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CNGS: Update on secondary beam layout

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Abstract

The conceptual technical design of the CNGS (CERN neutrino beam to Gran Sasso) facility has been presented in the report CERN 98-02 / INFN-AE/98-05. An updated beam design, in particular a revised neutrino beam optimised for ν_μ–ν_τ appearance experiments, has been described in an addendum (CERN-SL/99-034(DI) / INFN-AE/99-05). In this note, a slightly modified version of the CNGS secondary beam and an update of the parameter lists is given. The changes aim at technical improvements in the CNGS secondary beam components, without compromising on the expected lifetime of the components. A slight increase of expected ν_τ charged current events at Gran Sasso has been achieved in the simulations.

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Contents

1 Introduction

During the year 2000, Monte Carlo simulations of the CNGS neutrino beam have been intensively pursued. The aim of these simulations was three-fold: (a) to investigate possibilities to increase the expected number of ν_τ CC events (per proton on target) at Gran Sasso, (b) to study the sensitivity of the expected ν_τ CC events to various types of beam imperfections (eg. misalignments), (c) to improve, where possible, the technical aspects of the CNGS facility, e.g. space for target monitors, resistance of the horn to stresses, etc.. While this work is not complete, it was nevertheless felt that the most important results obtained so far should be summarised. Effects of systematic derivations from the theoretical beam have been studied and are presented in a separate note [1]. A summary of simulation results is given in section 2, the resulting CNGS neutrino beam and its performance is described in section 3. The appendices are updated versions of the ones given in previous CNGS documents [2, 3].

2 Summary of recent Monte Carlo simulations

During the year 2000, CNGS beam simulation studies concentrated on potential improvements of expected ν_τ per proton on target, on aspects of the technical reliability and feasibility, on the sensitivity to imperfections in the beam alignment as well as on the definition of a secondary beam monitoring system.

2.1 CNGS secondary beam, version 2000

The nominal particle focusing energies of the CNGS co-axial lenses (the horn and the reflector) remain 35 GeV and 50 GeV respectively. The main changes to the layout (cf. also Appendix A):

- The proton beam is assumed to be a factor of two less divergent, i.e. a factor of two larger in x,y spot size.
- The horn has been moved 1 m downstream, i.e. to a distance of 2.7 m from the proton beam focus, in order to gain space for a downstream target monitor (e.g. secondary emission counter, sometimes called TBID). The inner diameter of the neck of the horn has been enlarged from 5 mm to 18 mm. This allows to avoid the proton beam hitting the horn even in the case of considerable mis-steering.
- The current in the reflector has been increased from 150 to 180 kA. The material recuperated from WANF allows to make this extra step in current, and there is little concern about the stresses on the reflector even at this higher current. The shape of the neck of the reflector has been re-designed, and the opening reduced from to R = 100 mm to 70 mm. The diameter of the outer conductor of the reflector was reduced from R = 600 mm to 560 mm in order to make this object more easily transportable (in particular through the CNGS access gallery TA41).

- Under these new conditions, the shape of horn and reflector inner conductors were re-optimised.

- Due to the small variation of the expected performance of the CNGS (see below) with misalignments of horn and reflector, the remote controlled movements of these two devices were removed from the specifications.

2.2 Study of systematic deviations from the theoretical beam

Several possible imperfections of the CNGS beam were studied by simulation. Detailed results are given in [1]. The number of expected ν_τ CC events at Gran Sasso is found to be insensitive to any of the following deviations, within a range which is easily measureable by direct observations (position, current, etc.):

- primary proton beam parallel displacements and angular rotations in respect to the secondary beam elements (target, horn, reflector, etc.)

- wrong pointing of the secondary beam layout to Gran Sasso

- changes of primary proton beam size and divergence

- lateral and angular displacements of the horn and the reflector

- change of current in the horn and reflector

2.3 Secondary beam monitors

The simulations were also used to investigate the expected signals in various secondary beam monitors. Initially, it was considered that the proposed "hadron monitor", e.g. ionisation chambers just upstream of the decay tunnel, could be a very useful detector. However, further detailed simulations using FLUKA98 showed that the sensitivity of such a monitor is very limited due to the large electron flux from electromagnetic showers. No such monitor is now foreseen for CNGS.

On the other hand, a charged particle monitor located immediately after the target is found to be very sensitive to primary proton beam alignment errors. It has therefore been decided to include such a detector in the layout of CNGS.

An array of muon detectors in the two muon chambers of CNGS remains the key element for monitoring of the neutrino beam. Details of the layout and the technology (in particular in view of the difficult access conditions) still need to be worked out.

