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TRAJECTORY CORRECTION STUDIES FOR THE CNGS PROTON BEAM LINE

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The performance of the proposed trajectory correction scheme for the CNGS proton beam line was checked with an advanced simulation program. It was first investigated whether the scheme will be sufficient, and if some correctors or monitors could be suppressed in order to reduce the cost. The correction scheme was in particular tested for the case of faulty correctors or monitors. Possible critical scenarios were identified, which may not be visible in a purely statistical analysis. This part of the analysis was largely based on the experience with trajectory and orbit correction problems encountered in the SPS and LEP. The simulation of the trajectory correction procedure was done using recently developed software.

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The performance of the proposed trajectory correction scheme for the CNGS proton beam line was checked with an advanced simulation program. It was first investigated whether the scheme will be sufficient, and if some correctors or monitors could be suppressed in order to reduce the cost. The correction scheme was in particular tested for the case of faulty correctors or monitors. Possible critical scenarios were identified, which may not be visible in a purely statistical analysis. This part of the analysis was largely based on the experience with trajectory and orbit correction problems encountered in the SPS and LEP. The simulation of the trajectory correction procedure was done using recently developed software.

CNGS PROTON BEAM

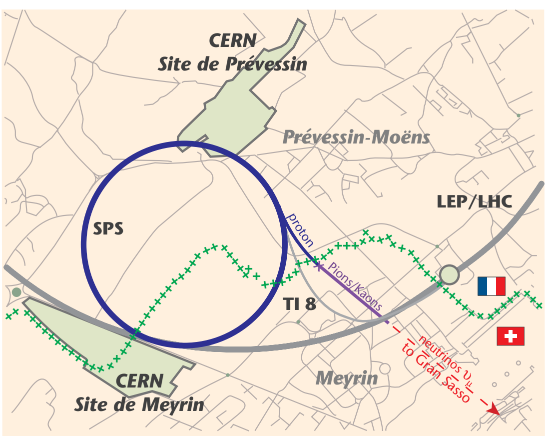

Figure 1: *Overview of the CNGS Layout.*

The CERN Neutrinos to Gran Sasso (CNGS) project has the aim to study neutrino oscillations in a long base-line experiment [1, 2, 3]. The general CNGS layout is shown in Fig.1. The proton beam is extracted from the SPS at 400 GeV, in two consecutive 10.5 μs fast extractions, in a 6 s cycle. The nominal intensity is 2.4×10^{13} p/extraction with an upgrade phase to 3.5×10^{13} p/extraction. In order to steer this intense beam through the 840 m proton beam line (TT41), beam position monitors and dipole correctors are positioned along the line. The relatively tight aperture -the strongest aperture constraint comes from the main dipoles- requires a precise control of the trajectory. For this study the following parameters were assumed: 5σ beam, β-beating of 20%, and β_{max} values taken in the FODO cells. The resulting maximum acceptable trajectory excursion is 4.3 mm with a worst case between two downstream main quadrupoles where good beam monitoring should be available.

BEAM LINE ERRORS

The following errors were included in the calculation of the trajectory:

Main quadrupole errors: All main quadrupoles are allowed to be displaced in the horizontal and vertical plane. The possible displacements are approximated by a Gaussian distribution with σ = 0.2 mm, cut at 3 σ.

Monitor errors: We assume calibration, mechanical and alignment errors in both planes which are represented by a flat random distribution of $\pm$ 0.5 mm.

Main dipole field errors: The specification requires that each magnets stays within $\pm$ 5.0 10^{-4} of the average field. The resulting distribution of the deflections is assumed Gaussian with σ = 2.0 μrad, cut at 2 σ, which corresponds approximately to $\pm$ 5.0 10^{-4} of the nominal deflection of 8 mrad.

Main dipole tilt errors: They are assumed to follow a Gaussian distribution with σ = 1.6 μrad, cut at 4 σ.

Injection errors: Injection errors are taken to be Gaussian with a r.m.s. position error of 0.5 mm and a r.m.s. angle error of 0.05 mrad, both cut at 2 σ.

The program we have used is the newly developed MAD-X program[4]. It allows the assignment of errors, to simulate the malfunctioning of machine elements and the application of various correction algorithms.

