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Results and Lessons from the Operation of Current Beams for Existing Neutrino Experiments

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An overview of the exploitation of accelerator neutrino beam facilities is presented. Emphasis is given on the elements of the secondary beam, i.e. the target and the equipment downstream of it. Using the examples of K2K, MiniBooNE, NuMI and CNGS, a number of lessons learnt in operating these neutrino beams are outlined. The T2K facility, presently under construction, is included in this overview.

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[1] Speaker

1. Introduction

The current beams for existing neutrino experiments are based on producing neutrinos from meson decay in flight. A proton beam is sent to a target, producing among many other particles pions and kaons. The charged π/K are energy-selected and guided using a magnetic focusing system. These mesons then decay in flight into muons and muon-neutrinos. Hadrons that have not interacted in the target or have not decayed are absorbed in a hadron stopper.

Physics requirements have been pushing the required power of the proton beam on target to values around and above 500 kW. The design of the production target is a compromise between the probability of the protons to interact and the re-interaction or scattering of the particles produced. Moreover, beam impact and target heating is a major issue in the design, and some form of cooling is needed.

The focusing system is usually built using one or several magnetic 'horns' [1]. These cylindrical structures, producing a toroidal field, have a very thin inner conductor to minimize particle interactions. Pulsed currents exceeding 200 kA are applied, requiring that the inner conductor be cooled - water-cooling is generally used.

The dimensions of the decay region depend on the energy of the mesons. Choosing to evacuate the decay tube or filling it with air/helium is weighed against the entrance window thickness and related safety issues.

The hadron absorber has to withstand the full beam power for at least one proton beam pulse (in case the beam misses the target) and has to continuously absorb some 5-10 percent of the beam power. All systems in operation and planned use water cooling of the hadron absorber.

Beam monitoring equipment is required upstream of the target to center the proton beam correctly. The radiation levels downstream of the target make it difficult to install sophisticated monitors. Beyond the hadron absorber, muon detectors provide valuable on-line information on the intensity and quality of the neutrino beam produced.

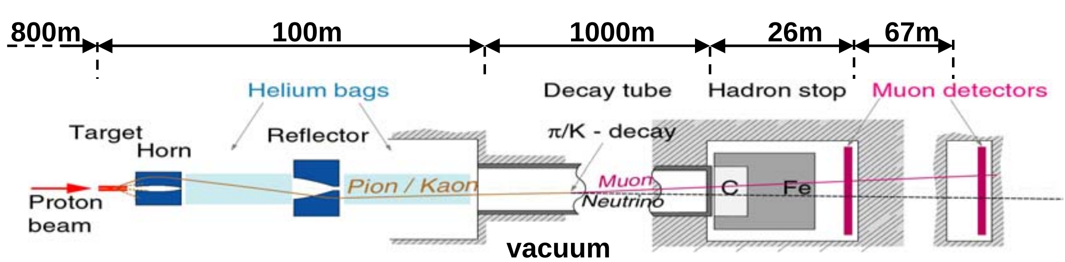

Figure 1: Layout of a typical conventional neutrino beam line (this example: CNGS).

In the following, the more recent and the presently operating neutrino beam facilities are described. Since most facilities had only minor difficulties with the proton beam operation, the emphasis here is on the target and secondary beam elements. Results and main lessons learnt are summarized. The T2K facility presently under construction in Japan is also mentioned in this context.

2. K2K

K2K was the first long baseline neutrino oscillation experiment, aiming to measure oscillation parameters indicated by atmospheric neutrino experiment. The data taking period lasted from March 1999 until November 2004.

Neutrinos were produced using a 12GeV proton beam from KEK-PS with a cycle length of 2.2sec and a beam spill of 1.1ms with $6 \cdot 10^{12}$ protons/spill. The average neutrino energy was about 1.3GeV. An energy dependent deficit of muon neutrinos was observed in the 'far detector' Super-Kamiokande, 250 km distant from the neutrino production.

