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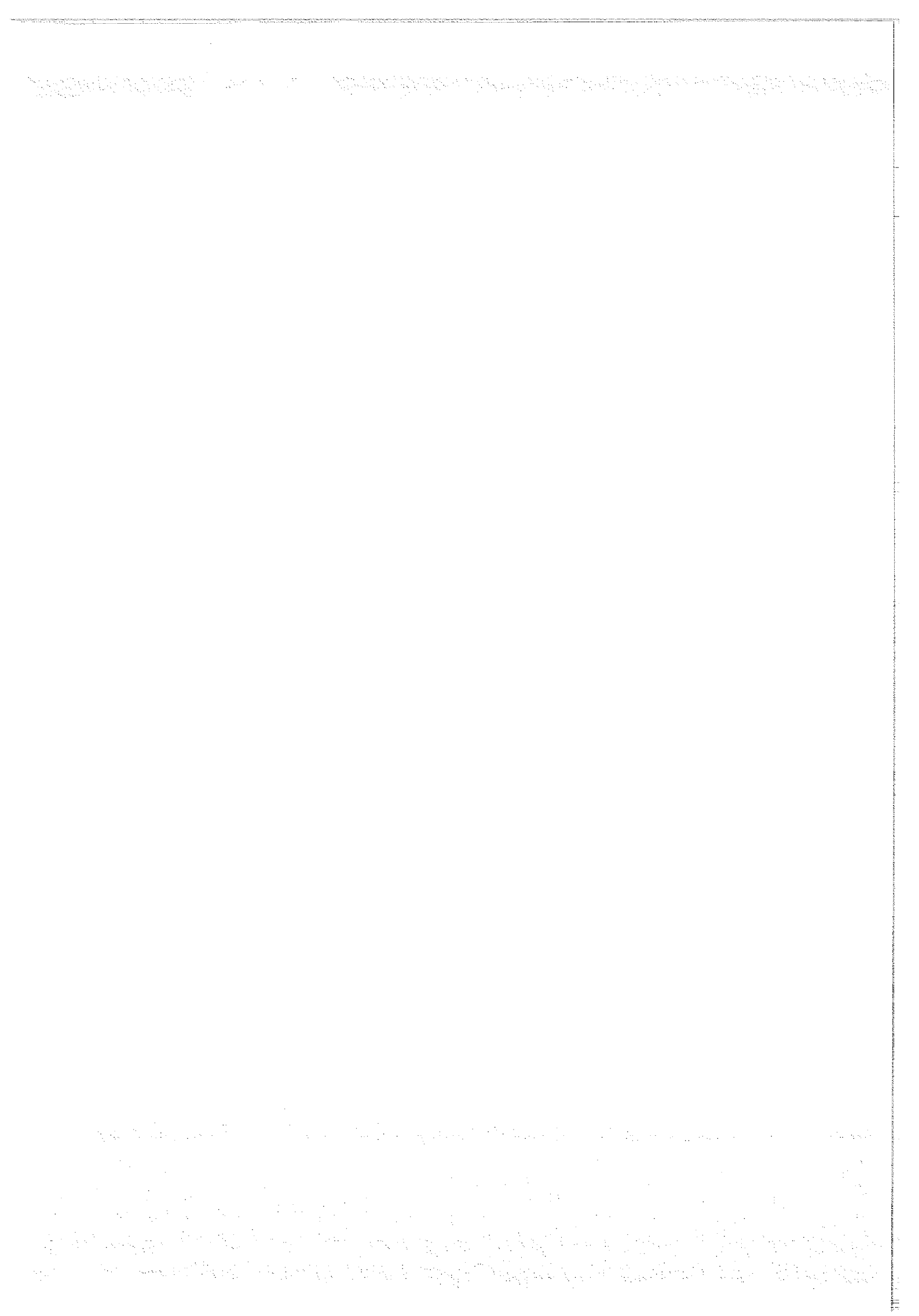
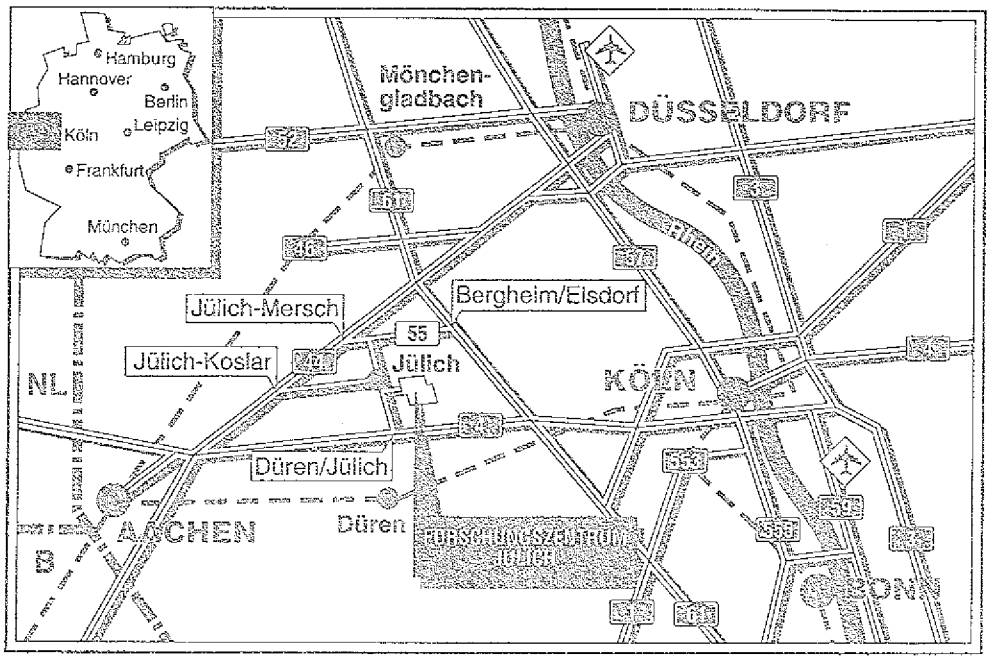
First Turn Simulations in the Cooler Synchrotron COSY

D. Dinev





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D. Dinev

Contents

1.Introduction

In order for the particles in a circular accelerator to be able to perform hundred of thousands turns before to reach the final energy of the machine they must first of all pass the very first turn.As a kind of simplification the particle motion in a circular accelerator can be described as oscillations around a closed curve,so-called closed or equilibrium orbit.The particles are injected into the machine so that the center of the particle bunch will move along this equilibrium orbit.

In practice however different kinds of imperfections exist.Fields in the bending magnets always differ from their designed values.The typical value of the relative field errors in the dipoles is $\sigma_{\Delta B/B}=5.10^{-4}$.

Also always the focusig quadrupole lenses are slightly displaced from their designed positions.The typical value of the misalignment errors is $\sigma_{\Delta x}=\sigma_{\Delta y}=0.1$mm.

Due to the errors the real equilibrium orbit does not coincide with the designed(reference) closed orbit.As long as the reference orbit follows the vacuum chamber axis the distored orbit diverges from this axis and the maximum deviations can reach tens of millimiters.A special systems of beam position monitors(BPM) and small correcting magnets as well as a great number of correcting algorithms have been developed to minimize the orbit deviations from the designed orbit-[1].

During the assembling and initial tuning of the accelerator much bigger errors than ones mentioned above may occur.Sometimes they are caused by unpredictable mistakes and there are several such cases in the accelerator practice.

In the precence of big linear errors the center of charge trajectory does not follow any more the orbit and can have very big deviations. Even more,the beam can hit somewhere the vacuum chamber not being able to make complete turn around the machine.

Launch errors in the injection system may also cause the beam loss or provided they are not so big-harmful coherent oscillations of the beam.

The situation is complicated by displacement errors in the BPMs and by the low resolution of the monitors for single-pass beam.

So we face the task of threading the beam entire turn around the accelerator ring.

Two different approaches are possible.

First we can try to thread the beam around the ring using the existing orbit correctors.Correcting algorithms have been developed for first turn treatment and some of them will be described in this paper.

In a different approach we can search for the sources of big errors-dipole magnets with big field errors or highly displaced quadrupoles.After finding of the candidates for error sources we should carefuly examine the corresponding elements.This approach has been successfuly applied for beam line steering and can also be used for the fist turn treatment.

The first turn correction is closely related to the beam line steering.In fact before closing the first turn onto the second the magnetic structure of a circular accelerator can be looked at as a beam line.

The beam losses are especially dangerous in the superconducting machines causing the loss of the superconductivity and thus making the tuning process much longer.

In big synchrotrons the distored orbit amplitude can reach values which are compatible with the vacuum chamber radius due mainly to the misalignments of the quadrupoles.This makes the first turn threading a very important task.

Having corrected the center of charge trajectory so that the beam goes entire turn around the ring we should close this trajectory i.e.make the second turn(and all following turns) to coincide with the first turn.In other words we have to establish a new(corrected) closed orbit passing through the injection point.

This paper is devoted to the first turn correction and related problems in particle accelerators of synchrotron type.The paper consists of two parts.The first part is a survey of the existing methods for first turn steering.The second part is entirely devoted to the first turn in the cooler synchrotron COSY which is under assembling in KFA-Julich,Germany.

The cooler synchrotron and storage ring COSY-fig.1 is designed to accelerate protons and light ions up to an energy of 2.5GeV ($0.9<B.\rho<12$ T.m)-[2].The lattice consists of two bending arcs,each having three identical periods and of two 40 meters long straight sections with $2\pi(\pi)$ phase advance(telescopes).The magnetic structure of each arc period is F-M-D-M-M-D-M-F (or with the opposite polarity of the quadrupoles).It has large flexibility enabling for different regimes of the machine to be realized,in particular ones with zero dispersion in the straight sections.The accelerator consists of 24 rectangular bending magnets,24 quadrupole lenses in the arcs and 32 quadrupole lenses in the straight sections.

The designed beam intensity is 2.10^{11}ppp.

In order to improve the beam quality both electron and stochastic cooling will be used.

The electron cooling will take place at the injection energy of about 40 MeV/nucleon and will reduce the transverce emittance below 5π mm.mrad and momentum spread below 5.10^{-4}.

The stochastic cooling of the dc-beam is predected and it will reduce the transverce emittance below 1π mm.mrad.

The main parameters of the cooler synchrotron COSY are summarized in Table 1.

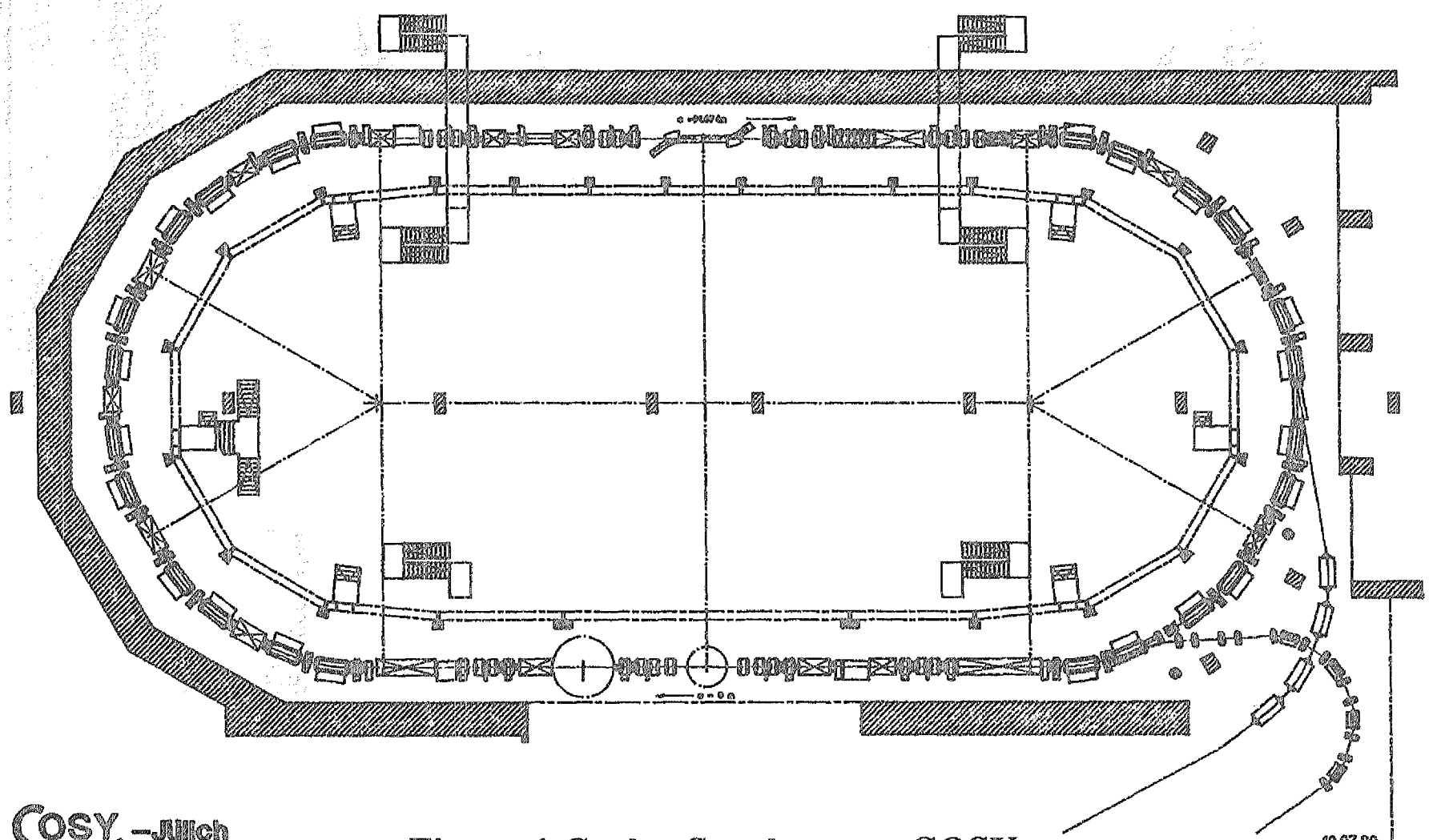

Figure 1.Cooler Synchrotron COSY

TABLE1. COSY MAIN PARAMETERS

momentum range		275 - 3300	MeV/c
kinetic energy range		40 - 2500	MeV
momentum at injection		275	MeV/c
energy at injection		40	MeV
max.number of stored protons		$< 2.10^{11}$	
max.number of stored part. without damping		$< 10^{10}$	
cycle data:	injection	<10	ms
	ramp up/down	2/2	s
	electron cooling	1..4	s
	stochastic cooling	10..100	s
geometry:	circumference	184	m
	length of straight sections	40	m
	length arc to arc	73	m
	length straight to straight	33	m
dipoles:	number	24	
	length	1.8	m
	radius	7	m
	type	C-type,box	
quadrupoles:number (arcs)	length	24	
	max.gradient	0.3	m
		7.5	T/m
quadrupoles:number (straights)	length	32	
	max.gradient	0.6	m
		7.5	T/m
lattice:	No of periods	6	
	structure	D-M-F-M--M-F-M-D	
		(F-M-D-M--M-D-M-F)	

2.METHODS FOR FIRST TURN AND BEAM LINE STEERING (SURVEY)

This section represents some algorithms for first turn and beam line steering.As we have mentioned in the introduction during the first turn every circular machine can be treated as a beam line(with the exception of the closing problems).One and the same method can be applied for beam steering in the both cases.We emphasis especially on kick error correction because of its importance for the first turn steering.Only a short description of the focus error treatment is given at the end of this chapter.

