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AUTOMATED BEAM OPTICS CORRECTION FOR EMITTANCE PRESERVATION

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The operation of ever more complex high energy particle accelerators requires a powerful and user friendly architecture of application programs for machine physics. Among the possible applications, those concerning beam optics have been selected and it is shown that all the first order corrections, whether they are related to linear or non-linear fields, can be treated within a unified system. Examples of application are given for various types of beam steering in the PS complex.

Keywords: Emittance preservation; Beam optics

INTRODUCTION

At CERN, the experience developed at the ISR, then for the p–$\bar{p}$ project and for LEP, has demonstrated that the performance and the reliability of a machine are tightly related to the quality of its application programs and, especially for large machines, to the on-line access to a database which contains all relevant parameters. In thirty years, computers and programming languages have dramatically evolved. The architecture described in this paper applies to a machine controlled by workstations using a UNIX operation system. The languages are SQL

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for the database, C for the graphics user interfaces and *Mathematica* functional programming for the algorithms. The modularity of the system allows updating of one part without interference with the other parts. The system has been tested for the bending properties of a machine but the procedure can be extended to the focusing properties as well. All the first order corrections, even if they are related to nonlinear fields, can indeed be achieved using an iterative linear solver and are characterized by a matrix which is pre-stored in a correction file. Applications for various types of beam steering are operational for the PS Booster and the PS Ring.

1 SYSTEM ASPECTS

The kernel of the system is the relational CERN Oracle Accelerator Database already used in production for LEP[1] and simulations for LHC. Data are entered through the object-oriented interface ACCIS,[2] acronym which stands for ACCelerators Information System. A dynamic link with Oracle database[3] allows the control system to retrieve

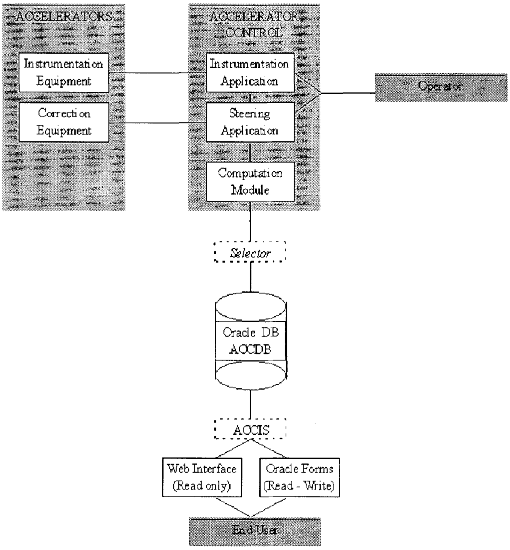


FIGURE 1 Full system software architecture with its present status and planned extensions.

up-to-date data and to run software applications on-line without the use of intermediate files. The description of the elements in the database is illustrated with two end-user modules (Figure 1). One uses a PC-based interface, and the other the World Wide Web.

1.1 Representation of the Accelerators in the Database

The tree-structured organization of the machines of the CERN PS complex is displayed in Figure 2 and the names of the corresponding classes in the database are in italic. Each physical element (dipole, quadrupole, ...) is the instance of a class called *Element* in the database. The element itself is divided into seven sub-classes whose most important ones for beam optics are *in situ properties* which gathers the

