Proc. 31st Int. Workshop on Vertex Detectors (VERTEX2022)
JPS Conf. Proc. **42**, 011007 (2024)
https://doi.org/10.7566/JPSCP.42.011007

Early data from the tracking detector for the FASER experiment

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(Received January 20, 2023)

FASER is a new experiment designed to search for new light weakly-interacting long-lived particles (LLPs) and studying high energy neutrinos in the very forward region of the LHC collisions at CERN. The experimental apparatus is situated 480 m downstream of the ATLAS interaction-point aligned with the beam collision axis. The FASER detector includes four identical tracker stations constructed from silicon micro-strip detectors. Three of the tracker stations form a tracking spectrometer, and enable FASER to detect the decay products of LLPs decaying inside the apparatus, whereas the fourth station is used for the neutrino analysis. All tracker stations have been installed in the LHC complex in 2021. FASER has already started physics data taking since the LHC resumed operation in July 2022. This contribution describes the design, construction and early data of the tracker stations.

KEYWORDS: silicon detectors, strip detectors, detector systems, high-energy physics, forward physics

1. The FASER experiment

FASER is a small and cost-efficient experiment searching for light, weakly-interacting, long-lived particles and high energetic neutrino in the very forward direction of the collisions at the Large Hadron Collider (LHC). The experiment has been proposed in 2017 [1], technically designed and built starting from 2018 [2–4] and the final detector was installed and commissioned in 2021 [5]. Since the beginning of LHC Run-3 in 2022, FASER has collected data very efficiently.

The detector itself is located in an old, unused service tunnel about 480 m away from the beam-beam interaction point of the ATLAS experiment (IP1). Due to the curvature of the LHC tunnel and the position of the service tunnel, FASER can be placed in the direct line of sight of the collision axis at IP1. The location in the side tunnel shields the detector very well from most of the beam induced background radiation. Particles coming from IP1 have to travel for a long distance through concrete and rock in order to reach FASER and, therefore, the only Standard Model particles that are expected to arrive at the detector location are muons and neutrinos. The goal is to find the decay products of exotic, weakly-interacting, long-lived particles which decay in the dedicated decay volume inside of the FASER detector.

Figure 1 shows FASER and all its sub-detectors. Particles coming from IP1 traverse at first FASERν, which is an emulsion-based extension of the FASER detector that allows for precise, flavor-resolved neutrino measurements [6]. Next follows a set of veto scintillators that allow discriminating incoming muons efficiently from a potential (invisible) exotic long-lived particle. The long-lived particle can decay in the following decay volume, which is a 1.5 m-long permanent magnet with a magnetic flux density of about 0.6 T and an aperture diameter of 20 cm. After the decay volume, an additional set of scintillators allow for triggering and additional timing measurements. Subsequently, particles will enter a spectrometer, which consists of three tracker stations [7] interleaved with two 1 m-long permanent magnets similar to the permanent magnet of the decay volume. The spectrometer