2.1.Beam Threading Algorithm

The idea of the method is straightforward-[3,4].The steering system consists of small correcting dipoles and beam position monitors(BPM) situated near to them-fig.2.

As BPMs electrostatic pickup electrodes are used.

Because the length of the correcting dipoles is small comparing to the accelerator circumference they can be considered to produce local orbit bumps.

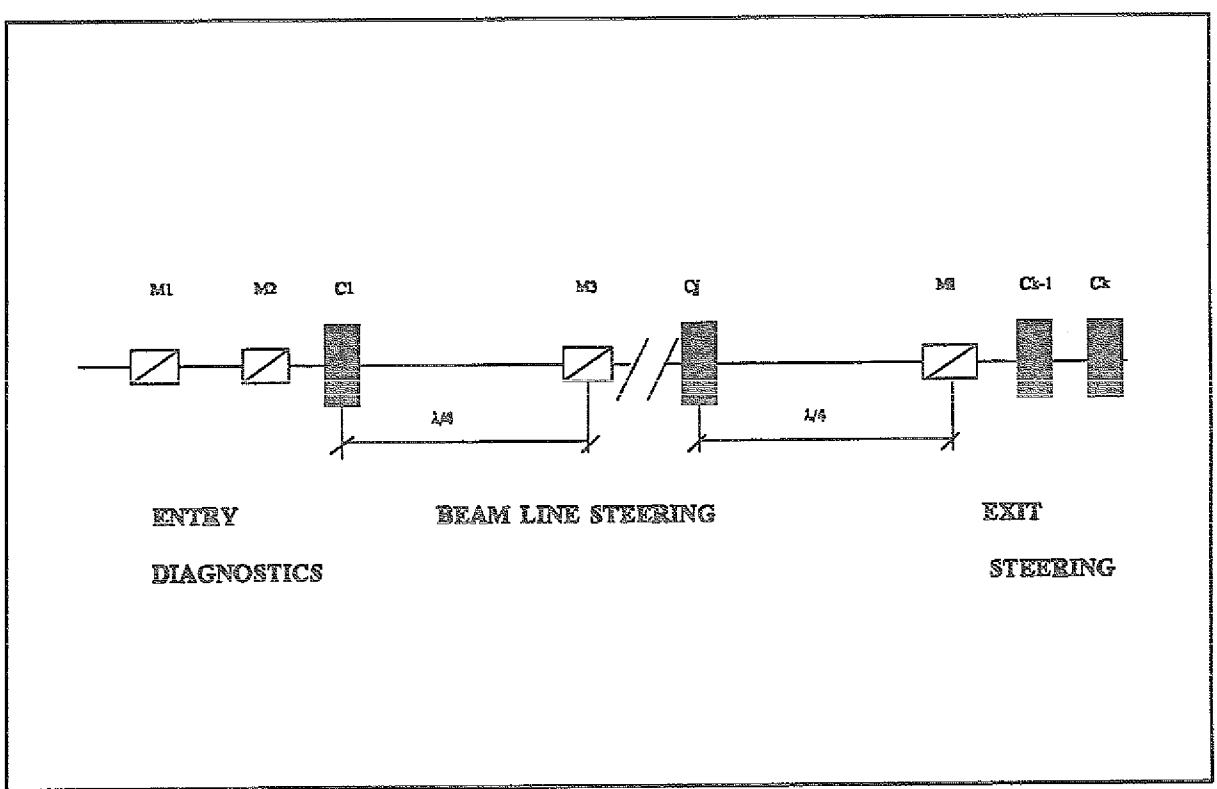

Figure 2.Beam line steering system.

let:

$$\epsilon_n = \frac{B_{cn}.l}{B.\rho} \qquad (2.1.1)$$

be the kick in the n-th corrector,where B.ρ denotes the beam rigidity.

If M^{ji} is the transfer matrix between j-th corrector and i-th BPM we can write:

$$x_i = m_{12}^{ji}.\epsilon_j = \sqrt{\beta_j \beta_i}\sin\mu_{ji}\epsilon_j \qquad (2.1.2)$$

where x_i is the deviation in the i-th BPM and we have expressed the matrix elements by the Twiss parameters-amplitude function β(s) and betatron phase advance μ(s):

$$\mu(s) = \int_0^s \frac{ds}{\beta(s)} \qquad (2.1.3)$$

Applying the principle of superposition we can write:

$$\begin{bmatrix} x_3 \\ x_4 \\ \dots \\ x_n \end{bmatrix} = \begin{bmatrix} \sqrt{\beta_1\beta_3}\sin\mu_{13} & 0 & \dots & 0 \\ \sqrt{\beta_1\beta_4}\sin\mu_{14} & \sqrt{\beta_2\beta_4}\sin\mu_{24} & \dots & 0 \\ \dots & \dots & \dots & \dots \\ \sqrt{\beta_1\beta_n}\sin\mu_{1n} & \sqrt{\beta_2\beta_n}\sin\mu_{2n} & \dots & \sqrt{\beta_{k-2}\beta_n}\sin\mu_{k-2n} \end{bmatrix} \cdot \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \dots \\ \epsilon_{k-2} \end{bmatrix}$$

The system of equations (2.1.4) can be solved with a trivial forward substitution.

It follows from (2.1.2) that the optimum phase distance between the corrector and the monitor in a corrector-monitor pair is $\pi/2$.In practice it is difficult for one to follow this requirement.

BPMs should be placed near to the points where β has maximum and where we can expect big center of charge deviations.This improves the BPMs sensitivity.

In order to minimize corrector strengths the correcting dipoles also should be placed near to the points where β has maximum.

Whereas in the simplest FODO structure it is easy for one to follow these rules situating the horizontal BPMs and correctors near to F quadrupoles and the vertical BPMs and correctors near to D quadrupoles in more sophisticated magnetic structures with many elements this is almost impossible.

The beam line steering systems have as a rule two additional parts-fig.2.

In the entrance of the line two pickups are used to measure the position and the slope of the injected beam.The credability of the entry angle reconstruction however is greatly improved if the two pickups are placed in drift space-[3].

At the exit of the line two correctors are used to match the center of charge position and slope to ones in the following accelerator or target.

2.2 Least Squares Algorithm

The Least Squares (LSQ) approach was successfully applied not only as a method for general orbit correction but also for first turn treatment-[5].

Let's have n BPMs and m correcting dipoles,$n \geq m$.

If c_k,k=1,2,...,m are some changes in the correcting currents,the theoretical changes in the center of charge trajectory x^c_i that they will cause generally speaking are:

$$x_i^c = \sum_{k=1}^{m} \left(\frac{\partial x_i^c}{\partial c_k} \right) \cdot c_k = \sum_{k=1}^{m} F_{ik} \cdot c_k \qquad (2.2.1)$$

In practice due to the error influence the measured center of the charge position x_i^m will not coincide with the designed position x_i^d.Let $\Delta x_i = x_i^d - x_i^m$ denotes the discrepancy between both.

The task of threading the beam around the entire circumference of the ring can be looked at as a least squares problem:

$$S^2 = \sum_{i=1}^{n} \left(\Delta x_i - x_i^c \right)^2 \Rightarrow Min \qquad (2.2.2)$$

The corrector strengths which minimize the discrepancy between the measured and desired trajectories follow from the well-known solution of the LSQ problem:

$$\vec{c} = \left(F^T.F\right)^{-1}.F^T.\Delta\vec{x} \qquad (2.2.3)$$

In the case of equal number of correctors and BPMs when F is square matrix (2.2.3) becomes:

$$\vec{c} = F^{-1}.\Delta\vec{x} \qquad (2.2.4)$$

Now F is the triangular matrix (2.1.4) as a BPM "sees" only those correctors which are placed downstream to it.

The LSQ method has been used in the Tevatron first turn correction-[5].In superconducting synchrotrons the orbit steering is of especial importance because the beam losses cause the loss of the superconductivity.This means that the accelerator will have about one hour stop at every tuning step and is a serious problem.The automatization of the tunning by means of the LSQ algorithm has allowed for an orbit close to the designed orbit to be established after several iterations of the correction.

2.3 Closed Bumps Algorithm

The classical method for general orbit correction by means of local orbit bumps can be applied also for first turn correction-[6].

The local orbit bump is produced by three correcting dipoles-fig 3.

Let n BPMs be placed between the correctors.

Let 'a' is the center of charge deviation in the middle corrector.The height 'a' can be used for the local orbit bump to be parametrized.

A kick ε_i centered in a point i produces changes in the center of charge position and angle at another point s given by:

$$\Delta x(s) = \sqrt{\beta_i \beta_s}\sin\mu_{is}\epsilon_i$$
$$\Delta x'(s) = \sqrt{\frac{\beta_i}{\beta_s}}(\cos\mu_{is} - \alpha_s.\sin\mu_{is})\epsilon_i \qquad (2.3.1)$$

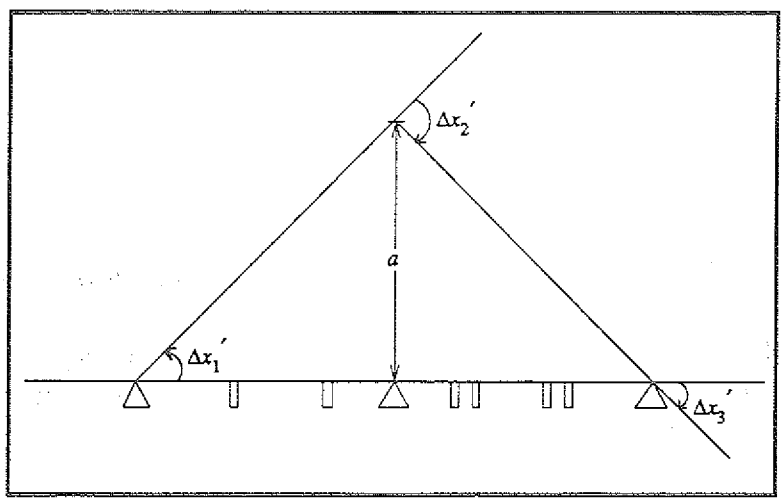

Figure 3.Closed orbit bumps correction

We will want to produce a local bump.This means that if the point s is situated anywhere outside the bump the effects of the three correctors should compensate each other:

$$\sum_{i=1}^{3} \Delta x_i(s) = 0$$
$$\sum_{i=1}^{3} \Delta x_i'(s) = 0 \qquad (2.3.2)$$

It follows from (2.3.1,2.3.2) that for s outside the bump:

$$\sum_{i=1}^{3} \sqrt{\beta_i}\, \epsilon_i \sin \mu_{is} = 0$$
$$\sum_{i=1}^{3} \sqrt{\beta_i}\, \epsilon_i \cos \mu_{is} = 0 \qquad (2.3.3)$$

The kick in the first correcting dipole should produce deviation equal to a in the middle corrector.It should be therefore:

$$\epsilon_1 = \frac{a}{\sqrt{\beta_1 \beta_2} \sin \mu_{12}} \qquad (2.3.4)$$

Given (2.3.4),(2.3.3) becomes a system of two equations with two unknowns ϵ_2 and ϵ_3. The solution is:

$$\epsilon_2 = \frac{a \sin \mu_{12}}{\beta_2 \sin \mu_{12} \sin \mu_{23}} \qquad (2.3.5)$$

and-

$$\epsilon_3 = \frac{a}{\sqrt{\beta_2 \beta_3} \sin \mu_{23}} \qquad (2.3.6)$$

In [6] the following goal function is introduced:

$$G(a) = \sum_{i=1}^{n} w_i^{PUE} (x_i^m - x_i^d + x_i^c)^2 + \sum_{j=1}^{3} w_j^{COR} P_j(\epsilon_j) \qquad (2.3.7)$$

In (2.3.7) x_i^m denotes again the measured deviation in the i-th BPM,x_i^d-the desired deviation.x_i^c is the deviation in the i-th BPM due to the three correctors and it can be easily calculated using the transfer matrices between the correctors and the monitor.

w_i^{PUE} is a weight associated with each monitor while w_j^c-a weight associated with each corrector.

P(ε) is a penalty function which punish the goal function if the kicks are too big.

In particular,the penalty function can be taken as:

$$P(a) = \begin{cases} k\,|\epsilon| \;, & if \;\; |\epsilon| > \epsilon_{max} \\ 0 \;, & otherwise \end{cases} \qquad (2.3.8)$$

where k>0 is a large constant.

G(a) is a function of only one independent variable-a.It can be easily minimized using for example the simplex method.

In order for the entire circumference of the accelerator ring to be corrected the above algorithm should be applied iteratively.The ring is devided into overlaping closed bumps and the correction is repeatedly used taken into account the results from the previous steps.

The algorithm is proposed for SSC and has been largely used for SSC furst turn and global closed orbit simulations.

2.4 Error Finding Methods

In the periods of machine assembling,initial tuning or upgrading relatively large errors can occur-launch errors in the position and slope of the center of charge of the injected beam,kick errors in the dipoles and misaligned quadrupoles and focus errors in the quadrupole gradients.

As the strengths of the correcting elements are limited it could be impossible to correct the center of charge trajectory to the required extent.That is why a different approach to the beam steering has been developed-[7,8].

In this approach we will rather search for the sources of big errors than try to correct them.After the places and magnitudes of such errors have been found one should carefuly check the coresponding elements trying to uncover the physical bases of the errors.

The error-finding approach has been successfully used in SLAC for beam steering in the linear electron-positron colider SLC-[7,8].

Two kinds of computer programs are used to determine the error candidates-modeling programs and error-simulating programs.

The modeling programs give the operator a mathematical model of the accelerator.They receive as input a full description of the accelerator elements (their location and strengths) and produce as output a file listing elements and corresponding transfer matreces and Twiss parameters.

Error-simulating programs calculate the effects on the beam parameters due to specific errors in the elements and generate simulated trajectories.To find the predicted trajectories this programs use the transfer matrices calculated by the modeling programs.

As a modeling program any lattice design program can be used.In practice Teapot-[11] and PETROC-[12] have been used for beam steering.

For simplification the error-simulating programs describe errors introducing thin-lens elements in the lattice.For simulating of focusing errors thin-lens quuadrupoles are inserted in the lattice quadrupoles and for simulating of kick errors thin-lens dipoles are inserted either in bending dipoles to describe field errors or in quadrupoles to describe allignment errors.

Two different kinds of error treatment exist:

A.Global surch. The method of global error surch makes use of a powerfull nonlinear optimization package.All the elements are suspected as possible sources of errors.Thin-lens elements describing errors are inserted in the elements.Then the optimization programs are used to find the settings of these thin-lens elements which will yield BPMs readings matching the measured trajectory.Those thin-lens elements which have nonzero strengths are the sites of possible errors.

B.Local surch. Only few of the elements are used as possible error sources.The operator has to make some guesses about the location of the errors and about the error-free regions.A highly-developed graphical interface can be very useful in this trial-and-error method.The operator display should be able to show a plot of the measured trajectory,desired trajectory and the difference between both.It is clear that an error originates in the region where the differences grow up.After determining the error places the operator tries to adjust the strengths of the corresponding thin-lens elements so that the calculated trajectory lies close to the measured trajectory.Nonlinear optimization programs are used again but due to the small number of independent variables the optimization problem is much more easy for solving.

