Abstract

Proton, electron, and heavy ion collisions have produced a wealth of information about subatomic particles. Historically, high energy physics (HEP) has pushed the energy frontier. Limitations of the proton and electron beams may make the muon beam a good candidate for the future of HEP. The large hurdle for the muon beam is cooling. Conventional cooling methods are too slow for the muon beam due to its short lifetime, so new methods must be used. Ionization and frictional cooling are the alternatives because they have the potential to cool the beam in adequate time. Frictional cooling, the process under study at Nevis, will be tested initially on a proton beam.

Particle Colliders

Electron

Electron-positron (lepton) collisions are much cleaner than Proton-anti-proton (hadron) collisions. The highest energy lepton only collision seen so far was at LEP in 2000 where a 104.5 GeV e+ and e- beam was collided, resulting in a 209 GeV center-of-mass energy collision.[1] The quest for higher center-of-mass energy electron collisions continues, but is inherently hindered in circular accelerators by the effects of synchrotron radiation. Synchrotron radiation is the release of energy by charged particles on an orbital or curved path, a path induced in a circular accelerator by the magnetic field. A charged particle's radiation due to transverse acceleration scales with the inverse of the mass to the fourth power.

$$P = \left(\frac{2c}{3}\right) e^2 b^4 \left(\frac{1}{r^2}\right) \left(\frac{E}{mc^2}\right)^4$$

Equation for the radiated power of a charged particle in a relativistic, accelerated orbit.

The electron beam requires a great deal more power to sustain the beam's energy than the heavier proton. This is because the electron beam loses energy at a rate 2000^4 times more quickly than the proton. Therefore, the next energy increase for electron collisions will most likely come from the NLC, a 20 mile long linear accelerator that's in its conceptual phase.[2] Linear accelerators eliminate the synchrotron radiation issue, but they are limited in the amount of linear gradient they can achieve. Technological limits do not limit the beam energy; financial limits impose space and accelerating chamber number restrictions.

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[1] http://sl.web.cern.ch/SL/opnews/Lep/lep00.html

[2] http://www-project.slac.stanford.edu/nlc/home.html

Proton

For the proton beam, almost 2000 times more massive than the electron beam, the effects of synchrotron radiation at high energies are negligible. Proton's can therefore take advantage of the circular accelerator to higher energies and attain extremely high energy collisions. CERN's LHC hopes to reach 7 TeV proton beams by 2005, with a 14 TeV center-of-mass energy collision.[3] The energies attainable for a proton beam in a circular accelerator are in fact so high that there is a struggle to produce sufficiently powerful magnets.[4] However, because a proton is not a point particle, not all the energy goes into the hard scatter. Only one tenth to one seventh of the energy in a hadron beam is used in the desirable parton-parton collision. The valence quarks only carry a fraction of the momentum of the hadron beam, yielding 1.5 to 2.3 TeV center-of-mass energies. [5] Another drawback of the hadron collisions are the less clean environments than those of the lepton collisions. This is due to the excess background from the breakup of spectator particles.

There are two problems and two solutions, but neither is paired to annihilate both problems in one particle. The best solution would be a particle that was more massive than the electron, so it would be negligibly affected by synchrotron radiation, but remain a point particle.

Muon

The muon is 200 times more massive than the electron and is a point particle, thus yielding cleaner collisions than protons with less energy loss due to synchrotron radiation than electrons when accelerated. With a muon collider we could push the energy frontier, while using less power and space than electron and proton colliders require. The muon collider is the ideal particle for Higgs studies, as the probability for Higgs production goes with the mass of the lepton squared. Another great benefit is the production of neutrinos as a by-product of the muon beam, providing a convenient source for further neutrino study. However, there are a number of problems facing the use of muons that must be addressed. Where will the muons come from? How will they be focused into a beam? Perhaps most challenging: how can muons be used if their mean life is 2.2 microseconds before decaying into pions?

Muons are like heavy electrons because they share many characteristics with electrons, such as spin, charge, and behavior during interactions, but they are 200 times the mass of the electron. High energy cosmic rays are mostly composed of protons that produce high-energy pions when they collide with gas in the atmosphere. These high-energy pions in

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[3] http://prst-ab.aps.org/pdf/PRSTAB/v2/i8/e081001
http://lhc-new-homepage.web.cern.ch/lhc-new-homepage/

[4] http://lhc.web.cern.ch/lhc/general/magnets.htm

[5] http://prst-ab.aps.org/pdf/PRSTAB/v2/i8/e081001

turn decay into high-energy muons, antimuons, and neutrinos.[6] The method to get muons for collisions is modeled after this phenomenon. While we can't use muons that decayed from cosmic rays, we can make pion beams from impinging a proton beam on a target, and those pion beams will then decay into muons. However, the resultant beam occupies a large phase space that is too large for collision in an accelerator by a factor of 10^6. This phase volume must be reduced for a muon collider to be feasible.[7]