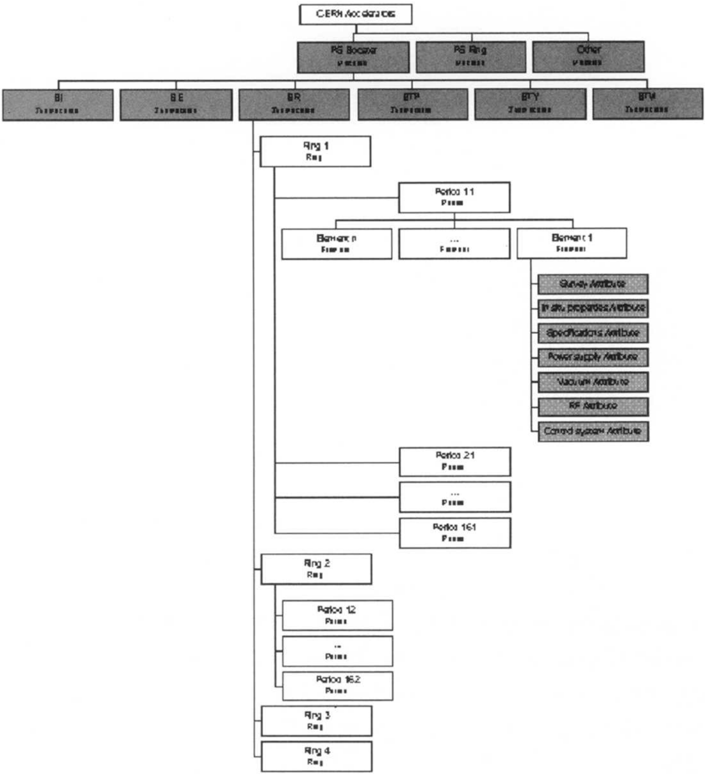


FIGURE 2 Hierarchical structure of the PS database.

attributes dependent on the context and *Survey* which contains the information of absolute position and orientation of the element in the machine.

1.2 Control Procedures

All the data stored in Accelerator Database is used for off-line homogenous documentation and also to feed on-line control applications. The modules already running in the control room are the Instrumentation, Steering and Computation applications. The last module is a *Mathematica* based software, whereas the others are written in C in the X-Window/Motif environment.

A link has been developed to connect the computation module with the database using the *MathLink* functions of *Mathematica*. It plays the role of a selector which retrieves the data pertinent to a given application like beam optics. The link is activated from within *Mathematica* using an *Install* statement:

```
Install["dblink"]
```

which sets the communication with the file *dblink*. The *Selector* function can then be called

```
Selector["Booster","BTY","ISOGPS"]
```

Its arguments are the names of the machine, sub-machine and sub-sub-machine to be studied as they appear in the database hierarchical tree. The output is a table similar to a spread-sheet.

```
{{BTY.BVT101,Bend,1.09482,0.2,0,0,0,0.1,0.1,0},

  .}}
```

Each row is attached to an element and the elements come in the order they are met by the beam along the machine. In the ten columns are stored the name, the type, the length, the deflection angle, the focusing strength, the first and second radial derivative of the focusing strength, the angles of the upstream and downstream end faces with the reference orbit and the tilt of the element. It has to be noted that the database contains the physical elements only, the drift spaces are produced by the selector.

Once optics data is available, an optical model of the machine is produced with the program *BeamOptics* and a correction matrix specific to a machine and to a type of correction is generated and eventually called by the correction program.

All the above manipulations are disconnected from the real time correction procedure. The actual correction is controlled from the operator's console using an application program which has the same "look and feel" for various corrections and machines. It receives input from the measurement devices, invokes the correction program and sends current settings to power supplies after validation by the operator.

2 UNIFIED TREATMENT OF FIRST ORDER CORRECTIONS

All the corrections performed in accelerators or storage rings, whether they are related to linear or non-linear fields are amenable to a first order perturbation theory of the beam emittance. The essential property of a first order perturbation lies in the additive effects of the fields and thus all the computing techniques of linear algebra can be applied.

2.1 Emittance Perturbation

In the theory of betatron oscillations, the emittance is commonly interpreted as the area of the phase space which encompasses a given proportion of all the particles but it can also be considered as a measure of the maximum amplitude of the betatron oscillation. It is convenient to normalize each particle position to the square root of the local β-function and to use the square root of the emittance and the betatron phase advance μ as polar coordinates. The normalized position q and its derivative $\dot{q}$ with respect to μ are then

$$q = \sqrt{\varepsilon}\cos(\mu - \mu_0), \qquad \dot{q} = \sqrt{\varepsilon}\sin(\mu - \mu_0).$$

The field error

$$F(q) = (a_n + ib_n)\frac{\left(\sqrt{\beta_x}q_x + i\sqrt{\beta_y}q_y\right)^{n-1}}{n!}$$

produces a change of $\dot{q}$

$$\Delta\dot{q} = \sqrt{\beta}F(q)\,\Delta l.$$

The upright and skew components are a_n and b_n, respectively. The vertical and horizontal components of the field are given by the real and imaginary parts of $F(q)$. The index n is equal to 1 for a dipole, 2 for a quadrupole, etc.