As an illustration of the error-finding methods we will give an example from the SLAC beam line -[8].Fig.4. shows the initial trajectory which due to some errors hits the beampipe.By means of one corrector the beam has been traced all the way down the pipe-fig.5.The dotted line on fig.5.shows the ideal model-based trajectory for the given corrector strength.Then the user plots the differences between the two trajectories.It is clear that an error originates in the region where the differences grow large.Following this recepy two alignment errors have been found downstream.Fig.6. represents a plot of the trajectory differences after the two major errors in the beam line have been removed.Now the actual trajectory and the designed trajectory match.

2.5 Graphics Interface

A powerfull graphical interface highly facilitates the process of first turn and beam line steering-[9,10].It allows the operator easily to build an intuition and an understanding of the correction task that should be solved.

One straightforward idea that has been mentioned above is to plot all the three of them-the actual trajectory,the desired trajectory and the differences between both.The region where the difference trajectory begins to grow up is a candidate for an error.

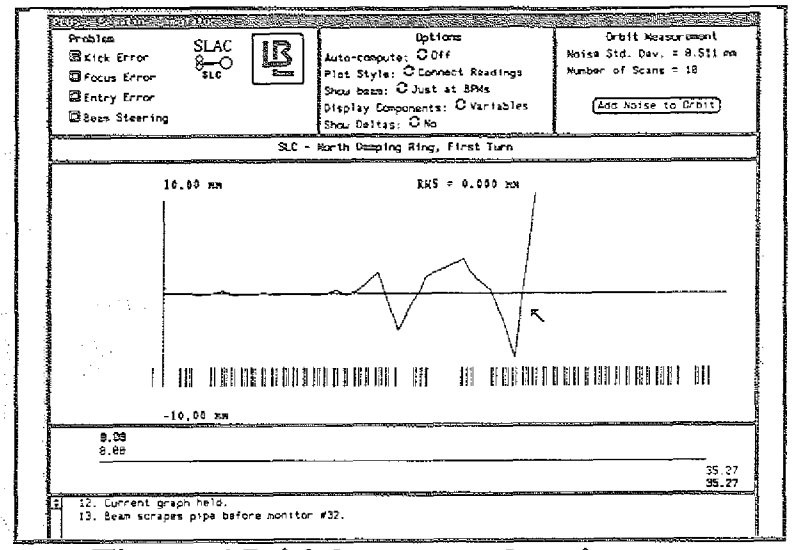

Figure 4.Initial measured trajectory.

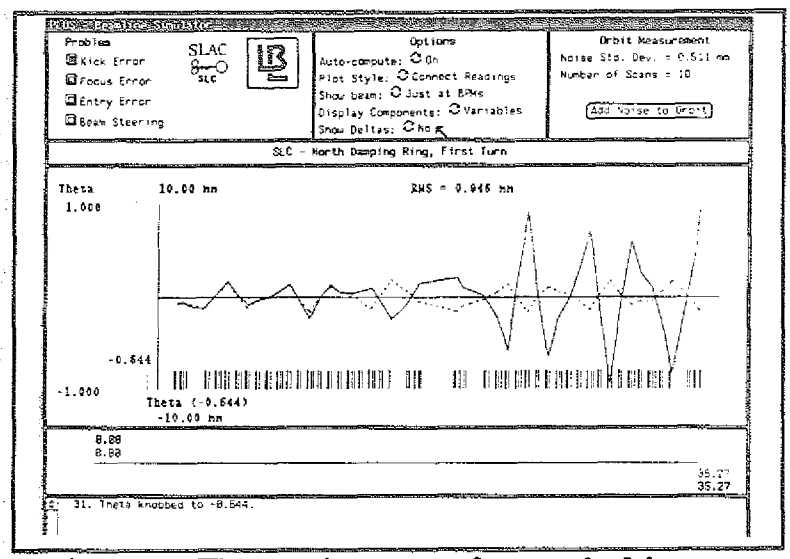

Figure 5.The trajectory after switching on the first corrector

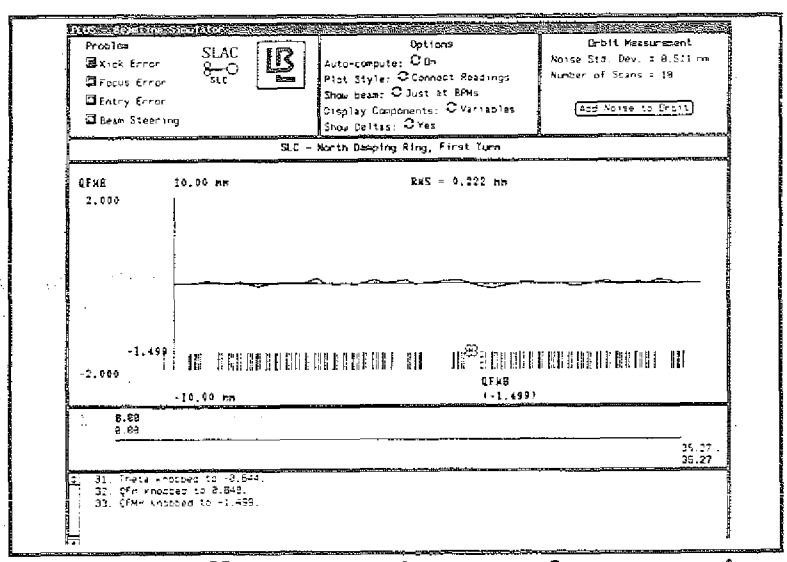

Figure 6.Difference trajectory after removing all errors.

Recently the graphical interface is implemented on scientific workstations with high resolution large-screen graphic monitor,using multitasking operating systems(UNIX),multiple windows,pointing devices and others.

A top view of the entire accelerator ring can be shown on the screen(so-called "bird eye view") or selected regions can be represented in larger scale.Using the mouse one can receive information on a given element,its status and strengths or to change these values.

Having such opportunities a skilful operator can very fast find the place of an error and manualy adjust its magnitude so that the simulating trajectory to coincide with the measured one.

The now standard X-Window System is widely used as a graphical interface as well as a specially written graphical languages(PDL-[9]).

A data file(which can be implemented as a shared memory file) containing all the data about elements and transfer matrices is used for communication between different programs.

As an example fig.7 represents the control graphics interface developed for SSC.

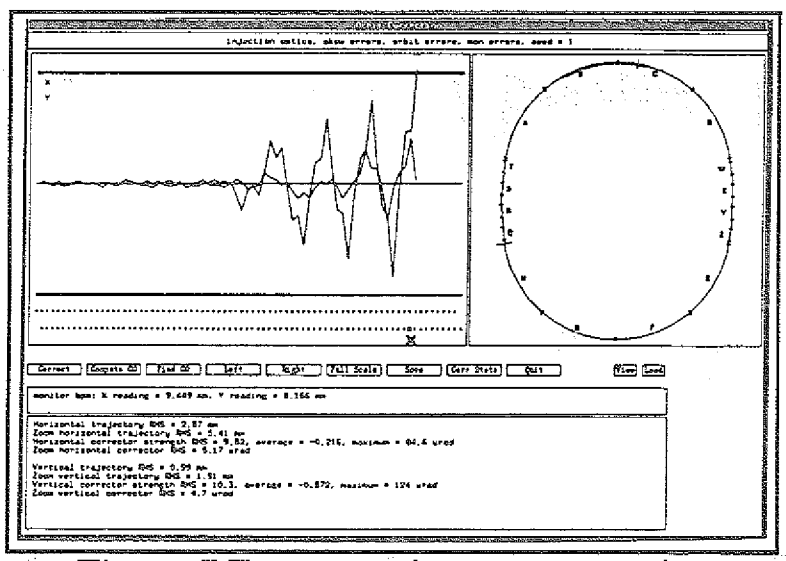

Figure 7.Example of control graphics interface.

2.6 Beam Line Expert Systems

Several expert systems have been developed to automate the use of the beam line correcting programs and to minimize the time necessary for line commisioning-[13,14,15].

These are hybrid programs combining traditional expert systems with their capabilities for qualitative reasoning,modeling programs giving a mathematical model of the machine and optimization programs.Combining numerical algorithms with symbolic reasoning these hybrid expert systems systematically performe the specific procedures that a human expert follows in order to correct the beam line.

First of all they look for error-free regions where the discrepancies between predicted and the measured trajectories are small.An assumption that every subregion between two adjacent error-free regions is a possible location of errors and that there is only one error element within each subregion is made.Then the described above error-finding procedures are used in order for the existance of beam line errors to be uncovered.

Frames are usualy used for representation of the domain knowledge.

LISP is the preferable language for the expert system implementation.

As an example we show on fig.8 the screen interface of the beam line expert sysytem ABLE(Automated Beam Line Expert) developed in SLAC-[13].

ABLE uses the knowledge about the beam line in order to decide which hypotesis about the errors are best.ABLE compares the results of various suggestions and can discard or performe one of them.New correcting strategies can be incorporated into the system without extensive rewriting of the code.

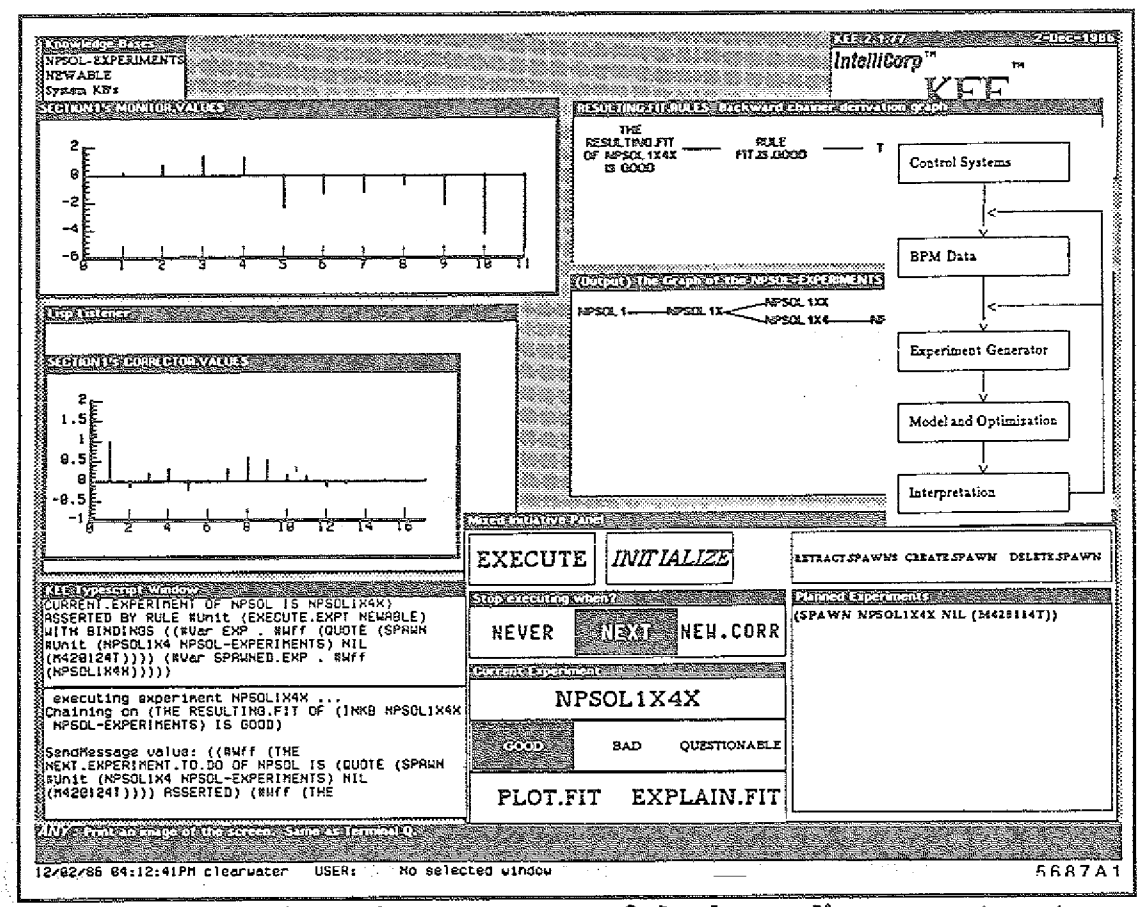

Figure 8.A typical display screen of the beam line expert system ABLE

2.7 Correcting of Focus Errors

We will give only a short description of the problem of correcting focus errors in a beam line taking as an example the Bevalac transfer line steering system in LBL Laboratory-[16].

This line is 260 meters long and serves as a transfer line between SuperHILAC and Bevatron.The correcting system consists of 15 control stations each having dipole and quadrupole correctors and a nine-segment Faraday cup for measuring the beam position and profile.The correction is realized repeatedly from station to station down the line.

For determining of focus errors the only available data are the horizontal and vertical envelope displacements at two adjacent control stations n and n+1.By means of the nine-segment Faraday cup the operator can measure only the discrepancy between the nominal and actual beam profiles.

In order to treat focus errors one should determine a special trajectory called tuning ray.This is a particle trajectory that passes through points lieing on the beam envelope both in station n and in station n+1.From the measured envelope deviations x_n and x_{n+1} in these stations and from the known matrix between them one can reconstruct the slopes x'_n and x'_{n+1}.

Two cases can be distinguished.

If the beam envelope does not exhibit visible waist the tuning ray closely matches the envelope.

In the presence of long drift space between the adjacent control stations the beam envelope has a pronounced waist.In this case the tuning ray is chosen to pass through the negative value of the measured envelope at the upstream station and the usual positive envelope displacement at the downstream station.

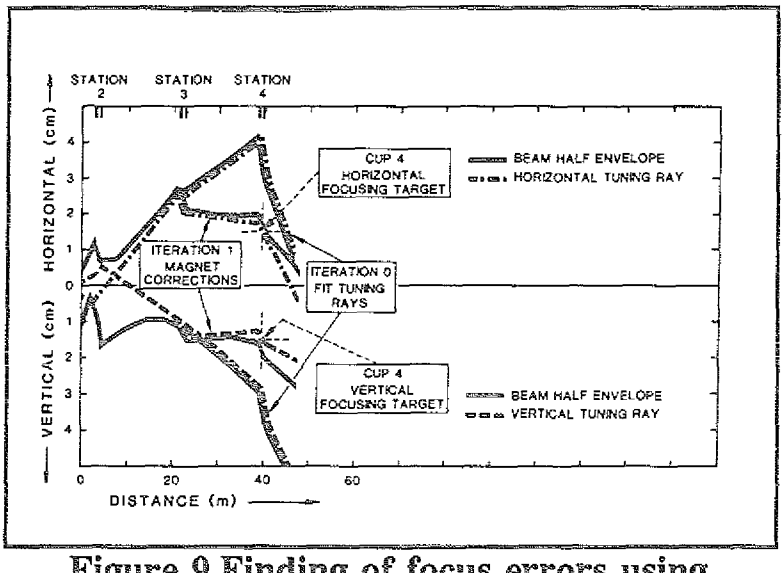

Figure 9.Finding of focus errors using a tuning ray

Having found the tuning ray one uses the quadrupole corrector in the upstream station n to correct the tuning ray displacement at station n+1 to match the desired beam envelope.

Fig.9. shows the implementation of the correcting algorithm in the Bevalac transfer line.The beam at station 4 is tuned using the correctors at station 3.

