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CERN BEAMS FOR LONG BASE LINE NEUTRINO OSCILLATION EXPERIMENTS

A. Ball, B. Bianchi, J.P. Revol, G.R. Stevenson, E. Weisse

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INTRODUCTION

The neutrino sector is of fundamental importance in physics. Beyond high energy physics it is also directly related to cosmology (dark matter) and to astrophysics (stellar energy generation mechanism).

There is today renewed interest in neutrino physics due to the experimental situation suggesting the idea of possible new physics in this area. Consequently, the case for long terrestrial base line neutrino oscillation experiments has become very strong since there is mounting evidence (atmospheric and solar neutrino studies) that a specific region at small Δm^2 (10^{-1} to 10^{-6} eV^2) should be carefully studied.

A favoured solution to the observed deficit of solar neutrinos is that, contrary to what is assumed in the Standard Model, neutrinos could have a non-zero mass and could mix in the same way quarks do. If that were the case, oscillations could occur between different neutrino species, either in vacuum or in matter where under certain conditions they could be enhanced (MSW).

Experiments searching for neutrino oscillations and using neutrino beams have been restricted to neutrino masses of the order of at best 0.1 eV^2. To extend the sensitivity of such experiments to much smaller masses, it is necessary to extend the baseline outside the natural boundaries of a laboratory.

It is therefore natural to investigate at CERN the possibilities of sending a neutrino (ν_μ or $\bar{\nu}_\mu$) beam in the direction of a detector situated far away, but having a sufficient size so that a significant event rate can be expected. Our study led to two very attractive possibilities: (1) The planned SPS–LHC proton transfer line (TI48) points almost exactly in the direction of the Gran Sasso Laboratory, 732 km away in Italy, where ICARUS (15,000 tons of liquid argon) is planned, and (2) the proton extraction (LSS2) towards the North area is already in the azimuthal direction of Super- kamiokande (22,000 tons of water) 8,752 km away in Japan. Dumand situated 10,400 km away in the Pacific ocean was also considered, but the fact that a 60° slope is needed for the beam at CERN, combined with the high energy threshold of the detector, makes it much less attractive.

It should also be noted that most large neutrino detectors are also used for the search for proton decay and the availability of accelerator neutrinos offers a unique way to calibrate the background to proton decay, by providing neutrino interactions in the proton decay kinematic region.

The fortunate situation of TI48 and LSS2 has naturally a very strong impact on the cost-effectiveness of the project and demonstrates again the extreme versatility of CERN facilities.

Geographic data for Gran Sasso and Superkamiokande:

The Gran Sasso distance to CERN is 732 km, and its direction in the CERN coordinate system is approximately given by [1] :

- Azimuth (with respect to geographic north) : 122.502°.
- Slope (with respect to the horizontal plane) : – 3.283°.

The Superkamiokande distance to CERN is 8752 km, and its direction is approximately given by [1] :

- Azimuth : 37.403°.
- Slope : – 43.381°.

CONCEPT OF A NEUTRINO TARGET STATION

There are several ways in which target areas have been designed for protons of several hundred GeV in order to minimize the effects of the high levels of induced radioactivity. In the North target areas of the SPS the approach has been to build as large a target hall as was economically possible in order to dilute the secondary particle fluxes by the simple inverse square law as much as possible before they hit the target station walls, thus reducing the interaction density in these walls and thus the levels of induced radioactivity. Local shields are placed around the principal points where protons interact both to reduce the levels of induced radioactivity in the surrounding components such as motors for positioning the targets, etc.. and to reduce as much as possible the total hadron path-length in air thus reducing the activity levels in the air. The large amount of space allows one to insert inactive shielding between a person working and the active components.

The approach used at FERMILAB was to minimize the volume of the target-station and to counter the effect of the extremely high levels of induced radioactivity by avoiding the need for human intervention directly on the equipment of the target station. All equipment is mounted on "trains" which can be removed from the target station to specially shielded areas serviced with manipulators in order to maintain and repair the active equipment.

The present approach of the neutrino cave at CERN is an example of a compromise between these two approaches which carries none of the advantages of either. The cave is not sufficiently large for persons to be able to protect themselves from the radioactivity either by local inactive shielding or by simple distance and it is sufficiently small to ensure high densities of secondary hadron interactions while requiring personal intervention.

The approach recommended here for any new neutrino target area is to follow that of the FERMILAB target stations, i.e. to mount the target, some local shielding and all beam monitoring equipment on one carriage, the horn on a second carriage and the reflector on a third. The three carriages would be connected by flexible attachments and would move on rails set into the ground. Alignment would be achieved by special jacks slotting into special reference marks in the walls and floor of the cave. Whereas this should present little difficulty for the 3 ° slope of the target station to Gran Sasso, significant design effort will be required to achieve a viable installation for Kamiokande.

The proposed concept involves filling in the excavated tunnel with iron and concrete, leaving only enough room for the trains to pass through. This shielding is to attenuate the secondary radiation so that as little radioactivity as possible is created in the rock around the target region. No services other than the rails and location points would be installed in the tunnel. This implies that all services must be brought to the neutrino cave via a parallel service tunnel of similar dimensions to the target tunnel placed some 8 m to the side and linked by small cross-galleries. These galleries and alcoves would contain the transformers for the horn and reflector. The galleries would be positioned so that services could be connected to the carriages from the safety of the service gallery.

