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Simultaneous orbit correction of two separate LHC beams sharing common elements

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Abstract

In the LHC the two beams share common elements near the crossing points of the machine. Since the two counter-rotating beams have the same sign of the charge, a magnet has a different effect on the two beams, which must be taken into account during the design process. This is also the case for orbit distortions originating from these common parts, e.g. misaligned common quadrupoles, and the orbit correctors in these areas. Any orbit corrector has a different effect on the two beams and cannot be used in a correction algorithm for a single beam only since it may have unwanted effects on the other beam. The existing closed orbit correction program COCU for SPS and LEP was modified to allow the simultaneous correction of both LHC beams, using the common correction dipoles as a single correction element but with a different response to the two beams.

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1 Introduction and formulation of the problem

The correction of the closed orbit in a circular accelerator is an essential ingredient for a successful operation. During the design stage, the consequences of linear and non-linear imperfections on beam dynamics are studied in calculations and an orbit correction is needed to correct for first order distortions. Many tools have been developpped to correct the closed orbit online for operation or offline for simulation purpose (see e.g. [1, 2]). However the closed orbit of the LHC exhibits some subtleties when examined closer [3, 4, 5]. Most of these are related to the area where the two beams share a common beam pipe. Unlike previous colliders such as the S$p\bar{p}$S and LEP, the two beams in the LHC are of the same type and therefore the two counterrotating beams cannot have the same orbit and need separate vacuum chambers for most of the circumference. In the region of the interaction points the two beams must share a common vacuum chamber and therefore have active and passive machine elements such as monitors, quadrupoles and dipole magnets in common. To avoid unwanted interactions, finite crossing angles are used to separate the beams [6, 7], producing large orbit deviations on the two beams and requiring a fine tuning of the beam orbits separately for the two beams. An imperfection, such as a misalignment of a common quadrupole will produce a closed orbit deviation on both beams simultaneously, but with a different effect since the optics functions of the two beams are not equal in the common region[3]. Generally one tries to correct orbit distortions as close as possible to their origin and correction dipoles are foreseen in these areas. However, the magnetic field of a common correction dipole will also act on both beams and in a different way. Therefore one has to correct the two beams simultaneously using a unique correction field in the common dipoles. Alternatively one could compute the correction for one ring only and apply it to both rings, hoping that this would improve both orbits. It also remains to be studied whether the simultaneous correction is efficient when the correcting dipole is not close to the disturbing element, since the optics functions of the two beams can be very different and do not allow a good correction when the distance becomes large. Present orbit correction programs [1] do not yet allow such a simultaneous correction with common elements. For most offline studies a primitive implementation of standard algorithms is sufficient [8, 9]. However, it may be desirable to extend these to the above mentioned functionality, although the first optimistic attempts have failed. We foresee such an extension to the MAD program [10] in the future. We have decided to modify the standard SPS and LEP orbit correction program COCU [1] to prove the feasibility of this simultaneous correction and to allow some necessary studies with the idea to provide an efficient code for orbit correction at an early stage. However, care must be taken to avoid performance degradation or interference with the already available functionality. In the following we shall formulate the problem and show a straightforward implementation together with a number of tests to verify the results and to draw a few conclusions on the feasibility of the approach. Some implementation details are discussed in the appendix.

2 Strategy

The general problem is usually to find a solution or an approximate solution minimizing an appropriate norm (e.g. least squares or l_1), of the equation:

$$\vec{m} - \vec{t} = \mathbf{A} \cdot \vec{c} \tag{1}$$

where

$$\vec{m} = (monitors\ ring\ 1, monitors\ ring\ 2) \tag{2}$$

contains the measured beam positions of ring 1 and ring 2 (here concatenated into one vector), $\vec{c}$ is the list of unknown correction strengths, expressed as deflection angles and $\mathbf{A}$ is the corresponding response matrix. The vector $\vec{t}$ contains the target orbits for both rings. In the LHC each ring has 504 beam position monitors and the vector $\vec{m}$ has 1008 elements. Although some beam position monitors may be physically common to both beams, they are logically separated because they measure the beam position of the two beams independently, e.g. with directional couplers, and are therefore not distinguished from monitors unique to one beam. Three types of correctors can be distinguished: correctors acting only on the beams in ring 1 or ring 2 which are mounted such that they do not affect the other beam. In each ring we have 246 correctors per plane. A third type of corrector is installed in the areas where the beams share a common beam pipe and therefore acts on both beams. In the LHC, 24 correctors are of this type. In the calculation this has to be taken into account, ensuring that the response of the beam to an excitation of such a magnet is correct for each of the two beams. For the computation we can write the vector $\vec{c}$ as:

$$\vec{c} = (correctors\ ring\ 1, common\ correctors, correctors\ ring\ 2) \tag{3}$$

with a length of 516 elements. Some kind of identification is needed whether a corrector acts on beam 1, beam 2 or both beams. In the LHC element database this distinction is accomplished by the element name, ending with '.B1', '.B2' or without a beam index [11]. We have therefore used this for our purpose although any other mechanism which uniquely relates the elements to one or both beams can be used. This identification process is implemented as a separate and exchangeable module in the program. Although conceptually simple, it requires a careful book-keeping during the whole correction process.

