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***Abstract*--We report on the status of the latest operation of the horn magnets. Our two types of large horn magnets were installed in the neutrino beam line at the KEK-12GeV Proton Synchrotron (KEK-PS) and have been operated since March 1999. These two focusing magnets were designed to be excited at pulsed-high currents of up to 250 kA. One of the special characters of our horn magnet is a built-in pion-production target at the most upstream part of the inner conductor. This configuration enable us to increase the neutrino flux as high as possible with low-energy primary protons from the KEK-PS. Our horns have a coaxial-shape structure with a large diameter, i.e. a large volume of the magnetic field, in order to collect pions as many as possible. We estimate that the neutrino flux is enhanced by a factor of 14 by using this horn system. Both horns have been excited over 10^6 times at pulsed currents of 175 kA - 250 kA. Some beginning problems were found in the peripheral apparatus of the horn magnets, and the built-in production target was found have a fatal mechanical damage. In the spring run, the performance of our horn magnet system was almost sufficient as the pion focusing device to confirm a long-baseline neutrino oscillation experiment.**

***Index terms*-- accelerator magnet, pulse magnet**

I. INTRODUCTION

The new beam line for a long-baseline neutrino oscillation experiment (K2K) [1] started in January 1999, at the KEK-12GeV Proton Synchrotron (KEK-PS). The artificially neutrinos were produced at the KEK site, Tsukuba, and were detected by the Super-Kamiokande, a huge 50000-ton water Cerenkov detector. The Super-Kamiokande is located about 250 km west of KEK. Secondary pions produced by the incident protons (12 GeV) had a low momentum with a range of a few GeV/c, and a wide production angle. Therefore, the horn magnets must gather these spread-out pions to maximize the neutrino flux. The focusing lens system consists of two magnets of the cylindrical type. The parents of neutrinos are pions and kaons, which are produced at a built-in target in the upstream horn. The magnetic volume and the distance of both horn magnets were designed to maximize the neutrino flux as much as possible by using computer codes, GEANT and FLUKA. We have already reported on the basic parameters and results of the test operation at MT15 in Beijing, People's Republic of China (1997) [2].

In February 1999, these two types of horn magnets were installed in this neutrino beam line and engineering runs started in March. During this engineering run we verified the performance of the horn magnets as the focusing device. In June, the K2K experiment observed the first neutrino event in the Super-Kamiokande detector. This detected event, which had been artificially produced and traversed through the earth, was the first neutrino at a few hundred km long-baseline in the world.

II. KEK HORN MAGNETS

The horn magnets are toroidal lenses designed to actually focus positive pions and kaons, which decay to give neutrinos. The structure of the electrical conductor of the horn magnet involves a double-coaxial cylinder with all aluminum alloy; a toroidal magnetic field was generated as $B=\mu_0 I/2\pi r$. Table I shows the basic design parameters of the horn magnets.

Table I
Horn magnets main parameter

	1st Horn	2nd Horn
Total weigth	~1000 kg	~1400 kg
Total length	2371 mm	2760 mm
Outer diameter of horn	620 mm	1520 mm
Thickness of outer conductor	10 mm	10 mm
Diameter of inner conductor	20-136 mm	700-100 mm
Thickness of inner conductor	3 mm	10 - 3 mm
Material of conductors	JIS-A6061-T6, A6061-T651	

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Table II
Electrical parameters of the two-horn load

	1st HORN	2nd HORN
Inductance in Horn	1.03 μH	0.618 μH
Resistance in Horn	187.1 μΩ	29.8 μΩ
Pulse width	2.5 ms	2.4 ms
Peak voltage in Horn	590 V	450 V
Excitation cycle	2.1 s	2.1 s
RMS current in Horn	5590 A	5590 A

In order to increase the acceptance for secondary pions, the production target had to be built in a toroidal magnetic field, that is in the first horn magnet. This target is also made of aluminum alloy with 20 mm diameter and 0.65 m length, and is as a part of the inner conductor. The higher current of the two horn magnets has a maximum of 250 kA; this pulsed current is synchronized with a fast-extracted proton beam from KEK-PS with a machine cycle of 2.1 s. Table II gives the parameters of the horn magnets as an electrical circuit.

