Conceptual Designs for a Wide-Band Low-Energy Neutrino Beam Target

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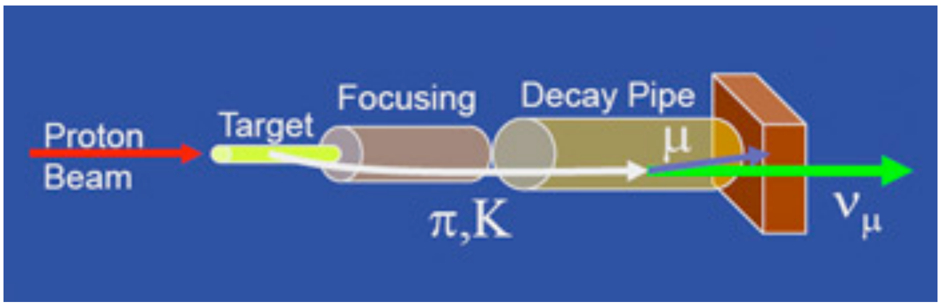
Abstract:

Neutrinos are neutral elementary particles. Neutrino accelerator experiments are designed to understand neutrino oscillation. One of the parameters in neutrino oscillation can expain why the world is dominated by matter instead of anti-matter. A proton accelerator releases a beam to hit a target and produces pions, which decay to neutrinos. To design a target for the Long Baseline Neutrino Experiment (LBNE), the study used the simulation program FLUKA to optimize pion production at momenta of 1-10 Gigaelectronvolts (GeV). Pion production efficiency as a function of target materials, proton energy beam (30 to 120GeV), target geometry (length and radius) and energy deposition were simulated. Mercury, tantalum produced most pions with 120GeV proton energy beam. A 30GeV proton beam with a mercury target had the highest efficiency with an increase of 117% in 1-3GeV pions compared to a graphite target with 120GeV proton beam. A new hybrid target was studied for the first time. For pions at 1-3GeV, a combination of tantalum and Super Invar with 30GeV proton beam can improve pion production up to 150%. From 3 to 6GeV, the efficiency was increased by 32.3%.

1 Introduction:

Introduction:

Neutrinos are nearly massless, neutral elementary particles. There are three flavors (types) of neutrinos: muon neutrinos, tau neutrinos and electron neutrinos. Neutrinos are made of three different mass states: state 1, state 2 and state 3. The difference among neutrinos is caused by various proportions of these three states. Neutrino oscillation, which is a change of flavors as neutrinos travel through space, can explain why the world is dominated by matter. To make neutrinos, a particle accelerator uses a proton beam to hit nuclei inside a target and produce pions. Pions are focused in a decay pipe and decay into muon neutrinos.



The graph shows how accelerator experiments produce neutrinos. *credit: Fermilab*

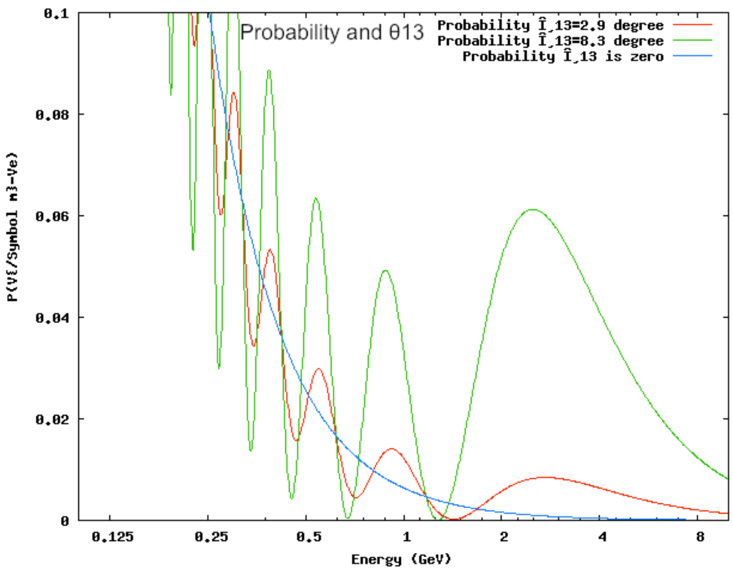
Neutrino accelerator experiments have advantages to measure neutrino oscillation because they can control the energy, the direction, and the flavor of neutrinos. However, damage caused by radiation effects from proton interaction can greatly reduce the longevity of the target (Kayser. 2008).

Very Long Baseline Neutrino Experiment:

This study is proposed for the Very Long Baseline Neutrino Experiment (LBNE). LBNE is a collaboration of 46 institutions, over 200 people. The study was conducted in Brookhaven National Lab (BNL), which had two Nobel prizes winners in neutrino physics. LBNE is going to be the largest US-based neutrino accelerator experiment that can explain the role neutrinos play in the universe. LBNE will use the highest-intensity proton beam in the world from an accelerator complex.The neutrino beam will travel 1300km from Fermilab to Homestake Mine near Lead, South Dakota (Cofield,2010). The proposal will be ready in 2012 and this study will an important component. LBNE aims to study anti-neutrinos and neutrinos. It will not only provide a crucial link to understanding matter and anti-matter asymmetry, which explains why the world is dominated by matter after the Big Bang, but also determine the mass differences of electron, muon and tau neutrinos, which will directly affect other neutrino experiments such as double Beta decay experiment (Kurt Riesselmann, 2010).

Neutrino Probability Function:

Kayser (2008) reports that there are 3 unknown parameters in neutrino oscillation: θ_{13}, CP (δ)and Δm_{31}^2 . θ_{13} is a parameter that indicates the degree of mixing angle between 1 and 3 states. Δm_{31}^2 is the difference of mass between 1 and 3, which also determines the mass difference of electron and muon neutrinos. δ explains why the world is dominated by matter because it detects the asymmetry of anti-neutrino and neutrino. These three parameters are closely related to each other, so it is hard to decide which parameter is changing the neutrino oscillation probability (Cervera et al, 2000). The parameters must be tested in different neutrino energy ranges to disentangle them (Rigolin et al, 2000). Any neutrinos that are above 4 GeV can cause background and therefore must be avoided (Wagner et al, 2005). The following graphs show the relation between parameters and neutrino oscillations.



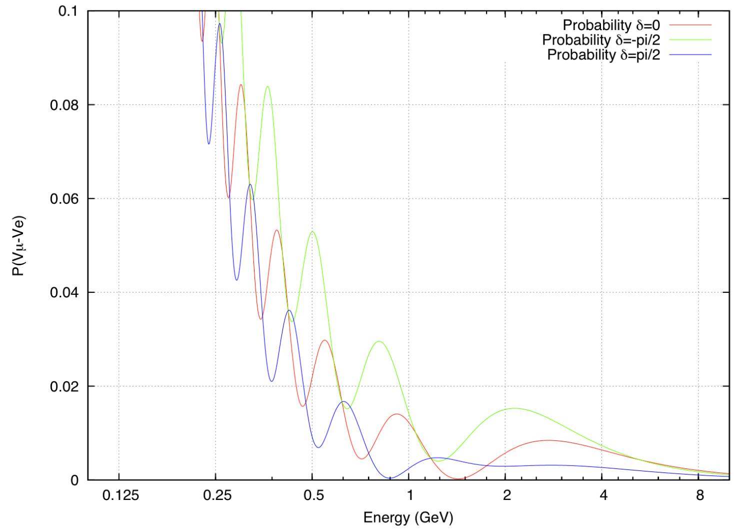


Figure A shows neutrino energy plotted againest oscillation probability from muon to electron neutrinos. θ_{13} determins the amplitude of probability, but not the phase. It affects neutrino oscillations in all energy range.

