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The FASER detector

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THE LARGE HADRON COLLIDER AND THE EXPERIMENTS FOR RUN 3 — ACCELERATOR AND EXPERIMENTS FOR LHC RUN3

The FASER detector



FASER Collaboration

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ABSTRACT: FASER, the ForwArD Search ExpeRiment, is an experiment dedicated to searching for light, extremely weakly-interacting particles at CERN's Large Hadron Collider (LHC). Such particles may be produced in the very forward direction of the LHC's high-energy collisions and then decay to visible particles inside the FASER detector, which is placed 480 m downstream of the ATLAS interaction point, aligned with the beam collisions axis. FASER also includes a sub-detector, FASER₂, designed to detect neutrinos produced in the LHC collisions and to study their properties. In this paper, each component of the FASER detector is described in detail, as well as the installation of the experiment system and its commissioning using cosmic-rays collected in September 2021 and during the LHC pilot beam test carried out in October 2021. FASER has successfully started taking LHC collision data in 2022, and will run throughout LHC Run 3.

KEYWORDS: Calorimeters; Gamma detectors (scintillators, CZT, HPGe, HgI etc); Particle tracking detectors (Solid-state detectors); Spectrometers

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Contents

1	Experimental overview	2
1.1	LHC Run 3 beam conditions and data	2
1.2	Physics reach for Long-Lived Particles	4
1.3	Neutrino physics programme	5
1.4	Detector requirements	7
1.5	The magnet system	9
1.6	The tracking system	9
1.7	The calorimeter and scintillator systems	10
1.8	Emulsion detector	11
1.9	Trigger and DAQ	11
1.10	Computing and software	12
1.11	Outline of this paper	12
2	The tracking system	12
2.1	SCT module	13
2.2	Tracker plane	14
2.3	Tracker stations	15
2.4	Alignment and metrology	17
2.5	Standalone tracking commissioning	18
3	The calorimeter, pre-shower and scintillator systems	20
3.1	Scintillator system	20
3.2	Calorimeters	22
3.3	Calibration system	24
3.4	Pre-installation commissioning	26
3.4.1	Standalone PMT tests	26
3.4.2	Scintillator counter measurements	28
3.4.3	Standalone calorimeter tests	31
3.4.4	LED calibration standalone tests	32
4	The trigger and data acquisition system	32
4.1	TDAQ core hardware overview	33
4.2	Readout hardware	34
4.2.1	Tracker readout board	34
4.2.2	CAEN digitizer	36
4.3	TDAQ software	37
4.4	Pre-installation commissioning	37

5	The magnet system	38
5.1	Magnetic design	39
5.2	Manufacturing and assembly	40
5.3	Magnetic measurements	41
5.4	Alignment	43
5.5	Magnet covers	44
6	Detector Control and Safety Systems	44
6.1	Power systems	45
6.2	Tracker cooling system	45
6.3	Tracker safety interlock	46
6.4	DCS software	47
7	The emulsion detector of FASER	48
7.1	Detector design	49
7.2	Emulsion films	49
7.3	Tungsten target	50
7.4	Mechanical structure	51
7.5	Operational procedure	53
7.6	Facility at CERN for the emulsion detector handling	53
7.7	Emulsion readout	55
7.8	Pilot analysis with the 2018 data	56
8	Detector integration	57
8.1	Preparation of TI12 for FASER	57
8.2	The detector support	58
8.2.1	The lower and upper baseplates	58
8.2.2	The upper frame	62
8.3	The cooling system	63
8.4	Detector grounding	64
8.5	Material inside the active detector volume	64
8.6	Detector installation	65
8.6.1	The detector and magnet alignment	68
9	Commissioning of the full detector	70
9.1	Commissioning with cosmic rays	70
9.1.1	Tracker	72
9.1.2	Calorimeter and scintillators systems	72
9.1.3	TDAQ system	73
9.2	Commissioning during the LHC pilot beam	74
10	Conclusions	77

1 Experimental overview

The ForWArD Search ExpeRiment (FASER [1–3]) is a new experiment at the CERN Large Hadron Collider (LHC) designed to search for light and very weakly-interacting new particles produced in the LHC collisions. With the addition of the FASER₂ sub-detector [4, 5], FASER can also detect and study neutrinos of all flavours produced at the LHC.

The detector is positioned on the beam collision axis line-of-sight (LOS) 480 m from the ATLAS collision point (interaction point 1, IP1) in an unused service tunnel, TI12. Figure 1 shows the location of the detector in TI12. To allow the detector to be placed on the LOS, a small trench was excavated in the TI12 tunnel. The size of this trench sets the overall detector dimensions, including the 10 cm radius transverse-size of the active part of the detector and the total length of about 7 m (FASER₂ has a transverse size of $25 \times 30 \text{ cm}^2$). The angular acceptance of FASER₁ covers the 0.21 mrad region (pseudorapidity 9.2) around the LOS, with respect to IP1, whereas FASER₂ extends to angles as large as 0.41 mrad (8.5).

Figure 2 shows a sketch of the FASER detector, with particles originating from collisions in IP1 entering from the right of the picture. From right to left, the detector consists of (i) a front scintillator veto system, (ii) the FASER₂ emulsion detector, (iii) the interface tracker (IFT), (iv) the FASER scintillator veto station, (v) the decay volume, (vi) the timing scintillator station, (vii) the FASER tracking spectrometer, (viii) the pre-shower scintillator system, and (ix) the electromagnetic (EM) calorimeter system. The detector includes three 0.57 T dipole magnets, one surrounding the decay volume and the other two embedded in the tracking spectrometer.

This paper describes the FASER detector as it was installed into the LHC complex in 2021. In the remainder of this section, an executive summary of the various detector components is reported, following a brief description of the expected Run 3 LHC beam conditions and dataset and the FASER physics programme. In the following sections, details of the various sub-detectors are provided, together with an overview of the installation procedure and the commissioning of the fully integrated detector.

1.1 LHC Run 3 beam conditions and data

LHC Run 3 follows the first two LHC running periods, and Long-Shutdown 2 (LS2). At the time of the FASER approval, it was scheduled to run from 2021 to 2023, and was expected to deliver 150 fb^{-1} of 14 TeV proton-proton collision data. Following delays accrued due to the COVID pandemic, the Run 3 schedule was updated, to start in 2022 and to run for four years, with an expected total luminosity of more than 150 fb^{-1} . Problems observed during the training of the LHC dipole magnets to high energy led to the decision to run the LHC at a centre-of-mass energy $\sqrt{s} = 13.6 \text{ TeV}$ during Run 3.²

During LS2 the LHC injector complex was significantly upgraded allowing it to deliver much brighter beams to the LHC, in anticipation of the high-luminosity (HL) LHC phase of operation (starting in Run 4). Since the LHC components and the experiments have not yet been upgraded to

¹The FASER detector uses a cartesian coordinate system with the z -axis pointing along the LOS away from IP1, the y -axis pointing vertically upwards, and the x -axis pointing horizontally towards the LHC machine. The origin of the coordinate system is aligned with the centre of the magnets in the transverse, $x-y$, plane and conventionally at the front surface of the second tracker station in the z coordinate.

²Most studies presented in this paper assume $\sqrt{s} = 14 \text{ TeV}$. However, the difference between 13.6 TeV and 14 TeV is expected to be negligible for FASER physics.



Figure 1. The FASER location: TI12 tunnel, 480 m downstream of the ATLAS interaction point. The detector is located along the beam collision axis line-of-sight.

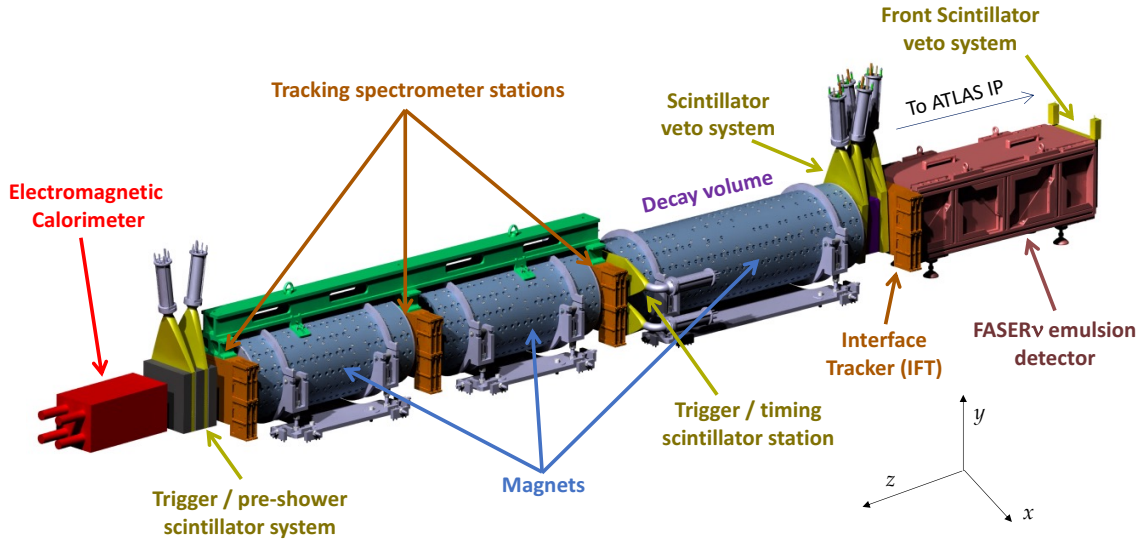


Figure 2. A sketch of the FASER detector, showing the different sub-detector systems. The FASER coordinate system is also shown.

be able to run at luminosities higher than $2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, the luminosity will be levelled at this value. This luminosity corresponds to about 55 interactions per bunch crossing (pileup), however given the large amount of shielding in front of the detector, FASER is not expected to observe signals from multiple simultaneous interactions.

The main LHC configuration parameters which can effect physics at FASER are the direction and magnitude of the beam crossing angle at IP1, since this moves the LOS compared to its nominal position assuming no-crossing angle ($\theta_{\text{cross}} = 0$) at IP1. In Run 3 the crossing plane in IP1 is vertical, but the direction (if the beams point up or down) will be changed during the run in order to distribute the radiation more evenly over the LHC magnets. The LOS at FASER moves by $480 \text{ m} \cdot \sin \theta_{\text{cross}} \cdot 2$. In Run 3 the half crossing angle during the physics fills will be in the range $160\text{--}135^\circ$ rad, and therefore this will move the position of the LOS at FASER by 7.7 - 6.5 cm. As

discussed in section 8, the mechanics of FASER are designed to be able to move the detector to be closer to the LOS. Detector movements are planned to be carried out during year end technical stops, when the crossing angle direction is changed.

The expected particle flux at FASER has been calculated assuming a luminosity of $2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Results from FLUKA [6] simulations have been compared to in situ measurements made in 2018 LHC running [3]. The FLUKA studies suggest that the only high-energy particles expected to traverse the FASER location are muons and neutrinos, originating from the interactions in IP1. The muons that reach FASER primarily arise from pion decays, where the pions originate from hadronic showers from collision debris interacting with the LHC infrastructure (beam pipe, absorbers, collimators) between the IP and FASER. The muon flux on the LOS as estimated by FLUKA is 0.4 Hz cm^{-2} . This has been confirmed using a small emulsion detector installed in the FASER location. Measurements of the correlation between the particle flux in this location and the instantaneous luminosity in IP1 showed that these particles are originating from IP1 collisions.

1.2 Physics reach for Long-Lived Particles

FASER searches for light, very weakly-interacting particles which may be produced in the collisions at IP1, travel long distances through concrete and rock without interacting and then decay to visible particles in the detector decay volume. The sensitivity reach for FASER for a large number of beyond the Standard Model (BSM) theories characterised by the presence of long-lived particles has been studied in detail and reported in ref. [7]. Renormalizable portal interaction models leading to dark photons are one of the first targets of searches carried out with FASER, since good sensitivity is expected already with 10–20% of the Run 3 dataset. Other scenarios considered include models with dark Higgs bosons, heavy neutral leptons, light gauge bosons, axion-like particles, and pseudoscalars with Yukawa-like couplings.

The dark photon (A') appears in dark (hidden) sector models in which the dark sector contains a new spin-1 vector boson with suppressed couplings (referred to as ϵ) to SM particles via its kinetic mixing with the SM photon. In such models the A' acts as a mediator between the SM and a hypothetical dark matter particle (χ). The A' phenomenology is defined by ϵ and the mass ($m_{A'}$), and there is a large region of viable parameter space yet to be constrained by experiments. If $m_{A'} < 2m_e$, the A' decays to SM particles, and FASER is mostly sensitive to the mass range $2m_e < m_{A'} < 2m_\mu$ such that the A' decays to an electron and positron pair. For sufficiently weak couplings, the A' is long-lived and can travel significant distances before decaying. The relevant parameter space for which FASER has sensitivity is $O(10^{-6}) < \epsilon < O(10^{-4})$ with $m_{A'} \lesssim 100 \text{ MeV}$, such that the A' may travel from IP1 to FASER without interacting and decay in FASER to an electron-positron pair. A sketch of such a detector signature is shown in figure 3. This signature is very clean with no expected non-BSM process able to mimic it.

The main production process for dark photons relevant for FASER is light meson decays, in particular the decay of π^0 mesons. Neutral pions may decay to a dark photon and a SM photon, with a branching fraction proportional to ϵ^2 . Pion production at the LHC is strongly peaked in the very forward direction, such that $O(1\%)$ of the pions produced with energy $\sqrt{s} > 10 \text{ GeV}$ are within the FASER angular acceptance 0.21 mrad , despite the fact that this covers only $O(10^{-8})$ of the total solid angle. Such pions have a large boost, as much as $O(1 \text{ TeV})$, along the beam direction in the lab frame, allowing dark photons produced in their decay to reach FASER even with relatively short lifetimes.

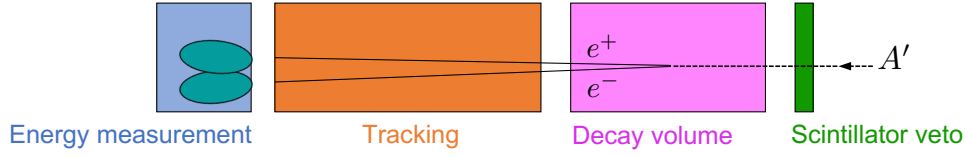


Figure 3. Sketch showing the detector signature of a dark photon (A') decaying to an electron-positron pair inside the decay volume of the FASER experiment. The A' enters the detector from the right.

During the Run 3 of the LHC around $O(10^{14})$ ϕ s are expected to be produced within the FASER angular acceptance. Hence a significant number of signal events can be detected in FASER, even taking into account the large suppression due to the $\phi \rightarrow e^+e^-$ branching fraction ($O(10^{-12})$ to $O(10^{-8})$) and the requirement that the ϕ decays inside the FASER detector volume. Figure 4 shows the expected FASER sensitivity to dark photons for different integrated luminosity scenarios. The contours are defined such that at least three signal events pass the kinematic and geometrical requirements and the dark photon decays inside the FASER decay volume. The contours assume 100% efficiency and zero background. It has been shown [2] that a reduction of the assumed efficiency does not affect the sensitivity curves substantially, due to the fact that the number of signal events falls off very rapidly at the edge of the sensitivity boundaries. The boundaries of the signal sensitivity contours are set primarily by the production rate falling off at too-small couplings and the ϕ s being too short-lived to decay in FASER at too-large couplings. More details on the theoretical aspects of the dark photon model, as well as the FASER sensitivity in other dark-sector models are discussed in ref. [7].

1.3 Neutrino physics programme

A huge number of neutrinos are produced in LHC collisions via hadron decays, and their flux is collimated along the beam collision axis. Table 1 summarizes the number of neutrinos expected to traverse, and under-go charged-current (CC) interactions in, the FASER emulsion detector (with a target mass of 1.1 tonnes), assuming a 150 fb^{-1} dataset for the LHC Run 3, as well as the expected average neutrino energy. The table includes all three neutrino flavours (summing ν and $\bar{\nu}$) and also shows the dominant production process. The numbers reported in the table are obtained using the SIBYLL 2.3d [8] generator to simulate hadron production and the fast neutrino flux simulation introduced in ref. [9] to propagate the SM hadrons through the LHC beam pipe and magnets and to simulate their decays into neutrinos. There are currently large theoretical uncertainties related to very forward hadron production, which translate into large uncertainties on the neutrino flux. As discussed in refs. [9–11], varying the generator or theoretical modelling can lead to changes of the order of 100% (ν_μ), 30% (ν_τ) and 100% (ν_e). FASER neutrino measurements as a function of energy and rapidity can therefore be used to constrain forward hadron production models.

Taking advantage of the huge neutrino flux, FASER will measure the neutrino CC interaction cross sections for all three neutrino flavours in an uncovered energy regime. Projections of the expected measurement precision are shown in figure 5. Here, the expected statistical uncertainty and the uncertainty related to the neutrino flux, estimated by comparing the SIBYLL 2.3d and DPMJET 3.2017 [12, 13] generators, are shown separately. Note, a number of different generators have also been studied including: EPOS-LHC [14], QGSJET II-04 [15], and Pythia 8 [16], but the

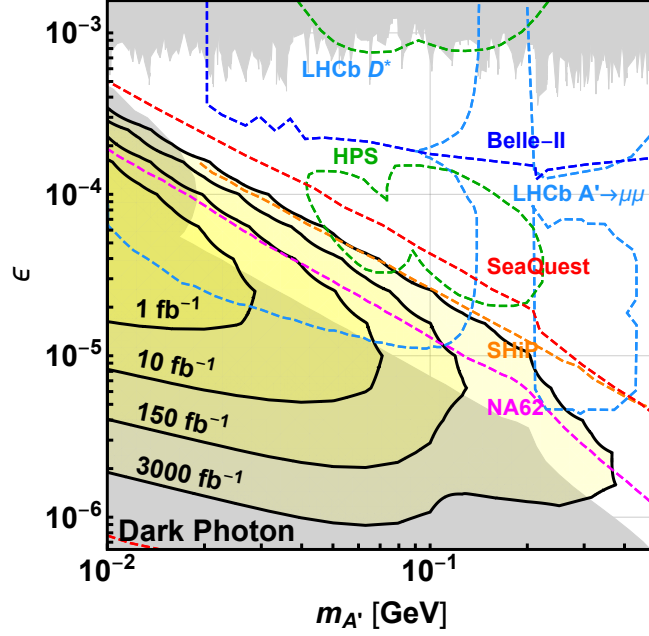


Figure 4. The expected sensitivity of FASER for dark photons as a function of the mass ($m_{A'}$) and coupling (ϵ), for different values of integrated luminosity. The regions of parameter space already excluded by experiment are shown in grey, and the projected reaches of some future experiments are shown in coloured lines. As discussed in the text, the FASER reach assumes full efficiency for selecting dark photons decaying inside the FASER decay volume, and no background. Details of the sensitivity projections shown for other experiments are given in ref. [7].

Table 1. Summary of the number of neutrinos traversing and interacting in FASER assuming a 150 fb^{-1} dataset for the LHC Run 3. The table also shows the dominant production process and the average energy of the interacting neutrinos. Only CC interactions are considered.

Dominant production process			
Number of ν traversing FASER	$3 \cdot 10^{11}$	$2 \cdot 10^{12}$	$8 \cdot 10^9$
Number of ν interacting in FASER (1.1 tonnes)	830	4400	14
Average energy of interacting neutrinos (GeV)	820	820	810

envelope of the range of predictions is covered by the difference between SIBYLL and DPMJET predictions. Experimental systematic uncertainties are not included, but are expected to be sub-dominant. For μ^\pm , the charge of the muon can be reconstructed in the FASER tracking spectrometer, making it possible to measure both the neutrino and anti-neutrino cross sections separately,³ as shown in the figure. The measured cross sections are interesting in their own right, but can also be used to constrain proton and nuclear parton distribution functions, formation times, colour transparency effects, non-standard neutrino interactions and neutrino oscillations in models with additional sterile

³Note the FASER spectrometer overlaps with only 42% of the FASER emulsion detector in the transverse plane, and therefore the number of muon neutrino interactions that can be used to measure the neutrino/anti-neutrino cross sections only corresponds to a target mass of 460 kg.

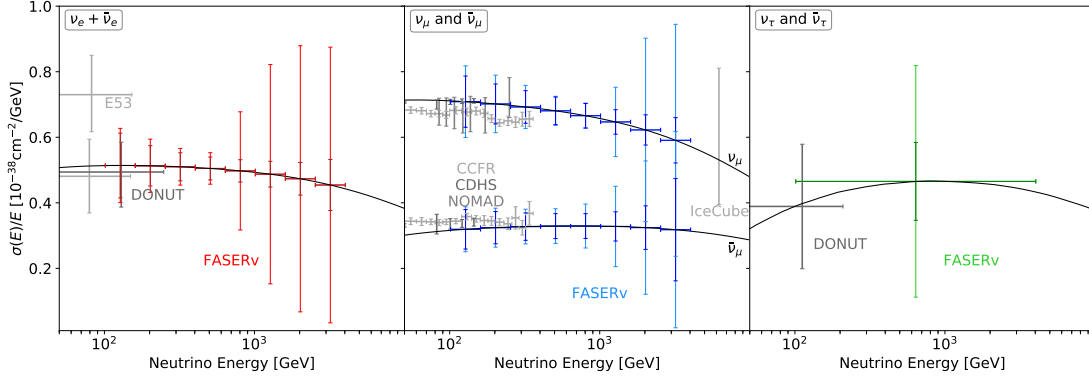


Figure 5. FASER ’s estimated ν -nucleon CC cross section sensitivity for $\nu_e + \bar{\nu}_e$ (left), ν_μ and $\bar{\nu}_\mu$ (centre), and ν_τ and $\bar{\nu}_\tau$ (right) for LHC Run 3. Existing constraints are shown in gray [20]. The black curve is the theoretical prediction for the DIS cross section per tungsten-weighted nucleon. The coloured error bars show FASER ’s cross section sensitivity, where the inner error bars correspond to statistical uncertainties, while the outer error bars show the combination of statistical and flux uncertainties.

neutrinos, as discussed in more detail in refs. [4, 17, 18]. In addition, the measurement of the neutrino flux can be used as a probe of forward particle production, which will help validate and improve the underlying hadronic interaction models and provides valuable input for astro-particle physics measurements.

As a proof of principle, the FASER Collaboration placed a small emulsion detector along the LOS for 4 weeks during the Run 2 of the LHC in 2018. With a fiducial mass of just 11 kg, this pilot detector was able to record the first neutrino interaction candidates at a particle collider [19].

1.4 Detector requirements

The most relevant detector requirements needed to fulfill the FASER physics programme on dark sector searches and neutrinos cross section measurements are listed below.

- Given its transverse size, fixed by the tunnel and trench constraints, the detector must be centred on the LOS to within about 10 cm to maximise the number of signal events, for both light BSM searches and neutrino analyses. This must be done for all possible beam crossing angles that will be used during data taking in IP1. Situating the detector on the LOS also maximises the neutrino energy.
- In order to be able to efficiently reject physics background events initiated by high-energy muons, the detector must include a system that vetoes charged particles entering the detector. The veto system should have an inefficiency of smaller than 10^{-9} , since the expected number of muons that will enter FASER during LHC Run 3 is $O(10^9)$.
- The detector must be able to track high energy charged-particles with good precision:
 - For light BSM searches, it must be able to separate very closely spaced charged particles. For a dark photon of mass 100 MeV and 2 TeV momentum, the opening angle of the decay products is only 50° rad, hence the magnetic field in the decay-volume and spectrometer must separate the decay products to measurable distances within the detector;

- To be able to measure e^+ and e^- , the charge of the produced muon must be measured up to several hundred GeV.
- To measure the energy of electron-positron pairs produced in dark-photon decays, or pairs of photons produced in Axion-like-particle decays, the electromagnetic calorimeter must be capable of measuring $O(\text{TeV})$ EM deposits with a few percent resolution.
- In order to be able to maximise the number of recorded neutrino interactions taking into account the space limitations, the neutrino detector must have a high-density and large-mass target.
- The neutrino detector should have the ability to identify different lepton flavours from neutrino CC interactions. This leads to the following requirements:
 - The detector must have sufficient target material to identify muons;
 - The detector needs to have finely-sampled detection layers to identify electrons and distinguish them from gamma rays;
 - The position and angular resolutions must be sufficiently good to be able to detect tau and charm decays.
- The neutrino detector should be able to measure muon and hadron momenta, the energy of electromagnetic showers, and estimate the neutrino energy.
- To enable the combination of information from the passive emulsion-based neutrino detector, and the rest of the FASER (active) detectors, a tracking detector placed immediately after the neutrino detector with sufficient precision is needed to allow matching of charged-particle tracks between the two systems. In the matching, all events triggered in the active detector during the time the emulsion detector was in place need to be considered. Therefore, in order to reduce the matching combinatorics, only triggered events in which the scintillator counters in front of the emulsion detector do not fire are taken into account. This reduces the number of triggered events considered in the matching process by $O(10^6)$.
- To ensure a good efficiency for collecting rare signal events, the trigger must be highly efficient and the data acquisition (DAQ) system needs to operate robustly with little dead-time. The expected trigger rate from muons produced in the IP1 collisions is $O(650 \text{ Hz})$ for a luminosity of $2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.

As a reminder, the radiation levels at the FASER location are expected to be substantially lower than around IP1. They have been estimated using FLUKA simulations, and validated using measurements taken during 2018 LHC running [3]. The FLUKA estimated dose is less than $5 \cdot 10^{-3} \text{ Gy}$ per year and a 1 MeV neutron equivalent fluence of less than $5 \cdot 10^7$ per year. The radiation level was measured using a BatMon radiation monitor [21], giving a measured high-energy hadron fluence below the device sensitivity (corresponding to $10^6/\text{cm}^2$), consistent with the expectation from the FLUKA simulation studies. For thermal neutrons the measured flux is $4 \cdot 10^6/\text{cm}^2$, to be compared with the simulation estimate of $3 \cdot 10^6/\text{cm}^2$. These radiation levels are low for the LHC complex, and enable non radiation-hard electronics to be used in the detector.

The detector was designed to fulfill the above requirements, but additional constraints have been also taken into account. In particular, the short time available⁴ for the design, construction, commissioning and installation implied the use of existing detector components. This allowed the cost of the detector, services and installation works to be minimized. Furthermore, due to the FASER location in the LHC tunnel, the installation of additional services is difficult and it was therefore important to minimize as much as possible the needed services. Since there is no direct access to the FASER location, and to get there one must walk about 500 m along the LHC tunnel, it was important to make the detector as robust and reliable as possible in order to minimize interventions for maintenance, especially during LHC operations.

In the remaining part of this section, a brief overview of each detector sub-system is given, while a specific description of each component is reported in the following dedicated sections.

1.5 The magnet system

The FASER detector is built around three dipole magnets with a 0.57 T field. Permanent magnets are used to minimise the required services. Each magnet has a 20 cm diameter aperture, and an outer diameter of 43 cm. The first dipole (1.5 m-long) surrounds the decay volume, and the other two (each 1 m-long) are part of the tracking spectrometer. The primary purpose of the magnets is to separate closely spaced charged particles produced in the decay of boosted, light BSM particle decays, and to measure the charge of muons arising from neutrino interactions.

1.6 The tracking system

The FASER detector tracking system is composed of two distinct parts, the tracking spectrometer and the IFT, and a detailed description as well as the results of its commissioning can be found in ref. [22]. The tracking spectrometer allows the trajectories of charged particles traversing the detector to be reconstructed, and their position and momentum to be measured. The IFT is placed right after the FASER emulsion detector, and enables tracks reconstructed in the emulsion to be matched with those in the active detectors. This allows for a time-stamp to be assigned to the reconstructed neutrino vertices, and hence enables the measurement of the charge of muons arising from the neutrino interaction. Once associated to a neutrino interaction vertex candidate, the information from the active detector can also help in background rejection and the neutrino energy reconstruction.

Both detectors in the tracking spectrometer and the IFT are made from the same hardware components. The tracking spectrometer consists of three tracking stations, and the IFT is an identical tracking station. There are therefore four tracking stations in the full FASER detector. Each tracking station consists of three double-layers of single-sided silicon microstrip detectors. A tracking layer is made up of eight silicon strip modules which are spares from the ATLAS experiment's SCT barrel detector [23], for a total of 96 modules in the full FASER detector. Each module is approximately $6 \times 12 \text{ cm}^2$, and they are arranged in two columns of 4 modules to give a $24 \times 24 \text{ cm}^2$ active detector area which covers the full aperture of the FASER magnets. The modules are operated with a bias voltage of 150 V, providing a hit efficiency well above 99%. Despite using detector modules from the

⁴FASER was formally approved by CERN in March 2019, with a schedule to install the detector before the end of LHC Long Shutdown 2 (LS2), at that time scheduled for the end of 2020. Since then, LS2 has been extended by 1 year due to the COVID-19 pandemic.

ATLAS experiment, the rest of the tracker system including the mechanics, readout system, cooling system and powering is newly designed and constructed for FASER.

The SCT modules have a strip pitch of 80 μm , and a stereo angle between the two sides of 40 mrad, leading to a track resolution of order of 20 μm in the precision coordinate, and 800 μm in the other coordinate. In FASER, the modules are aligned such that the precision coordinate corresponds to the magnet bending plane (). The detector is therefore able to resolve closely spaced charged particle tracks which are separated by 100-200 μm , and to measure the angle of charged particles needed to match tracks in the emulsion detector with the IFT. According to simulation studies, the track angular resolution for the IFT is 250 μrad and 13 mrad for the η and ϕ coordinates, respectively.

1.7 The calorimeter and scintillator systems

The FASER detector includes four scintillator stations, used for vetoing and trigger purposes, and an electromagnetic calorimeter, designed to measure the energy of high-energy electrons and photons and provide redundant triggering for signals with large energy deposits. In addition, the calorimeter in conjunction with scintillator counters placed at the back of the tracking spectrometer can provide simple particle identification.

Each of the four scintillator stations is composed of more than one scintillator counter, read out by photomultiplier tubes (PMTs), as detailed below:

- The first two stations are needed to veto charged particles entering the detector. One is placed in front of the FASER emulsion detector and consists of two scintillator counters. The other is located in front of the FASER decay volume and is made up of four scintillator counters. Each scintillator counter is read out by a single PMT. The veto scintillator stations must be able to veto charged particles with very high efficiency, to ensure the experiment remains background free with an expected 10^9 muons traversing FASER during Run 3 operations. The veto scintillators are larger than the active transverse size of FASER (given by the aperture of the magnets) in order to be able to veto muons that could enter FASER at an angle with respect to the detector axis.
- The timing scintillator station is placed after the decay volume. It consists of two scintillator counters, each read out by two PMTs. The station is designed to provide a trigger for charged particles exiting the decay volume, and to give a precise time for triggered events, with a resolution of better than 1 ns.
- A pre-shower scintillator station is placed at the back of the tracking spectrometer. It is composed of two scintillator counters, each read out by a single PMT, interleaved with two tungsten absorbers, and graphite blocks. The purpose of the pre-shower is to distinguish between calorimeter signals from neutrino interactions in the calorimeter, and photons. Photon showers start to develop in the tungsten absorbers (each of about one radiation length), therefore leaving signals in the scintillator counters. The graphite blocks are installed to minimize back-splash from the calorimeter leaving signals in the scintillator counters and the rear tracking station.

