Design and Performance of the FAST Detector

FAST Collaboration:

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Abstract

The Fibre Active Scintillator Target (FAST) experiment at the Paul Scherrer Institute (PSI) is designed to measure the $\mu^+$ lifetime to 4 ps statistical precision (2 ppm). After including theoretical and experimental uncertainties, this measurement will determine the Fermi constant, $G_F$, to 1 ppm precision. 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 $\mu^+$ lifetime ($\tau_\mu$) to 2 ppm precision and thereby to determine the Fermi coupling constant $G_F$ to 1 ppm precision [1]. Only positive muons are used since their lifetime is not influenced by nuclear capture. The FAST experiment [2], together with the MuLan experiment [3], belongs to the “new generation” of precise muon lifetime experiments. Compared with earlier measurements [4], this means increasing the event sample by a factor of 100, while, at the same time, reducing the systematic errors by an order of magnitude.

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The concept of FAST [2] is to design an experiment that suppresses as far as possible the systematic effects at the detector level. In this way, only small systematic corrections to the initial measurement are required to reach the final value of the $\mu^+$ lifetime. In order to collect the large required data sample (at least $2.5 \times 10^{11}$ measurements of the $\mu^+$ decay time), the experiment involves a fast and highly granular detector which can measure multiple muons in parallel. A $\pi^+$ beam is stopped inside an imaging target constructed from plastic scintillator bars ("pixels", $4 \times 4 \times 200$ mm$^3$ each), connected to position-sensitive photo-multipliers (PSPMs) via wavelength-shifting fibres. Every event consists of a $\pi^+$ beam particle stopped in the target, followed by the pion decay $\pi^+ \rightarrow \mu^+ \nu_\mu$, and the muon decay $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$ (Fig. 1). The entire $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ sequence is imaged in the $xy$ projection of the target, with the pixel granularity of $4 \times 4$ mm$^2$. The kinetic energy of the $\mu^+$ from the $\pi^+$ decay at rest is 4.1 MeV, which makes its range in plastic scintillator equal to about 1.4 mm (i.e. one pixel 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 $\pi^+$ and $\mu^+$ decay times measured. The approximate $z$ (vertical) coordinate of the $\pi^+$ stopping point is provided by a counter hodoscope which measures the $z$ position of the beam particle. In order to distribute the $\pi^+$ stopping points throughout the target, the beam optics is tuned to provide a wide beam that matches the $160 \times 100$ mm$^2$ aperture of a copper collimator placed upstream of the target; a wedge-shaped beam degrader ensures that the $\pi^+$ stopping points are distributed throughout the target 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 $\pi^+$ 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 $\tau_\mu$) provides sufficient lever-arm for a precise lifetime fit. The measurement of “negative” decay times allows precise calibration of various accidental backgrounds and other sources of systematic error.

Muon spin rotation ($\mu$SR) effects have been an important source of systematic uncertainty in previous experiments [4]. 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, $\mu$SR systematic errors are highly suppressed by requiring positive identification that each $\mu^+$ originates from a stopped $\pi^+$ beam particle and are further suppressed by the symmetry and large solid angular acceptance of the detector. Finally,
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 $\pi^+$ beam particle stopping in the target, followed by a $\pi^+ \rightarrow \mu^+$ decay (with the single pixel occupancy for the $\mu^+$) and, finally, a $\mu^+ \rightarrow e^+$ 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 acquisition chain of FAST.
in order to identify and calibrate any residual µSR effect, the FAST target is placed in a transverse magnetic field of 80 G, which is provided by a permanent dipole magnet, placed on the target sides (Fig. 1). The muons precess around the field direction with a frequency $f_\mu$ (Hz) = $13.55 \times 10^3$ B(Gauss) = 1.1 MHz and a precession period of $T_\mu = 0.92$ µs. This characteristic period is sufficiently rapid, compared with the 22 µs measurement interval, that residual µSR effects could be readily identifiable and therefore have only a minor influence on the lifetime measurement.