BEAM LINES AND TUNNELS

Gran Sasso

As part of the work for the LHC project at CERN injection transfer lines are being designed to bring the fast extracted beams from the SPS to the new collider [2]. The primary proton beam for a υ production target to feed Gran Sasso with only minor modifications can be derived from the one, TI48, which links SPS/LSS4 to LHC/P8. The geometry of TI48 is made of 2 arcs of 35° and 70° total horizontal deflection separated by a 1 km long straight section. The orientation of this straight section is such that only very minor extra horizontal and vertical deflections are needed to direct the protons exactly towards the Gran Sasso detector (Fig. 1 and 2). The required horizontal deflection is of the order of 31 milliradian, just enough for switching away from TI48 and for getting sufficient lateral separation at the position of the target station from the LHC injection line. The vertical deflection is about 32.5 milliradian downwards. The total length of the new beam line to implement these deflections and also to provide the necessary focussing of the small beam spot onto the target is about 140 m. Whereas the arcs of TI48 are made of superconducting magnets, for the branch towards the υ target classical warm magnets of types existing at CERN can be used. The total required bending power for 450 GeV/c beam momentum is 95 Teslameter and the number of quadrupoles is 10 equivalent type QTL. The beam line will be equipped with horizontally and vertically deflecting pairs of dipole correctors for precise final adjustment of the beam direction and with an adequate number of beam position, profile and intensity monitors.

An overall plan of the proposed modification to TI48 is given in Figure 1. More details are given in Figures 2 and 3 which contain a vertical section along the line of the proton beam to the neutrino target and a plan view of the underground constructions. Access to the new tunnels would be via a 9 m diameter vertical shaft, linking via a horizontal tunnel to a 10 m wide junction chamber. This would provide the necessary manoeuvering and storage area for the highly activated train carriages. In the Figures it is assumed that a separate service tunnel will be built alongside the target station. An alternative would be to use the TI48 tunnel itself as the service tunnel. However, because of the presence of the LHC injection line and the level and slope difference between TI48 and the neutrino target tunnel this latter may not be a practical proposition. This remains to be studied in detail.

At the end of the target tunnel the evacuated pion-decay tunnel is assumed in Figures 1-3 to extend for about 600 m. There is no reason, apart from the cost of tunnelling, why the tunnel could not extend further. At the end of the decay tunnel one must expect to build a dump for the remaining primary protons and secondary hadrons that will contain induced radioactivity to a proportion acceptable to the regulatory authorities. This dump cavern is close enough to TI48 however for access to be provided via the LHC injection tunnel.

Kamiokande

The most important feature of a beam towards Kamiokande is its inclination of nearly 45° downwards, which requires important vertical bending and which results in installations relatively deep underground. As far as the horizontal direction is concerned, the present extracted beam from LSS2 towards the North Experimental Area most closely fits to the requirements. It is therefore proposed to derive the beam feeding the target from this complex and most advantageously from ECN3 which is close to the surface level and which was designed for high intensity protons beams. The extra required horizontal deflection is of the order of 5° (see Fig. 4). In order to minimize the depth of the target station superconducting magnets are proposed for the 45° vertical bend. Assuming a field level of the order of 6T and adding a straight distance of 100 m from the last bending magnet for final beam focalization the target will be at a depth of about 175 m below the level of ECN3 (see Fig. 5). The feasibility of installing the 350 m long string of superconducting magnets on a slope up to 100% needs to be studied.

It must be noted that since at present the North Experimental Area can only be supplied with slow resonant extracted beams, provisions must be made for a fast extracted beam to the new zone.

Access for the train carriages could be provided along the beam tunnel from ECN3, where excellent crane-facilities are available for handling delicate highly radioactive objects. Access to the target cave for personnel and other equipment could be via a vertical shaft leading to the lower part of the target area. In this case it is not proposed to build a parallel service tunnel but to replace this by three horizontal galleries leading from the vertical shaft to the reflector and horn positions. If necessary, other horizontal service galleries could be built. Sketches of the proposed underground target area with the interlinking galleries and shafts are given in Figure 6.

An access to the dump cave is not proposed in the present plans. However, as with the Gran Sasso proposal, it is to be considered that the host states will insist that all radioactivity must be removed from the underground areas at the end of the experiments. This will not be a trivial operation. As for Gran Sasso, the figures indicate a decay tunnel length of only 600 m. To lenghen this tunnel would significantly increase tunnelling cost because of the quality of rock and the depth of the excavation.

THE TARGET

It is assumed that the same type of target as presently under construction for the experiment WA95 (Chorus), which is very similar to the one used previously for experiment W79 (Charm II). It consists of a string of Beryllium rods of 100 mm length each and a diameter of 3 mm. Each rod is inserted at either end into holes of a Beryllium plate. Cooling is provided by forced flow of gas. The target is mounted in a container which will be put in place by a precision plug-in technique. Compared to targets of different geometry and materials this type provides optimum efficiency, i.e. highest flux of neutrinos per primary proton. This type of target has been exposed for long periods with a double fast/slow extracted beam of spill length of 6 ms and a total intensity of $1.8 * 10^{13}$ protons per SPS cycle. A test, after the end of the WA79 experiment, to explore the limit of its performance by increasing the intensity for a short period to in total $2.4 * 10^{13}$ protons per cycle lead to destruction. The damage is still under investigation. Experience of this type of target with a fast extracted beam of 23 μs spill length exists from its use for producing the narrow band neutrino beam in 1979. The target was destroyed when the intensity temporarily was increased to $1.3 * 10^{13}$ protons per pulse. Therefore, at least at present, it is safe to assume a maximum intensity of $1 * 10^{13}$ protons per pulse. It needs to be studied whether a somewhat different geometry, e.g. by reducing the length of the rods could somewhat increase the performance.

