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A first study of a scintillating fibre detector for a muon ionisation cooling experiment

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Abstract

For the cooling experiment currently under investigation, it is necessary to track muons in a magnetic field with a precision of at least 0.2mm. A minimum of multiple scattering should be introduced by the measurement process. We investigate a detector made of three layers of 0.5mm square cross section scintillating fibres, which contributes only 0.4% of a radiation length to multiple scattering. To match the required instantaneous particle rate, a fast read-out system based LHC class components is presented. With this system, it would be possible to record 960 events per burst with bursts every few ms.

1 Introduction

Ionisation cooling is one of the most innovative parts of a possible future neutrino factory. The principle of ionisation cooling is to send a particle through an absorber, where its momentum is reduced uniformly. The longitudinal component of the momentum is then restored in a subsequent rf cavity. The result is a decrease in $x' = \mathrm{atan}\frac{p_t}{p_l}$, which also results in an emittance decrease. Although ionisation cooling has been intensely discussed, it has never been demonstrated experimentally.

The CERN Neutrino Factory scenario foresees a two stage cooling channel; the first part with 44MHz cavities that have a bore radius of 30cm and 2.4T super conducting solenoids and the second part with 88MHz cavities that feature a 15cm bore radius and 5T s.c. solenoids. [1]

Currently, an ionisation cooling experiment is being designed to test the 88MHz part of the CERN cooling channel design. [2] The cooling section of the experiment is planned to consist of a first liquid hydrogen absorber of 45cm, followed by 8 rf cavities, each 0.9m long with 4MV/m, followed by 90cm of hydrogen absorber, followed by another set of 8 cavities and a final absorber of 45cm of hydrogen. The focusing will be done by 6T solenoids that are mounted in between the cavities.

Before and after the cooling section there are two analysing sections with four scintillating fibre tracking detectors and one TOF counter each surrounded by the same solenoids. This note is about the design of these detectors, which are planned to be all of the same design, and the associated readout electronics.

The experiment will be a single particle experiment with individual muons passing through the apparatus. With four data points taken in a constant magnetic field it is possible to reconstruct the longitudinal and transverse momenta of the particle. It is then planed to construct various possible beams from the individual particle data. To measure the change in emittance between input and output with a 10% precision, 10^4 useful tracks are needed; for a 1% precision, the number of tracks needed is 10^6. These numbers are based on the fact that a 10% reduction of emittance will be achieved with the experimental setup and that there is a high correlation between muons that enter the apparatus and those that exit it.

It is planned to analyse the cooling rate of smaller emittance beams by "software collimation". This means, that in the data analysis, only particles within a specific, small emittance are counted. In order to have sufficient statistics for software collimation down to 10% of the original emittance, it is necessary to record 100 times the above given rates.

The useful rate will be further diminished by factors of about 3 for background particles, 3 for double hits, 4 for particles in the wrong phase and 1.1 for detector inefficiencies.

2 Outline of the Requirements

Due to constraints in power supply and cooling of the rf cavities, the cavities of the cooling channel have to be pulsed. It is foreseen to pulse them at 50Hz, with a flat top of about 100 μs. This results in a 0.5% duty cycle. Therefore, even though the number of events needed is not very high, the time structure of the experiment requires a "burst-like" data acquisition.

With the system proposed here, it is possible to record 960 events during the 100 μs flat top, resulting in a raw data rate of 48,000 events per second. Taking into account software collimation and all limiting factors described above, 10^4 useful muons in the smallest input emittance can be measured in 16 minutes.

Suitable beams have been identified at several facilities, including RAL and PSI.

3 Detector Geometry

A preliminary detector geometry has been chosen in order to estimate the number of channels and cost. The desired active area of the detector is a circular region with a diameter of 300 mm. In choosing the geometry, it is important to keep the detector as thin as possible in order to reduce the effect of multiple scattering, which introduces a systematic bias in the emittance reconstruction. [3]

In order to keep the thickness of the detector small but still maintain high efficiency, a three layer approach with 0.5 mm detector channel pitch has been chosen. All three layers and the structural epoxy combined contribute only 0.4% of a radiation length to multiple scattering. The three layers cross at 120 degrees, so that hits in any two layers can be used to reconstruct the muon position. This results in a hexagonal active region which circumscribes a 300 mm diameter circle. A schematic of this configuration is shown in Figure 1. This geometry gives a position resolution of about 150 μm.

