LARGE ACCEPTANCE MAGNETIC FOCUSSING HORNS FOR PRODUCTION OF A HIGH INTENSITY NARROW BAND NEUTRINO BEAM AT THE AGS*

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Abstract

A set of two large acceptance (20 to 140 mrad) horns have been designed and built to form a parallel beam of 3 GeV/c pions and kaons for the production of an intense, dichromatic neutrino beam. A set of beam plugs and collimators determined the momentum of the particles which pass through the horns. The cooling and maintenance of the horns and target was a particular concern since they were operated with an incident intensity of over 10^{13} proton/sec. These systems were designed for simplicity, reliability, and easy replacement.

Introduction

A collaboration of Brookhaven National Laboratory, Columbia University, University of Illinois and Johns Hopkins University proposed an experiment to search for neutrino oscillations with high sensitivity at the AGS.[1] A large increase in sensitivity over previous experiments came from having a very high flux of low energy neutrinos (~1 GeV/c) within a narrow energy band (±15%). The high flux was required to give sufficient event rate at the experiment located 1 km from the horns. This neutrino energy corresponds to the decay of 3 GeV/c pions which is at the peak of the pion production by the 28.5 GeV/c protons of the AGS. The energy definition allows candidates for neutrino oscillation as signalled by the appearance of a narrow energy band of electrons in the detector to be separated from a broad energy band of electrons resulting from neutrinos produced by kaon decay. This focussing system utilized a similar design to that employed in the construction of another narrow band system designed by Baltay and coworkers.[2] There were two focussing horns and a set of beam plugs and collimators which selected particles of the proper momentum, while stopping particles which were off momentum.

The construction of this new horn presented the opportunity to improve the horn design in a number of areas which had caused problems in the past such as the cooling water system and alignment procedures. Also the transport system was improved to minimize the radiation burden when replacing horn components. As with all new systems unexpected problems arose which will be described below.

Performance Specifications

In Table I we list the performance specifications which guided the design of this narrow band horn system.

Table I.

Particle momentum	3.0 GeV/c
Momentum spread	±15%
Angular acceptance	20 to 140 mrad
Horn current (horns in series)	240 KAmp
Incident beam intensity	1.5 x 10^{13} protons per 1.2 sec.

The incident beam energy of up to 80 KJoules represented a considerable thermal shock to the components as well as producing a large amount of residual radiation. The pulsed nature of the very high current presented a potential for structural fatigue and called for very conservative engineering design.

Horn Design

A cross section view of the horn system is shown in Fig. 1. The most critical design feature with regard to pion yield and good momentum definition was probably the inner conductor of Horn #1. Since the particles passed through the inner conductor at angles as small as 20 mrad, it was necessary to make the aluminum as thin as possible compatible with sufficient strength to withstand the compressive forces from currents up to 300 kA. Using 6061-T6 aluminum we settled on a thickness of 3.2 mm. Even with such a small thickness, the total amount of material in the pions passed through was 5-8 cm resulting in significant absorption (15-20%). The parabolic shape of the inner conductor was calculated such that the azimuthal magnetic field between the conductors would produce a converging cone of about 40 mrad at the exit of the first horn for 3 GeV/c particles.

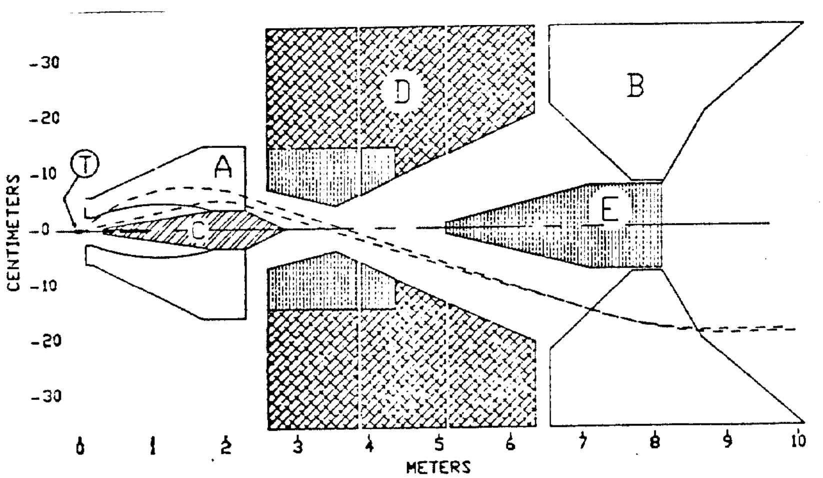

Fig. 1. A schematic cross section of the narrow band horn system. The elements of the system are: (T) the production target, (A) and (B) the first and second focussing horns, (C), (D), (E) are collimators and beam plugs (graphite insert in C) for defining the allowed particle trajectories. Collimator D was made of aluminum with a brass insert. Particle trajectories of 3 GeV/c leaving the center of the target at 30 and 100 mrad are indicated by the dashed lines.