Finally, the muons induced by ν_μ CC interactions in the rock at Gran Sasso could be detected in a relatively simple, large area monitor. Simulations show that this could give very valuable, almost "on-line" information on the CNGS neutrino beam quality: more than 200 events per day are expect in a monitor of $100\,\mathrm{m}^2$ (cf. the expected spectrum in Fig. 1). It is therefore proposed to LNGS that such a detector is envisaged as one of the facilities operated by the laboratory.

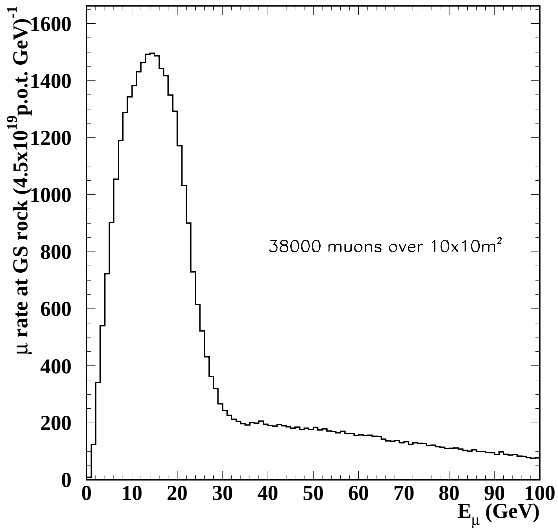

Figure 1: *Muons from ν_μ interactions in the rock observable in a $10\times 10\,m^2$ detector at Gran Sasso.*

3 Performance of the CNGS neutrino beam, version 2000

The main changes to the CNGS beam layout are summarized in section 2. Two methods were used to obtain Monte Carlo predictions of the new variant of the CNGS neutrino beam. On the one hand, the parametrised SPY data were used for the particle production in the CNGS target, combined with a fast tracking simulation [4]. On the other hand, FLUKA98 [5] was used for particle production and GEANT3.21 [6] for the simulations downstream of the target. The two simulation methods give very similar results, within the statistical uncertainty of the GEANT simulation. For simplicity, numerical results of the FLUKA98 / GEANT simulations are shown here.

The ν_μ fluence at Gran Sasso is shown in Fig. 2, the CC event distribution in Fig. 3. As discussed in ref. [3], the CNGS spectrum is matched with the product of oscillation probability times ν_τ cross section. The cut-off of the spectrum at around 30 GeV is intentional: appearance experiments at Gran Sasso typically do not want higher energies, as background channels would open up which could be difficult to separate from the ν_τ events.

Comparison of the realistic CNGS beam with an ideal "perfect focusing" case is shown in Figs. 4 and 5. These theoretical curves assume that there is no material after the target and that all particles produced will travel exactly in the direction of Gran Sasso. The high energy end of the distribution in Fig. 5 demonstrates that, even reducing the material thicknesses on the path of the secondary particles to zero, little improvement can be expected.

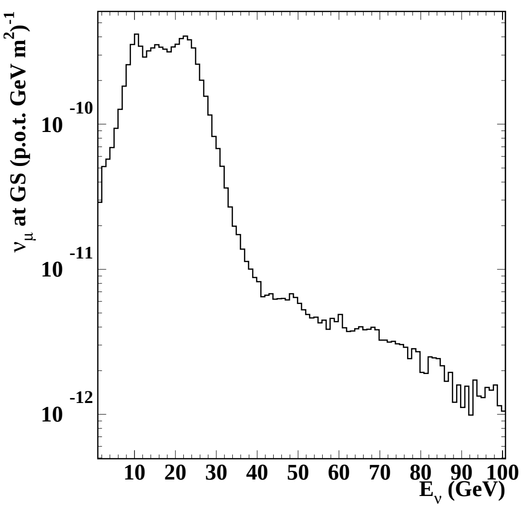

Figure 2: *Energy distribution of the ν_μ fluence at Gran Sasso.*

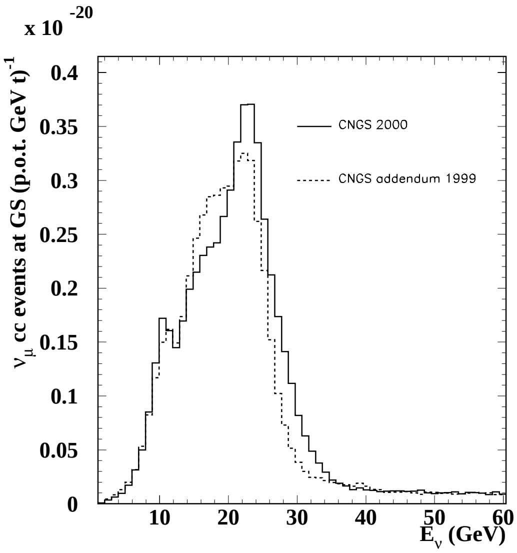

Figure 3: *Energy distribution of the CC ν_μ interactions at Gran Sasso (solid line). The dotted line shows the 1999 CNGS beam variant for comparison.*