THE FOCUSING ELEMENTS

Three possibilities can be considered for focusing the beam after the target :

- quadrupole focusing using one or more triplet structures,
- co-axial magnetic lenses usually known as horns and reflectors,
- plasma lenses in which the target forms the inner conductor.

The horn/reflector alternative is preferred as it gives a broader energy and angular acceptance - hence higher neutrino flux, is sign selective and is known to operate with high reliability (Fig. 7).

An essential feature of this type of beam is that there can be no correction of the beam direction after the target. All elements must be co-axial with a line between the target and detector to a high degree of precision and the incident proton beam must be steered coaxially through the target. This imposes stringent requirements on the alignement of the elements and rail system.

For 450 GeV/c incident protons, the magnetic horn would typically be of the order of 6 metres length and located 2 m behind the target, manufactured from anticorodal, with a cylindrical outer conductor of 250 mm radius and a thin 'paraboloid' inner conductor with radius from 180 mm to 8 mm. The inner conductor would be cooled by de-ionized water spray on a closed circuit system. The horn would be powered with a half-sinusoid pulse of 100 - 120 kA peak current and 3 msec duration obtained by discharge of a capacitor bank through a pulsed current transformer.

A single magnetic reflector (Fig. 8), of similar design to the horn, is envisaged. The potential gain in flux by adding further reflectors is usually negated by the increased absorption losses. The reflector length would ideally be ~ 10 m, with an outer conductor of 400 mm radius ; final dimensions would be conditioned by the size of the access shaft to the cavern.

The transformers would be located in the alcoves of the connecting galleries between the beam and service tunnels. The water and high current, strip-line connections at the junction of the beam tunnel and gallery must be designed so as to limit personnel radiation exposure and some sort of remote manipulation may have to be considered.

Some very preliminary calculations, extrapolating the CHORUS/ NOMAD neutrino polarity beam, indicate an rms neutrino beam radius of the order of 600 m for Gran Sasso at 700 km and neutrino flux of $6.10^4/m^2$ per 10^{13} incident protons in a 10 m radius detector with a mean energy of 40 GeV/c. The latter should be compared to a typical mean energy of 24 GeV/c in current beams in the West area, showing that the beam becomes considerably harder with distance. The ratio of ν_μ/ν_μ is less than 2% and the ratio of ν_e/ν_μ is in the region of 0.5%.

For 80 GeV/c incident protons the magnetic horn would be shorter (~ 2.5 m) and as close as possible to the rear of the target.

No flux estimates are yet available for Kamiokande (approx 9000 km). Installation of the horn and reflector system on a 45° slope pose additional problems but are not insuperable.

Since the beginning of SPS operation in 1976, neutrino beams of this type have been operated on a continuous basis for over 50% of the scheduled machine run time and taken 65% of all protons accelerated by the SPS.

DECAY TUNNEL

In the initial calculations, an evacuated decay tunnel of 1.1 m radius and total decay length from the target of 1100 m has been assumed. It seems probable that a smaller radius would be adequate if this reduces the costs of civil engineering. Increasing the length of the decay path from the target increases the neutrino flux but also favorises the high energy component.

BEAM CONSIDERATIONS

The normal SPS cycle, which provides beams for both SPS and LEP experiments, has a period of 14.4 seconds. Thus, in an operating year of 10^7 seconds there would be $7 * 10^5$ pulses which with 10^{13} protons per pulse would provide $7 * 10^{18}$ protons per year onto the neutrino production target.

The simplest modification to the normal SPS cycle would be the removal of the lepton pulses which feed LEP, resulting in a time-saving of 4.8 seconds. With this cycle which has a period of 9.6 seconds, the SPS could supply 10^{19} protons per year to the neutrino target.

With the appropriate machine development, it could be envisaged to shorten this cycle to 4.8 seconds which would mean that $2 * 10^{19}$ protons could be supplied to the neutrino target. In this case, the operation of the SPS would be dedicated to this experiment only.

CONCLUSIONS

Both the projects to supply neutrinos to Gran Sasso and to Kamiokande appear to be physically realisable. The Gran Sasso project contains less unknowns from the civil engineering and installation viewpoints. One already has good experience of tunnelling in the molasse and the slope of the floor of the target station is not too severe. On the other hand, for the Kamiokande project, special techniques would have to be developed for installing beam-line equipment and aligning it on slopes approaching 45 °. These techniques could be especially constraining for super- conducting magnets and the highly radioactive components of the target station. An additional difficulty to be overcome in the Kamiokande project is that a significant amount of excavation would have to take place in solid limestone instead of molasse. It has also been assumed that the decay tunnel could be excavated without the need for a second shaft to the end of the tunnel. If this were to be needed eventually, this would add about 50% to the length of tunnel to be excavated.

REFERENCES

[1] Private Communication, M. Mayoud, CERN-AT/SU.

[2] Design Study of the Large Hadron Collider (LHC), CERN 91-03, May 1991.