The calorimeter provides energy measurements with an expected precision at the one percent level for the energy range of interest. It consists of four spare modules from the LHCb experiment's outer electromagnetic calorimeter (ECAL) [24] and is 25 radiation lengths deep.

Each module is $12 \times 12 \text{ cm}^2$ in the transverse plane and made up of 66 layers of lead and plastic scintillator with wavelength shifting fibers bringing the collected light to a PMT at the back of the module. Since there is a single PMT per module, the calorimeter provides no longitudinal segmentation, and has a very coarse transverse segmentation provided by the 2×2 module configuration. The calorimeter can therefore not separate the two closely spaced electron showers expected from a dark photon decay, but instead measures the total electromagnetic energy in the event.

1.8 Emulsion detector

The FASER emulsion detector is made up of 770 1-mm-thick tungsten plates interleaved with emulsion films. The tungsten acts as the target for the neutrino to interact with, and the emulsion films record the trajectories of charged particles produced in the interaction with excellent position and angular resolution. The detector has a transverse size of $25 \times 30 \text{ cm}^2$ with a total target mass of 1.1 tonnes. Given that the emulsion is a passive detector, the detector needs to be extracted, and the emulsions developed and scanned before particle trajectories and corresponding neutrino interaction vertices can be reconstructed and used in data analysis.

The detector can be used to identify leptons produced in charged current neutrino interactions. Muons are identified as long tracks penetrating through the upto 8 interaction lengths of the detector. Electrons are identified by the shower they produce in the detector, and their energy can be estimated by the shower size. Finally, taus are identified by observing the short track, with either a kink (for 1-prong decays) or by a secondary vertex (for hadronic decays). It is also possible to estimate the momentum of charged particle tracks by the effect on the measured trajectory due to multiple scattering in the detector.

Since the detector records all charged particle trajectories passing through the emulsion films, it must be replaced before the track multiplicity becomes so high that the track and vertex reconstruction performance is significantly degraded. Given the exceptional track resolution, a multiplicity of less than $O(10^6)$ tracks per cm^2 is acceptable, meaning that the detector needs to be replaced after exposure to $30\text{--}50 \text{ fb}^{-1}$ of collision data. The operation can be done during scheduled technical stops of the LHC, which are typically three times per year and lasting a few days.

1.9 Trigger and DAQ

The FASER detector is triggered by signals in any of the scintillator stations or the calorimeter. The expected trigger rate is about 650 Hz at a luminosity of $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, which is dominated by muons traversing the detector from IP1. The measured muon flux on the LOS corresponds to about 150 Hz of muons within the magnet aperture. However, the scintillator counters are designed to cover a larger transverse size of up to $40 \times 40 \text{ cm}^2$ leading to an expected rate of 650 Hz.

The raw calorimeter and scintillator counter PMT signals are sent to a commercial digitizer card, which issues trigger signals if the waveforms are above pre-defined thresholds. These digitizer trigger signals are sent to a custom FPGA-based Trigger Logic Board (TLB) which can combine inputs to form a global trigger (Level 1 Accept, L1A). The TLB can pre-scale and inhibit triggers and run monitoring algorithms. The L1A signal is sent to the tracker readout boards (TRBs) and the digitizer, to initiate read out of the detector data. On receiving a L1A signal, the different types of readout boards send data over a dedicated fiber network to a software event builder DAQ process

running on a server situated on the surface (about 600 m away). The system allows monitoring of the data by software processes running on the DAQ server, while the DAQ electronics are situated in the TI12 tunnel close to the FASER detector. The trigger and data acquisition (TDAQ) hardware operates on the LHC clock, which is received, processed and distributed via a dedicated electronics board.

A detailed description of the FASER TDAQ system, and its commissioning can be found in ref. [25].

1.10 Computing and software

Computing is crucial for the success of the FASER experiment and development has to adhere to international standards and employ commercial solutions wherever possible. For this reason, the software framework, called Calypso [26], follows as closely as possible that of the ATLAS experiment, and it is based on the Gaudi [27] and Athena frameworks [28].

The raw data from the experiment are written to tape in the CERN Computing Centre using the CERN Tape Archiving system [29]. The data are promptly reconstructed at CERN to produce the *xAOD* analysis format [30] which can be accessed directly in the ROOT [31] analysis software. The prompt reconstruction software account for masking dead and noisy channels through calibration. The track reconstruction is based on the common ACTS [32] framework. The typical raw event size is 22 kBytes/event and the reconstructed data at *xAOD* level is at most 10 kBytes/event.

The detector simulation is based on the GEANT4 [33] package. It incorporates a detailed description of the detector geometry including material in the non-sensitive parts of the detector, implemented in GeoModel [34] as well as the magnetic field map. Simulated particles are tracked through the detector, recording hits in the sensitive elements. The output of the simulation is passed through a digitization process which simulates the detector electronics response (for example adding in detector noise), and producing an output that is equivalent to the raw detector data. The software also includes an event display program based on VP1 [35] which allows the reconstructed events to be visualized.

1.11 Outline of this paper

This paper is structured as follows. Sections 2, 3 and 4 outline the details of the design, construction and standalone commissioning of the tracking system, the calorimeter and scintillator system and the trigger and data acquisition system, respectively. This is followed by the description of the magnet system in section 5. The detector control and safety systems are described in section 6. Section 7 outlines the emulsion-based neutrino detector, before the integration and in-situ commissioning of the full experiment is detailed in sections 8 and section 9. Finally, section 10 provides the summary.

2 The tracking system

The tracking spectrometer and the interface tracker, IFT, are the two components of the FASER detector tracking system. The tracking spectrometer is composed of three tracker stations separated by two dipole magnets, and is designed to detect two oppositely charged particles arising from the decay of a light, long-lived, hypothetical new particle inside the FASER decay volume. The pair of charged particles would have high momentum and would be extremely collimated, hence the tracking system must be able to resolve two charged particles with a spatial separation down to $\mathcal{O}(100)$ μm . For example, for a signal particle with mass $m = 100$ MeV and energy $E = 2$ TeV decaying inside the

decay volume, the separation between the decay products at the first tracker station is $O(200 \text{ cm})$. The tracking spectrometer is composed of three tracker stations, with a total of nine planes of silicon strip modules that were originally the spares for the ATLAS SCT barrel detector [23]. All other parts of the tracker, including dedicated support frames, detector control system (DCS) and cooling system, readout electronics and services were newly developed for FASER. It aims to allow the reconstruction of all tracks that penetrate at least one full station.

The IFT has an identical design to the single tracking station of the tracking spectrometer and can be considered as a fourth tracker station. It enables tracks from a neutrino interaction in the emulsion detector to be matched to events in the spectrometer tracker stations. Both the IFT and the spectrometer fully cover the aperture of the magnets in the transverse ($x-y$) plane.

This section briefly describes the characteristics and specifications of the SCT modules, then it details the mechanical design of the tracker stations, alignment and metrology, and performance obtained during the commissioning. A more detailed description of the FASER tracking detector can be found in ref. [22].

2.1 SCT module

An SCT barrel module consists of four identical single-sided silicon microstrip detectors glued as pairs on the two sides of a central base board. The copper/polymide flex hybrid with the front-end ASICs (ABCD3TA chips [36]) is attached to the sensor assembly. The sensors use $0.35\text{-}\mu\text{m}$ technology where the sensor substrate is p -type with $285 \text{ }\mu\text{m}$ thickness and the n^+ implants are AC-coupled to aluminium readout strips via a silicon dioxide layer. Each sensor has the dimension of $640 \times 636 \text{ mm}^2$ with 768 readout strips at a constant pitch of $80 \text{ }\mu\text{m}$.

The ABCD3TA chip contains 128 readout channels that consist of a preamplifier, shaper and discriminator. The signal delivered by the preamplifier-shaper circuit has a peaking time of 25 ns, which is enough to ensure a discriminator time-walk of less than 16 ns and a double-pulse resolution better than 50 ns as required for operation at the ATLAS experiment. A common threshold is applied across the entire chip. However there is a spread in threshold offsets between different channels and thus a per-channel 4-bit chip parameter (the TrimDAC) is tuned as a threshold trim to retain a uniform response. The hit information is provided as 3-bit binary data on reception of a trigger.

Figure 6 shows a SCT barrel module in an aluminium test-box. On the front and back side of the module, the two sensors are bonded edge-to-edge to create about 12.4 cm-long readout strips. The sensors on each side are placed with a 40 mrad stereo angle so that the hit position can be identified with about $16 \text{ }\mu\text{m}$ resolution in the precision coordinate, and $816 \text{ }\mu\text{m}$ in the other coordinate. The flex hybrid with six ABCD3TA chips per side is bridged over the sensors via a carbon-carbon substrate. The hybrid is attached to beryllia (BeO) facing plates located on the two ends of the baseboard made of Thermal Pyrolytic Graphite (TPG) with an excellent in-plane thermal conductivity and low radiation length, which provides the mechanical support to the sensors and allows for the heat generated by the ABCD3TA chips to be dissipated.

The strip modules used for the FASER tracker have been selected among the existing spares of the SCT barrel modules. Since completion of the production in 2004, the modules were stored in individual sealed bags. Electrical tests were performed to select the modules to be used in the FASER tracker. The modules were selected based on the behaviour of the leakage current as a function of

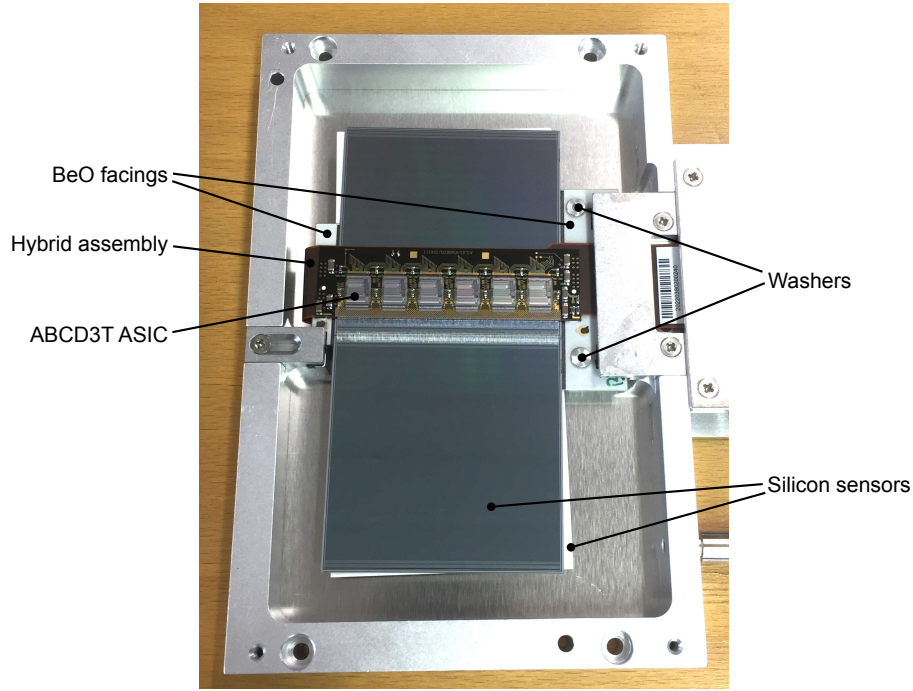


Figure 6. Photograph of a SCT barrel strip module.

bias voltage (High Voltage, HV) applied to the sensor, and to minimise the number of strips with large noise, low efficiency and cross-talk. In total, 96 modules are used for the four tracker stations.

2.2 Tracker plane

Figure 7 shows a schematic view of the tracker plane. Each plane consists of eight SCT barrel modules within an AW-5083 aluminium frame. Four modules are located on each side (front and back) of the frame as shown in figure 8. The distance between closest sensors in the modules along the out-of-plane direction is 2.4 mm, and the active area overlap along the strip-length is 2 mm. A flexible printed circuit board (called the “pigtail”) is attached to each module and routes the electric lines to the outside of the frame. Four pigtails (one per module) on each side of the tracker plane are connected to a single patch panel. The patch-panel is used as the interface between the DAQ and powering systems.

The aluminium frames were produced with CNC (Computer Numerical Control) machining. The size of the frame is 320 mm × 320 mm × 31.5 mm. The frame is cut out for most of the active area within the acceptance of the magnet aperture to minimize the material (figure 7). An inner cooling channel with 5 mm diameter was integrated into the frame for the water cooling which extracts heat generated by the ABCD3TA chips on the modules. Details of the water cooling system are described in section 6.2. A heat conducting thermal paste⁵ is used at the contact surface between the BeO facing plates of the SCT modules and the aluminium frame for a good thermal contact. An inlet for dry-air is also included in the frame to keep a low relative humidity inside.

⁵Electrolube HTCP-20S.

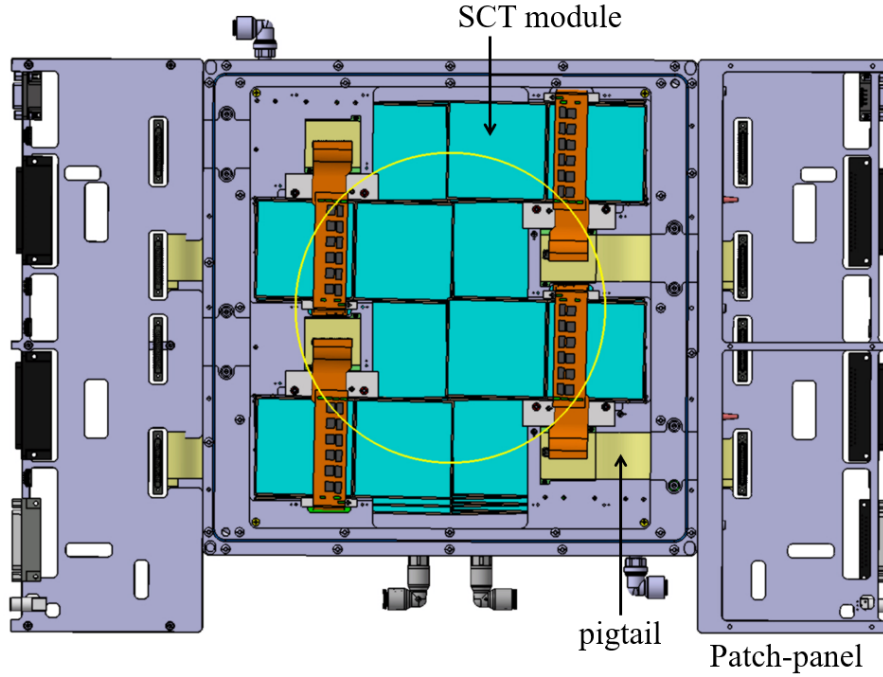


Figure 7. Schematic view of the tracker plane. The pigtail is connected to each hybrid on the SCT module. Note that adjacent SCT modules are mounted on different side of FASER module frame. The four pigtails in one side are connected to one patch panel. The circle represents the 200 mm-diameter magnet aperture.

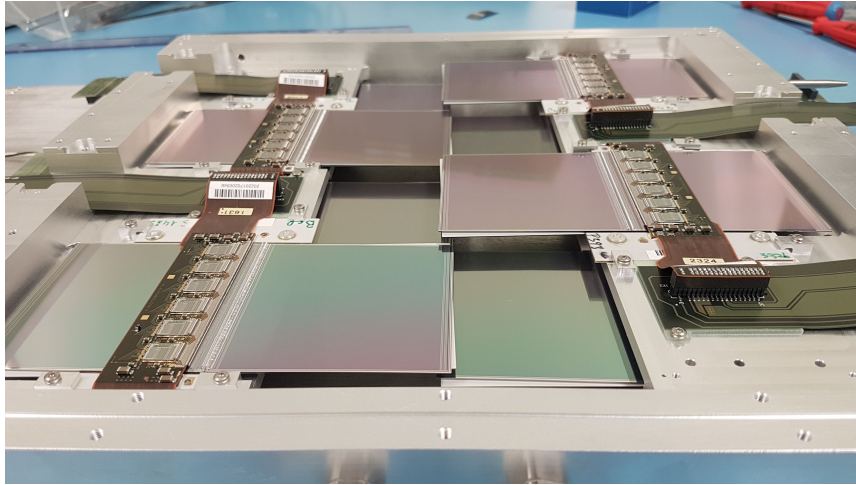


Figure 8. Photograph of a tracker plane with all eight SCT modules installed. The beam axis is perpendicular to the plane.

2.3 Tracker stations

The tracker station is an assembly of three planes as shown in the computer-aided drawing (CAD) view and picture of figure 9. The distance between the sensor cut edge and the sensitive region is 1 mm. For an individual plane, this results in a dead region of about 2 mm in between modules along the vertical direction. To overcome this, the three planes are staggered along the vertical direction with a

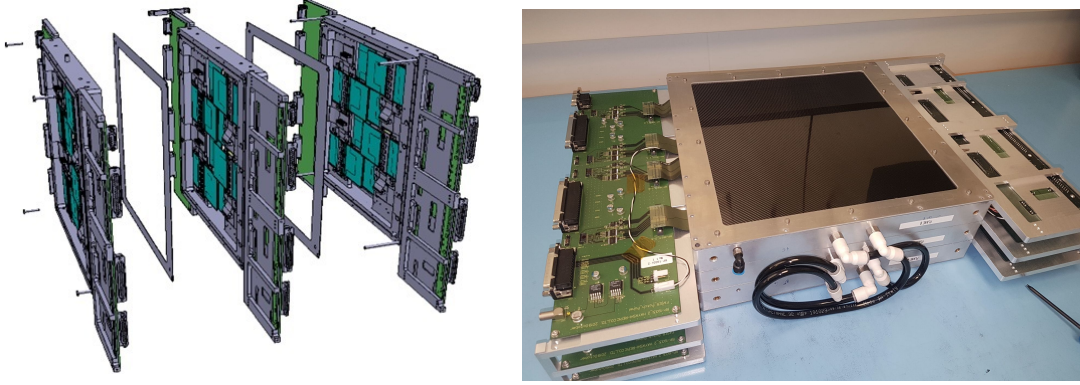


Figure 9. (left) Exploded CAD view of a tracker station and (right) photograph of a fully assembled station. The black cover on top of the station is a carbon-fibre plate. The cooling loops of each plane are connected together, so that per station there is only one inlet and one outlet for the cooling fluid.

relative shift of the middle (last) plane of 5 mm (5 mm) with respect to the first plane. This ensures that there are at least two 3D reconstructed hit points for a track crossing the station. An additional dead region corresponds to the vertical slice in the centre of each module. This represents 1.6% of the active area, and is accounted for in the detector description in the simulation and reconstruction.

Each station volume is closed by two end-covers made of carbon-fibre plates with $400 \text{ }\mu\text{m}$ thickness (standard T300 fibres). To prevent corrosion by the corona discharge processes that might occur after putting the frames in contact during the station assembly, a post-treatment with SURTEC-650 was performed for all aluminium parts. In addition, an O-ring sealing joint was attached between the frames for a good tightness and to keep the humidity inside the station as low as possible (typically 1%). The total weight of one station is about 15 kg without cables.

The thermal performance was investigated with various Finite Element Analysis (FEA) simulations. The temperature measured with a thermistor on the flex hybrid of the SCT module is required to be less than $35 \text{ }^\circ\text{C}$, which corresponds to the glass transition of the epoxy glue used for the module assembly. Keeping the coolant temperature at $15 \text{ }^\circ\text{C}$, a water flow of 3 l/min (considering a heat transfer coefficient for water of 500 W/m^2), and the outside air convection at $23 \text{ }^\circ\text{C}$, the FEA gives a maximum temperature on the ABCD3TA chips of $28 \text{ }^\circ\text{C}$, neglecting the temperature rise within the water channel due to the heat load. The latter is estimated to be $0.6 \text{ }^\circ\text{C}$ for 3 l/min . These results are in good agreement, within $2\text{--}3 \text{ }^\circ\text{C}$, with measurements taken during commissioning, hence validating the simulation. The FEA simulation was then used to estimate the temperatures on the silicon sensors and predicted $21\text{--}23 \text{ }^\circ\text{C}$, which is well within the specifications for the epoxy glue.

Table 2 summarizes the material budget in a tracker station. The central region with the least amount of material in the station, i.e., six silicon sensors and two carbon-fibre covers, accounts for a total of 2.1% of a radiation length (X_0). The worst case is when the particle penetrates the edge region that consists of six SCT modules including sensors, TPG baseboard, flex hybrid with carbon-carbon bridge and ABCD3TA chips as well as the aluminium frames and station covers. In such a case, the material budget becomes $21.5\% X_0$.

Simulation results based on a dark photon benchmark model with 100 MeV and 10^{-5} show that 70% of the dark photons are contained within the low-material central region of the tracker.

Table 2. Amount of material in ρ_0 in the active area of a tracking station for two regions: i) the central region ($\rho_0 = 4$ cm) with only the silicon sensor material and ii) the edge region. Details of the material in the SCT module are given in table 8 of ref. [23]. The numbers are calculated directly from the CAD description of the tracking station.

Component	Material	Number / station	ρ_0 (%)	
			Central region	Edge region
Silicon sensor	Si	6	1.8%	1.8%
Station Covers	CFRP	2	0.3%	0.3%
SCT module support	TPG	3	-	0.6%
C-C Hybrid	C (based)	3	-	2.2%
ABCD chips	Si	3	-	6.5%
Layer frame	Al	3	-	10.1%
Total / station	-	-	2.1%	21.5%

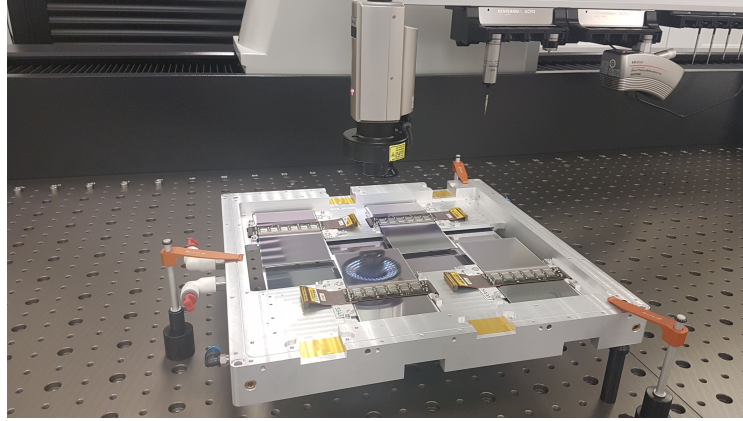


Figure 10. Metrology of a fully assembled tracker plane.

Finally, given the high-momentum spectrum expected for the signals of interest the effect of multiple scattering from the traversed material is negligible.

The three spectrometer tracker stations are mounted into the FASER detector with an AW-5083 aluminium structure (called the “backbone”) whilst the IFT is fixed on an independent support structure. The details are described in section 8.

2.4 Alignment and metrology

Metrology was performed for all assembled planes and stations at the University of Geneva using a Mitutoyo CRYSTA-Apex S CNC coordinate-measuring machine with an automatic probe changer (figure 10). Measurements were performed with a mechanical touch-probe and an optical camera.

There are four stainless steel targets on each frame (one in each corner) to define the plane reference coordinate system. The targets are visible from both sides, allowing measurements done on each side of the plane separately to be correlated. The silicon sensors of the SCT modules have a set of fiducial marks that were used for the mechanical alignment during module assembly. Some of the fiducial marks were measured in 3D with respect to the plane reference system. The precision for

in-plane and out-of-plane measurements was 5 mm and 10-15 mm, respectively. All frames satisfied the required tolerances (± 20 mm) with respect to the CAD manufacturing drawings. The maximum deviation was 100 mm in positioning the SCT modules, which is corrected for using the metrology measurements in the data events reconstruction.

2.5 Standalone tracking commissioning

A detailed overview of the commissioning of the tracking detector is given in ref. [22] and a brief summary is provided below. Various aspects of the electrical performance of the silicon sensors such as noise levels, number of bad strips, HV, and thermal behaviour were investigated at each stage of construction of the tracker. Individual SCT modules were qualified by using a test system developed at Cambridge University which is used for muon spectroscopy [37]. The planes and stations were tested with standalone operation of the tracker readout board (TRB) and with a similar DCS and cooling system as used in the completed FASER tracker.

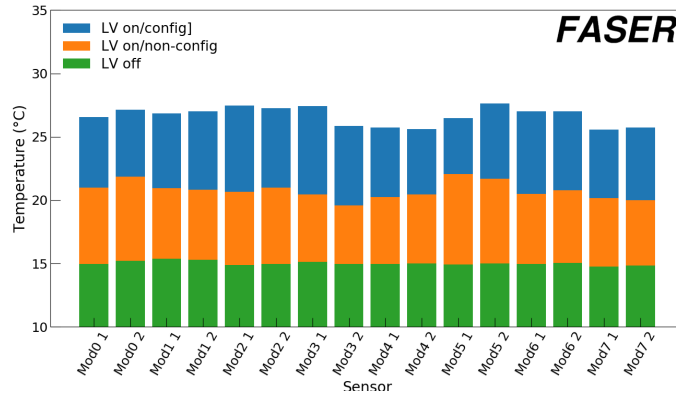


Figure 11. Thermal test results of the first station during surface commissioning. Temperature values of the SCT module NTCs for power-off (green), after powering the modules (orange) and after powering and configuring (blue).

Following the installation of the tracker in TI12, the total number of dead channels was measured to be about 0.5% of the total, including the region outside the main magnet acceptance (see also figure 7). The tracker is operated with a bias voltage of 150 V for the silicon sensors and at 15 °C as set by the cooling system. Figure 11 shows the temperature measured by NTC sensors on each module (two sensors per module) in one tracker plane, during the surface commissioning. The temperature without powering corresponds to the coolant temperature of 15 °C. When powered and configured, the module temperatures are kept well below 31 °C, the threshold temperature for the software interlock.

The calibration procedure of the ABCD3TA chips is performed by injecting a test pulse generated in the chips. The calibration steps consist in identifying noisy and dead strips, making adjustments of the timing between the test pulse and the level-1 trigger, and trimming of the threshold offsets. In addition, during combined detector data-taking, the tracker detector needs to be synchronized with the FASER trigger system triggering on a physics signal. Global time-tuning parameters for the tracker are configured on the TRB. More details are provided in section 4.2.1. The results shown in this section are obtained considering all four tracking stations (tracking spectrometer and IFT) after installation in TI12 and setting the temperature to 15 °C.

The hit occupancy, defined as the fraction of injected charge above threshold, is computed for each readout channel at various threshold points. Since the signal amplitude is convoluted with Gaussian electronics noise, the hit occupancy does not follow an ideal step-function but is smeared to give rise to the so-called $\frac{1}{2}$ -curve. The threshold at which the hit occupancy is 50% is called the $\frac{1}{2}$ point and corresponds to the amplitude of the test pulse.

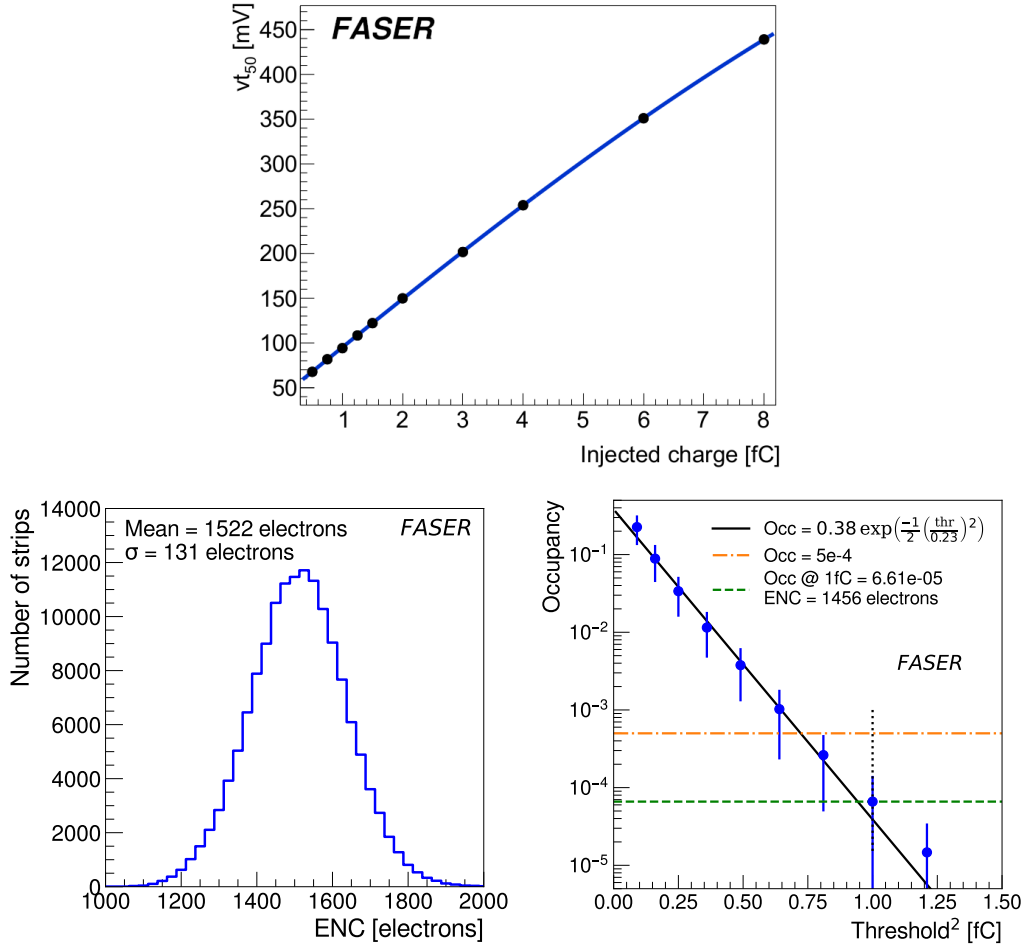


Figure 12. (top) v_{50} as a function of the injected charge, (bottom left) measured ENC of all strips in the four tracking stations, (bottom right) and the noise occupancy scan results for an example module.

Figure 12 (top) shows the typical curve of the v_{50} as a function of the injected charge. The gain of the amplifier (typically 50 mV/fC) is derived by fitting the v_{50} values at three different charges (1.5, 2.0 and 2.5 fC) with a linear function. Then, the Equivalent Noise Charge (ENC) is calculated by dividing the standard deviation of the $\frac{1}{2}$ -curve, extracted in a threshold scan with 2 fC injected charge, by the gain as shown in figure 12 (bottom left). The average ENC was evaluated to be 1522 electrons across all strips in the tracker. The noise hit occupancy at 1 fC threshold was measured to be $6.61 \cdot 10^{-5}$ (figure 12 (bottom right)) which is well below the specification requirement of $5 \cdot 10^{-4}$. In addition, the ENC was extracted to be 1456 electrons from the fitting, that is similar to the measured value with the injected charge (1522 electrons).

