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Design and performance of the FAST detector

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ABSTRACT

The Fibre Active Scintillator Target (FAST) experiment at the Paul Scherrer Institute (PSI) is designed for a high-precision measurement of the μ^+ lifetime, in the order of a few parts per million. This paper describes the design, construction and performance of the FAST detector and its readout electronics, trigger and data acquisition system.

1. Introduction

The goal of FAST is to measure the μ^+ lifetime (τ_μ) at a few ppm precision and thereby to precisely determine the Fermi coupling constant G_F [1]. Positive muons are measured since their lifetime is not influenced by nuclear capture. The FAST experiment [2,3], together with the MuLan experiment [4], belong to a new generation of precision muon lifetime measurements following the last round of experiments more than 30 years ago [5]. Compared with previous measurements, a factor 100 larger sample of events is required while, at the same time, systematic errors must be reduced by one order of magnitude.

The concept of FAST [2,3] is to design an experiment that, as much as possible, suppresses the systematic effects at the detector level. In this way, only small systematic corrections to the initial measurement are required to reach the desired precision on the μ^+ lifetime. In order to collect the large data sample (2.5×10^{11} measurements of the μ^+ decay time for a 2 ppm statistical precision of the μ^+ lifetime), the experiment consists of a fast and highly granular detector which can measure multiple muons in parallel over a decay interval of 30 μs.

2. Detector overview

A π^+ beam of momentum 165 MeV/c is stopped inside an imaging target constructed of plastic scintillator bars ("pixels" of dimension 4×4 mm^2 by 200 mm depth), connected to position-sensitive photo-multipliers (PSPMs) via wavelength-shifting fibres. An event consists of a π^+ beam particle stopped in the target, followed by the pion decay $\pi^+\rightarrow\mu^+\nu_\mu$ and then the muon decay $\mu^+\rightarrow e^+\overline{\nu}_\mu\nu_e$ (Fig. 1). The entire $\pi^+\rightarrow\mu^+\rightarrow e^+$ sequence is imaged in the xy projection of the target, with the pixel granularity of 4×4 mm^2. The kinetic energy of the μ^+ from the π^+ decay at rest is 4.1 MeV, which provides a range in plastic scintillator of about 1.4 mm (i.e. two adjacent pixels at maximum). The repeated modular structure of the detector allows the identification of several $\pi^+\rightarrow\mu^+\rightarrow e^+$ chains simultaneously in the target. The time and space coordinates (x, y) of every hit of the event are recorded, and the π^+ and μ^+ decay times measured. The approximate z (vertical) coordinate of the π^+ stopping point is provided by a counter hodoscope which measures the z position of the beam particle. In order to distribute the π^+ stopping points throughout the target, the beam optics is tuned to provide a wide beam that matches the 160×100 mm^2 aperture of a copper collimator placed just upstream; a wedge-shaped beam degrader distributes the stopping points in depth.

The PSPM pulses are amplified, discriminated and then time-stamped and registered in CAEN V767 TDCs (Fig. 2). The active target and its readout can image, measure and record events at high beam rates. The detector is operated at the PSI cyclotron in a