Phase space is the size of the beam not only in physical space, but also in momentum space. Phase space is six-dimensional, determining the location and momentum of particles in four-dimensional space-time.[8]

$$e_{6D} = s(x)s(P_x)s(y)s(P_y)s(z)s(P_z)$$

Equation for Phase Space

Cooling

A reduction of the phase volume is called cooling a beam. This entails the reduction of transverse-momentum and a decrease in the energy spread. Historically, beams have utilized stochastic cooling or electron cooling. The muon lifetime is 2 microseconds, so the cooling must take place within that amount of time. Stochastic and electron cooling are too slow to work on a muon beam.[9] A new method of cooling is called for to chill the muons, and two proposals have been put forward: ionization and frictional cooling.

Ionization

Ionization cooling entails passing the beam through an absorber thus reducing the transverse- and longitudinal-momentum. A muon beam is a good candidate for this method because of its low interaction with matter. The cooling cavities consist of solenoids and focus the beam, Hydrogen absorbers to reduce transverse energy spread, and RF cavities to re-accelerate the particle.[10] The longitudinal-momentum would be restored in this accelerating region. This scheme requires beam energies of hundreds of MeV. The energy rate loss at these high levels is not ideal because higher energy particles lose energy more quickly than lower energy particles (see energy rate loss diagram below).

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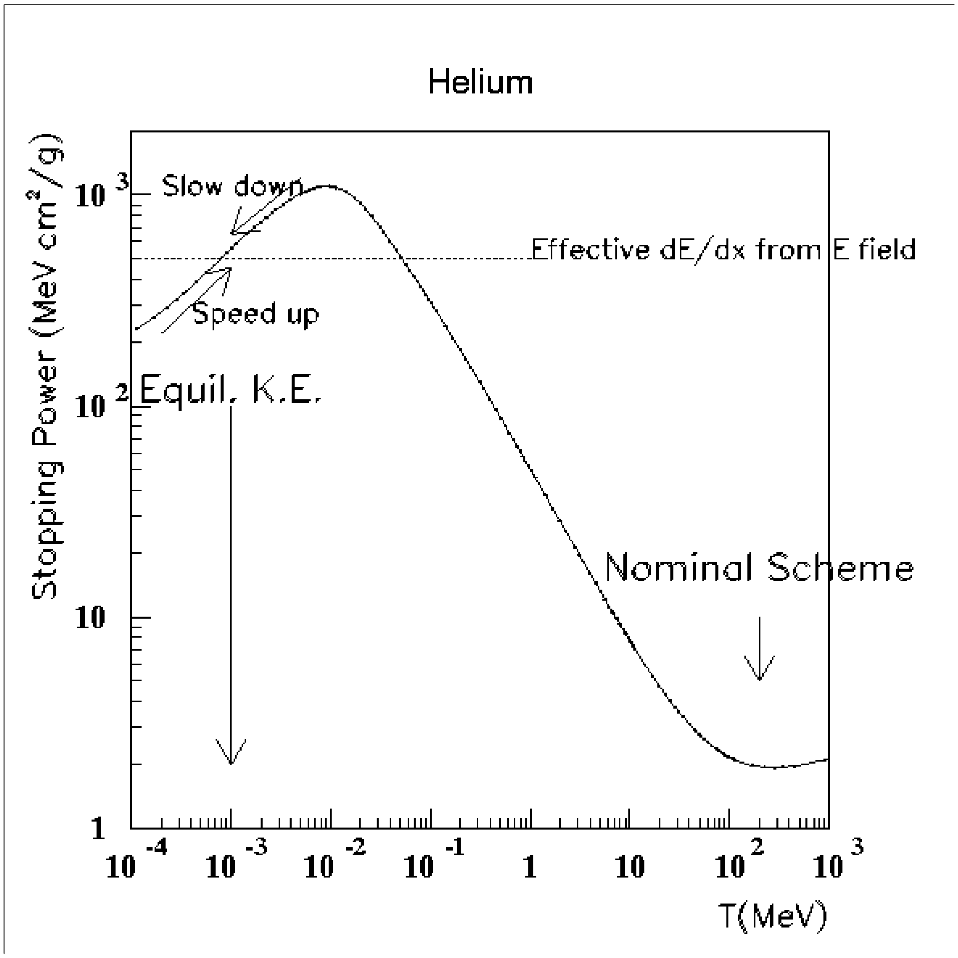
[6] http://www2.slac.stanford.edu/vvc/cosmicrays/cratmos.html