The imaging capability of the target provides both a clean identification of the initial muon in the $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ chain and also a strong rejection of accidental positron backgrounds in the muon decay, even in the presence of high beam rates. A two levels trigger system is designed to identify the $\pi^+ \rightarrow \mu^+$ chain in the target [5]. The first level trigger (LV1) selects beam pions and provides the zero-time reference ($t_e = 0$) for the event. The second level trigger (LV2) reconstructs the pion stop pixel, identifies the subsequent $\pi^+ \rightarrow \mu^+$ decay and determines the muon stop pixel. The identification of the incoming stopping $\pi^+$ and the subsequent $\mu^+$ utilises the pixel hit pattern of high-threshold pulses from the PSPMs. Custom-built threshold discriminators, including both low- and high-threshold outputs, are used to distinguish between minimum ionising particles (mip’s, such as positrons) and stopping pions and muons. The readout and trigger scheme for FAST is shown in Fig. 2.

Once the $\mu^+$ stop pixel has been identified by the LV2 trigger, all the information required to identify the $e^+$ and measure the muon decay time is contained in a 5 × 5 pixels array centred on the muon pixel (7 × 7 pixels array centered in the pion pixel). The imaging target therefore essentially comprises a large number of replicated mini-detectors placed side-by-side, each one capable of making an independent and simultaneous measurement of a $\mu^+$ decay. In view of this highly replicated design, systematic uncertainties due to non-uniformities in the detector or in the readout electronics can be identified and calibrated.

In order to handle the huge statistical sample required, all data are fully analysed in real time by a PC farm. Histograms of the muon lifetime and other parameters of the experiment are recorded. In addition, only a small subset (around 1%) of complete raw events are also stored, for later analysis of some of the systematic effects. All the histograms from the online analysis program are saved periodically (with a time granularity of a few minutes), in order to confirm the quality of all analysed data and check for possible time drifts. Around 1000 muon lifetime histograms –according to various variables such as the position of the decay in the target, or the $e^+$ hit pattern from the $\mu^+$ decay– are periodically recorded. In this way, the stability of the measured $\mu^+$ lifetime can be examined with respect to various criteria, in order to calibrate the systematic errors and determine the final value and precision of the lifetime.
measurement.

The FAST detector has been collecting data at PSI since 2006. A pilot physics run (~ $10^{10}$ muon lifetime events) in 2006 lead to the first $\mu^+$ lifetime measurement from FAST [6]. The full statistics data collection is now completed ($4.2 \times 10^{11}$ muon lifetime events), the data analysis is currently ongoing.

2 The $\pi^+$ beam and the LV1 trigger

The accelerator facility of the Paul Scherrer Institute (PSI) in Villigen, Switzerland, is specialized in the production of extremely luminous low-energy pion and muon beams. The main accelerator is an isochronous sector cyclotron providing a high power proton beam at an energy of 590 MeV and a current of 2 mA, with a RF cyclotron frequency of 50.63 MHz and 100% duty cycle. The proton beam is transported to two meson production target stations to generate secondary beams of pions and muons.

The FAST experiment is located in the $\pi$M1 secondary beam line. For FAST a $\pi^+$ beam is used with a momentum of 165 MeV/c and a momentum resolution of 0.1%; the intensity is around 0.5 MHz. The beam is operated in a strongly defocused configuration to provide a flat and wide distribution ($16 \times 10$ cm$^2$) in the FAST target.

The first level trigger system (LV1) defines an incoming beam particle by means of a coincidence of two scintillator counters, BC1 and BC2, located upstream of the detector (Figs. 1 and 2). BC1 ($30 \times 30$ cm$^2$ wide, 0.5 cm thick) is located at the end of the last quadrupole of the $\pi$M1 beamline, approximately 4 m upstream of the FAST detector. The counter BC2 ($16 \times 20$ cm$^2$ wide, 1 cm thick) is placed immediately in front of the target. Figure 3 shows the time-of-flight spectrum of BC2 pulses with respect to the machine RF. The three particle components ($\mu^+$, $e^+$, $\pi^+$) in the $\pi$M1 pion beam line can be clearly seen. A narrow coincidence (LV1 narrow trigger) is used to enhance the pion component and suppress the electrons and muons. Alternatively a wide coincidence (LV1 wide trigger) can select all beam particles. When beam positrons are selected for calibration purposes, a third beam counter BC3 ($30 \times 30$ cm$^2$ wide, 0.5 cm thick), located downstream of the target, is added in coincidence with the LV1 trigger.
3 The FAST target

