Proton Radiography Data Analysis

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ABSTRACT

We present a status report as of 9/1/2008 of the data analysis, comparison with Monte Carlo, and preliminary results for forward neutron production.

This is based on our proposal to the Stockpile Stewardship Academic Alliances for an extension of our 3-year grant beyond March, 2009.

Introduction

Proton radiography has become an important tool for predicting the performance of stockpiled nuclear weapons [1]. The Los Alamos Neutron Science Center (LANSCE) is carrying out an extensive program of experiments at the Proton Radiography Facility [2, 3]. Current proton radiography experiments at LANSCE are confined to relatively small targets on the order of centimeters in size because of the low beam energy. LANL scientists have made radiographs with 12 and 24 GeV protons produced by the accelerator at Brookhaven National Laboratory. These energies are in the range required for hydrotest radiography of more realistic targets [4]. The design of a facility for hydrotest radiography requires knowledge of the cross sections for producing high energy particles in the forward direction, which are incorporated into the Monte Carlo simulation used in designing the beam and detector. There are few existing measurements of cross sections for proton-nuclei interactions in the 50 GeV range, and very little data exist for forward neutron and photon production. Thus the data from the MIPP EMCAL and HCAL, for which our group was responsible, are critical to proton radiography. Since neutrons and photons cannot be focused by magnets, they cause a background "fog" on the images. This problem can be minimized by careful design of the focusing system and detectors.

The design of the focusing system and detectors is done using various Monte Carlo codes to simulate the interactions of protons in the object to be imaged and the subsequent interactions of the secondary particles in the material. There are, however, large differences between different hadronic shower simulation codes (FLUKA [5], MARS, MCNP [6], etc.). This imposes significant limitations on the simulations and design of the beam and detectors. The validation of these codes requires significantly more data, particularly in the forward direction for heavy target nuclei.

The physics goal of this analysis is to measure forward production of neutrons and photons produced by high-energy proton beams striking a variety of targets. The use of protons as a radiographic probe requires a knowledge of the proton interaction cross sections, the differential distribution of the outgoing proton in momentum and angle, and the distribution of produced particles, especially in the forward direction. Much of the energy is carried by forward-going neutrons and gammas. There is very little data on forward neutron and π^0 production, so that these measurements are particularly crucial. In addition, measurements of proton interactions with a wide range of nuclei (from hydrogen to uranium) will provide data for simulations of the technique and for interpretation of the images. The goal of Experiment 907 at Fermilab is to do a comprehensive set of measurements of production cross sections for protons, pions, kaons, neutrons, and photons for beam energies between 5 and 120 GeV for a wide variety of targets. These data will provide input to models used to generate simulated interactions for Monte Carlo studies of proton radiography and are critical to the success of proton radiography for stockpile stewardship.

We report on the status of the inclusive neutron analysis. Important discrepancies between our neutron production data and Monte Carlo expectations have already been found. The more challenging analysis of forward photon data has barely been started.

E-907 at Fermilab (MIPP)

E-907 (Main Injector Particle Production) at Fermilab is an approved experiment to measure particle production using primary and secondary beams from the Main Injector [7]. It is a collaboration of the University of Colorado, Fermi National Accelerator Laboratory, Harvard University, Illinois Institute of Technology, the University of Iowa, Indiana University, Lawrence Livermore Laboratory, the University of Michigan, Purdue University, the University of South Carolina, and the University of Virginia. MIPP will supply information critical to the Main Injector Neutrino Oscillation Search (MINOS) experiment and other basic physics experiments, as well as data needed to design and plan for proton radiography using higher energy beams.

E-907 officially started physics running at Fermilab in January 2005, and data taking continued through February 2006. Data were taken on a range of targets, from liquid hydrogen to uranium, at beam energies from 5 GeV/c to 120 GeV/c. The analysis of the data is challenging because data from many different detector systems must be understood and merged and over 31 million events were accumulated. The Pass 4 reconstruction of these data is complete; this pass includes vertex-finding and improved tracking in the TPC and spectrometer. The next pass, which includes complete particle identification code, is almost finished.