3.FIRST TURN CORRECTION IN THE COOLER SYNCHROTRON COSY

3.1 COSY Injection Scheme

The Cooler Synchrotron COSY uses the AVF cyclotron JULIC as injector.

A wide spectrum of ions,including negative ones.are foreseen for injection in COSY but the priority is given to H_2^+.H_2^+ ions with maximum energy of 45 MeV/nucleon (max B.ρ=2 T.m) and beam current of 10 μA (2.10^6 particles/bunch) will be injected into COSY via the stripping reaction $H_2^+ \rightarrow 2p+e$ in a thin ^{12}C foil-[17].The transverse emittance of the injected beam is $\varepsilon_H=\varepsilon_V=5\pi$ mm.mrad and the momentum spread is $\delta=1.5.10^{-3}$.

The equilibrium between the injected and lost particles is attained after some 10^3 turns(~1 ms) and the expected intensity of the circulating beam is 2.10^{10} ppp.Fig.10-[18] shows the typical time cycle of the injection bump magnets.The injection begins on the flat-top and lasts to the end of the cycle,i.e. about 12-20 ms.

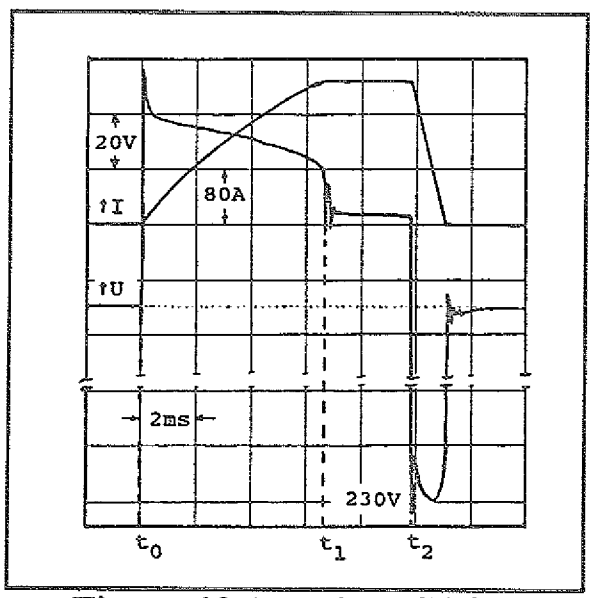

Figure 10.A typical COSY injection bumpers test pulse

The stripping target of ^{12}C or Al_2O_3 has a thickness of 20 μg/cm^2.It is placed in the drift space after the dipole magnet No 23 and its center is 50 mm far from the axis-fig.11.

The necessary closed orbit bump should be produced by means of three bump magnets,the first two with a length of 0.46 m and the last with 0.85 m length.The maximum available kicks in the bump magnets are 10 mrad.The main parameters of the bump magnets are given in table 2.

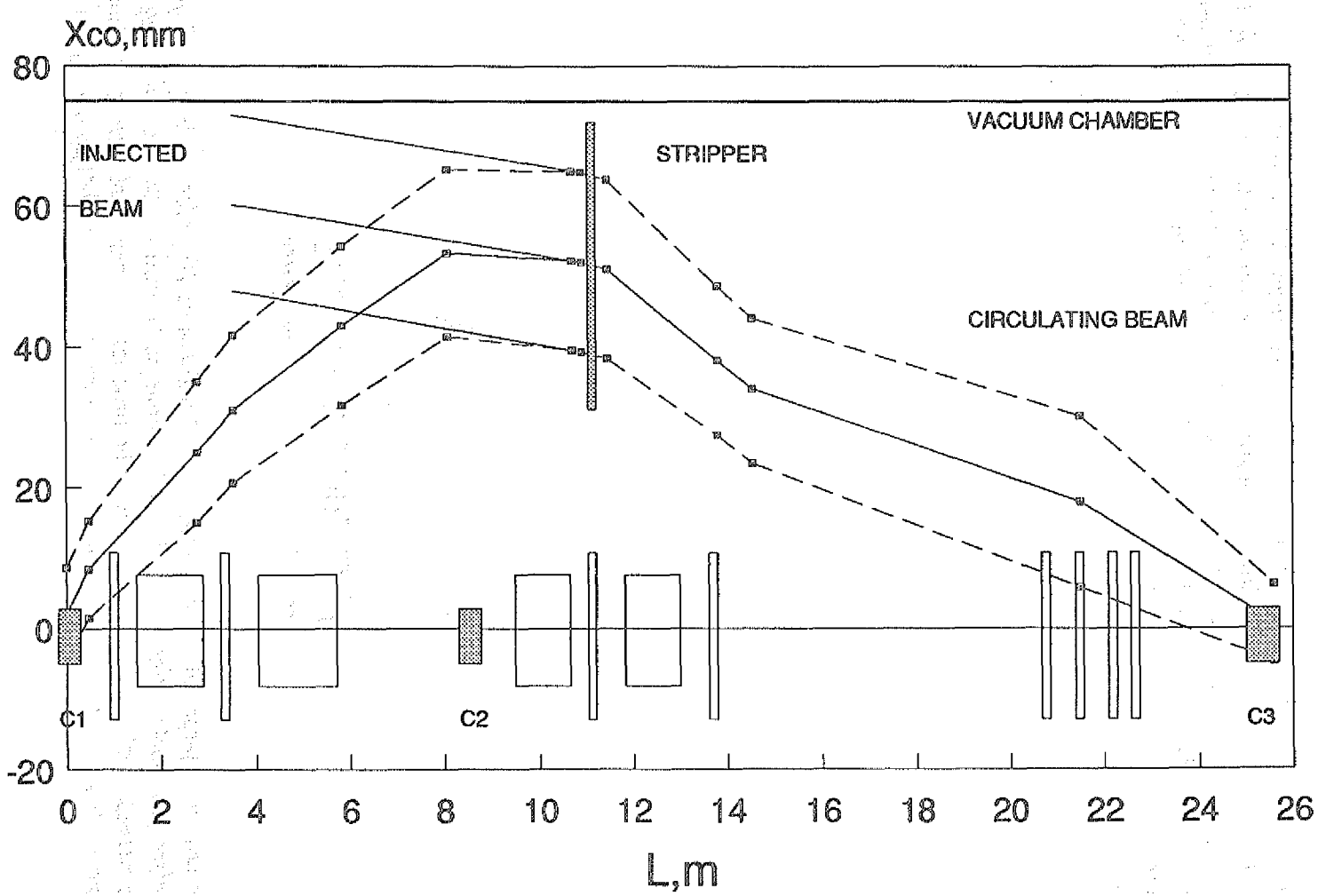

Figure 11.COSY stripping injection

TABLE 2.MAIN PARAMETERS OF THE BUMP MAGNETS

	Type A	Type B
Type	window frame	window frame
Max.kick, mrad	10	10
Max. field, T	0.029	0.057
Bending power, ∫B.dl, G.m	203	203
Max.exitation current, A	209	209
Equivalent magnetic length, m	0.70	0.35
Total length, m	0.85	0.46
Vertical gap height,mm	170	90
Horizontal gap width,mm	256	186
Rise time, ms	10	10
Flat top, ms	10	10
Fall time, ms	2..10	2..10
Max field error, %	~0.25	~0.25

3.2 Calculation of the Injection Bump. Systems with Three Bumpers

Describing the local orbit bump in §2.3 we assumed that the system consists of three bumpers and n BPMs between them.The orbit bump was parametrized by the orbit deviation in the middle magnet.

For the stripping injection we need a somewhat different scheme,consisting of three bumpers and one point under control-the stripping target-fig.11.Here we will analyze this scheme assuming arbitrary phase distances between the elements.

The constraints that should be fulfilled are:

$$\begin{aligned} x(s_s) &= x_s \\ x(s<s_{BM1}) &= x(s>s_{BM3}) = 0 \\ x'(s<s_{BM1}) &= x'(s>s_{BM3}) = 0 \end{aligned} \qquad (3.2.1)$$

Let M^1 denote the transfer matrix between BM_1 and BM_2;M^2-between BM_2 and BM_3 and finally M^3-between BM_2 and the stripping target.

These matrices can be expressed by the Twiss parameters.For two arbitrary points 1 and 2:

$$M_{12}=\begin{bmatrix} \sqrt{\frac{\beta_2}{\beta_1}}(\cos\mu_{12} + \alpha_1\sin\mu_{12}) & \sqrt{\beta_1\beta_2}\sin\mu_{12} \\ \frac{1}{\sqrt{\beta_1\beta_2}}(-\sin\mu_{12} - \alpha_1\alpha_2\sin\mu_{12} & \sqrt{\frac{\beta_1}{\beta_2}}(\cos\mu_{12} \\ +(\alpha_1-\alpha_2)\cos\mu_{12}) & -\alpha_2\sin\mu_{12}) \end{bmatrix}$$

For the beam deviation and slope in the middle bumper we can write:

$$\begin{aligned} x_2 &= m^1_{12}.\epsilon_1 = \sqrt{\beta_1\beta_2}\sin\mu_{12}\epsilon_1 \\ x'_2 &= m^1_{22}.\epsilon_1 = \sqrt{\frac{\beta_1}{\beta_2}}(\cos\mu_{12} - \alpha_2\sin\mu_{12})\epsilon_1 \end{aligned} \qquad (3.2.3)$$

where ε_1 is the kick in the bumper-(2.1.1) and μ_{12} is the phase advance between BM_1 and BM_2-(2.1.3).

Two constraints should be fulfilled in order for the bump to be closed.The first is:

$$x_3 = m_{11}^2 x_2 + m_{12}^2 (x_2 + \varepsilon_2) = 0 \qquad (3.2.4)$$

From (3.2.4,3.2.2) it follows that:

$$\sin\mu_{13}\sqrt{\beta_1}\varepsilon_1 + \sin\mu_{23}\sqrt{\beta_2}\varepsilon_2 = 0 \qquad (3.2.5)$$

(3.2.5) expresses the principle of superposition applied to the trajectories aroused by ε_1 and ε_2.

The second condition that should be performed is:

$$x'_3 = m_{21}^2 x_2 + m_{22}^2 (x_2 + \varepsilon_2) = -\varepsilon_3 \qquad (3.2.6)$$

From (3.2.6) and (3.2.2) it follows:

$$\cos\mu_{13}\sqrt{\beta_1}\varepsilon_1 + \cos\mu_{23}\sqrt{\beta_2}\varepsilon_2 + \sqrt{\beta_3}\varepsilon_3 = 0 \qquad (3.2.7)$$

For the trajectory displacement in the stripping target we can write:

$$x_s = m_{11}^3 x_2 + m_{12}^3 (x_2 + \varepsilon_2) \qquad (3.2.8)$$

Using (3.2.2) the above condition can be written as:

$$\sin\mu_{1s}\sqrt{\beta_1}\epsilon_1 + \sin\mu_{2s}\sqrt{\beta_2}\epsilon_2 = \frac{x_s}{\sqrt{\beta_s}} \qquad (3.2.9)$$

From the other hand if we reason backward we can deduce that:

$$\sin\mu_{s3}\sqrt{\beta_3}\epsilon_3 = \frac{x_s}{\sqrt{\beta_s}} \qquad (3.2.10)$$

Similarly we can write for the trajectory slope in the stripping target:
from the forward reasoning-

$$x'_s = \sqrt{\frac{\beta_1}{\beta_s}}\epsilon_1(\cos\mu_{1s} - \alpha_s\sin\mu_{1s}) + \sqrt{\frac{\beta_2}{\beta_s}}\epsilon_2(\cos\mu_{2s} - \alpha_s\sin\mu_{2s})$$

from the backward reasoning-

$$x'_s = \sqrt{\frac{\beta_3}{\beta_s}}(\cos\mu_{s3} - \alpha_3\sin\mu_{s3}) \qquad (3.2.12)$$

Thus in order to find the kicks $\epsilon_1,\epsilon_2,\epsilon_3$ which produce closed orbit bump with deviation x_s in the stripping target one should solve the system of three equations:

$$\begin{aligned} &\sin\mu_{13}\sqrt{\beta_1}\epsilon_1 + \sin\mu_{23}\sqrt{\beta_2}\epsilon_2 = 0 \\ &\cos\mu_{13}\sqrt{\beta_1}\epsilon_1 + \cos\mu_{23}\sqrt{\beta_2}\epsilon_2 + \sqrt{\beta_3}\epsilon_3 = 0 \\ &\sin\mu_{s3}\sqrt{\beta_3}\epsilon_3 = \frac{x_s}{\sqrt{\beta_s}} \end{aligned} \qquad (3.2.13)$$

Fig.12 shows the calculated injection bump for the COSY cooler synchrotron(3d3d target telescope structure).In order to receive fig.12 we have calculated the necessary strengths of the three bump magnets in approximation of localized trajectory bumps (solving (3.2.13)).After that we have improved the solution using the lattice design program MAD-[19],taking into account that the real bump magnets have nonzero length.The deviations measured by the BPMs are shown on fig.12.The trajectory was proved to be a closed orbit by center of charge tracking for many turns using appropreate injection parameters.

The structure of COSY lattice allows for many different regimes to be realized.Table 3 summarizes the parameters of the injection bumps for different structures of the target telescope.These are of special importance because the slopes of the incoming beam which can be maintained by the injection beam line are restricted.Also the maximum available kicks in the bumpers are 10 mrad.

The acceptance of the injection system is given on fig.14-[20].

From Table 3 and from fig.14 it follows that 2f2f variant of the target telescope lies out of the allowed acceptance.

3.3 The Influence of Linear Errors on the Injection Bump

All the results given in the previous chapter have been calculated assuming ideal magnetic elements.In practice however different errors exist.

One kind of errors disturbing the injection orbit bump are the well known linear perturbations causing closed orbit distortion-field errors in the dipoles,quadrupole misalignments and dipole tilts around the longitudinal axis.

For the cooler synchrotron COSY the expected levels of these perturbations are:

for the relative field errors-

$$\sigma_{\Delta B/B} = 2.10^{-4}$$

for the quadrupole misalignments-

$$\sigma_{\Delta x} = \sigma_{\Delta y} = 0.25 \text{ mm}$$

for dipole tilts-

$$\sigma_{\Delta \theta} = 3.10^{-4} \text{ rad}$$

where σ denotes standard deviation.

Given these levels one can simulate the disturbed injection bump.For one of the possible error distributions the disturbed orbit bump is shown on fig.13.

Despite of the orbit distortion we will continue to inject the beam using the launching conditions of the ideal orbit bump.In other words,in fact we will inject the beam so that the center of the charge will be injected off the actual equilibrium orbit.This will produce coherent oscillations of the beam.

Under the errors listed above these oscillations are shown on fig.15 for the two points with the biggest orbit deviations-the middle bump magnet and the stripping target.

In the case of relative field errors $\sigma_{\Delta B/B} = 5.10^{-4}$ (instead of 2.10^{-4}) the amplitude of the oscillations will be much larger-fig.16.

Another source of errors are the imperfections in the bump magnets themselves.Fortunately the first measurements of the COSY bump magnets power suplies have shown that relative field errors about 0.25% can be achieved.The effect of such small errors is almost negligible.