The emittance and phase perturbations are inferred from elementary geometry in the triangle ABC of Figure 3:

$$\Delta\varepsilon = 2\dot{q}\,\Delta\dot{q}, \qquad \Delta\mu = \frac{q\,\Delta\dot{q}}{\varepsilon}.$$

Yet very simple, those expressions become rather complicated when the various substitutions transform them into explicit functions of ε_x, ε_y, β_x, β_y, μ_x, μ_y, μ_{0x}, μ_{0y} and it is better, in the general case, to leave this task to a symbolic program like *Mathematica*. The important point is to interpret the growth of emittance.

A dipole error (Figure 4) affects all the particles in the same way and the change of radius r is equivalent to a change of position of the center of gravity measured by a pick-up electrode and given in the horizontal plane by

$$\Delta x_i = \sqrt{\beta_i\beta_j}\,\sin(\mu_i - \mu_j)\,\Delta\phi_j$$

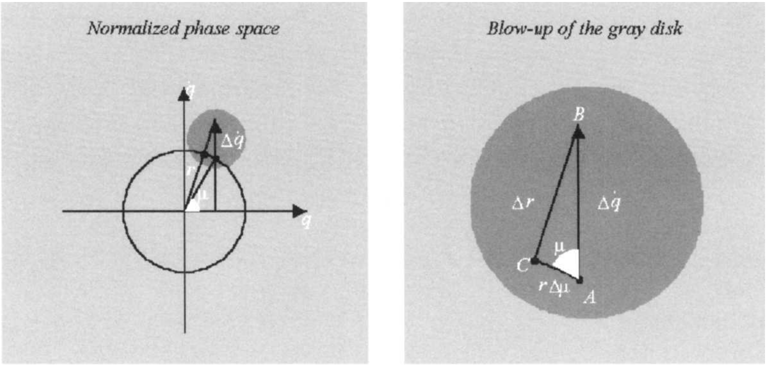


FIGURE 3 Normalized phase space ($r = \sqrt{\varepsilon}$, $\mu_0 = 0$).

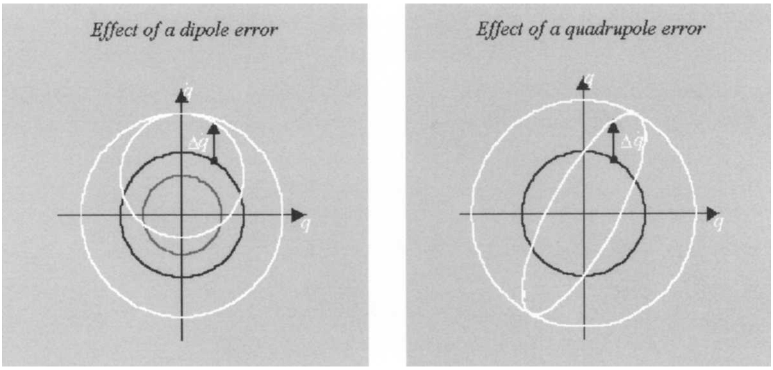


FIGURE 4 Transformation of the phase space due to a dipole or a quadrupole error.

for an extra deflection $\Delta\phi_j$. The indices i and j are referred to the observation and perturbation, respectively. The same formalism applies to the vertical plane.

