1.1 The Muon Veto Detector (MUV)

1.1.1 Introduction

1.1.1.1 Physics Requirements and General Layout

In addition to the straw chambers and the RICH detector, further muon reduction of the order of 10^{-5} with respect to pions is required and has to be fulfilled by the calorimetric and muon veto systems. The major part of the rejection is achieved by just requiring charged particles not to deposit significant energy in the calorimeters and to traverse a sufficiently thick layer of iron. However, in order to obtain the necessary total rejection power, muons that undergo catastrophic bremsstrahlung or direct pair production and deposit a major fraction of their energy in the calorimeters also have to be suppressed. To reject these rare events, electromagnetic muon showers must be distinguished from hadronic pion showers by measurements of the shower shape, therefore requiring a sufficient segmentation of the calorimetric system.

In order to suppress muon events already at the first trigger level by a factor of about 20, a fast muon veto detector is needed. This sub-detector should have a time resolution of less than 1 ns to reject events with coincident signals in the Giga Tracker and the CEDAR.

1.1.1.2 General Layout

The muon veto system (MUV) consists of three distinct parts, called MUV1, MUV2, and MUV3 in the following, according to their longitudinal position along the beam axis.

The first two modules, MUV1 and MUV2, follow directly the LKR calorimeter and work as hadronic calorimeters for the measurement of deposited energies and shower shapes of incident particles. While MUV2 is the front module of the former NA48 hadron calorimeter (HAC), but turned by 180° (as later explained), the MUV1 module is a newly constructed detector. Both modules are classic iron-scintillator sandwich calorimeters with 24 (MUV1) and 22 (MUV2) layers of scintillator strips. In both modules, the scintillator strips are alternatively oriented in the horizontal and vertical directions. In the MUV1 module, light is collected by wavelength shifting (WLS) fibers, while the MUV2 module routes the scintillator light by light guides directly to photo multiplier tubes (PMTs). The possibility of reusing the complete NA48 HAC (both front and back module) was investigated but rejected for several reasons:

- Required refurbishment of the NA48 HAC back module: The NA48 HAC was originally the NA31 hadron calorimeter and has been reused for the NA48 experiment. In contrast to the front module, the back module had not been equipped with new scintillators and PMTs in the transition from NA31 to NA48, leading to almost blind back module scintillators at the end of NA48 running period. From the experience of the refurbishment of the front module for NA48, the effort required for exchanging scintillators of the HAC back module was estimated to be similar to the effort of building a new module.

- Transversal segmentation: A newly constructed front module allows a finer segmentation in transversal direction to obtain a better distinction between hadronic pion and electromagnetic muon showers.

- Space requirements: Due to the need of a beam deflecting magnet before the end of the beam-line, the longitudinal space available for the HAC modules is less than in NA48. Since light guides and PMTs of the NA48 HAC back module need about 80 cm of longitudinal space in addition to the iron/scintillator layers, a new light collection system had to be built in any case.

The restricted longitudinal space also led to the decision to turn the NA48 HAC front module (MUV2) by 180°. After this rotation, the MUV2 light guides and PMTs point up-stream, surrounding the MUV1 module, leaving the MUV2 downstream space completely free.

After MUV1 and MUV2 and an 80 cm thick iron wall, the MUV3 module, or Fast Muon Veto, has the aim of detecting non-showering muons and acts as muon veto detector at trigger level. To achieve the required time resolution of less than 1 ns at each transversal position, a design is chosen, which employs scintillator tiles arranged to minimize differences in the light path trajectories.