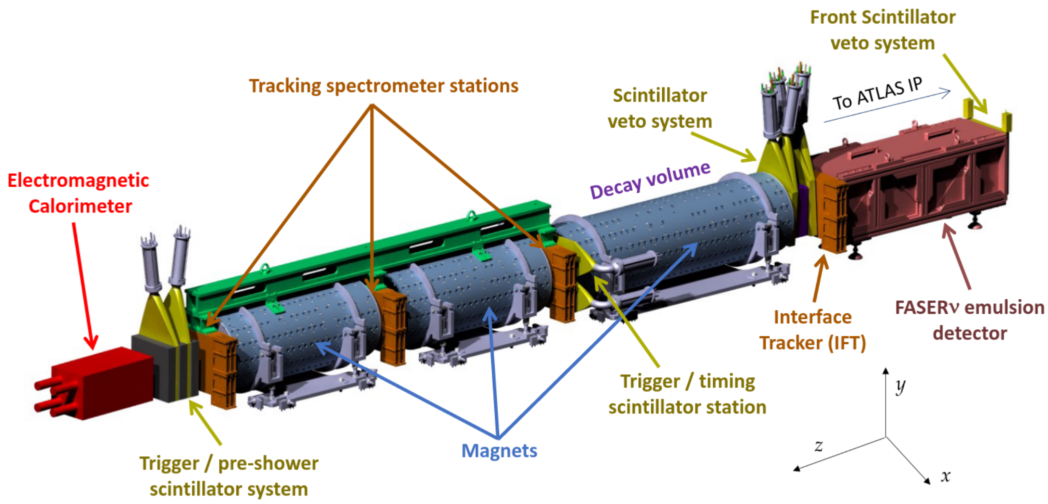

Fig. 1. Sketch of the FASER detector. The detector is pointing to the collision point of the ATLAS experiment. The particles from the interaction point are entering from the right. [5]

allows measuring the momentum of charged particles as well as the sign of its electric charge. The details of the tracker stations will be discussed in much more details in section 2. The spectrometer is followed by an additional set of scintillators which are used for triggering, but also act as a pre-shower detector helping with the particle identification. Finally, a stack of 2×2 calorimeter blocks with a depth of 25 radiation lengths are in place at the very end in order to measure the particle's energy. A detailed description of all the detector components can be found in [5].

The overall design of the FASER experiment is driven by the limited time available for the design and construction of the detector, the space-constrains in the service tunnel as well as the available budget. For these reasons, where ever possible, existing detector components have been reused. The calorimeter cells, for instance, are four spare units from the outer electromagnetic calorimeter of the LHCb experiment [8] while the tracker has been built from spare SCT barrel modules of the ATLAS experiment [9].

A typical signal FASER is searching for is a dark photon decaying into a positron-electron pair. Within FASER this would result in no signal in the veto station, a clear trigger signal from the remaining trigger stations, two highly collimated and oppositely charged tracks in the spectrometer, and a large energy deposition in the TeV range in the calorimeter. An excellent tracker is therefore a key ingredient for the discovery of the described signal.

2. Tracking Detector

The fundamental building block of the FASER tracker are spare silicon strip modules of the SCT subdetector of the ATLAS experiment (Figure 2 (left)) [9]. These modules consist of two silicon sensor pairs with the dimensions of about $12 \times 6\,\mathrm{cm}^2$ placed on top of each other with a stereo-angle of 40 mrad. Each silicon sensor consists of 768 strips with a pitch of $80\,\mu$m. The different strips are wirebonded to the ABCD readout chip [10] which features a binary readout with a trimmable threshold.

In order to completely cover the aperture of the magnets of the FASER detector ($d = 20\,\mathrm{cm}$) a set of 2×4 modules form a tracker plane with an sensitive area of $24 \times 24\,\mathrm{cm}^2$ (Figure 2 (middle)). A mechanical support structure made of aluminium holds the modules in place and acts in addition as a cooling interface as it features integrated cooling channels. The cooling plant is operated at $+15\,°\mathrm{C}$

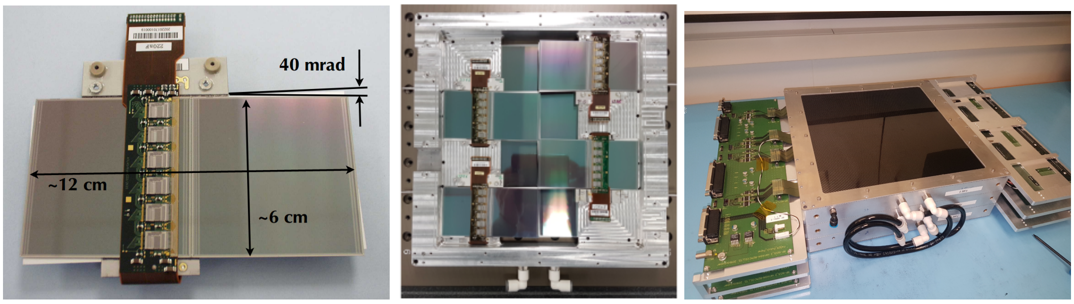

Fig. 2. The building blocks of the FASER Tracking Detector. Left: ATLAS SCT barrel stereo module. Middle: 8 modules arranged in a mechanical frame forming a tracking plane. Right: Three planes put together to form one of the four FASER tracking stations.

resulting in module temperatures at around +30 °C, which is sufficient for safe operation.

