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Aperture and Stability Studies for the CNGS proton beam line

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Abstract

The knowledge of the beam stability at the CNGS target is of great importance, both for the neutrino yield and for target rod resistance against non-symmetric beam impact. Therefore, simulating expected imperfections of the beam line elements and possible injection errors into the CNGS proton beam line, the beam spot stability at the target was investigated. Moreover, the mechanical aperture of the CNGS proton beam line was simulated and the results confirmed that the aperture is tight but sufficient.

CNGS PROTON BEAM

The CERN neutrinos to Gran Sasso (CNGS) project, presently under construction, has the aim to study neutrino oscillations in a long base-line experiment [1, 2, 3]. An intense proton beam is extracted from the SPS accelerator at a nominal energy of 400 GeV, transported through a 840 m long proton transfer line, before impinging on a graphite target. Secondary particles created in the target are directed towards Gran Sasso and will, in turn, decay in flight, producing muon-type neutrinos. These neutrinos, which hardly interact with matter, will travel 730 km through the earth towards the Gran Sasso laboratory, where the appearance of tau-type neutrinos will be studied.

The proton beam is extracted in two consecutive 10.5 μs fast extractions, in a 6 s cycle. The nominal intensity per extraction is 2.4 10^{13} p/extraction with an upgrade phase to 3.5 10^{13} p/extraction. The CNGS proton beam will be using the same fast extraction channel as the LHC beam, and both beams are injected into a common beam line (TT40) of about 100 m. The CNGS beam will then be transported along 740 m of beam line to the CNGS target. In order to steer this intense beam through the CNGS proton beam line (called TT41), beam position monitors and dipole correctors are positioned along the line.

SIMULATION PROGRAM

All simulations are done with the newly developed MAD-X program [4]. The tracking is done using a thin lens version of the lattice. The particles are assigned initial coordinates and momenta in six dimensional phase space and tracked through each element of the beam line. The coordinates at the start and end of the line are always provided, but observation points can also be defined at any position in the line. MAD-X allows to assign a physical aperture to each element and during tracking a particle is considered lost whenever its trajectory exceeds the aperture. Furthermore, the apertures can be misaligned, independent of the associated beam line elements, simulating a further restriction of the available space. For example, the aperture at a quadrupole could be reduced by displacing its vacuum chamber while leaving the magnet aligned. Some of the magnets are tilted and the tracking is following the reference path.

In order to analyse the output from MAD-X and perform various calculations at all positions recorded (e.g. beam size and position), a post-processing program was written, also allowing to plot the results obtained.

CHECK OF AVAILABLE APERTURE

To check the available aperture, a set of particles at the beginning of the TT41 line have been generated and tracked through the elements. The position and angle of all particles at the start of the beam line and at the target, as well as at other observation points, are stored for post processing.

The particles were generated according to a Gaussian distribution to follow the contour of the emittance ellipse. The nominal physical emittance is 28 nm, but in the following tracking studies, during the beam generation, an emittance 4 times larger was used in order to fill a larger part of the phase space. In this way the tails of the beam distribution are better populated. The phase space plots at the beginning of the beam line and at the target are shown in the Fig.1 and Fig.2. The circular or elliptical lines indicate the contour of 6 σ and 10 σ, respectively. The energy spread of the particles is taken as 0.06% r.m.s, which is close to the expected value. No particle loss is observed, confirming that the initial design of the beam line was correct. During this first tracking study, no aperture displacement was applied.

100000 particles were then tracked with different sets of momentum offset and aperture displacements. For an aperture displacement of $\pm$ 4.0 mm (expected uncorrected trajectory displacement [5]), and for a momentum offset of $\frac{\Delta p}{p}$ = 0.0015 (expected 2 σ value [6]), no particle was lost for the initial distributions described above.

BEAM STABILITY ON THE TARGET

The beam stability on the target is of great importance and we have evaluated the range of possible movement from extraction to extraction.