The amplitude β function in the middle bump magnet is 28,3 m and the dispersion is 1,4 m for the 3d3d target telescope varyant.For an emittance of the injected beam

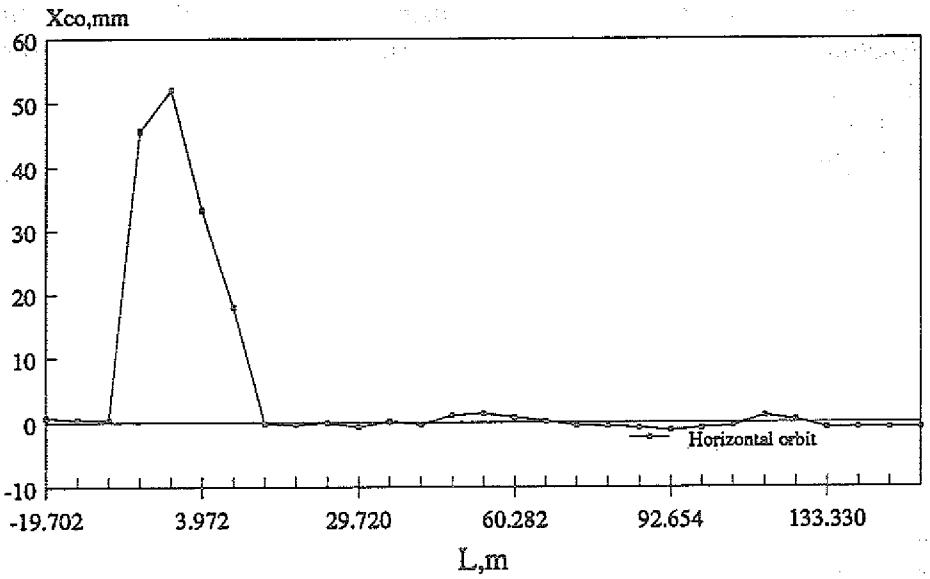

Figure 12.COSY injection bump
(3d3d target telescope structure)

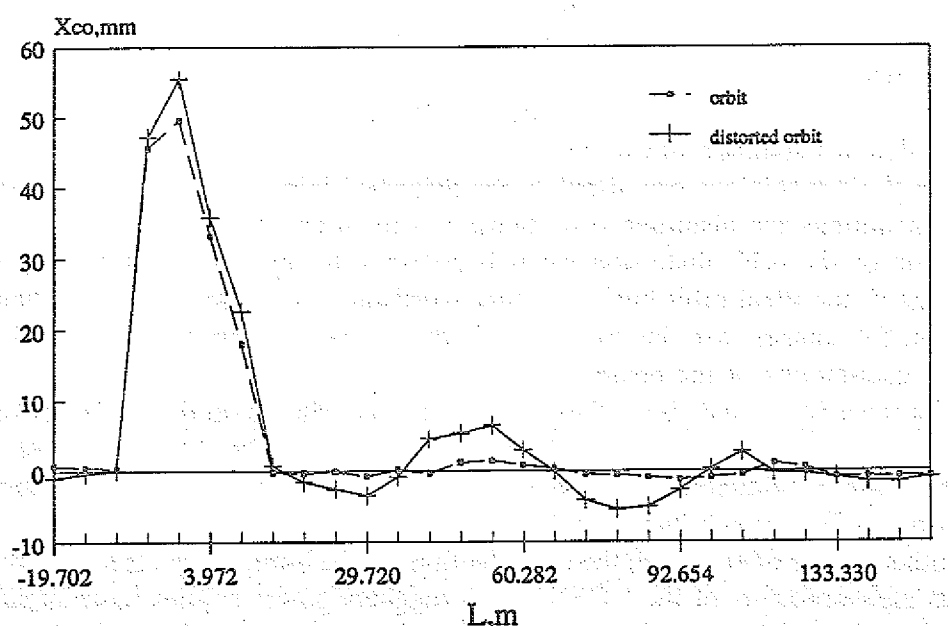

Figure 13.Distorted injection bump.

Table 3.INJECTION BUMPS

target telesc. structure	stripper				BM_1			BM_2			BM_3		
	β,m	μ.2π	x_{co},mm	x'_{co},mr	β,m	μ.2π	ε,mrad	β,m	μ.2π	ε,mrad	β,m	μ.2π	ε,mrad
3d3d	31.99	0.0005	50.2	-0.49	7.84	3.29	7.70	26.83	3.36	-5.62	8.40	0.11	4.89
4f3d	31.85	0.0005	50.3	-0.21	7.90	3.29	7.65	26.78	3.36	-5.29	7.62	0.12	4.67
4f3f	31.53	0.0005	50.1	-0.20	7.90	3.29	7.62	26.76	3.36	-5.25	7.62	0.12	4.63
3f4f	31.81	0.0005	49.8	0.19	7.91	3.29	7.38	26.74	3.36	-4.70	6.87	0.14	4.28
3d4f	31.90	0.0005	49.8	-0.47	7.89	3.29	7.71	26.79	3.36	-5.59	8.37	0.11	4.80
2d2d	31.90	0.0005	49.7	-1.10	7.90	3.29	7.96	26.80	3.36	-6.39	45.24	0.09	2.49
2f2f	31.45	0.0005	49.3	4.53	7.93	3.28	5.67	26.42	3.36	+1.01	2.81	0.43	12.00

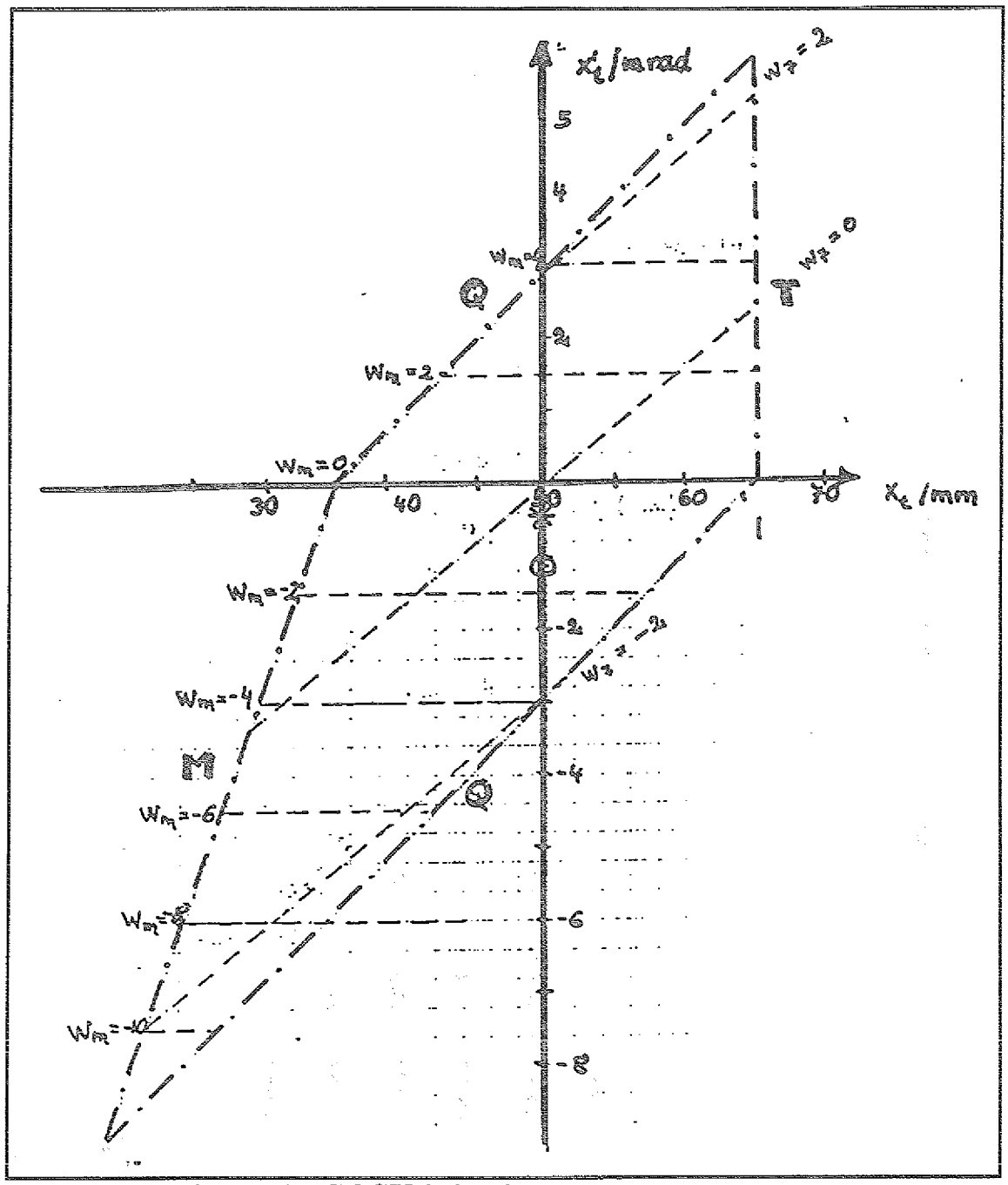

Figure 14.COSY injection system acceptance.

The draft represents the horizontal phase plane at the stripping target.Line M represents the aperture restrictions given by the dipole magnet MD23;line Q-by the quadrupole QT83;line T-by the target.With w_7 the lines of the steering magnet CO_7 are marked;with w_m - the lines of the magnet Di81.* denotes 3d3d varyant,o-2d2d varyant.

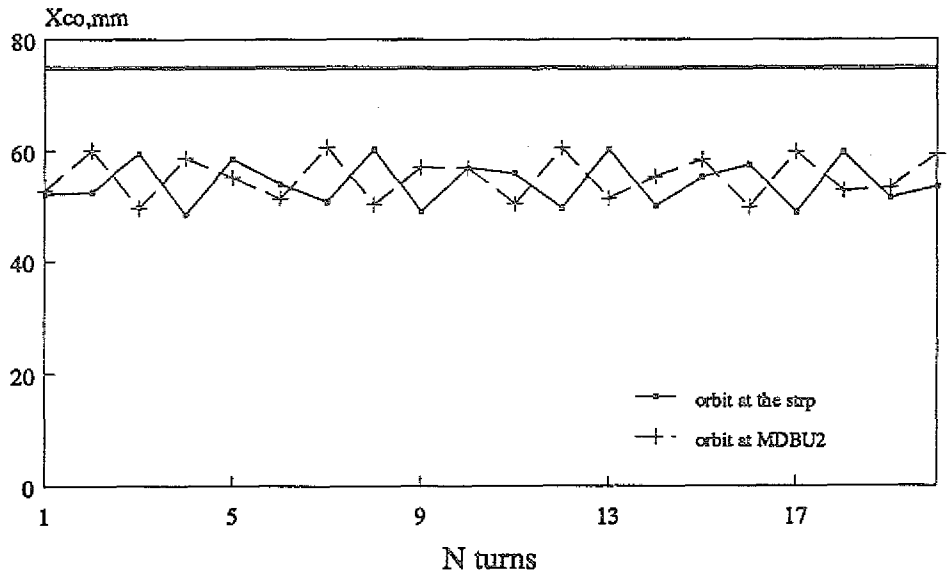

Figure 15.Coherent beam oscillations
(sigma(dB/B) = 2.10^-4)

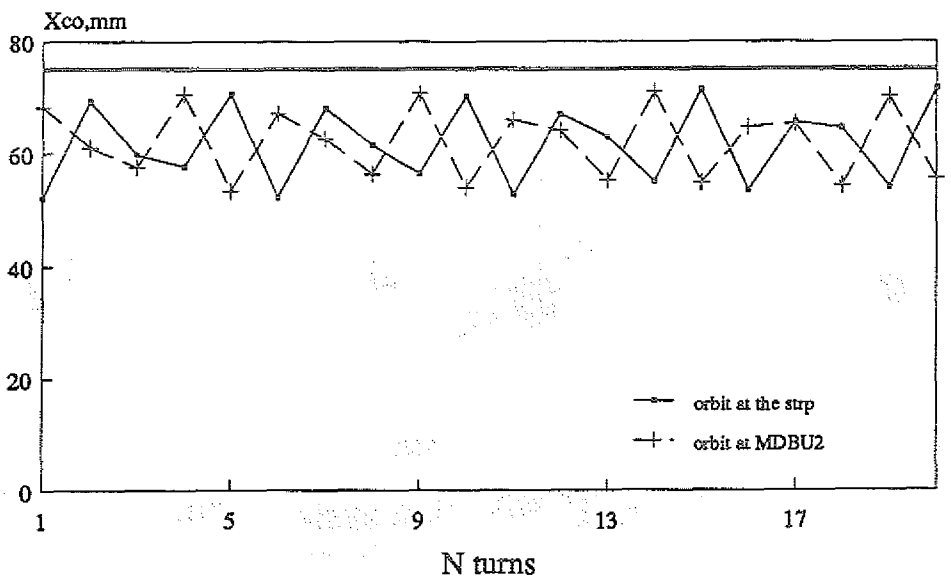

Figure 16.Coherent beam oscillations.
(sigma(dB/B)=5.10^-4)

$\varepsilon_h = \varepsilon_v = 5.\pi$ mm.mrad and momentum spread $\delta=\Delta p/p=\pm 1.5.10^{-3}$ we will have a horizontal radius of the beam in this point equal to 14 mm.Due to the coherent oscillations the center of charge can reach at the middle bumper an deviation from the axis equal to 61 mm.Adding to this the beam radius we get 75 mm,i.e.the beam will nearly touch the vacuum chamber,which is 75 mm far from the axis.We will even lose particles provided the field errors are as large as those on fig.16.

Two obvious ways of avoiding the harmful coherent oscillations exist.

First of all one can try to adjust the injection beam line so that the beam will be put rather on the distorted orbit than on the ideal one.

The better way is to correct the center of charge trajectory, making it to coincide with the predicted orbit.Correcting systems of orbit correcting dipoles and beam position monitors can be used for this.

3.4 Systems with Four Bumpers

Although COSY uses injection system consisting of three bump magnets we give here for completeness a short description of the injection systems using four bump magnets.Such systems allow to improve the injection bump shape-[21].An additional constraint of having zero slope at the stripping target is set-fig.17.

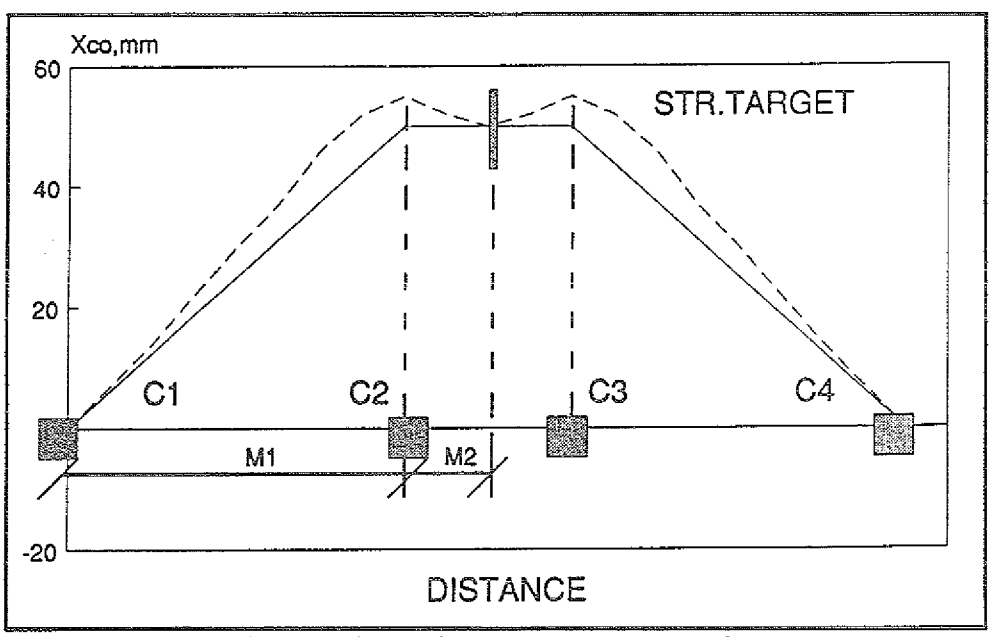

Figure 17.Injection system with four bump magnets

Two cases can be distinguished.