Figure B shows neutrino energy plotted against probability. The graph shows that CP dominates neutrino oscillations at low neutrino energy ranges. To measure the value of CP, neutrinos should be tested at 0.25GeV to 1GeV.

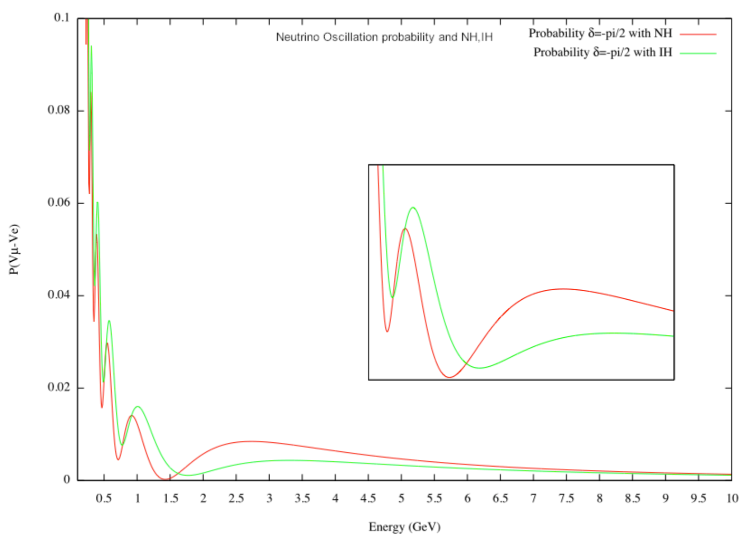
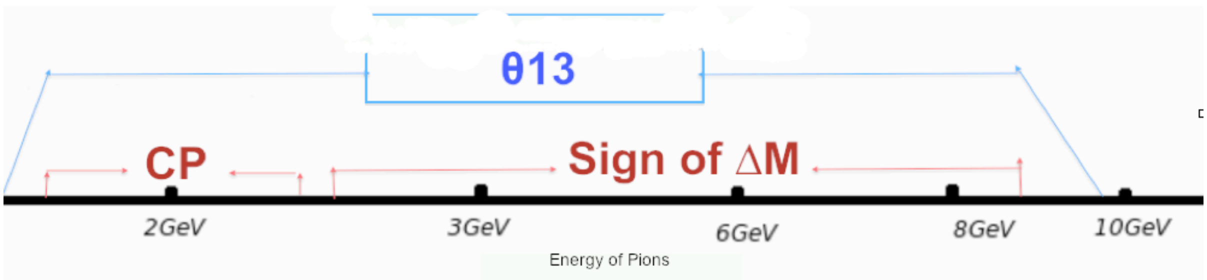


Figure C shows neutrino energy plotted against oscillation probability from muon to electron neutrinos when Δm_{31}^2 is different. Normal Hieachy (NH) means muon neutrinos is heavier than electron neutrinos, while Inverted Hieachy(IH) means the opposite. Δm_{31}^2 causes the shift of probability. Δm_{31}^2 changes the probability. At neutrino energy from 2GeV to 4GeV, the change is the biggest.

The maximum energy a muon neutrino can get from pion decay is (Gaisser et al, 2009)

$$E_{ve}^{\max} = 0.4 E_{\pi}$$

As a result, to get neutrino energy range from 0.5GeV to 4GeV, the corresponding pion energy range is 1.25GeV to 10GeV (Takahashi et al ,2005). The following chart shows the relation between energy of pions and the oscillation probability parameters.



Neutrino Oscillation Parameters and Energy of Pions

Proton Beam Target Materials:

Target materials are categorized based on their atomic numbers: High-atomic (High-Z) and Low-atomic (Low-Z) materials. "Pion showers" can be produced within a high-Z target. When a proton beam hits high-Z target, protons can trigger a series of interactions within the target, each of which can produce more than one pion at a time. One consequence of these interactions is that these targets will only produce low energy pions. Typical high-Z materials include Tantalum, Mercury, Tungsten. Mercury is currently being studied by Neutrino Factories (Kahn et al, 2001). Although mercury has a high pion production efficiency, it is a special material because of its liquid state. It doesn't suffer energy deposition, but the shock wave caused by proton beams can damage the target container (Lettry et al, 2008). Tungsten is being studied for the CERN neutrino experiment. A tungsten powder target is proposed to reduce its energy deposition. Most high-Z materials have low energy deposition resistance (McDonald et al, 1998). In fact, solid, low-Z materials could be used with proton energy beams not exceeding 2MW while high-Z materials could not withstand even the lowest energy beams (>1 MW) (Berk et al, 2005). However, low-Z materials are believed to have low pion production (Weng et al,2006). Kirk et al (2006) found that various forms of graphite may increase target longevity but cannot help to increase pions in a certain energy range. ATJ Graphite was studied because of its low coefficient of thermal expansion and high mechanical strength. It also suffered five times less strain than other graphites. Simos et al have done a series studies on the property of compound materials. Super Invar and Boron-Nitride are being considered for LBNE. Cubic-Boron-Nitride is composed of 50% boron and nitrogen. It can produce more pions because of its higher density. The low coefficient of thermal expansion makes Super Invar, which consists of 62% of Fe, 32% of NI and 5% of Co and has a property similar to high-Z materials, an attractive candidate as a shield material (Simons et al, 2003). This study addressed different target materials for the first time for LBNE. It also noticed that there is always a tradeoff between high-Z and low-Z materials.

Proton Energy Beam:

Kirk et al (2006) studied the relation between neutrino flux and the proton energy spectrum. He found that a proton beam with 30GeV or more could provide enough neutrino flux for neutrino oscillation experiments. High energy proton beams have larger interaction cross section and increased pion production. In addition, high energy proton beams don't scatter significantly and the relative decay kinematics ensure that neutrinos are emitted in the direction of the proton beam. High energy proton beams also tend to produce high energy pions.(Engel et al,2001). Two challenges are met to create a 120GeV-150GeV proton beam. The first one is related to the material of the target (Simos, 2004). The second one is that optimizing the parameters of the beam has a direct effect on the survivability of the target. Cervera at al, (2000) also suggests not to use beam energies greater than 150GeV.

