ION CHAMBERS FOR MONITORING THE NUMI BEAM AT FNAL

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Abstract

The Neutrinos at the Main Injector (NuMI) beamline will deliver an intense muon neutrino beam by focusing a beam of mesons into a long evacuated decay volume. The beam must be steered with 1 mrad angular accuracy toward the Soudan Underground Laboratory in northern Minnesota. We have built 4 arrays of ionization chambers to monitor the neutrino beam direction and quality. The arrays are located at 4 stations downstream of the decay volume, and measure the remnant hadron beam and tertiary muons produced along with neutrinos in meson decays.

INTRODUCTION

The NuMI beamline [1,2] at Fermilab will deliver an intense ν_μ beam to the MINOS detectors at FNAL and at the Soudan Laboratory in Minnesota. Additional experiments are foreseen. The primary beam is fast-extracted onto the NuMI production target in 8.56 μsec spills from the 120 GeV FNAL Main Injector. The beam line is designed to accept 4×10^{13} protons/spill. After the graphite target, two toroidal magnets called "horns" [3] sign-select and focus the secondary mesons (pions and kaons) into a 675 m volume evacuated to 1 Torr to reduce pion absorption, where they may decay to muons and neutrinos. The horns and target may be positioned so as to produce a variety of neutrino beam energies [4].

The instrumentation foreseen to ensure the neutrino beam quality on a spill-by-spill basis combines primary, secondary, and tertiary beam measurements. The primary beam direction is monitored by segmented foil secondary emission monitors [5] and by capacitative beam position monitors. Its intensity is measured by a beam current toroid (BCT). Additionally, the NuMI target is electrically isolated, so may be read out as a Budal-type monitor [6] of the primary beam's fraction on target. The above instrumentation measures the quality of the beam reaching the NuMI target.

Instrumentation to monitor the secondary hadron and the tertiary muon+neutrino beam is comprised of four ion chamber arrays, shown in Figure 1. Their purpose is to monitor the integrity of the NuMI target and of the horns which focus the secondary meson beam. The intensity and lateral profile of these beams are measured. Because every muon is produced by the pion decays which produce neutrinos, the muon beam provides a good measure of the focusing quality of the neutrino beam, as can be seen in Figure 2.

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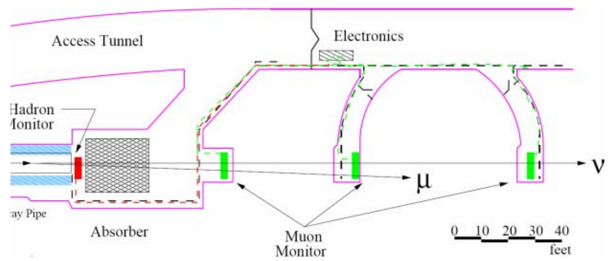

Figure 1: Layout of the secondary and tertiary beam monitors.

The hadron monitor sits downstream of the NuMI decay volume, immediately in front of the beam absorber. It measures approximately 1m×1m, and is segmented to measure the spatial profile of particles arriving at the detector. Monte Carlo calculations indicate that the charged particle rate at the center of the decay pipe is approximately 10^9particles/cm^2/spill, and is dominated by protons which did not interact in the target. The total radiation expected at the hadron monitor is approximately 2×10^9 Rad/year, dominated by protons and neutrons backscattered from the beam absorber.

The hadron monitor is a 7×7 ion chamber array which measures the proton beam profile at the end of the decay volume. The charged particle profile shows a prominent peak at beam center, due to protons which did not react in the NuMI target. During initial beam commissioning, the hadron monitor helps align the primary proton beam to within 3cm/725m=42 μrad precision. This compares well to the 14 μrad provided by the pre-target SEM's, which only periodically are inserted in the beam. During normal beam operations, the stability of this distribution monitors the integrity of the NuMI target, since the lateral profile at the hadron monitor broadens after scattering in the target.

The 3 muon monitors are located downstream of the beam absorber. Because of the steel and rock upstream of each alcove, they detect muons of increasingly higher momentum, hence detect only the decay products of higher energy parent pions. In the lowest energy ν beam, the parent pions have energies of 4-5 GeV, so many of the tertiary muons do not penetrate into Alcove 0. In the higher energy beams, the horn-focused pions have energies 12-30 GeV, so the muons penetrate into Alcoves 0, 1 and 2. Multiple scattering through the rock broadens the beam as it traverses further downstream into Alcoves 1 and 2.