A quadrupole error increases the betatron amplitude proportionally to the unperturbed amplitude. When a beam is transferred from one machine to the next, the Twiss parameters at the end of the transfer line may not coincide with the Twiss parameters of the receiving machine. There is then a mismatch which can be deduced from the measurement of the beam profile on three monitors and characterized by a mismatch vector[5]

$$V = \begin{pmatrix} \Delta\beta/\beta \\ \alpha(\Delta\beta/\beta) - \Delta\alpha \end{pmatrix}.$$

The relative variation of the β-function is the same as the relative variation of ε and the second component of V is just half the derivative of the first one with respect to μ:

$$\frac{\Delta\beta_i}{\beta_i} = \beta_j \sin 2(\mu_i - \mu_j)(\Delta Kl)_j.$$

The correction is performed with two quadrupoles per plane in the transfer line. The present system deals only with these types of error but many others such as tunes, chromaticity, dispersion mismatch can be treated in a similar way and will be implemented in the future. The analytical expressions have been given for a single passage of the particles, they can be extended to circular machines by considering n turns as the passage through n identical transfer lines, the phase advance increasing by $2\pi Q$ at each turn, the perturbation appears then as the sum of a series which can always be summed in a close form.

2.2 Correction Algorithm

Within the context of first order perturbations, a correction is characterized by some matrix A which contains as many columns as possible correctors. Each term of a column is the component of the error vector produced by a unit excitation of the corrector, all the other correctors being set to zero. The measured errors are collected in a vector b. The unknown corrections are the components of a vector x and are calculated so that the norm of the residual vector

$$r = Ax + b$$

is minimized using an iterative procedure (*Micado*).[5,6]

1. The correction magnet which yields the lowest residual r.m.s. distortion at monitor positions is first selected.
2. Then, the residual distortion is re-analyzed and the next best magnet selected yet keeping all the previously selected correctors but re-calculating their strengths.
3. The method proceeds until the residual r.m.s. distortion is comparable with measurement errors.

This technique, yet familiar for orbit correction, has actually been rarely applied to other types of corrections until now.

3 STEERING APPLICATIONS IN THE PS COMPLEX

Automating a process not only alleviates the operation tasks but represents a very severe test for the correctness of the measurement–calculation–correction chain and thus contributes to the reliability of the machine. In the various applications to the PS control, the problems which were encountered and their solutions will be reviewed.

3.1 Linac Line

In the transfer between linac and booster, the steering had to be often corrected because of changes originating from drifts in bending magnet power supplies, energy variations of the beam or the stray fields of the nearby PS. The Linac beam is continuous but can be considered as composed of four parts that are chopped into four batches injected into the four rings of the booster.[7] At the energy of 50 MeV, the beam is subject to strong space charge forces and the optics is traditionally calculated to ensure a good transmission of the beam envelope. However, the beam steering concerns the center of gravity which is not subject to the space charge and the optics is satisfactory when both the envelope and the motion of the center of gravity are under control. Taking these two constraints into account has considerably improved the stability of the beam (Figure 5). If the quadrupole strengths vary with the beam intensity, several matrices are then prepared to cope with the different regimes.

3.2 Transfer between Booster and PS

The ejection and recombination of the four booster beams is a complex procedure[8] (Figure 6) which has motivated the need of an

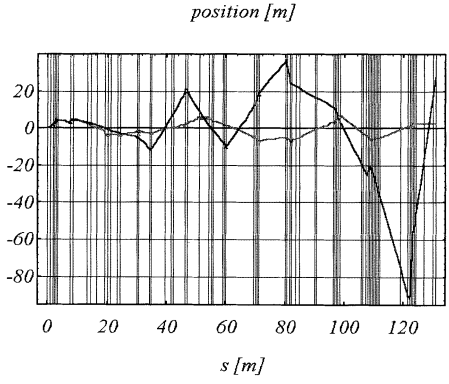


FIGURE 5 Horizontal trajectory in the linac line with the old (darker trace) and new (lighter trace) optics.

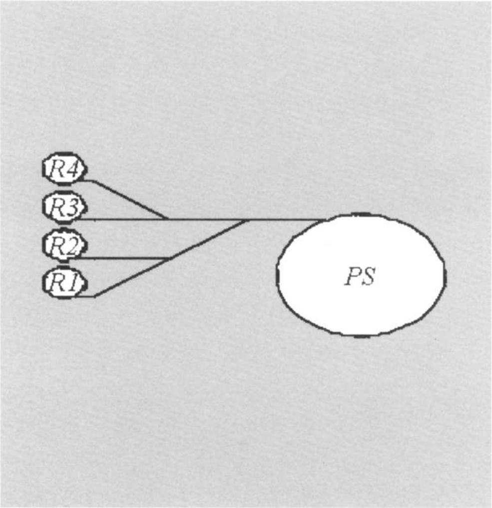


FIGURE 6 Schematic recombination of the four booster rings.

automated steering system.[9] The aim is to align the four booster beams as close to each other as possible at the entrance of the PS ring so that the common correction of coherent oscillations in the PS produces an emittance blow-up compatible with the tight tolerance imposed by the LHC beam.