The standard response matrix has to be modified accordingly:

$$\mathbf{A} = \begin{pmatrix} \left[\ response\ to\ ring\ 1\ correctors\ \right] & \left[\ 0\ \right] \\ \left[\ response\ to\ common\ correctors\ \right] & \left[\ response\ to\ common\ correctors\ \right] \\ \left[\ 0\ \right] & \left[\ response\ to\ ring\ 2\ correctors\ \right] \end{pmatrix} \tag{4}$$

The two block columns in $\mathbf{A}$ represent each the complete set (504) of beam position monitors in ring 1 and ring 2 respectively. Common monitors appear twice for the above mentioned reason. The three visible rows represent the set of correctors acting on ring 1, the common correctors acting on both beams and finally the correctors acting on ring 2. The order is arbitrary. The response of ring 1 correctors on beam 2 is identical to zero and similarly for ring 2 correctors. The common correctors have a finite response to both beams, depending on the optics which is different for the two beams. In a standard single beam orbit correction, only the upper left or lower right sub-matrices would be used. In total, the response matrix $\mathbf{A}$ has the dimension 1008 x 516. The response matrix can either be computed from the theoretical optics parameters or measured from the beam response to known excitations. However, for a machine like the LHC more than 1 million elements are needed for each optics (two planes !) which would make that rather impractical. Once this equation or the corresponding least squares minimization is solved, the application of $-\vec{c}$ to the appropriate correction magnets minimizes the closed orbit distortions. It should be mentioned here, that a boundary condition of that formulation is that the deflection angle of a common corrector has the **same** value for both beams, in particular it must have the same sign since it is treated as a single correction element. This may not be consistent with preferred conventions, in which case it can be treated with a few intelligent sign adjustments in the procedure. Furthermore, if a common corrector is disabled for one beam, it must automatically be disabled for the other beam too.

To solve the above problem, we have first applied the most commonly used algorithm in the SPS and LEP which is also available in MAD, although only for single beams. This is a best kick algorithm usually known as MICADO [12] which is already implemented in COCU [2]. Such an algorithm should give excellent results when the closed orbit distortions are due to a few localized misalignments, which are usually exactly identified and corrected. This allows a careful testing of the procedure. Furthermore, it does not require neither the correctors nor the beam position monitors to appear in any special order. In the second part we apply other important algorithms, such as short length corrections and global least squares minimization for the two beams. It should be clear that these techniques are also applicable for colliders with asymmetric rings, e.g. with different beam energy.

3 Tests and first conclusions

A set of tests must be performed to verify the correct functioning of the procedure, in particular since the final results cannot be directly confronted with other programs. For the tests we have used the LHC injection optics version 6.1 with necessary additions manually included. The distorted orbits and target orbits for both beams were computed with a recently modified version of MAD8 [10].

3.1 Verification of the beam response

The correct setting up of the response matrix can easily be checked using the simulate mode of the program [2]. In this mode the resulting orbit of a specified corrector strength is calculated using the same response matrix as set up for the correction algorithms. This simple test can be checked with MAD for the two beams separately while COCU should produce the correct result for both beams simultaneously. Such tests were made for correctors only acting on a single beam and for correctors in the common part, and proved the correctness of the setup of the matrix, provided the sign of the deflection is treated correctly, as mentioned above.

3.2 Common quadrupole misaligned

The purpose of the correction is to identify and correct the orbit distortions, mainly from misaligned quadrupoles. Therefore we have simulated such a displacement with MAD for the two rings separately and stored the results in vector $\vec{m}$ of equation (1).

3.2.1 A corrector close to the misaligned quadrupole is available

A quadrupole in the final focussing triplet, i.e. in the common part, was misaligned by 1 mm in the horizontal plane (MQXA.1R5). The resulting distorted orbits were calculated in separate MAD simulations, producing orbits for beam 1 and beam 2. In the first correction step with COCU we have computed the correction for ring 1 only, i.e. ignoring the contribution from ring 2 to the overall distortion. Only the most efficient corrector was used that should be the one next to the displaced quadrupole, i.e. a shared orbit corrector. The correction found was therefore applied to both rings simultaneously. The result is shown in Fig.1 and in Tab.1. The Fig.1 shows the orbits of ring 1 and ring 2 before and after correction. The beam position is shown in mm against the sequence number of the beam position monitor. Red and blue colour is used to distinguish the two

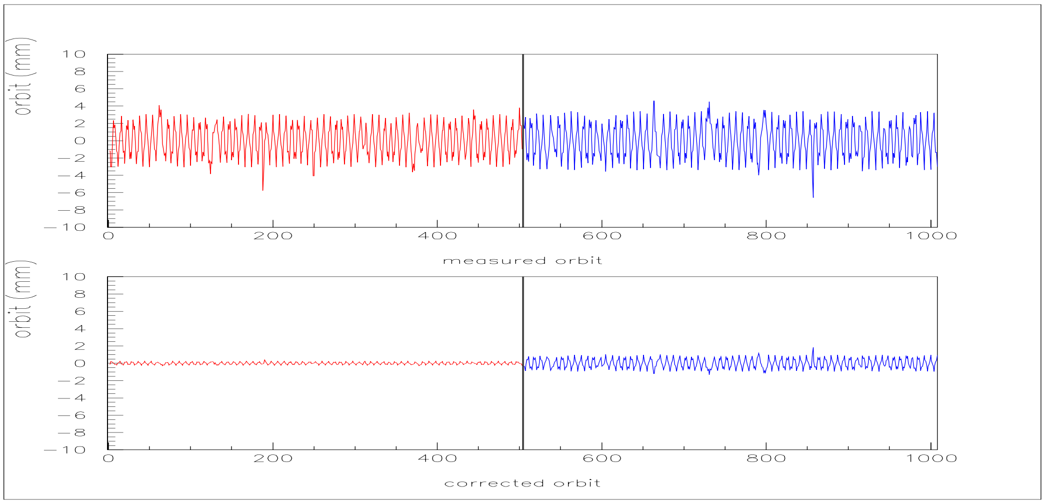

Figure 1: Orbit of ring 1 (red, left half) and ring 2 (blue, right half) before and after correction of ring 1.

