OVERVIEW OF RECENT FOCUSSING HORNS FOR THE BNL NEUTRINO PROGRAM

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Abstract

In this paper we present an overview of the two magnetic focussing horn systems recently constructed, installed, and operated in the fast extracted beam for the neutrino physics program at the AGS. These horn systems consist of a number of interrelated subsystems which operate together to produce a very intense, parallel beam of pions. The strong magnetic focussing is generated by pulsing the coaxial structures of the horns with currents of up to 300kA during the 2.5 μsec proton beam spill. Because of their high levels of induced radioactivity, these horns had to be designed for reliability and ease in installation. Both horn systems built had the same overall features, but the broad band system focussed pions over as large a momentum band as possible to maximize the neutrino flux. The narrow band systems restricted the momentum to ±15% of 3 GeV/c to provide kinematic constraints for the experiment. A synopsis of the design concepts and critical engineering requirements is given. Detailed discussion of the subsystems follows in the subsequent papers.

Introduction

For the past 20 years, high intensity neutrino beams have been an important part of the AGS high energy physics program at Brookhaven. The pion flux needed to produce neutrinos has been enhanced by more than an order of magnitude through by the use of focussing horns. Large toroidal magnetic fields are obtained by pulsing the coaxial structures in these horns with extremely high currents (300 kA) spanning the duration of the extracted beam (2.5 μsec). The initial concepts of Van der Meer and coworkers at CERN[1], were further developed by Palmer at BNL to arrive at the present BNL design.[2] The inner conductors of the horns are shaped such that the field integral seen by particles increases with their radius, thus providing a focussing lens. In Palmer's design there is a small diameter horn which contains the pion production target or is just downstream of it. Then a second large diameter horn, located about 10 meters downstream of the first horn, collects and bends the pions into a final parallel beam in the decay tunnel.

The original motivation for upgrading the horn systems at BNL was the request from Experiment 776 in 1982 for a narrow band horn of very large angular acceptance and relatively low momentum.[3] At this time, it was realized that this new horn provided a good opportunity for improving the horns with respect to better reliability, greater ease of handling, better thermal management, and improved production targets designed to handle the increased incident proton flux. This flux had risen from an average of ~0.5 to ~1.3 x 10^{13} protons/pulse.

With the present broad band horn, neutrino interaction rates of about one neutrino event per AGS pulse in a 100 fiducial ton detector located 150 meters from the target are observed. The enhancement of the neutrino flux and the reduction of the anti neutrino flux over a bare target are given in Fig. 1. This was determined in a careful study of the broad band spectrum carried out by the Experiment 734 collaboration.[4] The neutrino momentum spectrum of the narrow band horn used for Experiment 776 also peaks at ~1.3 GeV/c, but the collimators sharply limit the spectrum at higher and lower momenta to provide a beam of ±15% momentum bite.[5] This better definition of momentum is achieved at a reduction of about a factor of 20 in the total neutrino flux.

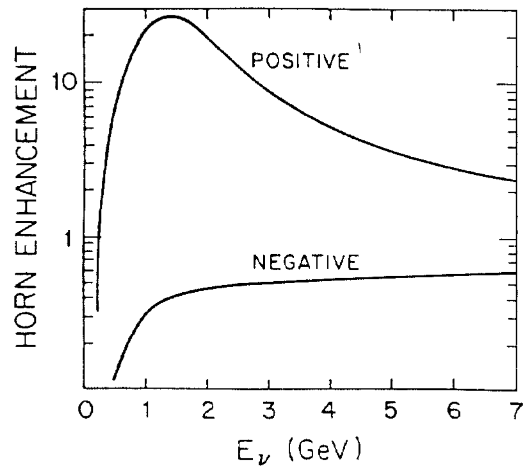

Fig. 1. Enhancement in neutrino (positive) flux relative to no horn as reported in Ref. 4. The supression of the anti neutrino (negative) flux is also shown.

Horn Systems

Although the horns themselves actually focus the pions which decay to give neutrinos, a number of interrelated systems must function to produce and transport the pulsed electric current, to provide closed loop cooling water, and to monitor the position and intensity of the primary proton beam. Sophisticated transport systems are required to install and remove the highly radioactive horn components. These systems are illustrated schematically in Fig. 2. In the following section we shall discuss each system in turn and state its critical engineering requirements.