Finally, a hit efficiency above 99.8% was confirmed in the 2021 testbeam which took place at the H2 beamline at the CERN-SPS (Super Proton Synchrotron) [38].

3 The calorimeter, pre-shower and scintillator systems

The FASER experiment has four scintillator stations with multiple scintillator counter layers in each station as well as a lead-scintillator electromagnetic calorimeter, all of which use photo-multiplier tubes to detect the scintillation signals. This section presents a detailed description of each component, as well as results from pre-installation and standalone commissioning tests.

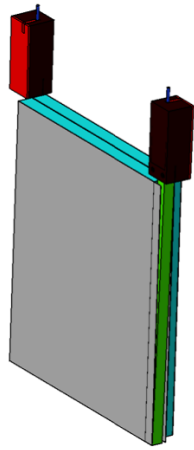
3.1 Scintillator system

To achieve high detection efficiency, especially for the veto stations, all scintillator layers are constructed from 10 or 20 mm thick EJ-200 plastic scintillator material [39]. The light output of this material is about 22 000 photons/cm for muons [40] and the thickness corresponds to 2.5–5% of a radiation length. The light in each scintillator counter layer is transmitted to one or two Hamamatsu PMTs through a wavelength shifting (WLS) rod or plastic light guides depending on the station type. The combined arrangement of scintillator, light guide/WLS rod and PMT(s) is referred to as a *scintillator module*. The scintillator counter layers, light guides and WLS rods are wrapped in 0.5 mm-thick aluminum foil to ensure light tightness and improve fire safety. In front of each PMT is placed an open-ended optical fiber for injecting light pulses from the calibration system, see section 3.3.

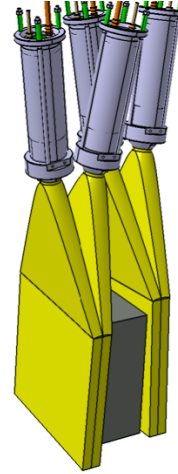
The first veto station is positioned upstream of the FASER emulsion detector to veto incoming muons and thus to provide discrimination between the muon-induced background and the neutrino interaction events. The design of the first scintillator veto station is heavily constrained by the limited space available around FASER. Therefore, its design is different to that of the other stations. It is constructed from two modules placed back-to-back. Each module is made up of a 30 cm × 35 cm, 2 cm thick EJ-200 plastic scintillator connected by a 1.5 cm × 1.5 cm × 37.5 cm EJ-280 plastic wavelength shifting rod [39] to a Hamamatsu H11934-300 PMT [41] as shown in figure 13(a). The H11934-300 PMT is a very compact 12 dynode-stage head-on PMT with a 23 mm × 23 mm sensitive photocathode, a typical gain of 1.2×10^6 , a fast rise time of 1.3 ns and low transit-time-spread of 0.27 ns, though the signal time precision is limited by the long emission time of the WLS rod.

The three downstream scintillator stations have a different design. EJ-200 plastic scintillator plates are again used but are connected via light guides to Hamamatsu H6410 PMT(s) [42]. The H6410 PMT is a large 12 dynode-stage head-on PMT, with a 47 mm sensitive aperture, a typical gain of 3×10^6 , a rise time of 2.7 ns and transit-time-spread of 1.1 ns for a single photo-electron. The head of the PMT assembly is mounted directly on to the end of the light-guide under spring-load to keep good optical contact between them. Two layers of permalloy tube protection surround the PMT to reduce the impact of magnetic fields.

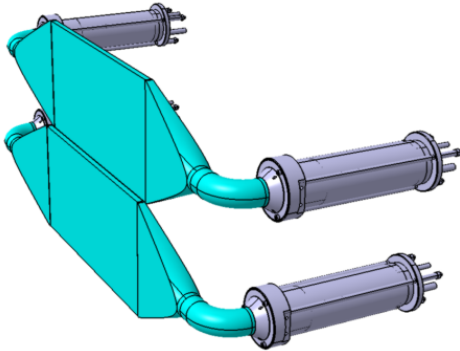
The second veto station, shown in figure 13(b) is located in front of the decay volume magnet. It features two pairs of modules, with the modules in a pair placed back-to-back for redundancy and improved veto efficiency. The station's primary purpose is to suppress events with incoming SM particles, mostly high-energy muons passing through the FASER decay volume. To avoid energetic photons arising from muon bremsstrahlung in front of the detector entering undetected, an absorber block of 10 cm-thick lead is placed between the two pairs of modules. This either absorbs the photons



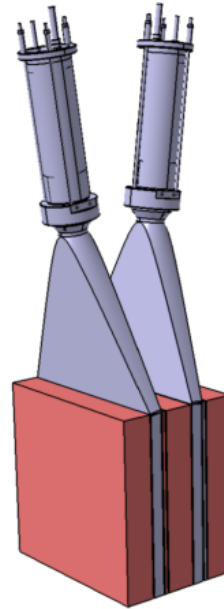
(a) First veto station.



(b) Second veto station.



(c) Timing station.



(d) Preshower station.

Figure 13. Drawings of the different scintillator stations. The PMTs are located at top and shown in grey (red for the first veto station) except for the timing station. The first station uses WLS rods shown in green to transport the light to the PMTs, while the others use triangular light-guides. For the second veto station and the preshower station, the absorbers are included in the drawings as the grey and red blocks, respectively.

completely or generate a shower that is detectable by the second pair of modules in this station. To suppress background related to muons from the interaction point, each pair of modules is required to detect more than 99.99% of the incoming muons. This is achieved by having a large scintillation signal and efficient light collection as well as a large coverage with respect to the detector aperture. Each module therefore consists of a 2 cm-thick, 30 cm \times 30 cm scintillator layer. The light guide

and PMT are oriented vertically above the scintillator to minimize the transverse size with the light guides tilted from vertical by 140 mrad in order for the PMTs of the two back-to-back layers not to overlap. The two pairs of modules are positioned either side of the lead blocks and each pair has a 65 mrad angular rotation around the LOS, again to avoid interference between neighbouring PMTs.

The third scintillator station, shown in figure 13(c), is primarily responsible for providing trigger and timing information for FASER. It is located after the decay volume magnet and before the first tracking station. It detects the appearance of a charged particle pair from the decay of a LLP in the decay volume and thus provides the primary trigger signal for physics analysis. It is also used to precisely measure the arrival time of the signal with respect to the interaction at the ATLAS interaction point. This timing information is used to suppress non-collision backgrounds, for which a resolution of better than 1 ns is required. Another design constraint on this station is that the material should be minimised, while maintaining a signal trigger efficiency above 98%. Finally, the active area of this station must be large enough to cover most of the magnet front surface in order to detect muons coming in at an angle, without passing through the veto stations or the first two tracker stations, but causing an electromagnetic shower in the magnet material and thus a detectable shower in the downstream calorimeter, as this could mimic a photon-only signature. The station is constructed from two 1-cm thick, 40-cm wide and 20-cm high scintillator layers, stacked vertically with a 5 mm overlap in the middle as shown in figure 13(c). Light guides on both sides of each scintillator layer connect to the same H6410 PMT type of assembly as used in the second veto station, but the light guide has 90° bend to minimize the transverse size of the station which is limited by the tunnel wall and trench width. The timing precision is optimized by reading out the scintillation signal on both ends of each scintillator as the horizontal time-walk cancels out when averaging the arrival time for the two PMTs.

The fourth and final scintillator station, shown in figure 13(d) is used both as an additional trigger station, which, if needed, can be used in a coincidence with the first trigger station to reduce the rate of non-physics triggers, and as the active sensor in the preshower detector. This station is located after the last magnet and tracker station and in front of the calorimeter system. The two scintillator modules are identical to the ones used in the second veto station. Both modules are preceded by a 3 mm-thick layer of radiator (tungsten) to create a simple preshower detector. This helps distinguish a physics signal of two close-by energetic photons, which would otherwise leave only large energy deposition in the calorimeter, from deep inelastic scattering of high-energy neutrinos. This is needed because the calorimeter does not have any longitudinal segmentation. To reduce backscatter from the calorimeter and preshower radiator into the last tracking station, a 5 cm-thick low-Z absorber material (graphite) is placed in front of each layer of tungsten and between the final scintillator module and the calorimeter. The scintillator modules are oriented vertically and the graphite absorber and tungsten radiator layers have the same $30\text{ cm} \times 30\text{ cm}$ transverse size as the scintillator modules. In total the preshower station has about 2.5 radiation lengths of material in front of the calorimeter.

3.2 Calorimeters

The calorimeter is constructed from spare LHCb outer ECAL modules [24], shown in figure 14. The LHCb Collaboration has kindly agreed to allow FASER to use eight of these modules on indefinite loan. The modules are of so-called Shashlik-type with interleaved scintillator and lead plates and 64 wavelength shifting fibers penetrating through the whole module and delivering the scintillation light to a single PMT situated in a steel tube at the centre of the calorimeter's modules. A single clear fiber

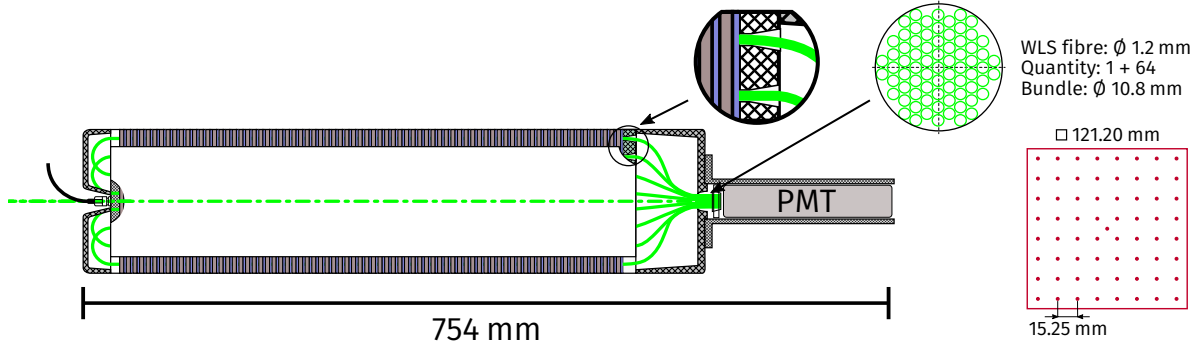


Figure 14. Design of a FASER (LHCb outer) calorimeter module.

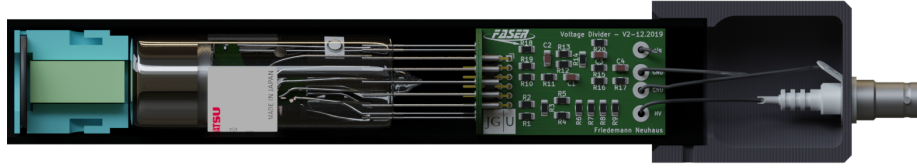


Figure 15. Design of a FASER PMT assembly with voltage divider and optical filter holder.

penetrates through the middle of the calorimeter in order to provide a light path for the LED calibration system, see section 3.3. The modules are 754 mm long, including the PMT, and have transverse dimensions of 121.2 mm \times 121.2 mm. Each module has a total depth of 25 radiation lengths and consists of 66 layers of 2 mm lead and 4 mm plastic scintillator, and 120 μ m-thick Tyvek reflective paper.

The light from a calorimeter module is measured using the same Hamamatsu R7899-20 PMT [43] type as used by LHCb. This is a ten dynode-stage head-on PMT with a cathode diameter of 22 mm and a typical gain of up to 2×10^6 . The voltage divider for the PMT was custom-built for FASER following the Hamamatsu recommendations for a tapered voltage-divider circuit in order to maintain good linearity for large pulses. The PMT and the voltage divider are situated inside the steel tube as illustrated in figure 15. The PMT is in addition surrounded by a permalloy protection tube to reduce the impact of magnetic fields. In front of that is a 32 mm long, 8 mm wide rectangular polystyrene light mixer to reduce the non-uniformity of the PMT response. An absorptive neutral density filter with 10 % transmission efficiency can be installed in the PMT assembly in front of the light mixer. This allows the PMT to be operated at higher gain where the non-linearity is small, see section 3.4.1, without saturating the readout electronics for energy deposits up to 4 TeV.

The full FASER acceptance is covered by four calorimeter modules in a 2×2 configuration. To avoid insensitive regions along the scintillating fibers and the gaps between modules, the modules are tilted horizontally and vertically by 50 mrad with respect to the LOS. To avoid light ingress into the calorimeter modules, all sides of the calorimeter are covered in 0.5 mm thick aluminium plates and gaps between the modules at the end are covered in aluminium tape as shown in figure 16. After installation in TI12, it was found that a measurable amount of electronic noise was picked up in the PMT assemblies from a nearby 4G GSM antenna which is part of the tunnel safety system. A Faraday-cage made from aluminium plates and connected to the detector ground plane was therefore constructed and installed around the calorimeter PMTs.

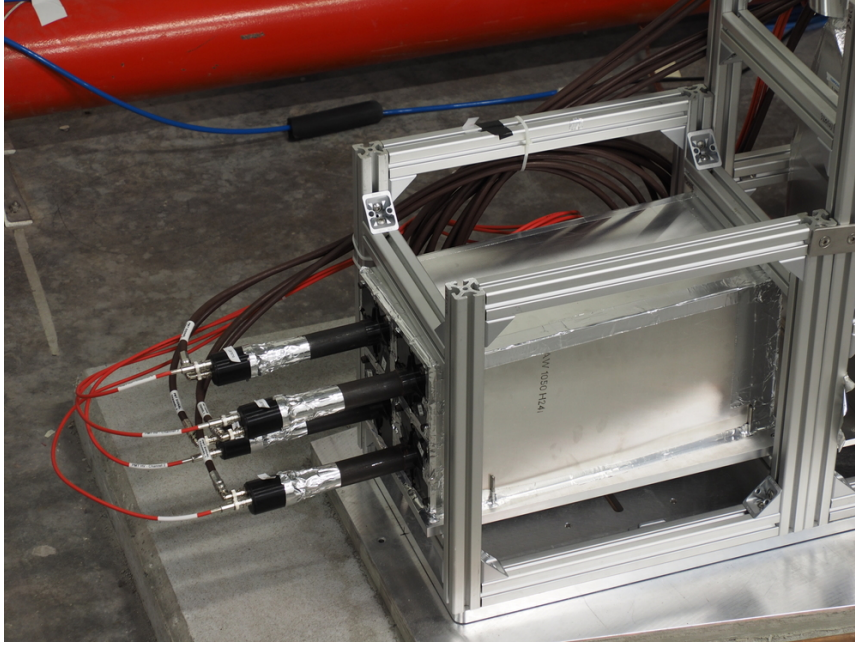


Figure 16. Assembled FASER calorimeter.

From previous LHCb measurements [44] and simulation studies about 2500 photo-electrons (250 when the neutral-density filter is installed) are expected per GeV of electron or photon energy. Figure 17 shows the predicted energy resolution estimated from simulation. Corrections for energy deposits in the extra material from the preshower station in front of the FASER calorimeter are also taken into account. The simulation results are compared to those from LHCb, where the solid line indicates the energy range probed by real measurements and the dashed line extrapolates the behaviour to higher energy. The predicted FASER energy resolution is given by

$$\frac{\sigma}{E} = \frac{9.2\%}{\sqrt{E}} \oplus 0.2\% \quad (3.1)$$

The simulation does not fully capture the expected 1% constant term and does not include contributions from electronic noise, which partially depends on the energy range the system is operated over. The resolution degrades at energies above 1 TeV due to leakage out of the back of the calorimeter. At 1 TeV, about 1.6% of electrons are expected to leak more than 3% of their energy, while for 5 TeV electrons 6.5% of them lose more than 3% of the energy out of the back. In addition a significant systematic uncertainty is expected on the overall energy scale as there are no high-energy electromagnetic signals in-situ which can be used for an absolute scale calibration.

3.3 Calibration system

A common practice for calibrating the energy response of calorimeters is using energy deposits from known processes e.g. $pp \rightarrow Z \rightarrow e^+e^-$ in ATLAS [45] and CMS [46]. The calorimeter of the FASER experiment does not have this possibility with the only charged particles crossing the detector at high rates being muons. However, as they are minimum ionizing, the signal from muons is quite low and can not be detected at the low gains the PMT are operated at. The only way to use muons to calibrate

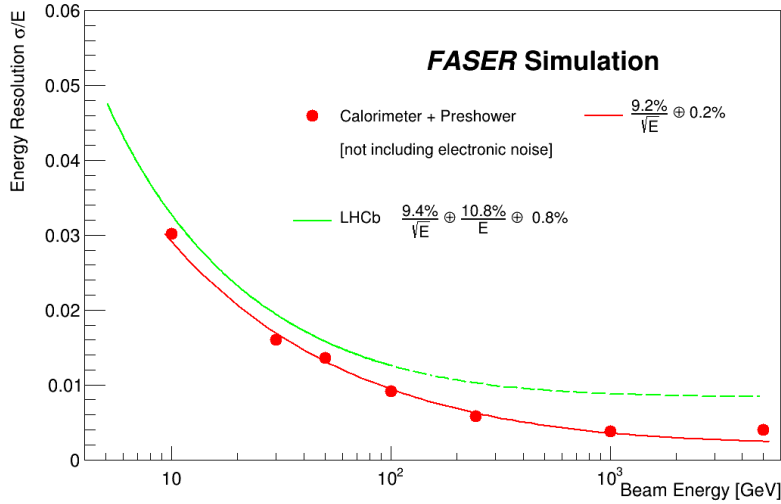


Figure 17. FASER calorimeter electron energy resolution from simulation as a function of electron energy compared to LHCb measurements (solid green line) and extrapolations (dashed green line). The FASER simulation does not include contributions from electronic noise.

the energy is to run at higher gains and then extrapolate down to the nominal operating range. The accuracy of this extrapolation is ensured by injecting a known amount of light into the module while lowering the PMT bias voltage in discrete steps and tracking the change in amplitude. To realize this, a dedicated LED-based calibration system was constructed. It is connected to the calibration port in the front of the calorimeter modules as can be seen in figure 14. The calibration system is also connected to all scintillator counter PMTs where it can be used to generate test pulses and monitor the long-term stability through regular dedicated calibration runs when there is no beam in the LHC.

In order to produce short light pulses, blue LEDs⁶ are driven by a commonly used circuit originally proposed by J.S. Kapustinsky [47]. The circuit works by quickly discharging a capacitor through the LED resulting in a short flash of light. To reduce the duration of the pulse, an inductor is put in parallel with the LED, producing a current opposite to the current from the discharging capacitor. The capacitor and inductance values are chosen such that the pulses have sufficient amplitudes to feed all four calorimeter modules using a single LED. The values chosen are 10 nF and 220 nH.

The calibration system features two independent LEDs with one channel used to drive the calorimeter and the second channel used for the scintillator counters. To ensure good light yield, a custom fibre bundle with four 1 mm diameter fibres is used to guide the light to the calorimeter modules. As the scintillator stations are operated at much higher gains, commercial off-the-shelf optical fibres are used. To split the light from the LED into multiple outputs, the LED is positioned in front of a fiber fan-out from an MPO multi-fiber connector to individual LC fiber connectors. The individual scintillator counters are then connected using class OM2 multi-mode fibres.

The calibration system is controlled by an 8-bit microcontroller.⁷ The system provides a simple HTTP-API to set and query all relevant parameters such as pulse frequency and amplitude as well as to enable and disable the two outputs. The frequency can be set in a range from 0.25 Hz to a few

⁶MULTICOMP PRO OVL-5523.

⁷Microchip ATmega328p.

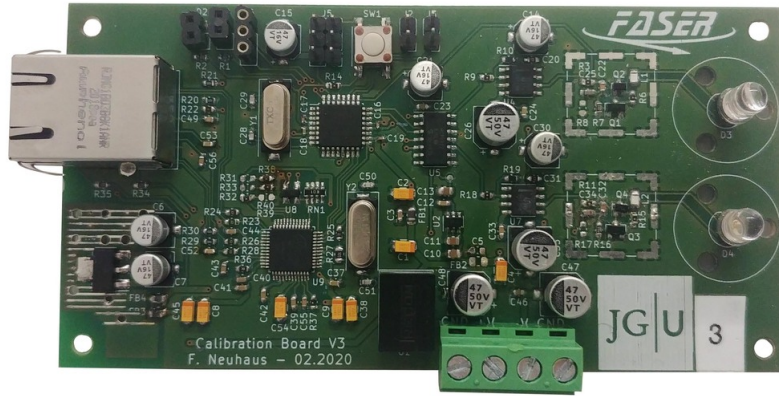


Figure 18. Photograph of the calorimeter calibration system board.

hundred Hz. For every pulse an additional TTL-signal is sent to the TDAQ system for triggering on the calibration pulses. The bias voltages are set by a 12-bit two channel DAC in combination with inverting op-amps, yielding a range between 0 V to 22.5 V. A picture of the calibration board is shown in figure 18.

In addition, the calibration board can be used to produce a random trigger for testing the DAQ behaviour. In this mode the LED drivers are disabled and only TTL-signals are generated.

3.4 Pre-installation commissioning

Before installation, all PMTs, scintillator counters, calorimeter modules and the calibration system, including spares, underwent a series of tests to ensure they were fully functional and to select the best performing PMTs/modules. The tests used a combination of light and gamma ray radiation sources as well as cosmic rays.⁸

3.4.1 Standalone PMT tests

Prior to installation, the individual PMTs performance were characterized to ensure they fulfilled specifications. Seven calorimeter PMTs were tested with the goal to select the four PMTs with highest gain for final installation. For the scintillator PMTs, the goal was to select and pair PMTs with similar gain for neighbouring modules, which provides better uniformity before voltage adjustments for a given station.

The quantum efficiency of each PMT as a function of the photon wavelength was measured using a dedicated setup at CERN. For most wavelengths, the quantum efficiency was consistent between all but one PMT (LB8764) as shown in figure 19. The emission peak for the Kuraray wavelength shifting fiber [48] is found at about 495 nm where the efficiency for all PMTs is around 17 %. The quantum efficiency for the scintillator counter PMTs was not measured as this would have required unsoldering the voltage divider from the pre-assembled PMTs.

The absolute gain of the PMTs was measured using single photons from a flashing, very low intensity LED, and results are shown in table 3 for the scintillator counter PMTs. All measured gains are

⁸The calorimeter performance was also characterized at the CERN SPS test beam using a combination of electron, muon and pion beams, the results of which will be presented in an upcoming paper [38].

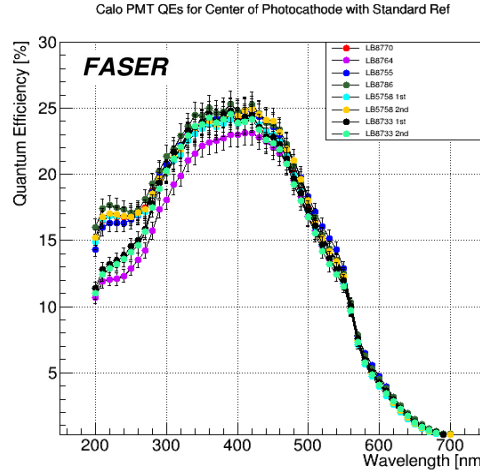


Figure 19. Measurement of the calorimeter PMT quantum efficiency as a function of photon wavelength. Two PMTs were measured twice to check the reproducibility of the measurement.

within a factor of two of the specified typical gain. The table also lists the scintillator module efficiency (at 95% CL) for minimum ionizing particle (MIP) signals and the most probable MIP signal expressed in photo-electrons as measured with cosmic ray muons (see section 3.4.2). For the calorimeter PMTs, figure 20 shows the measured gain for several applied voltages for the different PMTs measured using LED pulses. The absolute gain is measured at 1700 V using single photon-electron signals and extrapolated to lower voltages using a larger fixed pulse size. The PMTs show the same voltage dependence within 15%. The voltage dependence is monitored in-situ using the LED calibration system discussed in section 3.3. The four calorimeter PMTs with gain above 10^6 were selected for final installation, while for the scintillators, PMTs with similar gain were paired for neighbouring modules.

In calorimetry, a linear signal response is critical for an accurate measurement of deposited energy. The linearity of the PMT response as a function of the applied voltage was measured for each calorimeter PMT using two LED pulses separated by 550 ns, with the second pulse a fixed factor larger than the first pulse. The linearity is measured from the relative response to the two pulses as a function of the peak current of the larger pulse, normalized to the ratio measured in a linear regime. An example measurement is shown in figure 21 for one PMT and one pulse ratio. Only minor variations were found between the different PMTs, but $\sim 5\%$ non-linearity was observed at the maximum readout range (peak current ~ 40 mA) for voltage settings below 800 V. This motivates the use of an optical filter to enable physics operation at higher voltage. This measurement was carried out using the same digitizer as used in the final experiment (see section 4.2.2), thus demonstrating that non-linearity effects of the PMT are dominant as good linearity is seen for pulses measured at large high voltage settings.

Finally, the dark rate was measured as a function of signal threshold for different voltage settings and found to be very low. At 1500 V, all but one of the calorimeter PMTs had a rate of less than 10 Hz for a threshold set to that expected for a three photo-electron signal. For the H6410 and H11934 scintillator counter PMTs, the rate was at or below 10 Hz for a one photo-electron signal threshold at 2000 V and 850 V, respectively.

Table 3. Scintillator counter PMT gain measured with single photons at 950 V for Veto station 1 and 1700 V for the rest. The table also lists the scintillator module efficiency (at 95% CL) for MIP signals and the most probable MIP signal expressed in photo-electrons as measured with cosmic ray muons. The efficiencies are estimated with a threshold of half the most probable MIP signal. The precision of the efficiency measurements varies between PMTs as some measurements were done with significantly larger samples of cosmic rays.

Station	Module	Gain ($\times 10^6$)	MIP signal	
			Efficiency	Most probable signal
Veto station 1	1	4.85 ± 0.07	$> 99.99\%$	205 p.e.
	2	4.10 ± 0.17	$> 99.95\%$	200 p.e.
Veto station 2	1	2.69 ± 0.02	$> 99.985\%$	285 p.e.
	2	3.30 ± 0.04	$> 99.995\%$	380 p.e.
	3	4.19 ± 0.07	$> 99.996\%$	360 p.e.
	4	4.27 ± 0.08	$> 99.991\%$	305 p.e.
Timing station	1, PMT 1	1.44 ± 0.03	$> 99.7\%$	85 p.e.
	1, PMT 2	1.74 ± 0.03	$> 99.8\%$	135 p.e.
	2, PMT 1	2.20 ± 0.04	$> 99.8\%$	135 p.e.
	2, PMT 2	2.48 ± 0.05	$> 99.8\%$	115 p.e.
Preshower	1	3.96 ± 0.04	$> 99.96\%$	330 p.e.
	2	4.73 ± 0.05	$> 99.97\%$	370 p.e.

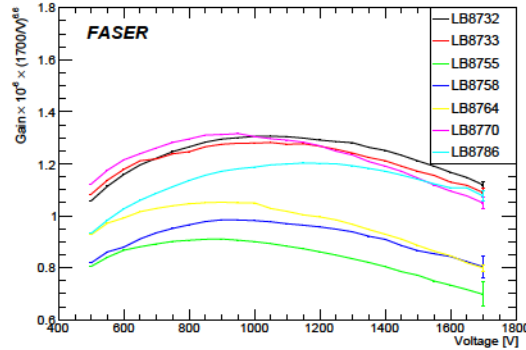


Figure 20. Measured calorimeter PMT gain as a function of applied voltages for the different PMTs measured using LED pulses. The absolute gain is measured at 1700 V using single photon-electron signals and extrapolated to lower voltages using a larger fixed pulse size. The gains are scaled by $10^{-6} \times \left(\frac{1700 \text{ V}}{V}\right)^{6.6}$ in order to easily compare the behaviour over the full measurement range. The measurement uncertainty of the absolute gain is shown with the error bars at 1700 V and applies to the full curve.

3.4.2 Scintillator counter measurements

The performance of each scintillator module was measured using cosmic ray muons. Multiple scintillator counters were stacked vertically above and below the scintillator module under test with up to 5 cm of copper shielding placed above to select a clean sample of events. For the veto station modules, additional and more precise measurements were performed by adding one tracker station below the scintillator module, as illustrated in figure 22, to select a very pure sample of single particle

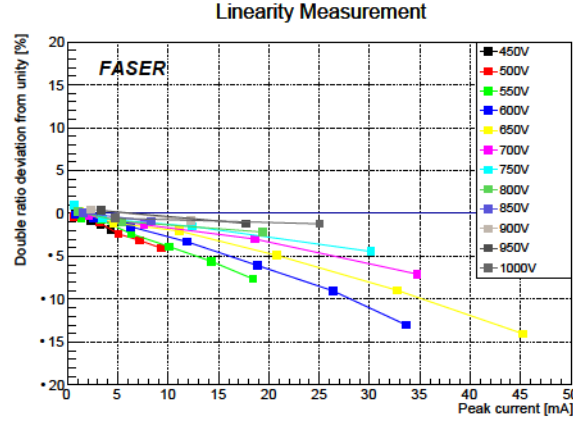


Figure 21. Measurement of the calorimeter PMT linearity for one PMT (LB8733) using a double pulsing system as explained in the text.

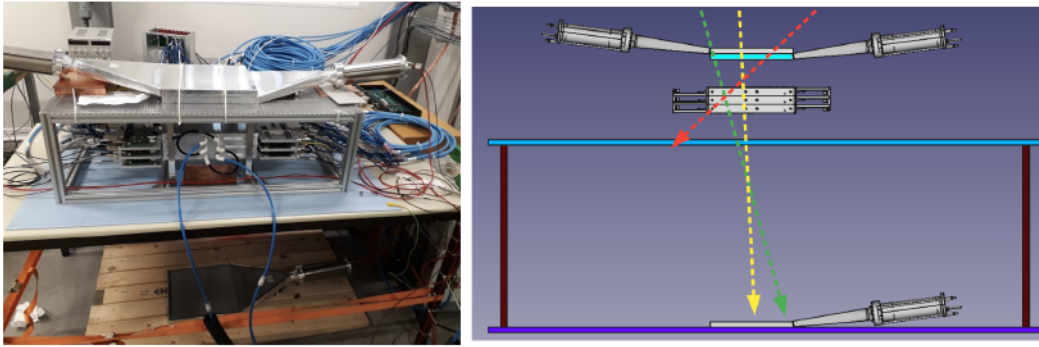


Figure 22. Left: detector setup for efficiency measurements. Right: schematic diagram of the setup with incident cosmic ray muons. Two scintillator modules are placed above a tracker station, all elevated by 90 cm above a third scintillator counter at the bottom used to select mostly approximately vertical cosmic ray muons. The scintillator module under test is highlighted in cyan colour.

cosmic rays. For each module, more than 50,000 events containing cosmic ray muons passing through the scintillator counters were collected. These samples were used to measure the muon signal in the scintillator counter and the detection efficiency for muons for a detection threshold of half of the most probable minimum ionizing particle signal. An example distribution of the measured signal is shown in figure 23 where no events below the selected threshold are observed out of more than 65,000 events. The resulting limits on the scintillator counter efficiency are shown in table 3 along with an estimate of the most probable light signal for a minimum ionizing particle. Only lower limits are shown since for all measurements the number of non-detected events are zero or just a few events. In the latter case, these events are consistent with being due to non-muon background events with the exception of module 1 in veto station 2, where the measured efficiency is $99.992 \pm 0.004\%$. This module has also a lower light yield than the rest of that type of scintillator modules. In all cases, the resulting efficiency when combining two modules in a station are well above those given by the requirements in section 3.1.