Imperfections

The following imperfections were included in the tracking program:

Injection errors: Injection errors which can not be corrected, thus changing from extraction to extraction, are

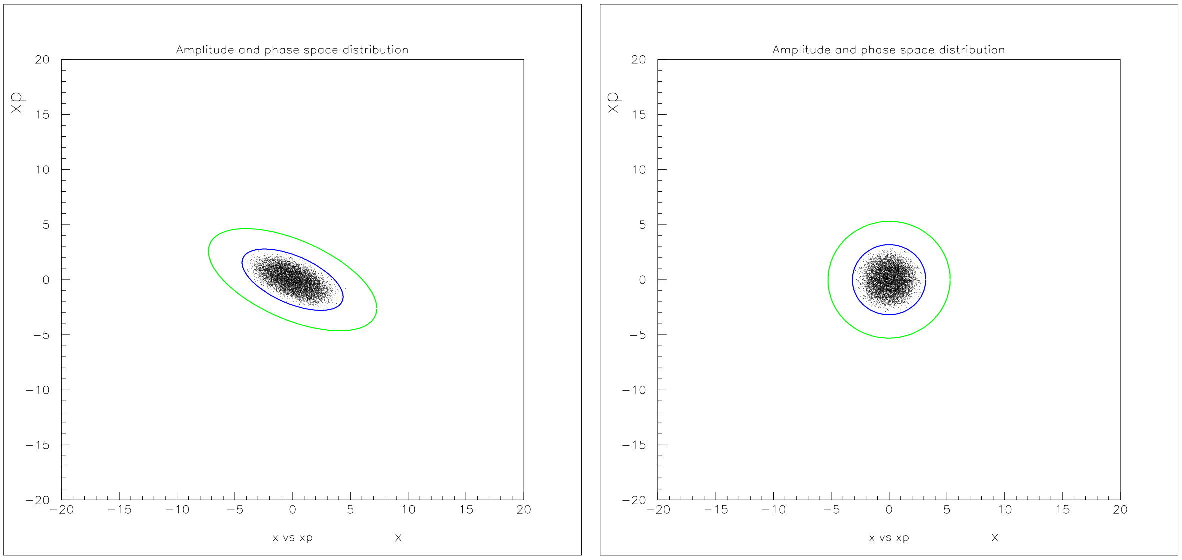

Figure 1: *Horizontal phase space at beginning of the beam line (left) and at the target (right). Units: 1 mm for the horizontal and 0.1 mrad for the vertical axis.*

originating from the magnets of the SPS extraction channel. They are taken to be Gaussian with a horizontal injection position error with a σ of 0.5 mm and a horizontal injection angle error with a σ of 0.01 mrad, both cut at $\pm$ 2 σ.

Main dipole field error: There are 73 main dipole magnets in the line for which field dipole errors will contribute to a deviation from the reference trajectory. 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 to be Gaussian with a σ of 2.0 μrad, cut at $\pm$ 2 σ, which corresponds approximately to $\pm$ 5.0 10^{-4} of the nominal deflection of 8 mrad. Design field errors in the dipoles of other types are neglected as only few magnets of these types are used in the line, compared to the 73 main dipole magnets in this single pass transfer line.

Main dipole tilt errors: For our simulations, the tilt errors are assumed to be distributed like a Gaussian with a σ of 1.6 μrad (0.2 mrad$\cdot$8 mrad nominal horizontal deflection), cut at $\pm$ 4 σ.

Main quadrupole errors: All main quadrupoles may experience unwanted displacement in the horizontal and vertical plane. These displacements are approximated by a Gaussian distribution with a σ of 0.2 mm. This distribution is cut at $\pm$ 3 σ.

Dipole power supply precision: The precision of the power supplies are specified to be $\pm$ 2* 10^{-5} for the main dipoles and $\pm$1* 10^{-4} for all the other dipole magnets.

Quadrupole power supply precision: $\pm$1* 10^{-4} were specified for all power suppies of the quadrupole magnets.

We assume that the initial optical parameters of the beam line are matched to the SPS optics at the extraction point.

Strategy for tracking

In the previous section we have introduced two types of errors: those which can fluctuate from extraction to extraction such as instability of the power supplies, and others which we assume to be constant with time, such as misalignments of beam line elements.

For the simulation we have started a particle (representing a bunch) at the beginning of the beam line and tracked it through the lattice with both static misalignments and other errors allowed to change from extraction to extraction (for each particle tracked), according to the above specifications (such as power supply ripple). The trajectory due to misalignments is assumed to be corrected to a reasonable degree so that the beam spot is centered at the target. The trajectory correction and the required corrector strengths was the subject of an earlier study [5]. Without errors all particles (bunches) should reach the end of the line at the same spot.