[7] http://prst-ab.aps.org/pdf/PRSTAB/v2/i8/e081001 p.2

[8] http://www.virtualchaos.org/science/un-phase.html

[9] http://linac96.web.cern.ch/Linac96/Proceedings/Friday/FR101/Paper.html

[10] http://fnalpubs.fnal.gov/archive/1998/conf/Conf-98-136.pdf
http://proj-bdl-nice.web.cern.ch/proj-bdl-nice/cool/coolingtest-6-8-2001.doc



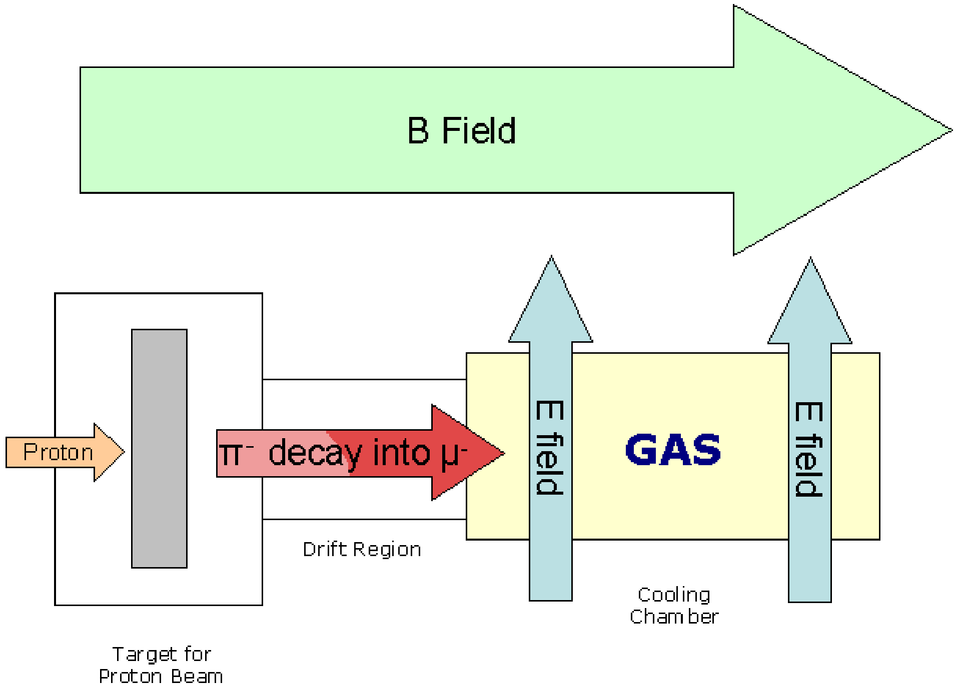
Energy rate loss diagram

So far, reduction factors of only 100 have been achieved via ionization cooling. This is far from the factor of 10^6 required to collide the muon beam.

Frictional

Frictional cooling is another alternative. It is done below the ionization peak and takes advantage of the high energy loss rate at those low kinetic energies. In this region an E field is applied, so when in combination with a B field, creates an equilibrium situation whereby the energy spread narrows to almost zero. This narrow spread is independent of how wide the energy spread was in its initial condition.

Muons enter the cooling cell (diagram below). The B field confines the particles to process around the magnetic field lines. The gas simply slows the particles down, reducing the impact that the B field can have on them, allowing them to exit the chamber once the transverse momentum is negligible.



Frictional Cooling System

This system is successful because it relies on the Lorentz force equation.

$$F = q(E + v \times B)$$

Lorentz force equation

When ? goes to zero because of energy reducing inelastic collisions with the gas, the E field will be the dominant contributor to force, and will pull the muon out of the chamber. When the E field moves the muon, this will create a velocity and a force from the B field. The v will then be subdued via inelastic collisions, thus enabling the E field to be the dominant contributor to the force again. The muon will have achieved an equilibrium condition with a narrow energy spread when it exits the system, regardless of its initial condition, and the phase space will be reduced. [11]

Summer Activities

At NEVIS this summer, the frictional cooling of a muon beam was our primary interest. This is a preliminary stage, so various triggering devices

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[11] http://pubweb.bnl.gov/people/bking/mucoll/papers/Caldwell.PDF

and detectors that will be used to verify if the beam has been cooled were investigated. The plan is to test the frictional cooling principle on a proton beam. Our triggering devices couldn't be tested with a proton beam readily, so we used alpha and beta sources.