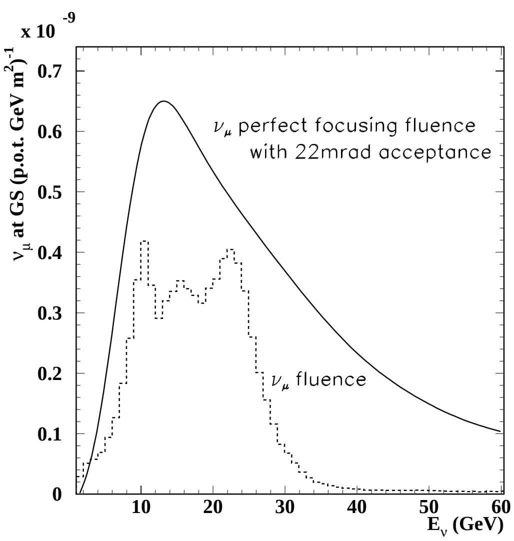

Figure 4: *Comparison of 'perfect focusing' with the ν_μ fluence at Gran Sasso. 22 mrad is the geometrical acceptance of the optical system for 35 GeV particles produced in the target.*

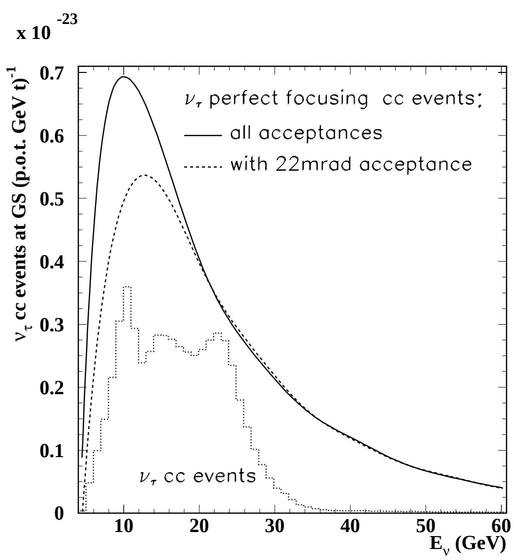

Figure 5: *Expected spectrum of ν_τ CC events at Gran Sasso for the CNGS beam, compared to the case of 'perfect focusing'.*

The resulting CNGS beam performance is summarized in Table 1. As in the previous simulations, the values given for the ν_μ beam have been obtained by averaging over a hypothetical detector with radius 100 m at Gran Sasso, while this radius has been set to 400 m for ν_e, $\overline{\nu_\mu}$ and $\overline{\nu_e}$.

The expected numbers of detectable ν_τ CC events for $sin^2 2\theta = 1$ and a few typical values of Δm^2 are shown in Table 2. When compared with the 1999 CNGS reference beam [3], a slight increase of around 4 % is found.

Table 1: *Predicted performance of the new CNGS reference beam. The statistical accuracy of the Monte-Carlo simulations is 1 % for the ν_μ component of the beam, somewhat larger for the other neutrino species.*

Energy region E_{ν_μ} [GeV]	1 - 30	1 - 100
ν_μ [m^{-2}/pot]	7.36×10^{-9}	7.78×10^{-9}
ν_μ CC events/pot/kt	5.05×10^{-17}	5.85×10^{-17}
$\langle E \rangle_{\nu_\mu \, fluence}$ [GeV]		17.7
fraction of other neutrino events:		
ν_e/ν_μ	0.8 %	
$\overline{\nu}_\mu/\nu_\mu$	2.1 %	
$\overline{\nu}_e/\nu_\mu$	0.07 %	

Table 2: *Expected number of ν_τ CC events at Gran Sasso per kt per year. Results of simulations for different values of Δm^2 and for $sin^2(2\theta) = 1$ are given for 4.5×10^{19} pot/year. These event numbers do not take detector efficiencies into account.*

Energy region E_{ν_τ} [GeV]	1 - 30	1 - 100
$\Delta m^2 = 1 \times 10^{-3}$ eV^2	2.44	2.53
$\Delta m^2 = 3 \times 10^{-3}$ eV^2	21.6	22.5
$\Delta m^2 = 5 \times 10^{-3}$ eV^2	58.3	60.5
$\Delta m^2 = 1 \times 10^{-2}$ eV^2	204	212

4 Summary

The work on CNGS secondary beam simulation performed during the year 2000 has been summarised. While there is only a minor improvement in the overall expected performance of the facility (in terms of ν_τ events per proton on target), there has been significant improvement on several technical aspects of the design. Further work will be needed, in order to complete the detailed layout of the target, focusing elements and the secondary beam monitoring devices, and to finalise the shielding layout in the target cavern.