Effect of injection errors

For the horizontal plane, it is clear that the spot size is dominated by the injection errors, provided they change from shot to shot and cannot be corrected or stabilized. The effective spot size (i.e. the convolution of the size of the beam and the distribution of the centre of the beam on the target) is larger than 1 σ of the nominal beam size. Since the injection errors (angle and position) appear only in the horizontal plane, the vertical beam position is determined by trajectory errors and the spot size is not increased.

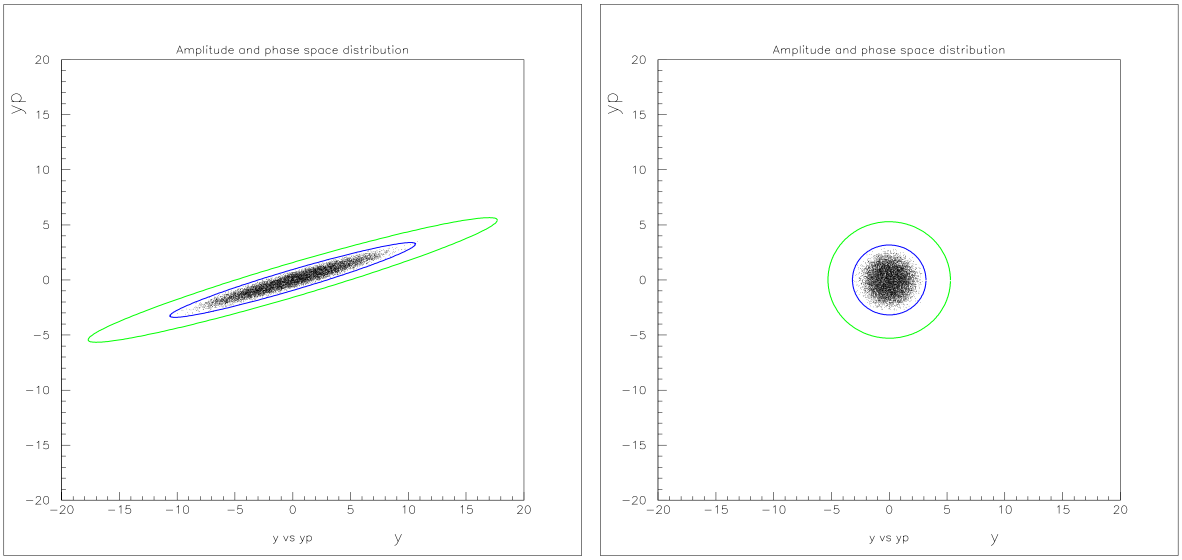

Figure 2: *Vertical phase space at beginning of the beam line (left) and at the target (left). Units: 1 mm for the horizontal and 0.1 mrad for the vertical axis.*

Type of error		Horizontal σ_x at target (mm)	Horizontal σ'_x at target (μrad)
Magnet (field and alignment) errors	see above	0.12 mm	11 μrad
Horizontal injection angle	10 μrad r.m.s.	0.11 mm	5 μrad
Horizontal injection position	0.5 mm r.m.s.	0.32 mm	21 μrad
Injection position and angle	see above	0.34 mm	21 μrad
Injection and magnet errors	see above	0.36 mm	22 μrad
Nominal beam size (r.m.s.)		0.53 mm	53 μrad
Effective total spot size (r.m.s.)		0.64 mm	57 μrad

Table 1: *Contribution of different errors to the beam stability and effective beam spot size on the target. Effective spot size is convolution of beam size and distribution of the bunch centre on the target.*

Effect of all errors combined together

We recorded the spot size including all errors, i.e. the magnet field errors and misalignments as well as both types of injection errors. The findings are summarized in Tab.1. Although on first sight the spread of the beam position on the target looks large when all errors are included, the actual increase of the effective spot size on the target, i.e. when the beam size is folded with the fluctuation of the bunch centre, is modest and probably acceptable.

CONCLUSIONS

Extensively exploiting new features in the MAD-X program we have evaluated the available mechanical aperture in the proton beam line TT41 and established the possible bottlenecks of the aperture. We found that the aperture is according to the design and expectations. We have further investigated the stability of the beam spot on the target, simulating the expected imperfections of the beam line elements and including possible injection errors. The increase of the effective beam spot on the target is acceptable when these imperfections remain within their specifications.

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