For low energy protons, direct production of charged pions plays a main role (Engel et al, 2003). It is believed that the low energy spectrum of pions per proton is independent of beam energy (Mokhkv et al, 2001). Bershears has found that when low energy protons hit the nuclei, pions would carry part of the nuclei energy, which complicates the measurement of pion energy. Simulations have shown that the best proton beam energy is around 30GeV for the highest efficiency of pion production. (Brooks, 2005).

Interaction Length:

Interaction length is the length that is required to reduce the number of relativistic charged particles by a factor 1/e .

The average number of protons left after interactions inside the target is:

$$N(L) = N_0 e^{\frac{-L}{L_{\text{int}}}}$$

where Lint is the interaction length of a target material, L is the actual target length and No is the original number of protons. (Tovey et al, 2008).

If a target has two interaction lengths, 86.5% of protons disappear through nuclei collisions. The function implies that the longer the target, the more protons interact and disappear. However, the survival chance for pions decreases with increase of target length. More pions are absorbed before they scatter out of a long target (Kugler et al.,1999). Some solutions to prevent pion absorption are to tilt the target by a small degree or to re-design target shapes (Hassenein et al., 2000). A balance between pion absorption and proton interaction needs to be found to produce the most pions. In addition, a slight change in target length will cause a big difference in designing the focusing horn system, which helps gather pions into the decay tunnel.

Target Radius:

In LBNE, a proton beam with a width of 1.5mm will be applied to hit a target. A target radius that is three time bigger than the radius of the proton beam is desirable because 99.75% of protons can hit the target (Chilton et al,2010). However, other experiments have shown that a target with a smaller radius can improve pion production even though that means a target has to suffer more stress (Skoro, 2009).

Energy Deposition:

After the proton beam hits the target, it will produce a lot of secondary particles which include high energy X rays, and gamma rays. X rays are emitted with neutron capture and inelastic scattering of neutrons and some massive particles due to the material itself (Ginell et al, 1970). All these reactions can cause changes in material structure and density, which affects longevity of a target. High-Z materials, including tantalum and tungsten, have large energy deposition while graphite and other low-Z materials usually have low energy deposition. They also have high radiation resistance and low thermal expansions (Benett et al. , 2002). For proton beam of the same power, the number of protons decreases with the increase of proton energy. In another word, a 30GeV beam is more likely to have more protons react in a target than a 120GeV beam does, thus causing a bigger energy deposition.

2 Engineering Goals:

The engineering goal was to maximize the efficiency to produce pions from 1GeV-10GeV. The hypothesis is if a material has a high atomic number, it should have a high pion production.

3 Methodology:

This experiment used the simulation program FLUKA2008 (Ferrari et al., 2005), (Battistoni et al., 2007). FLUKA is a fully integrated particle physics Monte Carlo simulation package. It has many applications in high energy experimental physics and target designs. Material information, beam energy spectra, interaction length and target shapes were compiled and simulated in FLUKA2008.

Proton Beam Target Materials:

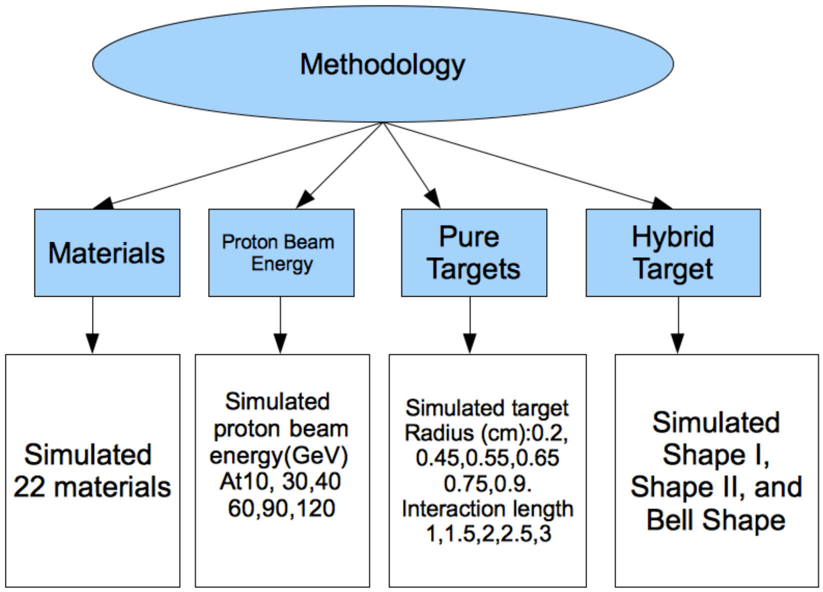
The experiment studied 22 target materials. These materials included:
aluminum, ATJ graphite, beryllium, calcium, chromium, copper, graphite with density of 1.67, graphite with density of 2.1, mercury, iron, lead, manganese, nickel, phosphorous, silicon, sodium, sulfur, tantalum, titanium, tin, and tungsten. This study also tested two compound materials, cubic Boron Nitride and Super Invar. A 120 GeV proton beam and 2 interaction lengths were used as control variable. All targets were cylinders with radius 0.45cm (3 times bigger than proton beam radius). The performance of a material was determined by the number of pions per proton. The top 5 materials, including two high-Z and two low-Z materials, were selected for further study.

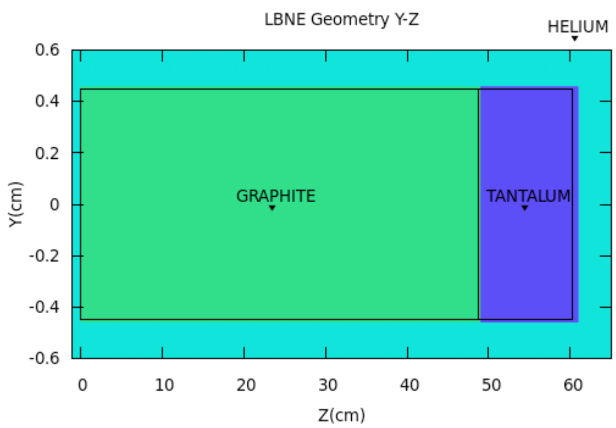
Proton Energy Spectrum:

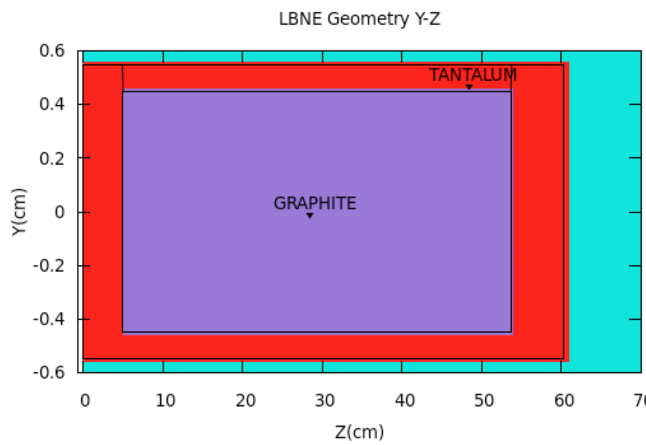
Proton beams were simulated at different energy ranges including 10GeV, 30GeV, 60GeV, 90GeV and 120GeV. This study measured the pion production efficiency (pions/proton/GeV) for different pion energy ranges, assuming all targets were hit by uniform proton beams. The number of pions from 1GeV-10GeV should be maximized while above 10GeV were minimized.