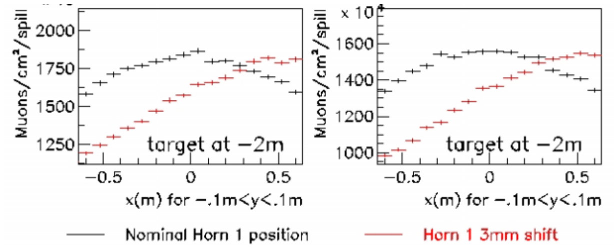

Figure 2: Monte Carlo calculations of muon beam profiles in Alcove 0 (left) and Alcove 1 (right) as seen during highest neutrino beam energy running. Shown are the profiles for normal beam (black points) and for the case in which the beam is mis-steered due to an offset of horn #1 by 3mm (red points). The error bars are due to limited Monte Carlo statistics.

Because of the broad muon profile in the low energy beam, the muon monitors can monitor only relative neutrino event rate spill-to-spill when running in that configuration. Periodic short runs are therefore envisioned using the higher energy neutrino beams, during which the muon beam centroid can be measured with approximately 1.5cm accuracy, leading to an angular precision toward MINOS of 0.015m/740m~20μradian. Higher energy beam running can be accomplished by moving the NuMI target remotely, and increases the charged particle flux at the muon monitors from $\sim 1\times10^7/\mathrm{cm}^2$/spill to $\sim 3\times10^7/\mathrm{cm}^2$/spill. Such a remote target re-configuration thus allows a measure of the alignment of the horn optics on a periodic basis.

CHAMBER CONSTRUCTION

The ion chambers are parallel plates made from ceramic wafers with Ag-Pt electrodes. Because of the need to calibrate and track the relative responses of the 243 chambers in the muon arrays, each chamber is illuminated by a 1 μCi ^{241}Am α source (E_α=5.5 MeV). The ionization current from such a source in pure He gas is typically 2-4 pA, which may be measured between spills to monitor gas, pressure, or temperature variations.

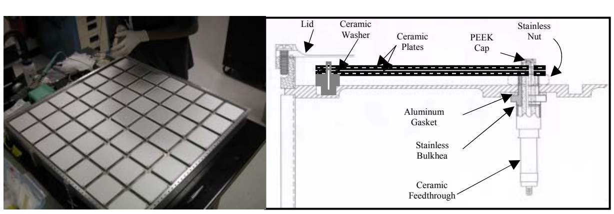

Figure 3: Construction details of the hadron monitor. (left) Beams' eye view of the opened Al vessel containing 49 parallel plate chambers. (right) Each ion chamber is supported on two ceramic-to-metal feedthroughs.

The hadron monitor is an array of 49 chambers mounted in a single Aluminum vessel. Each chamber requires 2 ceramic feedthroughs, one for signal readout and one for a bias voltage (see Figure 3). The vessel is sealed with an Pb-Sn solder wire, whose melting point of 300°C is well above the 50-60°C temperature at which the monitor will operate. The design maximizes use of Aluminum over stainless steel in order to reduce the presence of long-lived radionuclides in the detector; with its current proportion of 54lbs Aluminum and 4lbs. stainless, residual activation will be 58Rem/hr. The signal and HV lines are custom-made "cable" constructed of aluminum welding rod core, insulated by a ceramic tube, shielded by an aluminum sheath. After 1 m this cable transitions to a kapton-insulated cable.

The muon monitor stations are each 81 chamber arrays. The layout of 9×9 ion chambers is achieved by mounting 9 "tubes" onto a support structure vertically. Each tube contains a tray of 9 chambers, as shown in Figure 4. Because of the lower anticipated radiation levels in the muon alcoves, we routed the signals out to one end of the tube, where all feedthroughs come out one endplate of the tube. The endplates seal to the tubes using a soft Aluminum wire gasket. The HV feedthroughs are custom-made using PEEK tubes and compression fittings. The signal feedthroughs are 9-pin ceramic feedthroughs. The signal and HV routing within the tube is accomplished with shielded kapton-insulated cable. Care was taken to minimize any exposed signal conductors to the gas volume, particularly at the feedthroughs, lest ionization in the surrounding gas collect on the conductors. Such "stray ionization" which occurs away from the ceramic chambers degrades the measurements of the muon beam's spatial profile.

Tests were performed of the radiation damage to detector components at the University of Texas 1 MW fission reactor. Samples of ceramic circuit boards with Ag-Pt electrodes, of kapton-insulated coaxial cable, of PEEK plastic and of aluminum compression fittings were exposed to $\sim 1.2\times10^{10}$ Rad. After exposure, the dielectrics could hold off >1000V with <10nA current draw. Interestingly, the kapton cable became less flexible.