A Reference Parameter List - November 2000

Proton Beam: TT41

Maximum proton beam momentum (design)	450 GeV/c
Proton beam momentum (assumed for operation)	400 GeV/c
Proton beam normalised emittance (1σ)	12π mm mrad
β^* at the focus (H and V)	10 m
$\rightarrow$ beam size / divergence (1σ)	0.53 mm, 0.053 mrad
Minimum repetition time (dedicated operation at 400 GeV/c)	6 s
Time between bursts	50 ms
Proton intensity per extraction	2.4×10^{13}
Proton intensity per cycle	4.8×10^{13}
Proton intensity (for hadron stop considerations)	8×10^{12} protons/second, 200 days/year
Proton intensity (for environmental considerations)	7.6×10^{19} protons/year
Expected integrated number of protons per year at 400 GeV/c	4.5×10^{19} protons

Target Chamber: TCC4

Length of target chamber	115 m
Diameter of target chamber	6.5 m (int.)
Floor width of target chamber	5.6 m
Enlargement at target (optional)	7.4 m
Crane capacity	10 t
Free height under crane hook	3.7 m
Beam height in target chamber	1.6 m
Diameter of neutrino service gallery TSG4	3.4 m (int.)
Distance of service gallery from cavern	6.0 m
Length of junction tunnel to target chamber	8 m
Distance of proton focus to entrance of decay tunnel	100 m

Target: T40

Start coordinate (w.r.t. proton focus)	-0.5 m
End coordinate (w.r.t. proton focus)	$+1.5$ m
Target material	carbon, density 1.81 g/cm^3
Target rod length	10 cm
Diameter of rods	4 mm
Number of rods	13
Distance between rods	first 8 rods with 9 cm distance,

	last 5 rods with minimal distance

Note: the exact configuration of the 13 target rods is under investigation.

Helium tubes

Helium tube I

Start coordinate (w.r.t. proton focus)	12.00 m
End coordinate (w.r.t. proton focus)	42.00 m
Diameter first 6 m	0.80 m
Diameter remaining length	1.20 m

Helium tube II

Start coordinate (w.r.t. proton focus)	52.00 m
End coordinate (w.r.t. proton focus)	99.00 m
Diameter	1.20 m

Shielding / Collimation

Note: Shielding parameters have not been changed - the shielding in the target cavern is under study by G.R. Stevenson and H.H. Vincke. The results of these studies will also influence the size/shape of the Helium tubes.

Shielding 1 (around the target)

Material	iron / marble
Start coordinate (w.r.t. proton focus)	-1.5 m
End coordinate (w.r.t. proton focus)	$+1.7$ m
Cross-section	rectangular
Opening for target box	$60 \times 60\,\mathrm{cm}^2$
30 cm of marble added at downstream end of target	

Shielding 2 (around the horn)

Shielding underneath the horn	40 cm concrete
Side walls of 30 cm marble / 20 cm iron / 30 cm concrete	
Height of walls	3.20 m
Left wall, start coordinate (w.r.t. proton focus)	2.30 m
Left wall, end coordinate	10.80 m
Right wall, start coordinate	2.00 m
Right wall, end coordinate	11.00 m

Shielding 3 (around helium tube I)

Upstream shielding	0.50 m marble
Shielding collar, first 5 m	iron, $3 \times 3\,\mathrm{m}^2$
	opening $0.80 \times 0.80\,\mathrm{m}^2$

Shielding collar, remaining 25.5 m	0.20 m iron, 0.30 m concrete opening $1.20 \times 1.20\,\mathrm{m}^2$
(Height of collar 2.70 m)	

Shielding 4 (along helium tube II)

Shielding underneath the tube	0.40 m concrete
Side walls height	3.20 m
Left wall distance to axis	1.00 m
Left wall thickness	0.80 m
Right wall distance to axis	1.00 m
Right wall thickness	0.80 m

Shielding 5 (collimator around helium tube II)

Start of shielding	85 m
Length of shielding	5 m
Inner diameter	1.20 m
Outer diameter	3.80 m (exception: downwards)

Horn and Reflector (for more details, see Appendix B):

Distance proton beam focus - horn entrance	2.7 m
Length of horn	6.65 m
Current in horn	150 kA
Distance proton beam focus - reflector entrance	43.35 m
Length of reflector	6.65 m
Current in reflector	180 kA