EVALUATION OF THE ORIGINAL SCHEME

Description of the original trajectory correction scheme

In 2000, an extensive trajectory study for the LHC transfer lines was performed [5]. This trajectory study program was also applied to the CNGS proton beam line and it was tentatively concluded that it was sufficent to equip two consecutive quadrupoles per plane out of three with monitors (BPM) and correctors (referred to as a 2-in-3 scheme).

General considerations

In principle, the trajectory in a regular lattice can be corrected with a 2-in-3 corrector scheme. However, since in CNGS the phase advance per cell is close to $\pi/2$ in both planes, it is possible to produce unwanted π-bumps that may not be visible because the trajectory is heavily undersampled. Subsequent trajectory corrections can further enhance this 'invisible bump' unless special precautions are taken. The first analysis led to the conclusion that for the original scheme one can construct scenarios where the trajectory excursions are largely outside the allowed range without the possibility of measurement and thus correction.

Standard trajectory corrections were applied to simulate trajectories with all errors as specified, using the original scheme. It was immediately found that a monitor was missing in the original scheme. A satisfactory correction is impossible without this monitor. In the following studies, this monitor was therefore inserted.

Possible use of bending magnets as correctors

The bending magnets MHHC and MHHA can be used as correctors in addition to the dedicated correction magnets (called MH and MV). This helps to avoid creating bumps at the beginning of the line and to reduce the required strength of other correctors.

TRAJECTORY SIMULATION RESULTS

Efficiency studies of specific correctors

	Kick max (μrad)		Kick max (μrad)
MH01	101.2 (70.0)	MV00	35.4
MHHC	- (42.0)	MV02	30.5
MHHA	- (35.0)	MV03	31.6
MH02	33.5	MV05	37.5
MH06	32.2	MV09	32.3
MH08	57.4	MV11	46.6
MH12	33.5	MV15	32.0
MH14	39.0	MV17	48.4
MH18	37.1	MVG21	309.0 (-)
MHS22	83.0	MVS21	228.0 (37.9)
MHS24	197.4	MVS24	155.0 (92.0)

Table 1: Required corrector strengths for trajectory correction with nominal errors. Left for horizontal and right for vertical plane.

The required corrector strengths were recorded for 3000 error seeds and the maximum corrector strength used for each corrector is shown in Tab.1. The maximum needed corrector strengths remain below 60 μrad, with a few exceptions: the MH01 at the beginning of the line was as large as 101 μrad and the correctors at the end of the line (sequence number larger than 20) can go as high as 200 μrad. The strength required for the MH01 is therefore slightly higher than its maximum value (90 μm). The use of the two bending magnets MHHC and MHHA as additional correctors reduces the required strength to about 70 μrad (values in Tab.1 (left) in parenthesis). The correctors MVG21 and MVS21 in the vertical plane are very close to each other, without a monitor between them. As a result they can work "against" each other. Omitting the redundant corrector MVG21 we obtain the maximum strengths for the following correctors given in parenthesis in Tab.1 (right). The quality of the trajectory correction in the visible part is unaffected and the required strengths in the last two correctors is strongly reduced. Advanced algorithms (e.g. Singular Value Decomposition [6]) avoid the numerical problems, but since the corrector is truly redundant, its omission it the easier and cheaper solution.

Effect and correction of injection errors

Both, the position and the angle of the beam may be wrong at extraction from the SPS into the proton beam line. The resulting trajectories add linearly to the trajectories caused by the other imperfections. These other errors can be ignored in this example since they would only affect the beam later in the beam line. Scrutinizing the necessary strengths of the correctors to correct for injection errors, it is found that the wrong angle is practically always corrected by one or two correctors in each plane. Furthermore, and not surprisingly, the required strength is almost identical to the wrong angle. Therefore we need correctors that can handle strengths in the order of 100 μrad or more at the beginning of the line. In the vertical plane this is the corrector MV00 that is thus slightly above the maximum strength (90 μrad). In the case of a horizontal angle the strength must be provided by the corrector MH01, which is already close to its limit by the requirements of the regular trajectory correction. Neither for the trajectory correction nor for the correction of the injection error it can be abandoned. We have tried to salvage at least part of the strength using a procedure that has been implemented successfully in the trajectory correction package COCU [7] used for the SPS and LEP. When the correction is calculated, the strength

Ceiling for maximum strength	Trajectory (max.) (mm)	RMS (mm)
0 % $\equiv$ 0 μrad	5.0	2.0
33 % $\equiv$ 30 μrad	3.3	2.0
50 % $\equiv$ 45 μrad	2.9	1.5
67 % $\equiv$ 60 μrad	2.4	1.2
100 % $\equiv$ 90 μrad	1.5	0.6