The FAST target is a high granularity scintillator target, built of 1536 scintillator bars (pixels), each of dimensions $4 \times 4 \times 200$ mm$^3$, arranged vertically in a $32(x) \times 48(y)$ geometry (Fig. 1). The target dimensions are $128(x) \times 192(y) \times 200(z)$ mm$^3$. Each pixel bar is cut from plates of solid plastic scintillator Bicron BC-400, with a peak emission spectrum around 400 nm. The optical coupling between the scintillator bars and the PSPMs is obtained by wavelength shifting fibres: two Bicron BCF-92 fibres (1 mm diameter) are inserted in each scintillator bar. They are fast blue-to-green shifters, characterized by a long attenuation length of more than 3.5 m and an emission spectrum peaked around 480 nm. To house the fibres, two grooves are machined alongside each bar, on two adjacent sides. The two fibres are then inserted and glued into the grooves with an optical cement (Bicron BC-600). The filling factor (i.e. ratio of active scintillating to passive material) is 87.5%. Each scintillator bar is painted with a white reflective diffusive paint (Bicron BC-620) to enhance photon collection and optically isolate each pixel from its neighbours. All materials adopted for the FAST target are summarized in Table 1.

Figure 4 shows a few bars in different stages of their construction. After painting, the final 1536 bars forming the target are bundled in 96 groups of 16 bars each, in a $4 \times 4$ geometry (Fig. 4, right). This matches a single $4 \times 4$ multi-anode PSPM. The wavelength shifting fibres of one bundle are glued into a mask, which positions them with respect to the photocathode pads. The target, assembled in its final geometry, is housed in a special black painted aluminum frame (Fig. 5). The photomultipliers are mounted on the top of this frame.

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2 from Saint Gobain, http://www.detectors.saint-gobain.com
<table>
<thead>
<tr>
<th>Material</th>
<th>Technical Properties</th>
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<tbody>
<tr>
<td>Scintillator</td>
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</tr>
<tr>
<td>Bicron BC-400</td>
<td>refractive index $n = 1.58$</td>
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<tr>
<td></td>
<td>density $\rho = 1.032$ g/cm$^3$</td>
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<tr>
<td></td>
<td>emission peak wavelength $\sim 420$ nm</td>
</tr>
<tr>
<td></td>
<td>attenuation length $\lambda_l = 160$ cm</td>
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<td></td>
<td>decay time $t = 2.4$ ns</td>
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<td>Wave Length Shifters</td>
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<td>Bicron BCF-92</td>
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<td></td>
<td>attenuation length $\lambda_l &gt; 3.5$ m</td>
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<tr>
<td></td>
<td>absorption peak wavelength $\sim 400$ nm</td>
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<td></td>
<td>emission peak wavelength $\sim 480$ nm</td>
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<tr>
<td>Bicron BC-600</td>
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<td></td>
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<td></td>
<td>$&gt; 95% (\lambda \in [340, 400]$ nm)</td>
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<tr>
<td>Diffusive Paint</td>
<td></td>
</tr>
<tr>
<td>Bicron BC-620</td>
<td>reflectivity $&gt; 90% (\lambda &gt; 400$ nm)</td>
</tr>
</tbody>
</table>

Table 1
Materials adopted for the FAST target.

The $z$-counter hodoscope for the measurement of the vertical position of the particles entering the target consists of 16 scintillator bars (each of dimensions $10(x) \times 200(y) \times 10(z)$ mm$^3$) horizontally piled-up in front of the target (Figs. 1 and 6). Two 16ch PSPMs are used to read the 16 channels of the hodoscope\(^3\). Uniform illumination of the target is achieved by a wide beam profile, together with the wedge shaped beam degrader (Figs. 1 and 6). A permanent magnet which provides a horizontal dipole field of about 80 G across the target is positioned in the target region (Figs. 1 and 6), to control the $\mu$SR effects. The magnet is made of two magnetized ferrite plates, placed on either side of the target. Each of the two plates is formed from several ferrite blocks, separately magnetized, to achieve a field uniformity of $\pm 20\%$ within the target region [7].