Decay Tunnel: TND4

Upstream end of decay tunnel (w.r.t. focus)	100 m
Length of decay tunnel	992 m
Diameter of decay tunnel (TBM)	3.50 m (ext.)
Length of decay pipe	994.5 m
Diameter of decay pipe (inner diam. steel pipe)	2.45 m (96 inch)
Wall thickness decay pipe	16 - 19 - 22 mm
Concrete filling around pipe	ca. 53 cm
Entrance window decay pipe	diameter 1.40 m, 2 mm titanium T40
Protecting shutter (thickness)	3 cm steel
Exit window decay pipe	5 cm steel
Pressure in decay pipe (min.)	1-2 Torr
Pumping down time (max.)	2 weeks

Hadron Stop (TNB4) and Muon Chambers (TNM41, TNM42)

Upstream end of hadron stop cavern (w.r.t. proton focus)	$100 + 992$ m
Length of hadron stop cavern	26 m
Diameter of hadron stop cavern	6 m (int.)
Floor width of hadron stop cavern	5.4 m
Length of hadron stop	18.2 m
Cross-section of hadron stop	$4 \times 4\,\mathrm{m}^2$
Length of graphite insert	3 m
Cross-section of graphite insert	$2.6 \times 2.6\,\mathrm{m}^2$
Wall thickness of aluminium box around graphite	0.1 m
Length of airgap upstream of hadron stop	0.25 m
Length of airgap downstream of hadron stop (= approx. length of first muon chamber TNM41)	5 m
Concrete wall to separate hadron stop from first muon chamber	thickness to be defined
Length of "muon filter": Molasse	67 m
Length of 2nd muon chamber TNM42	5 m
Muon detector "service alcove" surface	$10 \times 4\,\mathrm{m}^2$
Access gallery to hadron stop: diameter	3.1 m (int.)
Access gallery to 2nd muon chamber: diameter	3.1 m (int.)

B Design of horn and reflector for the CNGS beam

Details of the new design of horn and reflector are summarised in this Appendix. The new, realistic co-ordinates of the inner and outer conductors, as used in the simulations of the new CNGS reference beam, are given in Table 6 and in the figures 7, 8 and 9. An updated table of the electrical characteristics of the new horn and reflector is shown as Table 3 - this takes into account the higher current of the reflector and includes corrected values of the inductances and resistances.

CNGS - Update of beam layout, November 2000	HORN 1			HORN 2 (REFLECTOR)		
Current	150 kA			180 kA		
Start of element on longitudinal axis	2.700 m			43.350 m		
Nominal length of horn	6.694 m			6.694 m		
	L [cm]	R [cm]	tt [cm]	L [cm]	R [cm]	tt [cm] [cm]
Upstream flange	0.0	35.80	0.30	0.0	55.80	0.30
	0.0	5.260	0.30	0.0	28.00	0.30
Central conductor	0.0	5.260	0.30	0.0	28.00	0.30
	39.0	5.640	0.20	291.3	22.67	0.20
	116.4	6.250	0.18	470.7	16.64	0.20
	200.3	6.580	0.18	539.8	13.45	0.20
	288.9	6.710	0.18	596.5	10.00	0.20
	379.2	6.490	0.18	631.7	7.00	0.20
	423.7	6.240	0.18	665.0	7.00	0.20
	466.8	5.890	0.18			
	507.8	5.440	0.18			
	545.8	4.890	0.18			
	579.4	4.250	0.18			
	609.3	3.520	0.22			
	633.1	2.710	0.29			
	650.6	1.840	0.43			
	662.3	1.220	0.64			
	665.0	1.220	0.64			
Downstream flange	665.0	0.122	0.60	665.0	7.00	0.30
	669.4	35.80	0.60	669.4	55.80	0.30
External conductor	L [cm]	R [cm]		L [cm]	R [cm]	
	0.0	35.80	1.60	0.0	55.80	1.60
	665.0	35.80	1.60	665	55.80	1.60
	669.4	35.80	1.60	669.4	55.80	1.60

R = mean radius
tt = total thickness (measured perpendicular to the slope of the conductor)
(R, L, tt as defined in the following figures).