rings, therefore in the right half of the plot (blue, ring 2) the correction is less efficient since only the r.m.s. of ring 1 was minimized. A similar correction was done for ring 2 only. In both cases the orbit could be corrected rather well, using a corrector very close to the misaligned magnet. The result of this second correction is shown in Fig.2 and Tab.1. The more interesting test was a correction of both beams simultaneously, i.e. trying to

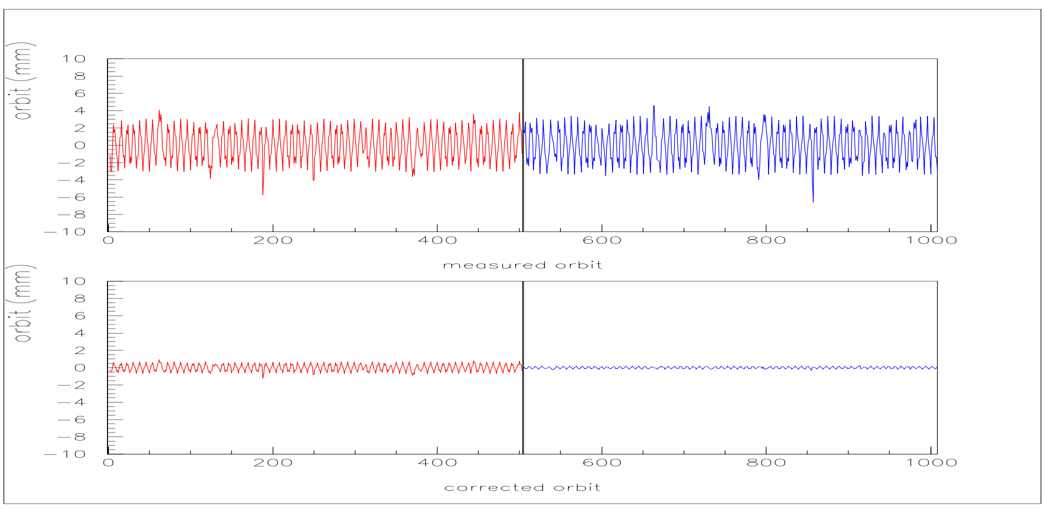

Figure 2: Orbit of ring 1 (red, left half) and ring 2 (blue, right half) before and after correction of ring 2.

minimize the r.m.s. of both beams together. This is shown in Fig.3 and Tab.1. The result is a smaller peak to peak and r.m.s. orbit than for individual correction, proving that this method is indeed superior to the simplified correction procedure.

3.2.2 A corrector close to the misaligned quadrupole is not available

In the previous case a quadrupole was selected where an orbit corrector was available next to it, i.e. the optics parameters are approximately the same for the corrector and the

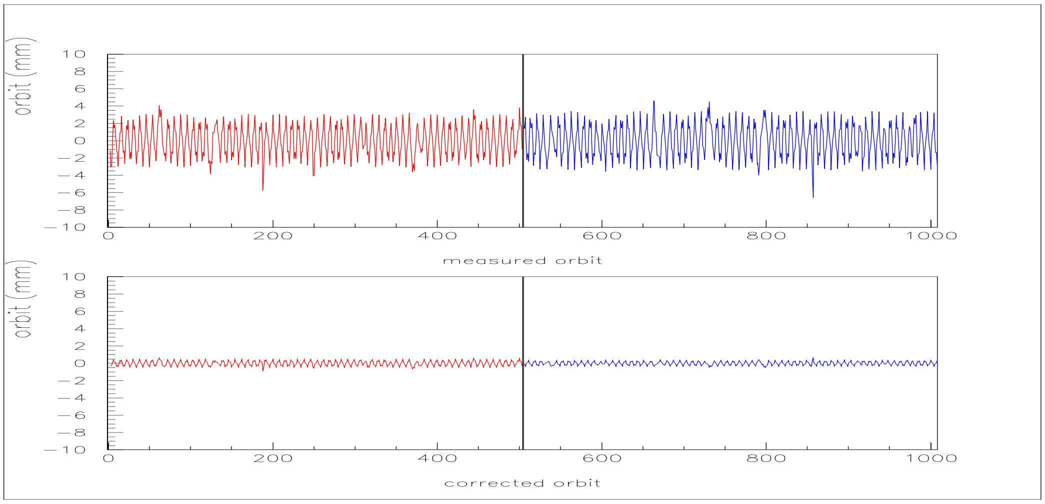

Figure 3: Orbit of ring 1 (red, left half) and ring 2 (blue, right half) before and after simultaneous correction of both rings.

Correction	Corrector	Strength [mrad]	peak-to-peak [mm]	r.m.s. [mm]
None	-	-	11.18	1.90
Ring 1	MCBX.1R5	-0.053	3.15	0.39
Ring 2	MCBX.1R5	-0.042	2.20	0.30
Ring 1+2	MCBX.1R5	-0.045	1.50	0.22

Table 1: *Horizontal misalignment by 1 mm of MQXA.1R5: correction results, individual and simultaneous correction. The last two columns refer always to the orbit of both LHC rings.*

quadrupole, and that is true for both beams. When a quadrupole is selected where no close corrector is available one has to expect that the simultaneous correction becomes more difficult since in this case the optics parameters at the selected corrector(s) have already diverged for the two beams and the solution is less efficient. This was tried in the next test where another quadrupole was misaligned (MQXA.3R5) and no corrector was made available in its immediate neighbourhood, i.e. the correctors MCBX.2R5 and MCBX.3R5 were disabled. The results of the tests are shown in Tab.2. The first observation was that in all cases two correctors were needed to make a good correction, even when only one beam was corrected. The results obtained with a simultaneous correction are much less satisfying than in the previous case, clearly demonstrating the importance of local correction possibilities, in particular in the area where the two beams share elements. The effect of a distant corrector on the two beams is so different from the original distortion, that a good solution cannot be found. It was shown in more tests, that the quality of the simultaneous correction degrades quickly when the distance of the distortion to the

