CLOSED ORBIT DISTORTIONS AND THEIR CORRECTIONS IN THE 600 MEV ELECTRON-POSITRON ACCUMULATOR AT LEP

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Abstract: This report covers the work done on closed orbit matters - starting at the design of the machine - with simulations of closed orbit distortions and their corrections which led to the saving of an expensive correction scheme with steering dipoles. It describes the analysis of measurements at commissioning and the orbit corrections with their impact on machine parameters such as injection efficiency and accumulation rate. The measuring system and its performance are indicated.

Methods, used at Simulations and Corrections

The MICADO METHOD

The MICADO METHOD [1] reduces orbit distortions by superposing orbit perturbations from a small number of correctors out of a total of N candidates. In a first iteration all correctors are tried out. The most efficient one is kept for the 2nd iteration where the minimisation is repeated, now combining the "best" magnet with one of the (N-1) still available candidates. Each iteration increases the number of correctors involved. The process is halted when the peak-to-peak distortion reaches a pre-defined value.

The FITTING METHOD and GOLD

The FITTING METHOD [2] and GOLD (a generic orbit and lattice debugger) [3] are based on fitting the measured positions of the closed orbit (c.o.) with betatron oscillations locally.

Discontinuities in the fits point to the sources of orbit distortions. The observation of the values of the fits - when suppressing detector readings in the suspected regions - allows to distinguish between a kick in the machine and a wrong monitor reading. In a second step, both the position and the magnitude of the kicks are evaluated in order to predict the corresponding improvement of the closed orbit distortions.

At simulation, we used MICADO. Early in the commissioning, GOLD was tried out for some orbit analysis, but the full c.o. analysis and corrections were based on MICADO and the FITTING METHOD. The latter two are related to lattice programs, namely PETROC [4] for the first one and MAD [5] for the second one.

Simulations at the Design Phase of the Accumulator and Decisions based on their Results

The lattice of the accumulator used for simulations consists of 68 magnetic elements: 16 combined function magnets, 40 quadrupole magnets and 12 sextupole magnets [6].

Several series of simulations with samples of 20 to 40 per series were done and they

a) led from an originally foreseen correction system with dipoles, regularly distributed w.r.t phase advance and optimally w.r.t. β functions to a system with unregularly distributed detectors and orbit corrections to be achieved by displacements of the ring magnets (quadrupole magnets);

b) provided us with expection values for closed orbit distortions due to field tolerances and precision of element positioning. They also indicated the efficiency of the correction systems and therefore the residual orbits we had to expect. This enabled us to define the minimum vertical gap height of the bending magnet, taking into account the beam dimensions at injection, some beam blow-up due to dilution of emittances at injection matching, and some beam stay clear for mis-steering.

The results of simulations are summarized in Table 1. The finally chosen correcting scheme was expected to provide corrections of a factor of 3.

Table 1 : Results from Simulations

Definitions $\hat{x}$ =max. absolute distortion from x-plane for 98 out of 100 machines with errors $x_{pp}=\lvert x_{max}\rvert+\lvert x_{min}\rvert \leq 2*\hat{x}$=peak to peak distr. $ex=x_{pp}$ before correction/x_{pp} after corr.		
Tolerances $\delta_x=\delta_z=2*10^{-4}$ [m] =error of positioning $\delta_{xd}=\delta_{zd}=4*10^{-4}$ [m] =tol. of detector signal $\delta_\alpha=2*10^{-4}$ [rad]=tilt around longit.axis $\Delta B/B=5*10^{-4}$ =field error in bending magnet equivalent to $7*10^{-4}$ [m] for comb.function magnet (all rms values) with $K=.5[m^{-2}]$, $\rho=1.43[m]$		
Expected distortions $\hat{x} \leq 6.8*10^{-3}$ [m] distortion f. field err. $\hat{x} \leq 1.9*10^{-3}$ [m] dist. from position.err. $\hat{x} \leq 9.4*10^{-3}$ [m] } distortion when all $\hat{z} \leq 8.1*10^{-3}$ [m] } errors present		
Orbit corrections with MICADO, PETROC as lattice program	ex	ez
1. window frame dipoles (Bmax $8*10^{-3}$ T) 14 vert. 16 horizon. 18 magnetic pickups, well distributed w.r.t phase advance	$\geq$10	$\geq$6.6
2. 14 vert. 12 horiz. dipoles, making use of 2 inj. bumpers, 17 pickups, no element in the injection/ejection zones	3.9	2.3
3. corr. by displacement of some of all ring magnets, 2 iterations, δ_{xd}, δ_{zd} including, needed max.kicks in x,z plane 2, 1.5 mrad = $\Delta x, \Delta z \sim 8, 6$ mm for unfavourable elements.	2	1.6
4. corr. by displacement of some of the 40 quadrup., displacem. limited to max. 3 mm δ_{xd}, δ_{zd} included, addition of one pickup more than 2 iterat. allowed (3-6 needed)	3	3