\(^3\) Only eight channels per PSPM are used for the $z$-counter hodoscope, in order to reduce the effect of cross-talk inside the PSPM.
Fig. 4. A few bars in different stages of their construction. Left: bare scintillator bars with the two grooves machined and the two wavelength shifting fibres inserted. Centre: two completed bars (fibres inserted and glued, bars painted). Right: one group of 16 bars, arranged in a $4 \times 4$ geometry. The black mask visible at the end of the fibres is needed for the optical coupling with the photomultiplier.

Fig. 5. The FAST target. The 50 cm long metal ruler provides the scale.

4 The photodetectors

The Hamamatsu H6568-10\textsuperscript{4} multianode position sensitive photomultipliers (PSPM) are used to readout the FAST target. The bare photomultiplier tube, without the base assembly, is the Hamamatsu R7600-00-M16. It is a 16ch photomultiplier, with $4 \times 4$ pixels photocathode, each with a photosensitive

area of $4 \times 4 \text{ mm}^2$. The cross talk among the channels is below 1%. A total of 96 PSPMs is required to read out the 1536 target pixels. To improve the optical coupling between fibres and photocathodes, a thin layer of optical grease (Bicron BC-630) is used.

5 The analogue readout electronics: preamplifiers and discriminators

The analogue front-end electronics of FAST (Fig. 2) is composed of custom made preamplifiers and discriminators. Both unit types have 16 channels, to match the number of PSPM output channels. In total, 96 preamplifiers and 96 discriminator units are required.

Each preamplifier card has $16 \times 50\Omega$ analogue lemo inputs and $16 \times 50\Omega$ analogue outputs. The amplifiers are based on 3 stages built with CLL449 1.1GHz Ultra Wideband Monolithic Op Amp circuits. Each channel has a gain of 5 and a bandwidth of 1 GHz. The channel offset voltages are adjustable by potentiometers. The 16 output connector is a simple 3M 16× type connector. To avoid crosstalk and to match the $50\Omega$ inputs of the discriminators a custom
made ribbon cable, composed of 16 coaxial cables, is used.

The FAST concept requires the use of custom made dual threshold discriminators. Every event \((\pi^+ \rightarrow \mu^+ \rightarrow e^+ \text{ chain})\) involves particles with different ionisation characteristics: as summarized in Table 2, the incoming \(\pi^+\) and the \(e^+\) tracks (mip’s) induce low amplitude signals, while the stopping \(\pi^+\) and the \(\mu^+\) decays generate signals with mean pulse heights about 4 times higher. To distinguish between this two processes the discriminators have two independent outputs, relative to two different thresholds: a low threshold (LL) and a high threshold (HL). Each FAST updating mode discriminator unit contains 16 leading-edge discriminator circuits, housed in a standard NIM box. They have the following characteristics: 50Ω input impedance, differential ECL outputs with 13 ns width, 2 ns time over threshold to trigger, 14 ns double hit resolution. The choice of the output signal timing characteristics is driven by the minimal requirement for the TDC input signal width. The threshold for the LL and HL outputs are independently set. The thresholds setting is handled by the detector slow control system. The LL discriminator outputs are time stamped by the TDCs, the HL output signals are used as input for the LV2 trigger logic (Fig. 2).