The current feeder of the horn entrance was divided in four lines in order to maintain the symmetry of the magnetic-field distribution. Each horn has one transformer with a transformational ratio of 20/2. Fig.1 shows the electric circuit of the power supply for one horn magnet. Also, Table III summarizes the electrical-circuit parameters, including those of the power supply.

The incident proton beam and the pulsed current in the horn magnets are shown in Fig.2. The intensity of incident protons on the target was an average of 4.7×10^{12} protons/pulse with a pulse width of 1.1 μs. The impedance of the second horn circuit is just slightly larger than that of the 1st horn magnet, and thus the pulsed current rise is a little fast than that of the 1st horn. Therefore, the firing timing of the second horn magnet was approximately 100 μs delay. The timing of the fast extracted beam sufficiently comes in within the 98% width of the current peak.

Table III
Electrical parameters of each circuits

	1st Horn Circuit	2nd Horn Circuit
Peak current in horn	250 kA	250 kA
Tamsformer ratio	20/2	20/2
Primary current peak	25 kA	25 kA
Inductance	286.7 μH	265.5 μH
Resistance	42.84 mΩ	29.09 mΩ
Capacitance in power supply	3.5 mF	4.0 mF
Capacitors	7 units x 500 μF	8 units x 500 μF
Thyristor switch (x3)	1.2 kV- 3000 A	1.2 kV- 3000 A
Critical current rise rate	300 A/μs	300 A/μs
Load in power supply	130 μH, 34 mΩ	130 μH, 34 mΩ
Charging voltage	5.9 kV	4.5 kV

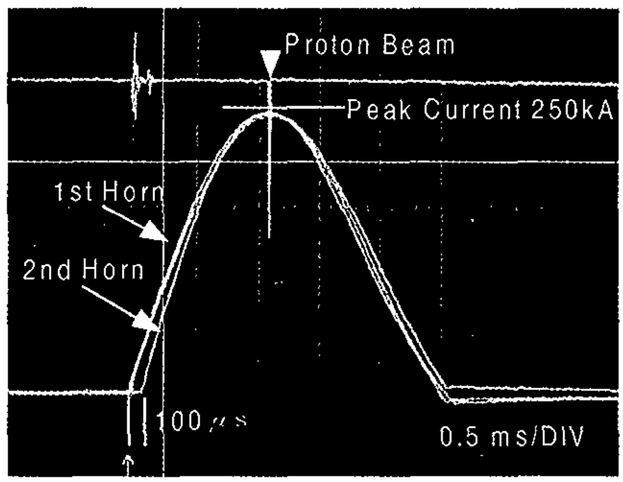

Fig.2. Incident proton beam and pulsed current in two horn magnets The current of the second horn was delayed 100 μs for synchronizing with the incident beam.