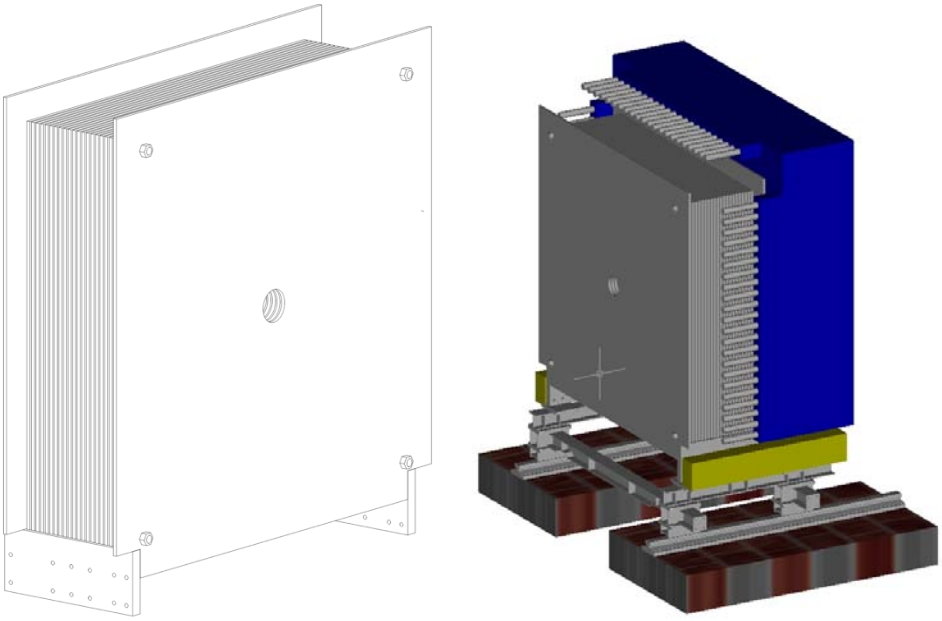

Figure 1 Right: Three-dimensional view of the MUV1 module. Left: View of MUV1 (grey) and MUV2 (blue). The beam is coming from the left.

The number of detection channels is summarized in Table 1.

Table 1 Number of read-out channels of the MUV detector.

Module	**Number of Channels**
MUV1	176
MUV2	88
MUV3 Design A (B)	296 (252)
Total	**560 (516)**

1.1.2 Mechanics and Support Structures

1.1.2.1 MUV1

The MUV1 module consists of 25 layers of SE35 steel. The inner 23 layers have dimensions of 2700 x 2600 x 25 mm^3, while the first and the last layer have the same thickness, but outer dimensions of 3200 x 3200 mm^2. These larger layers serve as support for the whole structure and for the WLS fibers, the photo detectors, and the read-out (Figure 1). The whole iron layer structure is held together by 5 cm diameter steel rods in each corner of the module, maintaining a spacing of 12 mm between the plates. In this way, no welding is necessary, and the MUV1 is constructed by simply stacking alternating iron and scintillator layers onto each other.

Each iron plate contains a central hole of 212 mm diameter for the beam pipe. For additional stabilization during movements and tilts of the MUV1 module, a steel tube of the same diameter can be inserted and fixed inside the central hole.

1.1.2.2 MUV2

The MUV2 module is the old NA48 HAC front module, but turned by 180 degrees, to allow servicing access to PMTs. The welded iron structure consists of 23 steel layers of 2600 x 2600 x 25 mm^3 dimension with 12 mm space between two consecutive iron layers, where a scintillator layer is housed. Each iron plate contains a central hole of 212 mm diameter (Figure 1). The scintillator in the NA48 front module was replaced in 1993/4 when the NA31 (predecessor experiment to NA48) front module was refurbished for use in NA48.