<table>
<thead>
<tr>
<th>Particle Type</th>
<th>Estimated Light Yield [pe]</th>
</tr>
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<tbody>
<tr>
<td>electrons (i.e. mip’s)</td>
<td>9</td>
</tr>
<tr>
<td>pions with 20 mm range</td>
<td>25</td>
</tr>
<tr>
<td>stopping pions</td>
<td>35</td>
</tr>
<tr>
<td>(\pi \rightarrow \mu) decay</td>
<td>35</td>
</tr>
</tbody>
</table>

\(\text{LL } V_{\text{thr}} = 100 \text{ mV} \\sim 3\)  
\(\text{HL } V_{\text{thr}} = 400 \text{ mV} \\sim 18\)

Table 2  
Typical light yields (in photoelectron units) of the FAST target for the different types of signals occurring in the detector. The chosen threshold values for the discriminators are also reported. The non linearity between the number of photoelectrons and \(V_{\text{thr}}\) is justified by an additional DC offset in the preamplifier, introduced in the matching between preamplifiers and discriminators, originated by a strong asymmetry in the power consumption of the discriminators.

6 The time measurement: TDCs

A high precision time measurement and high rate capabilities for the FAST detector are demanded. These requirements are met by the CAEN V767 Time to Digital Conversion (TDC) units, driven by a very precise and stable external clock.
The CAEN V767 TDC units\(^5\) are high performance TDCs, based on a custom 32-channels general purpose TDC chip developed by the CERN/ECP micro electronic group for high precision time measurements\(^8\). The CERN/ECP chip provides a time stamp of each incoming hit, with zero conversion time and a 20 bit dynamic range (the most significant 16 bits are the coarse time counting in clock cycles; the 5 LSB define the TDC tickmark size, depending on the clock speed). The two hits resolution on a single channel is 10 ns and the rate capability is up to 1 MHz/channel with all channels hit simultaneously. The CERN/ECP chip has an internal circular hit buffer and the capability to retain only those hits within a software set time window. In FAST, the trigger for the TDCs is provided by the pion entering into the target and the time window is set approximately to \([-8, 22]\) µs with respect to the trigger. Four CERN/ECP TDC chips are hosted in one CAEN V767 board, which manages the sharing of the information from the chips and the dispatch of the control signals (e.g. trigger and clock) to each chip. Beside this, the board is in charge of the VME interface of the TDC chips. It provides a local memory FIFO buffer, that can be readout via VME, in a completely independent way from the acquisition itself. Each CAEN V767 unit has a total of 128 independent Time to Digital Conversion channels. In total 16 TDC units are needed for the FAST readout, for a total of \(128 \times 16 = 2048\) available channels (1536 of which are used for data, the rest for control words information). Each TDC maps a rectangular region of the target (8 \(\times\) 12 pixels, see Fig. 1).

The TDC can be driven either by an internal 40 MHz clock or by an external clock (maximum allowed frequency 45 MHz). The requirements for FAST of high precision (\(\Delta t \sim 0.1\) ps) and high stability (\(\Delta t/t < \frac{0.1\text{ ps}}{2\mu s} \Rightarrow \Delta t/t < 5 \times 10^{-8}\)) are beyond the performance of temperature compensated crystal oscillators, like the ones internal to the CAEN V767 boards (\(\Delta t/t \sim 10^{-6}\)). This imposes the use of a more precise external clock. FAST adopts a 60 MHz Rubidium atomic frequency standard\(^6\), prescaled by a factor two to 30 MHz, with a precision that largely exceeds the requirements (\(\Delta t/t \sim 2 \times 10^{-10}\)). A calibration and monitoring system, based on a pair of these clock units – one to provide the clock to the TDCs, the other to verify possible time drifts – is used to verify the stability of the time measurement and the full functionality of the system. With the 30 MHz clock choice, the TDC LSB (1 tickmark) corresponds to 1.041667 ns. A small non linearity effect (deviation of the tick length over one 32 ticks clock cycle) at the level of 0.1%, is observed in the TDC’s, both from dedicated laboratory tests and in the collected data.

\(^5\) http://www.caen.it/nuclear/product.php?mod=V767
\(^6\) from Quartzlock UK, Totnes England
The Data Acquisition System (DAQ) for FAST is in charge of the following tasks:

1. Measure the timing of the raw pulses (LL outputs of the discriminators), corresponding to all hits in the detector. This is done by means of the CAEN V767 TDCs, clocked by the accurate frequency standard.
2. Build the events, grouping together the hits that are fragments of the same event.
3. Pass the fully reconstructed events to the analysis stage, which has to recognize the particles in the $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ chain and extract the muon decay time from it.