In addition to the position resolution, timing resolution is also important. Because of the relatively low light yield of the scintillating fibre, it will be necessary to have an additional time-of-flight system in the cooling experiment. The timing information from the scintillating fibres will be used for hit association along tracks and to resolve ambiguities in helix reconstruction arising from slow tracks which complete multiple revolutions between detector planes.

4 Technology Choices

Scintillating fibre with multianode photo-multiplier tube readout has been chosen because it meets the requirements set out above at a reasonable cost and without too much additional development work. In order to process the analog signals from the PMTs, a front-end chip which combines discriminator and charge measurement functions will be used in conjunction with a fast VME time to digital converter. This system is set out in Table 1. It should be noted that the readout determines the maximum possible data rate, and that the ASDQ/TDC solution described in Section 7.1 should not be operated above 500 kHz per channel hit rate.

Detector Geometry	hexagonal circumscribing 300 mm diameter circle
Spatial Resolution	$\approx 150\ \mu$m
Time Resolution	< 1 ns
X_{det}/X_0	$\approx 0.4\%$
Vacuum Compatible	Yes

Table 1: Characteristics of SciFi system

5 Tracking Area and Optical Connections

The tracking system described here is based on the design of the Scintillating Fiber Tracker used in the MuScat experiment. [4]

For the scintillating fibre, we have chosen Bicron BCF-12 [5], which is readily available and has good characteristics. The light yield is about 8000 photons per MeV deposited, with a decay time of 3.2 ns and an emission peak of 435 nm. With this fiber and the PMT described below, a mean of about 8 photo-electrons per muon is expected.

The time resolution is primarily determined by the number of photo-electrons and the scintillation decay time of the fibre. Taking into account the number of photo-electrons expected and the transit time spread of the PMT, the intrinsic time resolution of the system is about 350 ps, which will be broadened by the readout electronics.

5.1 Fiber Layout

The length of each scintillating fibre in the hexagonal configuration is 640 mm. An additional 200 mm per fibre is necessary for mounting during construction and is cut away. There are 1800 fibres in each detector plane, so the total amount of scintillating fibre required for 10 detectors is 15.2 km.

The fibres are mounted in a frame and then bonded using a small volume of epoxy to form a 1.7 mm thick sheet, which corresponds to about 0.4% of a radiation length. They are also embedded in epoxy at the edges of the frame and then flycut. This surface is coupled to clear fibres which transport the light to photomultiplier tubes. The clear fibres are formed into looms with one end set in a connector which is attached to the detector and the other end set in a block which forms a vacuum seal. The connector end is arranged as the fibres are in the detector, and the vacuum seal is arranged in a square array. The ordering of the fibres in this square array, combined with readout at both ends of the fibres allows for optical multiplexing of the signals.

In order to ease distribution of timing signals, it is envisioned that the PMTs and front-end electronics would be located close to the detectors, but that the TDCs would sit together in a central location. Several meters of clear fibre would be used to transport the light to the PMTs. Assuming three meters is required per channel, 54 km will be used for 10 detectors.

5.2 Optical Signal Multiplexing

In order to reduce the number of electronics channels required, some sort of optical multiplexing can be used, since this experiment expects only one particle per event and vetoes events with extra activity. The optical multiplexing scheme employed is based on reading out sixteen fibres on one anode of a multianode PMT. By reading out both ends of each fibre and grouping the fibres such that no two fibres share the same anode at both ends, 256 fibres are read out with two sixteen anode PMTs. In order to read out our detector, 18 PMTs will be required; a total of 180 for 10 planes.

5.3 Mechanical Construction

The trackers are constructed from a plastic frame, scintillating fibres and epoxy. The plastic frame is precision machined and then the fibres are strung in it, being epoxied at each end in turn so that they are taught within the frame. Finally, plates close the faces of the detector and epoxy is pulled into the center void using a vacuum. When the epoxy sets, the fibres are mechanically supported and fixed in position.

6 PMTs and Bases

The PMT chosen was the Hamamatsu R5900U-L16 linear multianode PMT. [6] This PMT has sixteen anodes which are 0.8 by 16 mm set at 1 mm pitch. Sixteen sets of sixteen fibres are read out by each tube. Since fibres are viewed by separate tubes at each end, 16 PMTs and bases are required for each detector.