Three tracker planes are eventually stacked in order to form a tracker station (Figure 2 (right)). A pair of carbon fiber entry and exit windows protects the silicon modules without adding too much material in the tracking volume. The volume inside of a tracker station is constantly flushed with dry air in order to avoid humidity close to the detector. Very careful metrology during the assembly of the tracker stations has been performed in order to guarantee a good understanding of the exact module positions inside each tracker station.

The three tracker stations behind the FASER decay volume are mechanically connected to each other via a rigid metal structure. An additional tracker station is placed in between FASERν and the veto station. The purpose of this interface tracker (IFT) station is to improve the matching between the reconstructed tracks from the emulsion detector and the remaining detector systems of FASER.

The tracker front-end chips are read out with custom designed readout boards. Details on the FASER trigger and data acquisition system can be found in [11]. Each tracker station is equipped with a number of temperature and humidity sensors which are continuously read out with a microcontroller. The monitoring values are stored in a database for the long-term history. Two temperature sensors per plane are used as input to a hardware-based interlock system which is connected to the HV and LV power supplies and can stop power in case of temperatures outside of the operational range. A detector control system (DCS) based on WinCC provides a finite state machine which allows the efficient and safe control of the involved power supplies of the entire FASER detector.

Many more technical details on the different parts of the FASER tracker system can also be found in [7].

3. Tracker Performance

In order to monitor the performance of the readout-chip, a set of standard calibrations is run on a regular basis. Besides the standard scan to identify (and mask) noisy and dead strips, the amplifier response of the different strips is measured regularly. For this, a threshold scan is performed for different injected test charges (1.5 fC, 2.0 fC, 2.5 fC) and the corresponding threshold is determined from the resulting s-curve. From the slope of a linear fit of this response curve, the amplifier gain for each strip is determined, which is depicted in Figure 3 (left). The distribution peaks around 50 mV/fC, which is in very good agreement with the design value of the chip [10] and the observations from the ATLAS SCT community [12]. From the width of the s-curve for an injected charge of 2 fC the electronic noise can be measured which is depicted in Figure 3 (right). The measured average noise of about 1500 electrons is again in very good agreement with the expectations from the chip design [10] and with SCT operation experience [12]. In both described plots, four measurements throughout

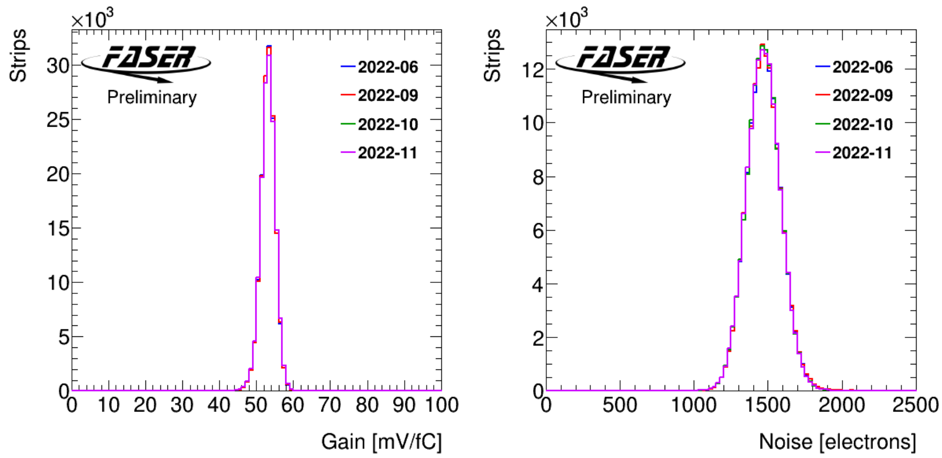

Fig. 3. Key properties of the readout chip measured over the course of the year 2022. Left: Relation between amplifier voltage and effective threshold charge. Right: Threshold dispersion at an injected charge of 2 fC. The distributions remain constant over the time of the detector operation.

