

Frank A. Nezrick  
Fermi National Accelerator Laboratory\*  
Batavia, Illinois 60510

### Introduction

The study of neutrino physics at Fermilab in the 15-foot bubble chamber and in electronic counter detectors is being actively and aggressively pursued. To increase the flux of neutrinos through the detectors over the entire neutrino energy spectrum, a high efficiency horn-focussed beam was developed. The horn system is well known for its high acceptance and highly achromatic focussing of charged particles<sup>1</sup> produced at the production target into a low divergence beam. This meson beam is allowed to decay in a 400 m long vacuum region producing neutrinos and muons. The muons are absorbed from the beam by using 1 Km of earth allowing the filtered neutrino beam to pass through the experimental detectors. This report covers the equipment and results of the focussing region.

The focussing system is composed of three horns constructed as two physical units called Horn #1 and Horn #2 which are connected in series by a high current transmission line. The horns are connected to the pulsed power supply by coaxial cables, the polarity reversed switch and the transmission line. Figure 1 is a schematic representation of the full horn system.

### System Design Criteria

Since horn focussed neutrino beams have been constructed at almost all of the high energy proton accelerators in the world, the starting point of the Fermilab design was the best and most reliable features of the existing systems. In addition the following requirements were imposed on the design:

- 1) Good focussing efficiency - A three horn focussing system was found to give a neutrino flux greater than 50% of that from perfect focussing over the entire energy spectrum. (See Neutrino Flux Calculations).
- 2) High operational reliability - Horn systems at other accelerators operate with pulsed currents ranging from 250 KA to 500 KA and operating voltages from 10 KV to 14 KV. Since most operational difficulties arise from high currents and/or high voltages, we choose a standard operating point of 150 KA and about 8 KV.
- 3) Minimize induced radioactivity and failures due to radiation - To minimize the induced radioactivity of the horns and transmission lines, aluminum was used

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almost exclusively. Radiation resistant materials (e.g. Kapton, and polyimides) were used extensively in the design of the horns and transmission lines.

- 4) Modular design - The transmission lines and horns were constructed in modular units so that individual modules can be replaced rapidly in case of failure.
- 5) Simplified target location - In previous designs the production targets were located inside the first horn. We require that the target be external to the horn and a conventional multiple target drive be used.
- 6) Be compatible with the train system - The focussing systems of the Fermilab neutrino area are mounted on special bed-plates carried on narrow gauge railroad cars<sup>2</sup> and are rolled into position after negotiating a 130 curve. Special flexible connections in the transmission lines and on the horns were designed to allow for the extra degrees of freedom required by this system.
- 7) Operation at a one-second repetition rate - The power supply and cooling systems are capable of a one-second repetition rate of the horn so that double pulsing on a one-second accelerator flat top or a fast low energy (e.g. proton energy of 70 GeV) accelerator cycle can be utilized.
- 8) Simultaneous horn operation and subsystem testing - By using two sets of switching circuits in the power supply in parallel, the power supply can be discharged into the normal horn load and in between accelerator cycles it can be discharged into a test station where subsystem testing can be accomplished.

### Power Supply

The horn pulsed power supply is described fully in a companion paper published in these proceedings.<sup>3</sup> A schematic representation of the power supply is given in Fig. 2. The approximate electrical properties of the two horn load are given on Table I. The electrical system can be described as a lightly damped L-R-C circuit with a logarithmic decrement of 15% and a natural frequency of about 1600 HZ. When the series switch closes the current through the load has a sinusoidal wave form with a quarter cycle of 155 usec. After the current reaches its peak value and the voltage on the capacitor bank swings negative the crowbar switch is closed and the power is dumped into the 16.7 mΩ resistor. The load current wave form is then of the form  $e^{-t/\tau}$  where  $\tau = 140$  usec. The

series and crowbar switches are size D ignitrous.

The focussing system is operated in Neu-hall which is underground and is a high radiation area. The power supply is located at ground level in a non-radiation area in the service building N1-A. The current is carried 41 m from the power supply to Neu-hall by 45 RG220 coaxial cables in parallel. In Neu-hall the cables terminate in a short two plate transmission line which couples to the polarity reversal switch.