Table 2: Correction of injection error with ceiling for strength of MH01.

computed for the MH01 is cut at a predefined fraction of its maximum strength and remains fixed for all subsequent iterations where additional correctors are added and computed. The remaining part of the strength is then available for regular trajectory corrections. The maximum trajectory and r.m.s. after this correction procedure are shown in Tab.2. The procedure was applied to the correction on an injection angle of 100 μrad. The results are encouraging and show that this strategy can be successfully used. Sharing the strength equally between the correction of an injection error and other beam line imperfections looks like an acceptable compromise.

IF THINGS GO WRONG ...

Although sufficient for 'reasonable' errors, the original scheme cannot handle particularly unlucky situations, such as π-bumps in places without monitors etc. This is only true when all elements are available and work according to the specifications. Experience shows that this is rarely the case. One has to expect faulty or unavailable correctors and monitors and in this situation the scheme deteriorates. In the following we restrict ourselves to study the effect of missing monitors.

Effect of monitors not working

The effect of missing monitors on the result of a correction can be critical. First, non-existing measurements can lead to large trajectory excursions where they are not visible. Secondly, the correction algorithms may not work as expected. Missing measurements can either lead to an ill-defined problem that leads to the collapse of the correction procedure, or the correction procedure itself produces 'bumps', i.e. large trajectory excursions in places without monitors. The creation of such bumps is not measurable but can fortunately be avoided by a smart correction procedure. However, it may lead to a reduced number of usable correctors and inevitably to a worse correction. In the following we have used a new feature in MAD-X, i.e. the possibility to disable beam position monitors randomly, given a probability for the fault. The results are shown in Tab.3.

	RMS max (mm)	trajectory max (mm)
X before	4.06 (3.42)	9.24 (13.06)
X after	1.36 (3.22) [2.1]	3.57 (11.93) [8.1]
Y before	3.23 (3.01)	7.66 (8.13)
Y after	1.28 (3.46) [2.2]	3.04 (12.97) [5.8]

Table 3: 2% of monitors unavailable, using 5 correctors.

Although only in some cases (2%) a monitor was considered faulty, the difference is quite significant. While the trajectory correction looks rather satisfactory considering only the monitors, it becomes a disaster in other, invisible parts of the machine (in parenthesis). In particular, invisible bumps are produced, mainly in the vertical plane, which make the maximum trajectory excursions larger after the correction. A procedure was applied to avoid **creating** bumps during the correction process and the results are shown in brackets in Tab.3. Although the result is better, it is still unacceptable. Inspecting the lattice, we observe that we could recover if all the BPM bodies foreseen are able to measure the trajectory in both planes. In Tab.4 we have again randomly disabled 2% of the available monitors. However, now with all monitors providing readings in both planes, it increases the number of monitors and improves the sampling significantly. The quality of the correction is now fully satisfactory and according to the specifications.

	RMS max (mm)	trajectory max (mm)
X before	3.18 (3.57)	9.02 (15.02)
X after	1.05 (1.19)	2.83 (5.26)
Y before	3.24 (3.20)	7.50 (8.02)
Y after	1.00 (1.01)	3.10 (4.12)
X before	3.18 (3.57)	9.02 (15.02)
X after	0.62 (0.77)	2.02 (3.48)
Y before	3.24 (3.20)	7.50 (8.02)
Y after	0.49 (0.77)	2.02 (3.19)

Table 4: 2% of monitors unavailable, using 5 (top) and all correctors (bottom). All monitors readings in both planes.

CONCLUSION

Based on a statistical analysis simulating 3000 different trajectories one could draw a first conclusion that in principle the trajectories can be corrected to the required precision with the proposed scheme. However, the trajectory correction scheme provides no margin and unlucky situations can become critical because of missing correction and monitoring elements. Whether the trajectory stays within the required aperture cannot be guaranteed since it is not visible in critical positions. Large injection errors may create problems since they reduce the availability of important correctors. A straightforward trajectory correction procedure cannot cope with such a situation. More sophisticated strategies like those developed for LEP should help significantly. Alternatively, all presently foreseen monitors should measure the trajectory in both planes. Following some simulations, this is our preferred choice, wich has now been implemented in the trajectory correction scheme.

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