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C. Rubbia
L. Evans
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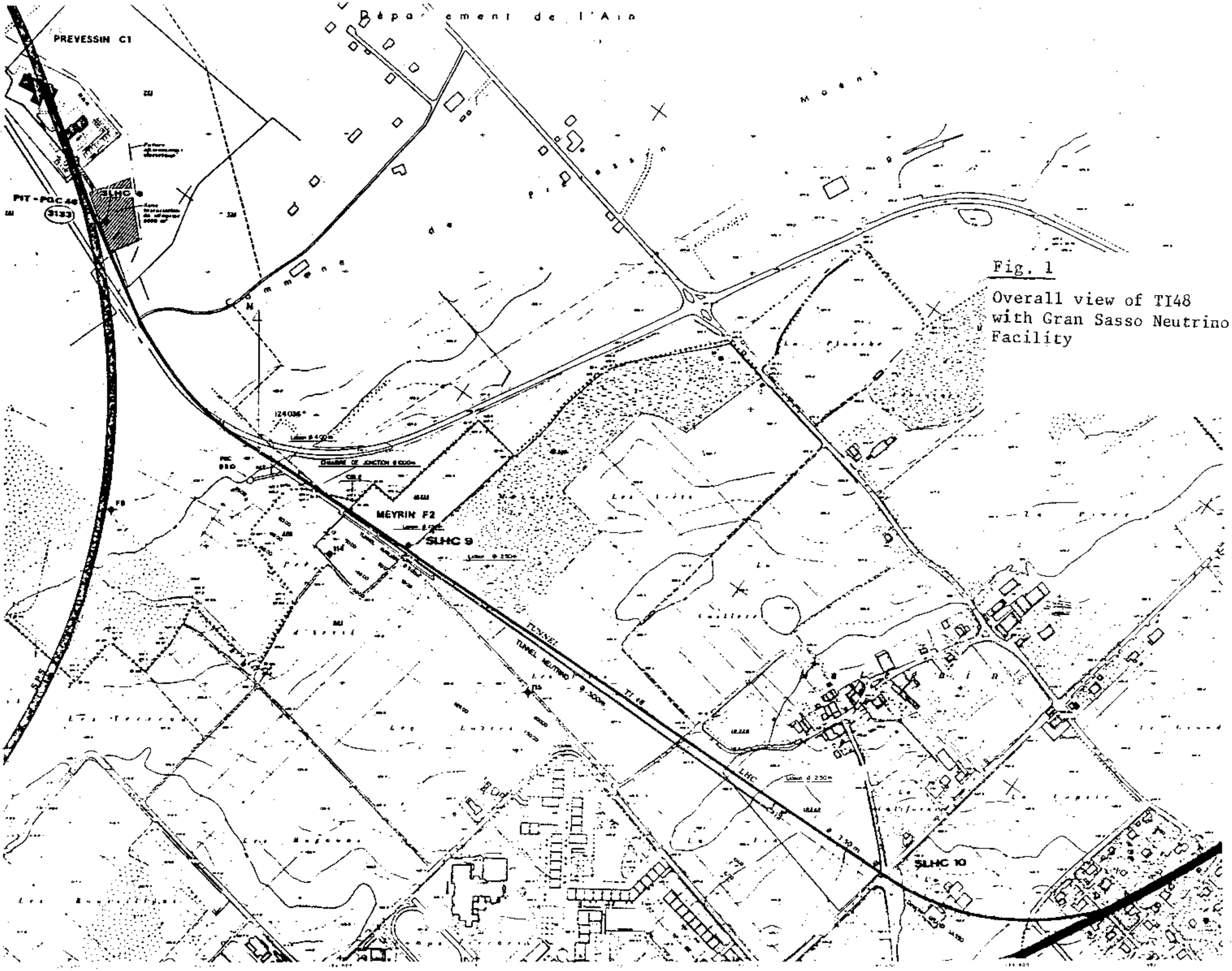

