Early performance of the tracking detector for the FASER experiment

Tomohiro Inada (CERN)

for the FASER Collaboration

Vancouver, 4th Dec 2023, HSTD 13 conference, Tomohiro Inada (CERN)
FASER - New experiment at the LHC Run3

Location and Background Considerations

- Located 480m away from IP1 (ATLAS)
- Placed in old transfer tunnel to SPS on the line of sight of the IP1 collision axis
- Extremely low radiation due to low dispersion function at FASER location
  - $<5 \times 10^{-3}$ Gy/year, $<5 \times 10^{7}$ neq@1MeV/year
- Extremely low background (100m of rock between FASER and IP1)
- Muons/neutrinos from pp interaction at IP1 ($0.4 \text{cm}^{-2} \text{s}^{-1}$ muons with $E>10\text{GeV}$ @ $2 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ LHC inst. luminosity)
- Off-orbit protons showering in collimators (negligible)
- Beam gas interactions (negligible)

FLUKA background model confirmed with in-situ measurements during Run-2
ForwArd Search ExpeRiment (FASER) at the LHC

- Placed 480 m downstream of the ATLAS IP on the beam axis
- Started the operation from July 2022 (LHC run3)

Physics motivation

- New long-lived particle searches in MeV-GeV masses
- All flavors of neutrinos at the TeV-energy frontier

Favorable location

- Very low background from collision
  - Only high-energy muon at about 1/cm²/sec
- Low radiation level from the LHC
  - $4 \times 10^6$ 1-MeV neutron/cm²/year
FASER Physics cases with Run3 data

Dark Photon searches

Search for Dark Photons with the FASER detector at the LHC

FASER Collaboration

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The first observation of Collider Neutrino

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**12th Physics 16, 113

The observation of neutrinos produced at a particle collider opens a new field of study and offers ways to test the limits of the standard model.

The Dawn of Collider Neutrino Physics

Elizabeth Worcester

Brookhaven National Laboratory, Upton, New York, US

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FASER detector

Small, inexpensive detector
10cm radius
7m long

“The FASER detector” paper
arxiv: 2207.11427

Electromagnetic Calorimeter
4 LHCb outer EM calorimeter modules

Tracking spectrometer stations
3 layers per station with 8 ATLAS SCT barrel modules in each layer

Magnets
0.57 T dipoles
200mm aperture
1.5m decay volume

Trigger / pre-shower scintillator system

Scintillator veto system
Three 20mm scint.
300x300mm wide

Front Scintillator veto system
Two 20mm scintillators
350x300mm wide

To ATLAS IP

Decay volume

Trigger / timing scintillator station
10mm thick scintillators with dual PMT readout
for triggering and timing measurement (σ=400ps)

3 layers per station with 8 ATLAS SCT barrel modules in each layer

FASERν emulsion detector
1.1 ton detector
730 layers of 1.09mm tungsten+emulsion neutrino target and tracking detector
provides $8\lambda_{int}$
All detector components are successfully installed in T12 in March 2022.


FASER Tracking components

3 tracker stations + Interface tracker placed after the FASERv emulsion detector

Semiconductor Tracker (SCT) modules
→ 8 modules per tracker plane

3 Tracker planes per station (12 in total)
- 80μm strip pitch, 40 mrad stereo angle (17μm / 580μm resolution)
- precision measurement in bending (vertical) plane
- 8 SCT modules give a 24cm x 24cm tracking layer
- ABCD readout chip
- Custom made flexible cable used to connect pigtail to PCB patch panel

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Tracker Readout, Cooling, and Power

- **Tracker Readout**
  - Tracker Readout Board (TRBs) : general purpose FPGA board,
    - 1 TRB / tracker plane (12 in total)
  - 3m-long Twinax cables used to send data from patch-panel to TRB

- **Cooling**
  - Low radiation environment
  - Remove heat from the on-detector ASIC (~40W/plane)
    - water chiller at about 15 °C sufficient

- **Power and DCS**
  - Wiener MPOD power supplies
  - Custom board for tracker interlock & monitoring (TIM)
    - monitoring tracker temperatures by sending Detector Control System (DCS)
FASER Operation in the LHC Run3

- Successfully operated during 2022-23
  - Successfully constructed, installed and commissioned
  - Continuous and largely automatic data-taking at up to 1.3 kHz
  - Lightweight operational model
    - No control room

- FASER detector operations have gone extremely well to date
- Recorded ~97% of the delivered data
- DAQ deadtime <2%
- No significant operational issues
- Lightweight operational model
- No control room
- Two shifters, controlling and monitoring the experiment from their laptop