The architecture of the DAQ system is schematically illustrated in Fig. 7. The 16 CAEN V767 TDCs are accommodated in eight VME crates. A VME-PCI interface (PVIC link\(^7\)) allows a CPU-less access to the VME bus by the dedicated DAQ PC’s (daq0x in figure) through their PCI bus. Eight PVIC chains are used in total, each one linking one VME crate to the corresponding dual processor DAQ PC. The maximum nominal data rate extraction from every VME-PVIC node is $\sim 20$ MB/sec. This limits the maximum data rate from the DAQ to 160 MB/sec. Data are read out from the DAQ PC’s by means of a collector PC, which receives data and routes them towards the event builder PC’s, sending time-slices of the collected data in a round-robin fashion. No event tagging is provided by the TDC itself. The reconstruction of the events is then performed at the event builder stage, on the basis of two control signals – tag1 and tag2 – sent simultaneously to all TDCs into two dedicated channels. The two tags are provided by two asynchronous clocks with periods chosen such that at least one tag1 and one tag2 appear in the TDC time window $[-8, +22]$ $\mu$s. The chosen tag period are 18 $\mu$s for tag1, 19 $\mu$s for tag2. The pair of their time difference w.r.t. the trigger time constitutes the unique event number attached to every fragment, that permits to group together the fragments coming from different TDCs but forming the same event. The probability of getting two uncorrelated fragments matched together is less than $10^{-6}$. The event builder PC’s are four dual processor machines, which also host the code running the full analysis. Once the event is completely built, it is passed to the analysis stage, and the relevant histograms are produced and stored on a RAID disk server. With the DAQ design of Fig. 7, bandwidth saturation is reached for TDC trigger rates (LV2) above 100 kHz. Both event reconstruction and analysis have to be performed in real time, because storing all data information on disk would require up to 7 TB per running day. Therefore, only the histograms plus a fraction of the full data sample ($\sim 1/100$) are

\(^7\)http://www.ces.ch/products/links/pvic_8026.html
stored.

Fig. 7. DAQ architecture design for FAST, corresponding to a maximum achievable bandwidth of 160 MB/sec (8 PVIC nodes).

8 The LV2 trigger system

The maximum data throughput that the FAST DAQ can sustain is 160 MB/sec (Fig. 7). Simulations of the response of the target at high beam rate, show however a data bandwidth exceeding this value by more than one order of magnitude. A second level trigger system (LV2) is needed to reduce the data bandwidth at an early stage of the DAQ.

The LV2 trigger [5] represents a selective trigger for the TDCs, the selection being based on the definition of a certain region of interest for each event. At the same time it also performs an event selection, retaining only those events where both the stopping $\pi^+$ and the subsequent $\pi^+ \rightarrow \mu^+$ decay are observed. In addition, it also provides the coordinates of the stopping particles, thus helping in the identification of the correct hits for the $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ chain in the analysis stage.

The LV2 uses as input the HL data from the discriminators, plus the LV1

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8 In these simulations it is assumed that all 16 TDCs are readout for every incoming LV1 beam trigger.
trigger, indicating a pion entering the target. It processes this information, in the following consecutive three stages:

(1) **First snapshot operation**: The system calculates the coordinates \((x_\pi, y_\pi)\) for the stopping \(\pi^+\). To do this, it latches all the HL hits from the discriminators in the time window \([t_0, t_0+15 \text{ ns}]\) – being \(t_0\) the time of the LV1 trigger – and identifies the most penetrating one, using a dedicated algorithm which accounts also for possible inefficiencies in the target.

(2) **Second snapshot operation**: The system searches for the presence of a hit in the same \((x_\pi, y_\pi)\) pixel or in an adjacent one, among the HL hits from the discriminators in the time window \([t_0+15 \text{ ns}, t_0+100 \text{ ns}]\). This second snapshot signal corresponds to the \(\pi^+ \rightarrow \mu^+\) decay and represents the second level trigger itself.