Fig. 1

Overall view of TI48
with Gran Sasso Neutrino
Facility

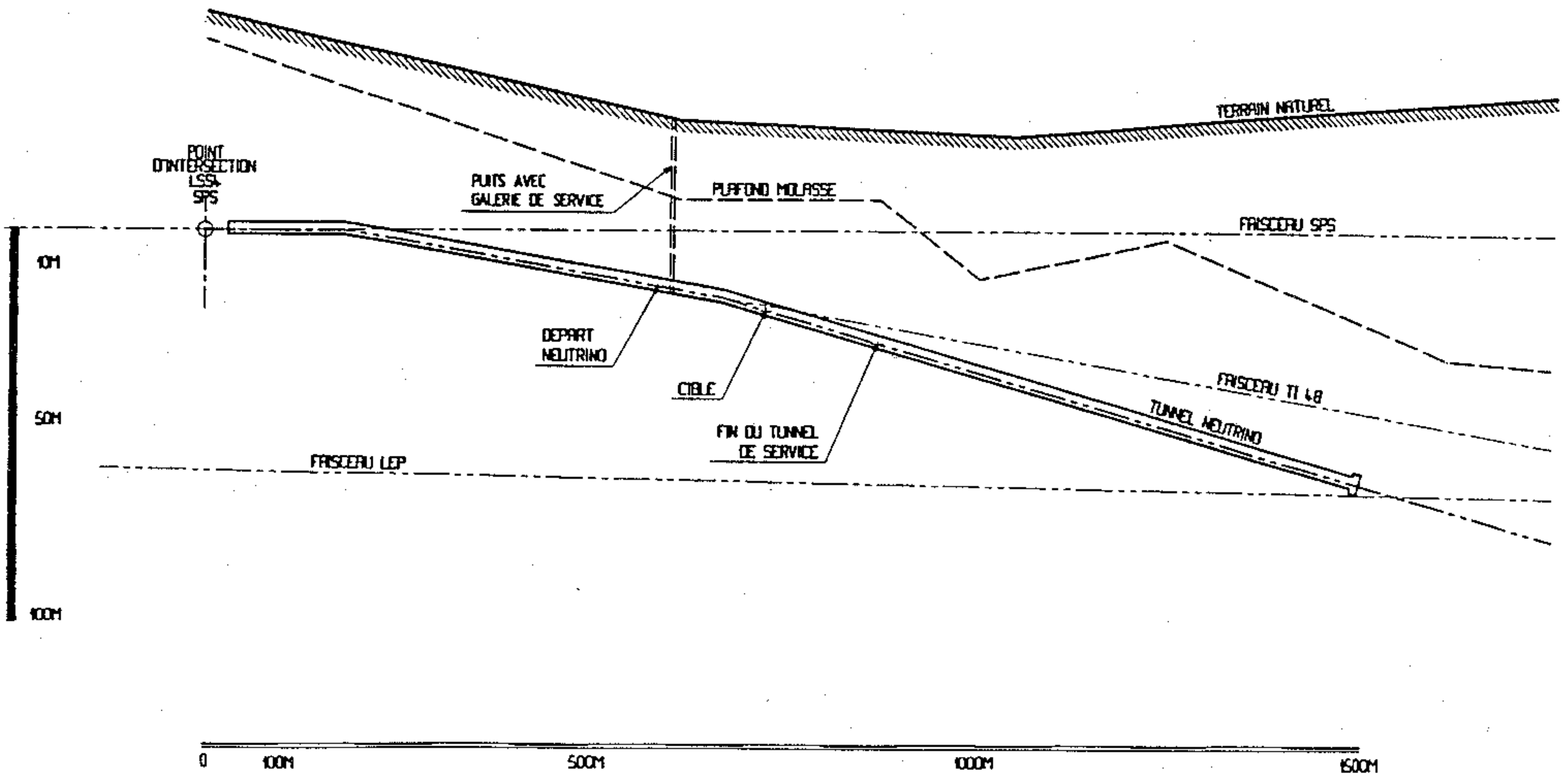

Fig. 2 - PROFIL EN LONG TUNNEL NEUTRINO GRAN SASSO

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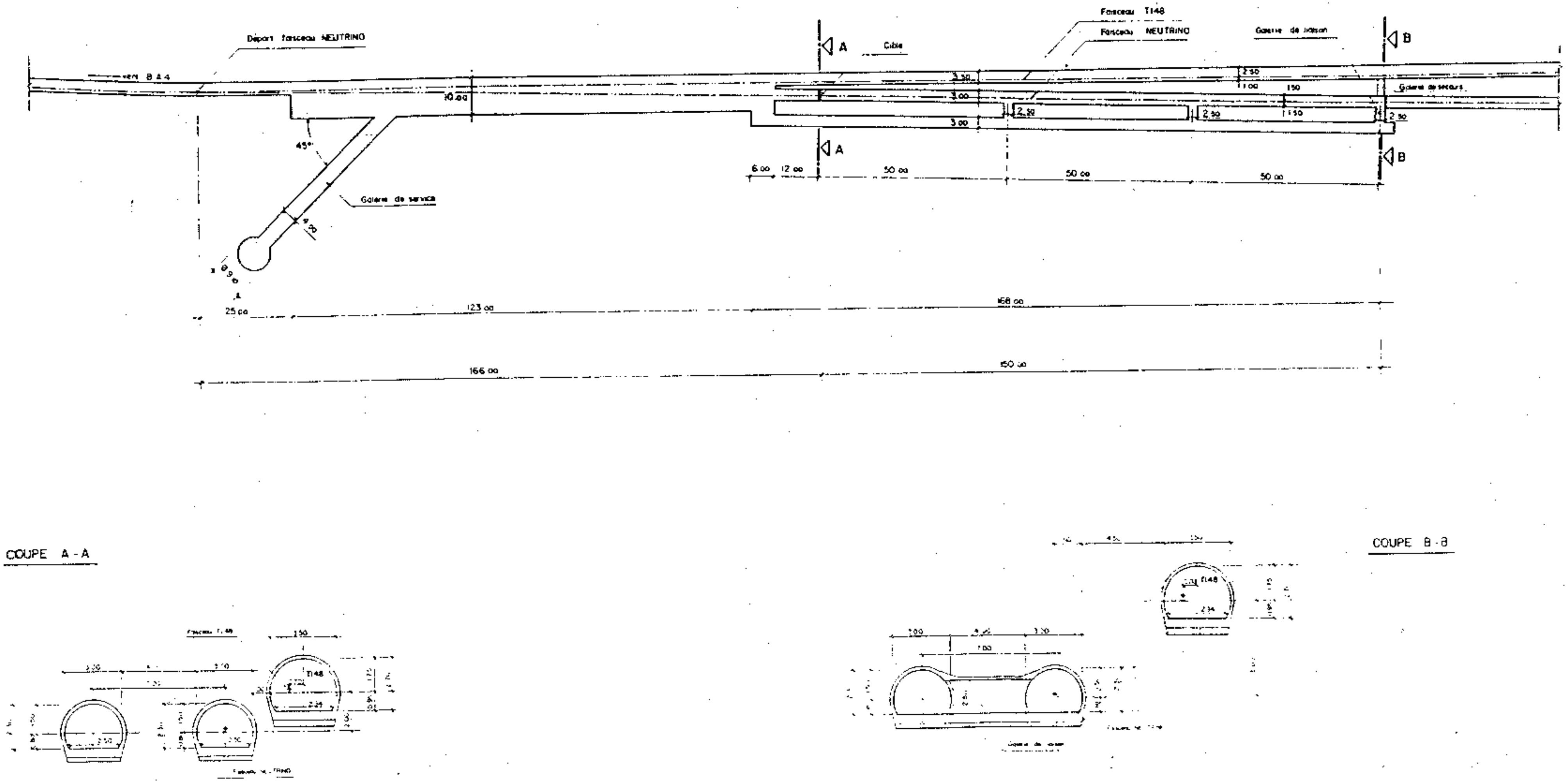