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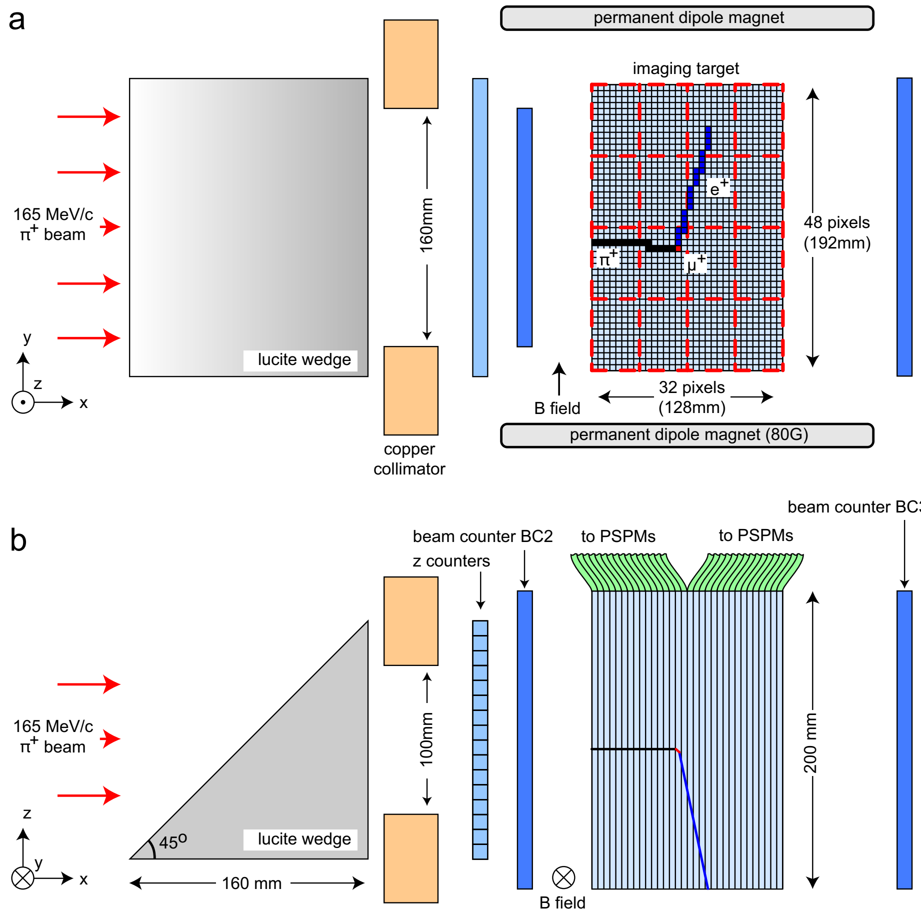

Fig. 1. Schematic drawing of the FAST detector, including (from right to left) the target, one beam counter, the z-counter hodoscope, the collimator and the wedge: (a) top view, and (b) side view. A representative event shows the π^+ beam particle stopping in the target, followed by a $\pi^+ \to \mu^+$ decay (with the single pixel occupancy for the μ^+) and, finally, a $\mu^+ \to e^+$ decay. The dashed rectangular shapes identified in the target show the regions mapped by each TDC.

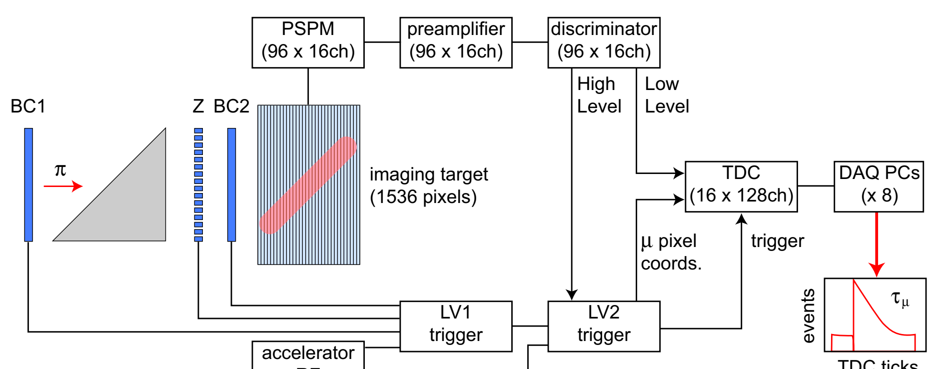

Fig. 2. Block diagram of the readout, trigger and data acquisition chain of FAST.

π^+ beam at up to 0.5 MHz rate. The beam has 100% duty cycle, which avoids gain shifts in the detector as a function of muon decay time that could arise with a pulsed beam.

The decay times are observed over a period of [−8,22] μs around the event start time. The measurement of the muon decays over the long period of 22 μs (around 10 τ_μ) provides sufficient lever-arm for a precise lifetime fit. The measurement of apparent negative decay times allows precise calibration of various accidental backgrounds and other sources of systematic error.

Muon spin rotation (μSR) effects have been an important source of systematic uncertainty in previous experiments [5]. Muon spin depolarisation and muon spin rotation in the local magnetic field at the detector, together with an asymmetric positron detection efficiency, can lead to a time-dependent detection efficiency and hence can affect the muon lifetime measurement. In FAST, μSR systematic errors are highly suppressed by requiring positive identification that each μ^+ originates from a stopped π^+ beam particle, and they are further suppressed by the symmetry and large solid angular acceptance of the detector. Finally, the target is located between the poles of a permanent magnet that provides 80 G transverse field (Fig. 1). This further suppresses μSR systematic errors and allows any residual contributions to be measured and