#### Polarity Reversal Switch

The polarity reversal switch is a 56 cm long section of transmission line which is connected between the RG220 cable termination and the main three plate transmission line which connects to Horn #1. At the polarity reversal switch end, the three plate transmission line is terminated as a two plate line. The polarity reversal switch is composed of two sections of two plate transmission line which either connect plus to plus and minus to minus (normal polarity) or plus to minus and minus to plus (reversed polarity) by a simple twist of the transmission line. In this way the current in the horn can be simply reversed allowing focussing (defocussing) of either neutrinos (antineutrinos) or antineutrinos (neutrinos). Using this method to reverse the polarity of the horn magnetic field, the outer conductor of the horns are at high potential when antineutrinos are focussed. This presents special insulating problems. To change the horn polarity the beam must be turned off, an entry must be made into Neu-hall and the polarity reversal switch must be physically changed. This takes from one to two hours.

#### Transmission Lines

Because of (1) the long distances between the polarity reversal switch and Horn #1 (12 m) and Horn #1 and Horn #2 (26 m), (2) the need for low inductance, (3) the tightness of space in the focussing region upstream of Horn #1 and between Horn #1 -#2 and (4) the high radiation levels in the focussing region, it was decided to use parallel plate transmission lines as current feeders rather than coaxial cables after the polarity reversal switch. A three plate transmission line was chosen because of its lower inductance, lower resistance and incoherent physical rigidity. The center conductor was spiral wrapped with 10 cm wide layers of Kapton. Extra Kapton was placed on both sides of the center conductor to build up the total insulator thickness to 1.6 mm. A typical cross section view of the transmission line is shown in Fig. 3.

To simplify installation, repair and motion of the horn train in and out of Neu-hall the transmission line is separated into five sections which are bolted together just before the system is put into its final location. A development program to replace these bolt joints by rotary joints is underway.

The transmission lines terminate in two-parallel-plate yokes which are connected to the horns by using high pressure remotely actuated mechanical clamps. The yokes are clamped to the endplates of the horns providing a symmetric four-point distribution of current into the horn inner and outer conductors. To minimize stress on the horn endplates, the transmission lines are supported on springs to balance their weights. To allow the horns to be aligned and to compensate for bedplate misalignments, the transmission line yokes have been slotted to a thickness of 4.8 mm making them quite flexible.

#### Horns

Guided by the design criteria, an optimal three horn system was calculated<sup>4</sup> for the Fermilab neutrino area. To simplify the installation, alignment and replacement, the three horns were packaged into two units. Using the convention that a horn is characterized by a single neck region. Two horns were packaged in Horn #1 and one horn in Horn #2. The distance from the downstream end of the production target to the upstream face of Horn #1 is 2.2 m. The distance from the upstream face of Horn #1 to the upstream face of Horn #2 is 29.9 m.

Since the horn structures are cylinders of revolution of straight line segments, their shapes can be specified by the cylindrical coordinates of the kink points of the inner conductor shape. (R is transverse to the beam axis and Z is along the beam axis). The shapes are given in Table II. The inductances of the horns were calculated and are given on Table I. To minimize meson absorption in the horn surfaces but still have satisfactory mechanical stability of the inner conductor a wall thickness of 2 mm was chosen for both horn inner conductors except in the neck regions where the thicknesses are 4 mm.

The horn inner conductors were constructed using new techniques. The Horn 1 inner conductor was machined from solid billets of 6061-T6 aluminum with typical lengths of 40 cm. The segments were then electron beam welded together into three units which were bolted together for the final assembly. Full penetration of the electron beam was insured by using backup rings which were later reamed out. This type of welding produced a very successful high quality void free weld joint. The neck region of Horn #2 was machined out of a solid billet of 6061-T6 Aluminum. However the cone sections were too large to be machined. They were made by spinning soft aluminum onto a steel mandrel. By a process of successive tempering and respinning the cones were eventually brought to the T6 condition with an acceptable tolerance on their shape.