Fig. 3 - Plan View of Gran Sasso Neutrino Target Zone

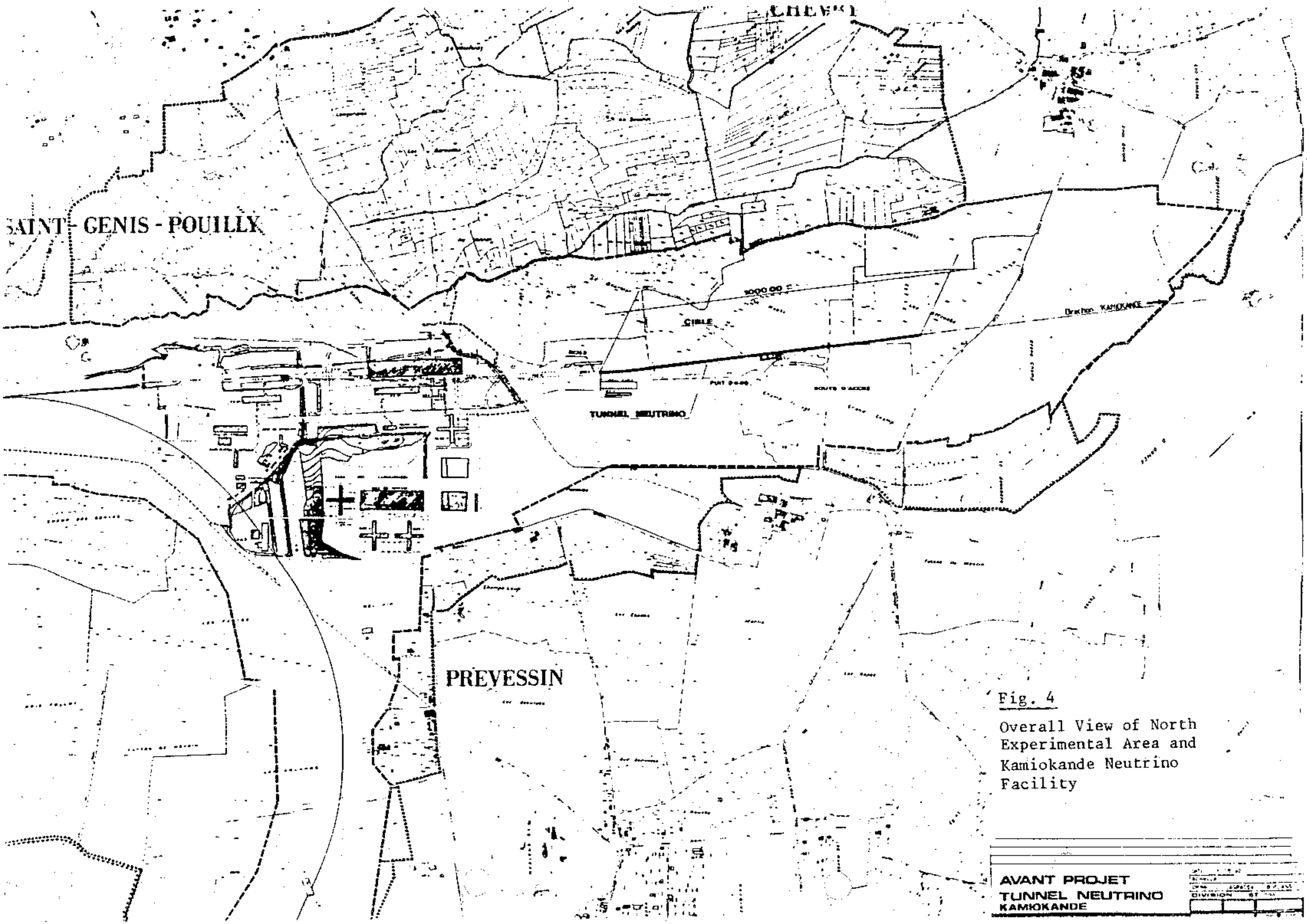

Fig. 4

Overall View of North Experimental Area and Kamiokande Neutrino Facility