(3) If both the first and second snapshots operations are fulfilled (i.e. both a pion and a muon are found), then the so-called “superpixel” – 7×7 pixels around \((x_\pi, y_\pi)\)– is calculated and a trigger is sent only to those TDCs containing at least one pixel of the superpixel. The average number of triggered TDCs is 2.4, instead of 16 (in each event it can be only 1, 2 or 4). Together with the trigger, the coordinates \((x_\mu, y_\mu)\) of the stopping muon from the 2\(^{nd}\) snapshot are sent to the TDC and then passed as additional information into the analysis.

The electronics system for the LV2 trigger consists of 17 FPGA-based boards, divided in 16 region processors, one per TDC, in charge of the 1\(^{st}\) and 2\(^{nd}\) snapshot operations, plus one main controller, which computes the superpixel location and sends the trigger to the interested TDCs. All LV2 boards are accommodated in a single 6U 19” crate and interconnected via a custom designed backplane. The LV2 system is designed for high rate environments. It operates at up to 1 MHz LV1 trigger rate and can process multiple LV1 triggers in parallel, provided they are separated by at least 50 ns (LV1 dead-time). This imposes a low processing time for each event (180 ns at maximum); with an appropriate input buffer to compensate the possibility of several LV1 signals in a short time, the electronics virtually turns into a dead-time-free system.

The global efficiency for the LV2, defined as the ratio between the number of output LV2 triggers and the number of input LV1 triggers, is about 40%, totally dominated by the double hit resolution of the discriminators. The working conditions for FAST correspond to a trigger rate LV2 \(\sim 100 \text{ kHz}\) (i.e. \(\sim 270 \text{ kHz}\) rate of LV1 pions in the target) which corresponds to a data taking period of a few months for the collection of the full statistical sample of \(\geq 2.5 \times 10^{11}\) events.
The task of the data analysis is the reconstruction of the correct $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ chain, out of all the hits belonging to the same event in the full $[-8, +22]$ $\mu$s time window. The reconstruction uses the position and time information of the LL hits recorded in the TDCs, plus the additional control words (LV1, LV2, $z$-counter) attached to every event and registered as well in the TDCs. The LV1 hits define the zero-time reference for the event ($t_e = 0$), the LV2 coordinates identify the muon stopping pixel and the $z$-counter hits measure the $z$ (vertical) position of the pion in the target. The event selection is structured in two steps. Firstly, a set of quality cuts is applied: they mainly reject events with pion stopping points either close to the edges of the target, or at a depth not compatible with the prediction from the $z$-counter measurement. Secondly, positron tracks are identified using a set of 512 predefined mask topologies in a $5 \times 5$ pixels matrix centered on $(x_\mu, y_\mu)$ i.e. fully contained in the superpixel.

The mask topologies are based purely on geometrical considerations and are chosen to be highly efficient for accepting true positrons from muon decays (including the effect of pixel inefficiencies), while suppressing false positrons due to tracks from other beam particles or decays elsewhere in the target that overlap the superpixel. If more positron candidates are found (two or more possible patterns fulfilled by different tracks) the event is rejected. Once a positron candidate is accepted, the absolute decay time is taken as the average of all the positron pixels within the superpixel. The efficiency of the total quality and geometrical cuts is approximately 60%, the efficiency for positron identification is around 70%, which makes the global efficiency (from data to muon lifetime histogram) equivalent to 42%.

As previously explained, the analysis of the full data sample is performed online. The original bulk of data is not retained after the analysis, but only a small fraction ($\sim 1/100$) of the events. The analysis output information is a set of histograms which are stored periodically (every few minutes) on disk, so that not only the results on the full statistics, but also the information about their time evolution are accessible. Together with the global lifetime histograms ($t_e - t_\mu$ or equivalently $t_e - t_\pi$ distribution) used for the muon lifetime measurement, additional histograms ($\sim 1200$) are produced online, including both control histograms to monitor the detector performance and several dedicated muon lifetime histograms to assess any potential systematic effect on the measurement (e.g. lifetime vs position of the decay in the target; lifetime vs positron pattern topology...).

