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The Timepix telescope for charged particle tracking

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ABSTRACT

The Timepix telescope has been developed as a general purpose tool for studying the performance of position sensitive charged particle detectors. Initiated as part of the infrastructure for the development of a new vertex detector for the LHCb experiment, the system was extended under the FP7 project AIDA to allow its use as an external facility by several groups within both the high energy and medical physics communities. Based at the CERN SPS, high track rates (up to 18 kHz), precise spatial resolution at the device under test (down to 1.6 μm), and a flexible integration method have all been demonstrated. The telescope is constructed using the Timepix ASIC, a hybrid pixel chip with an active area of $14 \times 14\ mm^2$.

1. Introduction

The telescope has been constructed around the Timepix ASIC [1], a hybrid pixel chip, bump bonded to 300 μm thick silicon sensors and exploiting both the small pixel pitch (55 μm) and the two complementary modes of operation. Each detector plane of the telescope can be run in either Time over Threshold (ToT) or Time of Arrival (ToA) mode, measuring either the charge deposited or arrival time of the particle respectively. Triggering of the system is by means of a camera-style shutter, with the entire matrix of 256×256 pixels continuously active while the shutter is open. When the shutter is closed, the readout of the full matrix is triggered, and the front end is completely inactive during this period.

2. Hardware overview

2.1. Telescope systems and hardware

The telescope is split into two separate arms. The arm upstream of the device under test consists of a single scintillator and 4 Timepix planes operating in ToT mode. This arm acts solely as a tracking system, and each of the planes are angled to 9° in both the x and y directions in order to maximise the single hit resolution due to optimal charge sharing [2]. The downstream arm contains a second scintillator, 4 Timepix planes operating in ToT mode (again angled in x and y), and a single Timepix plane operating in ToA mode. This final plane is orientated perpendicular to the beam direction, and is used to provide a time stamp to each spatially reconstructed track, which can be matched to the recorded scintillator times (described in detail below). Together, the telescope thus consists of crossed scintillators mounted at opposing ends of the setup, two separate tracking arms of 4 detectors each, and a single time-stamping plane, shown schematically in Fig. 1 [3].

The telescope is read out using a portable FPGA-based readout system, the RELAXd [4]. This allows the telescope to be operated by means of an externally generated shutter making use of the coincident scintillator signals. These are used to generate a beam present signal, which is vetoed by the busy signal which persists during the system readout. When the readout is complete, a new shutter is generated, with this process repeating for as long as the beam present remains. As the granularity of the chips is high, and the readout time is relatively long (of order 15 ms), multiple tracks are allowed to pass through the telescope during each shutter. This allows track rates far in excess of the frame rate (60 Hz) to be written to disk. While the shutter is open, the number of triggers allowed to pass through the telescope is controlled by counting the number of coincident scintillator hits: once the required number of tracks have traversed the system, the shutter is closed and the chips read out. Alternatively, a timer is used to close the telescope after a maximum shutter length has been reached, a particularly important requirement for the time stamping (see below). These two closing criteria allow complete control over both the occupancy and maximum shutter length.

Each arm is mechanically independent along the z- and y-axis, allowing the space between the arms to be varied to accommodate

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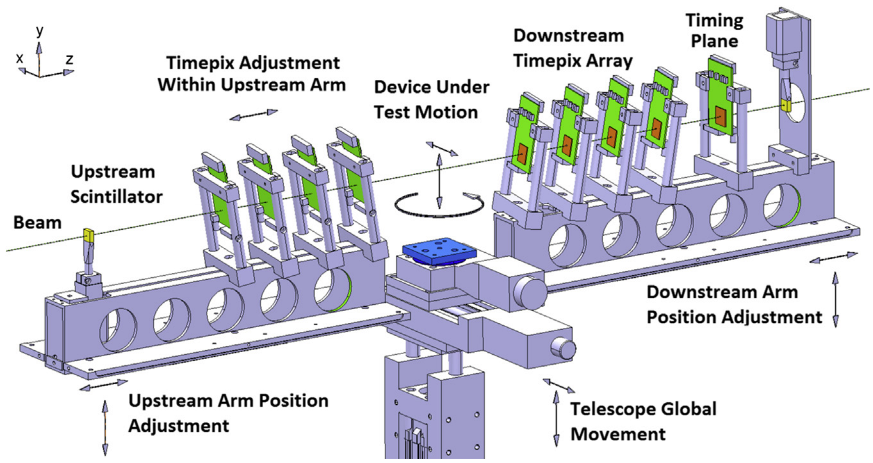

Fig. 1. Layout of the Timepix telescope.

for devices of varying size. The maximum clearance in this direction is around 46 cm.