Measurements, Analysis and Correction of the vertical Closed Orbit

Fig. 1 shows the vertical c.o. distortion and its fluctuations. z_{ppd} (z_{pp} at position of detectors) $= 9.4 \pm 1.3$ mm, it reduces to 6.8 ± 1.3 mm when the monitors 63,97 are corrected for their offset. Horizontally, one finds $x_{ppd} = 9.4 \pm 1.75$ mm. As a detailed aperture budget revealed that injection efficiency could be limited by vertical orbit distortions [7], correction was done for this plane.

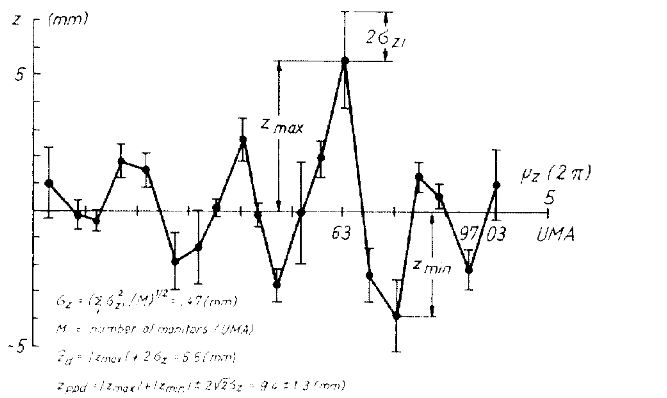

Fig. 1 Vertical orbit distortions, mean value of 8 series of measurements from a period of about one year

Orbit correction with the FITTING METHOD

From all vertical closed orbit measurements with the machine elements theoretically aligned, an important kick was located between the pick-ups 95,97; furthermore 63,97 were found to have an offset. The best correction was obtained with an element close to the quadrupole magnet QFL96. We have to underline that this was made possible because pick-up 03 was found to have a correct reading. In case 97 and 03 would have been discarded, locating the discontinuity of betatron oscillation would not have been possible, because of the phase advance, larger than π between the adjacent detectors up and downstream (95, 05). The detailed analysis [2] recommended QFL96 itself, as best corrector. A kick of 1.35 mrad $\hat{=}$ 2.58 mm displacement should reduce the distortion by 3.2. Fig. 2 shows the result. GOLD applied on one early set of data found .84 mrad also to stem from the quadrupole QFL96.

Orbit correction with the MICADO METHOD

Using the mean orbit distortion (Fig. 1), MICADO proposes as best corrector QFL04, no pick-ups

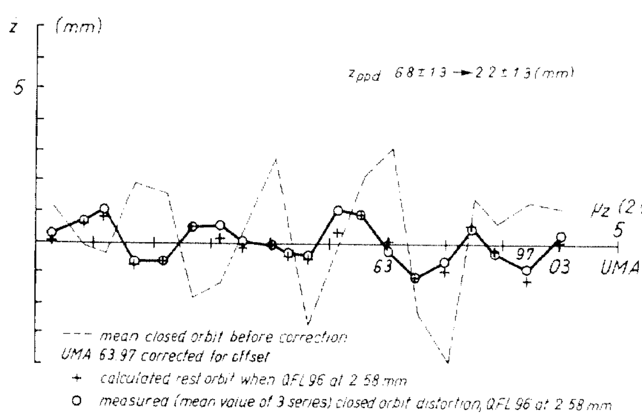

Fig. 2 Correction of the vertical closed orbit distortion, applying the FITTING METHOD

discarded. In order to estimate the robustness of this result, noise (σ = .47 mm) was superposed. 33 out of 40 runs indicated QFL04, the rest opted for QFL96, both being seperated by a phase advance of π. As mean value for the correcting kick - 1.34 mrad $\hat{=}$ -2.56 mm was found. The calculated correction should reduce the distortion by 1.8. Fig. 3 shows the result.