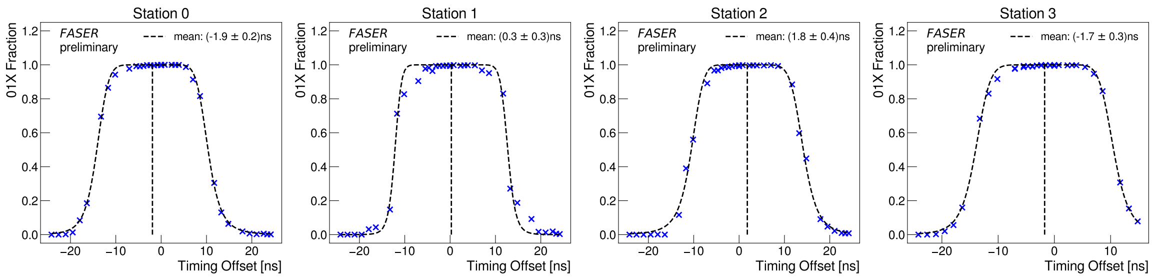

Fig. 4. Fine timing adjustments with collisions from early, low-luminosity LHC fills for the four different FASER tracking stations. For each received trigger, the readout chip returns the information of three consecutive bunch crossings (25 ns time bins) in its pipeline buffer. A hit with good timing is considered as 010 and 011 (=01X). The fine timing of the DAQ system has been adjusted such that the working points are in the middle of the efficiency plateau.

2022 are overlaid. Barely any differences between the measurements at different points in time are noticeable, which demonstrates how stably the readout chip has performed in 2022.

Despite the fact that the FASER tracker has been operated successfully since its installation in 2021 taking cosmic events, actual LHC collisions are required to fully optimize the timing and delays of the detector. Low-luminosity LHC fills during the intensity ramp-up of the LHC have been used for this purpose. The muon rate through FASER originating from LHC collisions amounts to about 1 kHz for these fills. The coarse timing of the detector was adjusted globally using trigger latency settings, while the fine timing was optimized for each station individually using clock delays on the different DAQ readout boards. Whenever a trigger arrives at the readout chip, the chip returns the three consecutive bunch crossing information in the pipeline buffer with the trigger at the middle bit. The hit patterns 010 and 011 (=01x) are thereby considered as a hits with good timing. Figure 4 shows the fraction of tracker hits with good timing for different fine timing settings. The dashed lines indicate the working points chosen for the different stations for the data taking period in 2022, which are always located in the middle of the efficiency plateaus.

The early LHC fills have also been used in order to measure the dependency of the hit efficiency

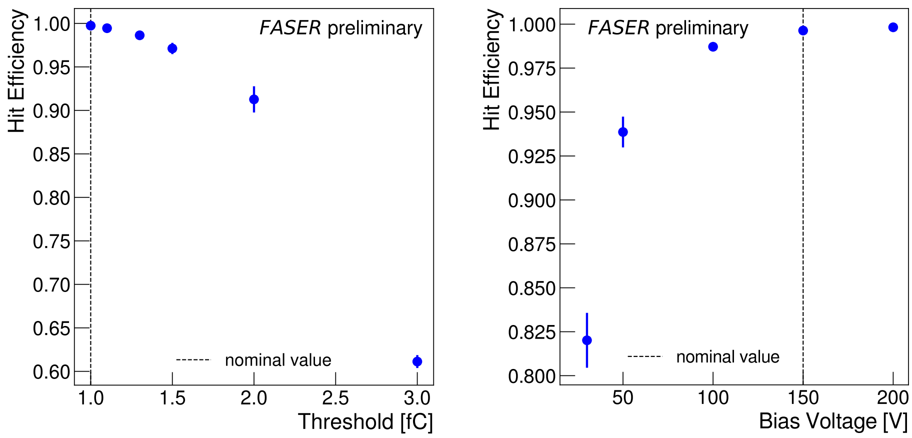

Fig. 5. Measured hit efficiency for different operation parameters. Left: Readout chip threshold. Right: Sensor bias voltage. A hit efficiency of 99.64% is achieved at the operation settings of the tracker (V_{bias} = 150 V, threshold=1.0 fC).

on the threshold settings in the readout chip as well as the sensor bias voltage. The hit efficiency is measured by changing the corresponding parameters just in one plane of a station and excluding this layer from the track reconstruction. If a strip in the excluded layer is showing a hit that is closer than 0.5 mm to the expected position from the reconstructed track, this hit is counted. Figure 5 shows the results of these measurements which are in very good agreement with the old measurements from the ATLAS SCT community [12] for an unirradiated detector. The dashed lines in the plots indicate the nominal operation settings for the FASER tracker in 2022. At a sensor bias voltage of 150 V and a threshold setting of 1.0 fC, a hit efficiency of 99.64% is achieved. It is worthwhile noting that the FASER tracker will not face any substantial radiation damage during its lifetime and, therefore, it is expected that those operation parameters will not require further adjustments in the future.