Correction	Correctors	Strength [mrad]	peak-to-peak [mm]	r.m.s. [mm]
None	-	-	14.12	2.75
Ring 1	MCBX.1R5 MCBX.1L5	-0.063 0.024	6.69	0.82
Ring 2	MCBX.1R5 MCBX.1L5	-0.043 0.012	5.17	0.75
Ring 1+2	MCBX.1R5 MCBX.1L5	-0.047 0.022	3.39	0.51
Ring 1+2	MCBX.3R5	-0.051	0.89	0.14

Table 2: *Horizontal misalignment by 1 mm of MQXA.3R5: correction results, individual and simultaneous correction.*

next corrector increases, not a surprising result. The correction with the close corrector (MCBX.3R5) immediately produced a very good result (Tab.2). It is therefore extremely important to have correctors at all quadrupoles that are common to both beams, as foreseen in the present layout.

3.3 Separate quadrupoles misaligned

A further test to verify the correct functioning was to misalign quadrupoles in the separated part of the rings, e.g. in the arcs. The quadrupoles MQ.20R6.B1 (ring 1) and MQ.33L1.B2 (ring 2) were misaligned by 1 mm each, producing an orbit with 9.7 mm peak-to-peak distortion and r.m.s. of 1.8 mm. The algorithm found correctly the corresponding correctors MCBH.20R6.B1 and MCBH.33L1.B2 with a deflection of -0.028 mrad for both correctors, resulting in 0.05 mm peak-to-peak orbit and r.m.s. of 0.01 mm. This is shown in Fig.4.

3.4 Mixture of separate and common quadrupoles misaligned

The Fig.5 shows the simulated and corrected orbits when quadrupoles in the common part were misaligned together with a random misalignment on all quadrupoles (r.m.s. was 40 μm) for ring 2, i.e. all orbit distortions in ring 1 come from the shared quadrupoles while the distortions in ring 2 come from both, shared and ring 2 quadrupoles. The correction program was run, allowing up to 200 correctors used without a preselection of correctors. The misaligned shared quadrupoles were all found correctly and almost all remaining correctors were chosen from the corrector set for ring 2 only. A few correctors for ring 1 only were selected, however with a very small correction strength (≤ 1 μrad) and mostly in the neighbourhood of the common area to help the correction with the shared correctors.

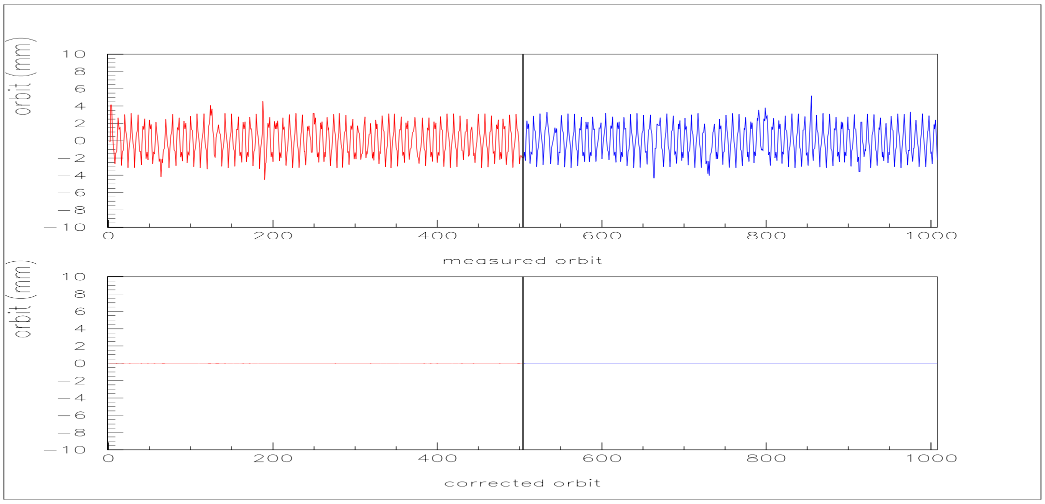

Figure 4: Orbit of ring 1 (red, left half) and ring 2 (blue, right half) before and after simultaneous correction of both rings. Misalignments on quadrupoles in separated rings.

3.5 Correction to a target orbit

Another rather demanding test is the correction towards a target orbit. The nominal target orbit of the LHC is not flat, but requires crossing angles and separation bumps in the crossing points and experiments [6, 7]. A possible test is therefore to define a flat target orbit with crossing angle bumps added. We have used an orbit generated similar to the one in Fig.5 but with different random misalignments. As the target orbit we have generated the orbits of the required crossing angle and separation bumps in IP5, i.e. a horizontal crossing angle of $\pm$ 160 μrad in the horizontal plane and a parallel separation bump of $\pm$ 2.5 mm in the vertical plane [6]. The results of the corrections are shown in Figs.6 and 7 and the desired bumps for the crossing angle and separation bumps are exactly reproduced with the correct strengths in the correctors. This is very satisfying since in the design of these bumps already a mixture between common and separate correctors was used [6, 7] which was correctly found. Furthermore, to make the test more significant, one of the common quadrupoles near this common corrector used for the bump was also moved, and the appropriate correction was found.

4 Other minimization algorithms

All tests so far were made using the MICADO algorithm, which is most commonly used in the SPS and LEP. However, it is only one out of about 20 possible correction algorithms available in COCU [2] that can be used alone or in combination. We have therefore implemented the two beam correction also in some of the other algorithms that are useful for colliders of the size of the LHC with a preference to those regularly used in LEP.