Radioactive Sources

Radionuclides are unstable nuclides that are radioactive. The instability of a nuclide depends on the ratio between number of protons and neutrons. Radionuclides emit three kinds of radiation: alpha, beta, and gamma.[12] A beta source has excess neutrons, and ejects an electron from inside the nucleus when a neutron decays into a proton. Our beta source is Strontium-90 with a 10 µC strength (a micro-curie is roughly 37,000 decays per second) and a mean energy of 200 keV and a maximum of 595 keV. An alpha source ejects large subatomic alpha particles, consisting of two protons and two neutrons. Our alpha source is Americium-241 with a 5 µC strength and a decay energy of 5.6 MeV.[13] The alpha has the benefit of higher decay energy than the beta, but has a smaller range in material. In addition to its lower rate, the alpha does not travel great distances. This is similar to the behavior of the proton, so the alpha best emulates the particle we will test our detectors on.

Detectors

The detectors we investigated were microchannel plates (MCP), a silicon detector, and scintillators attached to photomultiplier tubes (PMT). The goal was to set-up a double-trigger system in order to measure a particles time-of-flight. The object was to detect non-random coincidence of particles triggering on two detectors that were aligned along the particle path.

Scintillators

Scintillators give off light when charged particles pass through them. When attached to a PMT (PMTs convert photons into an electrical signal and then amplifies the signals) the generated signal can be triggered on to produce a rate. Scintillators are generally made of plastic with small elements that excite easily and decay, quickly in the release of photons.[14] We used a Bicron® organic BCF-12 blue emitting scintillator with a polystyrene-based core and a layer of PolyMethylMethaAcrylate cladding.[15] These scintillators are manufactured expressly for alpha, beta, and charged particle detection, which serve our purposes ideally.

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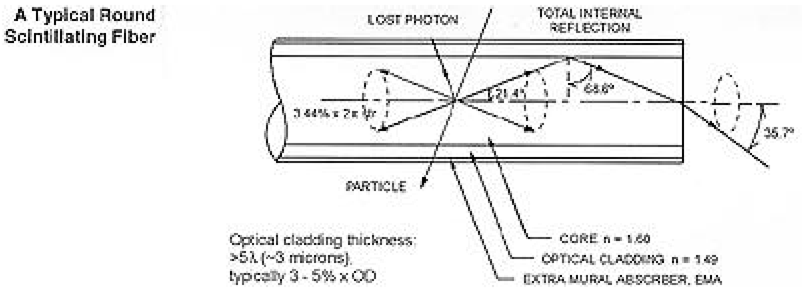
[12] http://www.epa.gov/radiation/understand/beta.htm

[13] http://www2.bnl.gov/ton/

[14] http://www2.slac.stanford.edu/vvc/applications/phototubes.html

[15] http://www.bicron.com/standscintillating.htm



Schematic of scintillator from Bicron®

The low stopping energy of the alpha compelled us to reduce the thickness of the scintillator. This was to ensure that the particle would trigger on the scintillator and retain enough energy to arrive at the second detector and trigger there as well. The alpha is similar in stopping energy to the proton, so this precaution was essential for when these triggers were to be used on the proton beam. The machine shop removed the PMMA cladding from the scintillator and drilled a hole that left a depth of only 200 microns. The hole had a 3mm diameter and the scintillator had a 5mm square width. The removal of the cladding most likely increased the angle of total internal reflection, thus making it easier for photons to refract and escape without being measured by the PMT.