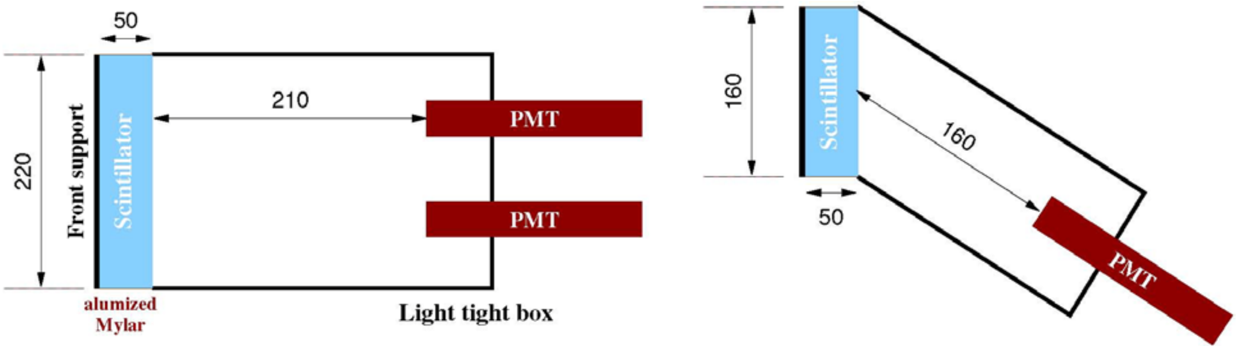

Figure 2 Layout of a single MUV3 tile counter. Left: Drawing A with two PMTs per tile. Right: Drawing B with one tilted PMT per tile. The beam is coming from the left.

1.1.2.3 MUV3

The MUV3 module is located behind an 80 cm thick iron wall filter and serves as a fast muon veto in the lowest trigger level (L0). As a good time resolution is essential, no WLS fibers are used, but instead there are direct optical connections between scintillators and PMTs. The MUV3 will consist of an array of 5 cm thick scintillator tiles. The light produced by traversing charged particles is collected by PMT's positioned about 20 cm down-stream. Due to this geometry, the maximum time jitter between photons from particles hitting different parts of the scintillator tiles is less than 250 ps. However, the time resolution may be spoiled by Cherenkov photons that are produced by particles traversing the PMT windows. These Cherenkov photons arrive earlier than photons produced in the scintillators, whose typical decay time is about 2 ns, thus shifting the measured arrival time by about –2 ns. To overcome this problem, two different design options are studied and under test (Figure 2). Option A consists of 12 x 12 scintillator tiles of 220 x 220 x 50 mm^3 size, with each tile being read out by two PMT's (Figure 3). The output time of the coincidence of the two PMT signals, corresponds to the time defined by the PMT which is unaffected by the Cherenkov photons. Option B places the PMT behind a neighboring tile, so that possible Cherenkov signals are in coincidence with a scintillator signal from the neighboring tile. In this option only one PMT per tile is needed. Therefore, with the same number of read-out channels and the same MUV3 front face, the tile cross-section may be reduced to 160 x 160 mm^2, arranged in a grid of 16 x 16 tiles. Both design options have been proven, under test, to have sufficient light yield as well as time resolution. The final design decision will be taken after analysis of test beam data, currently being performed.

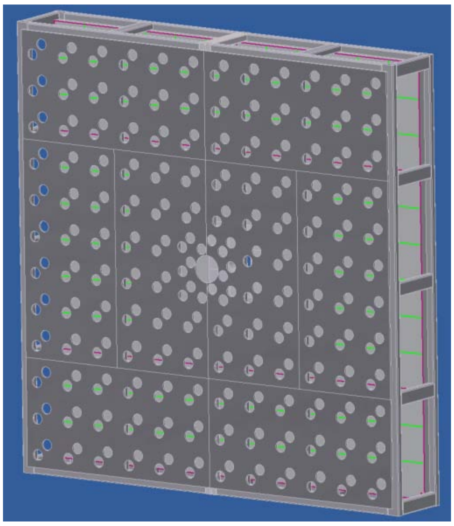

Figure 3 Layout of the complete MUV3 module for option A (without PMT's).