4.1 Short length corrections

A very important type of corrections frequently used in operation is a "short length correction", i.e. a local correction over a specified length of the machine, leaving the rest of the machine unchanged. This requires a closure of the applied corrections [2]. In the particular case of two beams with common elements, a local correction must not propagate into the other beam. If the algorithms are correctly applied, only local correctors acting on

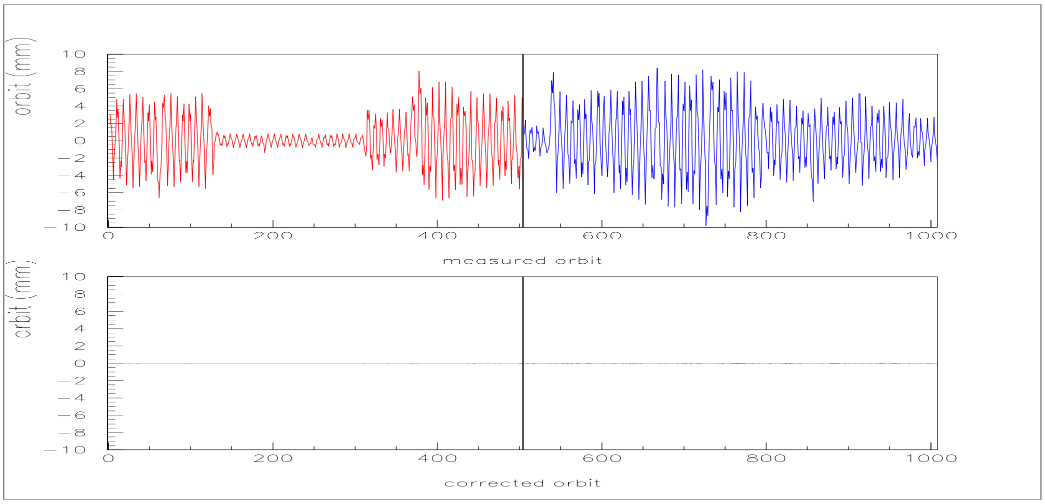

Figure 5: Orbit of ring 1 (red, left half) and ring 2 (blue, right half) before and after simultaneous correction of both rings. Misalignments on quadrupoles in ring 2 and common quadrupoles.

one beam should be found. This was tried and the results are shown for a local correction in ring 1 (Fig.8) and in ring 2 (Fig.9), respectively. In these tests the mode SHORTLE [2] was used for the correction which is a best kick method similar to MICADO, but modified for the purpose of local corrections. Another local correction method heavily used in LEP is the mode GRAPE, which is based on a gradient projection method which is a steepest descent method and finds the minimum of a function under linear constraints. The closure of the local correction is imposed as such a linear constraint. For details see [2]. The results of this method applied to ring 1 and ring 2 are shown in Figs.10 and 11.

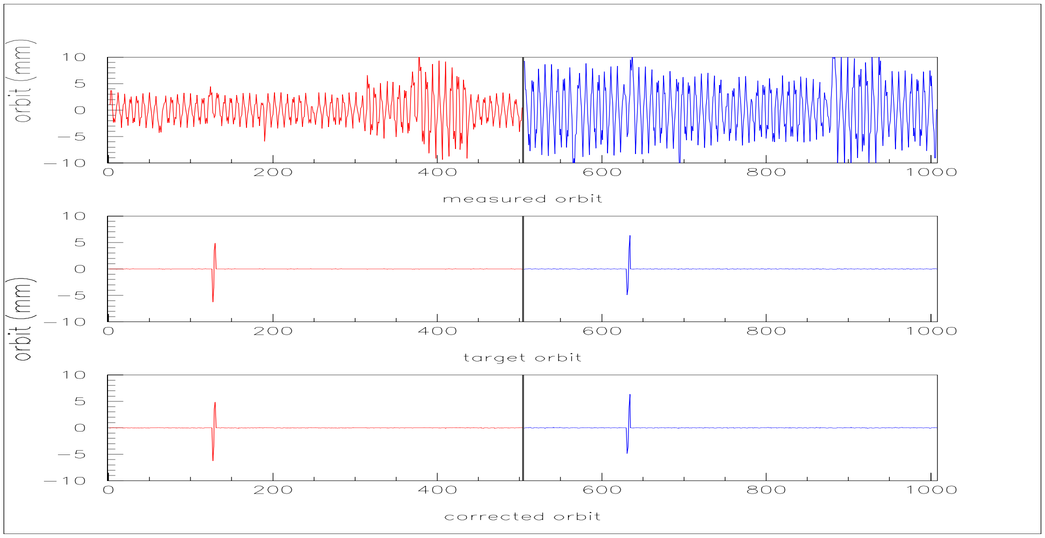

Figure 6: Horizontal orbit of ring 1 (red, left half) and ring 2 (blue, right half) after simultaneous correction to a target orbit. Target orbit is ideal orbit with crossing angle bumps in IP5.