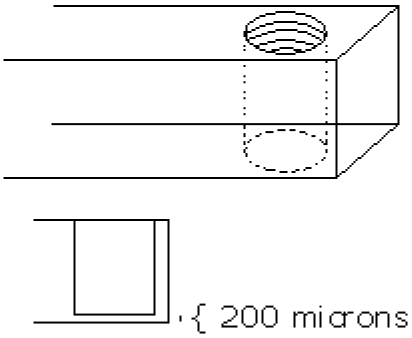
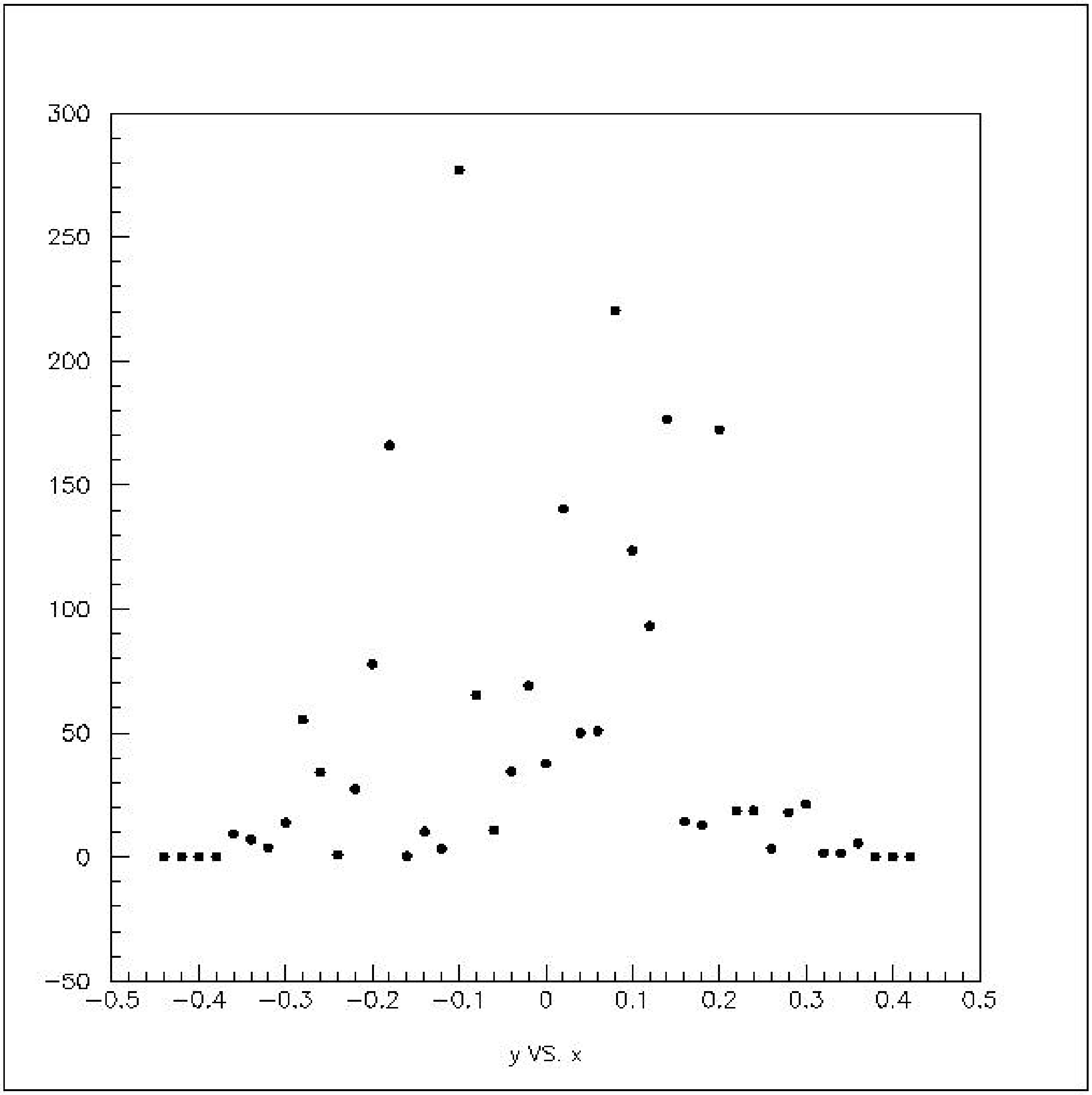


Diagram of the drilled scintillator.