In the first case a drift space is situated between the second and third bump magnets.Using the matrix (3.2.2) we have for the kick in the first bumper:

$$\epsilon_1 = \frac{x_2(=x_s)}{m^1_{12}} = \frac{x_s}{\sqrt{\beta_{C1}\beta_{c2}}\sin\mu_{12}} \qquad (3.4.1)$$

where we have denoted with M^1 the transfer matrix from C_1 to C_2,and with M^2 the transfer matrix from C_2 to the stripping target.

The kick in the second bumper should counteract the trajectory slope x'_2:

$$\epsilon_2 = -x'_2 = -m^1_{22}.\epsilon_1 = -\frac{x_s}{\beta_{c2}}(ctg\mu_{12} - \alpha_2) \qquad (3.4.2)$$

Finally from the symmetry:

$$\begin{aligned} \epsilon_3 &= -\frac{x_s}{\beta_{C3}}(ctg\mu_{34} - \alpha_3) \\ \epsilon_4 &= \frac{x_s}{\sqrt{\beta_{C3}\beta_{C4}}\sin\mu_{34}} \end{aligned} \qquad (3.4.3)$$

In the second case when no drift space but some elements(quadrupoles for instance) lie between the second and the third bumper it is still possible to obtain a zero slope in the stripping target although the trajectory is more complicated-the dotted line on fig.17.

From the transfer matrix M^1:

$$\begin{aligned} x_2 &= m^1_{12}.\epsilon_1 \\ x'_2 &= m^1_{22}.\epsilon_1 \end{aligned} \qquad (3.4.4)$$

From the constraints that should be fulfilled at the stripping target:

$$\begin{aligned} x_s &= m_{11}^2 . x_2 + m_{12}^2 . (x'_2 + \epsilon_2) \\ 0 &= m_{21}^2 . x_2 + m_{22}^2 . (x'_2 + \epsilon_2) \end{aligned} \tag{3.4.5}$$

(3.4.5) yields:

$$\begin{aligned} x_s &= \frac{m_{12}^1}{m_{22}^2} . \epsilon_1 \\ \epsilon_2 &= -\frac{m_{22}^3}{m_{22}^2} . \epsilon_1 \end{aligned} \tag{3.4.6}$$

where we have denoted with M^3 the product $M^2.M^1$,i.e.the transfer matrix between C_1 and the stripping target.

Applying the Twiss representation of the transfer matrix (3.2.2) we get:

$$\begin{aligned} x_s &= \sqrt{\beta_{C1}\beta_s} \frac{\sin\mu_{12}}{(\cos\mu_{2s} - \alpha_s \sin\mu_{2s})} \epsilon_1 \\ \epsilon_2 &= -\sqrt{\frac{\beta_{C1}}{\beta_{C2}}} \frac{(\cos\mu_{1s} - \alpha_s \sin\mu_{1s})}{(\cos\mu_{2s} - \alpha_s \sin_{2s})} \epsilon_1 \end{aligned} \tag{3.4.7}$$

And from the symmetry:

$$\begin{aligned} x_s &= \sqrt{\beta_s \beta_{C4}} . \frac{\sin\mu_{34}}{(\cos\mu_{s3} - \alpha_s . \sin\mu_{s3})} \\ \epsilon_3 &= -\sqrt{\frac{\beta_{C4}}{\beta_{C3}}} . \frac{(\cos\mu_{s4} - \alpha_s . \sin\mu_{s4})}{(\cos\mu_{s3} - \alpha_s . \sin\mu_{s3})} \end{aligned} \tag{3.4.8}$$

3.5 First Turn Correction

In the very begining of the accelerator operation (during the initial tuning) rather big errors may occur.Such big errors may cause a complete beam loss before a full turn around the circumference to be performed.

As an example of such hypothetical big error we have simulated the case of an error $\Delta B/B = 5.10^{-3}$ in the first lattice dipole.Fig.18. shows the distorted injection orbit which reaches 69 mm.

As we have mentioned before two ways of operation are possible in principle.The first one is to try to launch the injected beam on the distored orbit using two correcting magnets placed in the injection beam line.Generally speaking it is possible to adjust the launch parameters-deviation and slope using two dipole correctors.

However if for some extra reasons we have big errors (much bigger than the random errors in dipole fields and quadrupole positions) our orbit will be highly perturbated.In such cases even following the distored orbit (which is a closed curve) we will lose most of the particles on the walls of the vacuum chamber-fig.19.

Even if we have no extra big error it is preferable to act actively on the beam and to try to correct the injection orbit making it to coincide with the designed orbit as close as possible.

This second approach assumes the use of a system of correcting magnets and related with them detectors measuring the orbit deviations.

Let's return back to our hypotethical case of 5.10^{-3} relative field error in the first lattice dipole.If we continue to inject the beam following the ideal launch parameters-fig.19,it will not be able to make full turn around the machine and will hit the vacuum chamber just before the last monitor BPM28.Thus we have information about the orbit not from all BPMs and our first task is to thread the beam along the entire circumference of the machine.

By that time our circular accelerator acts as a beam line and we can use one of the beam threading algorithms described in part 2.

For the cooler synchrotron COSY we have used the least squares approach.

However because very often the available corrector strengths are not big enough for the exact correction to be realized we have improved the algorithm adding parameter constraints.In order to limit the maximum corrector kicks we use the penalty function method-[22].

3.6 Correcting Algorithm

Working on the first turn (until the beam closes itself on the second turn) one may look at the accelerator as a beam line.The BPMs "see" only those correctors which are placed before them.

Let:

$$\eta_i = \frac{x_i}{\sqrt{\beta_i^{PUE}}} \qquad (3.6.1)$$

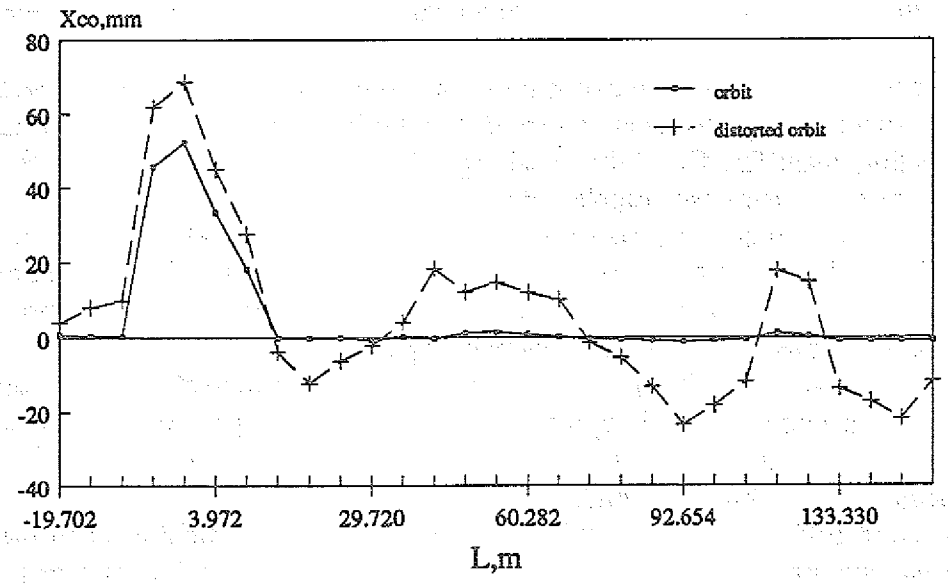

Figure 18.Distorted injection orbit.
(error dB/B=5.10^-3 in MDBE1)

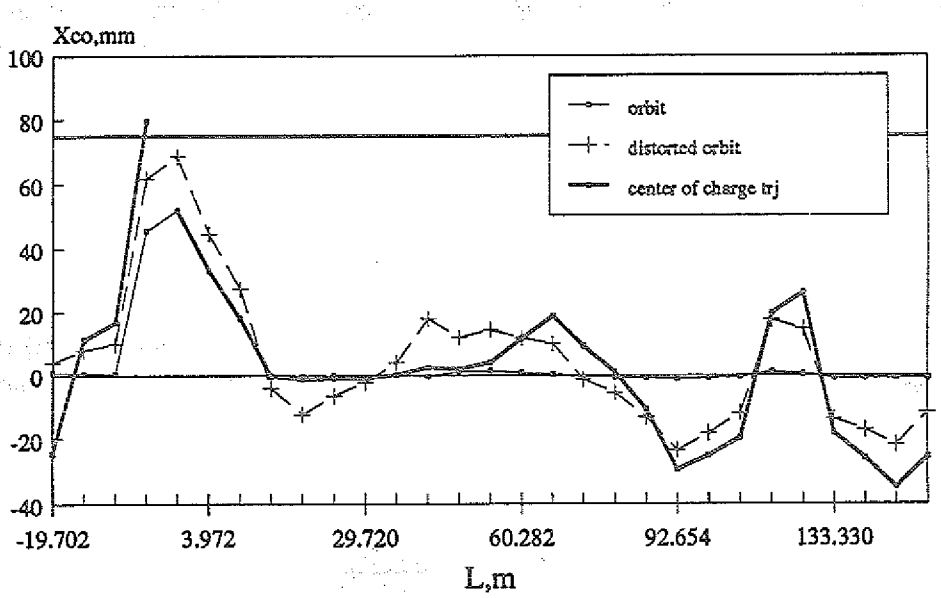

Figure 19.Center of charge trajectory.
(error dB/B=5.10^-3 in MDBE1)

is the normalized deviation of the center of the beam charge in the i-th pickup.

Let:

$$\epsilon_j^* = \sqrt{\beta_j^{COR}}\,\epsilon_j \qquad (3.6.2)$$

is the "generalized" kick in the j-th correcting magnet.

Applying the principle of superposition we can write:

$$\eta_i = \sum_{j=1}^{K} a_{ij}\epsilon_j^* \qquad (3.6.3)$$

where:

$$a_{ij} = \sin Q(\phi_i^{PUE} - \phi_j^{COR})\,e(\phi_i^{PUE} - \phi_j^{COR}) \qquad (3.6.4)$$

and:

$$e(x) = \begin{cases} 1, & x>0 \\ 0, & x<0 \end{cases} \qquad (3.6.5)$$

is the Heviside function.

Following the least squares approach we will define our goal function as:

$$\Psi(\epsilon_j^*) = \sum_{i=1}^{n}\left[(\eta_i^{PUE} - \eta_i^{des}) + \sum_{j=1}^{k} a_{ij}\epsilon_j^*\right]^2 \Rightarrow Min \qquad (3.6.6)$$

In (3.6.6) η^{des} denotes the desired center of charge trajectory ;n and k are the current numbers of used pickups and correctors.In the case when we lose the beam before the full turn to be carried out the current number of used pickups n is less than the total number of pickups N and the current number of switched on correctors k is less than the total number of available correctors K.The current correctors number-k is chosen so that $\phi_k<\phi_n$.

It makes sense to add the very next pickup to the pickups actualy reading beam deviations,assuming that it reads a trajectory deviation equal to +(or -) the radius of the vacuum chamber.This gives an additional information about the trajectory slope in the last pickup.

In practice there are limitations on the maximum allowed kicks in the correcting magnets:

$$| \epsilon_j | < \Delta \qquad (3.6.7)$$

Thus we face a constrained optimization problem-[22].

In order to solve this problem we will use the penalty function method.

The general idea of the method of the penalty functions is to reduce the constrained optimization problem to a series of unconstrained problems.To do this we will add to our goal function (3.6.6) a so-called penalty function $\alpha(\epsilon_j^*)$ which is chosen in such a way that it will "punish" the function $\Psi(\epsilon_j^*)$ if the constraints (3.6.7) are broken.

We have chosen:

$$\alpha(\epsilon_j^*) = \sum_{j=1}^{K} \max(0 , \epsilon_j^{*2} - \Delta^2) \qquad (3.6.8)$$

where:

$$\Delta_j = \frac{\Delta}{\sqrt{\beta_j^{COR}}} \qquad (3.6.9)$$

We will solve the following series of unconstrained optimization tasks:

$$\Psi'(\epsilon_j^*, \mu_k) = \Psi(\epsilon_j^*) + \mu_k \alpha(\epsilon_j^*) \Rightarrow Min \qquad (3.6.10)$$

where $\mu_k>0$,k=1,2,3... are parameters and:

$$\lim_{k \to \infty} \mu_k = \infty \qquad (3.6.11)$$

Let $\varepsilon^*_{j,k}$,k=1,2,3... are the consecutive points of minimum of $\Psi'(\varepsilon^*_j,\mu_k)$.
Then it can be proved-[22] that under some conditions concerning the goal function:

$$\lim_{k\to\infty} \epsilon^*_{j,k} = \epsilon^*_{j,opt} \tag{3.6.12}$$

and:

$$\lim_{k\to\infty} \left[\min \Psi'(\epsilon^*_j, \mu_k) \right] = \Psi(\epsilon^*_{j,opt}) \tag{3.6.13}$$

$\varepsilon^*_{j,opt}$ being the minimum point of (3.6.6) under the constraints (3.6.7).

The solution of the minimization problem (3.6.10) can be written in the following matrix form:

$$\vec{\epsilon}^*_j = -(A^T A + \mu_k E)^{-1} A^T.(\vec{\eta}^{PUE} - \vec{\eta}^{des}) \tag{3.6.14}$$

where A is the matrix (3.6.4),E denotes the identity matrix and $\vec{\eta}^{PUE}$ and $\vec{\eta}^{des}$ are the vectors of the measured and desired trajectories.

In practice one starts with a sufficiently small value μ_1;solves (3.6.10) and checks:

$$\mu_k.\alpha(\epsilon^*_{j,k}) < \delta \tag{3.6.15}$$

where δ is the desired accuracy.

If (3.6.15) is not fulfilled he goes to the next value of the parameter μ_k:

$$\mu_{k+1} = \beta.\mu_k \tag{3.6.16}$$

3.7 The Computer Program FTURN

We have realized the above described correcting algorithm in the computer code FTURN. FTURN is a C-language program.

Some of the input parameters are entered into the computer from the keyboard during a dialogue with the user.

The data about the BPMs are read from the input files XPUE.DAT for the horizonthal pickups and YPUE.DAT for the vertical pickups.These files contain the following tables(including the first four title lines):

MONITORS DATA

No	Beta,m	Mu	Xdes,mm	X,mm
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-

The data about the correcting dipoles are read from the input/output files XCOR.DAT for the horizontal correctors and YCOR.DAT for the vertical correctors.These files containe the following tables(including the first four title lines):

CORRECTORS DATA

No	Beta,m	Mu	Eps
-	-	-	-
-	-	-	-
-	-	-	-

In the begining of the correction session correctors kicks ε_j in the files XCOR.DAT and YCOR.DAT are set equal to zero.The first iteration of the correction process sets some nonzero values for these kicks.Every next iteration of the correction algorithm adds the newly calculated corrector kicks to the old ones.Thus the values of the corrector kicks in the files XCOR.DAT and YCOR.DAT correspond to the final correction.