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The outer conductor of the first horn was set by the desire to accept particles up to 140 mrad where the particle yield begins to fall. Since all selected particles remain inside this conductor there were no constraints on its thickness.

The function of the second horn was to accept a conical beam of particles at 40 mrad with respect to the horn axis and deflect it to make it parallel to the horn axis. The angular spread of the beam was calculated to be ± 2 mrad (± 4 mrad after multiple coulomb scattering). The two rays drawn in Fig. 1 show trajectories of acceptable 3 GeV/c particles. The design of the second horn was simpler since the particles pass through more nearly normal to the aluminum conductor. For this horn more straightforward conical forms could be used.

The system of collimators and plugs was chosen in such a way as to select a momentum bite of $\Delta p/p \approx \pm 11\%$ (15% after multiple coulomb scattering), while at the same time keeping the wide band background to a minimum. The collimators were made of aluminum except very near the beam, where brass was used in order to increase the particle attenuations.

Beam Plug

Since the beam plug had to absorb a significant portion (10%) of incident beam shock heating, considerable studies were performed to be sure that this plug would remain intact. Since water cooling had been a problem with the previous narrow band horn, it was decided to use a high melting point material for the plug, and cool it by gas convection and radiation. To further reduce the localized heating in the beam plug, a 6mm diameter cylinder of graphite was inserted in the front end of the plug to disperse the energy of the beam along the first 60 cm. The plug was machined out of Incoloy 800, a high temperature stainless, and then chemically blackened to enhance radiative transfer. Finally, the annular space between the plug and the inner conductor was pressurized with helium to 1.7 atmospheres to enhance the convective cooling and minimize chemical activity. Modelling with a finite difference program indicated that the maximum termperature at the center of the plug for 10^{13} protons/sec would be between 800 and 900°C, while the melting point of the Incoloy is 1385°C.

Production Target

The target used to produce the pions for the neutrino beam is patterned after targets developed at CERN for antiproton production.[3] The target core consists of a rod, 3mm in diameter and 100mm long. Since a high density material was requested by the experiment to maximize particle production within the short depth of field of the horn, an alloy of 75% tungsten and 25% rhenium was employed. Its density was 19.7 g/cm^3. ATJ graphite (density $\sim$2 g/cm^3) surrounded the rod to provide a containment structure and reasonable heat transfer. Surrounding the graphite was a thin aluminum container with radial fins cooled by forced air at $\sim$10 m/sec. Calculations indicated an average temperature of the W/Re rod of $\sim$700°C and a temperature at the exterior of the container of 150°C for 10^{13} protons incident. A thermocouple on the outside of the aluminum container showed a temperature that was in agreement.

Electrical Systems

Three changes resulting from the reconstruction of the North Area and the requirements of Exp. 776 posed new electrical design problems. First, the physical size of both horns changed, next the assembly was located considerably further away from the power supply and third the method of connecting to the horns was different. The inductance of the system was important since it determined whether the voltage required would exceed the limits of the current power supply. A value of 0.96 μH for the two series horns was obtained by numerical integration. Coaxial feeders were designed to feed power to the devices along the strongback supports. Stripline structures called "keys" were made to bridge from the coax to the horns. Estimates of the inductance which these keys would add totalled 0.6 μH. Also coaxial "flexures" were provided at two points along the coaxial lines to provide flexibility and as a means of disconnecting one horn from the other.

The decision to move the target upstream by nearly 25 m also posed some new problems. A power feed system would have to be made which was capable of carrying the full current, while being sufficiently radiation hard to function in the high radiation environment. It was decided to construct a low inductance (3 nH/m) coaxial feed system similar to that which had been used for years to interconnect the old horns. The coaxial feeds in this system were constructed by wrapping a 10cm diameter aluminum tube with six layers of .012mm Kapton. The outer conductor was formed by clamping another thin, split aluminum tube over the insulation. Silver plating was employed on all connecting surfaces.

Connecting the 24m long runs of coaxial feed lines with the coaxial feeds on the horns was a quick disconnect stripline connection. With this design, the horn can be disconnected in a matter of minutes. This is a vast improvement over the old system which required extended work in a high radiation area.

Water System

Approximately 5kW of energy was removed from the first horn by forced convection to a flowing water system. This energy resulted from electrical heating of the inner conductor and beam energy deposition in the beam plug. Prior horn designs have been plagued by water system problems so that it was decided to employ a novel approach. High purity water from a closed circulation system was brought to a distribution manifold located above the first horn. The water then passed through 20 discharge tubes located about 3 cm above corresponding funnels on the horn outer conductor. The free fall of the water to the funnels provides an insulating gap in the water system. The low velocity water flowing out the nozzles at the bottom of the funnels then forms a film around the inner conductor as it flows downward to the outer conductor. Draw tubes lead the water from the outer conductor to a return pipe. Again the water system was isolated from the horn voltage by a free fall gap.