The MIPP Forward Detectors

A perspective layout of the MIPP detectors is shown in Fig. 1 with the beam coming from the upper left. The experiment is set up in the Fermilab Meson Center beam line. Our group has many years of experience with neutron scattering experiments and hadron calorimeters. Thus it was natural for the University of Michigan group to take responsibility for the MIPP electromagnetic shower detector (EMCAL) and the neutron calorimeter (HCAL). The purpose of the EMCAL is to detect and measure the angles and energies of forward photons. The HCAL detects neutrons and other hadrons and measures their energies.

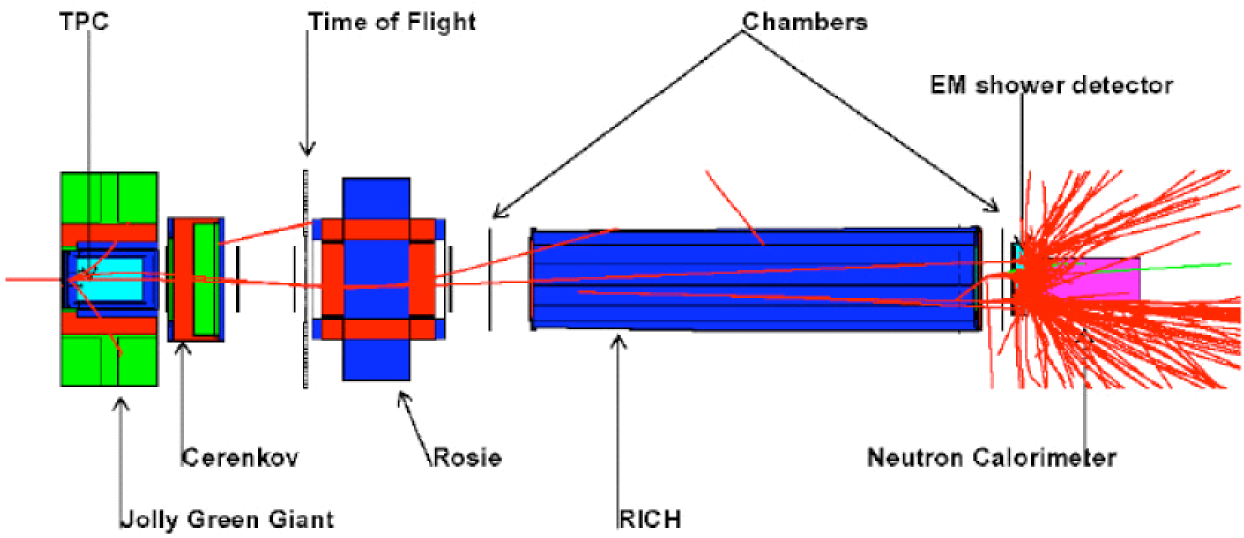

FIGURE 1. Schematic plan view of MIPP showing Monte Carlo generated showers in the EMCAL and HCAL

Status

The calibrations of both the EMCAL and the HCAL are well understood. A paper describing the calibration has been accepted for publication in Nuclear Instruments and Methods [8]; this will be the first publication in a refereed journal from MIPP.

A comparison of our overall hadron energy resolution to that of other calorimeters is shown in Table I. The energy resolution is comparable to or better than that of the others. Ours has the advantages of good spatial resolution in the EMCAL, low cost, and excellent separation between photons and hadrons (Figure 2).

Table I. Comparison of MIPP energy resolution for protons with other calorimeters.				
Experiment	**Cal Type**	**Resolution**	**Resolution @ 20 GeV**	**Resolution @ 120 GeV**
MIPP	Pb/Gas+Fe/Scint	$55.4\% / \sqrt{E} \oplus 2.6\%$	13.8%	5.9%
D0	U/LAr	$44\% / \sqrt{E} \oplus 4\%$	10.6%	5.7%
FOCUS	Fe/Scint	$85\% / \sqrt{E} + 0.86\%$	19.9%	8.6%
HyperCP[1]	Fe/Scint	n/a	n/a	9%
L3	BGO + U/Gas	$44\% / \sqrt{E} + 7\%$	17%	11%
RD-34	Fe/Scint	$41.3\% / \sqrt{E} + 4.3\%$	13.5%	8.1%
WA78	Fe/Scint	$55\% / \sqrt{E} \oplus 1.7\%$	12.4%	5.3%
ZEUS[2]	U/Scint	$43.6\% / \sqrt{E}$	9.7%	4%
ZEUS[3]	Pb/Scint	$70\% / \sqrt{E}$	n/a	6%

[1] The HyperCP resolution was measured with 70 GeV protons.