1. Target assemblies. There were two target assemblies. For the narrow band horn a short, high density target was used in order that the source of pions be short (15 cm) and small in cross section (3 mm in diameter). Greater yields for the broad band horn were achieved with a longer (50 cm), lower density material. The critical requirements for these targets were strong materials with a very high resistance to radiation damage. The proton beam deposits about 6 kJ of energy every 1.4 sec, and the accumulated radiation dose in the target is over 10^{21} particles/cm^2. Pure metals are very radiation resistant, strong enough to withstand the thermal and mechanical shock of the beam pulse, and have good thermal conduction for dissipating the heat. Copper was used in the narrow band horn, and titanium in the broad band horn. Previously, sapphire rods has been utilized in place of the titanium, but the crystal structure disintegrated with time. Since the broad band target was an integral part of the horn, it was cooled with water. The narrow band horn target was external and utilized a separate air cooling system. The thermal management aspects of these targets are described in detail in Ref. 6.

2. Horn No. 1. The first horn was by far the most demanding from the engineering point of view. Since the particles pass through the inner conductor at small angles from the target, there is a great premium of making the inner aluminum conductor as thin as possible. This inner conductor is subject to cyclic stresses of up to 4000 psi from the magnetic field, so the mechanical construction must be done carefully to avoid dangerous stress concentrations. A thermal load of about 6 kW results from heating from the beam and heating from the pulsed current. This necessitated water cooling of

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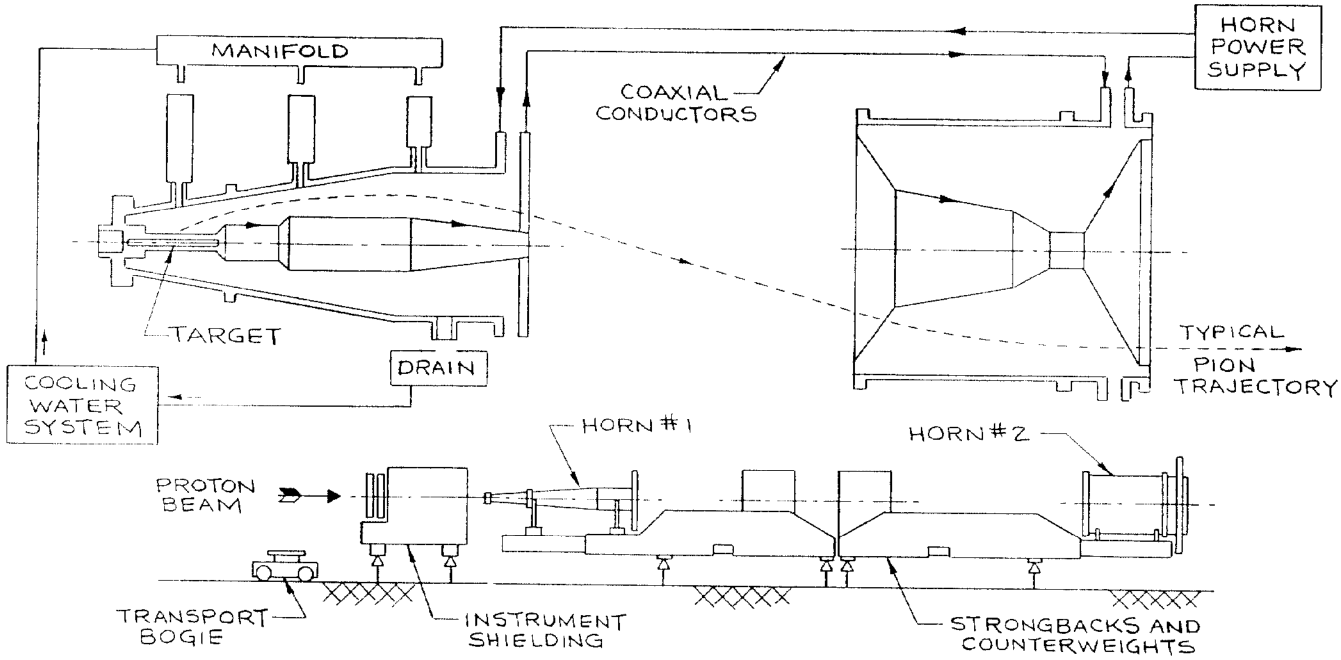