Geometry:

In Geometry, the study was divided into 2 sections. The first part was to optimize a pure material target. The study tested the relationship of interaction length, target radius and pion production efficiencies. 1, 1.5, 2. 2.5 and 3 interaction lengths were simulated. Target radius of 0.2cm, 0.45cm, 0.55cm, 0.65cm, 0.75cm and 0.9cm were tested. The second part was to simulate three different hybrid targets. The first shape, called Target I (Figure 2) was a horizontal compound target. The purpose of this target was to take advantages of both low and high-Z materials and reduce the total energy depositions. A low-Z material was placed in front to buffer the high radiation resistance. Hybrid targets were operated under two different proton beams. A 120GeV proton beam was tested for all selected materials. The other proton beam was chosen based on proton energy spectrum study in previous section. Experiment number 0, 1, 2, 3, 4 and 5 had target I (Figure 2) shapes. Target II shape (Figure 3) had a smaller target with 0.45cm radius inside a target of 0.55cm radius. The bigger target was used both as a target material and a shield material. Experiments 6, 7, 8, 9,10 and 11 used the target II shape and 12, 13, 14, 15, 16 and 17 were bell shapes (Figure 4). The first two targets for each shape were a combination of Tantalum and graphite; the second two were BN and Super-Invar and the last two were Super Invar and Tantalum. Target geometry methodology and hybrid target shapes are shown in the following graph:







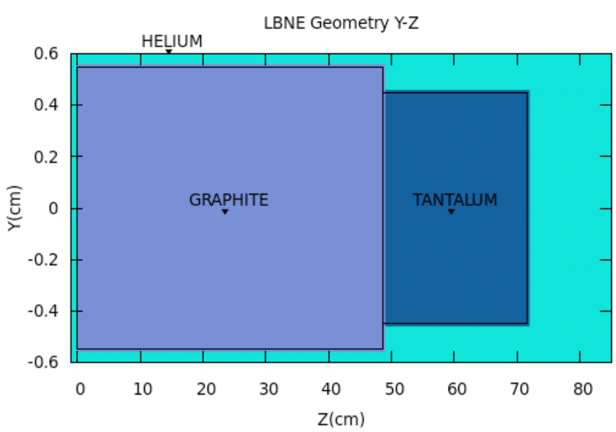


Figure 2,3,4 (clockwise) are hybrid targets Shape I, Target II and Bell Shape

Data Analysis:

The data produced from the FLUKA simulation were analyzed and presented by the data analysis program GNUplot. Two types of final graphs were produced. The first ones were histograms that showed the total amount of pions in different energy ranges while the second types of graph showed the pion production efficiency.

<u>4 Results:</u>

Proton Beam Target Materials:

Materials are arranged based on their atomic number (Z). The graph shows high-Z materials have higher total pion productions than low-Z materials do. Materials with high production or high radiation resistance were selected for further study.

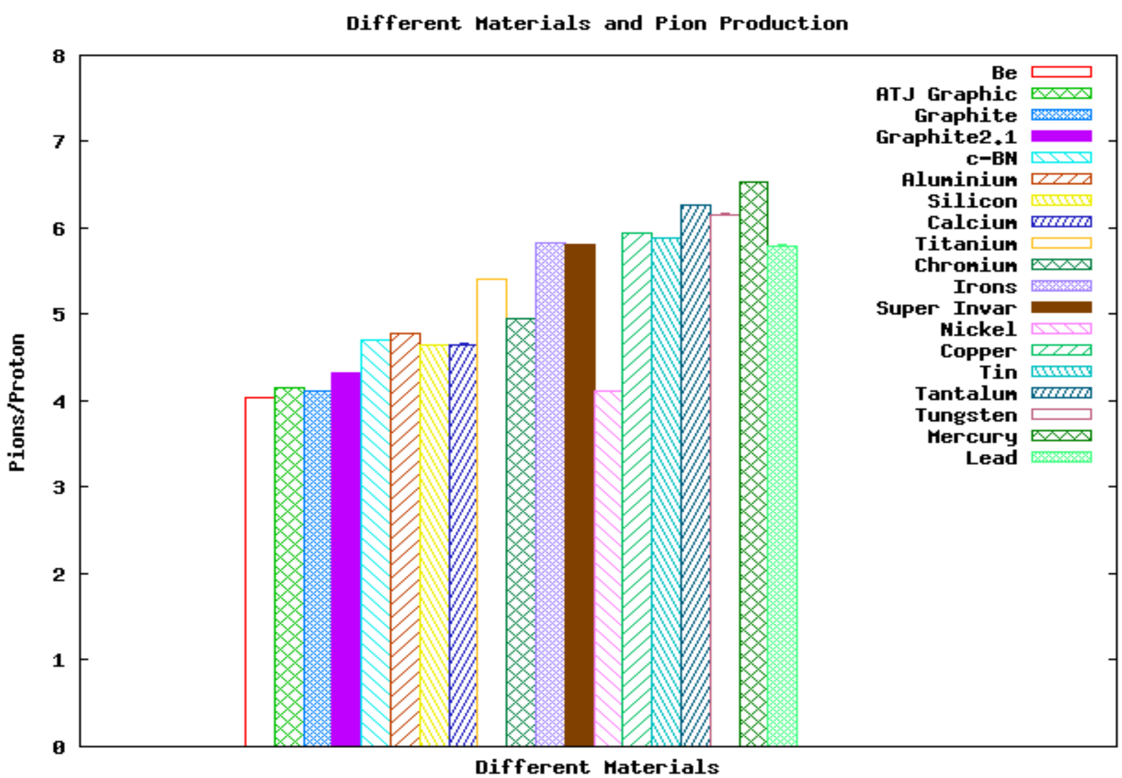


Figure 5 shows the pions per protons that are produced in all energy range with 120GeV proton beam. The x-axis is different materials and y axis is pions/proton.

Proton Beam Energy:

Pion production efficiencies in three pion energy ranges was tested. A 30GeV proton beam is optimal for pions from 1GeV to 6GeV. A 120GeV proton beam has the highest efficiency to produce pions from 6GeV to 10GeV. The study also shows that high-Z materials produce more low energy pions while low-Z materials have a high efficiency to produce high energy pions.