The timing resolution of the timing station modules was tested using cosmic ray muons in a similar setup. The other scintillator counters were arranged with a minimal overlap between

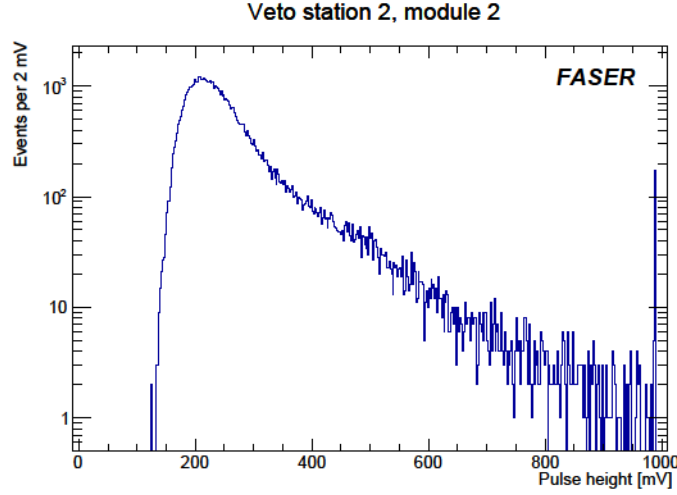


Figure 23. Pulse height distribution in veto station 2, module 2 PMT measured for cosmic ray muons selected independently using two other scintillator counters and a tracker station. The readout for the pulse height saturated at 1000 mV.

them in order to select muons in a narrow region of the module. The time for a signal to arrive at the PMT at each end of the module depends on the location at which the muon traversed the scintillator counter. By using the time difference between the PMTs on each side it is possible to extract the time resolution. The spread in time difference between PMTs was measured at two known points along the length of the timing scintillator. As shown in figure 24, it is about 500 ps. This implies a precision on a single PMT timing measurement of about 350 ps and therefore, assuming measurements are uncorrelated, an expected precision of the average signal time measurement from both PMTs of 250 ps. This is well below the 1 ns requirement and close to the intrinsic 180 ps spread in the collision time.

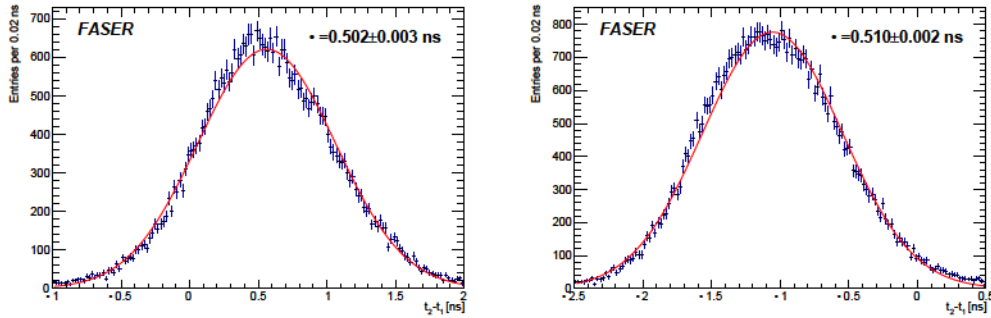


Figure 24. The time difference in the reconstructed arrival time for the left and right PMT in a timing module for cosmic rays 15 cm (left) and 28 cm (right) from the left edge (PMT 1) of the 40-cm wide scintillator plate. The distribution have been fitted with a Gaussian function shown in red to measure the timing resolution.

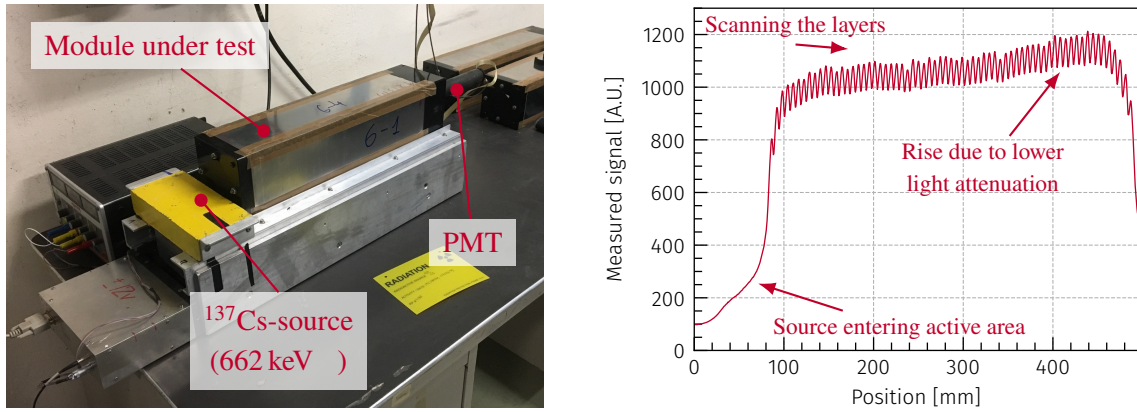


Figure 25. LHCb test setup used to scan the calorimeter modules (left) and the measured response for one side of a calorimeter module (right).

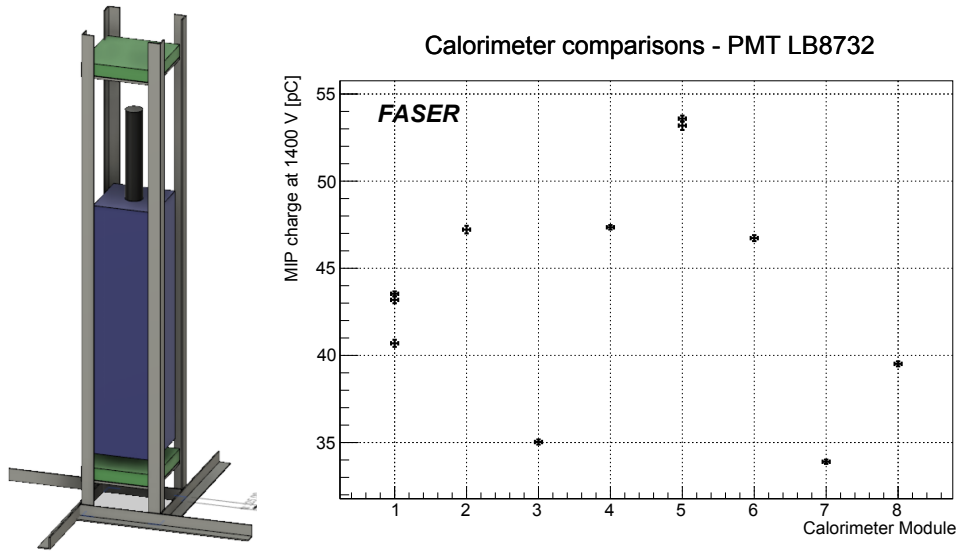


Figure 26. Left: calorimeter cosmic ray test stand with scintillator counters for triggering shown in green above and below the module under test. Right: calorimeter signal for cosmic ray muons as measured with the same PMT at 1400 V. For module 1 and 5, several measurements were done with the PMT removed and reinserted at a different rotation between measurements.

3.4.3 Standalone calorimeter tests

Eight calorimeter modules were tested to select the four final modules. An initial test was done using a ^{137}Cs radioactive source scanned along each side of the calorimeter module to confirm that all modules were fully functional after more than ten years in storage. The setup, along with the results for one side of a module, are shown in figure 25.

The calorimeter performance was measured using cosmic rays with the setup shown in figure 26 (left). Scintillator counters above and below the calorimeter module were used to trigger on vertical cosmic rays and the deposited charge was measured at different PMT voltage settings. Figure 26 (right) presents a comparison of the response for the eight modules, all measured using the same PMT

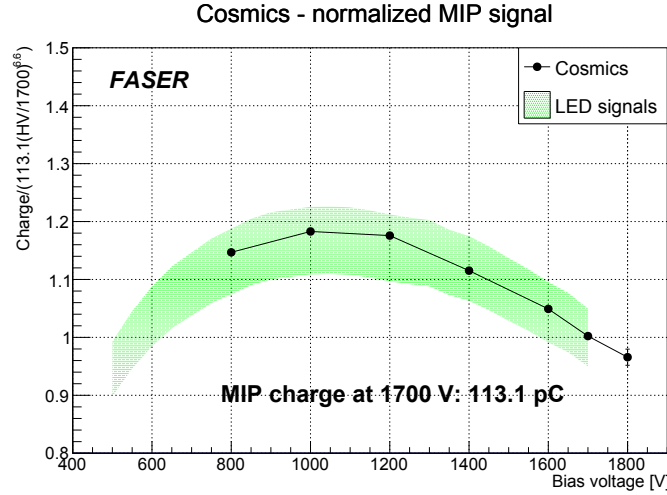


Figure 27. Calorimeter signal for cosmic ray muons as measured with the one PMT at different bias voltages compared to voltage dependence measured using LED signals. The signals have been normalized to 1 at 1700 V and the $^{-6}$ dependence divided out to ease comparison. The green band corresponds to the 5% uncertainty assigned to the LED measurement systematic uncertainty.

at 1400 V. All modules demonstrated good performance and modules 2, 4, 5 and 6 were selected for installation as they had the most similar response. The dependence on the PMT voltage and the comparison to the dependence measured using LED signals is shown in figure 27 for one specific PMT, LB8732. Agreement between cosmic ray and LED signals is found to be better than 5% for all modules.

3.4.4 LED calibration standalone tests

To evaluate the stability of the calibration system, the response to calibration pulses was measured using two photomultipliers over a duration of 15 days with a frequency of 100 Hz and a fixed pulse amplitude. The relative amplitude is shown in figure 28. The relative deviation was found to be around 1.5%. In addition, no degradation of the LED light yield was observed over the two week period. As the in-situ calibration procedure is performed over a period of about 30 minutes, the drift is small enough to not significantly influence the calibration which does not rely on the absolute intensity of the calibration pulses, but the drift limit the ability to precisely monitor the PMT stability over extended periods.

4 The trigger and data acquisition system

The FASER trigger and data acquisition (TDAQ) system hardware and software are designed to be lightweight but robust as the experiment aims to capture a potentially extremely rare signal over four years of data-taking. The complete trigger logic takes place in hardware installed in a rack for electronics next to the detector itself. The number of hardware components is minimal to reduce the amount of cabling and equipment, which are inaccessible during data-taking. Data from each sub-component is transferred via a 1 Gbit/s link to the FASER TI12 Ethernet switch and thereafter via a 10 Gbit/s optical fiber line directly to a single DAQ PC above surface, where software combines the data of each sub-component to build complete events and record them to file. The experiment triggers on any high-energy particle traversing its detector volume. The expected trigger rate in

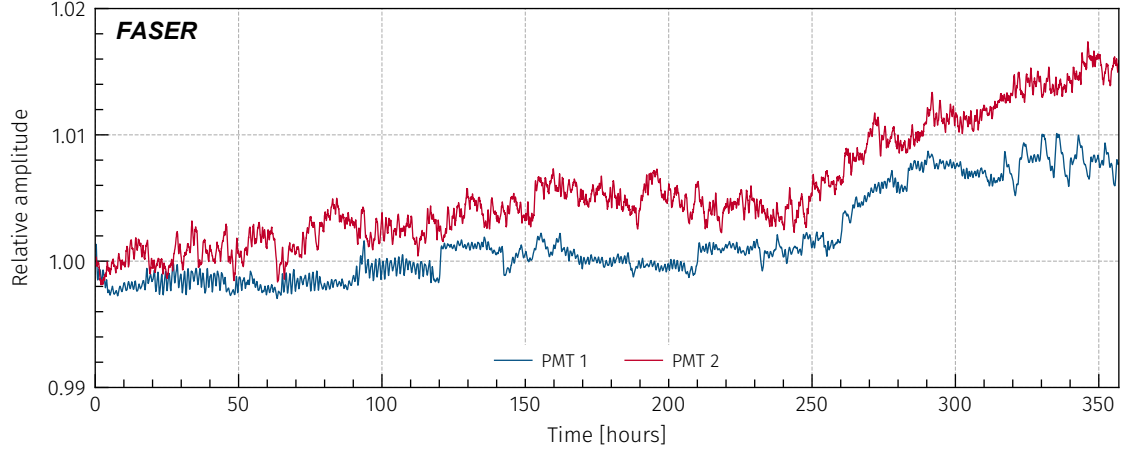


Figure 28. Measurement of the signal amplitude for calibration pulses over a duration of 15 days to evaluate the long-term stability. The amplitude is normalized to the first few pulses.

the scintillator counters for an instantaneous luminosity of $2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ is roughly 650 Hz, predicted by simulation and in-situ measurements [3]. This is dominated by muons originating from the ATLAS IP. Around 5 Hz of energetic signatures is deposited in the calorimeter. The event size is almost 22 kBytes/event, thus the expected data recording rate is around 14 MBytes/s. The FASER experiment is planned to be operated remotely with no shifters populating a control room. The TDAQ design therefore emphasises abundant monitoring and alerts.

The current section provides an overview of the TDAQ core hardware (section 4.1), description of individual readout components (section 4.2), and finally an overview of the software (section 4.3). A complete and detailed description of the TDAQ system can be found in ref. [25].

4.1 TDAQ core hardware overview

At the core of the TDAQ system is the FASER Trigger Logic Board (TLB), the central trigger logic processor that manages trigger signals by combining them and regulating their rate via prescales and vetoing, and the FASER clock board that provides a stable clock to drive the system. The detector components used for triggering are the four calorimeter modules and the four scintillator stations. The PMT pulses are first digitized by a CAEN digitizer board (described in section 4.2.2 below), which transmits trigger signals for pulses exceeding a preset threshold to the TLB.

The core system runs on the LHC clock signal with a frequency of 40.08 MHz, corresponding to the frequency of proton bunch-crossings. The period of one clock cycle is thus equal to the spacing between bunch-crossings, or 25 ns. The clock signal as well as the LHC orbit signal at 11.245 kHz, are part of the beam synchronous timing (BST) system, transmitted over optical fibers to beam instrumentation equipment around the LHC using the TTC system [49]. For FASER, this signal is received by a legacy VME system, the BST receiver interface for beam observation system (BOBR) [50], produced by the LHC beam instrumentation group. However, the LHC clock provided by the BOBR has a non-negligible jitter, mainly due to noise in its power module, changes during the energy ramp of the LHC, and is not guaranteed to be continuous when there is no beam in the LHC. For this reason, the FASER TDAQ incorporates the FASER clock board that provides a high-quality, uninterrupted reference clock with a constant phase with respect to the LHC clock

across power-cycles. The clock board cleans the jitter of the BOBR to less than 4 ps and a zero-delay feature of the jitter cleaner guarantees that the output FASER clock is aligned to the LHC clock with its phase unchanged across resets and power-cycles.

The TLB is a custom GPIO board with an adapter card. The GPIO board was developed as a general readout board utilising a CYCLONE V A7 FPGA (Field Programmable Gate Array). The FPGA is nominally driven by the external LHC clock input but can be driven by a 40 MHz oscillator on the GPIO board itself.

When an event satisfies a trigger logic, the TLB distributes a global Level-1 accept (L1A) signal to all readout components (the Tracker Readout Boards (TRBs) (section 4.2.1) and the digitizer (section 4.2.2)) to initiate the readout of an event. It may also send a L1A based on an internal trigger or the LED calibration signal. Both the TLB and TRBs run on the LHC clock, while the digitizer runs on its own internal 500 MHz clock; nevertheless it receives the LHC clock to record as a reference clock so that the relative timing of PMT pulses can be calculated in software. In addition, the TLB receives the LHC orbit signal that it distributes to the TRBs and the digitizer. The TLB and TRB both have an on-board bunch counter that is incremented with every clock cycle and reset with the orbit signal, otherwise known as the bunch counter reset (BCR) signal. A bunch counter for the digitizer is calculated in software based on a timestamp reset by the orbit signal, and the expected LHC clock frequency. Figure 29 provides an overview of the TDAQ hardware system.

The TLB includes tunable delays for the L1A and BCR signals to ensure that data from the correct event is read out. Triggers may be vetoed due to several sources. A settable simple deadtime window vetoes any triggers for N clock cycles following a L1A. Both the TRBs and the digitizer can send a busy signal to the TLB to halt triggers while reading out data. A TRB is only able to read out one SCT event at a time, thus it activates a busy signal for the duration of its event readout. The digitizer activates a busy signal based on the occupancy of its readout buffers. Further sources of deadtime are an on-board rate limiter, which limits the output trigger rate to 2.2 kHz to guard against noise bursts, and a bunch-crossing reset veto which disallows L1As for the duration of a bunch-counter reset on the SCT modules. An event readout typically takes around 340 clock cycles in total, and around 208 clock cycles from tracker busy signal only. Upon a L1A, the TLB sends out a data packet containing trigger information for that event. The TLB regularly publishes monitoring data packets containing monitoring numbers such as trigger item counts and veto counts.

4.2 Readout hardware

In the following the readout components that receive the global L1A signal, the tracker readout boards and the digitizer, are described.

4.2.1 Tracker readout board

The Tracker Readout Board operates and reads out the SCT modules. It consists of a GPIO board of the same design as the TLB described above and its adapter card as shown in figure 30. The adapter card works as an interface between the tracker patch-panel and the TLB and is directly attached to the GPIO board.

The TRBs are housed on the detector in a custom-made mini-crate, with the mini-crate backplane providing 24 V power as well as the TLB signals for the GPIO boards. The TRB is connected to the TLB via a RJ45 connector located on the rear side of the mini-crate backplane.

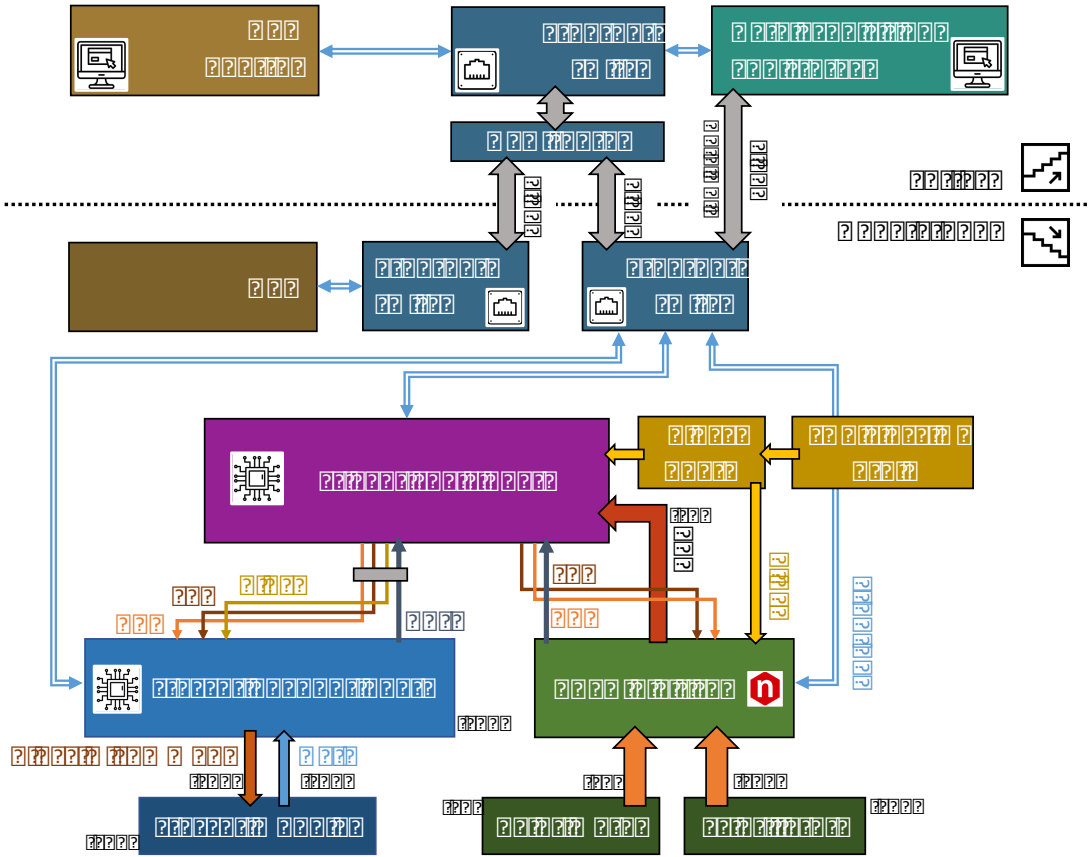


Figure 29. A simple schema of the FASER TDAQ architecture. The numbers in parentheses indicate the number of channels or lines. The blue double-line arrows indicate the connections via Ethernet. The grey thick arrow indicates fibers from the TI12 tunnel to the surface. The digitizer, clock board and TLB are housed in a VME crate. The TRBs are located in two dedicated mini-crates just above the tracker structure, one of the two housing the IFT TRBs.

One TRB reads out eight SCT modules corresponding to one tracker plane. Therefore, a total of nine TRBs are used for the FASER tracking spectrometer, and a further three TRBs are used for the IFT. The TRB adapter card is connected with the tracker plane patch-panel via 8 Samtec twinax Firefly cables.

In order to configure the tracker modules as well as transmit to them timing and trigger signals, the TRB must send configuration commands and data encoded in a bit-stream to the tracker modules. The TRB firmware therefore has the functionality to prepare the bit-stream understood by the SCT modules from commands and data received from the host PC. When in data taking mode, the TRB can be operated both in standalone mode and within the global system. The standalone mode is used during calibration scans, generating an internal trigger with a self-regulated rate and running on its own internal 40 MHz clock. Once included in the global system in data taking mode, the TRB receives and is driven by the L1A signals, BCR signals and external clock signal provided by the TLB as described in the previous section.

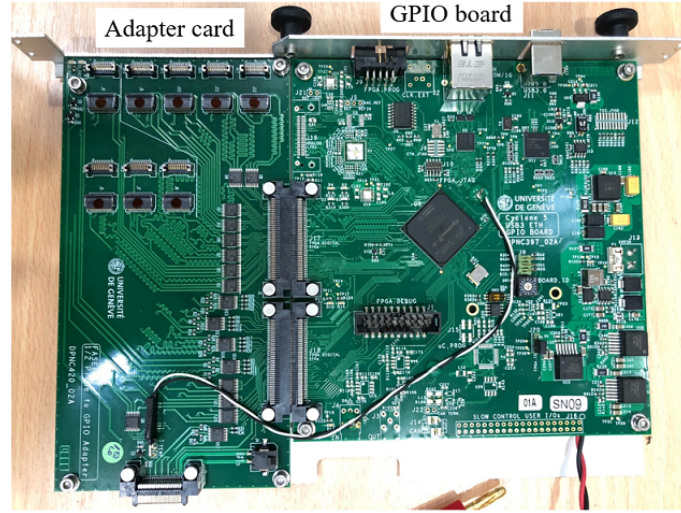


Figure 30. FASER tracker readout board (TRB) consisting of a GPIO board and adapter card.

The time tuning of the L1A signal is especially important in the case of the tracker readout, as the SCT hit readout window extends only across 3 clock cycles, equivalent to 3 proton bunch-crossings. During physics data taking the L1A and BCR signals arrive at the SCT modules with a fixed latency. The tracker readout has an internal pipeline of 132 clock cycles, so that the TLB L1A signal must arrive at the SCT modules 132 clock ticks after the charged particle traversed the tracker plane. There are inherent delays in signal propagation from the occurrence of an event to the arrival of the L1A at the TRB. To cover the full 132 clock cycle latency, both the TRB and TLB have settable coarse time delays in increments of clock ticks for the L1A/BCR signals. A signal delay of up to 127 clock ticks on the TLB and a further adjustment of 0 to 7 clock ticks on a TRB are possible, where the latter allows one to adjust for different particle times-of-flight at each tracker station location in the final detector setup. Tracker hits are sampled at the rate of the input clock and 3 samples (corresponding to 3 clock cycles or bunch-crossings) are ultimately recorded. The timing of the tracker sampling of hits can be adjusted with a resolution of 390 ps via an adjustment of the input clock phase on the TRB. The fine time tuning ensures the silicon hits are sampled on the pulse peak, maximising the hit detection efficiency.

4.2.2 CAEN digitizer

The readout electronics of the calorimeter and scintillator detectors need to sample the signals from the calorimeter and scintillator counter PMTs, provide trigger input signals to the TLB and buffer the calorimeter and scintillator counter data, which are read out upon a trigger signal. This functionality is accomplished by using a VME-based system consisting of a single 16-channel, 14-bit CAEN VX1730 digitizer board⁹ that is controlled and read out via Ethernet using the Struck Innovative Systems SIS3153 VME interface board.¹⁰ The dynamic range of a digitizer channel is 2 V with a programmable offset of up to 1 V that can be set independently on each channel. The signals on each channel are continuously digitized at 500 MHz and stored in a circular buffer to be read out on

⁹VX1730 / VX1730S 16/8 Channel 14 bit 500 MS/s Digitizer. <https://www.caen.it/products/vx1730>.

¹⁰Struck innovative systems, SIS3153 USB3.0 and Ethernet to VME interface, <https://www.struck.de/sis3153.html>.

receiving a trigger signal. The full waveform for each channel is read out for a user-defined period of up to 1.2 s. The long readout window allows for a detailed offline analysis of the waveform, in particular in the case of any anomalous signal, but can be later reduced after experience with beam data is collected. The on-board trigger logic has, for each channel, a user-defined, fixed, absolute threshold that can be set to generate an over/under-threshold signal. The scintillator counter trigger threshold is below that of a single minimum ionizing particle, while the calorimeter threshold is set to trigger on electromagnetic showers depositing more than about 20 GeV of energy. The trigger channels are combined in pairs into eight trigger signals using a logical AND or OR, depending on the need. The trigger signals are propagated and further combined in the TLB as described above.

4.3 TDAQ software

Event building and writing to file is hosted on a single DAQ server on the surface. The DAQ server is a 24-core, 48-thread AMD CPU SuperMicro server, with 64 Gigabyte memory, two 500 Gigabyte SSDs for the operating system and two 8 TB hard-drives for data storage. FASER DAQ, FASER's event building and writing software framework, relies on DAQling [51, 52], a lightweight open-source DAQ framework designed for the data acquisition of small and medium sized experiments. The framework builds DAQ modules written in C++ and enables synchronised Finite State Machine (FSM)-like control of all module processes. DAQ modules are connected via an asynchronous messaging communication layer for the throughput of data packets. The configuration of modules is stored in a JSON format, while control is handled via python applications.

Figure 31 presents the structure of the FASER DAQ [53]. During physics data taking, the complete framework runs 16 DAQ modules as the main event handlers: 12 receiver modules (one for each TRB/tracker plane), a receiver module each for the TLB and digitizer, an event builder module, and a file writer. Receiver modules communicate with the readout boards to retrieve event data fragments and dress these with a header that includes the event ID and bunch counter ID (BC ID). The event builder stores the fragments received from each receiver module and in parallel matches them based on a common event ID to form a complete event within a configurable time before timeout. Events are given a header that includes a time stamp, event ID, BC ID and trigger bit information, and sent to the file writer, which buffers events and eventually writes them to file. Several recording streams exist to pipe complete events, incomplete (timed-out), corrupted and duplicate events to separate files. In addition, another $O(20)$ monitoring modules are run online, dedicated to monitoring specific event features in events from the event builder. Monitoring metrics and histograms are regularly published to a Redis database [54].

A Run Control web interface allows a user to choose the run configurations and control the FASER DAQ FSM. Separate web pages visualise the monitoring metrics. Metric values defined in DAQ modules are regularly sent to an InfluxDB [55] database and presented in Grafana [56] dashboards, while a custom online histogramming API polls the Redis database to display histograms live.

4.4 Pre-installation commissioning

The commissioning of the TDAQ system before installation in the TI12 tunnel began with the qualification of the hardware functionality of each standalone component in 2019. Throughout 2020, communication and readout was tested by combining components, culminating in a cosmic-ray test

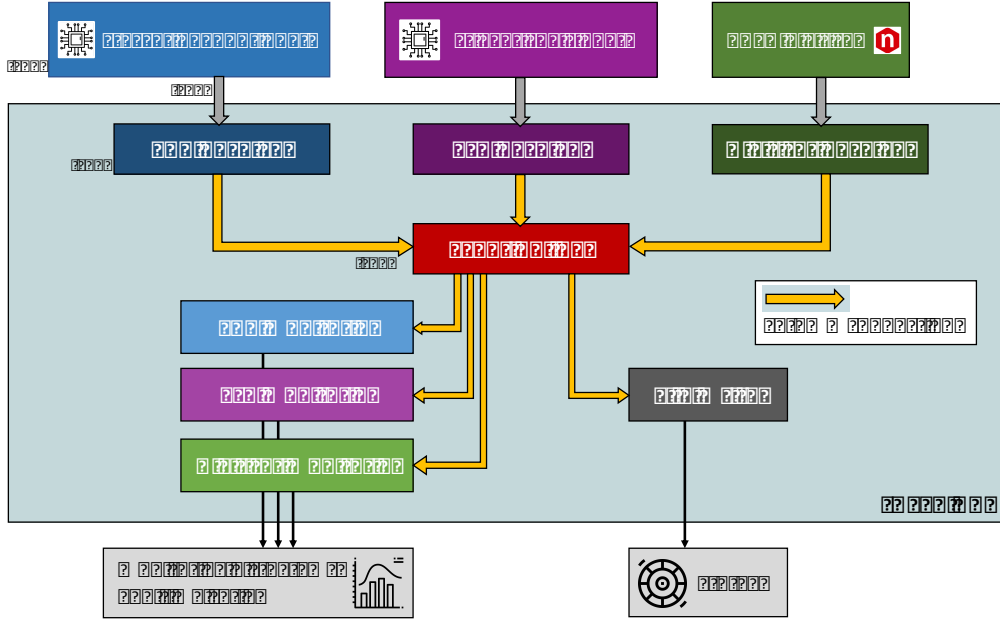


Figure 31. Overview of the FASER DAQ software processes, with a communication layer between DAQ modules based on the ZeroMQ messaging library [57].

stand, consisting of a FASER tracker station and FASER scintillator counters for triggering, in a dedicated surface area at the CERN Preveessin site. This allowed testing of the TLB coincidence triggering and L1A delay to the tracker readout (so that tracker hits from the cosmic muon interaction appear in the readout window), as well as testing of the run control, monitoring and alerts. More details of the TDAQ commissioning is described in ref. [25]. Further commissioning of the TDAQ system as part of combined running with the installed detector is detailed in section 9.