FASER Monitoring and Operation Model

- Live monitoring via Grafana for the entire detector system
  - DAQ status
  - DCS status
  - LHC/trigger status

- System in operation since FASER installation in 03/2021 and data preserved in a centrally maintained database
- Built-in alert system sends alarms to expert groups
- FASER (tracker) is operated/supervised entirely remotely by two people (no control room)
- Continuous monitoring of:
  - Leakage currents
  - LV power
  - Environmental conditions
  - Data quality

Benedikt Vormwald
- Many thanks to ATLAS Collaboration for providing IP1 luminosity information!
- benedikt.vormwald@cern.ch

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Tracker calibration

- Tracker calibrations are performed regularly during non-beam time with internal calibration circuit ref: arXiv:2112.01116

- Keep uniformity of threshold distributions
  - Estimated response curves by changing injection charges and measured the values at 50 % occupancy (i.e. vt50)
    - Showing good linearity around 1 fC
  - Averaged adjusted gain over all chips is ~54 mV/fC
    - Good agreement with previous studies by ATLAS SCT group NIM A 568 (2006) 642-671

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Long-term stability (Gain)

- Gain = relation between comparator voltage and effective threshold charge
- Performed regular calibration runs in 2022 and 2023 during non LHC beam time
- Monitored the average and standard deviation (spread) of distributions in each layer
  - Please note that defective strips are removed before
  - Have been achieving stable operation, keeping the consistency of the tracker performance
Long-term stability (ENC noise)

- Noise = threshold dispersion at charge injection of 2fC
- Performed calibration runs in 2022 and 2023 during non LHC beam time
- Monitored the average and standard deviation (spread) of distributions in each layer
  - Please note that defective strips are removed before
  - Have been achieving stable operation, keeping the consistency of the tracker performance.
Monitoring defective strips for 2022-2023

- Monitored # of defective strips during 2-year operation
- Criteria for defective strips: 1) dead and noisy strips identified by a regular calibration, 2) low gain (<40 mV/fC), 3) low ENC (<850 electrons), 4) untrimmable strips (i.e. showing non-uniformity of the threshold)
- ST3/L0 shows the largest number (>100), which is almost clustered in 1 chip (known before)
- More than 99.7% of strips are available in all layers
Monitoring noisy strips for 2022-2023

- Monitored # of noisy strips during 2-year operation, identified at offline analysis
- Criteria for noisy strips: occupancy > 0.01 (requirement is $5 \times 10^{-4}$)
- Only 0.2 % of all strips are identified as noisy
  - Heavily overlapped with the ones labelled as defective
Detector Hit Map

Distribution of **hits on track** show excellent detector coverage in all layers.
Inefficiencies in between modules from module edges expected.
Station design **shifts planes +/- 5mm** in order to avoid overlapping inefficiencies.

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Detector Timing and Hit Efficiency

Early LHC fills used to timing scan:
- ~1kHz of muon rate through FASER
- ABCD chip readout
  - returns last 3 bits in its pipeline upon arrival of L1A
  - Hit = pattern 010 and 011 (= 01X)
- Fine timing via clock adjustment on the tracker DAQ boards
- Chose center of the efficiency plateau

Efficiency evaluation:
- Track reconstruction per station with 1 of 6 strip sensor layers blinded
- Efficiency = find strip in blinded sensor layer compatible with track ($\Delta y=500\mu m$)
- Hit efficiency of $99.64 \pm 0.10\%$ at threshold 1.0 fC and sensor bias 150V
Track reconstruction with ACTS software

Tracking is performed based on software (Calypso) based on ACTS*

* ACTS: A Common Tracking Software

- (Combinatorial) Kalman Filter w/ cluster or spacepoint
- Same Event Data Model with ATLAS (Athena)

Use Kalman filter to resolve ambiguity
First alignment with collision data

- First alignment: should be simple and robust for 3 stations
- Iterative local chi2 alignment inside each tracker station
  - Using good tracks (e.g. pz>300GeV, nClusters>14, chi2 <200, r<95mm)
- Validated with MC simulation
- Only consider 2 of 6 degree of freedoms, Y translation and Z rotation
  - Silicon strip detector, precision on Y is much better than X
  - Track parameters and residuals are improved significantly
- Global alignment algorithm has been tested in these days, including the IFT
Future prospects

- Track matching between trackers and the emulsion detector
  - Enable charge identification or $\nu_\mu / \bar{\nu}_\mu$ classification, and potentially $\nu_\tau / \bar{\nu}_\tau$
  - Alignment is the crucial part due to the difference of a spatial resolution