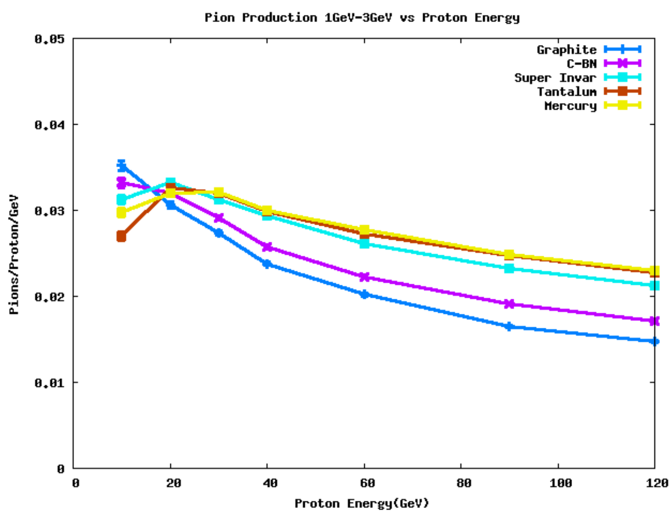
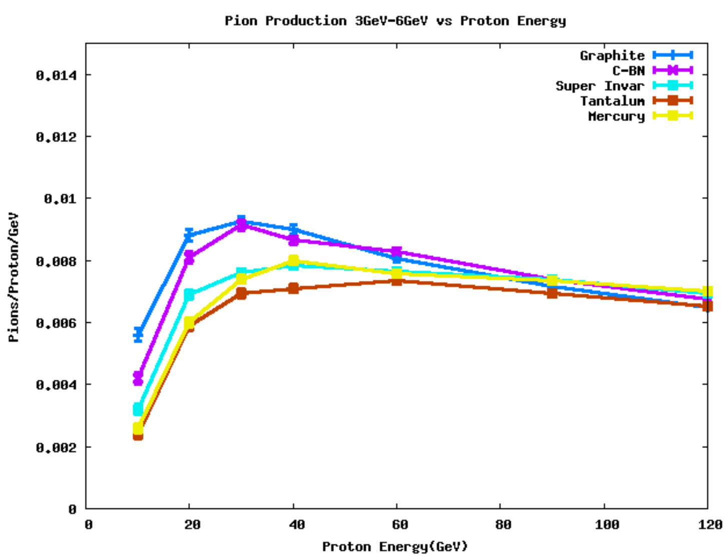


Figure 6 using proton energy plotted against pions/proton/GeV at 1GeV-3GeV



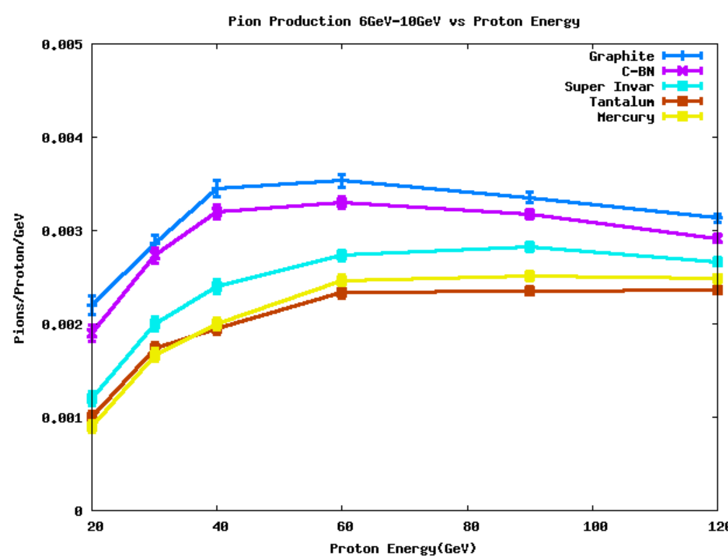


Figure 7 and 8 use proton energy plotted against pion production for pions from 3GeV-6GeV and 6GeV-10GeV

Target Length:
Figures 9, 10, 11 indicate that a long target length helps low energy pion production. However, for pions at 3GeV-6GeV, improvements are not significant after 2.5 interaction lengths.

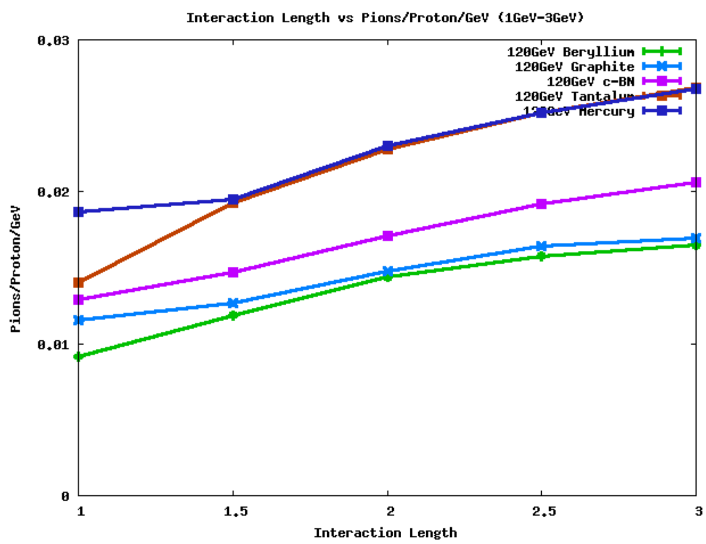
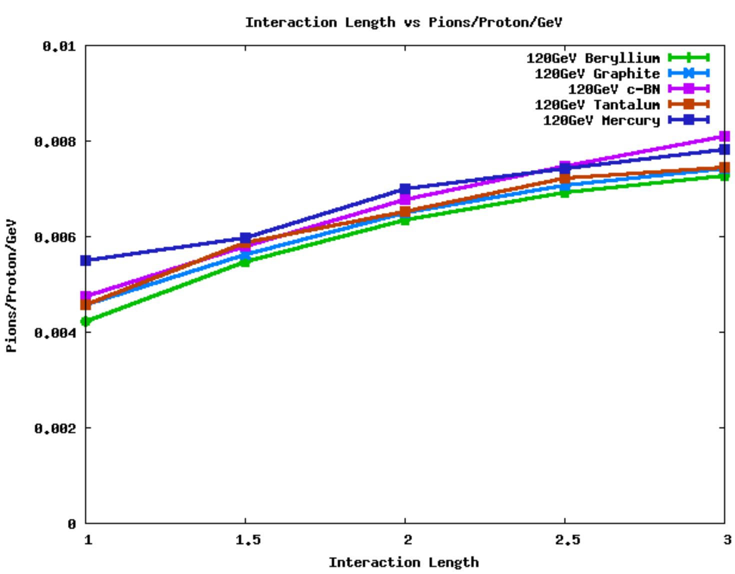
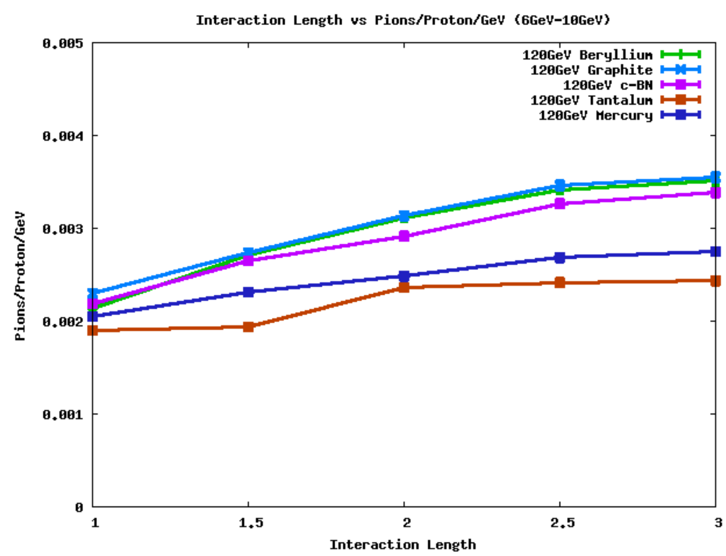


Figure 9,10, 11 (clockwise) use target length plotted against Pions/Proton/GeV at pions energy at 1GeV-3GeV, 3GeV-6GeV, 6GeV-10GeV.