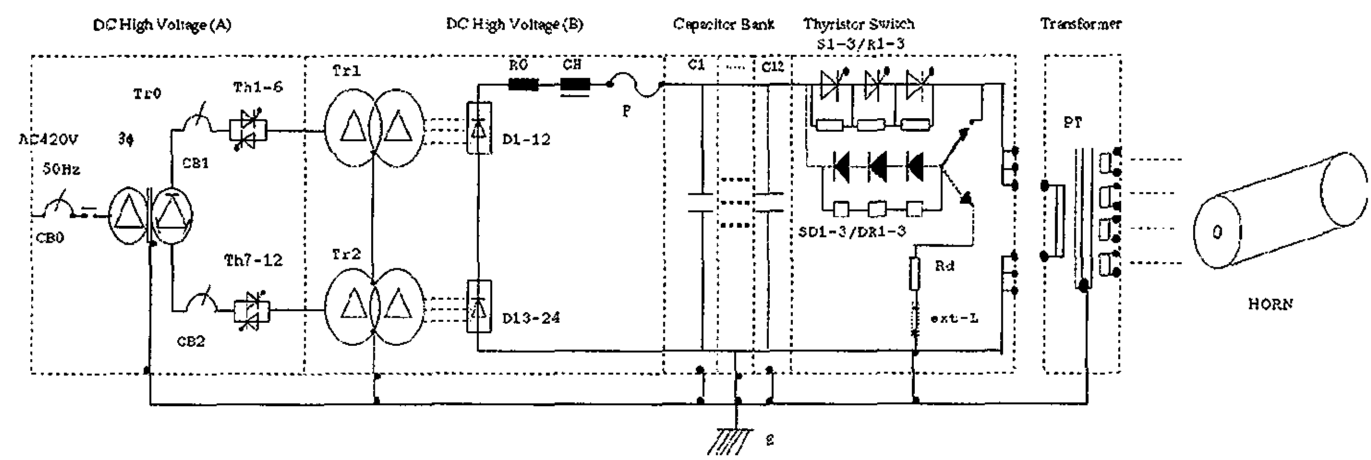

Fig.1. Electric circuit of the power supply

III. Operation Results

The period from March to the end of Jun was used for an engineering run, which verified the performance of the horn as a focusing device. The first experience of the horn magnets was long-term operation for over 1 million excitations. Fig.3 shows the accumulation of the excitation times until the autumn of 1999. The breaks and the plateaus of the lines were some occasional problems during these runs.

During the initial 3 weeks operation was conducted at a current of 175 kA. Into $5x10^{+5}$ excitations, the branch pipe of the water supply manifold of the 1st horn broke off at welding joint.

This manifold was made of a stainless steel pipe (ϕ 22mm diameter); the joint of the welding point was not a socket joint. In spite of the 70% excitation, the crack was caused at the welding joint by a strong resonance with the excitation vibrations of the horn magnet. The first horn magnet itself was included the production target and was heavily exposed to radioactivity during 3 weeks. Therefore, it was necessary after one month (in April) that the hard parts of the manifold had to be replaced by temporary soft parts (i.e., the syn-flex tubes with urethane rubber).

The flow cycle of the cooling water was employed two closed systems. The primary cycle in the target station was dirty water using sprayed cooling with a target rod. Therefore, this water became extremely radioactive. The amount of radioactivity of $1.7x10^{18}$ protons on target is shown in Table IV. The pH of this water was a weak acid with 5.1. It is thought that the carbon dioxide gas in air was absorbed into this cooling water.

In May, the alignment of the beam axis to the Super-Kamiokande was carried out by varying the beam position at the entrance of the production target, and the performance of horn magnets was taken at from 175 kA to 250 kA excitations. There was a significant increase in the neutrino flux with the focusing power of the horn magnets. Fig.4 shows the neutrino flux in the Front Detector at 175 kA-250 kA.

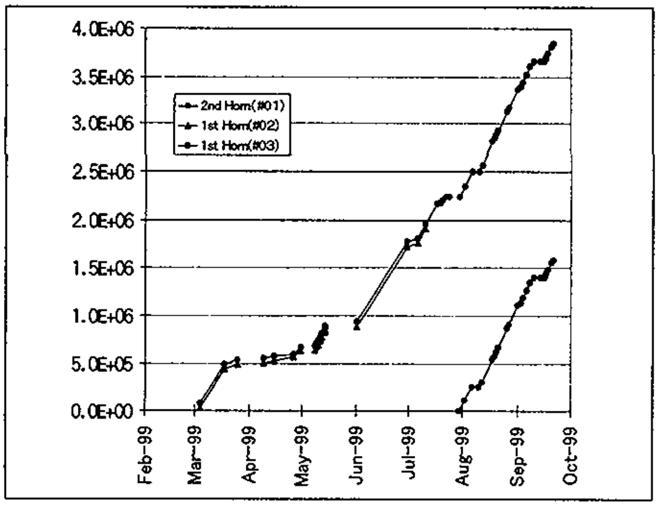

Fig.3. Accumulation of excitation times. On July 10, the target rod in the first horn magnet was broken; a new horn magnet started 250 kA operation from August.