The mechanical shock of the current passing through the horn inner conductor can produce transverse oscillation modes of the center conductor which could produce metal fatigue. To dampen these transverse modes

2 mm thick insulator disks were used to hold the center conductor rigid relative to the outer conductor. Three disks were used in Horn #1 and two disks in Horn #2. Disks were also used inside the two horns, adjacent to the endplates, to protect their high voltage joint from the cooling media and associated dirt.

The outer conductors were constructed as cylinders with a 9.5 mm wall thickness. The Horn #1 outer conductor is in four sections while the Horn #2 outer conductor is in three sections.

The horns are aligned to the railroad bedplates by precision tapered pin and socket mounts which can be aligned. A horn can be simply removed in case of failure and another put in place without redoing the main alignment. A complete spare Horn #1 exists as well as a spare Horn #1 inner conductor.

#### Horn Cooling Systems

Horn #1 is cooled by water sprayed on the inner conductor between beam pulses. Horn #2 is force air cooled. The cooling systems are sized to properly cool the neck regions of the horns which have the largest Joule heating. The Horn #1 first neck has a temperature rise of about 2°C per pulse with a one second repetition rate while Horn #2 neck will only be about 0.3°C per pulse.

The Horn #1 water cooling system is a pulsed closed loop low conductivity system which when pulsed produces 15 GPM at 140 PSI through spray nozzels. The nozzels are located symmetrically around the horn axis and directs the water onto the center conductor. The water system is located in Neuhall about 15 m from Horn #1.

The Horn #2 cooling system is forced air which is directed onto the center conductor by apertures in the bottom of the outer conductor. Since the air around Horn #2 is stagnant and warm, cool air is brought through ductwork from Neuhall blown onto the inner conductor and then returned back into Neuhall through another duct. Two high speed turbine blowers in parallel are used to move the air. Appropriate instrumentation and interlocks exist to insure proper functioning of the cooling systems during operation.

#### System Operation

The horn system has been operated with Horn #1 for over 500,000 pulses for neutrinos and antineutrinos with few operational difficulties. During one horn operation the nominal 140,000A can be achieved with a working capacitor bank voltage of about 4500 volts. The value of the magnetic field in the horn is determined from a pickup coil placed in the horn a known distance from the axis. The coil output is proportional to  $\dot{B}$ . The field value is then obtained in hardware by  $\int \dot{B} dt$ .

The full two horn system was tested for the first time in November, 1974. A high

voltage short in the transmission line yoke feeding Horn #2 terminated the test. The yoke design has been improved and the full two horn system should be ready for testing in March, 1975.

With the one horn system the observed quarter cycle of the current wave form was 115  $\mu$ s. For the two horn system it was 155  $\mu$ s. These values agree well with the expected quarter cycle based on the calculated inductances of the horns. Because of the relatively fast current pulse in the horn it is necessary to operate with the fast extracted proton beam where the spill varies from 20  $\mu$ sec. to 60  $\mu$ sec. The long term stability of the quarter cycle, horn magnetic field and the absolute timing of the horn discharge relative to the beam are well within acceptable limits.

#### Neutrino Flux Calculations

The neutrino flux at the bubble chamber was calculated for the no horn, Horn #1 and Horn #1 plus Horn #2 cases for 300 GeV protons on the target. The NUADA neutrino flux program<sup>5</sup> was used with the Hagedorn-Ranft particle production model.<sup>6</sup> The target was taken as a 40 cm long aluminum rod 6 mm in diameter. The flux was averaged over a diameter of 2.7 m. The neutrino energy spectra are given in Fig. 4.

#### Future Development

If the present fast extraction mode of operation is maintained (20 - 60  $\mu$ sec. spill) then Horn #1 should be attempted to be air cooled. This is desirable because the pulsed water system requires high maintenance and water leaks in the horn pose high voltage problems.

An effort to reduce the amount of meson absorption in the horns should be made. The present system absorbs about 25% of the mesons which pass through the horns. This not only reduces the neutrino flux but add uncertainties in the determination of the neutrino spectrum. By making the inner conductor, support disks and joints thinner the absorption could be reduced by 50%.

High flux dichromatic neutrino beams can be achieved by using special horn inner conductor shapes. This exciting prospect can be pursued along the lines of the previously proposed monohorn study.<sup>7</sup> This new beam could be achieved by primarily modifying the horn shapes and inserting collimators and beam plugs.