[2] The ZEUS resolution is for all events. The resolution for events fully contained in the calorimeter is 7.8% at 20 GeV and 3.2% at 120 GeV.

[3] ZEUS Forward Neutron Calorimeter. The resolution is for hadrons incident at the center of the tower modules. The resolution is $62\% / \sqrt{E}$ for hadrons incident at the center of the calorimeter.

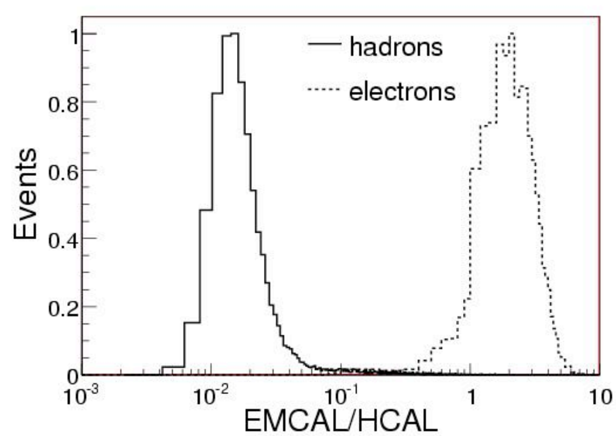

FIGURE 2. Ratio of energy in the EMCAL to the energy in the HCAL for 18.5 GeV electrons (dotted line) and 20 GeV hadrons (solid line). This shows that we have excellent separation between electrons/photons and neutrons.

We have made a preliminary analysis of neutron and proton production by 120 GeV/c protons for carbon and bismuth targets and compared the data with a Monte Carlo simulation based on the commonly used FLUKA2006 code [5].

Neutron momenta were calculated by subtracting the summed energy of charged tracks within the HCAL volume from the total HCAL energy deposit. Further it was required that the neutron momentum be at least 20 GeV/c. We also required that the position of the incident beam and the reconstructed interaction vertex were consistent with the production target, and that the interaction trigger was satisfied.

Figure 3 compares our neutron momentum spectra for carbon (1.94% interaction lengths) and bismuth (0.87% interaction lengths) targets to that expected from the Monte Carlo simulation. The shapes are quite different. The discrepancies are more apparent in Figure 4 that compares the ratio of data to Monte Carlo. While the analysis is still preliminary, it points to a significant underestimate of neutron yields by the Monte Carlo, both at high and low neutron momenta.

In Table II we compare the total cross sections for producing a neutron with momentum >20 GeV/c going into the fiducial volume of the HCAL. The measured cross sections are more than a factor of 2 higher than the FLUKA predictions for both carbon and bismuth, while the Bi/C ratios are within 20%. However, it is known that the neutron cross sections built into FLUKA are uncertain by at least a factor of 2. [9]

Table II– Total cross sections for producing a neutron >20 GeV/c into the HCAL

	Carbon	Bismuth	Bi/Carbon
Monte Carlo	43 mb	244 mb	5.73
Data	111 mb	538 mb	4.84

In Figures 5 and 6 we compare the neutron angular distributions from carbon and bismuth targets with the FLUKA predictions. The neutron angles were found using the small fraction of the events in which the neutrons began to shower in the EMCAL. Good spatial resolution is provided by the 2.54 cm pitch of the EMCAL proportional tubes. The angular distribution is truncated at about 0.02 radians by the geometric acceptance of the HCAL. There is a large discrepancy between the data and Monte Carlo at very small angles, especially for bismuth. This apparently is due to the lack of inclusion of Coulomb diffraction dissociation in FLUKA.