An additional set of control histograms is produced in quasi-real time on the

9 Typically three positron hits for the $e^+$ track resulting from the $\mu^+$ decay are found in the superpixel, and they are sufficient to define the time of the track.
prescaled sample to monitor the stability of the system. The histograms contain information on critical quantities (timing, multiplicities, TDC operation and LV2 functionality), allowing a fast monitoring of the data quality. A subset of these histograms is used to validate the corresponding data sample by comparing it with a reference run. If any distribution falls outside the predefined tolerance range, a warning is registered by the monitor program and, eventually, an automatic action is taken on the system. A web-based interface allows remote, platform-independent visualization of the monitor information.

10 Detector commissioning and performance

The performance of the FAST detector has been assessed using dedicated positron runs for calibrations and efficiency, and the first pilot physics run of 2006 [6].

Positrons from the beam are good tools to measure both the detection efficiency for each pixel in the target and the time resolution of the full readout chain. Beam positrons are identified in the FAST target as straight mip tracks crossing the full detector and uniformly illuminating all pixels. The target response is equalized by adjusting individually the high voltages for the PSPMs. The high voltage tuning is done both without and with the magnetic field in the target region. Compatible settings are obtained in both cases. The measured average pixel detection efficiency for mips, after the target equalization and including geometrical effects in the definition of straight tracks, is around 85%. The time resolution of the full readout chain is \( \sigma = 0.994 \pm 0.001 \) TDC ticks (Fig. 8). It is defined as the deviation of the times of the hits belonging to a positron track with respect to their average. This resolution includes both the hardware resolution coming from small differences in cable lengths, and the fine adjustment of the time in the software, needed to synchronize the zero time of each TDC with the particle tracks. The measured efficiency and time resolution are good enough to perform a measurement with the expected precision.

The FAST detector has been operated in fully realistic data taking conditions, in the pilot physics run of 2006, at a reduced LV2 trigger rate of 30 kHz. A total of \( 1.073 \times 10^{10} \) muon decay events were recorded. Figure 9 shows the typical geometrical uniformity achieved for the pions stopping points. A good uniformity in both the horizontal and vertical planes is obtained. The effect of the wedge, combined with the hodoscope counter \((z\text{ coordinate})\) is clearly visible. Fig. 10 represents the muon lifetime distribution. Together with positive times positrons, from which the lifetime \( \tau_{\mu} \) is measured, also the positron times up to \( 8 \mu s \) before the arrival of the beam pions \((t_e = 0)\) are recorded, for a detailed study of the structure of accidental background.
Details of the physics measurement and analysis method are in reference [6]. The results show the high performance obtained with the FAST detector, as well as the control of systematic uncertainties to perform a measurement of $G_F$ at the level of 1 ppm precision.

Fig. 8. Time difference between the times of the hits of a straight track and the average time of the track itself, measured in TDC ticks. The fitted $\sigma$ represents the achieved time resolution of the full readout chain ($\sim 1$ ns).

Fig. 9. Distributions of the stopping pion points for a typical pion run. On the left is the stopping pion distribution in the horizontal ($x,y$) plane. On the right is the stopping pion distribution in the vertical ($x,z$) plane, showing the effect of the wedge.

11 Conclusions

FAST is a detector for a high precision measurement of the positive muon lifetime $\tau_\mu$ and the Fermi coupling constant $G_F$. The experiment is designed to suppress as far as possible the systematic errors at the detector level. It
Fig. 10. Muon lifetime distribution obtained in the pilot physics run of 2006 [6]. A total of $1.073 \times 10^{10}$ events were recorded at an average LV2 trigger rate of 30 kHz.

The FAST performance has been assessed in several dedicated testbeams and calibration runs. A first physics run of about $10^{10}$ events allowed for a measurement of $\tau_\mu$ to a precision of 16 ppm (8 ppm precision on $G_F$) [6]. Since then, the experiment has been operated in nominal running conditions. At present FAST has completed the data taking. A total statistics of $4.2 \times 10^{11}$ muon lifetime events has been collected and the systematics analysis studies towards the final $\tau_\mu$ measurement are currently ongoing.

References


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