2.1 K2K Secondary Neutrino Beam Line

The K2K aluminum target was 66cm long, with a diameter of 30mm (initially 20mm) and was an integral part of the inner conductor in the first horn. There were two water cooled horns supplied with a current of 250kA and a pulse length of 2.5ms. The 200m long decay volume started 19m downstream of the target and it was filled with helium at 1atm. The hadron absorber at the end of the decay tube consisted of 3.5m iron and 2m concrete. Muon profile and intensity were measured using ionization chambers and silicon pad detectors installed downstream of the beam dump.

In order to measure the direction, flux and energy spectrum of the neutrinos at KEK a 'near detector' was installed 294m downstream the target. This detector consisted of two systems: a 1 kton water Cherenkov detector and a fine-grained detector (muon range detector, scintillating fiber and bar trackers).

2.2 Results and Lessons from the K2K Run

During the data taking period between 1999 and 2004 in total $1.049 \cdot 10^{20}$ protons were delivered out of which $0.922 \cdot 10^{20}$ protons were used for the analysis. 112 neutrino events were observed in Super-K, while the expected number of events was 158.1+9.2/-8.6 in case of no oscillation. This results into $\Delta m^2_{23}=(2.8 \pm 0.4) \cdot 10^{-3}\,eV^2$ at $\sin^2(2\theta_{23})=1$ (90%CL) [2].

The K2K horns were designed for 10^7 cycles. Every year the horns were preventively exchanged. There was no facility for remote handling of the horns. The first horn-1 had to be exchanged very early in the run (July 1999); It was found that the 20mm diameter Aluminum target rod (original design) was broken. After in-depth analysis, it was decided that the Aluminum target must have a diameter of 30mm. In total five horn-1 and four horn-2 were used. In November 2004 the inner conductor of horn-1 broke. At this point, the radiation levels were too high for a horn replacement. Since the delivered protons on target had meanwhile reached the design value of 10^{20}, the K2K run was terminated in December 2004.

The K2K experience seems to indicate that the target should be decoupled from the inner conductor of the horn, in order to avoid fatigue caused from heating and vibrations. It also shows the importance of remote handling of the equipment installed in the target cavern as high radiation levels are already reached after some months of operation.

3. MiniBooNE

MiniBooNE tests the LSND indication, i.e. an excess of electron neutrino candidates at the $\Delta m^2 \sim 1eV^2$ scale. Keeping the same experimental constraints for L/E (500MeV / 500m) but having different signal signatures, backgrounds and sources of systematic errors, MiniBooNE searches for $\nu_\mu \rightarrow \nu_e$ oscillation in an 'appearance experiment'.

The muon-neutrinos are produced by the 8GeV Fermilab Booster. The proton beam has a maximal intensity of $5 \cdot 10^{12}$ protons per 1.6µs beam spill at a rate of 5Hz. The neutrino detector of 12.2 m diameter is situated 541 m downstream the target. It is filled with 800t pure mineral oil and lined with photomultiplier tubes (PMTs).

3.1 MiniBooNE Secondary Neutrino Beam Line

The 71 cm long MiniBooNE target, made of Beryllium, is segmented into seven 'slugs'. It is cantilevered into the neck of the horn. The target is air-cooled. The (single) horn is powered with 170kA with a pulse length of 140µs. It is designed for 10^8 cycles. A spare horn is available. The polarity of the horn can be changed within 1-2 weeks. The charged pions and kaons pass through a 60cm diameter collimator and decay in the 50m long decay tunnel. The tunnel has 1.8m diameter and is filled with air at 1bar. In addition to the hadron absorber downstream of the decay tunnel there is also a moveable iron absorber at 25m (halfway). This absorber can be lowered into the tunnel to provide systematic checks on the electron-neutrino contamination from the muon decays. Both absorbers contain muon monitors (ionization chambers).