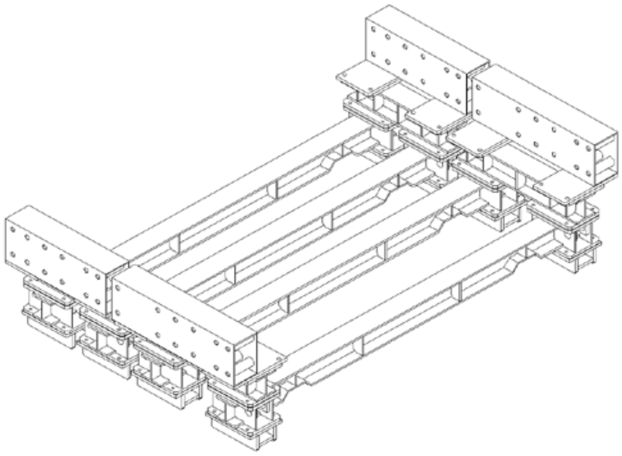

Figure 4 Supporting chariots of MUV1 and MUV2. Most parts of the structure are reused from the NA48 HAC support.

1.1.2.4 Support Structure

The whole muon veto system sits on a pair of rails running in the longitudinal direction. In contrast to the NA48 HAC, where both modules shared a common support structure, each module of the muon veto system (MUV1, MUV2, and MUV3 together with the iron wall) uses its own supporting chariot (see Figure 4 for MUV1 & MUV2). The chariots can be moved independently from each other by the use of winches.

1.1.3 Scintillators and Light Transport

1.1.3.1 MUV1 Scintillators

The MUV1 module houses 2 x 12 layers of scintillators, alternatively oriented in the horizontal and vertical directions. Except for the strips close to the central beam hole and the very outer strips, the size of the scintillator strips is 2616 x 60 x 10 mm^3. They thus cover the whole width of the MUV1 module, allowing a light read-out on both sides. Each scintillator layer consists in total of 48 scintillator strips (Figure 5 left): 34 strips of 2616 mm length, 6 somewhat shorter (with 2496, 2376, and 2256 mm length, respectively) to accommodate the support rods in the corners, and 8 strips of about half length and 54 mm width around the beam hole. The total number of scintillator strips in all 24 layers is 1152.

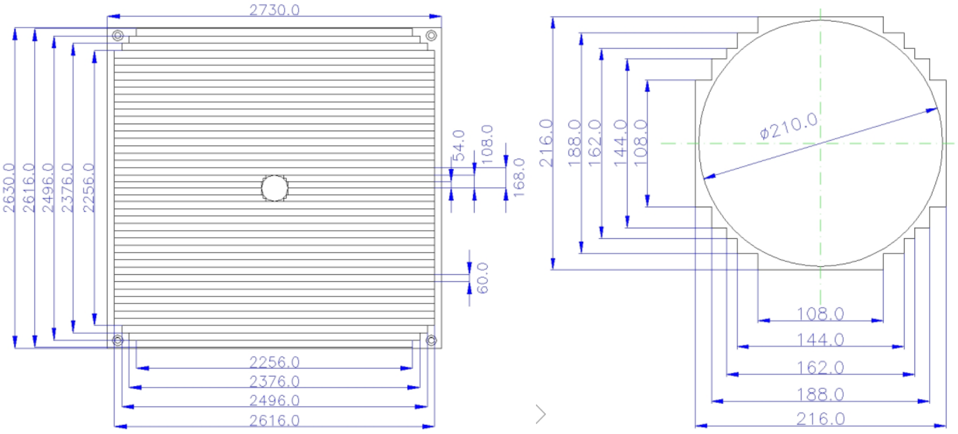

Figure 5 (Left) Layout and sizes of one (horizontal) scintillator layer of the MUV1 module. (Right) Drawing of the spacers in the MUV1 beam pipe region.

In the beam pipe region, the scintillator strips are terminated by a steel spacer ring around the beam pipe. To achieve the maximum acceptance in the region close to the beam pipe, for each orientation the four scintillator strips closer to the beam pipe are cut in two parts and read out at only one end. The ends of four of the eight scintillator strips so obtained are shaped in steps to match the circular shape of the beam pipe as shown in Figure 5 right.

The strip width of 6 cm is a compromise between the need of high granularity and the affordable number of PMTs and read-out channels. Monte Carlo studies showed that a smaller strip width of 4 cm would increase the muon rejection only at a percent level.