Target Radius:

The study used a proton beam with 0.15cm width. The minimum target radius is 0.2cm while the maximum is 0.9cm. Tantalum targets with radius of 0.45cm have the highest low energy pion efficiency. Super Invar and Graphite with 0.55cm radius produce the median and high energy pions most efficiency.

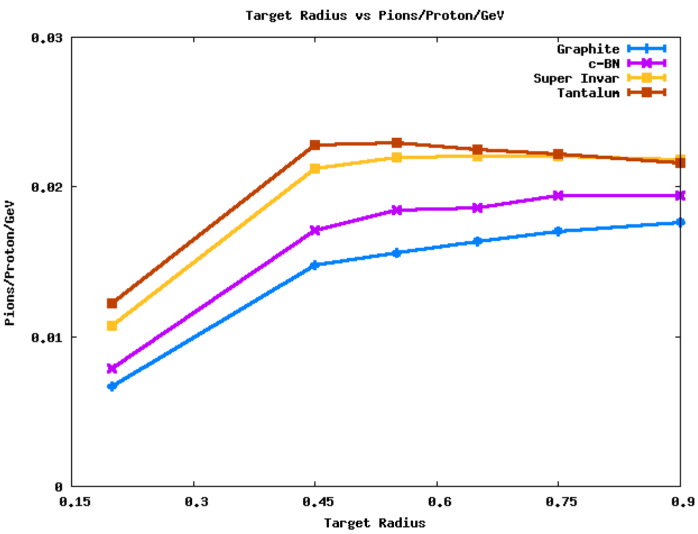
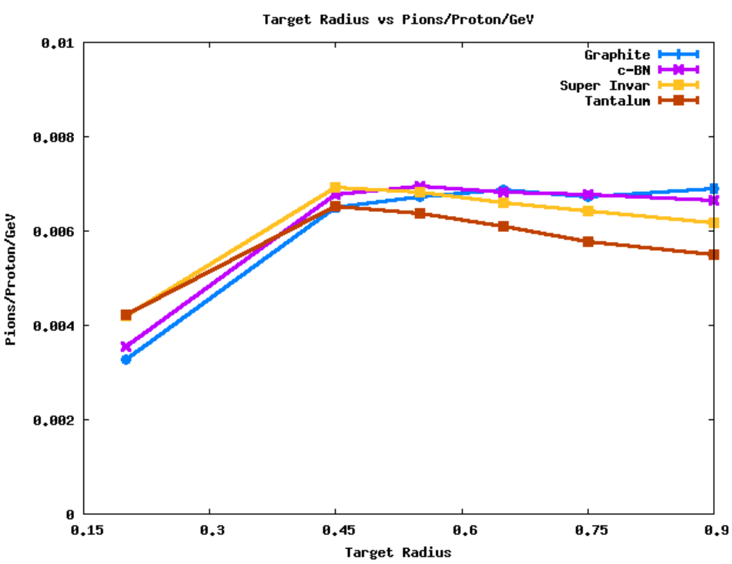
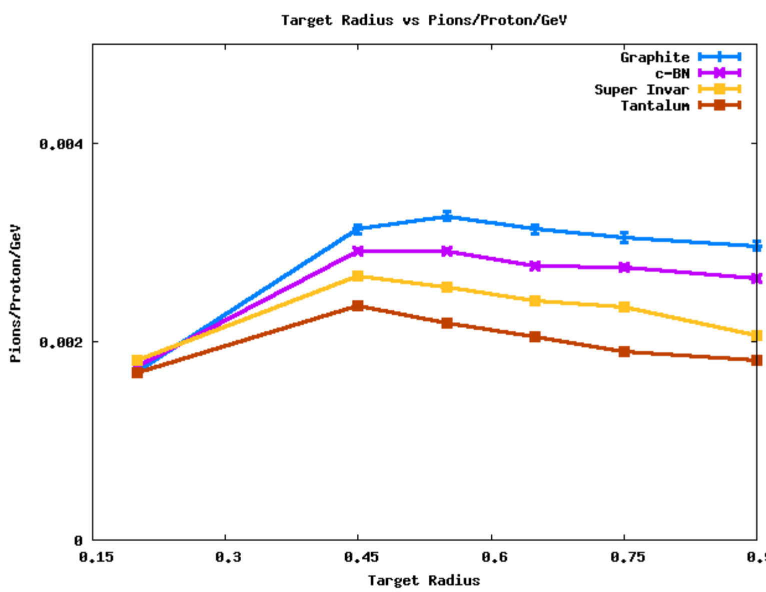


Figure 12, 13, 14 using radius (cm) plots against pions/proton/GeV at 1GeV-3GeV, 3GeV-6GeV, 6GeV-10GeV.





Hybrid targets:

This section applied the results from previous sections. All targets were simulated at 30GeV, which was an optimal beam energy and 120GeV, which was a conventional beam energy. All designs increased the efficiency of low and medium energy pion production. Target I shapes have in general higher production compared to other shapes.