If it is important to increase the quarter cycle of the horn system so that longer proton spills (~ 1 m sec.) can be used, then transformer coupling of the horns to the power supply could be pursued.<sup>8</sup> In this solution it probably would be necessary to water cool both horns.

Acknowledgements

The neutrino horn system was developed and constructed by the collaborative efforts of the Neutrino Department and the Accelerator Division. The original design concepts were established in early 1970 by G. Lee, R. Winje and F. Nezrick. G. Lee, J. Simon, and J. Grimson and the Target Handling Group under D. Theriot in various phases designed the horns and transmission lines and organized the system into an operating target train load. R. Winje spearheaded the power supply design and construction. The Neutrino Department beam technicians under G. Woods and W. Williams assisted by the 30-inch bubble chamber crew constructed the power supply, the interlocks and controls and evolved the power supply into an operating unit of high reliability.

References

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- <sup>3</sup>R. Winje, "A 230KJ Pulsed Power Supply," to be published, proceedings of this conference.
- <sup>4</sup>D. C. Carey et al., "500 GeV Neutrino Beams at NAL," Fermilab Report TM-472, October 1970.
- <sup>5</sup>D. C. Carey and V. A. White, "NUADA-The Fermilab Neutrino Flux Program." To be published as a Fermilab internal report.
- <sup>6</sup>R. Hagedorn and J. Ranft. Supplemento Al Nuovo Cimento, Ser. 1, 6, 169 (1968) and updates.
- <sup>7</sup>F. A. Nezrick, "A Monoenergetic Neutrino Beam Using Current-Sheet Focusing Elements," Nuclear Science, Vol. NS-18, No. 3 pg. 759 (1971).
- <sup>8</sup>F. A. Nezrick, "Can the Horn System be Modified to Accomodate a 1 m sec. spill?" Fermilab Internal Report TM-536 (1974).

Figure Captions

- Fig. 1: Schematic layout of the Neutrino Horn Focussing System
- Fig. 2: Schematic electrical circuit of the Horn Pulsed Power Supply.
- Fig. 3: Typical Cross Sectional view of the three plate transmission line.
- Fig. 4: Neutrino Flux calculated for No horn, one horn and two horn focussing for 300 GeV protons.

TABLE I

Approximate Electrical Properties  
of the Two Horn Load

Load Component	Inductance μH	Resistance mΩ
45 RG 220 cables in parallel	0.2	0.9
Transmission lines	0.9	7.0
Horn #1	1.6	0.7
Horn #2	1.3	0.3
<b>TOTAL LOAD</b>	<b>4.0</b>	<b>8.9</b>

TABLE II

Horn Shapes Specified in the Cylindrical  
Coordinates of the Inner Conductor Kink Points

Horn #1	R(cm)	Z(cm)
	15.0	0.0
	7.0	0.0
	0.7	90.0
	0.7	120.0
	9.0	310.0
	1.5	360.0
	1.5	380.0
	5.7	400.0
	15.0	400.0
Horn #2	35.0	0.0
	26.0	0.0
	16.0	210.0
	3.0	300.0
	3.0	360.0
	16.0	450.0
	26.0	550.0
	35.0	550.0