Each of the four booster beam trajectories has to be individually steered by using two closed orbit correctors in the ring and one corrector in the ejection line for each plane. A first complication arises: the correction matrix is hybrid and contains both closed orbit and transfer line coefficients.

Then there is a common part where all four rings are affected by common correctors. The steering matrices have thus coupling coefficients which take the action of a same corrector on different beams into consideration and the optimization procedure works on the four beams globally. Once the general correction method is assessed, the iterative process converges only when it is realized that the pick-up misalignments with respect to the magnetic axis of the quadrupoles have to be corrected. This correct alignment is further complicated by the presence of quadrupoles common to pairs of rings 3–4 and 1–2. In those quadrupoles, the reference trajectories are indeed off-axis.

All that considerations concern the beam steering, similar problems concern the beam focusing and are evoked in Jansson and Lindroos' paper.

Last, it can be noted that the "switch-yard" configuration of the booster-PS transfer is very common in experimental areas and that the present development would find a natural application in delivering beams to fixed target physics experiments.

3.3 Betatron Coherent Oscillations in the PS

The coherent oscillations of protons or electrons at injection are corrected using two successive turns measured shortly after injection. There are 40 pick-up stations in the PS ring. The correction requires two correction magnets per plane. The trajectories are measured on all the pick-ups of the ring. The contribution of the closed orbit to the particle position is eliminated by taking the difference between the two turns. The result takes then the form of a betatron oscillation after division by $2\pi Q$.[9] Knowing the theoretical tune is usually sufficient to reduce the oscillation. The method has however been generalized to automatically deduce the tune from the trajectory measurements and further improve the quality of the correction (Figure 7).

3.4 Closed Orbit Correction

Corrections of closed orbits are needed to increase the machine aperture and thus diminish beam losses. The observation system used for the coherent oscillations is resumed for the closed orbit. The horizontal and vertical closed orbits are corrected using a few magnets, less than the betatron tune, chosen among 50 horizontal and 20 vertical correctors (Figure 8).

3.5 Trajectory Correction and Beam Profile Measurements

The beam trajectory has also to be corrected to take advantage of the full range of the secondary emission monitors which measure the beam profiles. In TT2, the transfer line which connects the PS to the SPS, the monitors have the high resolution (0.35/0.5 mm wire step sizes)