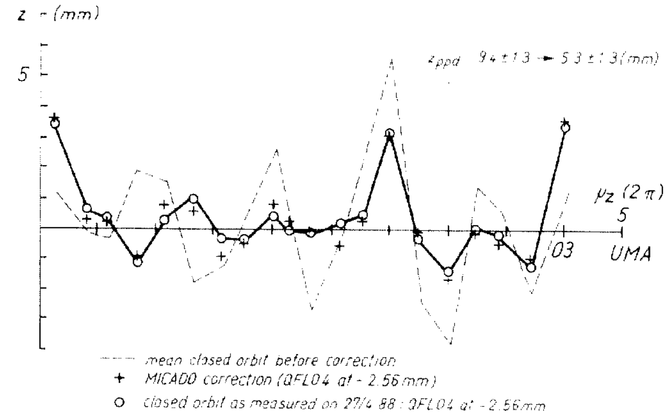

Fig. 3 Correction of the vertical closed orbit distortion applying the MICADO METHOD

Beam Parameters as Function of C.O. Distortion

The e+ injection system

The stacking in betatron phase space is based on a fast radial orbit deformation moving the beam close to the injection system. The injection system has been designed for a 100% accumulation efficiency [8] with a 10 π mmmrad emittance in both planes.

First results

During the initial phase of e+ running-in, accumulation efficiency has been found to be around 40%. Losses occurred mainly at the first turns in the accumulator (EPA), depending strongly on the vertical trajectory at the entrance of the machine [7].

Measurements of the vertical beam emittance and matching have been done, leading to a value of ϵ_z=14 π mm mrad after blow-up by the mismatch. This is above the acceptance of the vacuum chamber with an initial 10 mm closed orbit distortion, allowing for 10 π mm mrad.

Influence of vertical c.o. distortion on injection efficiency and accumulation rate

In our experiments, injection efficiency has been characterised by η being the ratio of the beam current after 10 turns in EPA to the incoming current taken in front of the injection septum.

By variations of the current of the last vertical steering element in the transfer line, we scanned the vertical aperture of EPA.

Fig. 4 shows η as a function of the current. Closed orbit correction, QFL96 at + 2.58 mm, increases η and provides a flat top of $\pm$ 2A, equivalent to a stay clear of $\pm$ 2 mm at βmax in the machine [7]. An improvement of the accumulation rate of about 30% has been observed as well.

The maximum of the curves in Fig. 4 are not settled yet with a precision of some %, as reproductivity of measurements spaced by weeks, has proved to be difficult. The key feature, always well observed, is the flat top.

The two different orbit corrections (MICADO, FITTING) can, however, lead to quite different injection margins, measured at 80% of ηmax/η, see Fig. 5.

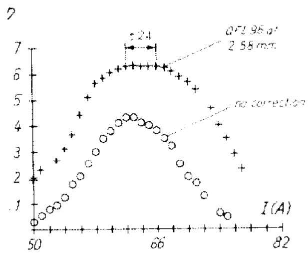

Fig. 4 Injection efficiency and stay clear as function of the vertical orbit correction

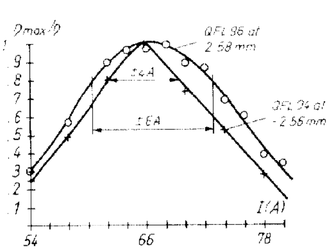

Fig. 5 MARGINS at injection for two different closed orbit corrections

Description of the Measuring System

Nineteen magnetic pickups [9] are distributed, non-regularly with respect to phase advance (see Table 2) over the machine with $Q_x = 4.56$, $Q_z = 4.36$. Single bunch trajectories are measured, integrating the signal over one bunch length. For closed orbit measurements, mean values of n measured trajectories are taken at time intervals of 3 ms. The detectors have bandwidths of .06-250 MHz for the sum signal and .50-250 MHz for the difference signals. The sensitivities with respect to beam currents and closed orbit displacements are .47 V/A, 15 V/A.m. Signal accuracy is of the order of .2 mm (=1 σ) for beam intensities of 5 to 15 $* 10^8$ particles per bunch integrating over $30 \leq n \leq 100$ trajectories [10].