Fig. 2. Schematic of the Broad Band Horn Systems. A trajectory of a pion through the horns is illustrated. The correct scales are given in the lower figure, but expanded vertically in the upper figure for clarity.

this inner conductor. The close proximity of all parts of the horn to the target, meant that all insulating materials were subject to high radiation levels (~5 x 10^9 rads). The narrow band horn had an additional heating load due to the presence of a beam plug which absorbed much of the uninteracted proton beam. The choice of materials and assembly are given in detail in Ref. 7, and the novel cooling arrangement is described in Ref 6.

3. Horn No. 2. The second horn was of similar construction for both the narrow band and broad band horns. Since the particles passed more nearly perpendicular to the conductors and at larger radii, and since the conductors were subject to less stress, the inner conductors could be heavier. The design and construction of these horns was relatively straightforward.

4. Horn Power Supply and Power Distribution. In order to achieve sufficient field strengths, a peak current of 300 kA is required. Given that the switching equipment can operate reliably up to about 12 kV, a capacitor bank of 850 µf is needed. The current pulse is a half sine wave of 58 µsec rise time which means that there is a neglible change in the horn current during the 2.5 µsec beam spill. As noted in Ref. 8, the 1.4 sec AGS repetition rate set the requirements for the charging supply, and heavy duty switching tubes were needed to connect the capacitor bank to the horns. In order to keep the inductance in the power distribution conductors much less than that in the horns, specially designed large diameter coaxial lines were manufactured. These had to be carefully constructed to avoid failure from the cyclic mechanical and thermal stresses as discussed in Ref 7.

5. Cooling Water System. As noted above, cooling water is required for the inner conductors of Horn No.1 and their associated targets or beam plugs. The water system had to be closed loop because of the induced radioactivity in the water. Also, as a consequence of the activity, precautions were needed to shield the pipes from the outside world, and to minimize exposure to the personnel doing maintenance. Reliability and interlocks were another important consideration since even a short term loss of cooling water would result in a meltdown of the inner conductor. Another dominant factor was ease in disconnection of the water system from the horn, since this needed to be done in a high radiation area. The solutions to this list of problems in presented in Ref. 6.

6. Mechanical Support and Transport System. In Ref. 9, the details of a system to support and remove the horns are described in detail. One of the major objectives of the recent horn improvements was to significantly reduce the exposure to personnel during installation or removal of the horns. Since radiation fields of over 100 Rem/hr are possible near the horn components, it was clear that operations should take place at as great a distance as possible and as quickly as possible. A goal was set for less than 1 Person-Rem of exposure during removal after a few days of cooldown following a horn component failure. The mechanical support system also featured automatic alignment of the horn components, and provision for sighting and remote adjustment. The components of the narrow band horns, for example, had to be held concentric to within ±0.13 mm.

7. Instrumentation. Proper steering of the primary proton beam on the pion production target was critical to the production of a satisfactory neutrino beam. For the narrow band beam, the beam needed to be kept focussed and centered on a 3 mm diameter target. The primary reference was an aluminum oxide flag mounted directly on or just before the target. This provides a simple and direct measurement of the beam position just before the protons strike of the target. By viewing the flag with a video camera fitted with a telescope, radiation exposure to the camera can be kept to a tolerable level. Simple mechanical rods allowed the flags to be changed very quickly. A set of three SWIC's followed the trajectory of the beam between the last quadrupole and the target. Two other devices which were useful for double checking the beam position were an ionization chamber which viewed the target through a concrete collimator from a slightly upstream position and a thermocouple mounted on the target container. These both produced a large enhancements above background when the beam was centered on the target.

Downstream of the horns a number of devices were employed to determine the properties of the secondary beam. A single scintillation counter provided a reference signal to check the timing of the horn. The profiles of the pion distribution were measured by ion chambers segmented into arcs of various radii,[11] and by a cross of ionization detectors.