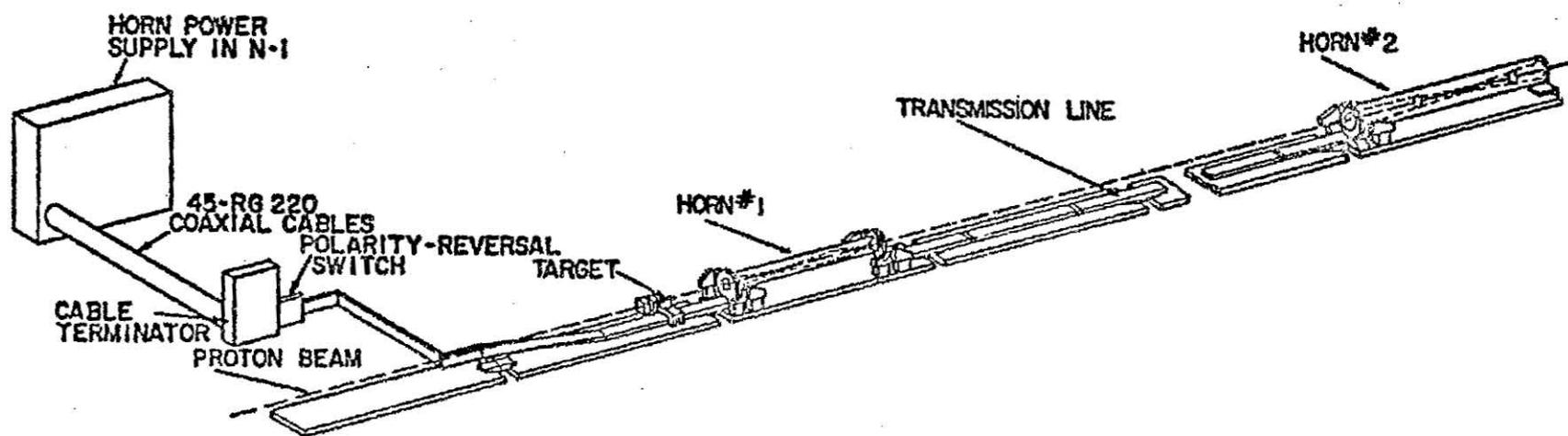


Fig. 1

