyze the EPA orbit in some minutes whilst it took about some hours to do it with the Fortran program. However when we tried to apply this system to a larger machine like SPS (LEP was not built yet), we observed that it was no longer faster than the old procedure based on the Fortran program : it took some days to do the analysis. This was due to weaknesses in the organization of the system and also to the fact that we were not able to find efficient rules nor to identify a large number of typical patterns in the residue tables.

When LEP was in operation, we decided to launch again the study with a new mind. Drawing lessons from the past, the expert-system approach was dropped. In what follows, we show why this approach was not the right thing to do.

II. WHAT EXPERT-SYSTEMS ARE AND ARE NOT

A general definition of what is an expert-system could be "a system for representing large quantities of knowledge" [5]. More precisely an expert-system is "a computer program that has a lot of knowledge in a specific field and is able to reach human-expert results in that field" [6]. But this definition does not take into account the methodological aspect of expert-systems, which consists of putting apart the knowledge of a specific field on one side (men-