FTURN has two main options-beam threading and first turn closing.The closing option will be discused further in this part.

Fig.20 represents the FTURN block diagram.

3.8 Examples

First we will continue with the example described in §3.5.The state before the correction was given on fig.19.The corrected center of charge trajectory applying FTURN is shown on fig.21.To achieve this result we have applied FTURN in two succesive correction iterations.The maximum necessary corrector kick was 1.6 mrad.All the 20 horizontal orbit correctors have been used.

Fig.22 shows the corrected trajectory given the same errors when we have restricted the corrector strengths to 1.2 mrad.

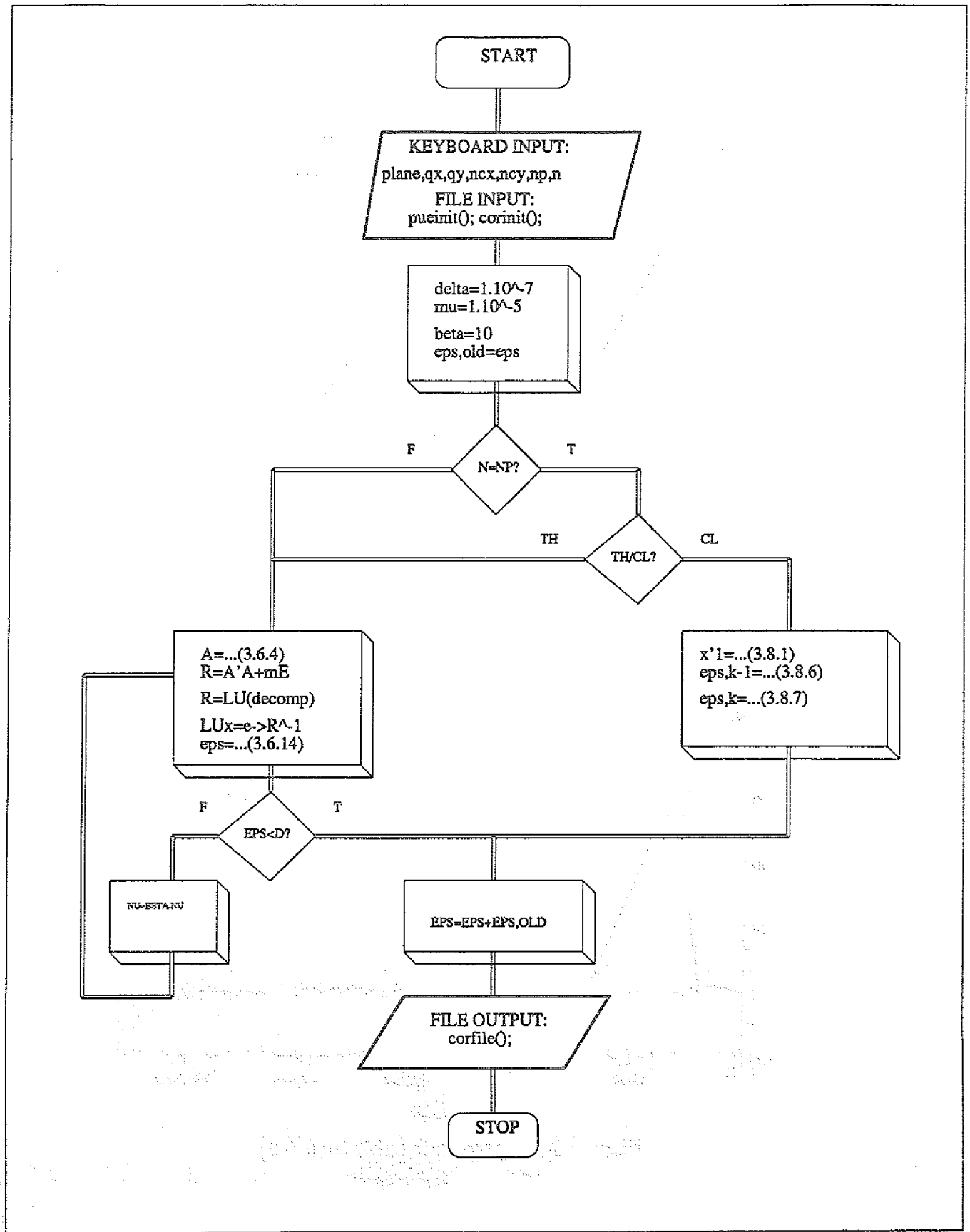

Figure 20.FTURN block diagram

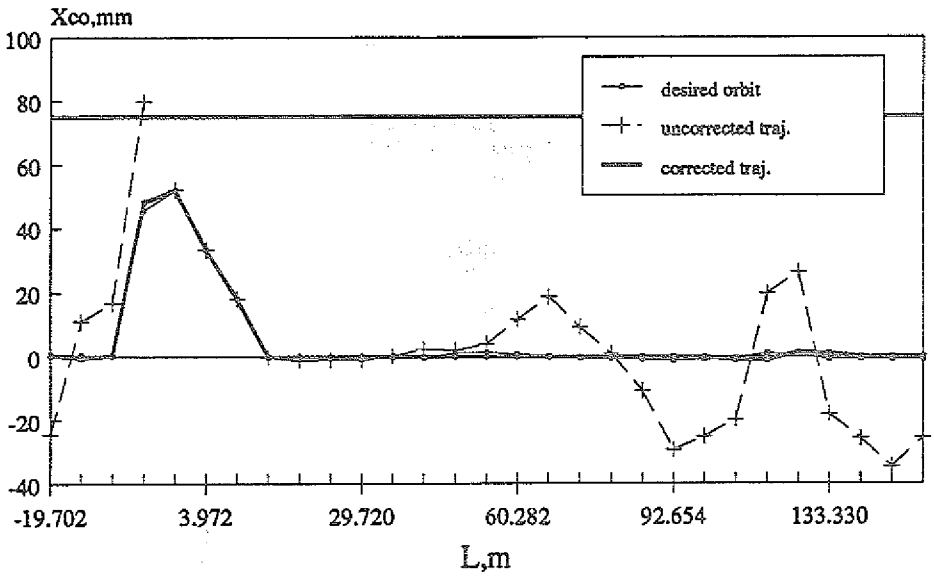

Figure 21. Corrected first turn traj.
(error dB/B=5.10^-3 in MDBE1)

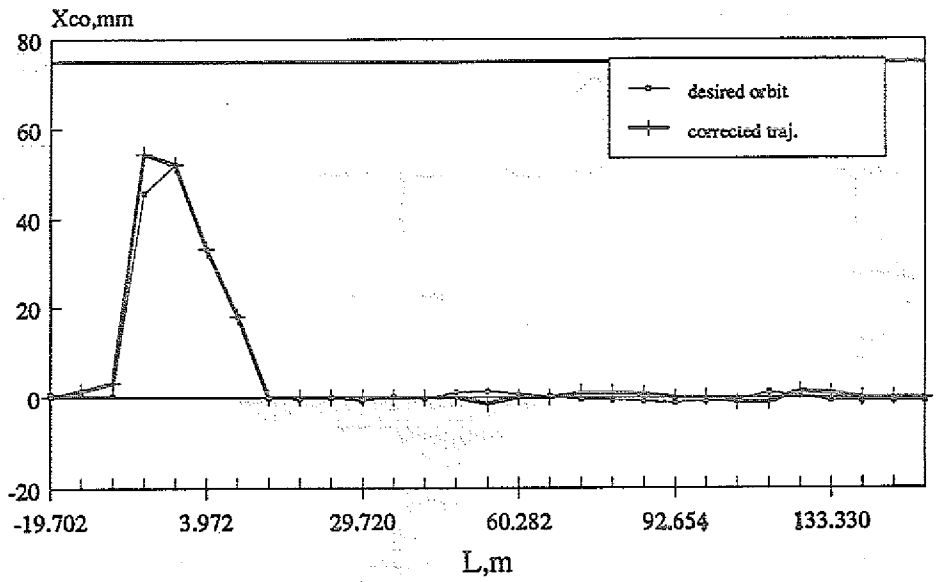

Figure 22.Corrected furst turn traj.
(kicks < 1.2 mrad)

In order to to examine one very poor case we assumed that relative field errors equal to 5.10^{-3} acted simultaneously in the first and last bending magnets-fig.23.The beam undergone to such errors was not able to pass even 2/3 of the circumference.After the first iteration of FTURN correction we threaded the beam almost to the end of the accelerator circumference-fig.24.The second iteration of FTURN (using the new pickup readings) allowed for the full first turn to be achieved-fig.25.

The center of charge trajectory on fig.25 lies quite close to the designed injection orbit.Nevertheless our final goal is not reached yet because the trajectory doesn't close itself,i.e.the second turn doesn't coincide with the first one.

An additional procedure of closing the second turn onto the first turn has to be applied.

3.9 First Turn Closing

After threading the beam entire turn around the accelerator one should ensure that the beam closes itself,i.e. that the second (and all following turns) coincides with the first turn.

One straightforward idea is to use the last two correctors in the ring for the beam closing.This is similar to the exit steering in the beam lines-fig.2.

To performe the closing we need information about both first and second turns.This information can be provided by the first two BPMs if they work in the single turn mode.

Let x_1^1 and x_2^1 are the first turn readings in BPM_1 and BPM_2 and x_1^2 and $_2^2$-the second turn readings.

Let also M^1 is the beam transfer matrix between C_{k-1} and BPM_1 ; M^2-between C_k and BPM_2 ; M^3-between BPM_1 and BPM_2.

Knowing the transfer matrix M^3 between BPM_1 and BPM_2 and the readings in these monitors (x_1 and x_2) we can calculate the slope in the first monitor:

$$x'_1 = \frac{x_2 - m_{11}^3 x_1}{m_{12}^3} \qquad (3.8.1)$$

where:

$$m_{11}^3 = \sqrt{\frac{\beta_2^{PUE}}{\beta_1^{PUE}}}\left[\cos(\mu_2^{PUE} - \mu_1^{PUE}) + \alpha_1^{PUE}\sin(\mu_2^{PUE} - \mu_1^{PUE})\right] \qquad (8.2)$$

$$m_{12}^3 = \sqrt{\beta_1^{PUE}\beta_2^{PUE}}\sin(\mu_2^{PUE} - \mu_1^{PUE}) \qquad (3.8.3)$$

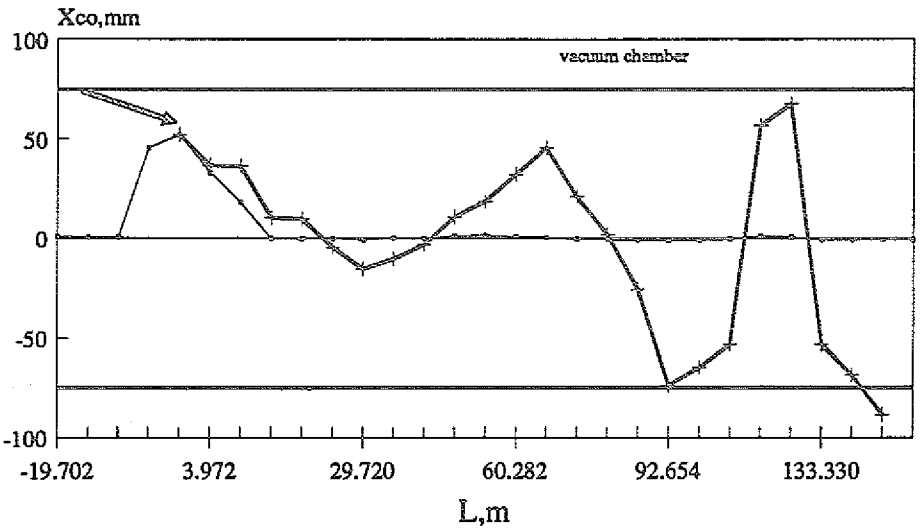

Figure 23.Center of charge trajectory
(relative field errors 5.10^-3 in
MDBE1 and MDBE24)

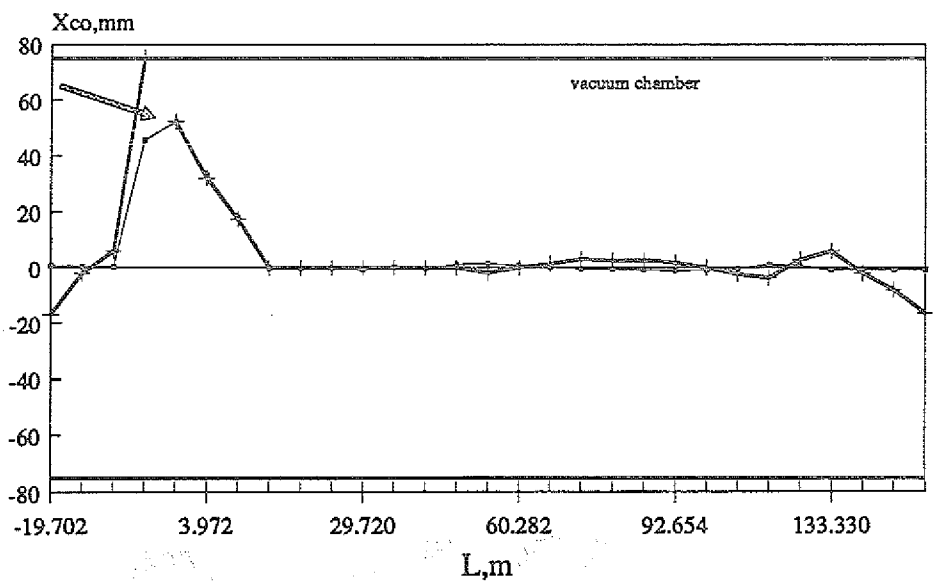

Figure 24.The trajectory from fig.23
after the first correction

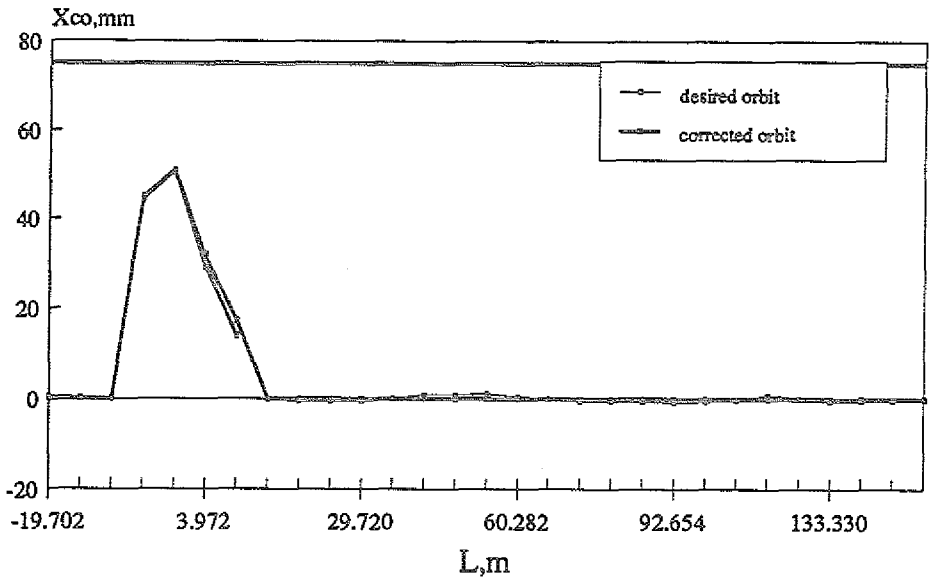

Figure 25.Corrected orbit
(before closing)