FASER MC simulation
Event display of neutrino interaction

$\nu_\tau$ event ($\tau \rightarrow \mu$ decay)
Conclusion

- **FASER** is the new experiment at the LHC from Run3
- Data-taking is super smooth, recorded ~98% of delivered data.
- FASER tracker is consists of **4 Silicon strip trackers**
  - Keeping the consistency of the tracker performance for 2-year operation
  - More than >99.7% strips are available
  - ATLAS SCT is working very well even about >15 years after the construction (~2005-2006)
- The first alignment with collision data is done with simple and robust ways
  - To be improved with a global alignment algorithm such as millepede II
  - Try to match tracks between the IFT and emulsion for $\nu_\mu/\bar{\nu}_\mu$ classification

- **Recent publications**
  - Search for Dark Photons with the FASER Detector at the LHC
    - arXiv: 2308.05587
  - First Direct Observation of Collider Neutrinos with FASER at the LHC
    - Physical Review Letters and arXiv: 2303.14185
  - The tracking detector of the FASER experiment
    - NIMA 166825 (2022) and arXiv: 2112.01116
Back Up
FASER SCT Tracker

Decided not to use the ATLAS SCT readout to simplify the system.

Custom made flex cable used to connect pigtail on SCT module to custom PCB patch panel which separates out power (HV, LV), readout, monitoring lines.

Patch-panel

Flex cable
The Barrel Module

- 2112 Identical Barrel Modules required for SCT mounted on 4 Barrels (B3, B4, B5, B6)

- 4 single-sided p-in-n ac-coupled silicon microstrip sensors, 80 µm pitch, mounted back-to-back, 40 mrad stereo rotation angle

- 12 128-channel ABCD3TA binary readout ASICs

- Thermo-mechanical baseboard - encapsulated thermalised pyrolitic graphite with fused BeO facings

- Bridged wrap-around hybrid - copper-polyimide flex glued on carbon-carbon substrate
SCT modules used had passed ATLAS QA in ~2005 and then been kept in storage. Important to test their functionality.
SCT module QA at CERN in March 2019. Identified > 80 good spare modules – more than enough for FASER needs.
Performance seems not to be degraded by long term storage/age.
FASER SCT Tracker: Mechanics

CNC machining of layer frame gives position of each SCT module at better than 10um. Metrology of frame – measures fiducial marks on SCT modules with a few um accuracy. Fully automated procedure – measures all marks on one side in 15mins. Will form the basis of the per plane alignment.

Precision of the 3 layers in a station defined by precision pin in frame (10um accuracy).
FASER SCT Tracker Cooling

- Due to the low radiation in TI12 the silicon can be operated at room temperature, but the detector needs to be cooled to remove heat from the on-detector ASICs
  - ~5W per module => 40W/plane => 360W in full detector
- Tracking layer designed to give sufficient thermal and mechanical properties, whilst minimizing material in tracking volume
- Use simple water chiller with inlet temperature 10-15 degrees
  - Tracking stations flushed with dry air to avoid condensation
  - Hardware interlock to turn off tracker if cooling / humidity control fails

SMC chiller

Tracking layer frame, CNC machined from single Al block. Frame contains 5mm cooling pipe running around the outside. Thermal performance validated by FEA simulations and measurements (NTC on each SCT module, and 2 on frame)
FASER SCT Tracker Cooling

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Tracker Cooling system

Two air-cooled water chillers used, whose coolant temperature at \(15\, ^\circ\text{C}\):

- one is running to cool the detector and the other acts as a hot spare
- If both chillers are not operating correctly, the power supply system is forced to be turned off by the hardware interlock system
- Module temperature is kept well below \(30\, ^\circ\text{C}\)

<table>
<thead>
<tr>
<th>Sensor</th>
<th>DCS warning</th>
<th>DCS automatic actions</th>
<th>Hardware interlock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module temperature</td>
<td>&gt;30°C</td>
<td>&gt;31°C</td>
<td>-</td>
</tr>
<tr>
<td>Plane humidity</td>
<td>&gt;10%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Frame temperature</td>
<td>&gt;23.0°C</td>
<td>-</td>
<td>&lt;5°C or &gt;25°C</td>
</tr>
</tbody>
</table>

Glass-transition temperature of the glue: 35°C
Tracker Plane Metrology and Survey

Each plane/station is measured with a mechanical touch-probe and an optical camera

- All frames satisfied the required tolerances ($\pm 20 \mu m$) with respect to the CAD manufacturing drawings
- The maximum deviation was $100 \mu m$ in positioning the SCT module

Before and after installation TI12, 3D laser scanning was performed by the CERN survey group

- measured the position of the survey points on the tracker station with $O(16 \mu m)$ accuracy.