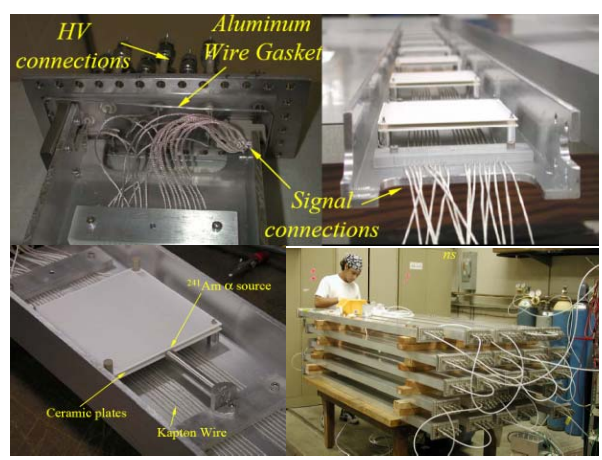

Figure 4: Construction details of the muon monitor tubes. (top left) Endplate with feedthroughs; (top right) tray of ceramic chambers; (bottom left) one of the 9 ion chambers within a tube. (bottom right) Twenty seven tubes (9 required for each of 3 alcoves).

MUON CHAMBER CALIBRATION

The measurement of muon beam profiles requires a 1% relative chamber-to-chamber calibration within the muon monitor arrays. In fact, the uncertainties in muon beam centroid position are dominated by the chamber-to-chamber calibration uncertainty, not by the inter-chamber spacing or the number of chambers in the array.

The calibration procedure was to irradiate each of the detectors within the muon tubes with a source (1 Ci ^{241}Am, 30-60 keV γ rays). The relative ionization currents induced by this source equals the relative calibration factor to be applied to each of the chambers within the muon system. All 9 chambers within a tube were read out simultaneously during one tube's calibration, so that the relative sizes of the signals from the 1 μCi α sources could be studied as well. We monitored temperature and absolute gas pressure within the tube with dedicated sensors to correct for any variations over the course of testing all the tubes. As a check of these sensors, a "reference chamber" was constructed and placed in series with the tube's gas flow. This reference chamber had a 40 μCi α source mounted inside it to act as a standard signal which should change only if gas pressure, temperature, or purity level changes.

Some of the calibration results are given in Figure 5. As a check of the calibration procedure's precision and repeatability, as well of that of the pressure and temperature monitoring, we measured one particular chamber approximately 100 times. The repeatability is 0.2pA/123.0pA≈0.2%,. A histogram of the plateau ionization currents of all the calibrated chambers is shown in the right plot of Figure 5. The 20 pA variation in chamber plateau currents reflects differences in the chamber assembly, such as the electrode spacing.

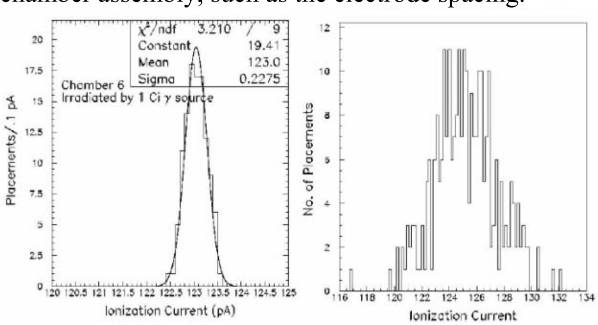

Figure 5: Results of muon monitor calibrations using a 1 Ci γ source. (left) Repeatability of the source calibration of a single chamber within one tube. (right) Plateau currents from all 288 (243 + 45 spares) chambers irradiated with the calibration source.

BEAM TESTS

Two tests of He-filled ion chambers have been performed, both of which are described elsewhere. The first occurred at 8 GeV FNAL Booster beam dump [7], with beam intensity varied from 10^9/spill to 4×10^{12}/spill. The second occurred at the BNL ATF [8], where the beam was of 40 MeV electrons, intensities from 10^7/spill to 10^9/spill. The purpose of the tests was to demonstrate the linear response of the chambers' collected charge *vs.* incident particle flux. Because the 8.56 μsec NuMI spill time is short compared to the transit time for positive ions in the chamber [9], a build-up of ions can screen the chamber field (space charge) and reduce the electron drift to the point of diminished charge collection. The observed space charge effects occurred at intensities an order of magnitude larger than required for NuMI.

BACKGROUNDS

The hadron monitor and Alcove 0 muon detectors are exposed to, by virtue of their close proximity to the beam absorber, relatively large rates of low energy neutrons. Monte Carlo estimates of the neutron rates indicate as much as a factor of 10 more neutrons than charged particles reaching those detectors. We attempted to measure using radioactive sources the ionization rate from neutron-induced recoils in our chambers [10]. The results indicate a background rate from neutrons of <¼ that expected from charged particles.

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