5 The magnet system

Three dipole magnets are installed in the FASER detector, based on a Halbach array permanent magnet (PM) design [58]. The longest, 1.5-m long, surrounds the decay volume, and is followed by two 1-m long dipoles installed along the tracking spectrometer. They produce a field of 0.57 T inside an aperture diameter of 200 mm. The main parameters are listed in table 4.

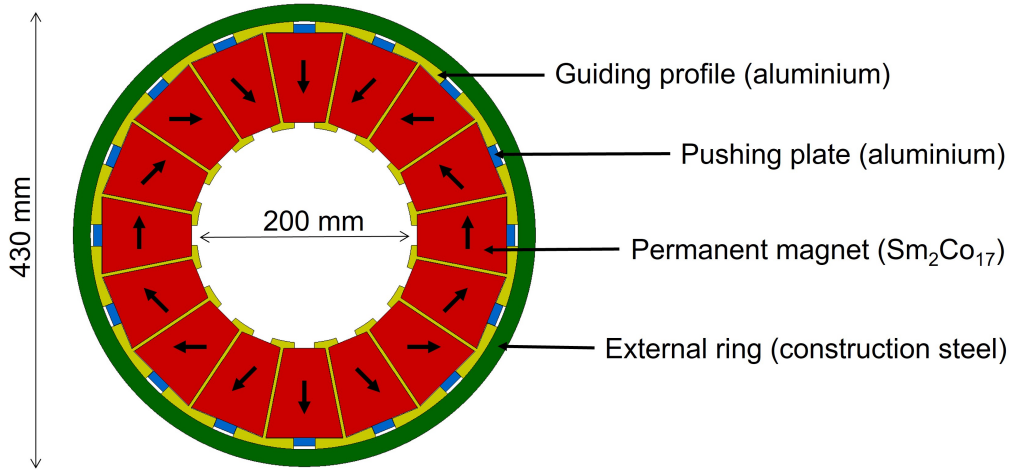
The main advantage of the Halbach design is to produce a strong and homogeneous field inside a relatively large aperture while keeping compact overall dimensions. The FASER location in the TI12 tunnel gives tight constraints on the magnet dimensions. Due to the limited depth of the trench, only 250 mm are available between the trench floor and the dipole central axis when aligned on the beam collision axis LOS. In addition, at the back of the detector there is only 250 mm in the horizontal plane between the magnet central axis and the tunnel wall.

The design is based on a Halbach array with 16 magnet sectors. The number of sectors was defined to keep the permanent magnet blocks to reasonable dimensions and to provide a field homogeneity of better than 3% inside the whole dipole aperture. The cross section of the dipole is identical for both models and is shown in figure 32. The permanent magnet blocks, made of

Table 4. Main design parameters of the FASER dipoles.

Parameter	Short Model	Long Model	Unit
Aperture diameter	200	200	mm
Length	1000	1500	mm
Outer diameter	430	430	mm
Mass	914	1331	kg
Mass of permanent magnet	606	909	kg
Nominal field at the centre	0.57	0.57	T
Good field region (GFR) radius	100	100	mm
Field homogeneity in GFR	3	3	%
Permanent magnet material	Sm ₂ Co ₁₇	Sm ₂ Co ₁₇	-

rare earth Samarium Cobalt Sm₂Co₁₇, have a trapezoidal shape, with five different easy axis^u orientations to shape the dipolar field inside the aperture. The blocks are 83.3 mm long, and are arranged in 12 (18) rings of 16 blocks each for the short (long) magnet(s). They are installed inside a structure made of aluminium guiding profiles attached to an external steel ring. The PM blocks are locked in position with aluminium pushing plates.

**Figure 32.** Cross section of FASER dipole. The arrows indicate the direction of the magnetic field in each of the permanent magnetic blocks.

5.1 Magnetic design

The main magnet design parameters such as the number of sectors in the array, the PM grade and geometry, and the dipole dimensions were defined using the 2D magnetic design shown in figure 33, using FEMM [59]. The maximum clearance between magnet sectors has been set to 3 mm to limit the impact on field homogeneity and, at the same time, ensure a good rigidity of the aluminium guiding profiles.

^uThe easy axis defines the direction for which the spontaneous magnetization of the material is easiest.

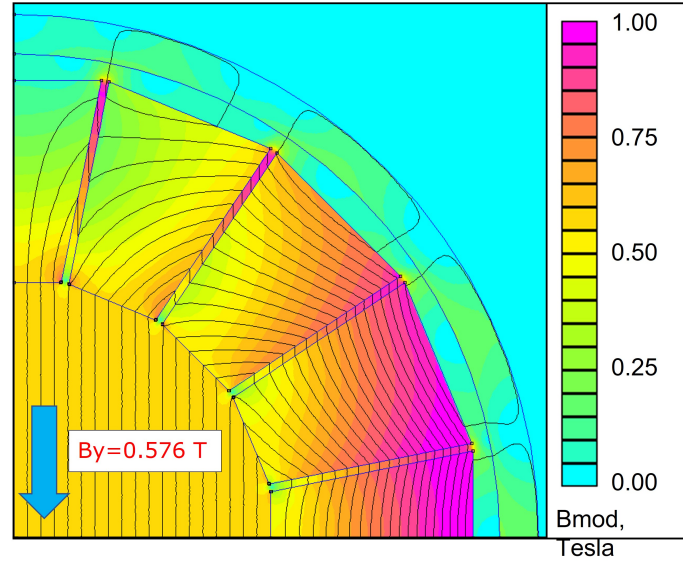


Figure 33. 2D magnetic field distribution.

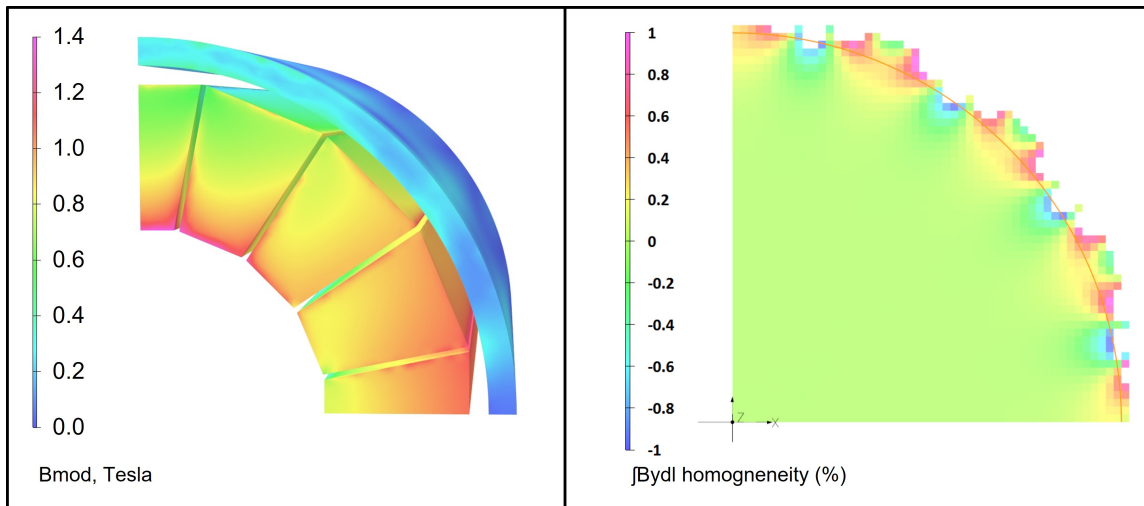


Figure 34. left: the magnitude of the magnetic field (B_{mod}) distribution (T), right: the integrated field homogeneity (%).

The integrated field homogeneity inside the good field region was evaluated with the 3D magnetic design using Opera 3D/TOSCA [60] as shown in figure 34. The tolerances on the PM blocks were specified to keep the integrated field homogeneity within 3% in the good field region. This requires the dimensions of the PM blocks to be within $\pm 0.025 \text{ mm}$ and a maximum deviation of the field axis direction below 3° .

5.2 Manufacturing and assembly

The PM blocks were produced with Samarium Cobalt grade YXG32H. The good temperature stability and high intrinsic coercivity minimizing the risk of local demagnetization during assembly

were the main reasons to use Samarium Cobalt. Each PM block was made of two parts glued together with the joint plane parallel or perpendicular to the magnetization direction. In total 690 PM blocks with five different easy axis orientations were produced, with a total mass of 2130 kg.

The external ring was made of construction steel grade S355JR. Non-magnetic material such as stainless steel could also be used, but soft magnetic material has the advantage of creating a radial magnetic shielding and, therefore, more stability for magnetic forces during assembly, as the PM blocks are attracted to this external ring until the insertion of the last magnet sector.

The guiding profiles were machined from aluminium grade 6082. In the mechanical structure of the dipoles, the guiding profiles holding the PM blocks in the assembly are also used for the PM block insertion as shown in figure 35. The profiles are manufactured to be 0.5 m longer than the external ring. Each PM block is inserted between two profiles without external forces and pushed inside the dipole assembly with a dedicated tooling. The magnetic forces during assembly were calculated to define the optimal insertion sequence. At the end of the assembly the extra length of guiding profile was trimmed off and a protective cover was installed.

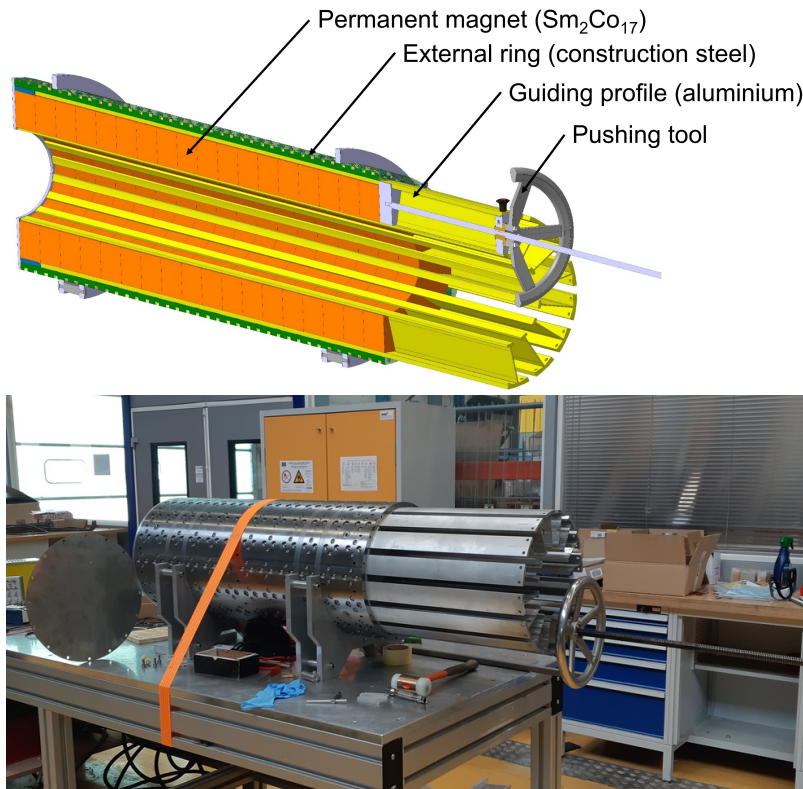


Figure 35. Top: tooling for permanent magnet insertion. Bottom: insertion of a permanent magnet block.

5.3 Magnetic measurements

The 690 permanent magnet blocks were individually characterized at CERN. The magnetic moment and the deviation of the magnetization direction were measured to avoid polarity errors and significant field inhomogeneity, which is almost impossible to correct once the dipole is assembled. The measurements were carried out with a three-dimensional Helmholtz-Coil [61]. An average magnetic



Figure 36. Top: one of the FASER dipoles under measurement using the single-stretched wire at CERN. Bottom: one of the FASER dipoles under measurement using the 3D Hall probe mapper at CERN. (This figure is taken from [62].)

moment of 331.3 Am^2 was measured over the magnet production with a peak-to-peak variation of 2.0% (0.6%). The deviation of the magnetization direction was within 1.44° (0.39°) in the horizontal plane and 1.9° (0.49°) in the vertical plane. As all PM blocks were within the specified tolerances, it was not necessary to apply local field corrections in the dipole assembly by assigning a specific position to each PM block.

A number of magnetic measurements were performed during the assembly process, mainly to avoid the risk of positioning or polarity errors when inserting a PM block. A dedicated tooling based on a rotating Hall probe and an angular encoder was developed, to allow errors to be caught in the assembly process while they could still be corrected.

The assembled dipoles were measured [62] with a single-stretched wire (SSW) and the 3D Hall probe mapper, as shown in figure 36. The integrated field, the integrated 2D field homogeneity and field orthogonality, relative to the optical reference targets measured with a laser system, were measured with the SSW. These measurements are summarized in table 5.

Measurements of integrated higher-order field harmonics were also made with the SSW, at the reference radius 67 mm up to order 15. A skew sextupole (≈ 3) harmonic of 30 to 40 units is present in all three dipoles. According to past studies on Halbach arrays [58], this irregularity is due to a small clearance between some of the magnets created by magnetic forces. Nevertheless, the magnetic measurements of the three FASER dipoles are within specified values. In addition, the local field homogeneity was measured with the 3D Hall probe mapper and was found to be within the specifications. Finally, the stray magnetic field was measured. The stray field outside the sides of the magnet is zero. Figure 37 shows the stray field in the central axis of the magnet outside the aperture, this shows that the field drops below 10 mT at a distance of 250 mm from the end of the magnet.

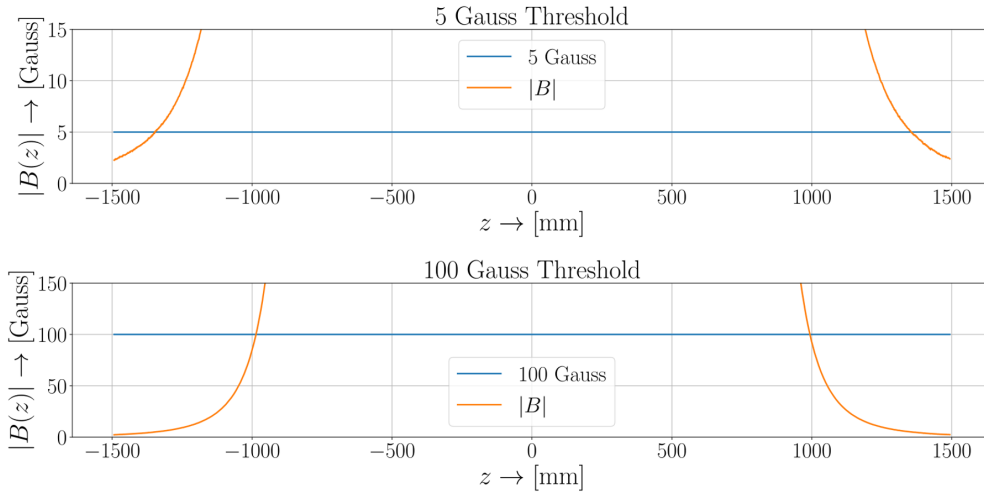


Figure 37. The measured stray field along the magnet central axis for the 1.5-m long dipole. The magnet is placed between -750 – 750 mm and the measurements show that the stray field drops below 5 Gauss (0.5 mT) about 600 mm from the magnet aperture (top), and below 100 Gauss (10 mT) about 250 mm from the magnet aperture (bottom). (This figure is taken from ref. [62]).

Table 5. Measured integrated field and field orthogonality for the three dipoles.

Magnet	Dipole 1 (short)	Dipole 2 (short)	Dipole 3 (long)	Unit
Roll Angle	0.57692	0.57840	0.86150	Tm
	0.00021	0.00040	0.00250	Tm
	1.57045	1.57008	1.57366	rad

5.4 Alignment

Optical references, installed on the external ring are related to the dipole mechanical centre and are used to align the dipole to the beam collision axis LOS. The supporting structure shown in figure 38 allows movement of the magnet in the three directions. The roll angle is measured with a reference surface located on the side of the dipole.

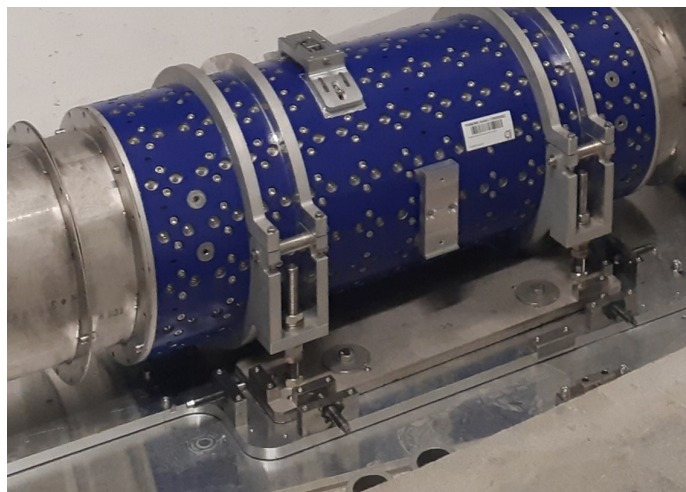


Figure 38. Support and alignment structure.

5.5 Magnet covers

To ensure no metallic objects get stuck inside the magnet aperture, magnet covers are installed on both ends of each magnet. For the two spectrometer magnets, 5-mm-thick plastic covers which can be opened during physics operations are used. This minimizes the material in the active detector volume for physics, while the covers are closed during any work needed on the detector apparatus. For the decay volume magnet, there is not sufficient room for a magnet cover that can be opened, and instead permanent covers of plastic (3-mm-thick, on one end) and reinforced carbon fiber (0.4-mm-thick, on the other end) are used.

6 Detector Control and Safety Systems

The detector control system, DCS, of the FASER experiment controls and monitors the parameters of the experiment's power system, monitors the environmental conditions in the detector and the cavern, monitors and configures the safety-interlocks of the detector, and implements automatic procedures and alerts to ensure the safe operation of the experiment.

The diagram in figure 39 shows the components handled by the DCS and their corresponding connectivity. These items can be grouped in the following categories:

- HV and LV detector power systems
- Safety interlock (Tracker)
- Cooling system — via Detector Safety System (DSS) (Tracker)
- Power Distribution Units (PDUs)
- VME crate
- Environmental conditions

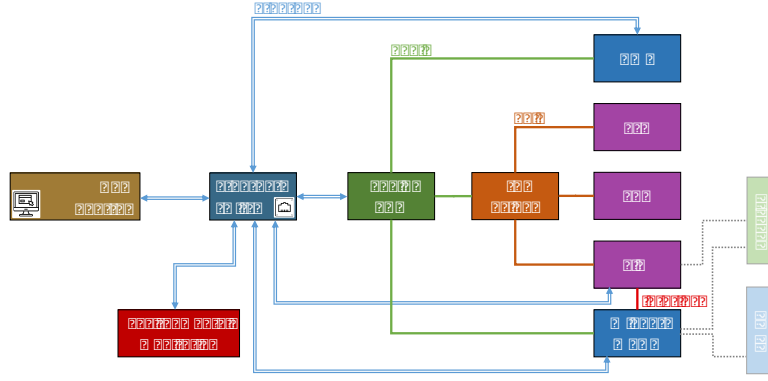


Figure 39. The DCS control hierarchy of the power system components of the FASER experiment and the connections between them. MPOD Wiener indicates the LV/HV Power Supply System. The Tracker Interlock and Monitoring board (TIM, see section 6.3) implements the track safety system (hardware interlock). The DCS connections to the detector are also shown, while the Detector Safety System for a cooling failure is not depicted for simplicity.

6.1 Power systems

A total of four HV¹² and 24 LV power-supplies¹³ are used to bias the silicon sensors and power the ABCD3TA chips in the SCT modules, respectively, and are stored in three 19-inch rack mountable crates called the MPOD LV/HV Power Supply System.¹⁴ An additional HV¹⁵ power supply, also stored in the MPOD crates, is used to power the PMTs for the calorimeter, pre-shower, veto and timing scintillator stations. For other electronics, one 19-inch rack mountable box (called the PSbox) is also installed, which holds fifteen 24 V power supplies.¹⁶ Two custom-made PCBs, the HV splitter board and the LV protection board, are placed between these power supplies and the detector. The HV splitter board is used to divide one HV channel to the four SCT modules in one patch-panel, corresponding to half a tracker plane. The LV protection board equips an integrated circuit¹⁷ which can protect against over-voltage possibly caused by single event effects of radiation in the LV power supply. The patch-panel and other electronics are powered via the power distribution units which are remotely controlled via Ethernet.¹⁸

6.2 Tracker cooling system

The FASER cooling system was designed and built by the CERN cooling and ventilation group (EN-CV). It consists of two air-cooled water chillers¹⁹ in which one is running to cool the detector and the other acts as a hot spare. The system with all instruments is mounted on a single support structure. An additional water reservoir is also installed to allow refilling the water tank in the chillers automatically.

¹²EHS 84 05p manufactured by Iseg Spezialelektronik GmbH.

¹³MPV 8008I manufactured by W-IE-NE-R Power Electronics GmbH.

¹⁴MRAAH2500A2H manufactured by W-IE-NE-R Power Electronics GmbH.

¹⁵EHS F030n by Iseg Spezialelektronik GmbH.

¹⁶TXL 035-24S manufactured by Traco Power.

¹⁷LTC4365 manufactured by ANALOGUE DEVICE.

¹⁸NETIO PowerPDU 4C.

¹⁹HRS030-AF-20MT manufactured by SMC Corporation.

Each chiller has the cooling capability of about 1.8 kW at 15 °C with a temperature difference, 3 °C between inlet and outlet temperature. Given that one SCT module consumes 6 W, leading to a required total cooling power of 576 W for the four tracker stations, the cooling capability is sufficient.

In case of a failure of the running chiller, the other can take over the cooling automatically by controlling the valves. Under usual condition, both chillers are running, where one is connected to the detector and the other is bypassed. If both chillers are not operational, the power supply system is forced to be turned off through a hardware interlock signal.

6.3 Tracker safety interlock

Two stages of the interlock system based on hardware and software mechanisms protect the detector from electrical and thermal damage. Electrical failure can be caused by over-voltage and over-current on the detector electronics and silicon sensors. Over-heating damages the ABCD3TA chips (for 40 °C [36]) and can cause problems in the mechanical integrity and alignment of the modules due to the glass-transition of the glue used for the module assembly (for 35 °C [63]).

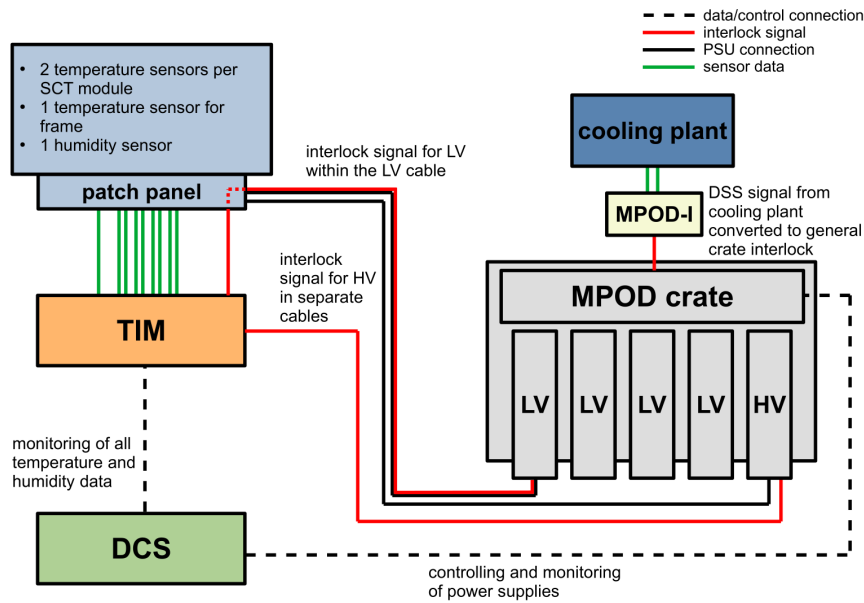


Figure 40. Schematic overview of the interlock system of the FASER tracker.

Figure 40 shows an overview of the interlock system of the FASER tracker. Two NTC-10k thermistors are mounted on each SCT module. In addition, there is one NTC-10k thermistor attached to the mechanical frame as well as one humidity sensor (HIH-4000) inside the plane. They are electrically connected to one TIM (Tracker Interlock and Monitoring board) through the patch-panel, which is equipped by a AM335X micro-controller and three comparators. Each of the four tracker stations has an associated TIM, which digitizes signals from the temperature and humidity sensors and provides the information to the DCS via an Ethernet connection. An analog comparator circuit uses the frame temperature to generate the hardware interlock signal to the LV and HV power supplies. The signal for the HV power supply is provided with a dedicated cable while that for the LV power supply is propagated with the LV cable via the patch-panel. The LV protection board placed in the LV line gives additional protection from over-voltage for each channel.

The DCS controls all of the power supplies and centrally monitors the temperature and humidity measurements provided from the TIM as well as the voltage and current of the HV and LV, storing the information into a database. In addition, it can turn off the power supplies in case a deviation from the detector operation parameters is detected.

The Wiener MPOD (Multichannel Power Supply System) Interlock (MPOD-I) PCB receives the Detector Safety Signal (DSS) from the cooling plant and provides the interlock signal to turn off the entire set of MPOD crates in case of a failure in the cooling plant.

An automatic software action shuts down the tracker in cases that the temperature measured by the NTCs on the module reaches 31 °C. The hardware interlock takes action at temperature on the mechanical frame of the plane above 25 °C.

6.4 DCS software

The DCS software is implemented with the SIEMENS Simatic WinCC Open Architecture, which is a SCADA system used at CERN by the LHC experiments.

The communication between the different devices handled by the DCS and the DCS back-end is routed via a commodity switch using standard 1 Gbit/s Ethernet in a network secured from the general CERN network. The communication between the DCS and HV/LV MPOD modules is handled through the OPC-UA protocol, the communication between the DCS and the TIM board and the PDU is handled through the MODBUS protocol, and the DCS monitoring of the cooling system is done through a subscription to the DIP [64] publication by the CERN cooling and ventilation group.

To ensure the safety of the detector, the DCS triggers alerts and automatic emergency procedures and controls the safety interlocks of the experiment. The DCS also implements autonomous integrity checks and diagnostics and provides a user interface to inform FASER on-call experts on the state and status of the experiment. In addition, the DCS is the interface for configuring and monitoring the parameters of the detector interlock systems, as discussed in section 6.3.

Transitions between the different operational states of the experiment are implemented as a Finite State Machine (FSM) (see figure 41). Transitions are initiated either by a user input or by an autonomous protocol. The action of the transition is initiated by propagating a transition signal through a sub-system hierarchy which in turn triggers a series of autonomous actions that configure the necessary parameters to achieve the transition between the different operational states.

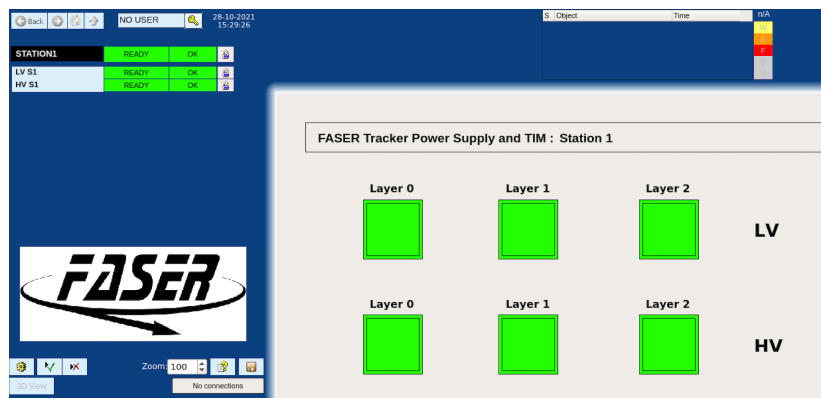


Figure 41. A DCS FSM panel via which the low and high voltage of a tracker station is controlled.

The DCS also records time series of the detector parameters, as well as the operational state and the detector status. The time series are persistently archived for later retrieval in an Oracle database, which allows for offline data quality checks. Figure 42 shows an example of a time series for values monitored by the DCS. The DCS monitors approximately 600 parameters at a 1 Hz rate, collecting data at a rate of 1.3 kBytes/s.

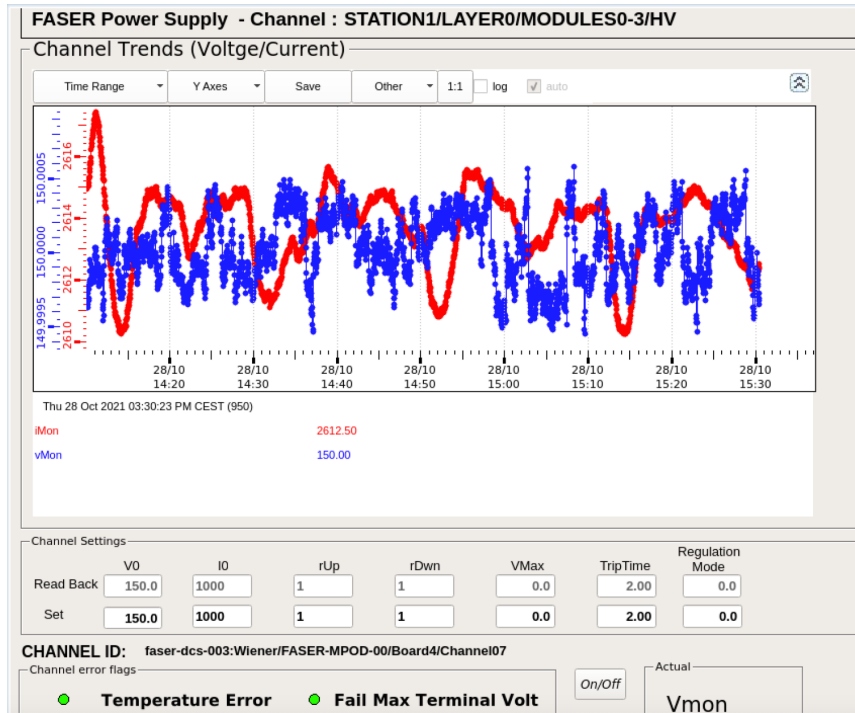


Figure 42. Example of the time series for high-voltage channel controlled and monitored by the FASER DCS.

The Oracle DCS data is sampled once per minute and archived in an InfluxDB database along with DAQ monitoring, see section 4.3. Host system monitoring (CPU/memory usage, disk status, etc.) for the DAQ and DCS servers are regularly archived as well. This data can easily be monitored from remote using Grafana dashboards and various alert messages are generated for on-call experts in case of unusual values before the automatic actions of the DCS system are activated.

7 The emulsion detector of FASER

The FASER_{em} detector [4, 5] is located in front of the main FASER detector along the beam collision axis to maximize the neutrino interaction rate of all three flavours. The detector includes an emulsion detector, a veto station and an interface tracker to the FASER spectrometer, as shown in figure 43. The IFT is placed downstream of the emulsion detector, and along with the veto scintillators, placed upstream of the emulsion detector, enable a global analysis that links information from FASER_{em} with the FASER spectrometer and makes muon charge measurements possible. This section provides an overview of the emulsion detector for FASER_{em}, including results from a pilot analysis carried out in 2018. The IFT is discussed in section 2, and the veto scintillators in section 3.