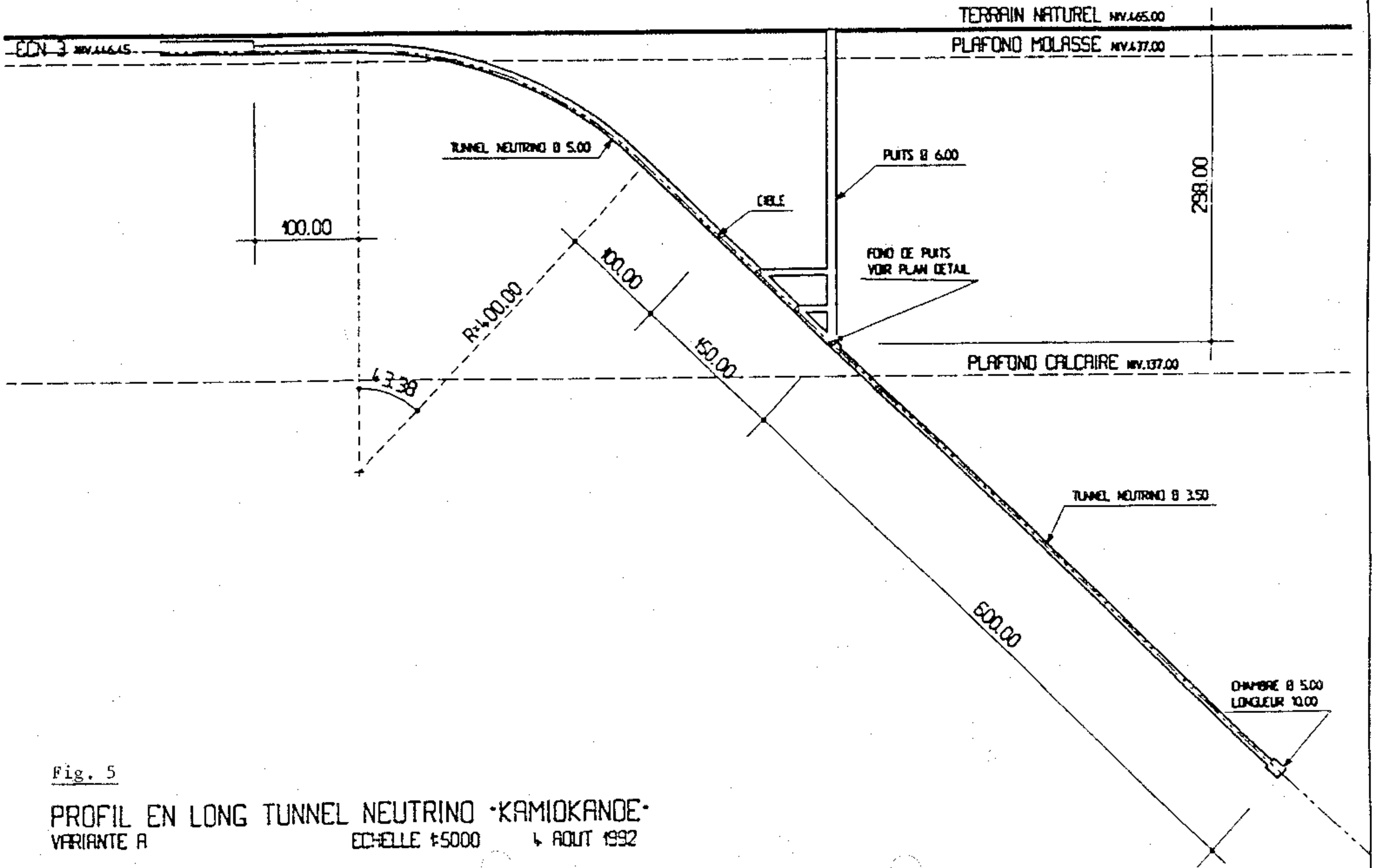

Fig. 5

PROFIL EN LONG TUNNEL NEUTRINO ·KAMIOKANDE·
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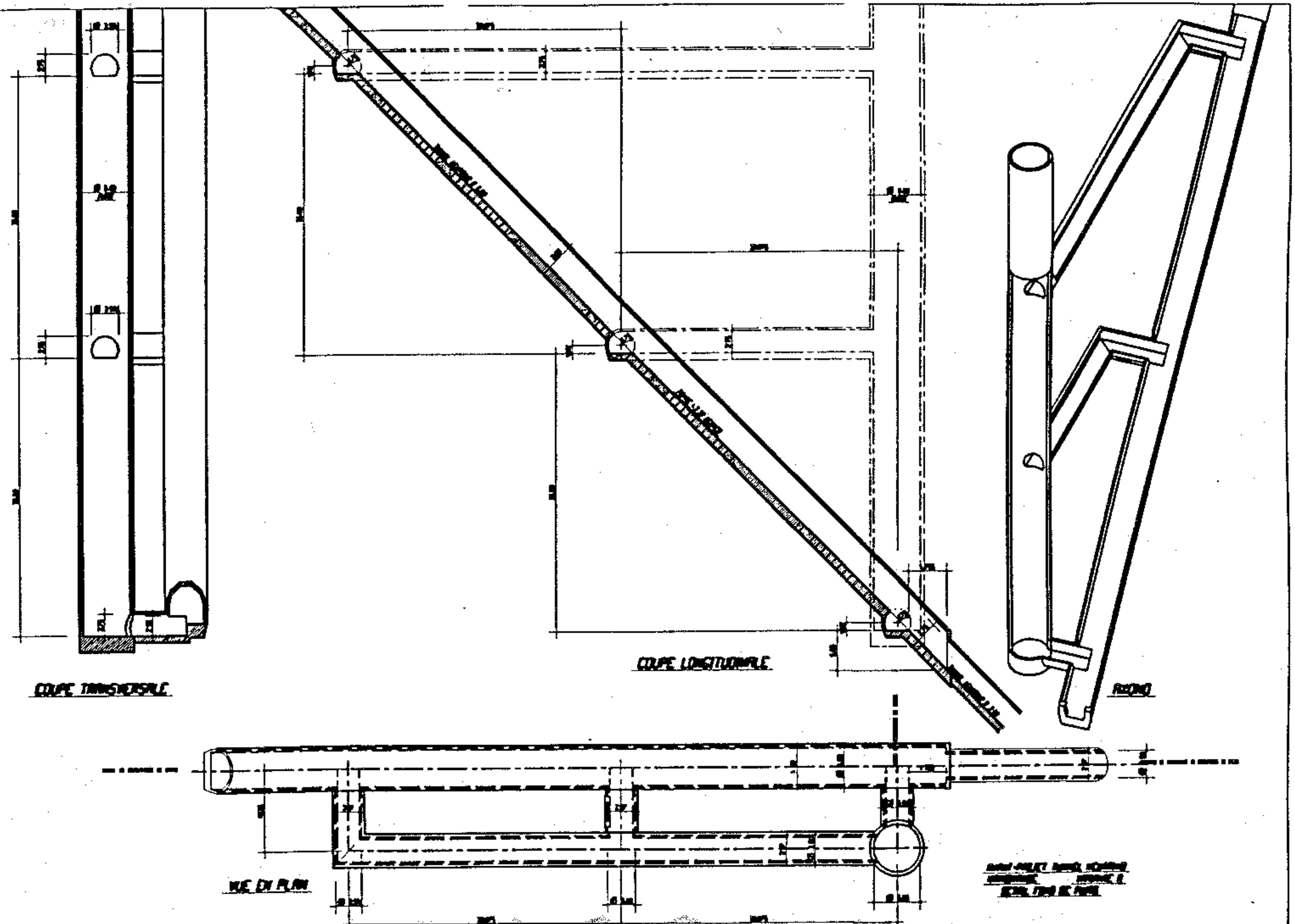