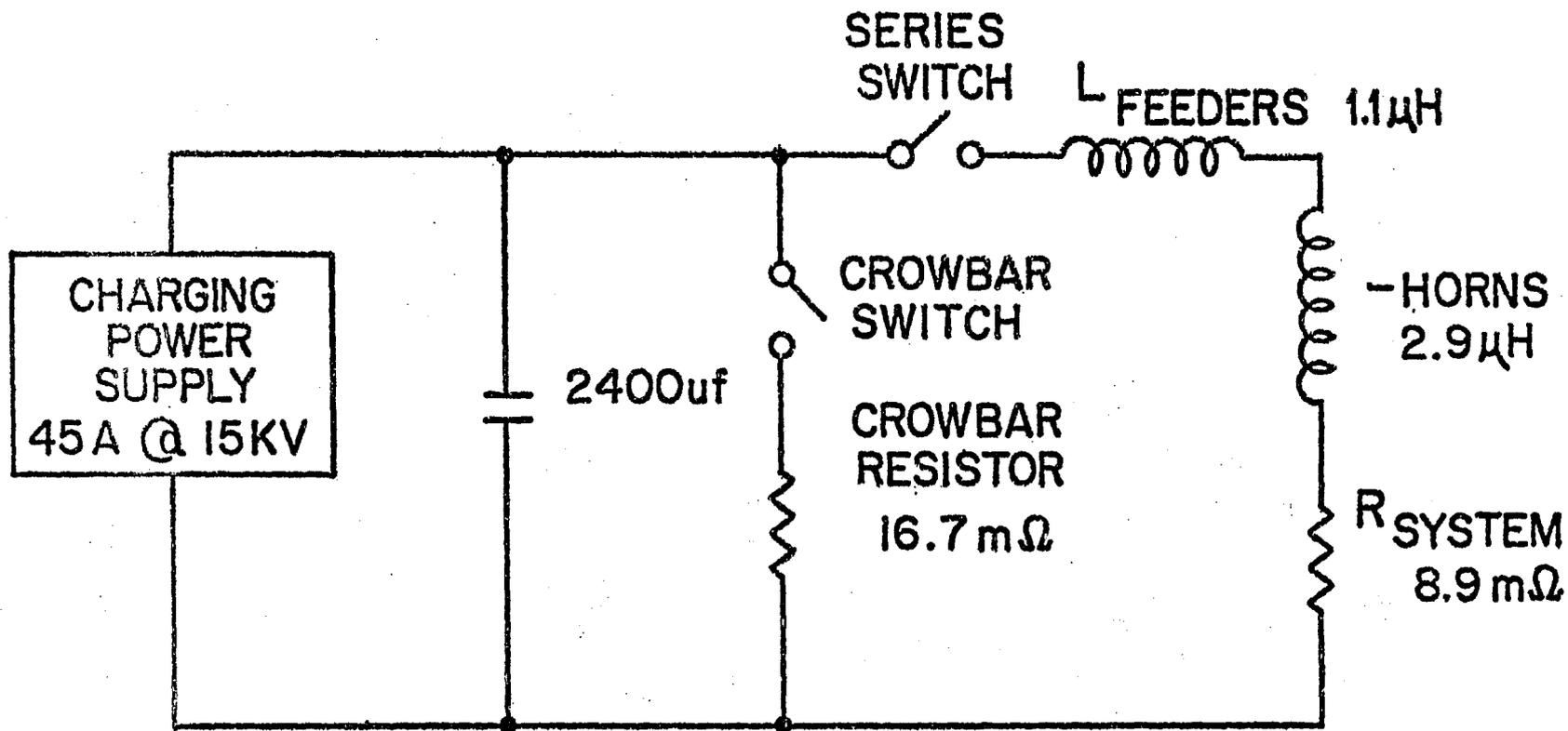
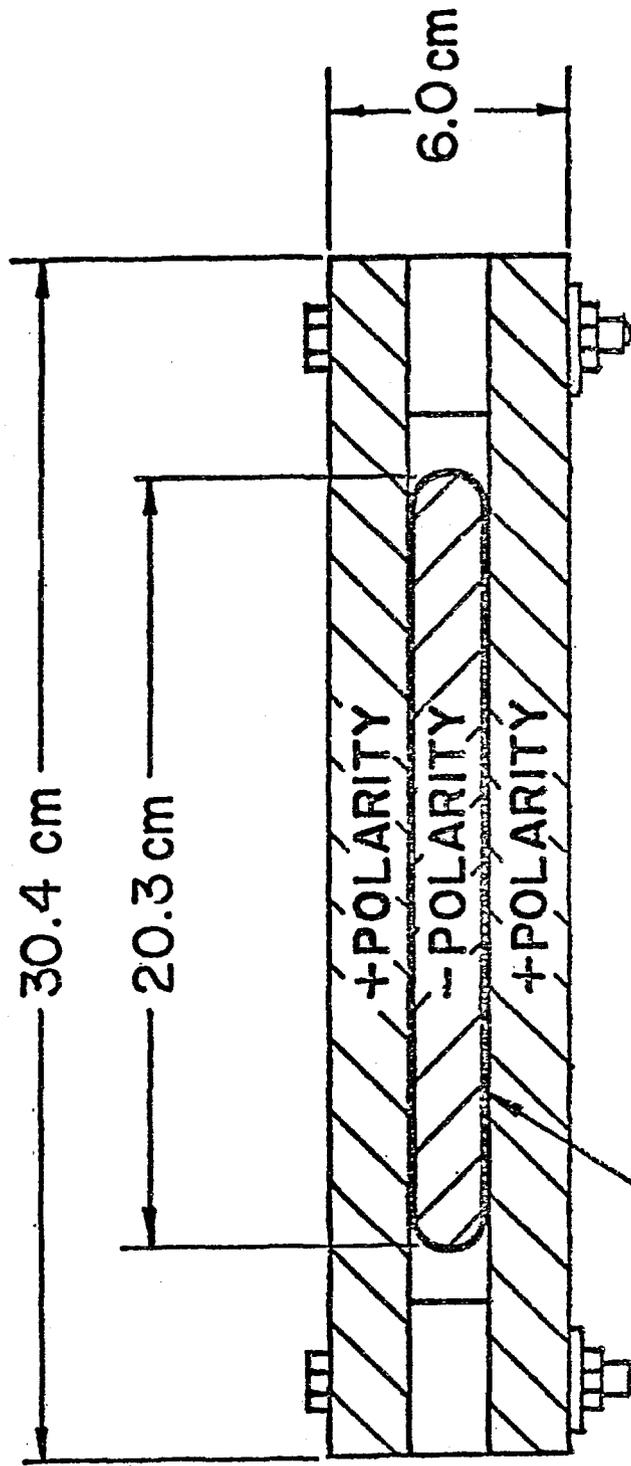