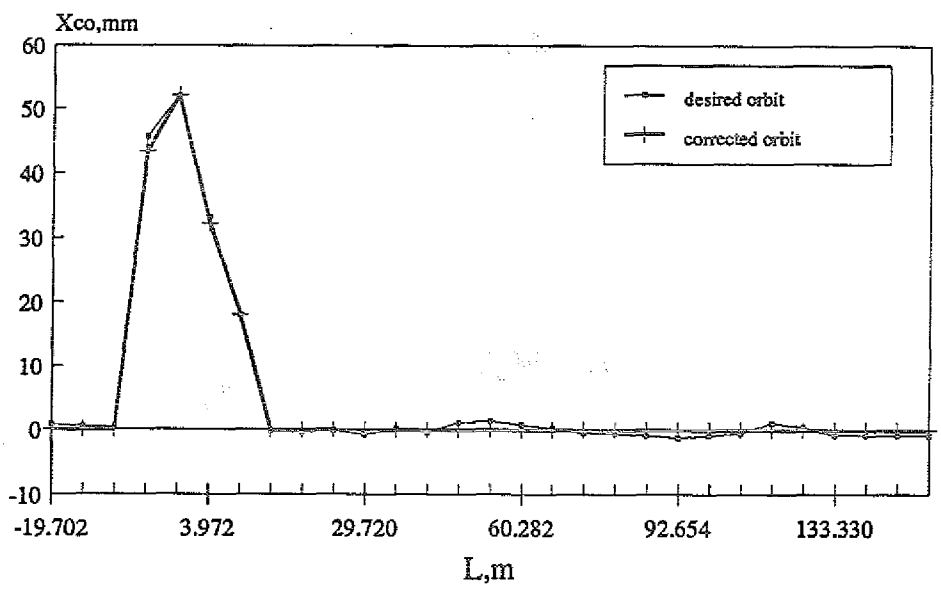

Figure 26.Corrected orbit
(after closing)

In order for the second turn to be closed onto the first one the strengths of the two correctors should fulfil the following equations:

$$M^1 \cdot \begin{pmatrix} 0 \\ \epsilon_{k-1} \end{pmatrix} + M^2 \cdot \begin{pmatrix} 0 \\ \epsilon_k \end{pmatrix} = \begin{pmatrix} \Delta x_1 \\ \Delta x'_1 \end{pmatrix} \tag{3.8.4}$$

where:

$$\begin{aligned} \Delta x_1 &= x_1^1 - x_1^2 \\ \Delta x'_1 &= x'^1_1 - x'^2_1 \end{aligned} \tag{3.8.5}$$

are the linear and angular discrepancies between the second and the first turns in BPM_1.

We receive from (3.8.4):

$$\epsilon_{k-1} = \frac{\Delta x m_{22}^2 - \Delta x' m_{12}^2}{m_{12}^1 m_{22}^2 - m_{22}^1 m_{12}^2} \tag{3.8.6}$$

$$\epsilon_k = \frac{\Delta x' m_{12}^1 - \Delta x m_{22}^1}{m_{12}^1 m_{22}^2 - m_{22}^1 m_{12}^2} \tag{3.8.7}$$

where:

$$m_{12}^1 = \sqrt{\beta_1^{PUE} \beta_{k-1}^{C}} \sin(\mu_1^{PUE} - \mu_{k-1}^{C}) \tag{3.8.8}$$

$$m_{22}^{1}=\sqrt{\frac{\beta_{k-1}^{C}}{\beta_{1}^{PUE}}}\left[\cos(\mu_{1}^{PUE}-\mu_{k-1}^{C})-\alpha_{1}^{PUE}\sin(\mu_{1}^{PUE}-\mu_{k-1}^{C})\right] \qquad (8.9)$$

$$m_{12}^{2}=\sqrt{\beta_{1}^{PUE}\beta_{k}^{C}}\sin(\mu_{1}^{PUE}-\mu_{k}^{C}) \qquad (3.8.10)$$

$$m_{22}^{2}=\sqrt{\frac{\beta_{k}^{C}}{\beta_{1}^{PUE}}}\left[\cos(\mu_{1}^{PUE}-\mu_{k}^{C})-\alpha_{1}^{PUE}\sin(\mu_{1}^{PUE}-\mu_{k}^{C})\right] \qquad (8.11)$$

The above procedure is implemented in the computer code FTURN.All the necessary data are read interactively from the keyboard.The calculated kicks in the last two correctors in the ring are put into the output files XCOR.DAT and YCOR.DAT.

The procedure should be applied iteratively until the necessary accuracy of the closing will be reached,because the changes in the settings of the C_{k-1} and C_k slightly change the Twiss functions.

Fig.26 shows the corrected trajectory from fig.25 after several iterations of the closing procedure.

It is also possible to treat the closing problem applying the LSQ correction algorithm.As a matter of fact one can look at the first turn monitor readings as a desired trajectory and at the second turn as a trajectory to be corrected.

The first several beam position monitors give information both about the first turn and the second turn.

The last several correctors in the ring can be used to match the second turn onto the first,following the LSQ procedure.

We give an example of this approach on fig.27.It represents the center of charge trajectory under relative field error $5.0.10^{-3}$ in MDBE22 dipole.The beam successfully goes the entire ring but the second turn is far away from the first one and has big deviations.

To close the second turn onto the first we have used the first four position monitors-N0 25,26,27,28 and the last four correctors-No 14,15,16,17.One should not forget to add 2π to the monitor's phase if the monotor reads the second turn deviations.

The closed trajectory is shown on fig.28.

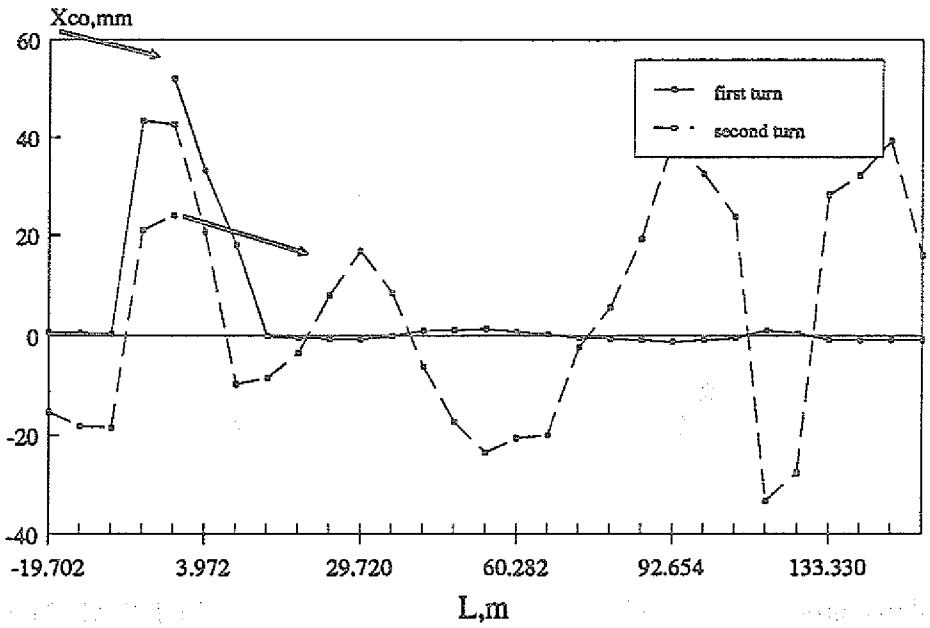

Figure 27.Trajectory before closing

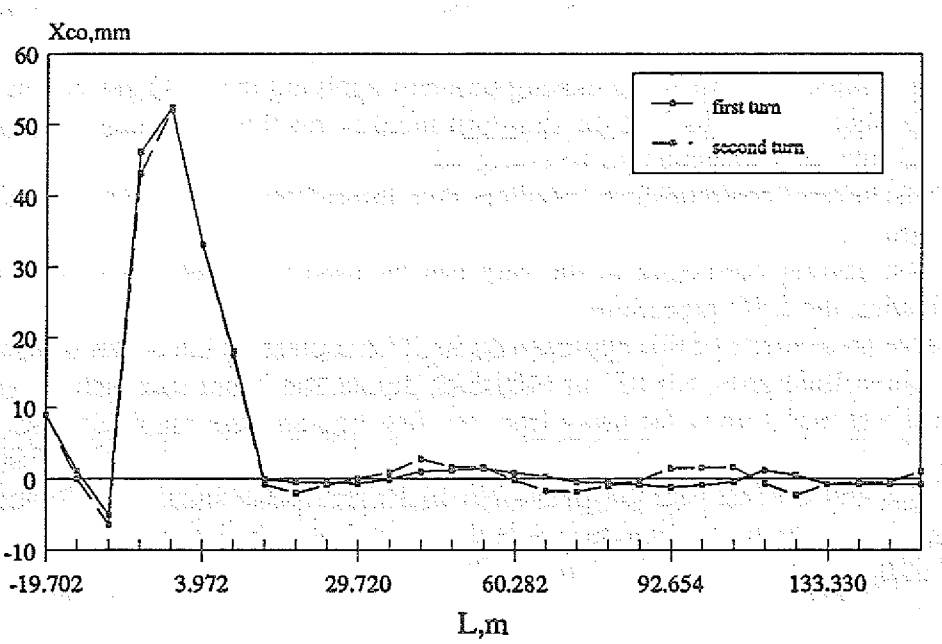

Figure 28.Trajectory after closing

4.Conclusions

The injection orbit in the cooler synchrotron COSY has been studied without and with the influence of dipole errors and quadrupole misalignments.A large number of possible lattice configurations have been examined and some of them have been proved to lie out of the injection acceptance.

The errors will cause coherent beam oscillations if the orbit has not been corrected.The amplitudes of these coherent oscillations are such that the beam will almost touch the vacuum chamber assuming 2.10^{-4} relative field errors and we will even lose particles assuming 5.10^{-4} relative field errors.

In order to thread the beam entire turn around the accelerator ring and make the center of charge trajectory to follow the injection orbit as close as possible a first turn correction algorithm has been developed.The algorithm uses the least squares approach but allows for constraints on the correctors kicks to be set.

The first turn correction algorithm has been coded in the C-language program FTURN.

A lot of COSY first turn simulations have been done.They show that provided we are able to measure the first turn orbit with a satisfactory accuracy it will be possible to thread the beam entire circumference around the machine and to match the designed injection orbit quite closely.

The problem of closing the second turn onto the first one has also been discussed.Two technics have been tried for this-first turn closing by means of the last two correctors in the ring and first turn closing applying the LSQ algorithm.

Both the first turn correction and the first turn closing should be applied iteratively until the necessary accuracy will be reach.

The procedure of the first turn steering includes:

a.) Threading the beam entire turn around the ring.Making the center of charge trajectory to follow the designed injection orbit.

b.) Closing the second turn onto the first turn.

c.) Fine-steering the closed orbit in the acceleration mode with one of the global orbit correction algorithms-[1] ,when the injection bump magnets are swith off and the beam position monitors work in multi-turn regime with much better accuracy.

5.Acknowledgements

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References

1. D.Dinev.Simulation and Correction of the Closed Orbit in the Cooler Synchrotron COSY.KFA-Julich,Jul-2406,Nov.1990.

2. K.Kilian,R.Maier,S.Martin,U.Pfister.Cooler Synchrotron COSY-Julich.User Guide.KFA-Julich,May,1990.

3. P.J.Bryant.Beam Transfer Lines.CERN Accelerators School,General Accelerator Physics.Gif-sen-Yvette,Paris,1984,p.358.

4. J.P.Koutchouk.Trajectory and Closed Orbit Correction.CERN LEP-TH/89-2,Geneva,1989.

5. R.Raya,A.Russell,C.Aukenbrandt.The Tevatron Orbit Program.Nuclear Instruments and Methods,v.A242,1989,p.15.

6. V.Paxson,S.Peggs,L.Schachinger.Interactive First Turn and Global Orbit Correction.European Particle Accelerator Conference,Rome,1988,v.2,p.824.

7. J.C.Sheppard et al.Beam Steering in the SLC Linac.IEEE Trans.Nucl.Sci.,v.NS-32,p.2180,1985.

8. M.Lee et al.Modern Approach to Accelerator Simulation and On-line Control.IEEE Trans.Nucl.Sci.1987 Particle Accelerator Conference,v.1,p.611.

9. V.Paxson et al.A Scientific Workstation Operator Interface for Accelerator Control.IEEE Trans.Nucl.Sci.1987 Particle Accelerator Conference,v.1,p.556.

10. E.Theil et al.The Inpact of New Computer Technology on Accelerator Control.IEEE Trans.Nucl.Sci.1987 Particle Accelerator Conference,v.1,p.529.

11. L.Schachinger,R.Talman.Teapot:A Thin-Element Accelerator Program for Optics and Tracking.Particle Accelerators,v.22,1987.

12. G.Guignard,Y.Marty.PETROC user's guide.CERN/ISR-BOM-TH/81-32,Geneva,1981.

13. S.H.Clearwater,M.J.Lee.Prototype Development of a Beam Line Expert System.IEEE Trans.Nucl.Sci.1987 Particle Accelerator Conference,v.1,p.532.

14. M.J.Lee,S.Kleban.SLC Beam Line Error Analysis using a Model-Based Expert System.European Particle Accelerator Conference,Rome,1988,p.767.

15. D.P.Weygand.Artificial Inteligence and Accelerator Control.IEEE Trans.Nucl.Sci.1987 Particle Accelerator Conference,v.1,p.564.

16. H.Pines,F.Selph.Automatic Tuning of the LBL Bevalac Transfer Line.IEEE Trans.Nucl.Sci,v.NS-28,1981,p.2165.

17. M.Rogge et al.The Injection-Extraction Beam Lines at COSY.KFA-Institut fur Kernphysik,1986 Annual Report,p.120.
D.Prasuhn.Internal Target Experiments and Stripping Ingection in COSY.KFA-Institut fur Kernphysik.1990 Annual Report,p.163.

18. U.Bechstedt et al. Injection and Extraction Magnets of COSY-Julich.Second European Particle Accelerator Conference,Nice,1990,p.1257.

19. F.Ch.Iselin,J.Niederer.The MAD Program.Version 6.User's Reference Manual.CERN/LEP-TH/87-33,Geneva,1987.

20. M.Rogge,S.Martin,D.Prasuhn.Remarks on the Steerer Settings in the Injection Beam Line at the COSY Tune 3.38/3.38.COSY Internal Report,6.6.91,1991.

21. C.W.Planner,G.H.Rees.A Separated H^- Injection System in a Modified Accumulator Lattice for the TRIUMF Kaon Factory.TRI-DN-89-K98,Vancouver,1989.

22. P.E.Gill,W.Murray,M.H.Wainwright.Practical Optimization.Accademic Press,1982.

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