Fig. 6 - Projections of Kamiokande Neutrino Target Zone

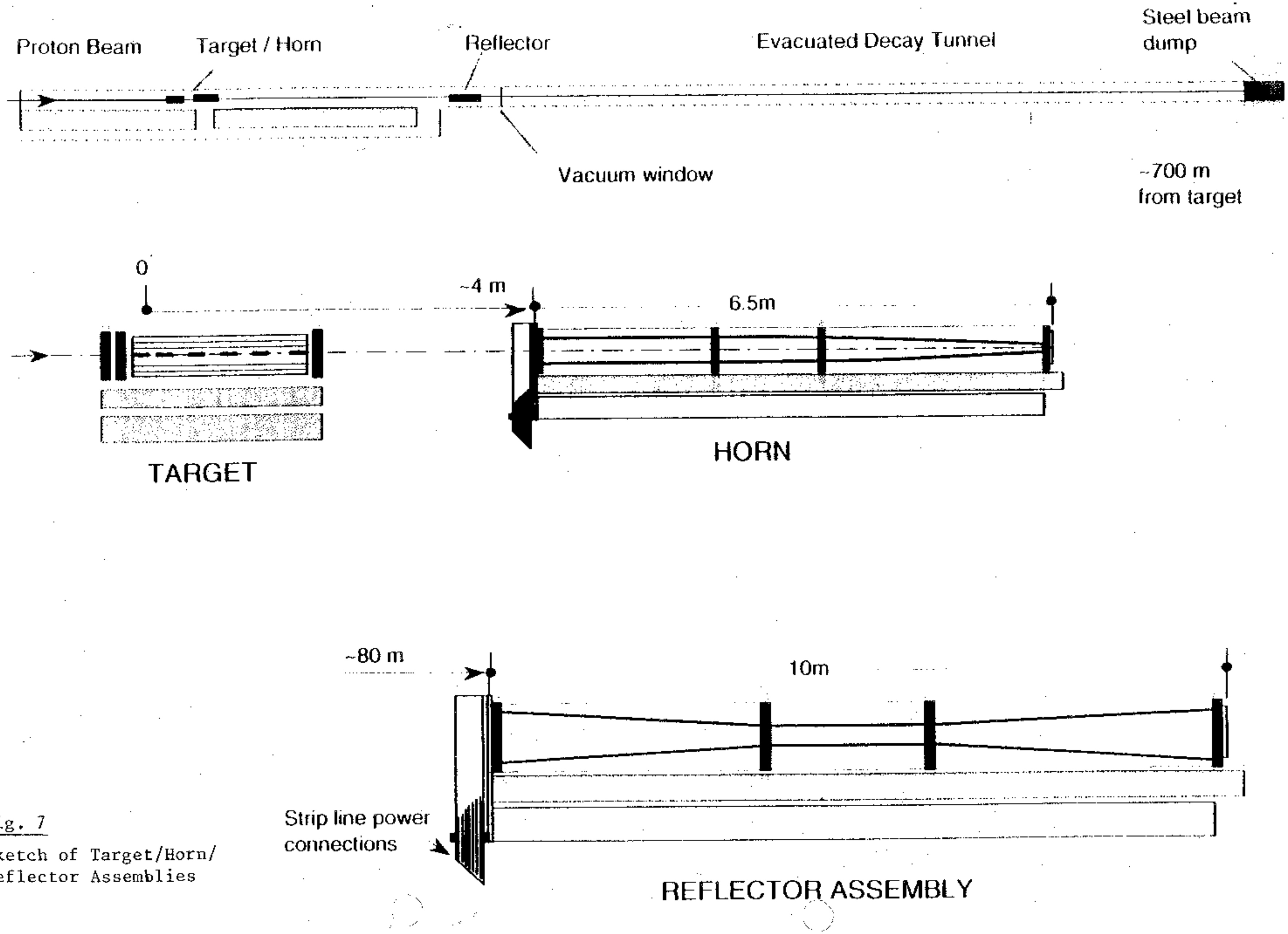

Fig. 7

Sketch of Target/Horn/
Reflector Assemblies

Fig. 8 - **PRINCIPLE of REFLECTOR**