7.1 Detector design

The emulsion detector is made of a repeated structure of emulsion films interleaved with 1-mm-thick pure (99.95%) tungsten plates. The emulsion film is composed of two emulsion layers, each 65 μm thick, that are poured onto both sides of a 210- μm -thick plastic base. The whole emulsion detector contains a total of 770 emulsion films with the dimensions of 25 cm \times 30 cm, and a total tungsten mass of 1.1 tons. The total tungsten length is 770 mm, corresponding to 220 radiation lengths and 7.8 hadronic interaction lengths. The emulsion detector has the ability to identify different lepton flavours: sufficient target material to identify muons; finely sampled detection layers to identify electrons and to distinguish them from gamma rays; good position and angular resolutions to detect tau and charm decays. The detector can also measure the momenta of muons and hadrons via multiple scattering information, the energy of electromagnetic showers, and estimate the energy of neutrinos.

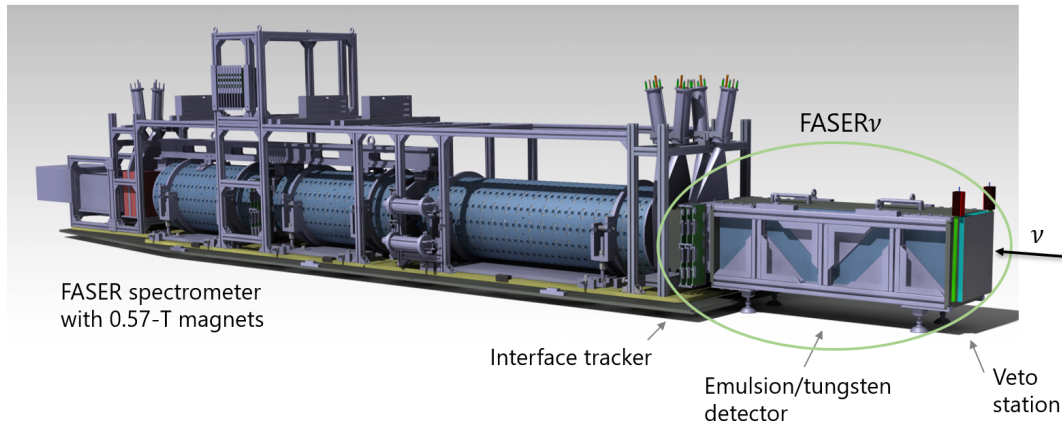


Figure 43. A sketch of the FASER detector, highlighting the FASER ν detector.

The emulsion detector readout and reconstruction works for a track density up to 10^6 tracks/cm². To keep the detector occupancy sufficiently low, the emulsion films will be replaced during every technical stop of the LHC, which takes place about every three months. This corresponds to 10–50 fb^{-1} of data in each data-taking period. In 2018 *in situ* measurements were performed [5] and measured a charged particle flux of $3 \times 10^4/\text{cm}^2/\text{fb}^{-1}$ at the FASER location. When the emulsion films are removed, the track density is roughly $0.3\text{--}1.5 \times 10^6$ tracks/cm². The experience with these *in situ* measurements demonstrates the ability to analyze emulsion films in this environment.

7.2 Emulsion films

The emulsion sensitive layers consist of silver bromide crystals, which are semiconductors with a band gap of 2.684 eV, dispersed in a gelatine substrate. The diameter of the crystals used for FASER is approximately 200 nm. When a charged particle passes through the crystal, electrons are excited through electromagnetic interaction to the conduction band, trapped in lattice defects, and groups of silver atoms (so-called latent images) are formed with interstitial silver ions. They can then be amplified and fixed by specific chemical development. An emulsion detector with 200 nm crystals has a spatial resolution of 50 nm. The two-dimensional intrinsic angular resolution of a double-sided

emulsion film with 200-nm-diameter crystals and a base thickness of 210 μm is therefore 0.35 mrad. More details on the emulsion technology are summarized in ref. [65].

The emulsion gel and film production is performed at a large-scale production facility established in Nagoya University. The left panel of figure 44 shows an electron microscope photo of the produced silver bromide crystals. The sensitivity of the emulsion layers was checked by exposing the produced emulsion to electrons with several tens of MeV at the UVSOR Synchrotron Facility (Okazaki, Japan), measuring 45 grains per 100 μm for minimum ionizing particles (the right panel of figure 44). This sensitivity is sufficient for detecting minimum ionizing particles by setting the emulsion thickness to 65 μm . The produced emulsion gel is then used to produce films (65 μm emulsion layers deposited on both sides of 210 μm plastic base) using the coating system shown in figure 45. The production of emulsion gel and films are scheduled a few months before each installation. The 770 emulsion films produced in each batch correspond to a total area of 58 m^2 .

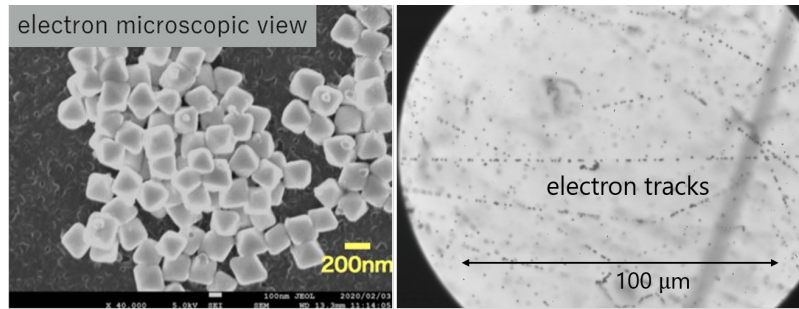


Figure 44. Left: microscopic view of silver bromide crystals. Right: γ -ray tracks in an emulsion layer.

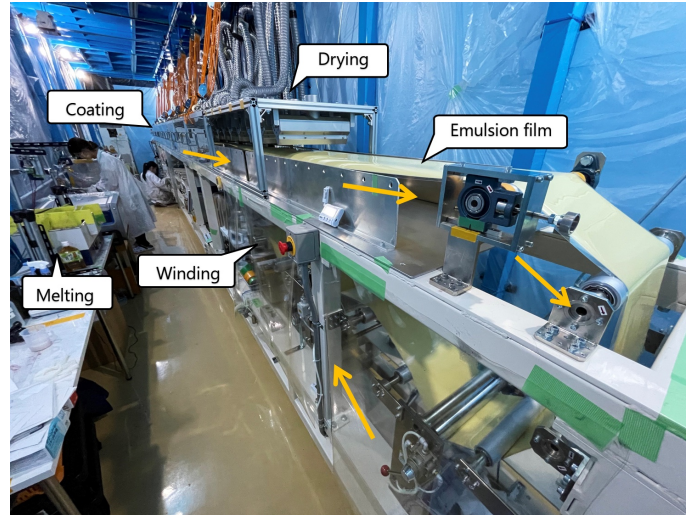


Figure 45. A picture of the emulsion film coating system.

7.3 Tungsten target

Table 6 shows the properties of possible target materials. Tungsten was chosen as the target material for the following reasons. First, its high density allows for a higher neutrino interaction rate, keeping

the detector small. Space for the detector along the beam collision axis is limited by the size of the FASER trench, and it is important to make the detector size small, which also lowers the cost of the emulsion. Second, its short radiation length is good for a higher performance both in electromagnetic shower reconstruction, keeping shower tracks to a small radius, and in momentum measurement using multiple Coulomb scattering. Last, radioactivity levels are sufficiently low to guarantee the safe use of the emulsion films.

The thermal expansion coefficient of tungsten is very small, $4.5 \cdot 10^{-6}/\text{K}$. The temperature in the TI12 tunnel was monitored in 2018 and its variation was found to be very small, namely 0.1°C RMS. The linear thermal expansion of 25 cm of tungsten is then expected to be $0.1\text{ }\mu\text{m}$. Since the thermal expansion coefficient is very different between emulsion films ($10^{-4}/\text{K}$) and tungsten, it is necessary to exert a large mechanical pressure on the emulsion films and tungsten plates in such a way that the soft emulsion films follow the thermal expansion of the tungsten plates.

A total of 1600 1-mm-thick tungsten plates were purchased to be used for the FASER detector. A dedicated device for measuring and mapping the thickness was prepared to check the tungsten plate thickness uniformity. The thickness was measured semi-automatically at 24 points on each plate, and the maximum difference among the 24 points was checked. The plates with a difference smaller than $80\text{ }\mu\text{m}$ are used to construct the emulsion detector, corresponding to about 97% of the measured tungsten plates. The average thickness of the qualified tungsten plates is $1093\text{ }\mu\text{m}$, with an RMS of $25\text{ }\mu\text{m}$.

Table 6. Properties of possible target materials.

Material	Atomic number	Density [g/cm ³]	Hadronic Interaction [cm]	Radiation length length [mm]	Thermal expansion [10^{-6}K^{-1}]
Iron	26	7.87	16.8	17.6	11.8
Tungsten	74	19.30	9.9	3.5	4.5
Lead	82	11.35	17.6	5.6	29

7.4 Mechanical structure

The mechanical structure was designed to keep the emulsion films aligned. The position alignment has to be kept within sub-micrometer accuracy during data taking so that particle momenta can be measured by the multiple Coulomb scattering (MCS) coordinate method described in ref. [66].

To put sufficient pressure on the emulsion films and tungsten plates, the following steps are taken. First, 10 emulsion films and 10 tungsten plates are vacuum-packed with aluminum-laminated foils to create a modular structure in the detector, as shown in figure 46. The pressure on each module is given by atmospheric pressure. All the 77 modules are then installed in a mechanical structure, which presses all the modules to one side, again, to keep the position relation between the modules. The mechanical support, including a presser with a thickness of 3.5 cm, is called the FASER box (in order to allow the replacement of the emulsion detector in a short access, two FASER boxes have been constructed). The design and a picture of the box are shown in figure 47. The inner dimensions of the box are 27 cm \times 30 cm \times 104 cm, and the outer dimensions are 39 cm \times 37 cm \times 116 cm. The upstream and downstream walls are 2 cm thick stainless steel, and the side walls are 1 cm thick aluminum plates. Additional structures with 5 cm \times 5 cm aluminum frames are placed on the sides and bottom of the

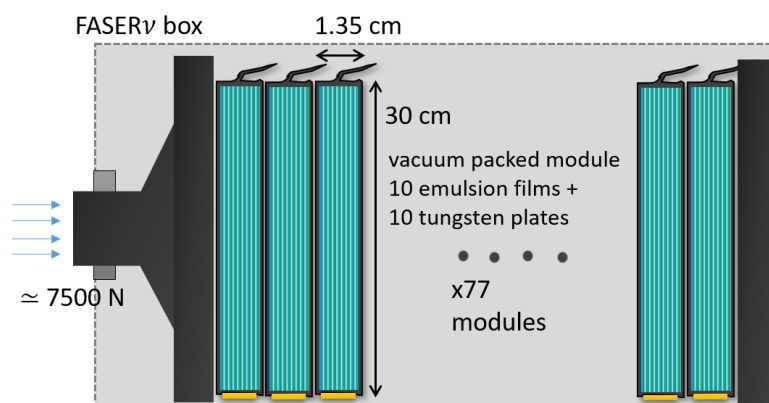


Figure 46. Module structure of the emulsion/tungsten detector.

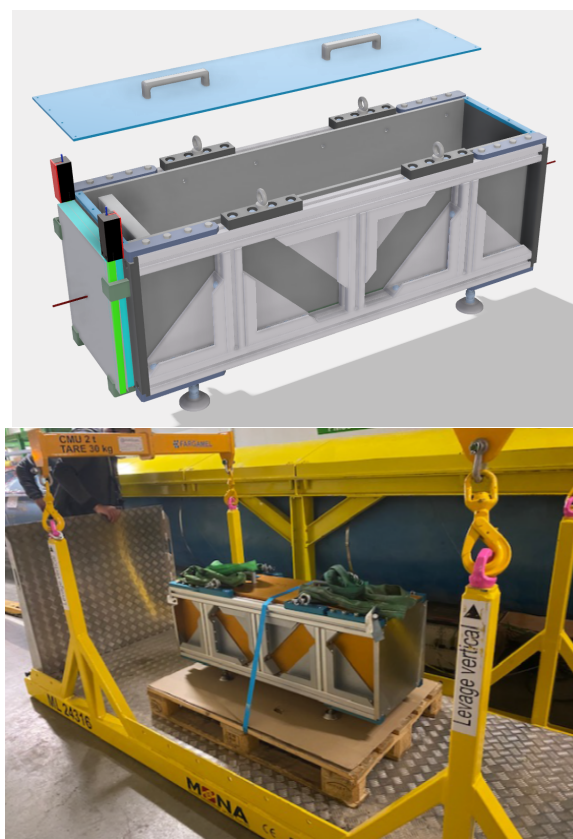


Figure 47. Design of the FASERν box (top) and a picture of the produced box (bottom).

box for strength. The total weight of the empty box is approximately 190 kg. The height of the box above the trench floor can be adjusted depending on the LOS position, which can vary from year to year due to the change of the beam crossing angle as discussed in section 1.1. The 77 vacuum-packed modules are housed in the structure, and a force of 7500 N is imposed by the presser located upstream.

To avoid temperature fluctuations, which may cause a mis-alignment between the emulsion modules, an insulating wall is placed between the IFT and the FASER box. It is made of an aerogel-based insulation blanket²⁰ wrapped with aluminum foil. In order to keep the thermal stability of the FASERnu box, the part of the trench where this is installed is covered by an aluminium cover, lined with the same thermal insulation. Being isolated from the rest of the electronic detectors, the temperature of the FASER box reaches an equilibrium with the trench wall. Temperatures at various positions around the FASER box is monitored via temperature sensors during data taking.

7.5 Operational procedure

The emulsion/tungsten detector is assembled in the dark room at CERN just before each installation. The detector is then transported to the experimental site in one piece. This minimizes the amount of underground work under restricted conditions.

For each installation of the FASER box, the detector is brought down to the LHC tunnel using the elevator at Point 1 where the ATLAS interaction point is located (see figure 1). It is transported along the LHC beamline on an electric cart, and then carried over the LHC in UJ12 using the crane employed for the main FASER detector installation. A protection device was installed under this crane, with dimensions similar to those of the detector and a 1.5 tonne load capability. The detector is then installed into the FASER trench in front of the main FASER detector by using the crane installed in TI12. Figure 48 shows a photo of the installed FASER box.

The detector will be replaced during planned technical stops. The exchange procedure steps are: (1) construction of the new emulsion modules using the second (unused) set of tungsten plates. These modules are assembled into the unused FASER box; (2) extraction of the exposed FASER box and installation of the newly assembled FASER box; (3) disassembly of the emulsion films and their chemical development.

A specific chemical development amplifies the recorded signals in silver bromide crystals. The chemical solutions needed for the development are described in table 7. In the developer solution, filaments of metallic silver start to grow from the latent image speck and become visible as dots under optical microscopes. The amplification gain is about $O 10^8$, and depends on the temperature and duration of the treatment. The chemical solutions is prepared and the development carried out in the dark room at CERN, which is equipped so that 100 films/day can be processed.

7.6 Facility at CERN for the emulsion detector handling

Emulsion films are sensitive to light, therefore an assembly of the emulsion/tungsten detector and chemical development of the emulsion films is performed in the dark room facility at CERN. The facility was originally set up for the CHORUS experiment and has been used by several experiments since then. In preparation for LHC Run 3, the facility is being refurbished, to allow several emulsion-based experiments to use it in parallel.

²⁰SPACETHERM A1 from the Proctor Group.

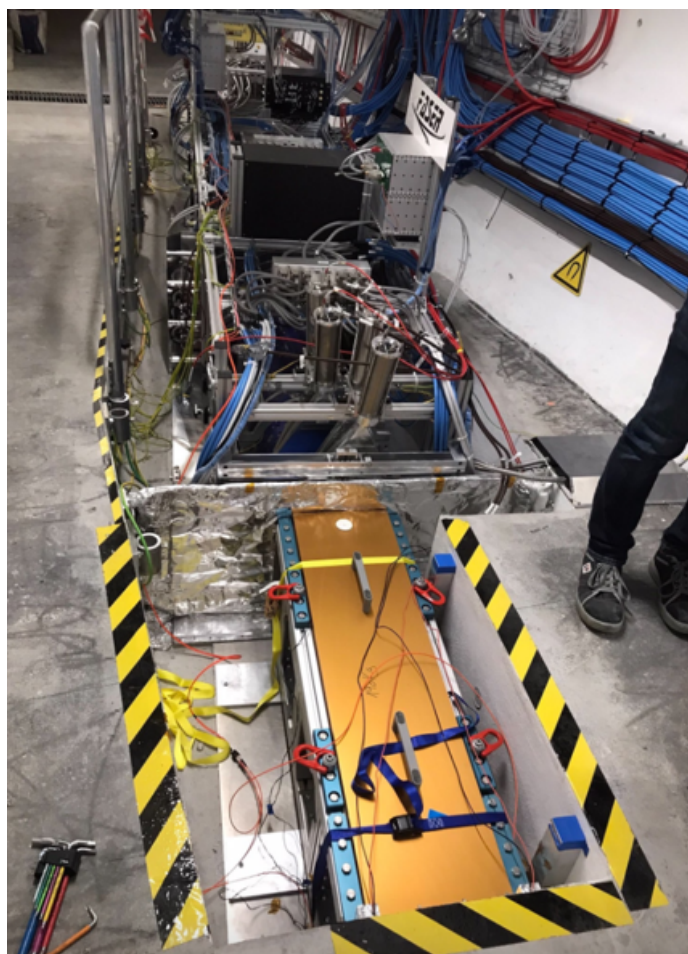


Figure 48. A picture of the FASER box installed in the FASER trench. The cover of the trench where FASER is placed was not installed when this picture was taken.

Table 7. Solutions required for the emulsion chemical development. The last column reports the amount required with respect to 58 m², which corresponds to a production batch for one full detector replacement.

Solution	Time and temperature	Function	Chemical	Amount /58 m ²
Developer	20 min at 20pm0 1°C	Chemical amplification of signal with a gain of $O 10^8$	OPERA Dev (Fujifilm), RD-90s starter (Fujifilm)	370 L
Stopper	10 min	Stop chemical amplification	Acetic acid	180 L
Fixer	90 min	Resolve unused silver bromide crystals	UR-F1 (Fujifilm)	1100 L
Wash	300 min	Wash out all chemicals	Running water	50 L
Thickener	20 min	Control emulsion layer thickness	Glycerine, Drywell (Fujifilm)	
Drying	1 day	Dry films	Air at R.H. 50–60%	



Figure 49. Dark room facility at CERN available for the FASER detector assembly and chemical processing. The facility was recently refurbished and is ready for the first installation.

While the refurbishment is ongoing, operation tests were performed using the available space in October 2021 together with the NA65/DsTau experiment [67], by going through assembly and chemical development. Figure 49 shows a picture of the current facility.

7.7 Emulsion readout

The emulsion readout system takes a sequence of tomographic images by changing the focal plane through each emulsion layer. The digitized images are then analyzed to recognize sequences of grains as a track segment. The FASER event analysis is based on the readout of the full emulsion detector by the Hyper Track Selector (HTS) system [68]. A picture of the HTS system is shown in figure 50. The HTS includes a dedicated lens, camera, XYZ-axis stage, and computer cluster for image processing. It takes 22 tomographic images, and 16 successive images in the emulsion layer are used for track recognition. The HTS system makes use of a custom-made objective lens with a very large field of view of $51\text{ mm} \times 51\text{ mm}$ and a magnification of 12.1. The optical path is split 6-fold. Correspondingly, the image is projected onto six mosaic camera modules to cover the large field of view with high resolution. Each mosaic camera module consists of 12 2.2-Mpixel image sensors. In total, 72 image sensors work in parallel to build the large field of view. The raw image data throughput from 72 image sensors amounts to 48 GBytes/s, which is then processed in real time by 36 tracking computers with two GPUs each. The readout speed of the HTS system is $0.45\text{ m}^2/\text{hour}/\text{layer}$, where layer refers to one of the two emulsion layers on both sides of the films. Currently, an upgraded HTS system (HTS2, which will be about 5 times faster) is under commissioning. The baseline plan for FASER is to use the HTS system, since its performance, such as the readout speed and resolution, is already proven. The total emulsion film surface to be analyzed in FASER is $174\text{ m}^2/\text{year}$ implying a readout time of 770 hours/year. Assuming some hours of machine time each day, it will be possible to finish reading out the data taken in each year

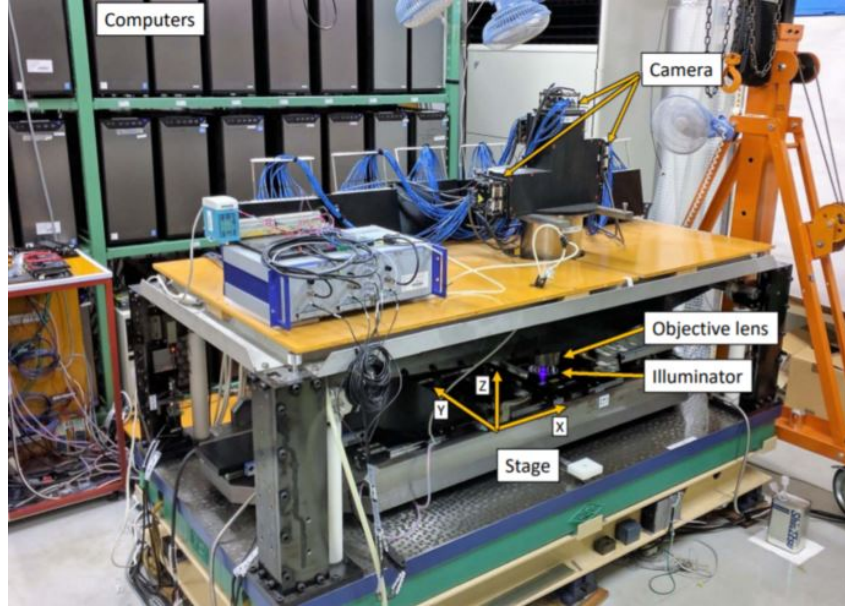


Figure 50. The fast emulsion readout system HTS, with a readout speed of $0.45 \text{ m}^2/\text{hour}/\text{layer}$. Reproduced from [68]. CC BY 4.0.

within a year. The HTS system was also used for the readout of the 2018 pilot detector, which led to the observation of the first neutrino interaction candidates at the LHC [19].

7.8 Pilot analysis with the 2018 data

In 2018, a pilot emulsion detector was installed in the TI18 tunnel. An integrated luminosity of 12.2 fb^{-1} was collected during four weeks of data taking from September to October with collisions at 13 TeV centre-of-mass energy. The analysis of the pilot detector demonstrated that the emulsion readout and reconstruction can work in the actual experimental environment. The data analysis is based on the readout of the full emulsion films by the HTS system. Data processing was divided into sub-volumes with a maximum size of $2 \times 2 \text{ cm}^2$ 25 emulsion films. After a precise alignment procedure, tracks are reconstructed in multiple films with a dedicated tracking algorithm for high-density environments [69].

The majority of the tracks observed in the detector are expected to be background muons and related electromagnetic showers. These background charged particles were analysed using a unit of 10 emulsion films. In this case the angular resolution is expected to be 0.05 mrad. Figure 51 (left) shows the observed angular distribution peaked in the direction of the ATLAS IP. There are two peaks separated by 2.5 mrad. The reason for the two-peak structure is not understood, but simulation studies are ongoing, which could inform future data measurements. It's clear that the angular resolution should be better than the angular spread of the peaks. For example, the horizontal angular spread of one of the peaks (left in the figure) is 0.6 mrad, equivalent to the multiple Coulomb scattering of 700 GeV particles through 100 m of rock. The charged particle flux within 10 mrad from the peak angle is measured to be $1.7 \pm 0.1 \times 10^4 \text{ tracks/cm}^2/\text{fb}^{-1}$, which is consistent with the values previously reported [3, 4] and also consistent with the FLUKA prediction of $2.5 \times 10^4 \text{ tracks/cm}^2/\text{fb}^{-1}$ for 10 GeV. The expected uncertainty on the FLUKA estimate is of the order of 50%.

For the neutrino analysis, vertex reconstruction was performed by searching for converging patterns of at least five tracks with a impact parameter to the vertex within $5\text{ }\mu\text{m}$. Additional topological cuts were applied to these vertices to select high-energy interactions and suppress neutral hadron backgrounds. Vertices are categorized as charged or neutral based on the presence or absence of charged parent tracks. Within the fiducial volume, 18 neutral vertices passed the vertex selection criteria. Figure 51 (right) shows a selected neutral vertex. A multivariate discriminant was then applied to distinguish neutrino signal from neutral hadron background, resulting in a 2.7σ excess of the neutrino-like signal. A more detailed description of the pilot detector analysis can be found in ref. [19].

The above measurements of the charged particle flux and results detecting the first neutrino interaction candidates proved FASER ν 's ability to study neutrinos at the LHC.

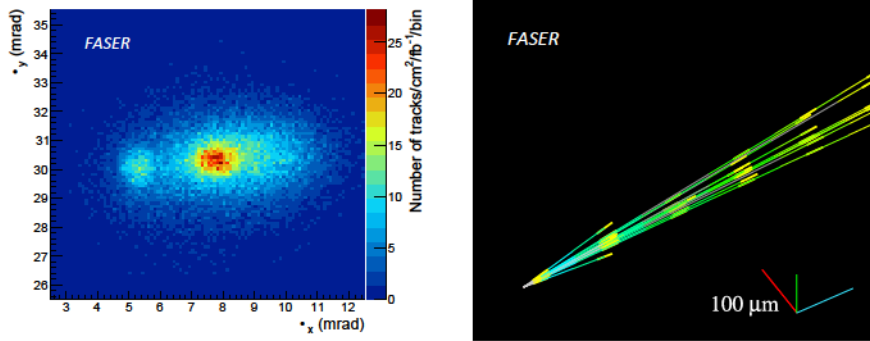


Figure 51. (left) A zoom of the angular distribution observed in the pilot run module. The uncertainty in the angle of the installed detector with respect to the LOS means that the measured angular peak is compatible with pointing back to the IP. (right) Event displays of one of the neutral vertices in a tilted view.

8 Detector integration

The integration and installation of the FASER detector in its final location started in 2020 with preparation of the TI12 tunnel and engineering work on detector supports. This is described in this section, together with the installation procedure and the detector and magnet alignment procedure.

8.1 Preparation of TI12 for FASER

In 2018 the TI12 tunnel had no working services installed, and contained substantial obsolete ventilation and electrical equipment left over from the former LEP collider, as can be seen in figure 52 (left). During the first half of 2019 this equipment was removed, to allow the start of the FASER works.

The FASER trench is needed to allow the detector to be positioned on the LOS, which was precisely mapped out at the mm-level by the CERN survey team. It was designed to minimize the amount of civil engineering works that needed to be carried out in the tunnel. Particular attention was paid to keeping the structural integrity of the tunnel, minimizing the amount of dust produced, and minimizing the time needed for the works to be compatible with the overall LS2 schedule. The trench design is shown in figure 53 and in figure 54. The main trench is about 5.5 m long and 1.4 m wide, and is 60 cm deep at the front of the FASER detector and 20 cm deep at the back. This compensates for the TI12 tunnel sloping up away from the LHC. The bottom of the trench is parallel

to the LOS at an angle of about 1% to the horizontal. At the front of the main trench is an additional, more narrow part where FASER is installed. Figure 52 (right) shows a photo of the trench, which was completed in May 2020.

After the civil engineering works were done, 3D laser scanning was performed by the CERN survey group to check for potential deviations with respect to the design. A rendering of the 3D scan is shown in figure 55, and shows the comparison with the CAD model by superimposing the two shapes in CAD software. The maximum deviation was found to be within 10 mm and located on the edges of the trench floor, further small civil engineering works were done to correct for this deviation and to allow the lower baseplate to be installed in the correct position as described in section 8.2.1.

During the summer of 2020, the needed infrastructure for FASER was installed in the TI12 tunnel. Figure 56 shows an integration drawing of the tunnel highlighting most of the installed infrastructure. This included installation of electrical power, lighting, handling equipment for the detector installation, compressed air connections, optical fiber connections to the surface, and electrical racks.

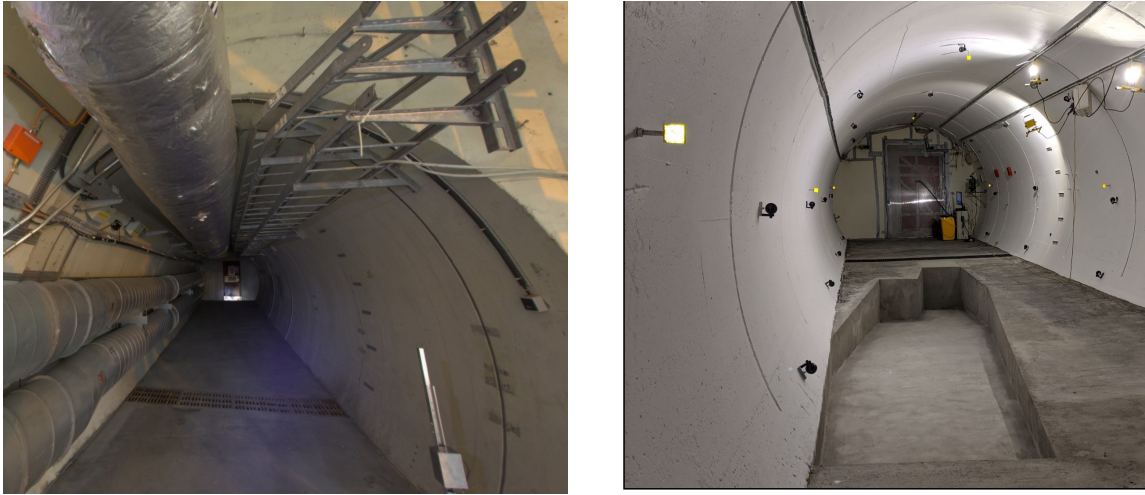


Figure 52. The TI12 tunnel (left) before the FASER preparation work (right) after the tunnel has been cleared out and the FASER trench dug in the tunnel floor.

8.2 The detector support

8.2.1 The lower and upper baseplates

As an interface between the base of the FASER detector and the floor of the trench, two aluminium baseplates are used. These baseplates allow the full detector to be moved horizontally (perpendicularly to the LOS) such that the detector can follow changes in the LOS due to a horizontal beam crossing angle at IP1 (as described in section 1.1). Due to the position of the LOS with respect to the TI12 tunnel wall, the detector is only able to move around 5 cm towards the wall. Although this is less than the maximum movement of the crossing angle, a movement of 5 cm still gives a significant increase in signal acceptance for such a scenario.