The MUV1 scintillators are produced at IHEP in Protvino. They are made of polystyrene (Styron 143E) as carrier substrate with 2% scintillating fluors (p-terphenyl) and 0.05% POPOP. While p-terphenyl emits scintillation light at about 300 – 400 nm in the ultra-violet, POPOP shifts the wavelength to 380 – 500 nm. The procedure used to fabricate the scintillators was newly developed: the mixture of polystyrene pellets, p-terphenyl, and POPOP is melted under a 10^{-4} bar vacuum at about 250 °C. This procedure allows the fabrication of large numbers of long scintillator strips in a relatively short time. One production cycle of heating, melting and cooling needs about 14 hours.

Compared to commercially available scintillators (e.g. Bicron BC 408), the MUV1 scintillators have a shorter attenuation length (< 1 m). However, because of the read-out by WLS fibers (see below), the attenuation length is not an important issue for the detector performance. It was therefore decided to fabricate all MUV1 scintillators at IHEP.

1.1.3.2 MUV1 Light Collection and Transport

For the read-out of MUV1, wavelength-shifting (WLS) fibers are used. This choice was taken to compensate the short attenuation length of the scintillators and also to comply with the space requirements from the surrounding MUV2 PMTs.

Each scintillating strip is read out by two WLS fibers, placed in grooves at 15 and 45 mm along the 60 mm strip width. Several different fiber types from Bicron and Kuraray (Y-11) have been investigated. The preliminary choice is 1.2 mm diameter, multi-cladded fibers BC-91A from Bicron. The fibers shift the scintillator output light to wavelengths between 470 and 570 nm. They are optically connected to the scintillators with optical cement BC-600. It was decided not to use epoxy glue because of possible aging of the fiber cladding.

All fibers have a length of about 500 cm with small variations (< 10 cm), depending on the longitudinal position of the corresponding scintillator. The 12 x 2 fibers of one longitudinal row of scintillators are bundled to direct the light to one single PMT; therefore no longitudinal segmentation exists. The connection to the PMT is made by a matrix, which holds all 24 fibers within the active PMT area of 26 mm diameter.

1.1.3.3 MUV2 Scintillators and Light Transport

The scintillators of the MUV2 module, which is the NA31/NA48 HAC back/front module, were replaced for the start of the NA48 experiment and for NA62 the module is being reused. The scintillators are of type BC-408 from Bicron. Each scintillator plane, inserted between the iron plates, consists of 44 strips. Each strip spans only half the calorimeter so that each plane is made of two half-planes. The two central strips of each half-plane are also three step shaped at one end to wrap around the central hole for the beam pipe (as in MUV1), so they have a width of 108 mm with a length of 1194 mm at the first step and 1243 mm at the third step. All other strips are 1300 mm long and 119 mm wide. The thickness of each scintillator is 4.5 mm (Figure 6).

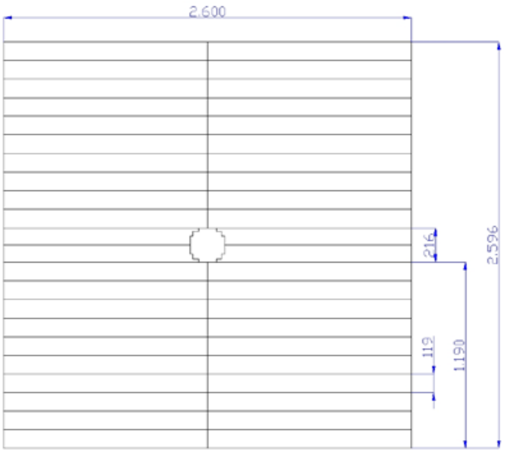

Figure 6 Layout of one (horizontal) scintillator layer of the MUV2 module.

There are in total 24 scintillator planes, so that the MUV2 module – contrary to MUV1 - starts and ends with a scintillator layer. As in the MUV1 module, the strips are alternately aligned in horizontal and vertical directions. Consecutive strips with an identical x/y position and alignment are coupled to the same photomultiplier using *Plexiglas* light-guides “forks”.