Figure 6: *Table of detailed co-ordinates of the CNGS horn and reflector, version 2000.*

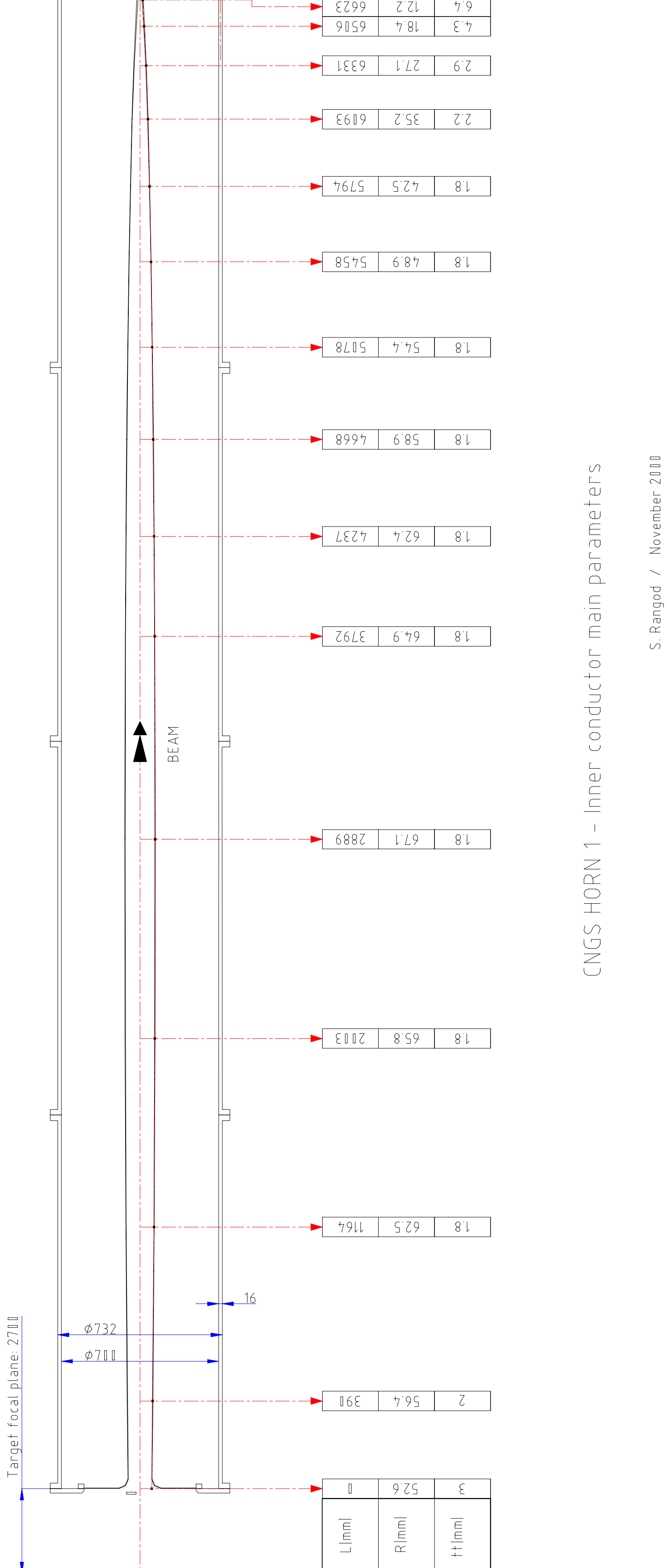

Figure 7: *Cross section of the first horn.*

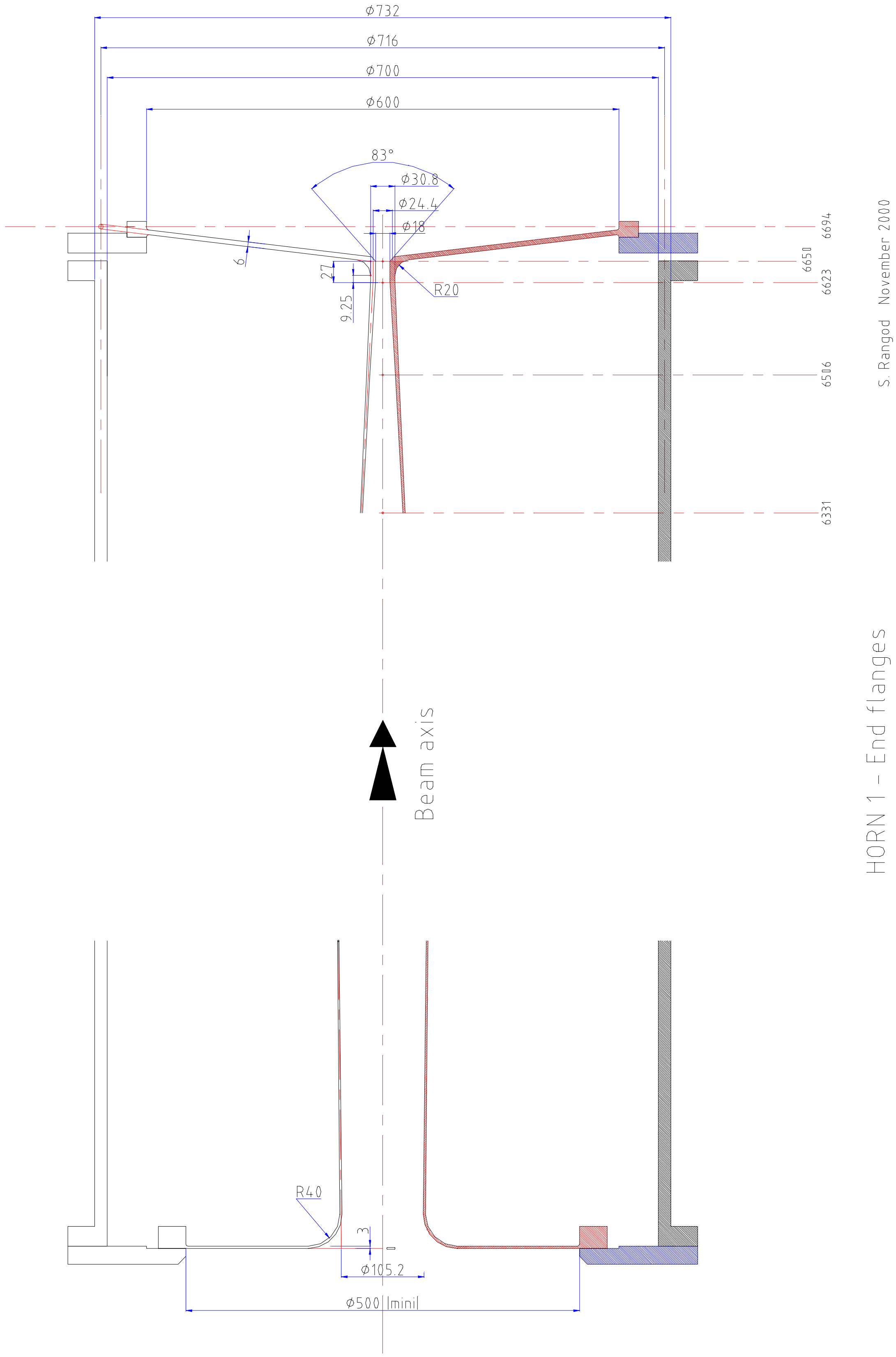

Figure 8: *Cross section of the end-flanges of the first horn.*

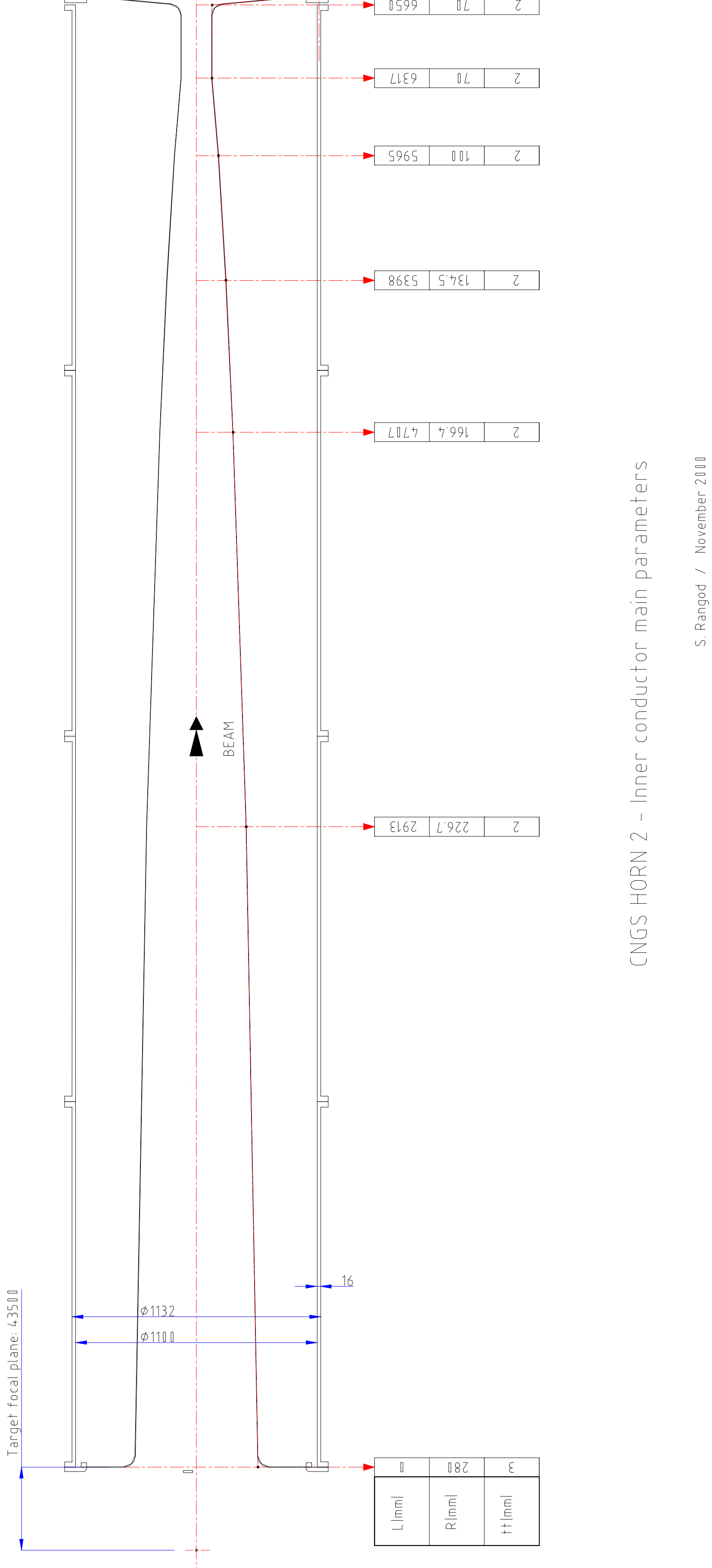

Figure 9: *Cross section of the second horn (reflector).*

Table 3: *Horn and reflector electrical characteristics*

	CNGS HORN	CNGS REFLECTOR
Peak current horn/reflector	150 kA	180 kA
Transformer ratio	14	14
Primary peak current	10714 A	12857 A
Inductance horn/reflector	$2.7\,\mu\text{H} \times 14^2 = 0.53\,\text{mH}$	$1.5\,\mu\text{H} \times 14^2 = 0.30\,\text{mH}$
Inductance total circuit	0.76 mH	0.52 mH
Resistance horn/reflector	$0.60\,\text{m}\Omega \times 14^2 = 0.118\,\Omega$	$0.21\,\text{m}\Omega \times 14^2 = 0.041\,\Omega$
Resistance total circuit	$0.248\,\Omega$	$0.170\,\Omega$