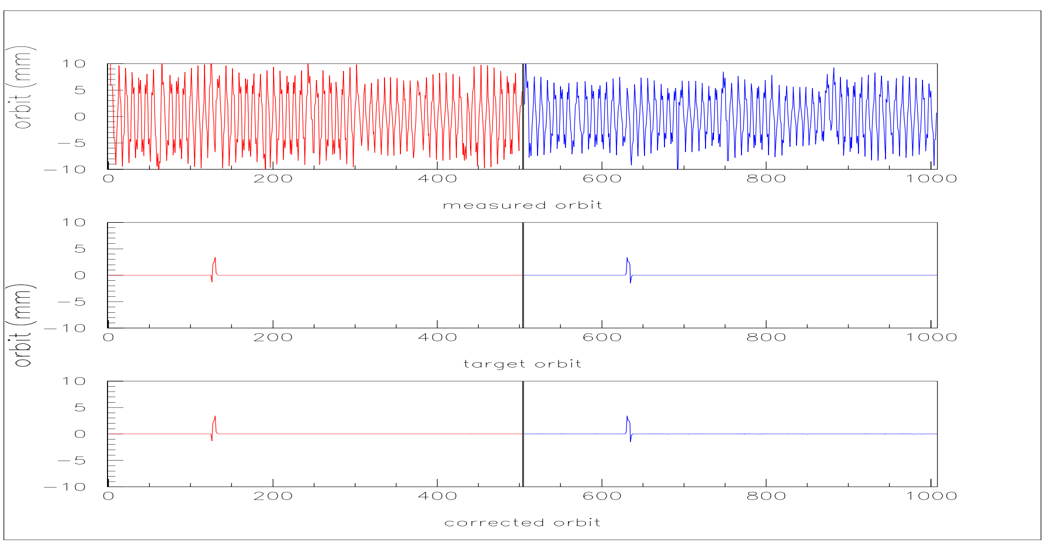

Figure 7: Vertical orbit of ring 1 (red, left half) and ring 2 (blue, right half) after simultaneous correction to a target orbit. Target orbit is ideal orbit with separation bump in IP5.

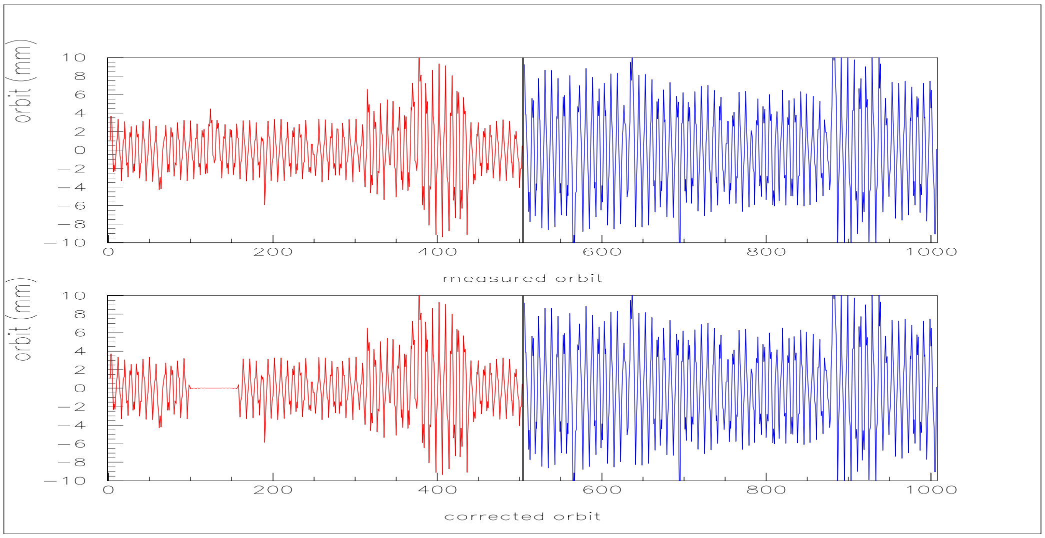

Figure 8: Vertical orbit of ring 1 (red, left half) and ring 2 (blue, right half) after simultaneous correction of a short length region in ring 1. Correction was done with the COCU short-length algorithm SHORTLE [2].

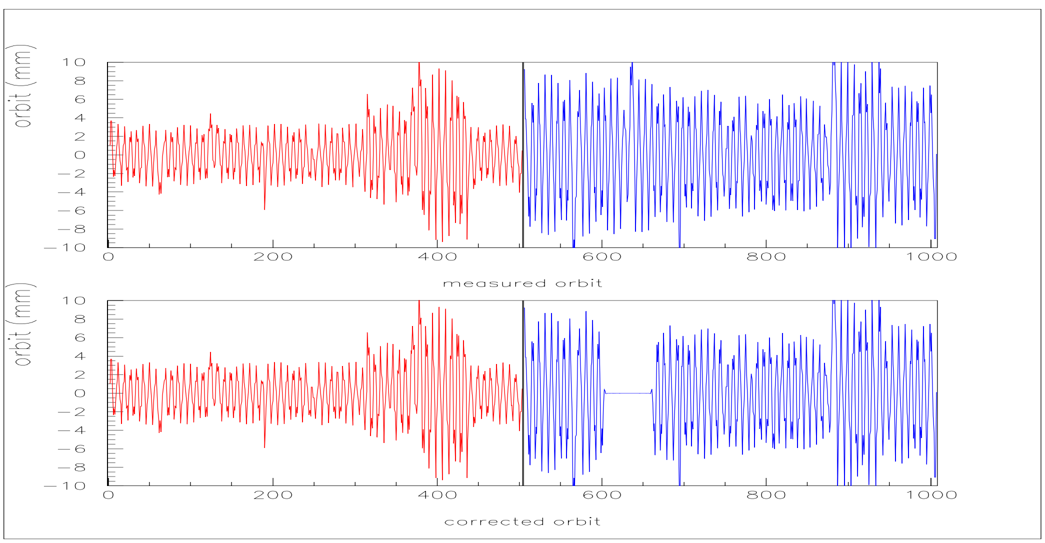

Figure 9: Vertical orbit of ring 1 (red, left half) and ring 2 (blue, right half) after simultaneous correction of a short length region in ring 2. Correction was done with the COCU short-length algorithm SHORTLE [2].