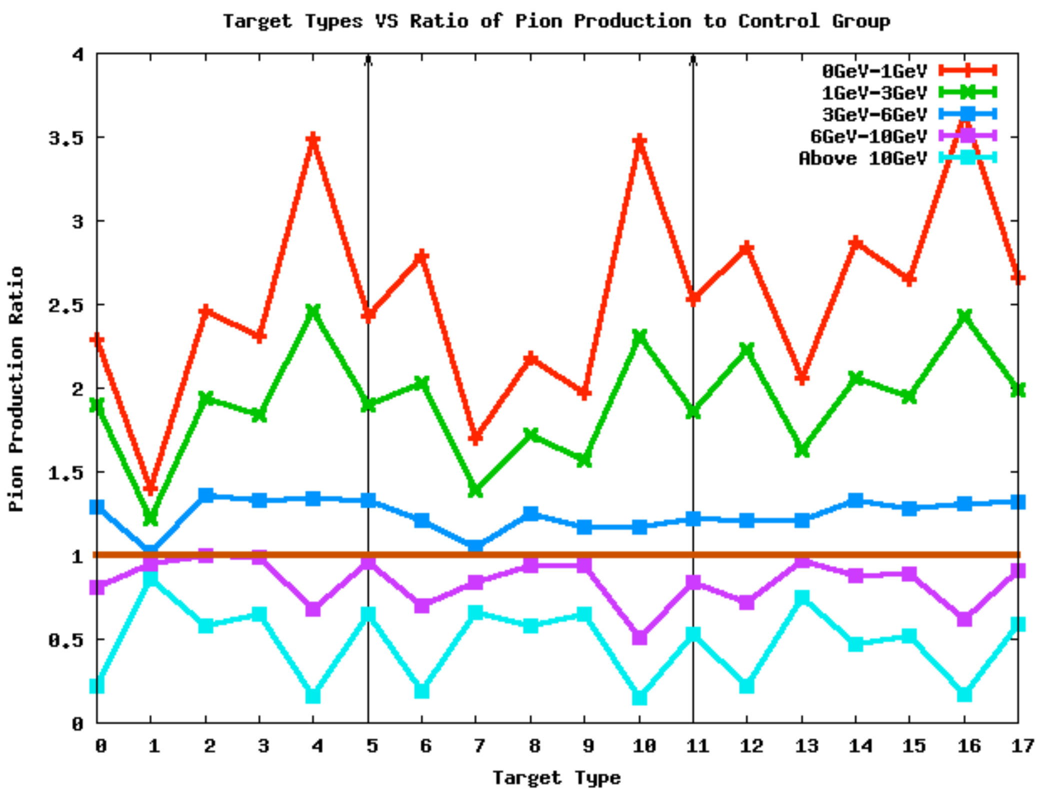


Figure 15 uses different types of target shapes (number from 0-17) plotted against ratio of pion production to control target (Graphite with 2 interaction length). Each vertical line contains the same target shapes. The first section is Target I. The second and third target shapes are Target II and Bell Shapes. The brown horizontal line is a cylinder of graphite at 120GeV. Type 0-17 stand for Target I Tantalum Graphite 30GeV (0), Target I Tantalum Graphite 120GeV (1), Target I BN Invar 90GeV (2), Target I BN Invar 120GeV (3), Target I Invar Tantalum 30GeV (4), Target I Invar Tantalum 120GeV (5), Target II Tantalum Graphite 30GeV (6), Target II Tantalum Graphite 120GeV (7), Target II BN Invar 90GeV (8), Target II BN Invar 120GeV (9), Target II Invar Tantalum 30GeV (10), Target II Invar Tantalum 120GeV (11), Bell Tantalum Graphite 30GeV (12), Bell Tantalum Graphite 120GeV (13), Bell BN Invar 90GeV (14), Bell BN Invar 120GeV (15), Bell Invar Tantalum 30GeV (16), Bell Invar Tantalum 120GeV (17).

Selection Criteria:

The selection is based on the ratio of pion production efficiency to the controlled target, a graphite cylinder target with 2 interactions length and 120GeV proton beam. 1.5 means the new hybrid target pion production efficiency is 150% of the controlled one.

Geometry Selection	
Pion Energy (GeV)	Selection Criteria
1-3	>1.5
3-6	>1.5
6-10	>0.8
10-	<0.5

Energy deposition:

The graphs show the energy deposition from pion and proton interactions (Joules) that targets suffer. With the increase of proton energy, the energy deposition decreases. Graphite targets have the lowest energy deposition. For hybrid targets that have high pion production, their energy depositions are lower than a pure target.

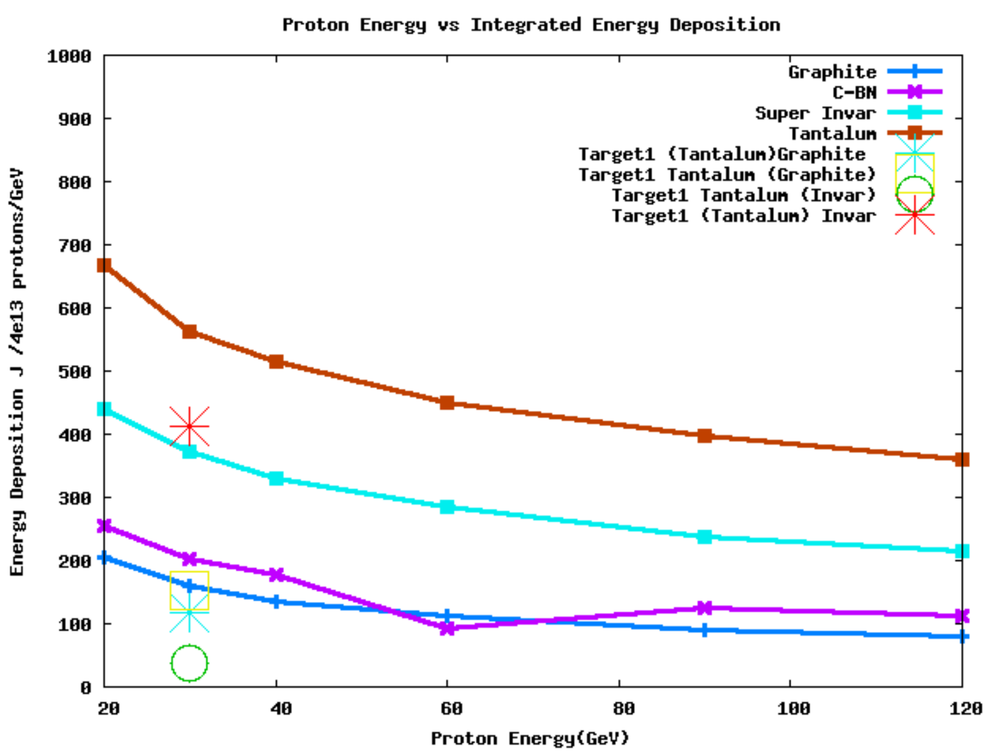


Figure 16 uses proton energy plotted against proton energy deposition (Joules)

5 Discussion:

Target Material Selection:

Figure 5 supports Kahn et al study (2001) that Mercury produces the most pions. The high production of Super Invar suggests it as one of the candidates for target materials. This study also considered Tantalum and Tungsten as target materials for LBNE based on their high efficiencies despite their weak radiation resistance. Figure 5 showed a general trend of increase of pion production with the increase of materials' atomic numbers. The excellent production ability of high-Z materials can be explained by the phenomena of pion shower, where more re-interactions produce more low energy pions when the proton beam has high energy.