1.1.3.4 MUV3 Scintillators

The scintillator tiles for the MUV3 module are produced at IHEP in Protvino, using the same mixture of raw materials. However, a different production technique is used: Large blocks of scintillator material are produced by polymerisation with the same mixture of raw materials as for MUV1. The tiles are then cut in the required size from the blocks and polished.

1.1.3.5 Photodetectors

For MUV1, several photomultiplier options have been investigated and tested. The main option is the model Hamamatsu R6095, which has a surface of 5.3 cm^2, enough for the cross section of 24 WLS fibers, and with sufficient quantum efficiency in the green range. The final decision about the MUV1 PMTs will be taken after tests with the full-size scintillator strips.

The MUV2 module reuses the 3’’ PMTs (THORN EMI 9265KA) of the NA48 HAC.

For the MUV3 module, the 2’’ PMTs (THORN EMI 9814) from the NA48 AKL are reused. Their number is sufficient for about 80% of the MUV3 counters, depending on the chosen design. For the remaining counters, PMTs with similar characteristics will be selected.

1.1.4 Expected Performances

1.1.4.1 Test Results

Scintillator strips of dimension 500 x 40 x 10 mm^3, produced by melting, with Y-11 WLS fiber read-out have been tested with cosmic rays at IHEP and compared to similar strips produced by different techniques. Both the number of photoelectrons (~13 at the fiber far end) and the time resolution (~1.5 ns) did not show significant differences with respect to the other strips.

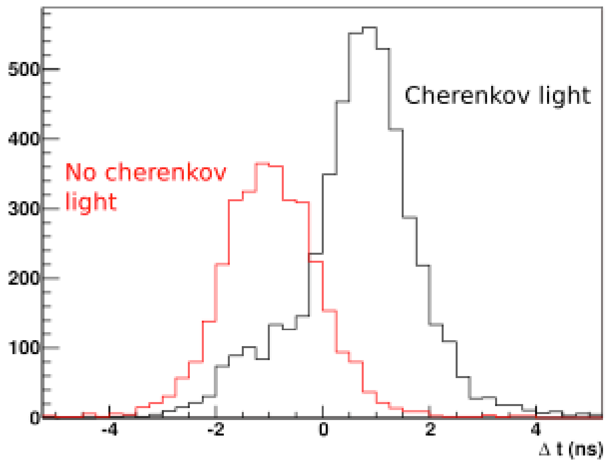

Figure 7 Test beam result for the MUV3 time resolution (layout option A) with the beam passing between the PMTs (red curve) and traversing one of the PMT windows (black).

In addition, several prototype modules of the MUV3 (option A and B) have been tested at a test beam at the CERN PS. The yield of photoelectrons was determined to be 20 – 25 per traversing particle. The time resolution was measured to be 0.5-0.6 ns for particles traversing in between the two PMTs of one module. Most particles passing through one of the PMT windows caused the expected anticipation time shift of about 2 ns (Figure 7). However, when taking into account the low probability of producing Cherenkov photons by a PMT window hit, the overall time resolution of the MUV3 prototype modules was still below 0.6 ns.

1.1.4.2 Simulations

A full GEANT3 simulation of the expected muon suppression of the MUV1 detector together with the LKR calorimeter has been performed. As described in the introduction, the main suppression is achieved by vetoing signals in the MUV3 module and by requiring minimum E/p in the LKR and minimum energy deposition in the MUV1. However, to also reduce background from muon catastrophic energy loss before MUV3, the shower shapes in the LKR and the MUV1 were evaluated. By combining all separation criteria, for momenta 12 < p < 35 GeV/c a total $K\mu 2$ suppression of > 2 x 10^6 at a signal efficiency of 50-60% can be achieved. This figure becomes even better when considering only momenta larger than 25 GeV/c, where the particle ID capability of the RICH detector becomes worse.

Bibliography

There are no sources in the current document.