Fig. 2

Schematic Representation of the Pulsed Power Supply



1.6 mm KAPTON INSULATION FULL LENGTH

Fig. 3

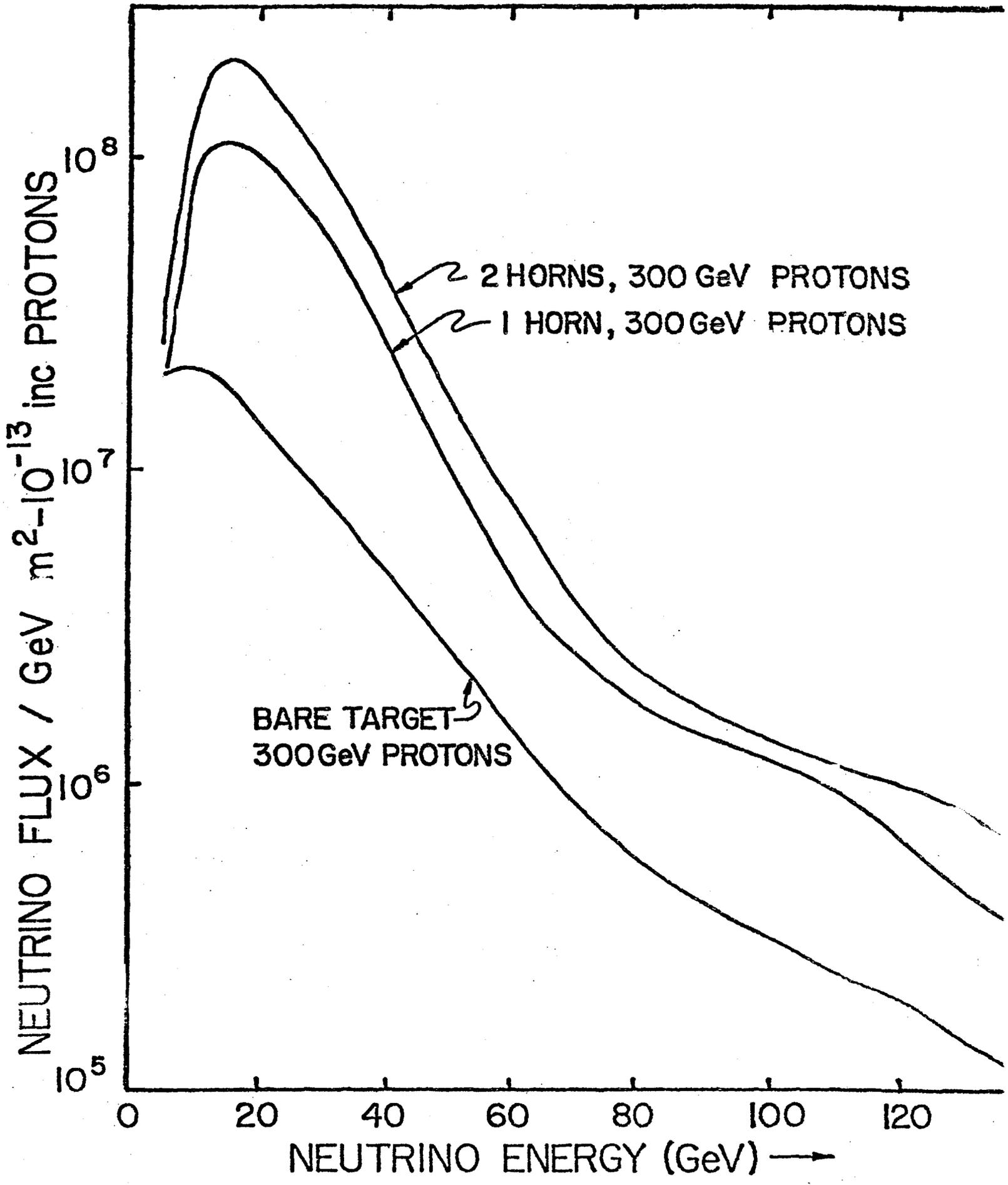


Fig. 4