Figure 6 shows the hit maps of reconstructed space points of all the different layers and stations of the FASER tracker for data collected during LHC fill 8491 corresponding to an integrated luminosity of 559.8 pb^{-1}. The arrangement of the different detector modules in each plane is clearly visible. Due to an overlap of the modules at $x = 0$ mm, a higher hit density can be observed at this location. In the y-direction the module sensors have an insensitive region of about 1 mm each. In order not to generate holes in the detector hit acceptance, the planes within a station are shifted with respect to each other by ±5 mm in the y direction. In station 3 layer 0 an inefficient region can be spotted which originates from a noisy chip with many masked strips. Due to the large number of available tracking layers, this has however no impact on the detector performance.

Overall, only less than 0.5% of strips are found noisy or masked and are therefore excluded from data taking.

4. Operation

The FASER detector including the FASER tracker is operated completely remotely by two people. No dedicated control room exists. A Run manager powers the detector, supervises the data taking runs, and coordinates calibration activities during inter-fills and tunnel accesses. A second person monitors several time per day the key properties of the detector, like leakage currents, LV power, environmental conditions, and general data quality. The work of the operation team is supported by monitoring and communication tools, like Grafana dashboards and mattermost communication channels with automatic alerts. The detector can be operated from anywhere in the world.

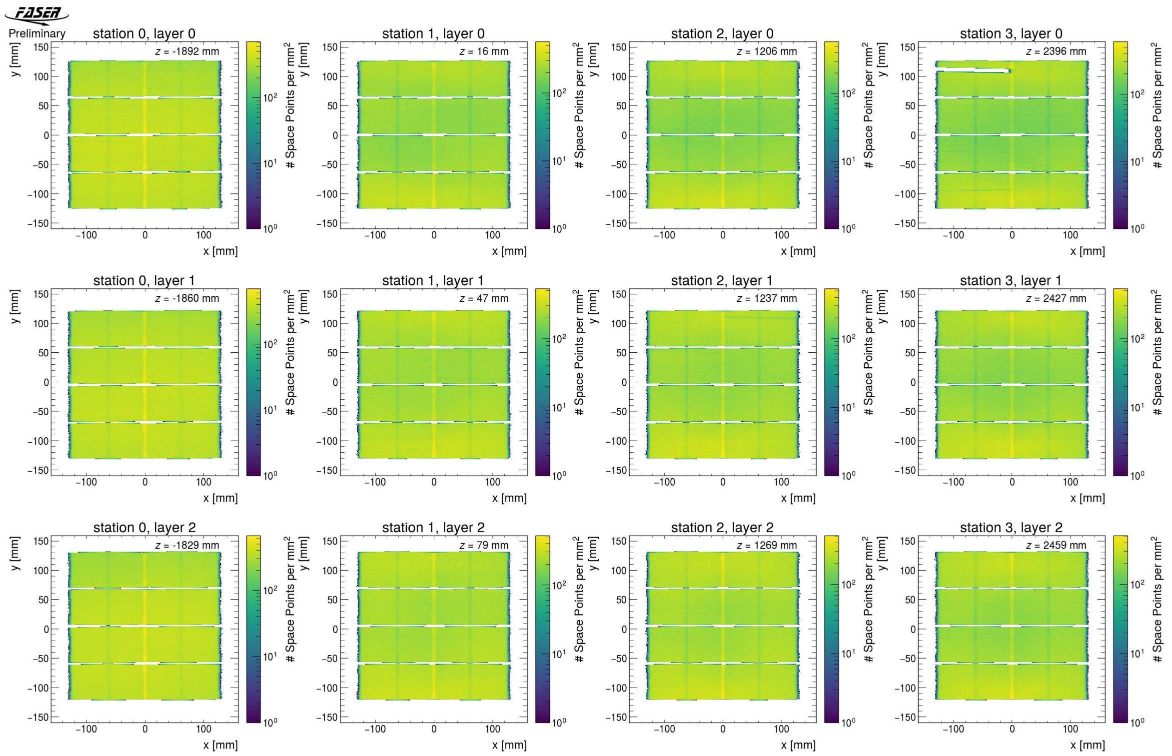