The analysis of forward photon production is more challenging and has barely been started

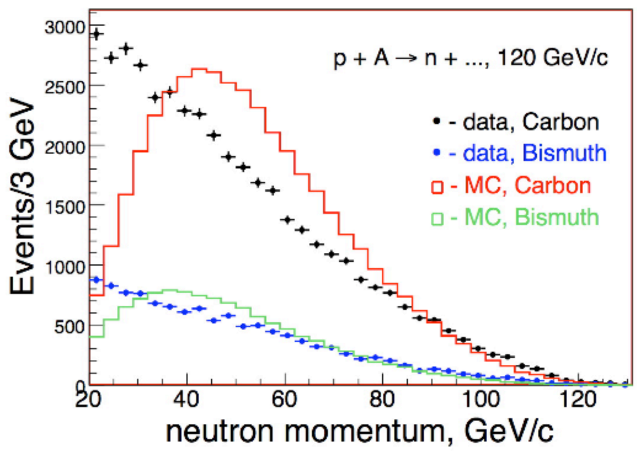

Figure 3. Comparison of data and Monte Carlo for neutrons produced by 120 GeV protons on carbon and bismuth targets. The Monte Carlo is normalized to the same total events as the data.

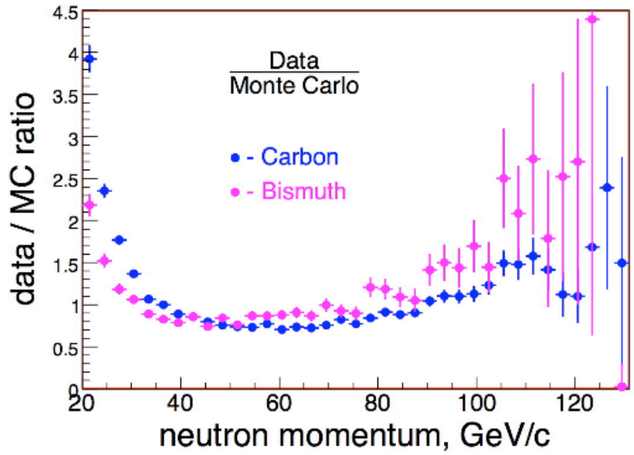

Figure 4. Ratio of data to Monte Carlo for neutrons produced by 120 GeV protons on carbon and bismuth targets. Note the large discrepancies at both low and high momenta. The data include a significant contamination of K^0_L below 50 GeV/c, which is not yet incorporated into the Monte Carlo.

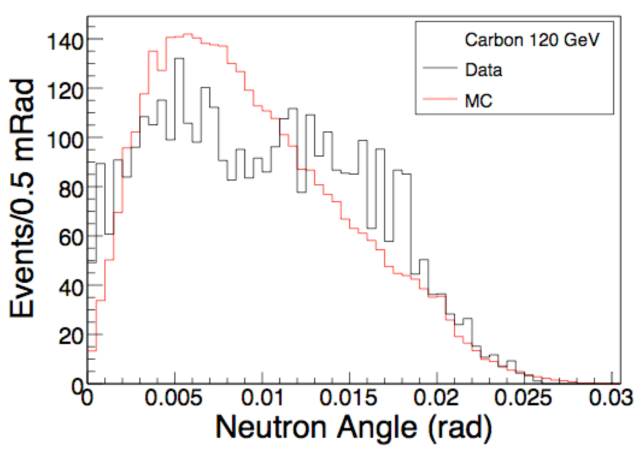

Figure 5. Comparison of data and Monte Carlo for neutrons produced by 120 GeV protons on a carbon target. The distribution is truncated at about 0.02 rad by the fiducial volume of the HCAL.

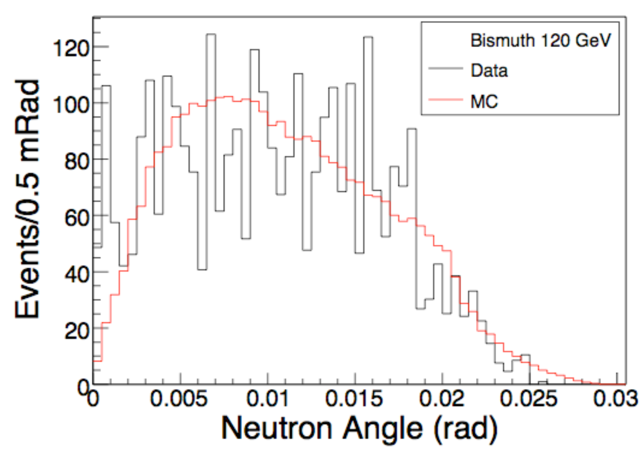

Figure 6. Comparison of data and Monte Carlo for neutrons produced by 120 GeV protons on a bismuth target. Note the significant discrepancy at small angles.