Proton Beam Energy:

The proton energy study shows an agreement with Brook's (2005) study that 30GeV is an optimized proton beam energy. At 30GeV, materials have the highest efficiencies to produce pions per GeV from 3GeV-10GeV. Although when the proton beam is 10GeV, targets tend to produce low energy pions most efficiently, it is not a practicable beamline because it fails to produce high energy pions, thus leaving 30GeV as one of the most idealized proton beam energies. Since a 30GeV proton beam produces pions more efficiently than 120GeV does, it is believed that the number of protons is more important than the energy of protons in determining pion production. However, the results contrast with Mokhkv (2002) study that low energy pions are independent from proton beam spectrum. In contrast, materials uniformly show a decrease of efficiencies with the increase of proton beam energy. The difference may be caused by different simulation programs. The study from Mokhkv used Mars 2003 as simulation program, but this study applied FLUKA 2008. Figure 8 shows that 120GeV proton beams have higher high energy pion production efficiencies, which agrees with Engel's study (2001) that high energy proton beams tend to produce high energy pions. Overall, applying a 30GeV proton beam produces more neutrinos at the same beam power and thus improves the accuracy to test one period of neutrino oscillations

Target Length:

For the target length, the study found that 2.5 interaction length has higher median and high energy pion production efficiencies compared to a 2 interaction length target. This result further interprets the proton loss function (Tovey et al, 2008), which states that the longer the target is, the more protons will disappear. It is shown that pion production efficiency is limited by nuclear interactions and the number of protons. The low efficiency of a long target can be caused by the fact that at the end of a target, protons annihilate by other interactions rather than producing pions. The results also support that a long target will absorb pions before they can scatter and be collected (Kulger et al,1999). More studies on nuclear interactions within targets should be done. Though it is suggested to increase an additional 0.5 interaction length on the current target design with 2 interaction lengths, the process is difficult because the target has to be equipped with a new horn system to collect these pions. Before making any modifications, it is important to re-estimate the cost and benefit to increase the target length.

Target Radius:

Former studies show that a target with a radius three times bigger than the radius of its proton beam (Rprotonbeam=0.15cm) can have the best production efficiency. However, this study suggests a Tantalum target with a 0.45cm radius is optimal. A graphite target should have an optimized radius of 0.55cm. This modified result can improve both low pion energy (1GeV-3GeV) and high pion energy (6GeV-10GeV), which also serves as a basis for the following hybrid target designs. More low energy pions, corresponding to 0.4GeV-1.25GeV neutrino, can detect the value of delta-CP easier because delta-CP dominates the neutrino oscillation probability in this range. Pions with energy from 6GeV to 10GeV can provide more accurate data on Δm^2_{31}, which dominates oscillations at high neutrino energy ranges. The different pion production efficiency of different materials may be caused by various nuclear interactions within targets. The further understanding of their interactions needs to be studied, which is also one of the limits in this experiment.

Hybrid Targets:

The study suggests that a hybrid target can increase low and median energy pion production efficiency, which agrees with the original hypothesis. Bell shapes, which combined optimized radius of different materials, fail to confirm the results from the previous sections that high-Z targets and low-Z targets have their highest efficiencies at 0.45cm and 0.55cm radius. The combination of two optimized radius doesn't result in the highest efficiency. It may be explained that the changing of target shapes causes the difference in nuclear interaction within the target, which still needs to be proved. The study of hybrid targets still needs to be tested through real experiments. However, an increase of 150% in low energy pion production is impressive. In addition, the improvement promises a bright future for hybrid target designs, which will drive more mature studies to eventually apply hybrid targets in real experiments.

Energy Deposition:

The energy deposition study confirms Siever (2001) study that with the increase of proton beam energy, the energy deposition decreases. This may be explained by the fact that a target under 30GeV experiences more interactions and thus causes more damage. Tantalum targets suffer the worse energy deposition because of their high-Z material properties (Siever, 2001). Though low-Z materials don't have good pion productions, Figure 16 supports the Benett et al (2002) study that they have low energy deposition and can have longer working time. This founding reevaluates Graphite importance and supports the current trend to use Graphite as a target material. The study shows an agreement with Simos study that BN has low energy deposition. For hybrid targets, the study shows that Shape I targets have low energy deposition, which highlights their possibilities for future applications.

Summary Table:

The following table summaries the target design results from the study. The table shows the optimized target materials, proton beam energy, target length, target radius and hybrid target shape. For each different pion energy ranges, bold font optimized targets show the greatest improvement. The four best optimized target combination are: 0.45cm Tantalum cylinder target, Target I Invar Tantalum 30GeV and graphite target with 40GeV proton beam.

Target Design Results					
Pion Production efficiency (Pions/ Proton/GeV)	0GeV-1GeV	1GeV-3GeV	3GeV-6GeV	6GeV-10GeV	10GeV- (Lease Production)
Materials (120GeV) : pions in all energy range	Mercury, Tantalum, Tungsten, Super Invar , Boron Nitride, Graphite 0.0544±1.9e-4, 0.0522±1.86e-4, 0.05133±1.84e-4,0.04835±1.79e-4, 0.03915±1.6e-4,0.0291±1.39e-4				
Graphite, 120GeV, 0.45cm, 2 interaction length (control group)	0.0098±8.08e-5	0.0147±9.89e-5	0.0065±6.583e-5	0.00313±4.568e-5	0.00358±4.88e-5
Target Length (120GeV)	2, Tantalum	3, Tantalum	2.5, Tantalum	2.5, Graphite	3, Tantalum
	0.0298±1.4e-4	0.0314± 1.44e-4	0.0074±0.723e-5	0.00313±4.568e-5	0.00175 ±3.415e-5
	204.08%	113.60%	13.80%	0%	-51.11%
Target Radius (120GeV)	**0.45cm, Tantalum**	0.45cm, Tantalum	0.55cm, Super Invar	0.55cm, Graphite	0.9cm, Tantalum
	0.0403±1.64e-4	0.0228±1.23e-4	0.00695±6.8e-5	0.00325±4.65e-5	0.0016±3.26e-5
	311.22%	55.10%	6.92%	3.83%	-55.30%
Proton Energy Beam	10GeV, Mercury	30GeV, Mercury	**30GeV, Graphite**	**40GeV, Graphite**	<30GeV Tantalum
	0.038±5.5e-4	0.03204±2.9e-4	0.00926±1.57e-4	0.00345±8.30e-5	0
	287.75%	117.90%	42.46%	10.22%	0%

Hybrid Targets	Bell Invar Tantalum 30GeV	**Target I Invar Tantalum 30GeV**	Bell Invar BN 90GeV	Bell tantalum Graphite 120GeV	**Target I Invar Tantalum 30GeV**
	0.0367±3.128e-4	0.03633±3.1126e-4	0.0086±8.74e-5	0.0027±4.24e-5	0.0006±4e-5
	274.44%	147.14%	32.30%	-13.73%	-83.24%

6 Conclusion:

Parameters such as target material, proton beam energy, target geometry (target length, target radius) and hybrid targets were simulated and presented in this paper. Low and medium energy pion productions have been increased significantly through the use of a hybrid target. The improvement can be used for LBNE to produce more neutrinos with the same expense. Though the study is still in its early stage, it shows a promising future for hybrid targets. In order to use the optimized targets in the LBNE project, more detailed studies should be conducted. For target materials, optimized materials can be modified by changing their density or state (solid to powder). After obtaining a 30GeV proton beam, the study on how to apply the beam to the target, such as various angles and frequency should be tested. The effect on neutrino detection background and sensitivity caused by various proton beams has to be studied. To fully understand the pion production efficiency of hybrid targets, interactions inside the targets should be studied. Based on these results, modification for hybrid targets, such as the arrangement of different materials, needs to be conducted.

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