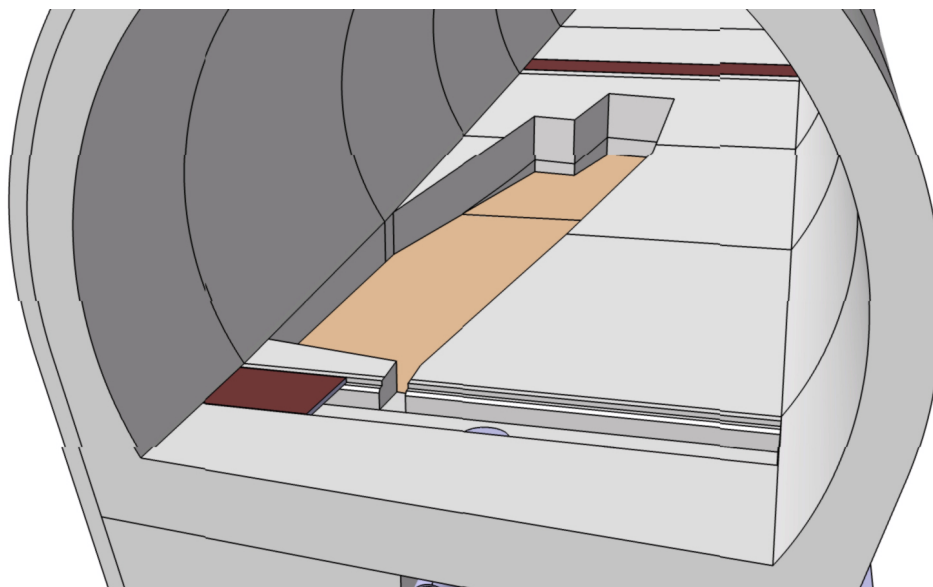


Figure 53. The 3D CAD model of the FASER trench design in TI12.

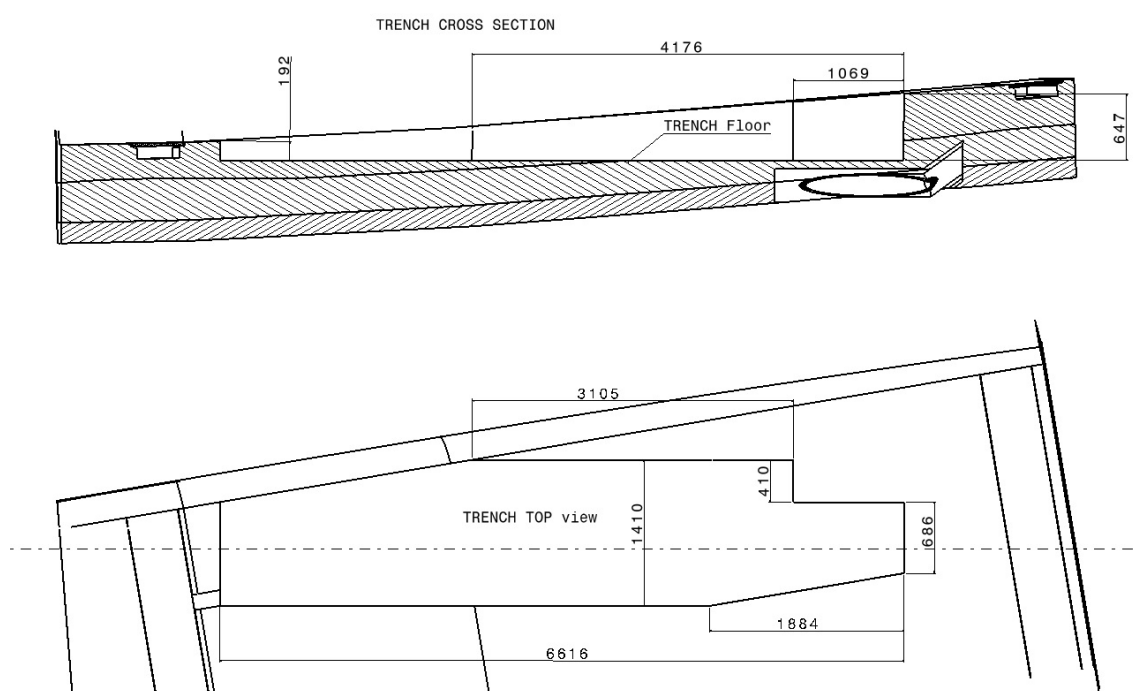


Figure 54. The design of the FASER trench (top: side view; bottom: plan view), with key dimensions shown in mm.

The lower baseplate is machined from AW5083 stabilized aluminium and is 5460 mm long, 1030 mm wide, and 15 mm thick. It was constructed in three sections for CNC machining purposes, which are connected together with nine stainless steel screws (M6 size). The lower baseplate was grouted to the trench floor using around a 10 mm thickness of grout.²¹ During the grouting process

²¹*SikaGrout-314 N* grout.

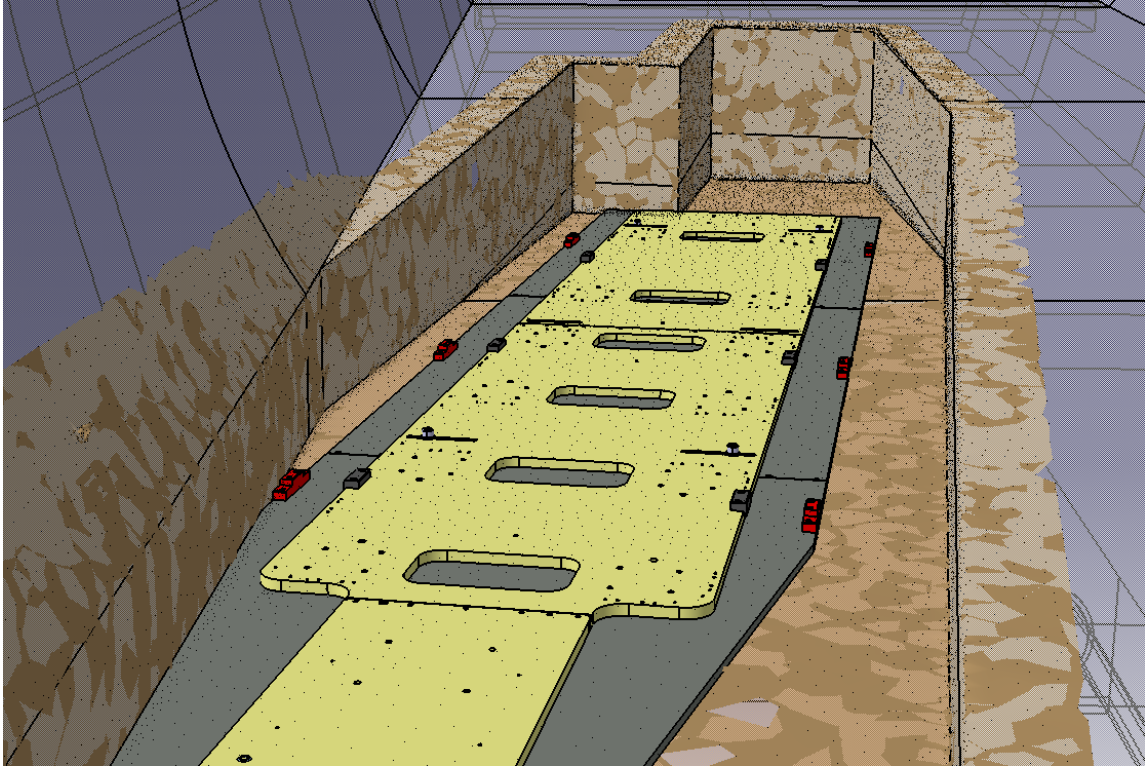


Figure 55. Comparison between the 3D scan of the FASER trench and the CAD model, also showing the lower and upper baseplates. The solid lines are from the CAD model, and dots are the measurements from the laser scan that have been smoothed in the trench region to give the brown coloured surfaces. The yellow and dark-grey colours show the upper and lower baseplate positions from the CAD model.

the lower baseplate was supported and aligned with the LOS using 12 jackscrews (M12 size). The screws were adjusted during a careful alignment procedure to ensure the flatness of the baseplate and that it was parallel to the theoretical LOS. The alignment was carried out by the CERN survey team, using a Leica laser tracker. Once aligned, the grouting was carried out by pouring liquid grout through dedicated holes in the baseplate and placing weights on the baseplate during the three day drying period. The whole grouting process was tested on the surface at CERN using a second baseplate identical to that used in TI12. During the tests, several attempts were made to ensure the correct fluidity of the grout and define the final procedure. After the grouting, the baseplate was surveyed to determine the final position. The key areas below the magnet fixations stayed within 1.3 mm (with a flatness of around 0.5 mm) with respect to the CAD nominal position. Some displacements at the very end of the lower baseplate were observed, of the order of 3-4 mm in the vertical direction. All the in-plane surveyed points stayed within 2 mm of the design. Overall, this is considered to be acceptable given the size of the plates. The flexibility of aluminium ensures that the upper baseplate, resting on top of the lower baseplate, adjusts to the residual non-flatness.

The technical design of the upper baseplate is shown in figure 57. It is 5250 mm long, 760 mm wide, 20 mm thick, and machined from AW5083 stabilized aluminium (as for the lower baseplate). It was constructed in three sections which are connected together with seven stainless steel screws of M8 size. A total of 15 sliding pads in Bronze CuSn8 are attached to the bottom side of the

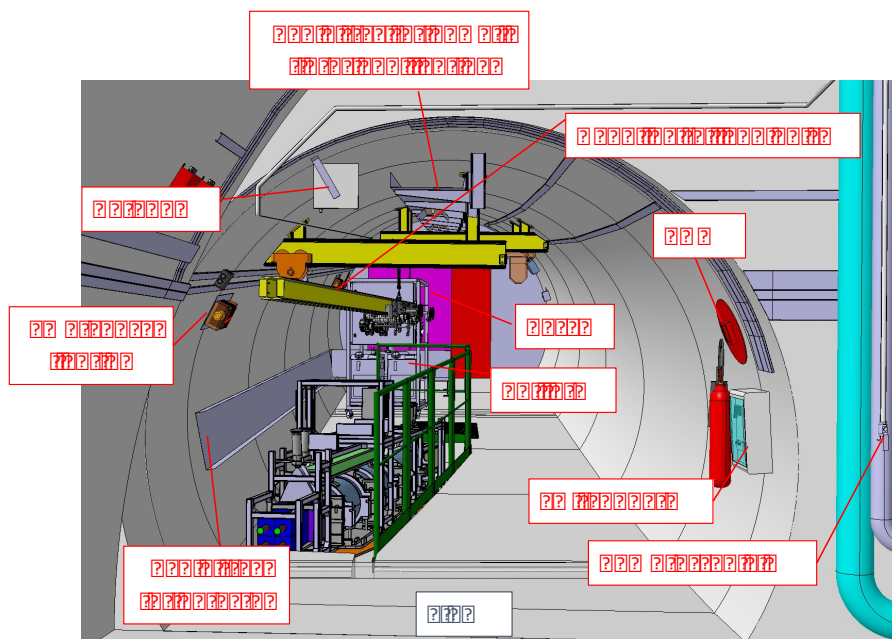


Figure 56. An integration picture of the TI12 tunnel showing the different infrastructure installed for FASER.

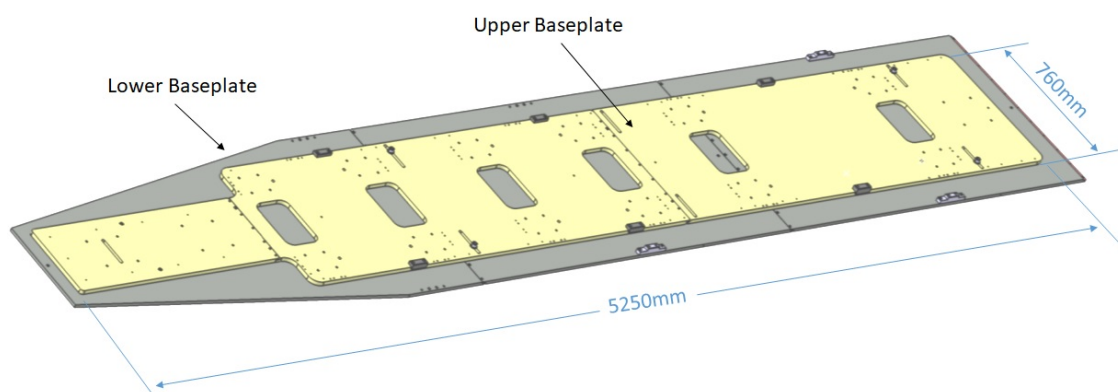


Figure 57. The design of the upper baseplate, shown resting onto the lower baseplate. The main dimensions are shown.

upper baseplate, which allow it to smoothly slide over the lower baseplate minimizing the friction between the two pieces. The sliding is done by applying a lateral force simultaneously at three sliding positions using a hydraulic jack pushing system.²² The sliding system was successfully tested on the surface, with parts of the detector installed onto the upper baseplate, and the rest of the detector weight faked with a concrete block. When in position, the upper baseplate is secured to the lower one by seven M16 stainless steel screws attached through slotted holes in the upper baseplate. The upper baseplate has also a number of threaded holes to allow the supports of the three magnets (described in section 5.4) to be secured, as well as holes to install the detector upper frame discussed in the next section. Figure 58 shows a photo of the two baseplates installed in the FASER trench in TI12.

²²Enerpac manual pump, single speed, with three compact jacks, 5 tons maximum total force.



Figure 58. A picture of the upper and lower baseplates installed in the FASER trench, before the detector was installed.

8.2.2 The upper frame

As discussed in section 5.4, the FASER magnets have their own tunable supports which attach directly to the upper baseplate, and the FASER tracker system is supported by the two short magnets. However the other FASER components (except for FASER) are supported by an aluminium profile structure referred to as the upper frame. The upper frame supports three of the scintillator stations (not including those in front of FASER) the calorimeter system, as well as on-board electronics, on-detector cables, and cooling manifolds and piping. The detectors supported by the upper frame do not need a precise alignment, hence their position is only accurate at better than the 10 mm level. The frame is made of aluminum profiles, with 40 mm square cross section, connected together by angle brackets (all materials are non-magnetic). The design of the frame is flexible and allows the calorimeter and scintillator stations to be raised/lowered to be coarsely aligned with the magnets

and tracker. Figure 59 gives the main overall dimensions of the upper frame, and figure 60 shows a picture of the upper frame during a test installation in TI12. During this test, the FASER magnets were installed, but most of the other parts of the detector were not yet included.

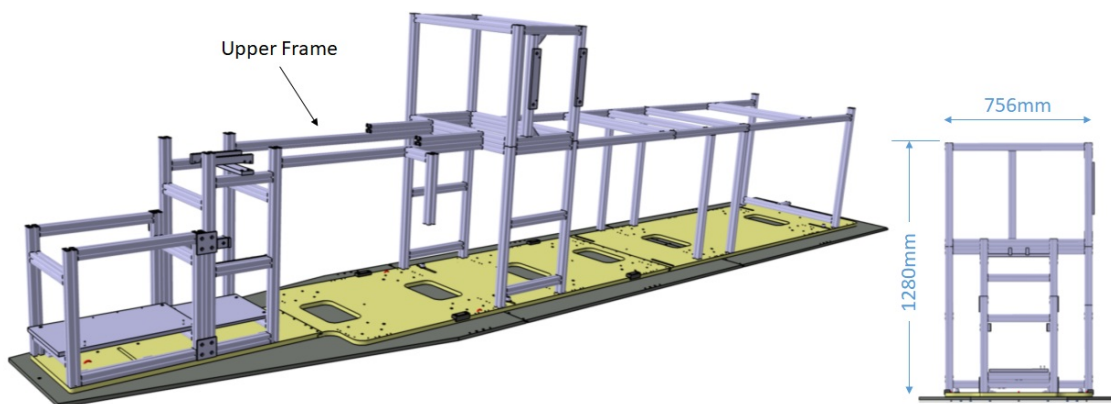


Figure 59. A CAD model of the upper frame with some dimensions.

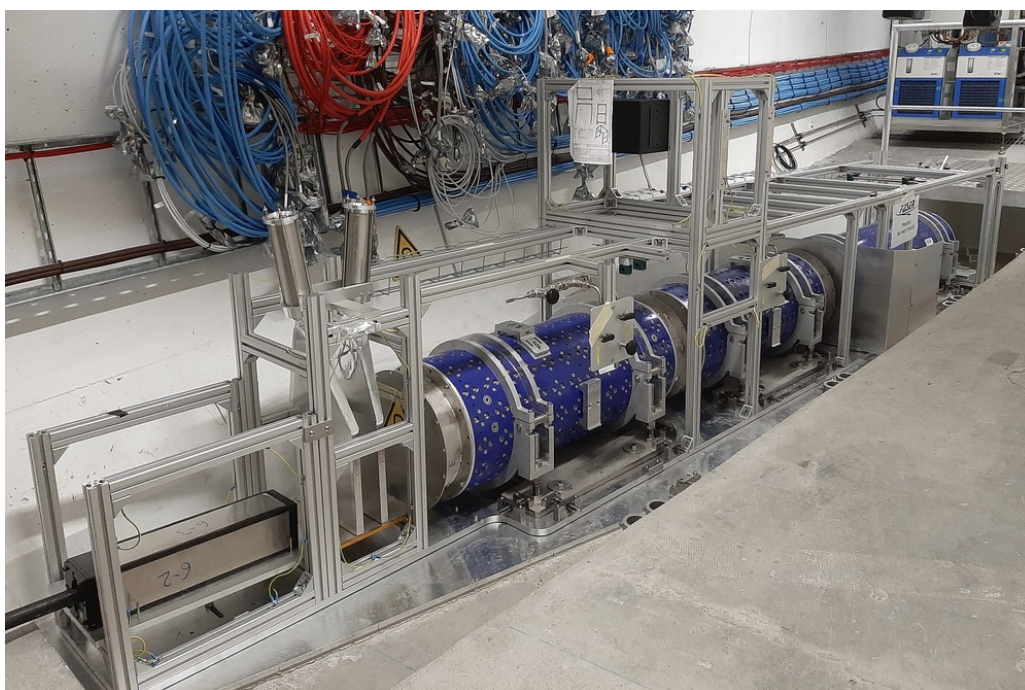


Figure 60. A picture of the upper frame, during a test installation in TI12.

8.3 The cooling system

The cooling system uses two water chillers²³ from which two inlet/outlet pipes supply the four tracking stations of FASER. A manifolding system connects each station by means of flexible polyurethane pipes with 8 mm outer diameter and 5.5 mm inner diameter. A patch panel allows for

²³HRS030 from SMC company.

smooth control of the water flow to each station and balances the flow across the four stations (a flow meter is used once to set the right parameters per circuit). Figure 61 shows the main cooling circuit from cooling unit to tracking stations. The stainless steel pipes are rigidly connected to the upper frame with isolating clamps, to minimize the heat loss along the path and limit the temperature increase between the set point and the inlet of each stations. The maximum measured water flow per station is about 2.7 /min and depends on the pressure drop along the system (which is a function of the pipe length, diameter, manifolds, and bends). The temperature on the chiller is set to a minimum of 15 C, to prevent condensation on the pipes. As discussed in section 6.2, the measured temperatures on the tracker stations are well within the tolerance to safely run the electronics.

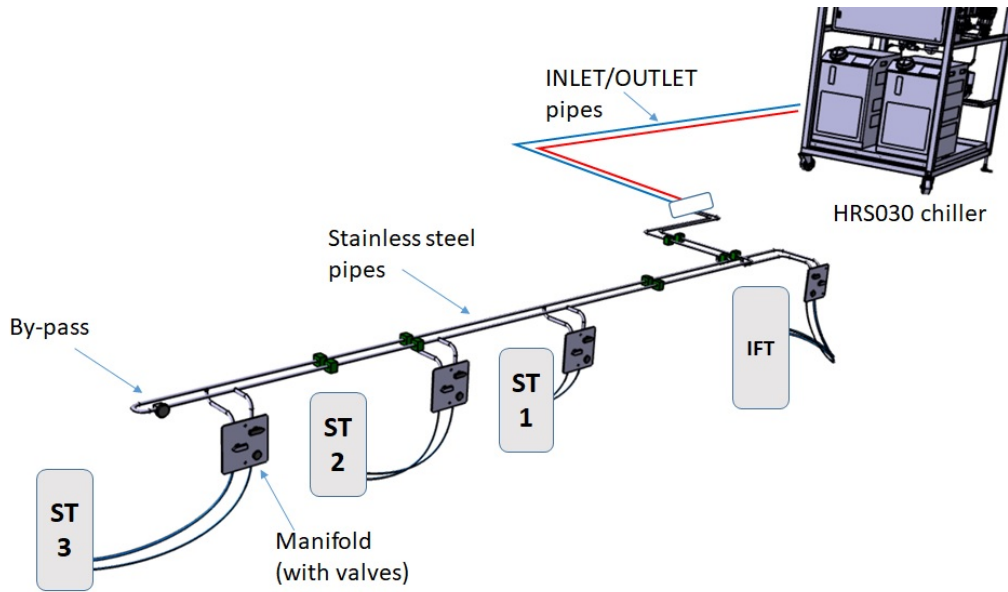


Figure 61. A picture of the cooling system for FASER tracker.

8.4 Detector grounding

The electronic components of the detector are grounded following a meshed common bonded network. The common ground of each component is connected to the main LHC earth via two copper grounding bars installed on the side of the FASER trench (these can be seen in figure 58), with a separate connection for the two electronics racks housing the TDAQ equipment and MPOD power supplies, and for the cooling unit. All cable trays are grounded at both ends. The tracker power supplies have individual floating grounds, and are grounded on the tracker patch panels, whereas the PMT power supplies have a common ground.

For safety reasons all metallic components on the detector are connected to the ground to ensure they are equipotentially bonded.

8.5 Material inside the active detector volume

In order to reduce backgrounds to searches for new physics, the amount of material inside the transverse region of the detector active area, and longitudinally from the last veto scintillator until

the pre-shower scintillator station should be minimized. The amount of material in this region has been optimized for this purpose and is summarized in table 8. As expected, the largest fraction of material is in the tracking stations, followed by the material in the timing scintillator station and the covers on the front and back of the decay volume magnet.

Table 8. A summary of the amount of material in the part of the detector in which material is minimized to reduce physics backgrounds. As discussed in section 2.3, the material in the tracker stations is minimal in the central region (≈ 4 cm) and larger in the edge region. Both regions are shown in the table.

Component	Material	ρ_0 (%)	
		Central region	Edge region
Scintillator timing station — scintillator	1 cm polyvinyltoluene	2.4%	2.4%
Scintillator timing station — foil wrapping	1 mm Al	1.1%	1.1%
3 Tracking stations	See table 2	6.3%	64.5%
Decay volume magnet cover — front	0.4 mm CFRP	0.15%	0.15%
Decay volume magnet cover — back	3 mm plastic	0.75%	0.75%
Total	-	10.7%	68.9%

8.6 Detector installation

After the installation of the services in TI12, the main FASER detector (not including the FASER systems) was installed in March 2021. The installation of the detector components proceeded in steps as detailed in the following.

- Installation of the detector cooling unit and the related piping up to the trench.
- Installation of the lower baseplate.
- Pulling of about 150 power and readout cables from the two electronics racks, along the tunnel wall, and up to the FASER trench. The cables were then tested and a careful mapping carried out. The cables were left coiled up against the wall, until the detector was installed.
- Installation of the upper baseplate.
- Installation of the two short FASER magnets.
- Installation of the timing scintillator station. Since this sits within a few mm of the long FASER magnet, it was necessary for this to be installed before the last magnet.
- Installation of the long magnet.
- Alignment of all three magnets (see section 8.6.1).
- Installation of the FASER tracker. This was installed as a single unit, with the three tracking stations attached to the backbone. As shown in figure 62, there is not enough clearance for connecting all the cables on the trench wall side of the patch panels. Consequently, some of the cables and the cooling pipes were pre-attached before the installation. The tracker

was slowly lowered onto the two short magnets using the crane installed over the FASER trench. Figure 63 shows a picture of the tracker being lowered onto the detector. Following the installation, a survey was carried out to precisely measure the position of the tracking stations (see section 8.6.1).

- Installation of the veto and pre-shower scintillator stations. They were then attached to the upper baseplate.
- Construction of the upper frame. The frame was constructed around the installed components, and the tracker on-detector electronics mounted on the upper frame.
- Installation of the four cooling manifolds onto the upper frame. They were installed along with the on-detector cooling piping, which was connected to the piping from the cooling unit. The tracker station cooling loops, and dry-air connections, were then connected and the cooling system tested.
- On-detector cabling for the tracker. For the tracker powering, the short cables from the tracker patch panels to the splitter boxes were routed on the upper frame, and the long cables routed from the cable tray along the tunnel wall were connected to the splitter boxes. The TRB cables were routed to the mini-crate, and the DCS cables to the TIM box. At this stage the tracking stations were tested. Calibrations and checks demonstrated similar performance to those seen during testing on the surface, as described in section 2.5.
- Installation of the calorimeter. The scintillator counter PMTs and calorimeter PMTs were also connected and their correct functionality verified.
- Installation of the detector grounding.

These installation steps were carried out without problems during a 3-week period. A photo of the FASER detector after installation can be seen in figure 64. In December 2021, the IFT tracker station was installed, and commissioned. As shown in figure 65, the IFT is attached to the upper frame with dedicated mechanics that allows the position to be precisely tuned.

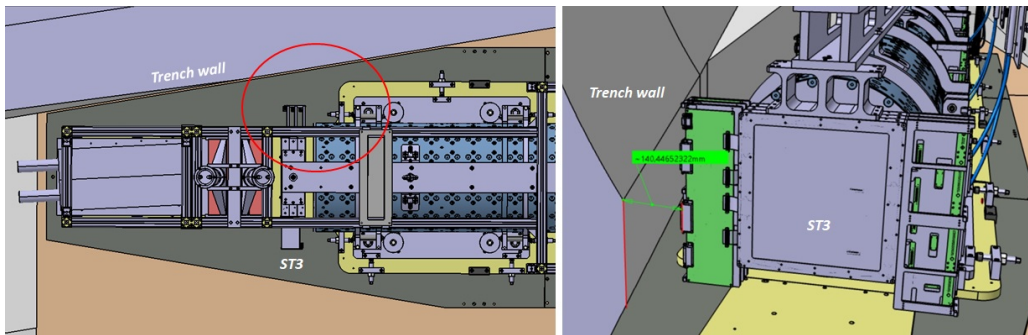


Figure 62. Plan view (left) and view from the back (right) of the CAD model, showing the back region of the FASER detector, and highlighting how close the patch panels on the back tracker station are to the tunnel wall (about 14 cm).

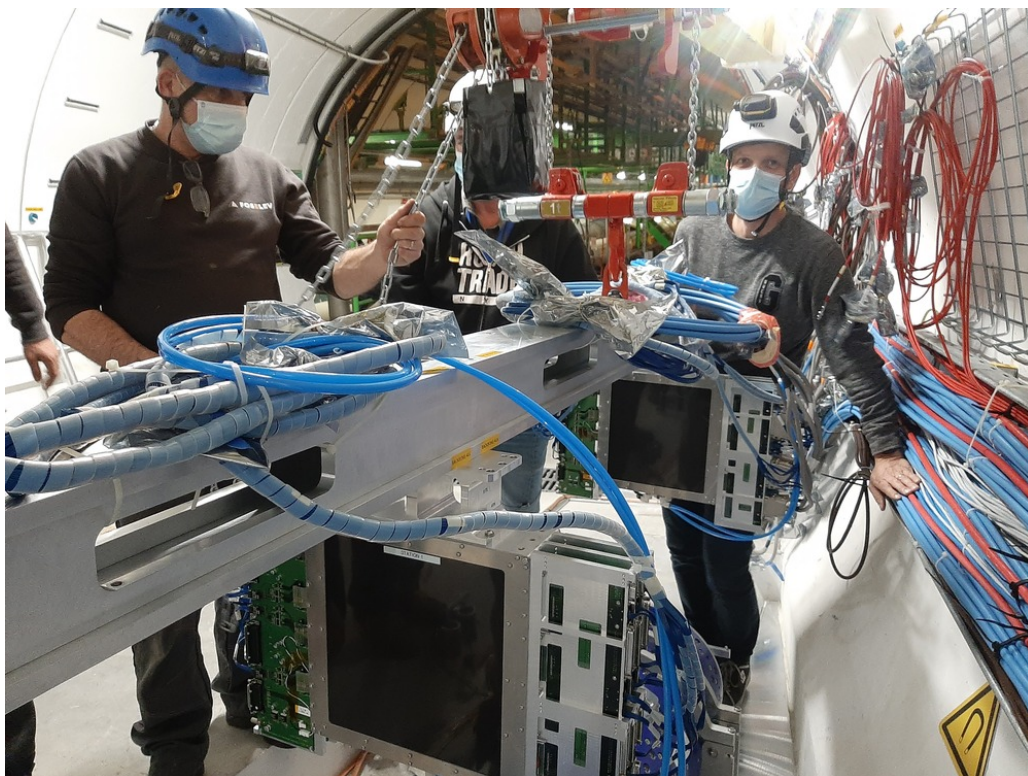


Figure 63. A picture of the FASER tracker being installed onto the detector.



Figure 64. The FASER detector after installation in TI12.

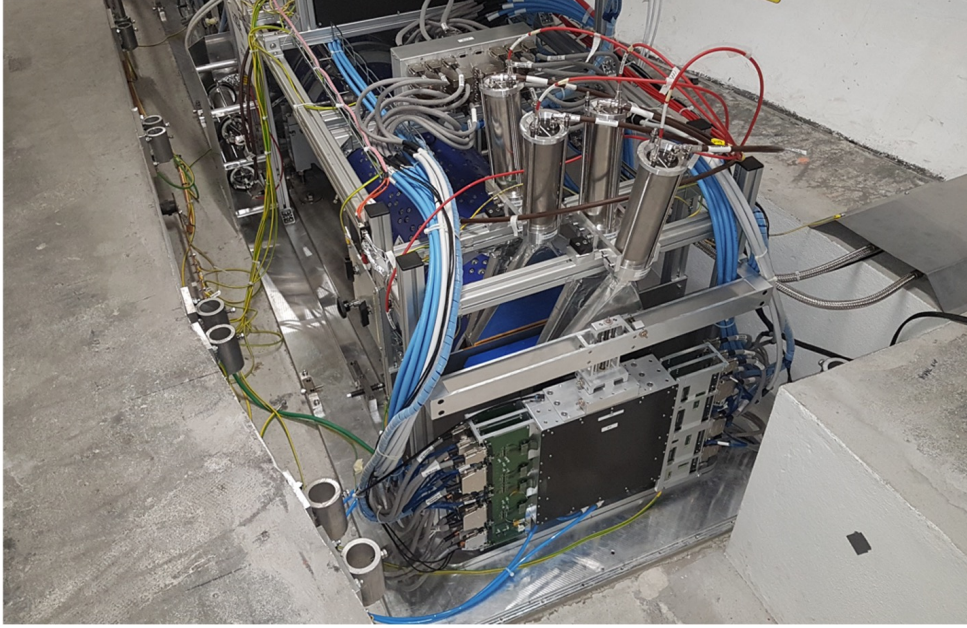


Figure 65. The IFT tracker station, installed at the front of the main FASER detector.