Objectives, MIPP Run II

So far we have mainly looked at inclusive production of neutrons vs. momentum for 120 GeV/c protons on carbon and bismuth targets and have done preliminary Monte Carlo simulations. The work on the angular and transverse momentum distributions of the neutrons has just been started. We have spent a lot of time understanding the trigger efficiencies. The results so far are very encouraging and we are confident we can meet our goals. This effort has to be extended to other targets and other beam momenta. Analysis of 58 and 84 GeV/c data with carbon, bismuth, and liquid hydrogen targets is underway.

The signature for a photon in the calorimeters is the opposite of that for a neutron: most of the energy appears in the EMCAL rather than the HCAL. As can be seen from Fig. 2, our neutron/ photon separation is very good. The initial look at the photon inclusive production appears promising but this effort has only just begun.

The large discrepancies between our data and the Monte Carlo predictions discussed above point to the need to improve and better understand the simulations. So far we have only used the FLUKA2006 code. The MCNP6 code is being developed at LANL for proton radiography with beams up to 50 GeV [6]. A comparison of our results with MCNP predictions needs to be done.

An upgrade of the MIPP detectors for a second run is planned. Repairs in the coils of the "Jolly Green Giant" magnet have already been made. The readout systems for the Time Projection Chamber and EMCAL will have to be completely replaced. This will allow us to take data at a much higher rate. The readout system for the EMCAL is over 25 years old. The designs for the new electronics are well underway. We are working with Fermilab engineers on the new design for the EMCAL electronics. A prototype board will be ready for testing shortly.

We are also planning to add fast trigger capabilities for the EMCAL and HCAL so that we can trigger on neutral particles in the calorimeters. The calorimeters were not included in the triggers for the first run. This meant that there was no trigger for events with low charged multiplicity so that only a small fraction of the triggers were useful for the forward neutron and proton analyses. The analysis of orders-of-magnitude more data will present a significant challenge.

Appendix I. References

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2) www.lansce.lanl.gov/pRad/docs/pRadCall2009.pdf

3) N.S. King et al., An 800-MeV proton radiography facility for dynamic experiments, Nucl. Instr. Meth. A, 424, 84 (1999)

4) G. E. Hogan et al., Proton Radiography, Proceedings of the 1999 Particle Accelerator Conference, New York, 1999, LA-UR-99-1542.