3.2 Results and Lessons from the MiniBooNE Run

Two independent blind analyses have been carried out with the result that no evidence for $\nu_\mu \rightarrow \nu_e$ oscillation has been observed [3]. Since the start of the experiment in 2002 until now (10 Aug 08) in total $1.17 \cdot 10^{21}$ protons on target have been accumulated. This corresponds to nearly 900000 neutrino events. Currently MiniBooNE runs in anti-neutrino mode, in order to search for anti-neutrino disappearance as well as to continue anti-neutrino cross-section measurements.

In 2003, after $\sim 10^8$ pulses, the horn had to be exchanged due to a water leak and a ground fault caused most probable by galvanic corrosion at a bellows seal in a small volume of trapped water. The re-designed new horn is still running and has now collected $\sim 2 \cdot 10^8$ cycles. MiniBooNE provides a demonstration that mechanical fatigue may not be the major issue for horn lifetime: In a humid and radioactive environment much care should be taken in the design of the auxiliary systems of the horns as well as in the choice of materials.

During the early anti-neutrino run in 2006 a drop in the event yield has been observed. The reason was that the hardened steel chains of several absorber plates from the 25m movable absorber were weakened by the radioactive atmosphere in the decay tunnel and, consequently, some absorber plates fell into the beam line. The plates were remounted using softer steel which is not subject to the hydrogen embrittlement effect. One may conclude that, in order to reduce aggressive radicals in the decay tube, air inside the tube should be avoided. Note that the decay tube of K2K was filled with helium, and T2K has chosen the same option. In December 2007, NuMI has switched from vacuum to a helium-filled decay tube. The decay tube in CNGS is under vacuum.

4. NuMI

NuMI, Neutrinos at the Main Injector, also verifies the $\nu_\mu \rightarrow \nu_\tau$ mixing hypothesis through muon neutrino disappearance and makes precise measurements of the oscillation parameters Δm^2_{23} and $\sin^2 2\theta_{23}$. NuMI was commissioned in 2004 and is fully operational since 2005. The disappearance of muon neutrinos is measured in the MINOS detector, a 5.4kton magnetized tracking detector in Minnesota, at 735km from Fermilab.

The neutrinos are produced by the 120GeV/c proton beam from the Main Injector at Fermilab. The average intensity per pulse in 2007/2008 is $3 \cdot 10^{13}$ protons per 10μs and a cycle length of 1.9s. The majority of the data are taken with the low energy version of the neutrino beam at ~4GeV.

4.1 NuMI Secondary Neutrino Beam Line

The NuMI target is made of 47 graphite segments, each 20mm long and a cross-section of $6.4 \times 15\text{mm}^2$. The target is water cooled and mounted on a rail-drive system with 2.5 m travel inside the horn. This allows changing remotely the neutrino energy spectrum. The two NuMI horns are water cooled, pulsed with 2ms half-sine wave pulse of up to 200kA and are designed for 10^7 cycles. Target and horns are hanging on support modules, suspended from the shielding modules and services are connected at the top of the shielding. Remote connection for water and current, as well as remote exchange is foreseen.

The decay tube of 2m diameter is 675m long and was under vacuum. Since December 2007 the tube is filled with Helium at 1bar. The hadron absorber is made of 2.4m Aluminum and 2.3m iron. A hadron monitor upstream and three muon monitors downstream of the absorber are used to measure the spatial distribution of the charged hadrons and muons as well as to check the alignment of the beam.

The 1kton near detector, 1km from the target, is functionally identical to the far detector and shares the basic detector technology and granularity.

4.2 Results and Lessons from the NuMI Run

The total number of protons on target so far is $\sim 5 \cdot 10^{20}$. Recent results for the oscillation parameters are $\Delta m^2_{23} = (2.43 \pm 0.13) \cdot 10^{-3} \text{eV}^2$ at $\sin^2 2\theta_{23} = 1_{-0.05}$ [4].

Since the start-up of the NuMI run, the target and the horns faced several problems; target drive failure, horn ground fault, water leaks, water line contamination by resin beads, etc… Although the equipment design foresees complete replacement of radioactive elements, many of the problems occurring up to now were repairable. This is possible thanks to a work cell which is installed in the downstream part of the target area; the target or horns can be remotely moved into the shielded work cell onto a remote lifting table and can be investigated through lead-glass windows before and during repair work. Connections are done through the module on top (see

Fig. 2). Hence during the design of secondary beam line equipment repair work must be kept in mind. Thorough tests before first beam should be performed. Proper tooling as well as training must be foreseen.