An Historical Synopsis

In this section a short history of the recent horn construction is given. More details are given in Ref. 10. Experiment 776 was approved in Spring of 1982 for an run involving a narrow band horn. About a year and a half of design effort ensued, so that by the end of 1983, initial fabrication of components had begun. The desire for a more extended pion decay space, coupled with the reduced radiation burden associated with doing the installation in a new section of tunnel, led to the decision to construct a block house 25 meters upstream of the old horn. The block house was constructed during the summer of 1984. As soon as beneficial occupancy was allowed, installation of the tracks for the transport system, and piers for the support system was begun. A preliminary pulsing of the horns was carried out in September in a downstream location. With the successful completion of that test, final installation could start.

The initial two and a half months of operation, begun in mid November 1984, was very difficult. Initially the horn ran relatively smoothly, but after a few weeks there were a series of failures in the coaxial conductors. Then it was discovered that the tungsten-rhenium target was disintegrating and contaminating the tunnel. These difficulties provided ample opportunity to exercise the transport system, and the greatest exposure during a horn removal was 0.8 Person-rem.

The period from February to the summer run was spent rebuilding and augmenting the coaxial conductors, and changing to a hermetically sealed copper target. There were occasional failures during the summer and fall running periods, but no sustained downtimes. The major problems at this time were associated with the couplers and keys connecting the coaxial conductors to the horns.

Following the resolution of the difficulties with the narrow band horn, the broad band horn was constructed incorporating features to eliminate these problems. This included a titanium target and strengthened connectors to the horn.

In February, the broad band horn was commissioned without incident and an extended run began in early March. The run continued for 60 days without any significant downtime for the horn as illustrated in Fig. 3. This shows the accumulation of almost 3×10^{19} protons on target. In the last three days, it was discovered that an insulating cup had cracked, but the horn was able to operate at a somewhat reduced voltage.

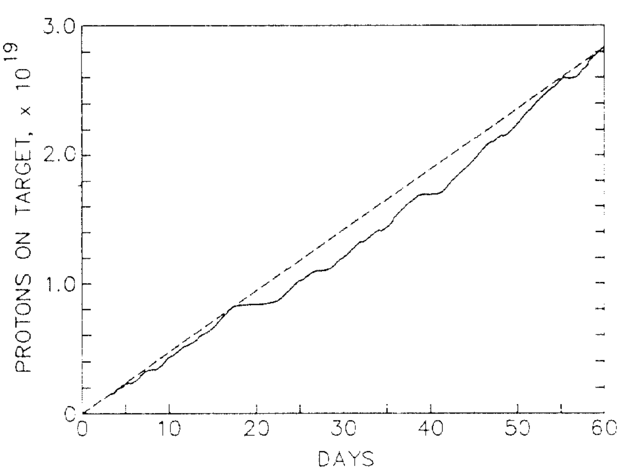

Fig. 3. Accumulation of protons on target for the Broad Band run during the Spring of 1986 versus the projected number as indicated by the dotted line. The occasional short pauses were due to AGS maintenance and repair.

The lesson learned here seems to be that it is possible to build horns of sufficient reliability if they are constructed according to very conservative engineering principles with considerable regard to cyclic mechanical stress. The cooling system, which had been a principle cause of failures for earlier horns, now operated almost without incident for both the narrow and broad band runs. A relatively straightforward support system allowed the horns to be installed and removed within an acceptable radiation limit. Again, a great deal of emphasis must be placed on detailed planning and design to minimize problems which might appear after the components become highly radioactive.

Acknowledgements

Designing, building, installing and operating these focussing horns has been a very large effort on the part of a large number of people. The technicians of the Beam and Physics Support Group were the primary builders and operators of the horns and associated power supplies. The Experimental Areas Group supervised the block house construction, installed the proton beam transport, constructed the cooling system enclosure, and a took care of a miriad of other details. The efforts of the design room in not only drafting, but assisting with the assembly of the components is gratefully acknowledged.

Members of the Experiment 776 provided the specifications for the conductors and collimators in the narow band horns. The physicists of Experiment 734 provided many helpful suggestions for the modifications of the broad band horns.

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