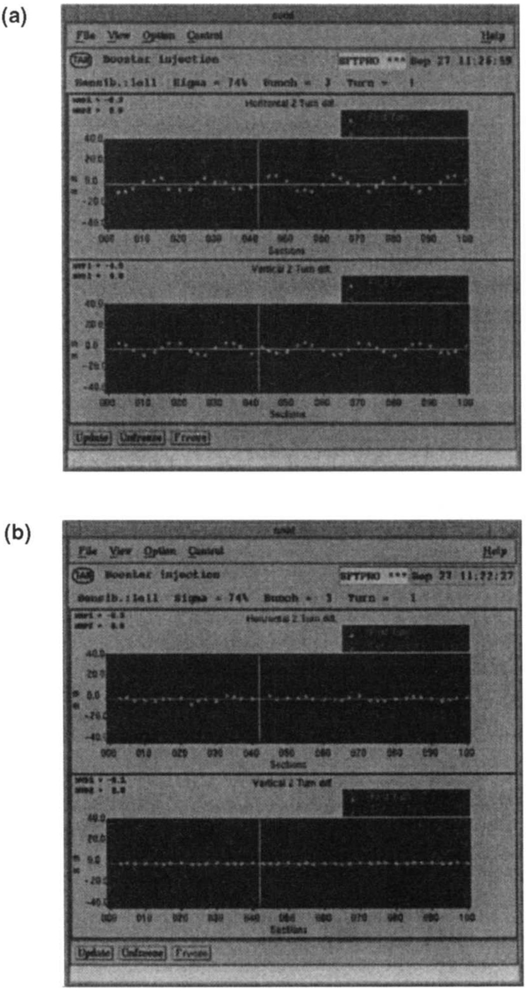
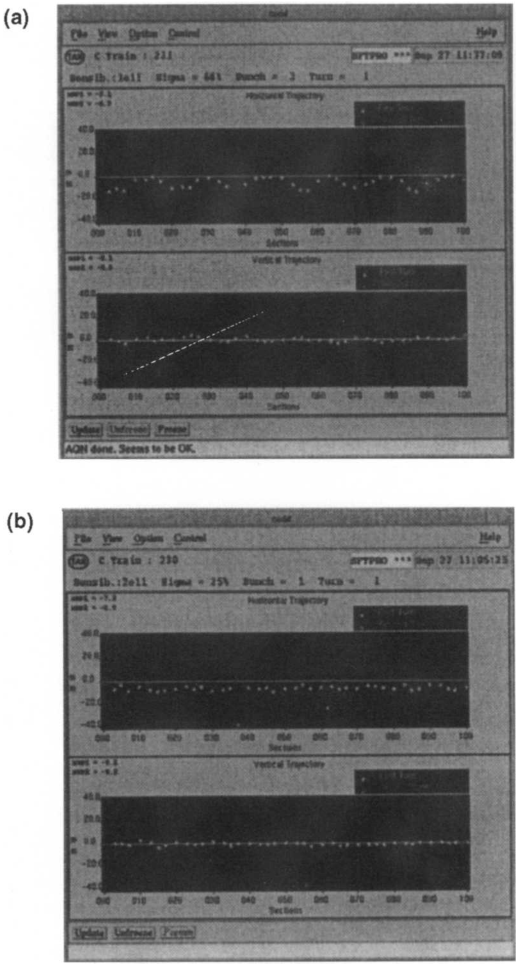


FIGURE 7 Pick-up signals before (left) and after (right) PS coherent oscillation corrections.

required by the brightness of LHC beams. The beam emittance is measured with the technique of the three monitors[10] and the position signal is the center of the beam distribution. Centering the beam on the three monitors is the simplest of the problems which have been dealt with (Figure 9). Historically, it was the first test of the general correction system[11] and it revealed alignment and polarity errors.



AQN done. Seems to be OK.

FIGURE 8 Pick-up signals before (left) and after (right) PS closed orbit corrections.

CONCLUSION

A general correction system of any first order perturbation of the reference magnetic field has been described. The initial investment and the maintenance cost of commercial products (Oracle and *Mathematica*) being accepted, the software development is free, the modularity avoids redundancy and correction algorithms written by

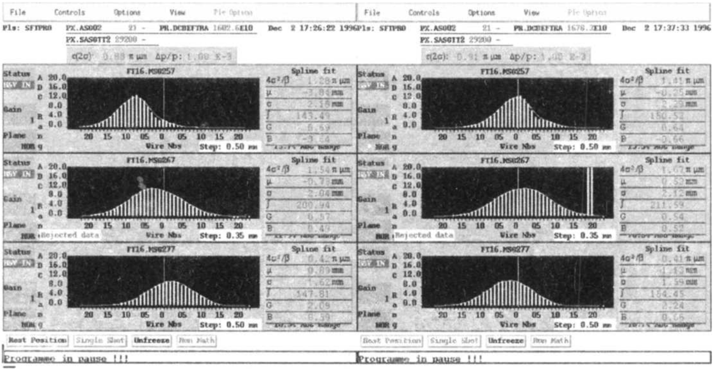


FIGURE 9 SEM-grid signals before (left) and after (right) centering.

machine physicists can be plugged into the system without re-coding by control experts. The system has been applied to the CERN PS complex with the production of bright beams for LHC in mind. The next developments will concern its portability so that it can be implemented in any machine on request.

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