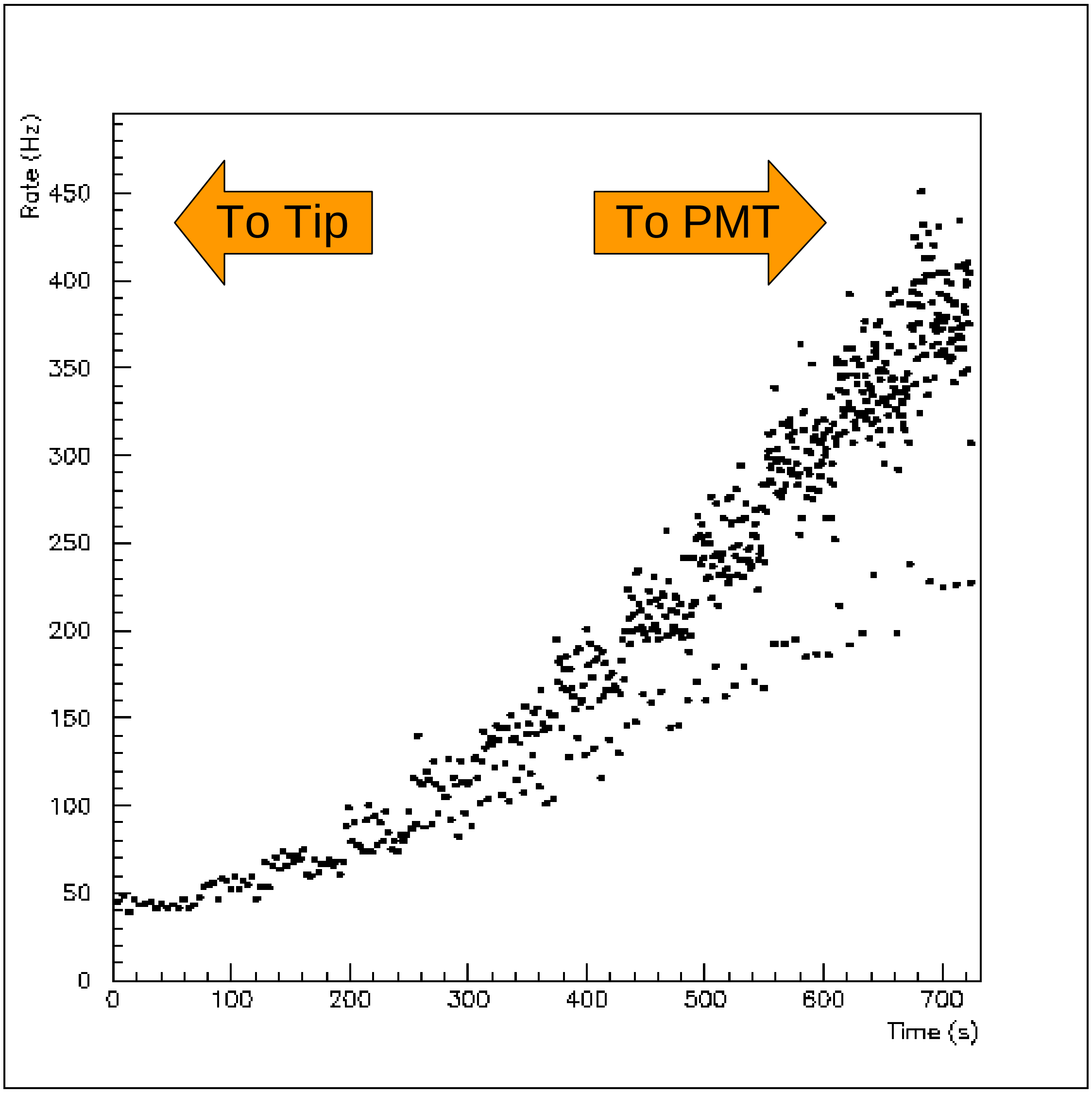
A collimator was used to direct the radiation towards the hole to reduce background caused by trigger from non-hole scintillation.

I wrote a program that projected what the expected trigger rate would be based on the collimator height, radius, and distance from the scintillator. This program was adapted to show how this rate changed when the source was scanned across the scintillator. The diagram below illustrates that rate change as a function of position. This helped determine the ideal dimensions for the collimator.