Table IV. Radioactivity in cooling water circuit

Isotope	Half life	Concentration
3-H	12.3y	9.33e+1 Bq/cm^3
7-Be	53.3d	4.76e+2
22-Na	2.6y	2.07e-1
48-V	15.97d	5.47e-3
52-Mn	5.59d	7.34e-2
54-Mn	312.2d	4.24e-2
56-Co	77.1d	2.28e-2
58-Co	70.92d	6.19e-2

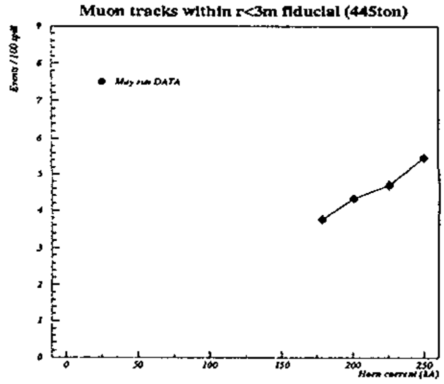

Fig.4. Neutrino flux in Front Detector at 175 kA-250 kA

The horn magnets, themselves were inclined to the Super-Kamiokande with 1.05 degrees. Moreover, a flexible feeder was installed so as to enable fine adjustments in two directions of the neutrino beam. The accuracy of both adjustments were approximately 0.04 mrad.

A second breakage occurred in the flexible feeders of the current circuit, which broke after $8.5x10^{+5}$ excitations. One feeder consists with 16 cables that are stranded with 7 fine copper wires. The diameter of one wire is 2.6 mm. One horn magnet has 8 flexible feeders for 4 symmetrical circuits. These feeders were prepared for three dimensions of freedom.

The main cause of snapping is thought to be that this freedom caused a loosing and twisting motion of a stranded cable. If the directions of current in the two wires or two cables are the same, the mutual forces are attractive. If the directions are opposite, the repulsive forces push out each other during every excitation. As a result, the stranded wires were cut off at the boundary of the soldering point of a copper wire. For the present, we give up to any fine adjust by remote control after this; all flexible feeders have replaced the sets of 6mm thickness and 60 mm wide copper plates.

During one month, in June, the horn magnets were safely operated at 200 kA (80% of maximum operation) to check the whole data-taking system as a K2K experiment.

On June 19, 1999, the K2K experiment observed, its first neutrino event in the Super-Kamiokande detector, the first step towards verification of the neutrino oscillation results announced by the Super-Kamiokande experiment in June last year [3].

Thereafter, the horn magnet was continuously operated at 250 kA (as full power) without a incident beam. The target rod (20 mm diameter in the first horn magnet) was broken after 2 million excitations by every pulling force. The total force is approximately 43 kN in the backward direction. The initial safety factor was 2.5 at the target rod, and 11.1 at cylinder part. The safety factor of the target rod is insufficient for repetition stress after a few million excitations. The safety factor has dropped to one third. Now, the target rod has been replaced to another with 25 mm diameter; moreover, the durability of repetition stress has been verified.

IV. Future Design

The simulation results have suggested that the amount of a neutrino flux with a 25 mm target is a little smaller than that of a 20 mm target, i.e. a 4% decrease. The main reasons for the decrease is absorption in the skin wall of the target rod.

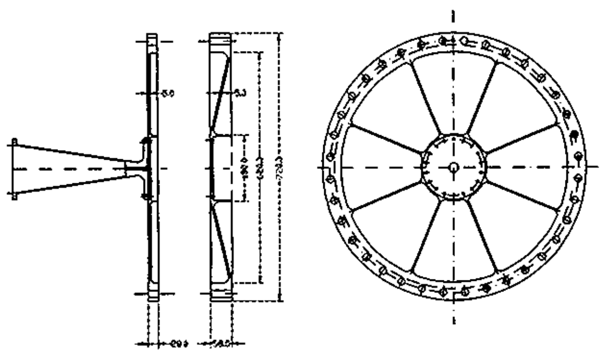

Fig.5. End cap
Left side is the old type of end cap; right is the renewal type.

Therefore, we reconsidered the structure of the end cap in the first horn, which protects the thin target rod from the strong pulling force. Fig.5 shows a cross-sectional drawing of the old and renewed end caps. The structure of the new end cap is parabolic in shape; it preserves the target rod from pulling backward.

V. Conclusion

The two types of horn magnets were installed in the neutrino beam line in February 1999. From March to June, the performance of the horn magnets was evaluated using a proton beam. During the first long-term operation of over 1 million excitations, some unexpected problems were found. We learned a few important principles about how to reliably build horn magnets for long-term operation.

The K2K experiment using horn magnets first observed artificially produced neutrino at 250 km long baseline on June 19, 1999.

Moreover, the horn magnets have been improved to allow the stability of long-term operation at 250 kA.

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