Fig. 6. Hit maps of the reconstructed space points. The arrangement of the different modules can be recognized. In order to avoid gaps in the hit acceptance of the detector originating from insensitive regions of the modules at the borders in the different planes, the planes are shifted by 5 mm in y direction with respect to each other. The shown data corresponds to an integrated luminosity of 559.8 pb^{-1}.

With this operation model in place, FASER has successfully collected almost 40 fb^{-1} of data in 2022.

Figure 7 (top) shows an event display with a muon candidate with $p = 21.9$ GeV traversing the entire FASER detector. In the bottom of the figure, a zoomed-in figure shows clearly the 6 activated silicon strips in the first tracking station.

5. Conclusions

FASER is a small and cheap experiment exploring the extreme forward direction 480 m downstream of IP1 looking for light, weakly-coupled and long-lived particles. The detector has been operated very successfully since its installation in 2021. Since 2022, FASER collects data from LHC collisions. By the end of the year, almost 40 fb^{-1} of data have been recorded. The FASER tracker as one of the main sub-detectors has performed extremely well during this data taking period, with a hit efficiency of 99.6% and less than 0.5% of inactive strips. The tracker behaves exactly as expected and no surprises have been found during operation. As a next important step, the final detector alignment needs to be finished, which is on-going at the time of the writing of these proceedings. The operation model of the FASER tracker has been well exercised and established. The FASER tracker is ready for the next years of LHC data taking to come.

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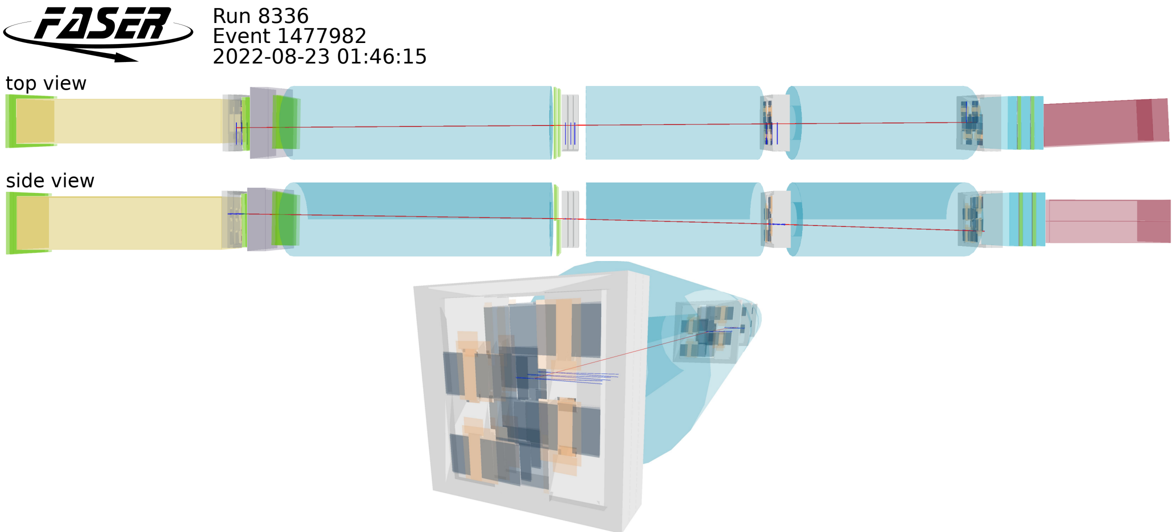

Fig. 7. Event display of a muon candidate with p = 21.9 GeV traversing the FASER detector. In the zoomed-in tracker station, six activated silicon strips can be observed.

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