The water system was judged superior to past systems for several reasons. Past systems used high pressure distribution to spray nozzles which developed leaks under the vibration of the horn pulsing. The current system was gravity fed from a very low head so that the pressure near the horn is only about 5cm of water. Since the water system was electrically isolated by two gaps, the use of insulated pipe was avoided, resulting in a completely radiation-hard piping system. This design has resulted in a robust system which has eliminated failures so far and as a result greatly reduced personnel exposure.

Beam Monitoring

In order for the beam to function properly, spot size and position had to be held in within 1 mm at the target. An instrumentation package was designed to monitor this during operation. Considerable redundancy was provided within this package because instrumentation near the target location is inaccessible for repairs due to the high residual radiation. The devices provided were a flag, three SWIC's, a target thermocouple, a target monitor, and an array of muon monitors.

The target monitor is an ion counter placed within the target shield block. A hole, molded into the concrete, points from the counter toward the target. This monitor is very sensitive to back scattering from the target, making it a sensitive detector of targeting. This monitor and the target thermocouple proved to be excellent tools. With them it was possible to produce beam scans across the target which were sensitive measurements of beam/target position and beam size. Scans of this type were used to show that the beam was less than 1 mm in diameter. A radially and azimuthally segmented ion chamber 40m downstream of the horns monitored the profile of the emerging particles.

Transport System

The requirement of the transport system was to minimize the time to remove and then install a replacement horn in an area of high residual radiation levels. We used a system of two rigid strong backs on which the two horns could be placed and prealigned outside of the radiation area. These were transported along tracks on bogies with motorized lifting plates which could both lift and turn. The turning action was required to negotiate a right angle turn out of the tunnel, and the lifting feature enabled the strongbacks to be lowered onto jack stands in position. Then the bogies were removed before bringing beam to the target. The jack stands were remotely driven by long shafts to minimize exposure of the surveyors. A shielded locomotive pulled these assemblies along the tracks. A recent removal of an irradiated horn resulted in less than 300 mRem of exposure with contact readings on the horn of up to 18 Rem/hr.

Operational Experience

After two test periods of about 10^5 pulses at full horn current to check out the electrical, mechanical and hydraulic features of the horns and associated systems, an extended physics run for Exp. 776 was begun. During the initial two weeks the incident proton intensity was kept low while the performance of the horns and targets was determined by the particle monitors. The remainder of the eight week was run at a high intensity. The total accumulated flux was about 1.5×10^{19} protons. Approximately 1.5×10^6 pulses at 240 kA were applied to the horns during this time.

The alignment system proved to be very stable and periodic inspections showed no displacements greater than 0.25 mm. Similarly, the water system ran without incident, showing that the low pressure, decoupled system was considerably more reliable than the previous high pressure systems. Inspection of the beam plug in Horn #1 subsequent to the run showed that the concept of cooling by convection and conduction in helium gas and radiative heat transfer was sound. The Incoloy 800 material showed no evidence of thermal damage from the beam.

Initial comparisons of the optical properties of the horn system indicate a not unreasonable agreement with calculation, but detailed comparisons require more refined analysis of neutrino events from the Exp. 776 detector.

The power feed system was a major problem area despite the fact that much of the design was based on components which had been in service for a decade. The 24m long coaxial feeder failed six times due to shorts through the Kapton insulation, and subsequent destruction of the aluminum conductor. A very early failure during the test phase was traced to a metal chip trapped in the insulation, but the source of the other failures was uncertain. After damping the voltage reflection from the horn with a "snubber" network, and thermally prestressing the coaxial feeder, there were no failures of the feeder during the final three weeks. For future runs the number of turns of Kapton insulation will be doubled, and the number of coaxial feeders will be increased from 2 to 4. Also, better provision will be made for thermal expansion of the coaxial feeder. After about 10^6 pulses there were two failures related to the stripline "keys" connecting the coaxial feeders to the horns. The failure of the keys could be traced to the pulsed electromagnetic forces between the parallel conductor which resulted in long term metal fatigue. Additional clamping and strengthening is expected to eliminate these failures in the future.

From the experimenter's point of view, the target was satisfactory, and showed no change in yield during the experimental run. During preparations for a repair, a layer of contaminated dust (~20 nCi/100 cm^2) was found spread around the horn area, which had not been previously found. Analysis of the contamination lead one to believe that the activated W/Re target rod had powdered and been transported by the cooling air stream. Disassembly in a hot cell showed no damage to the target container, but many fractures in the W/Re rod. The W/Re rod will be replaced by one of copper, and the container will be hermetically sealed and interlocked for future running.

Conclusions

Most of the subsystems of this horn focussing system performed well. The two horns, collimator and beam plugs showed no degradation after the 8 weeks of extended running. The transport and survey systems worked well and proved that with careful design considerable reductions in radiation exposure are achievable. The innovative features of the completely redesigned water system, lead to a stable cooling system which was easy to connect and which showed no evidence of electrical or mechanical failure. Likewise, the beam monitoring equipment performed satisfactorily.

After making improvements to the coaxial feeders and the production target, an extended run of the horns is planned for this summer.

Acknowledgments

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