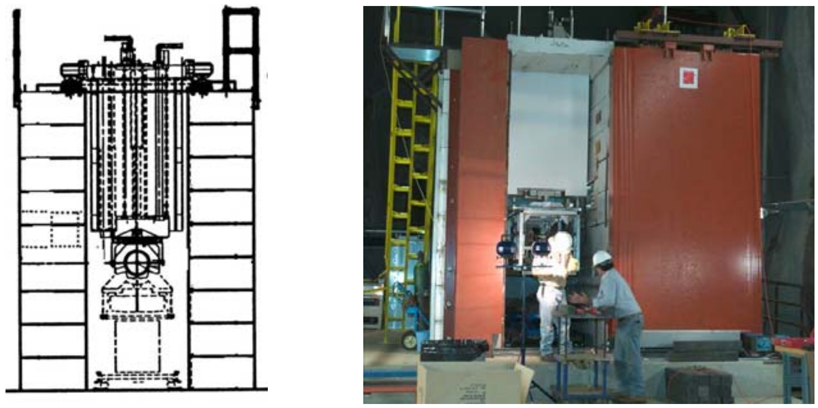

Figure 2: Sketch (left) and photo (right) of the NuMI Work cell.

A major issue at NuMI was the tritium levels in the water pumped from the NuMI tunnels. They were considerably higher than expected, although still very low compared to the regulatory limits. The source was traced to the tritium production in the steel surrounding the target chase. This was then carried to the tunnel water by moisture in the chase air. An efficient remedy was found using dehumidification of the target hall and the target chase air.

5. CNGS

CNGS, CERN Neutrinos to Gran Sasso, sends muon neutrinos with an average energy of ~17GeV/c from CERN over 732km to Gran Sasso, Italy. There, two detectors are located: OPERA, a 1200t detector made of 146000 emulsion bricks and ICARUS, a 600t liquid Argon detector. CNGS is the first experiment in which the measurement of the oscillation parameters is done by observation of tau-neutrino appearance.

The muon neutrinos are produced from the 400GeV/c SPS proton beam. The nominal intensity is $2.4\cdot10^{13}$ protons on target per 10.5µs extraction. During the 6 s cycle, there are two extractions separated by 50ms.

CNGS was commissioned in 2006. During 2007 CNGS was running for 6 weeks [5]. The CNGS run 2008 started in June after the completion of the OPERA detector and finishing modifications in the CNGS facility. In 2008 so far (status 25 September) $0.9\cdot10^{19}$ protons on target have been gathered and OPERA has collected more than 730 brick events.

5.1 CNGS Secondary Neutrino Beam Line

The CNGS target unit is made of 13 graphite rods of 4mm diameter each (first two rods have 5mm diameter). The rods are 10cm long and interspaced with 9cm. Five units are assembled into a target magazine, where one unit is used and the other four are kept as in-situ spares. The two magnetic horns are water cooled and pulsed twice every 6s cycle with a current of 150kA (180kA) during a few milliseconds. Polarity change can be done remotely. Special features are implemented to exchange the target or the horns remotely.

The CNGS decay tube is 1000m long, with a diameter of 2.45m and is under vacuum at less than 1mbar. Downstream of this tunnel, the hadron absorber, made of 3m graphite and 15m iron, is designed to absorb up to 100kW of protons and hadrons. Two muon monitor stations, separated by 67m of rock provide on-line feedback for the quality control of the neutrino beam. They are arranged in a cross-shaped array (see Fig. 3a) and measure the muon intensity and the vertical and horizontal muon profiles.