7 Readout Electronics

A method for digitising the signals from the PMTs is necessary. Although the number of channels is not too large (288 per detector), the time requirements are somewhat stringent, since hundreds of events must be taken in each 20 microsecond bunch. This means it is not possible to have significant deadtime between events. The scheme chosen here attempts to use readily available parts to create a pipelined readout.

Two pieces of information from each pulse are important. One is the exact timing of the pulse, since this will be used both to associate hits with each other and to measure time-of-flight along the particle's path. The second important piece of information is the pulse height. This is important for rejecting pile-up and improving position resolution via energy sharing reconstruction techniques.

7.1 Signal Processing and TDC Option

It is possible to encode the pulse height information in a pulse length and use a fast TDC with capability of measuring pulse start and stop times.

7.1.1 Front-end analog processing

The University of Pennsylvania has developed a number of ASICs for drift chamber readout. The ASDQ [7], which was developed for wire chamber readout with dE/dx could be adapted to our application. These chips would be available if we required them.

If we adjust the front-end so that 2 photo-electrons correspond to 4 fC of charge, then the ASDQ can be operated such that pulse lengths will be between 15 and 60 ns for pulses between 2 and 100 photo-electrons.

7.1.2 TDC

A number of fast TDC ASICs exist. Of these, the TMC family has been developed by Arai et al. [8, 9] and the AMT-1 will be commercially available as a VME module from AMSC Co.,LTD, starting in January 2002. Prototypes will be produced this autumn. It is likely to be a 24 channel module. Each module is capable of storing 320 hits in a common pipeline. If the 16 channels of a PMT are connected to 16 channels of the TDC and the remaining channels are left empty, the average capacity per channel is 20 hits. If a deeper pipeline is required, in order to increase the effective data rate, it is possible to use more TDCs than there are PMTs and leave more channels in each module empty.

7.2 Infrastructure

The above option will require one VME crate per detector, VME CPUs and 100Mb/s ethernet for readout. In addition, a small farm of perhaps 4 fast PCs will be required to control the data acquisition, log data to disk and tape and do fast offline reconstruction. The data rate produced by the 10 detectors will be 11 MB/s, so a fibre optic network will be needed to link the 10 DAQ PCs to the event builder.

8 Conclusion

The possibility of using scintillating fibres for the instrumentation of a cooling experiment has been examined. Within the requirements imposed by the pulsed operation of the rf cavities the proposed scheme seems feasible and delivers the required statistics within a reasonable amount of time. A more detailed study is needed to provide a layout of the detector and the readout electronics.

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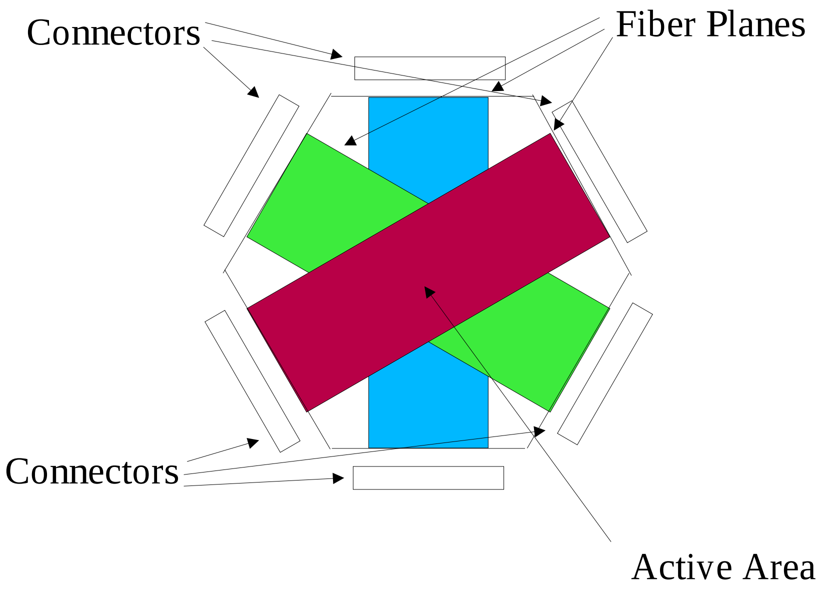

Figure 1: Hexagonal Detector Layout