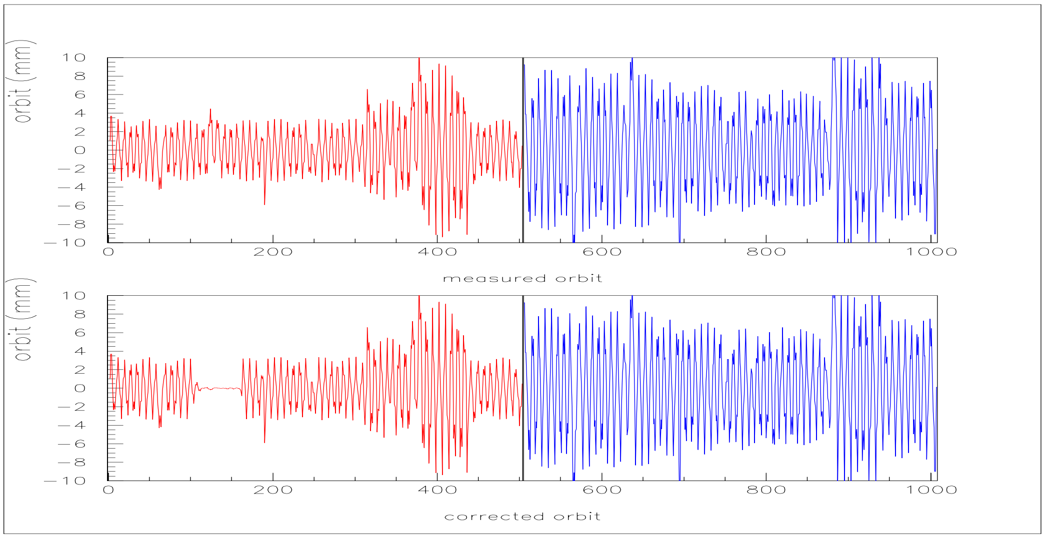

Figure 10: Vertical orbit of ring 1 (red, left half) and ring 2 (blue, right half) after simultaneous correction of a short length region in ring 1. Correction was done with the COCU short-length algorithm GRAPE [2].

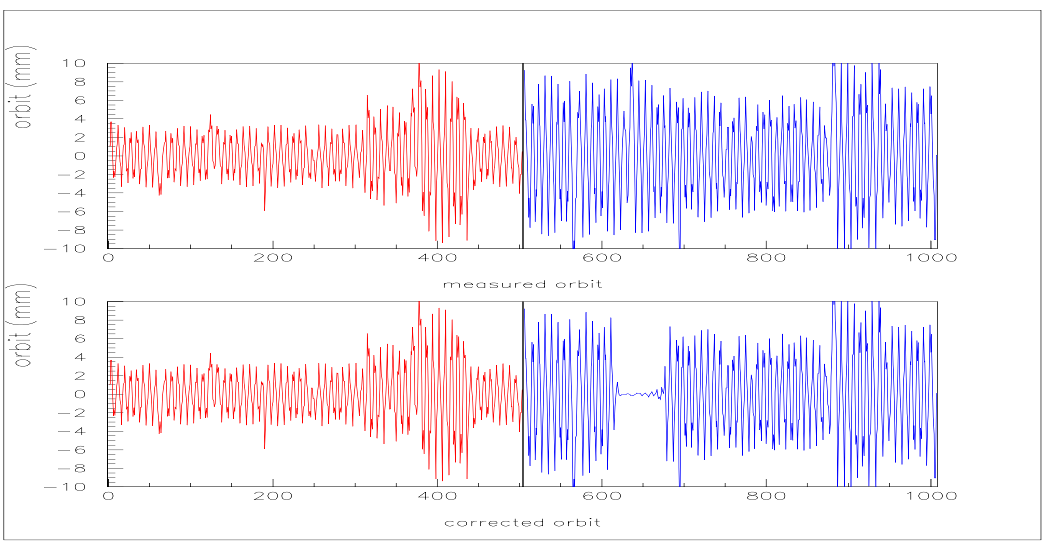

Figure 11: Vertical orbit of ring 1 (red, left half) and ring 2 (blue, right half) after simultaneous correction of a short length region in ring 2. Correction was done with the COCU short-length algorithm GRAPE [2].

4.2 Complete least squares minimization

To test other possible algorithms to solve eq. (1) for the response matrix (4), we have tried a solution by a pseudo inversion. In case the response matrix is not rank deficient, such a global least squares minimization can be attempted.

The linear system:

$$\vec{m} - \vec{t} = \mathbf{A} \cdot \vec{c} \tag{5}$$

has an approximate solution with minimum least squares of the form:

$$\vec{c} = (A \cdot A^t)^{-1} \cdot A^t \cdot (\vec{m} - \vec{t}) \tag{6}$$

however with the full response matrix using all available correctors. This usually works well in simulations, but with random errors on the measured orbits (pickup noise etc.) a best kick method is often the better choice.

This algorithm has been implemented as the ”PSINOM” mode but it requires a non-singular response matrix [2]. The matrix must therefore be properly conditioned, e.g. with a singular value decomposition as described in [2].