Total capacitance for one switching section	$45.4\,\mu\text{F} \times 90 = 4086\,\mu\text{F}$	$45.4\,\mu\text{F} \times 75 = 3405\,\mu\text{F}$
Total capacitance for two switching sections	$45.4\,\mu\text{F} \times 90 \times 2 = 8172\,\mu\text{F}$	$45.4\,\mu\text{F} \times 75 \times 2 = 6810\,\mu\text{F}$
Pulse duration	5.8 ms	4.3 ms
Charging voltage	6762 V	6796 V
Total stored energy	$2 \times 93.4\,\text{kJ} = 186.8\,\text{kJ}$	$2 \times 79\,\text{kJ} = 158\,\text{kJ}$
Voltage on horn/reflector	340 V	275 V
Duty cycle	2 pulses, 50 ms apart, every 6 s	
r.m.s. current on primary (2 pulses)	332 A	343 A
r.m.s. current on secondary (2 pulses)	4647 A	4807 A
Mean power dissipated in horn/reflector by current only (2 pulses)	12.6 kW	4.8 kW
Mean power dissipated in horn/reflector by beam (4.8×10^{13} p.o.t.	6 kW	0.2 kW
Total power dissipated in horn/reflector (2 pulses)	18.6 kW	5.0 kW
Waterflow for $\delta\theta = 6^o$C	44.4 l/min	12.0 l/min

References

[1] F. Pietropaolo and N. Vassilopoulos, CERN SL note, in preparation.

[2] G. Acquistapace et al. The CERN Neutrino Beam to Gran Sasso, Report CERN 98-02 and INFN/AE-98/05.

[3] R. Bailey et al. The CERN Neutrino Beam to Gran Sasso (NGS), Report CERN-SL/99-034(DI) and INFN/AE-99/05.

[4] M. Bonesini et al., "On particle production for high energy neutrino beams", to be submitted to Europ. J. Phys.; F. Pietropaolo, private communication.

[5] G. Collazuol et al., *Neutrino beams: production models and experimental data*, Nucl. Inst. Meth. **A449** (2000) 609; and A. Guglielmi, private communication.

[6] The CERN program library; and N. Vassilopoulos, private communication.

[7] H. Vincke and G.R. Stevenson, *Energy Deposition in the Focussing Devices of the CERN Neutrino Beam to Gran Sasso (CNGS) facility*, CERN/TIS-RP/TM/99.