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5) http://www.fluka.org/

6) F. B. Brown, Monte Carlo Methods & MCNP Code Development, LA-UR-05-2729

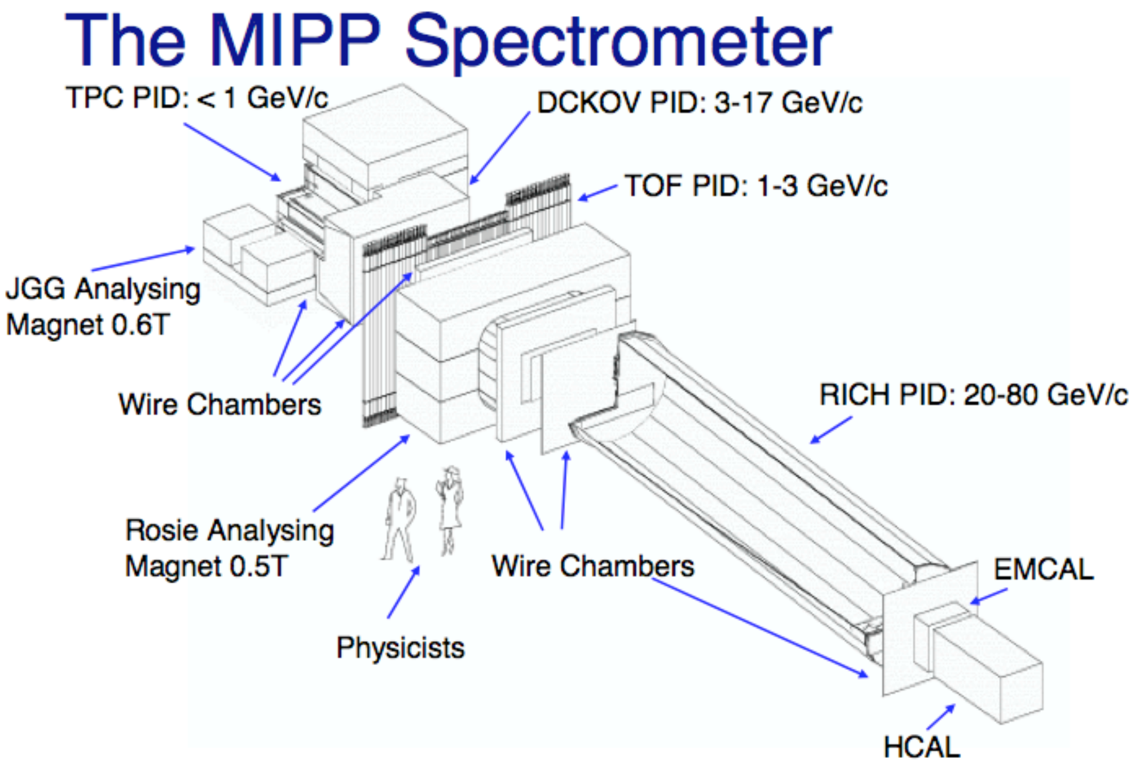
7) R. Raja, Nucl. Instr. Meth. A553, 225 (2005)

8) T. S. Nigmanov et al., Electromagnetic and Hadron Calorimeters in the MIPP Experiment, to be published in Nucl. Instr. Meth. A.

9) S. Striganov, Fermilab, private communication, 2008

Appendix II.   Facilities

A perspective layout of the MIPP detectors is shown below with the beam coming from the upper left. The experiment is set up in the Fermilab Meson Center beam line. The purpose of the EMCAL is to detect and measure the angles and energies of forward photons. The HCAL detects neutrons and other hadrons and measures their energies.



Perspective view of the MIPP Detectors. Beam comes from upper left.

Appendix III. Equipment

Figure III-1 shows a side view of the EMCAL and HCAL. Figure III-2 shows a more detailed side view of the HCAL. The EMCAL uses lead plates interspersed with wire proportional chambers. Photons shower in the lead plates and their energies and locations can be determined by the proportional chambers. Most of the photon energy is contained within the EMCAL. The HCAL consists of 1" thick steel plates interspersed with sheets of plastic scintillator. The light from the plastic scintillators is collected by optical fibers and brought to 8 photomultiplier tubes. The energy of the hadron can be estimated by the total pulse height from the phototubes.