The result of this algorithm will be a correction using all available correctors. The result is equivalent to a correction with the MICADO algorithm when the number of MICADO iterations equals the number of correctors. The result of this correction mode is shown in Fig.12 with the same measured and target orbits as in Fig.7. The result obtained

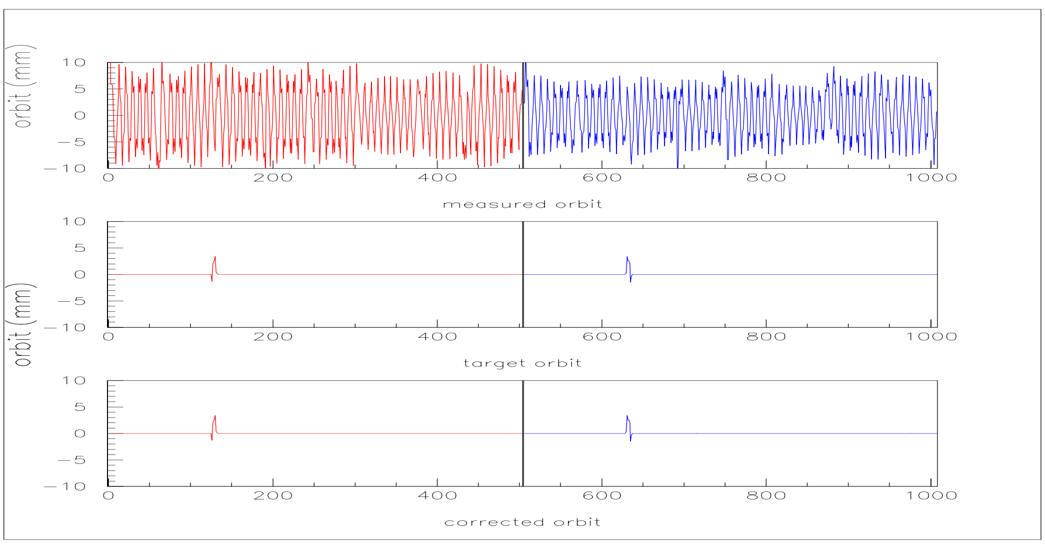

Figure 12: Vertical orbit of ring 1 (red, left half) and ring 2 (blue, right half) after simultaneous correction to a target orbit. Target orbit is ideal orbit with separation bump in IP5. Correction was done with PSINOM [2], following a singular value decomposition.

is identical to the MICADO algorithm when it is used with all available correctors.

This proves that the strategy is robust, independent of the algorithm applied.

5 Summary

We have succeeded in modifying the existing orbit correction program COCU to handle two separate beams with shared elements. The algorithm is robust, fast, and well suited for online corrections. The implementation was straightforward due to the built-in flexibility and modularity of the existing code. The tests confirm the expected results. However, COCU is conceived as a very high speed online tool and this has some implications that need to be considered. It is meant as the algorithmic kernel of a program used by operators in a control room and the system independent interface is designed for easy integration into any type of control system. In particular, it has no graphical user interface and the stand alone offline use requires some advanced knowledge of its functioning and possibly some additional software. Therefore it should not be considered as a trailer to accelerator design programs such as e.g. MAD [8, 9] for offline simulation purposes. In particular different sign conventions etc. could make the combined use of COCU with other optics programs unnecessarily complicated. We therefore highly recommend to make an effort to implement this functionality where it is needed (i.e. MAD for the LHC), given that the principle is proven.

References

[1] D. Brandt, W. Herr, J. Miles and R. Schmidt; *A new Closed Orbit Correction Procedure for the SPS and LEP*, Nucl. Inst. Meth. **A293**, (1990) 305.

[2] W. Herr; *Algorithms and Procedures in the Closed Orbit Correction Package COCU*, CERN/SL 95-07 (AP), CERN, (1995).

[3] LHC Conceptual Design, CERN/AC/95-05, (1995).

[4] W. Herr; *Beam-beam effects in the LHC*, Part. Acc. **50** (1995) 69.

[5] H. Grote; *Self-consistent Orbits for beam-beam interactions in the LHC*, LHC Project Note 216 CERN, (2000).

[6] O. Brüning, W. Herr and R. Ostojic; *A beam separation and collision scheme for IP1 and IP5 at the LHC for optics version 6.0*, LHC Project Report 315 CERN, (1999).

[7] O. Brüning, W. Herr and R. Ostojic; *A beam separation and collision scheme for IP2 and IP8 at the LHC for optics version 6.0*, LHC Project Report 367 CERN, (1999).

[8] H. Grote and F.C. Iselin; *The MAD Program*, CERN/SL 90-13 (AP) (Revision 3), CERN, (1992).

[9] F.C. Iselin et al.; *MAD Version 9*, CERN/SL 2000-026 (AP), CERN, (2000).

[10] H. Grote; Private Communication, (Juli 2000).

[11] E. Wildner; Private Communication, (August 2000).

[12] B. Autin and Y. Marti; *Closed Orbit Correction of A.G. Machines using a limited Number of Magnets*; CERN ISR MA/73-17(1973)

[13] W. Herr and R. Schmidt; *MOPS FORTRAN 77 User Guide* CERN/SPS/88-44 (AMS).

Appendix A - Running instructions

All communication between COCU and outside programs is done via MOPS data structures [13] that can be generated from various programming languages. Assuming prior knowledge, the user can fill the structures directly with the data or use the available utility programs. To use these utilities, the measured orbits and optics parameters must be available in standardized ASCII files and for convenience and compatibility the optics parameters and orbits can be stored in separate file of identical structure. The interactive utilities will sequentially read the input files and produce the required structure.

The version of COCU that can handle the simultaneous correction of two beams (Version 12.00 or later) is backward compatible and like all other versions is driven by commands. To enable the two beam correction mode, the command

```
TWO-BEAM-CORRECTION 1
```

should be put somewhere in the command file [1]. Without this command or with

```
TWO-BEAM-CORRECTION 0
```

a standard orbit correction will be done with erroneous results when the orbits and optics parameters of two beams are loaded.

As mentioned in the text, some care must be taken concerning the sign of the correctors. Therefore it is recommended to change the sign of the orbit of ring 2 when it is loaded. After the correction the sign of all correctors found for ring 2 only must be changed. The sign of correctors for ring 1 are correct and the sign of all common correctors are correct in the reference of ring 1.