8.6.1 The detector and magnet alignment

There have been several stages in the FASER alignment process and the related survey carried out by the CERN survey group in T112. As a very first step, a 3D laser scan was performed in T112 to check the FASER trench and add corrective works where needed. After this, the alignment of the lower baseplates was performed. The core part of the tracker system alignment and related survey was carried out when the three magnets were fixed to the upper baseplate, and again after installation of the three tracker stations. Finally, a dedicated alignment and survey was carried out once the IFT tracker station was integrated. As well as the survey work in T112, the individual tracker stations were measured during the metrology to ensure the required precision is achieved, as discussed in section 2.4. Similarly, the tracker backbone was also measured. For each survey campaign, the measurements were recorded as Cartesian coordinate points in the LHC reference system, using a Leica laser tracker.²⁴ The surveyed points were then compared to the nominal CAD model to compute the deviations in mm. Figures 66 and 67 show the positions and labels of the measured points for the survey of the lower baseplate, and the magnets and tracker backbone, respectively, as well as the coordinate system.²⁵

The survey measured 16 points on the magnets and 20 points on the tracker backbone, and the results were compared to the nominal CAD model. The magnet measurements are summarized in table 9. Since the crossing angle for 2022 running pushes the LOS downwards, the magnets were aligned to be as low as possible. During the survey they were measured to be lower than the nominal position (assuming zero crossing angle) by 12.3 mm (± 0.2 mm). The magnets were measured to be within 0.3 mm of the nominal position in the horizontal (\pm) and longitudinal (\pm) directions, and the angle between the magnetic axis and the vertical axis (referred to as roll angle) was measured to be less than 0.2 mrad for all three magnets.

²⁴Leica laser tracker AT 403.

²⁵Note the coordinate system used here is not the same as the FASER coordinate system shown in figure 2.

Table 9. Positions of the three FASER magnets with respect to the nominal position in mm. The positions are calculated from the magnet geometry and the survey measurements for each magnet. The measurements are in the FASER coordinate system, with the magnets deliberately positioned as low as possible to partially follow the downward movement of the LOS due to the crossing angle, where the final position is 12.3 mm below the nominal location. The measured roll angle of each magnets is also shown (in mrad).

Measurement position	(mm)	(mm)	(mm)	Roll angle (mrad)
Decay Volume magnet: front	0.13	12 24	0 23	0.06
Decay Volume magnet: back	0.19	12 48	0 23	
1 st Spectrometer magnet: front	0.13	12 33	0.30	0 14
1 st Spectrometer magnet: back	0.10	12 22	0.30	
2 nd Spectrometer magnet: front	0.03	12 13	0 12	0.17
2 nd Spectrometer magnet: back	0.19	12 13	0 12	

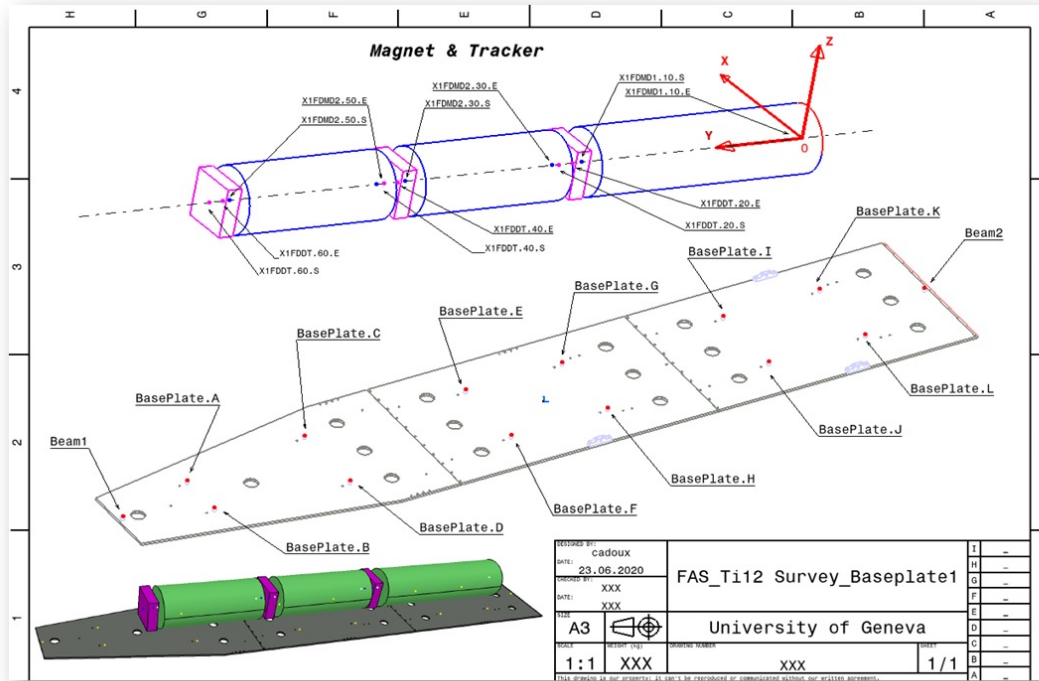


Figure 66. Drawing of the lower baseplate showing the measured survey points and coordinate system used in the survey.

The survey in TI12 of the tracker backbone, including the interface to each tracking station, measured the position of the survey points on the tracker station with $O 16 \text{ m}$ accuracy. This information, combined with the metrology data taken with the individual tracker planes (described in section 2.4) allows the position of the silicon sensors in the detector frame to be known to $O 100 \text{ m}$ precision, each measurement is significantly more precise but when taking into account the full system and possible movements after the measurements were taken this is the expected level

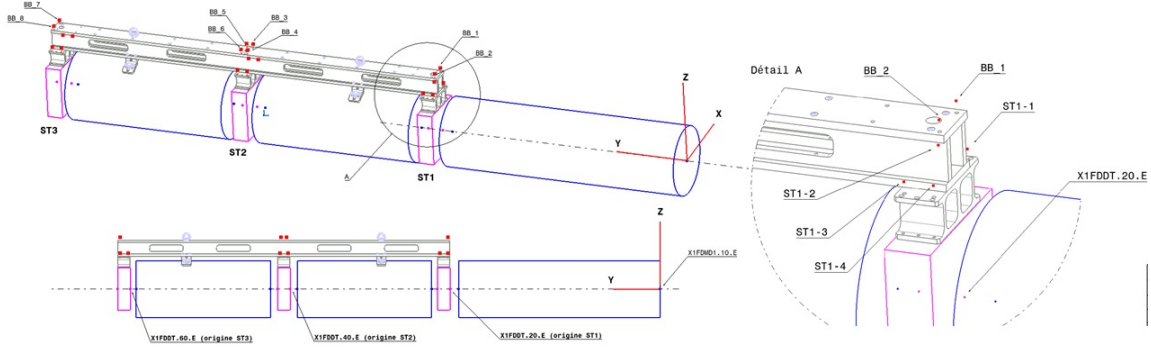


Figure 67. Drawing of the magnets and the trackers stations showing the position and labels of the survey points. The coordinate system used in the survey is also shown.

of precision. The precision of the measurements of the position of the IFT sensors will likely be worse due to the more complex mechanics supporting the IFT. The results will be used as the first alignment in the simulation and reconstruction software, and will be refined by track-based alignment measurements. Finally, the survey measurements allow the distance of the FASER detector at 0 (corresponding to the front of the second tracking station) from the nominal IP1 collision point, which is calculated to be 477 759 m, to be precisely known.

9 Commissioning of the full detector

All sub-detector components, except the IFT tracking station, the FASER emulsion detector and the FASER veto scintillator systems, were installed in March 2021 in TI12. Following this, the detector was commissioned in situ using cosmic-ray events collected for several months. In October 2021 there was a two week pilot beam test in the LHC, during which beams were circulated and collided, allowing further commissioning of the detector using beam data.

The commissioning studies done in situ allows to verify the performance/functionality of the different detector components, and to demonstrate that the full detector can operate with the central TDAQ and DCS systems. However, there are intrinsic limitations on the kind of studies that can be performed on these data. The rate, angular distribution and random arrival time of cosmic-ray muons does not allow to commission the full combined reconstruction and calibration/alignment of the detector. The pilot beam test proved to be useful for a first timing-in of the detector and trigger, and to assess beam-related backgrounds, but data are not available at a sufficient rate for detailed studies. The full commissioning of the detector and the assessment of the object reconstruction capabilities is only possible with first high energy collisions and is not part of this paper.

9.1 Commissioning with cosmic rays

A cosmic-ray dataset of the order of 125 M events was recorded during $O 10^7$ s of running between April and September 2021, triggering either on the scintillator counters or on the single calorimeter modules. The overall trigger rate was about 15 Hz, dominated by noise-induced triggers in the veto and timing scintillator stations. The trigger thresholds were generally set to be sensitive to the signal of a minimum ionizing particle. Table 10 shows the rate of the different triggers during a typical cosmic data taking run.

Table 10. Summary of the rate of the different triggers during cosmic-ray running of the full detector in TI12. Note that the timing station has a higher noise rate, since the trigger is not given by the AND of signals in separate scintillator counters, but rather by the AND of signals from two PMTs attached to the same scintillator.

Trigger	Rate (Hz)
Veto scintillator station	3.5
Timing scintillator station	10
Pre-shower scintillator station	0.25
Calorimeter	0.25
Random	1
Total rate	15

During cosmic-ray data taking the rate of tracks crossing the front and back tracking stations (which are close to scintillator stations which provide triggers) is $O\ 0.01\ \text{Hz}$, whereas there is not a suitable trigger for tracks going through the middle tracking station. Because of the angular distribution of the cosmic-ray flux, and particularly at a depth of 80 m under the ground, it is rare to have a cosmic-ray muon travelling at a shallow enough angle to traverse more than one tracking station. An estimate of the expected rate for tracks to traverse one, two and all three tracking stations was made by an analytical integration of the cosmic-rays flux taken from ref. [70]. Muons were assumed to propagate to TI12 following the model from ref. [71], taking into account the detector geometry, including the scintillator counters used for triggering. A comparison of the observed and measured rates is shown in table 11: no track passing through all three stations has been observed, in agreement with the very low probability expected from simulation.

Figure 68 shows a simplified event display of a cosmic-ray muon traversing the middle and back tracking stations, and also leaving signals in the pre-shower scintillator station and in one of the calorimeter modules. Over the period April–September 2021 (with the detector turned off for most of August due to magnet training in the LHC close to FASER) more than 100 of such “two-station” events were recorded.

Table 11. Summary of the observed and expected rate of tracks traversing different numbers of tracking stations during cosmic-rays running (about 100 days) of the full detector in TI12. No event has been yet seen with a cosmic ray traversing the three tracker stations.

Event type	Observed Rate	Expected Rate
Track in 1 tracker station	0.016 Hz	0.011 Hz
Track in 2 tracker station	$1\ 28\ 6\ 2\ 5\ \text{hrs}^{-1}$	$1/28\ \text{hrs}^{-1}$
Track in 3 tracker station	Not yet observed	$1/82\ \text{days}^{-1}$

The cosmic-ray data taking was used by the different detector systems for various commissioning and performance studies, as briefly detailed below.

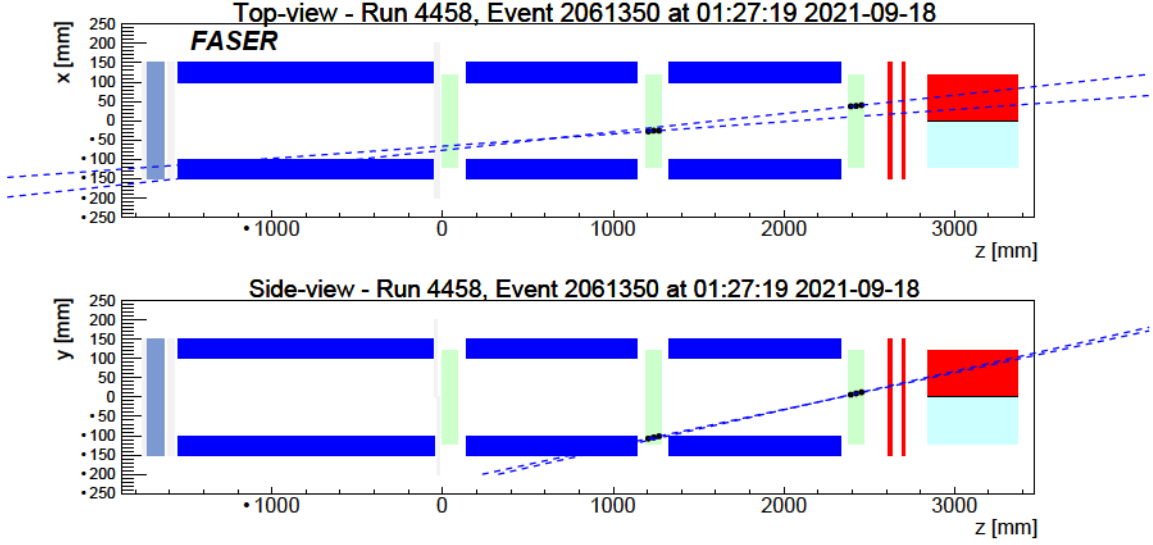


Figure 68. An event display of a cosmic-ray muon traversing part of the detector. The view is shown both from the top (top row) and the side (bottom row). Non-triggered and triggered scintillator counters (calorimeter modules) are shown in grey (light-blue) and red respectively. Tracker stations are shown in green, while 3D tracker hits are shown as black dots and track segments formed from hits in a single station are indicated with a dashed blue line. The dark blue areas are the magnet material.

9.1.1 Tracker

The noise occupancy of the SCT modules on the tracking stations was measured at the nominal 1 fC thresholds using randomly triggered events taken during cosmic-ray runs. The strip-by-strip tracker noise occupancy considering all four tracking stations (tracking spectrometer and IFT) is shown in figure 69. Less than 0.4% of the strips have a noise occupancy above 5×10^{-4} . The results are in good agreement with the pre-commissioning results on single SCT modules as discussed in section 2.5.

The long-term operations of the tracker during the cosmic-ray data taking with the full detector demonstrated that all SCT modules can be kept well below 30 degrees, and that the tracking spectrometer was able to operate efficiently and safely for single runs over many days.

9.1.2 Calorimeter and scintillators systems

After installation, the first cosmic-ray data were used for an in situ adjustment of the PMT gains to equalize the MIP signal response of PMTs in the same station and to achieve a certain dynamic range, given the 2 V maximum signal voltage of the digitizer. The veto stations were adjusted to a dynamic range of a signal equivalent to about 10 MIPs for high single particle detection efficiency. Initially, the same adjustment was done for the pre-shower station, but later the gain was reduced by a factor of ten in order not to saturate on large electromagnetic showers, following evidence from test-beam measurements. The timing scintillators initially used a relatively low gain and had a dynamic range of up to about 60 MIPs. In a later stage, the gain was increased by a factor of six to improve the signal efficiency and the timing resolution. These gains can be fine-tuned once a large sample of horizontal muons is collected from the first collisions.

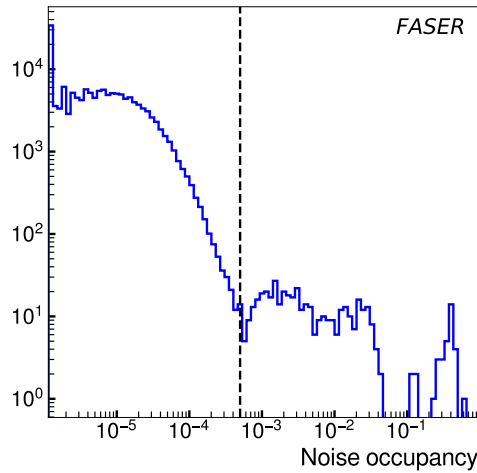


Figure 69. Strip-by-strip tracker noise occupancy measured from random triggers during combined runs. The dashed vertical line indicates noise occupancy of $5 \cdot 10^{-4}$.

For the calorimeter system, data were taken at several gain settings without the optical filters installed in order to maximize sensitivity in the initial commissioning. Cosmic-ray and noise data were taken at a medium gain of about $3 \cdot 10^4$ for 81.5 days, corresponding roughly to the expected time of stable beam collisions in a full year of the LHC. During this time only 15 events were recorded with one calorimeter channel in saturation, corresponding to a deposited energy of more than roughly 60 GeV. This shows that cosmic-rays background is not significant in physics data analyses: such low number of events can easily be suppressed with additional selections on the signal timing and on the pre-shower signals.

As noted in section 3.2, the calorimeter PMTs were initially affected by noise picked up from a nearby GSM antenna. Before installation of the Faraday cage around the PMTs, the RMS of the PMT pedestal measured in the digitizer was between 0.35 and 0.60 mV, depending on the channel. After the installation this was reduced to between 0.33 and 0.40 mV, very close to the intrinsic noise level in the digitizer of 0.30 mV. The noise level in the scintillator counter PMTs all lie in the same range. At this noise level, it is possible to have a single PMT trigger threshold of 3 mV (0.15% of the full range) for the calorimeter PMTs at medium gain, and maintain a noise trigger rate below 0.5 Hz.

The LED calibration system has been used regularly to monitor the calorimeter response versus gain and time. Figure 70 shows the change in response, measured as the average charge collected in each of the four modules during LED calibration runs, over a period of five weeks. During this time the calorimeter and calibration system settings were kept unchanged. The calibration system and the PMTs were found to be stable to within 1%.

9.1.3 TDAQ system

The long-term stability of the TDAQ system for the detector in its final location was continuously tested during the combined cosmic-ray data taking. The limitations of the TDAQ hardware and software have been probed by running dedicated high-rate tests. Here, noise signals from a signal generator were fed into the digitizer and input trigger rates of 250-5000 Hz were invoked by adjusting

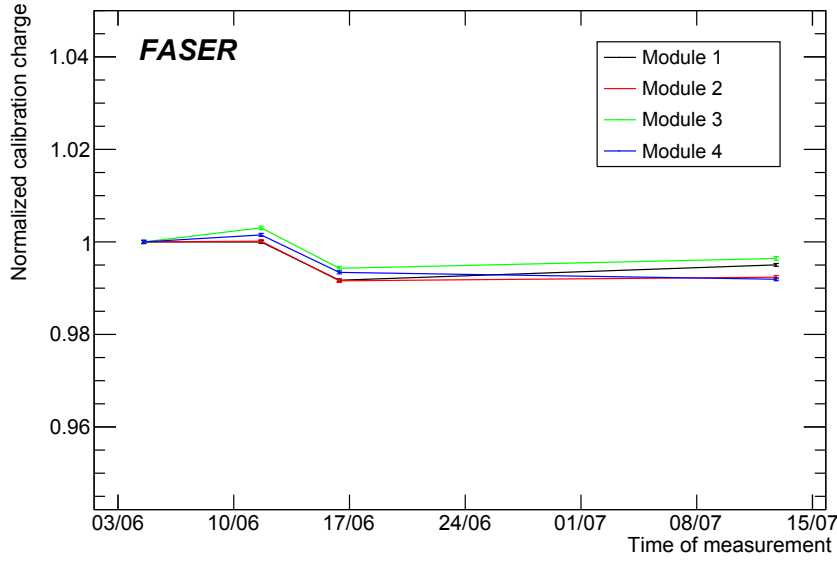


Figure 70. Average charge measured in the four calorimeter modules during four separate LED calibration runs with the same settings. The charge has been normalized to 1 for the first run.

the injected signal amplitude. The detector deadtime, buffer occupancy, missing fragment errors and event counts in particular were carefully monitored during high rate tests. Results showed that for rates up to 900 Hz, the deadtime is dominated by the tracker busy signal contributing up to a fraction of 0.7%. The rate limiter is the dominant source of deadtime from 900 Hz to 4 kHz input rate up to a fraction of 42%. The first hardware readout limitation is the digitizer which reaches full buffer occupancy at a readout rate of 2.2 kHz, corresponding to 47 MBytes/s. This happens to be the maximum rate of the rate limiter. There are several options to optimise the digitizer configurations that ease this limitation in case rates above 2.2 kHz are met during data taking [25]. The FASER DAQ software has been proven to run without signs of limitations during high rate tests. Stress tests have been performed on the DAQ software using emulated trigger and data input at beyond hardware-limited rates. The main DAQ limitation is the 1 Gbit/s link between the digitizer and the TI12 Ethernet switch due to the large payload size. This link saturates around 5 kHz, but higher rates can be achieved by reducing the readout window for the digitized signals.

9.2 Commissioning during the LHC pilot beam

During the last two weeks of October 2021, the LHC carried out a pilot beam test, in which proton beams were circulated in the LHC, and during some periods the beams were brought into collision. The primary purpose of this test was to check the LHC beam pipe aperture, and to test and commission the beam systems after many interventions during the LS2. However, the pilot beam test provided a valuable opportunity to operate FASER and to take data during beam operations.

The LHC operated with a maximum of only four circulating bunches per beam, with nominal per-bunch intensity (around 10^{11} protons per bunch), and a beam energy of 450 GeV. During periods of collisions, only two of the bunches were colliding at each interaction point, leading to a maximum

luminosity of $10^{28} \text{ cm}^{-2} \text{ s}^{-1}$ (about 4 orders of magnitude lower than the expected luminosity during Run 3 physics operations).

For the two-week period, the FASER experiment acquired data continuously using both the nominal cosmic triggers, triggering on single signals per scintillator station and calorimeter module, and a coincidence trigger that required a signal in the veto scintillators (positioned at the front of the upstream magnet) and the pre-shower scintillators (positioned after the last tracker station).

Several hundred events were observed containing traversing charged particles that can be traced back to the filled proton bunch interactions in the direction of the IP1 interaction point. The LHC circulated two bunches colliding in IP1, and two bunches that were not colliding, and an equal number of events with traversing tracks in FASER were observed for these two sets of bunches, strongly suggesting that the observed signals are arising only from beam backgrounds rather than collision products. This is consistent with the expectation given the low luminosity of these collisions and that the collisions were at low energy ($\sqrt{s} = 900 \text{ GeV}$). The collected number of events was sufficient to do an early coarse time adjustment of the trigger and readout signals to have coincident signals from all scintillator counters and calorimeter modules for potential collisions.

Figure 71 shows an example event containing a charged particle traversing the full detector, triggering each scintillator or calorimeter station and leaving traceable track hits in each tracker station. The scintillator station timings match that of a particle entering the front of the detector, from the direction of IP1. The arrival signal time as seen in the different PMTs for beam particles can be seen in figure 72 where one should note that the calorimeter PMT signals are expected to be faster than the scintillator PMTs owing to a 23 ns shorter transition time for the calorimeter PMTs. To adjust for the time-of-flight of particles originating on the LOS upstream of the detector, the veto scintillator and the timing station trigger signals are delayed by 1/2 a clock cycle, equivalent to 1/2 a bunch-crossing.

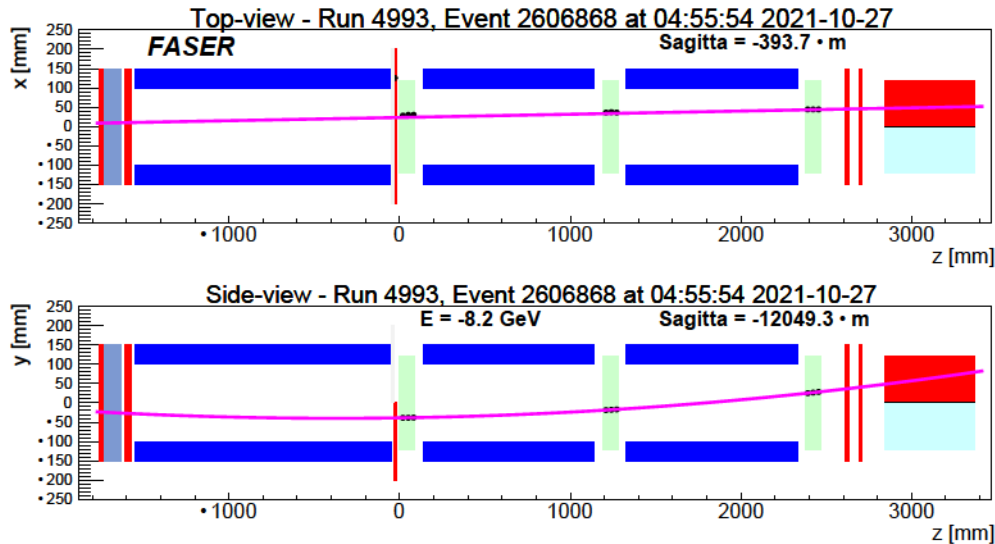


Figure 71. An event display of a charged particle traversing the full detector during an LHC stable beam run with two 450 GeV colliding beams. The layout of the display and the sub-detector systems are the same as those in figure 68. The purple line is a combined track fit to the hits in the tracking stations.

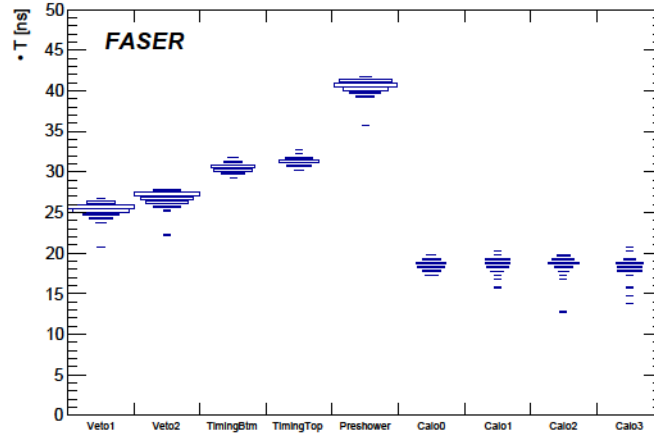


Figure 72. The signal arrival time measured for different scintillator and calorimeter stations/modules with respect to the start of the bunch crossing for single muon tracks recorded during the 2021 pilot beam test.

Events triggering the coincidence trigger occurred in specific BC IDs with a consistent offset to the BC ID of filled proton bunches in the beam approaching FASER from the direction of IP1.

The beam events with a single particle passing through the FASER spectrometer can be used for a first, in situ measurement of the timing resolution of the timing scintillator station. Figure 73 shows the time distribution measured in the top and bottom timing scintillator layers. The hit time is calculated as the average time in the two PMTs attached to each layer with respect to the start of the beam bunch crossing. A fixed offset is subtracted. A resolution of just over 400 ps is obtained, which is worse than the expected 250 ps as discussed in section 3.4.2, but still well below the requirement for background suppression. The overall time resolution of the veto and pre-shower scintillator stations are worse than 400 ps due to the intrinsic time-walk. However, selecting events with a reconstructed track pointing to the bottom quarter of the scintillator station, where the time-walk variation is the smallest, a spread of around 250 ps is measured.

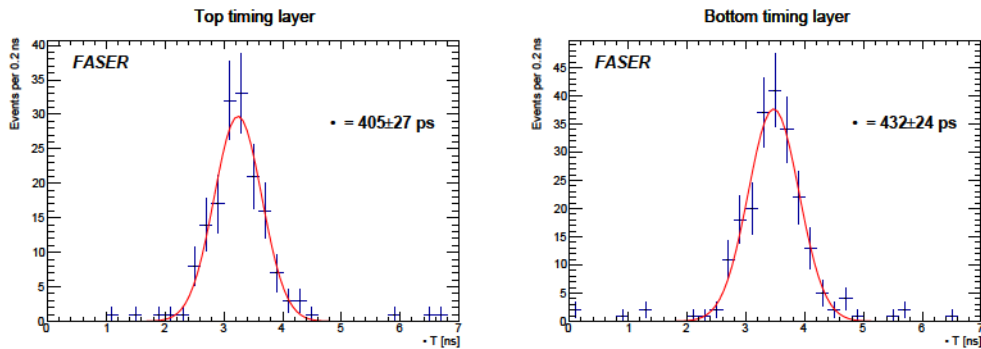


Figure 73. Average signal arrival time for the two PMTs in the top (left) and bottom (right) timing scintillator layer with respect to the start of the bunch crossing for single muon tracks recorded during the 2021 pilot beam test. The data are fitted with a Gaussian function to extract the timing resolution values.

10 Conclusions

Following CERN approval of the FASER experiment in March 2019, the collaboration proceeded to design, build and commission its sub-detector components and the needed infrastructure before installation of the full detector in the TI12 tunnel of the LHC complex in March 2021. This paper presents an overview of the sub-components, including a tracking spectrometer complemented by the Interface Tracker; a decay volume; a set of scintillator systems to veto events, provide timing or act as a pre-shower; an electromagnetic calorimeter system; and the FASER emulsion detector dedicated to the study of neutrinos produced in LHC collisions via hadron decays. The decay volume and the tracking spectrometer are immersed in a 0.57 T dipole magnetic field, also detailed in the paper. The FASER detector is triggered by signals in any of the scintillator stations or the calorimeter. The trigger and data acquisition system are also discussed. Similarly, details have been provided on the detector control system of the experiment that ensures safe operation. Emphasis has been given to the description of the detector integration phase, including the preparation of the TI12 tunnel, the design and manufacturing of the detector support, the installation of the experiment system and its commissioning using cosmic-rays collected between April and September 2021 and during the LHC pilot beam test carried out in October 2021.

The installed detector is fully operational and shows excellent performance. For the tracker, the number of non-operational channels is less than 0.5%, and the measured gain and noise from calibration runs are well within the specifications. The individual scintillator counter efficiencies, measured with cosmic ray muons and during testbeam, are higher than 99.9% and within the experiment's requirements. The electromagnetic calorimeter system has been studied using cosmic ray muons and pilot beam data, and shows good performance, within the experiments specifications. The trigger and data acquisition system has been fully tested, and demonstrated to operate with no more than 5% deadtime up to almost 2 kHz trigger rate, well above the expected rate of 650 Hz, meeting target expectations. The full system has been operated for several months cosmic rays data-taking in TI12, and as part of the LHC pilot beam test in October 2021, accumulating valuable operational experience and data for performance studies.

The FASER detector was ready for physics data-taking in time for the first proton-proton collisions in 2022. It has successfully started taking LHC collision data in July 2022, and will run throughout LHC Run 3. It will offer exciting opportunities to complement the LHC's ongoing physics programme on searches for light, long-lived new particles produced in the far-forward region, and to measure neutrino interaction charged-current cross sections for all three neutrino flavours in a previously uncovered energy regime.

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EP-SO). For the FASER site preparation and installation of the services and the detector we acknowledge invaluable support from the following CERN teams: transport and handling (EN-HE), installation of services (EN-EL, EN-CV), cabling (BE-EA, EP-DT), and survey (BE-GM). We acknowledge support from the CERN magnet group (TE-MS) for the design, construction and measurements of the FASER magnets.

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