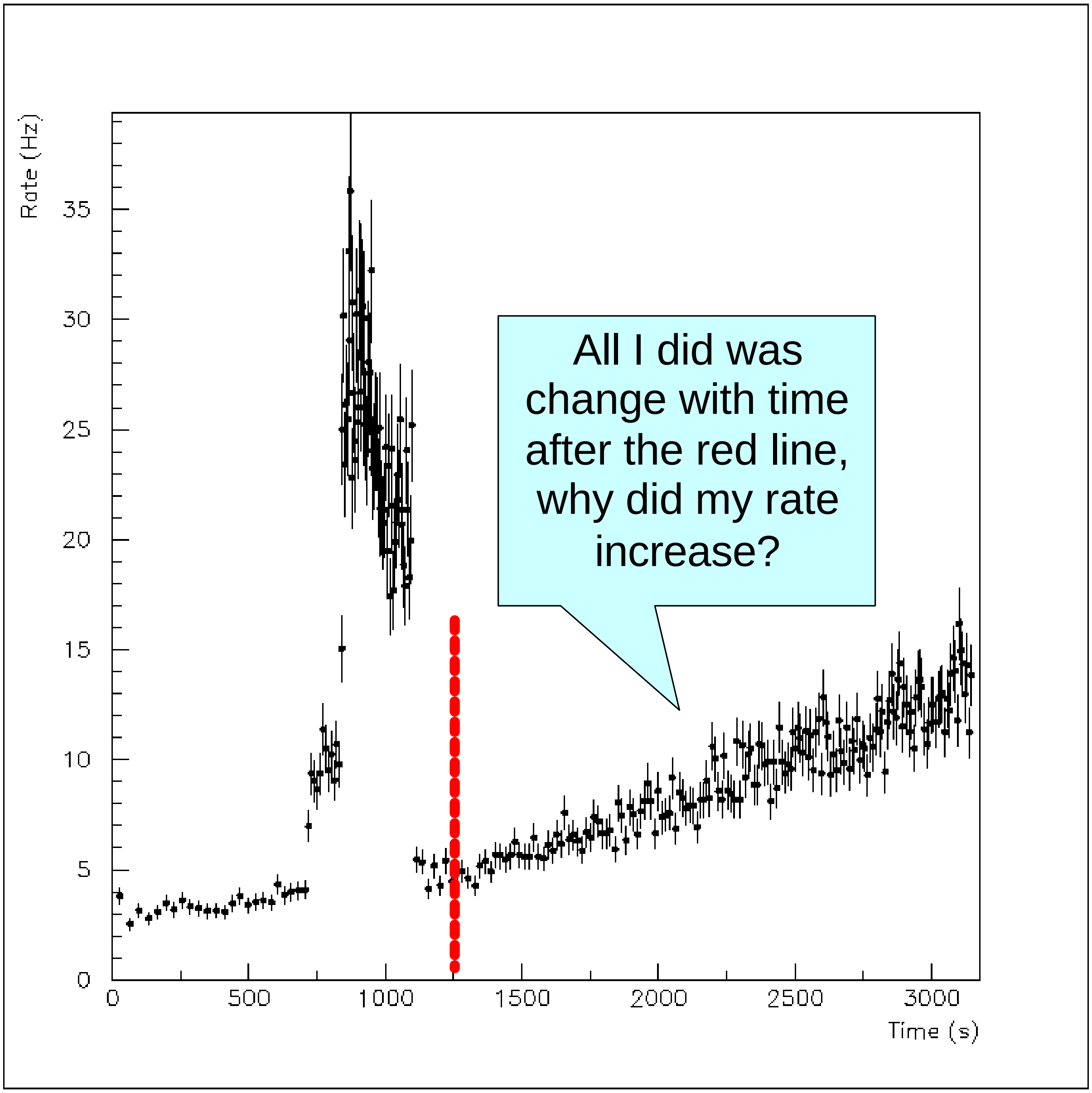
Scanning source across scintillator.
x-axis: position (cm) y-axis: rate (Hz)
Beta source with .25 cm diameter collimator
Source 1.45 cm from target, collimator 1.3 cm tall

Despite great potential, the scintillating stick did not prove to be a useful triggering device. This was because of a high attenuation length. We found that when a source was scanned at the location of our shallow section on the stick, it was so great a distance from the PMT that the rate did not rise above background. Although the stick was shortened, increasing the rate at the shallow point, the rate changed dramatically with very small changes in distance from the PMT, smaller even than the width of the collimator or the hole's diameter.



Rate falloff diagram

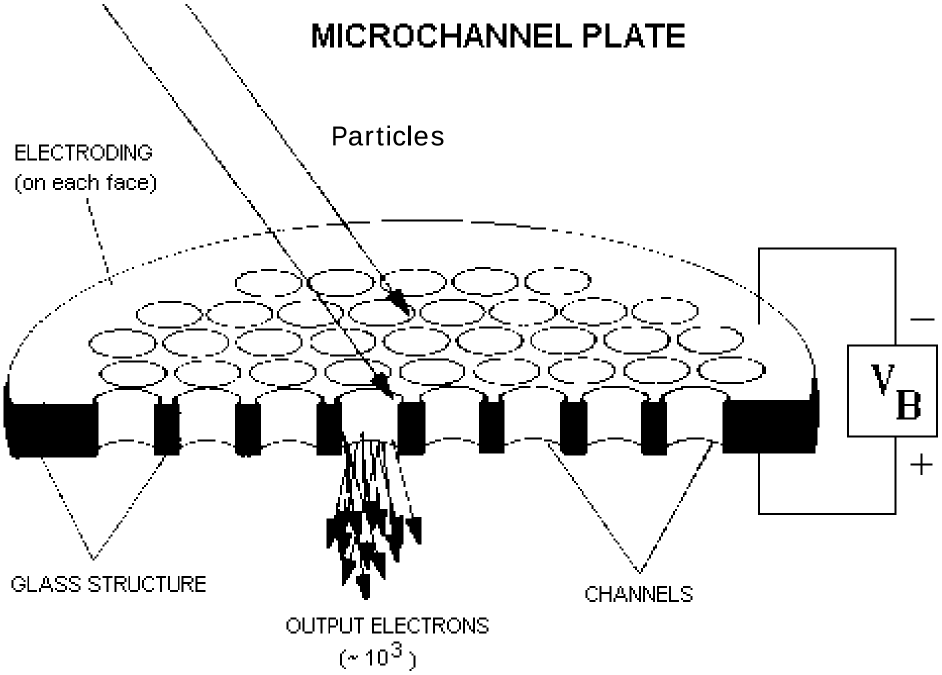
Another problem with the PMT scintillator set-up was an increase in rate with time when all variables were held constant. It was discovered that there were two culprits for this. First, there was a faulty power supply that increased its output voltage with time, thus increasing the voltage applied to the PMT with time. The second culprit was the heating up of the PMT in vacuum. The vacuum was essential in order to increase the distance the alpha could travel. The solution for this was to place the PMT in a heat sink. Our heat sink was a large piece of aluminum with a great deal of surface area that was fit around the PMT like a glove, and helped dissipate the heat with its large surface area. A new power supply and the heat sink eliminated the rate increase with time.