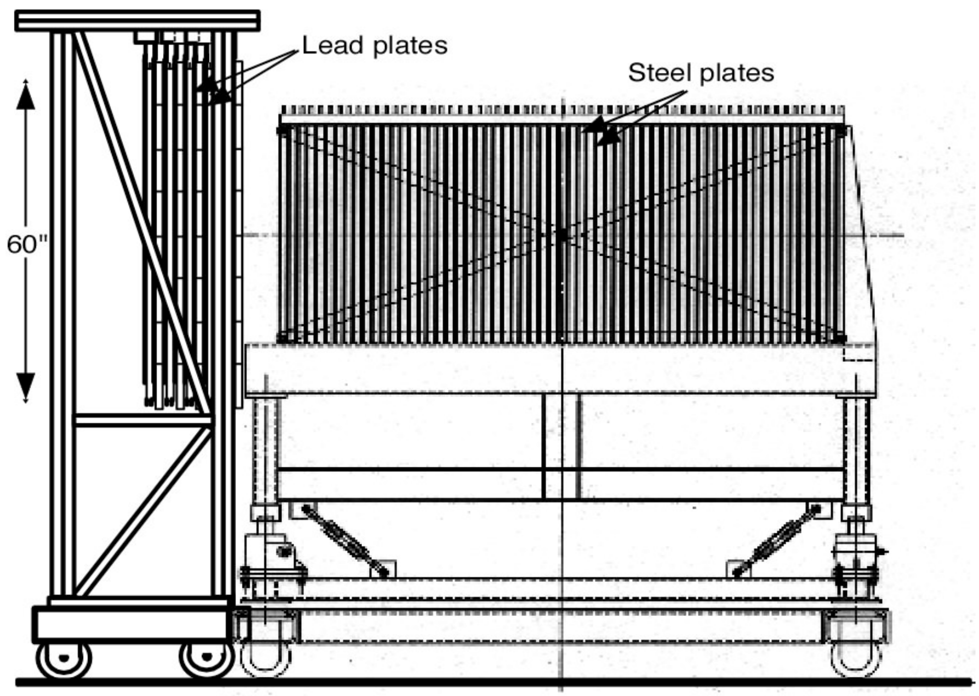


Figure III-1. Side view of the EMCAL and HCAL

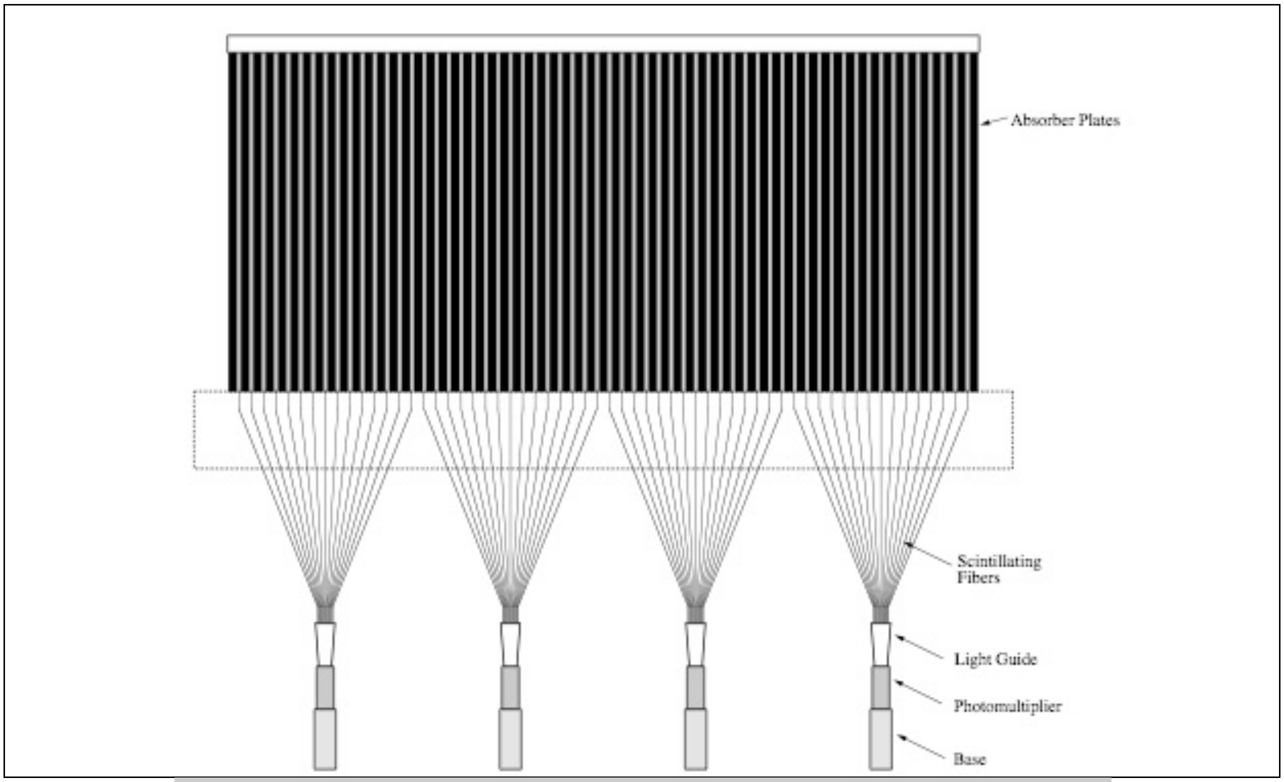


Figure III-2. Detailed side view of the HCAL. The absorber plates are 2.54 cm steel.