5.2 Results and Lessons from the CNGS Run

In the horizontal muon profiles an asymmetry between operating in neutrino mode (focusing of mesons with positive charge) and anti-neutrino mode (mesons with negative charge) has been observed. This can be explained due to the earth magnetic field in the 1000m long decay tube which results in the profile shifts of the observed magnitude (see Fig. 3b). Due to the possibility of changing remotely the polarity this effect could be studied in detail.

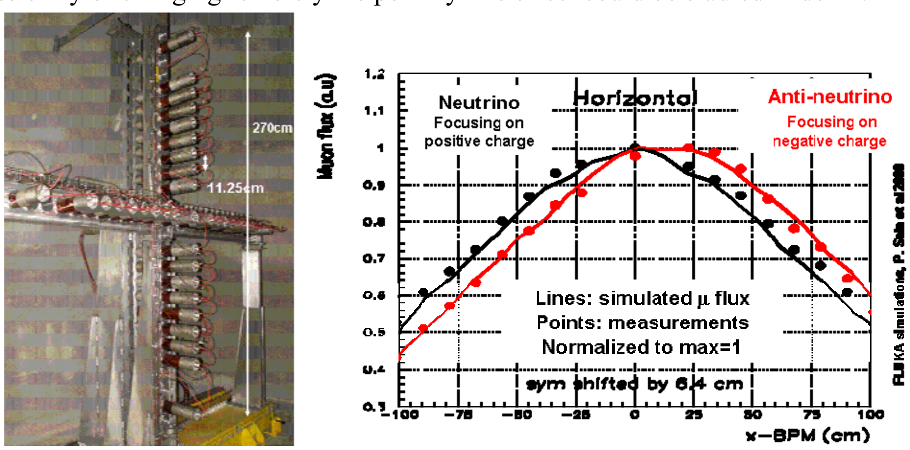

Figure 3: Left: CNGS Muon detector station. Right: measurements and simulations of the horizontal muon profiles in neutrino and anti-neutrino mode.

During the 2006 CNGS run, after only $4 \cdot 10^5$ horn pulses, a leak in a water outlet of the 2^{nd} horn cooling circuit has been detected. This was caused by a design fault in a ceramic insulator brazing. Thanks to detailed dose planning, tooling and training as well as additional local shielding a repair was possible.

CNGS has no surface building above the target and hence a large fraction of electronics is installed near the CNGS target area. During the CNGS run in 2007, a failure in the control of the ventilation system was caused by radiation effects (SEU, single event upsets due to high energy hadron fluence). The remedy was (a) to move as much electronics as possible out of the CNGS tunnel area and (b) to create in the tunnel a radiation safe area for the electronics by adding shielding. This decreased the radiation to electronics by up to a factor 10^6. The lesson learnt: In these harsh environments the radiation hardness of the installed electronics and materials must be addressed already during the design phase. Standard electronics components should be avoided in these areas.

6. T2K

T2K (Tokai to Kamioka) is an off-axis $\nu_\mu \rightarrow \nu_e$ appearance experiments to measure the mixing angle θ_{13} as well as to perform precise measurements of Δm^2_{23} and $\sin^2 2\theta_{23.}$ The low energy off-axis beam is tunable by changing the off-axis angle between 2° and 2.5° which corresponds to a neutrino energy E_ν between 0.8-0.65GeV.

First beam is expected in April 2009 [6]. The neutrinos will be produced at J-PARC from the 0.75MW 50GeV proton beam from the Main Ring MR and will be sent 295km along to the 50kton Water Cherenkov Super-Kamiokande detector.

The T2K secondary beam design has profited a lot from the experiences gained in the current neutrino beam line: careful design and extensive testing of the equipment and all the accessory systems has been performed. The entire volume of the target station is filled with Helium in order to reduce the production of aggressive chemical substances and tritium. Remote handling of all equipment is foreseen.

7. Summary

The operation of high power neutrino beams at the present levels of up to 500 kW has proven challenging, in particular concerning the equipment downstream of the target. Lessons learnt, of which some have been outlined here, indicate critical issues to be considered in the preparation of future facilities in the multi-MW domain.

8. Acknowledgement

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