Treatment of the raw signal

Calibration of offset and gain is achieved simulating a bunch (pulse length 16 ns, current 30 mA) on a wire passing through the detector. The raw signals are after digitalisation corrected for offset, non linearities in sensitivity (gain) and horizontal to vertical coupling. The total correction has the form $z = .24 + 31.9\ (1 + .06 * u)\ v - 1.61\ v^3$. U,v are the ratios of difference to sum signals for x and z plane. The correction for x has the same form.

Check of the detector sensitivity using the beam

As shown earlier [11], good agreement of the calculated (based on the model of the machine) and measured closed orbit perturbation had been found.

This fact is used to verify regularly the sensitivity of the detectors. Table 2 shows the ratio of the displacement of the beam Δz and the current ΔI of the only vertical dipole in the ring, calculated and measured.

Table 2: Orbit distortion from known perturbation

UMA	β_z	α_z	μ_z	Δz/ΔI c	Δz/ΔI m	UMA	β_z	α_z	μ_z	Δz/ΔI c	Δz/ΔI m
03	11.5	1.49	.15	.51	.48	53	11.4	1.50	2.33	1.31	1.40
05	.8	-.39	.42	.30	.30	55	.8	-.41	2.60	-.02	-.03
11	5.3	.82	.61	-.09	-.05	61	5.4	.86	2.79	-.85	-.79
13	13.1	-.03	.85	-1.41	-1.47	63	13.0	-.05	3.03	-.51	-.50
23	13.5	-.05	1.10	.07	.09	73	13.5	.05	3.27	1.28	1.40
33	13.0	.05	1.33	1.40	1.55	83	13.1	.03	3.52	.62	.60
41	5.4	-.86	1.58	.07	.09	91	5.3	-.82	3.76	.85	.89
45	.8	.41	1.77	-.30	-.31	95	.8	.39	3.95	.01	-.01
47	11.4	-1.50	2.03	-.47	-.45	97	11.5	-1.49	4.21	-1.32	-1.36
49	3.4	.05	2.17	.36	.37						
DVT	13.1	.00	3.52	β[m], μ[2π], Δz/ΔI[mm/A], 1[A]=2[mrad]							
UMA=pickup, DVT=vertical dipole, c=calculated, m=measured value											

Analysis of Results

The measurements of c.o. distortions confirm the prediction by simulation, taking into account that true maxima - slightly higher than those at detectors - may be between positions of detectors. Moreover, simulations predicted correction efficiencies $e_z = 3$, applying several iterations. Observing all imposed restrictions (see Table. 1), one iteration with MICADO or the elimination of one source of perturbations with the FITTING METHOD leads already to $e_z = 1.8$, respectively 3.1. In addition, some stay clear (Fig. 4) is gained. This is very much appreciated when variation of energy and its dispersion at the LINAC render injection difficult. Concerning the injection margin, correction by the FITTING METHOD is more favourable than by MICADO (Fig. 5).

Statistics on measurements confirm the expected performance of the measuring system as long as analysis is restricted to measurements done within several hours. Measured linearity and amplification factors of the detectors agree with calculated values (see Table 2) within better than 11% for c.o. perturbations of $z_{pp} = 10$mm.

Observing the reproductivity of measurements over a longer period reveals stronger fluctuations $\sigma_x = .62$ mm, $\sigma_z = .47$ mm (instead of .2 mm). During that period neither significant changes of magnetic elements nor modifications of the machine conditions have occured. In addition, comparing series of measurements of two consecutive runs (one week apart) give the same order of fluctuations found for the whole period. This needs still some explanations; it should be kept in mind (see Table 1) that minor displacements (of the order of $\Delta\delta \sim 2*10^{-5}$ m) of magnets can lead to orbit fluctuations of $.4*10^{-3}$ m already.

The achieved closed orbit correction for a peak to peak distortion $z_{ppd} = 6.8$ mm is $z_{ppd} = 2.2$ mm. The fluctuation (at 2σ) of the peak-to-peak measurements is 1.3 mm. This gives a signal to noise ratio of 1.7. Under these circumstances any further correction of the orbit becomes difficult.

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