Rate increase diagram

MCP

Another triggering device that was used to detect particles in the double trigger system was a microchannel plate (MCP). An MCP is like many small PMTs on a grid with small distances between them. The walls of the MCP tubes are clad with lead oxide. Alphas and protons are ideal for MCPs because they do not penetrate deeply before triggering the release of secondary electrons from the clad tubes. We yield a full gain of the MCP with these particles because of their short penetration distance. Electrons can penetrate the plates entirely, never triggering a cascade of secondary electrons, reducing the signal. Since the tubes are so small and segregated from one another, the MCP can project the position of the particles entry to the plate. For our purposes, we were only concerned with the rate, so the location of the signal on the plate was unimportant. Electrons, ionized particles, and high energy photons (X-rays and UV) can be detected by MCPs.[16] These particles enter one of the channels, and are accelerated through the channel by a bias voltage that is applied across the plate (see following diagram). The amplification occurs when the particles hit the walls of the channel during their journey.



The walls emit electrons when hit. The precise amplitude gain varies based on the bias voltage and the plate. Our plate had a gain of 10^4 to 10^5 with a bias voltage of 1000V. However, our set-up had two plates aligned in a chevron pattern and doubled to 2000V across both plates, thus making the

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[16] http://www.proxitronic.de/prod/omcp/eos.htm#MCP%20Electron%20Multiplication

total gain 10^8 to 10^{10}. With these amplifications, our signal was very easy to observe when present. However, the plates are very delicate. The surface can be easily cracked and tarnished, and therefore cause shorts on the plate.

Silicon

The final detector that we investigated was a Silicon detector. They are not commonly produced as thinly as we had them made, partially because it is very difficult to guarantee uniformity in thickness across the surface.[17] The non-uniformity on the order of thickness we obtained (15 µm) is ±0.5 µm. That is a 3% variation in energy depletion of the particle being detected.

Silicon detectors work when a particle interacts with the semi-conducting silicon as it passes through the detector. The particle interacts with valence and conduction band electrons.[18] The excited electrons accumulate charge, and induce a current. Based on an alteration of the current, the detector notes the presence or absence of a particle. The magnitude of the current change can indicate the energy of the particle.

The silicon detector and the MCP are the best detectors for our purposes. However, we have yet to test them together. These detectors will enable us to determine time of flight measurements for a beam. Once we have the time of flight, and knowing the length of the drift region, we will be able to determine the velocity, the momentum, the energy and, should we include a material in the particles path, the energy loss as well. This will enable us to verify if frictional cooling is effective, initially with a proton beam at RARAF, eventually with a muon beam.

Window on Gas Chamber

Low energy protons do not penetrate very deeply, so we must take into consideration the boundaries of the gas cell that will be cooling the beam. If the end walls, or windows, are too thick, the proton beam will lose a great deal of energy during its flight and perhaps not make it to the final detector. Extremely thin windows were selected to be on the ends of the chamber. However, despite the low impact these windows have on the proton beam energy, they make it difficult to keep an amount of helium in the chamber, and a vacuum around the chamber, without a leak. A leak would be further catastrophic because it would be difficult to remove all the helium from the vacuum chamber, and it would be a long time before a low pressure vacuum could be achieved. The situation is further complicated by the fact that it is very difficult to mount the windows (As they are small in diameter as well as depth) on the gas chamber. Our current method is to epoxy the window to washers that will be epoxied to the gas chamber. This method has not yet been tested.

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[17] http://www.ortec-online.com/detectors/chargedparticle/introduction/thickness.htm

[18] http://www.edmundoptics.com/IOD/DisplayProduct.cfm?productid=1305

Energy Loss Program

I edited a program that had been developed to indicate ideal energies and gas chamber densities for the frictional cooling system. I altered it to indicate what the anticipated kinetic energy would be at various positions within the system with varieties of the E field, B field, gas chamber, and window set-up.

It is expected that frictional cooling will be successful. The real mystery that lies ahead for the muon collider is going to come when we look for the capture cross section of the muon. It is not known at the low energies where we plan to operate. If it is too high, we may lose too much of our beam in the process of cooling, and the colliding of muon beams would be practical.