A high precision TDC (time-to-digital convertor), built on VME, is used to record the times of each shutter, and both the raw and synchronous triggers. The system has a precision of around 1 ns. The remaining hardware consists of the various low- and high-voltage power supplies which are used to run the telescope, and are all remote configurable for minimisation of interventions.

2.2. Device under test

A space in the centre of the telescope is provided to accommodate the device under test (DUT). Remote operation of several motion stages is available, giving micron precision movement in the x and y directions and rotation around the y-axis to an accuracy of a hundredth of a degree. This is illustrated schematically with the setup in Fig. 1. Hardware communication between the DUT and the telescope has been deliberately kept to a minimum in order to reduce the level of integration required before data taking. For a simple triggered DUT (devices that require a single trigger for each particle, such as LHC-style devices), a trigger is provided which may optionally be synchronised to an external clock. If a busy signal is available from the device, then this can be used to veto triggers to the TDC system while the device is unable to accept further events. This ensures that the number of triggers seen by both the timing system and the DUT is identical.

3. Data analysis

A software package has been developed to analyse the telescope data. This is built on a modular, GAUDI-like structure [5], written in C++, and consists of two distinct stages. In the first, termed the amalgamation, the raw data files from all devices (telescope, TDC, and optionally DUT) are read in and matched based on their file timestamps, taking advantage of the beam structure present in the SPS (10 s of beam-on followed by approximately 40 s of beam-off). This is performed with no knowledge of timing within a shutter or of spatial information from the telescope, and produces an ntuple containing all of the data, sorted into simple classes for easier handling. This ntuple only needs to be produced once, and serves as the input for the second software stage (the analysis).

The analysis step sees several algorithms run sequentially, on a frame-by-frame basis, on the structured ntuple. Information is passed between algorithms by means of a “Clipboard”, which is present in the initiation of each algorithm. A list of default global parameters is supplied via a single C-file, with all run specific information contained in a configuration file. This configuration file allows the user to specify which algorithms are run on the data, run-specific information such as the device ID of the DUT, and any specific requirements on the telescope reconstruction (such as number of planes required for each track, etc.). A typical analysis sequence would consist of: clustering (telescope only), pattern recognition, track fitting, time stamping, and some algorithm to analyse the DUT. A brief description of the main points in this chain are given below.

3.1. Pattern recognition

The pattern recognition algorithm picks up clusters from the telescope planes, and uses clusters from the most upstream plane as seeds for track making. Two methods have been implemented to perform this function, both reliant on fast nearest-neighbour algorithms [6]. In the first, the seed cluster is effectively extrapolated directly along the z-axis. The x–y position of the seed is used in the nearest neighbour search on the following telescope plane, and if a cluster is found within the radial limits of the search then it is added to the track. This new cluster is then used to search on the following plane, and so on for the rest of the telescope. As expected, this method predominantly finds straight or shallow angled tracks. In the event of a large extrapolation distance between the telescope arms and significant multiple scattering, degradation of the pattern recognition was expected; to this end a second method using a continual fit and extrapolation was developed. For the first cluster, this method is necessarily identical to the previous method. However, once a second cluster has been added to the prototrack with the seed cluster, a linear fit of the clusters is made, and a projection made to the following telescope plane. If a cluster is found on this plane, the now three-point track is refitted, and linearly extrapolated again. This continues until the requisite number of clusters have been found to produce a track.

An obvious drawback to this method of reconstruction is the chance that two tracks overlap, and that within the error provided by multiple scattering and the single plane resolution they cannot be individually resolved. This will scale as a function of the total telescope occupancy, and would be expected to account for increasing inefficiencies in the track reconstruction at high track rates. To reduce the effect of mis-reconstructed tracks on the analysis of the DUT, a χ^2 cut is performed on all tracks, to preserve only those of sufficient quality.