FIRST DATA FROM THE ATLAS INNER DETECTOR FSI ALIGNMENT SYSTEM*

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Abstract

As installation of the Large Hadron Collider nears completion in 2008, the focus shifts to commissioning and alignment of the particle detectors. The ATLAS inner detector is equipped with an optical alignment system that monitors micron level motion of the tracker structure in real-time. We present first data from the new Frequency Scanning Interferometry system which has been installed at CERN during 2007. Hundreds of simultaneous, remote distance measurements are combined to reconstruct changes in the tracker shape. We present a novel design, multiple fibre-coupled, Super-Invar reference interferometer and extended analysis techniques. These deliver shortened measurement times and improved system precision.

INTRODUCTION

During the past two years the Inner Detector has been installed at the heart of the ATLAS experiment [1], as in Figure 1, in readiness for first collisions at the LHC at CERN later in 2008. As part of the detector commissioning, it is critical to determine the silicon strip positions within the Inner Detector to $< 10\ \mu$m, in order not to degrade the tracking performance [1]. Since conventional surveys are impossible inside an operational particle tracker, an automated, remotely measured optical alignment system has been developed to monitor real-time shape deformations that are inaccessible with tracks. This system consists of a geodetic grid of 842 fibre-coupled interferometers, formed between nodes attached to the support structure, as shown in part in Figure 2. The grid line lengths are measured simultaneously using Frequency Scanning Interferometry (FSI) to a precision of $< 1\ \mu$m. [2, 3, 4, 5]

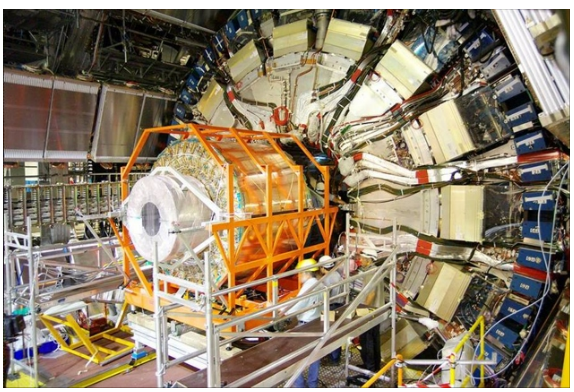

Figure 1: The Inner Detector (Barrel SCT+TRT) during insertion into the heart of the ATLAS experiment.

Figure 2: The FSI grid nodes installed within a support cylinder of the SemiConductor Tracker. Each grid line is an interferometric length measurement precise to $< 1\ \mu$m.

Further to previous IWAA reports [6, 7, 8, 9], this paper focuses on recent developments following the installation of the FSI alignment system at CERN during 2007. After a brief review of the FSI principle, special emphasis is given to the novel design of the evacuated Reference Interferometry System, on which the precise measurements are based. Several improvements to the FSI technique are presented, together with a preliminary analysis of the first commissioning data from the new system. An update is also provided on the light distribution and read-out system necessary for the many hundreds of simultaneous precise, distance measurements.

FREQUENCY SCANNING INTERFEROMETRY

FSI is a technique for remote, multiple, simultaneous and precise distance measurements. A narrow line-width tunable laser simultaneously illuminates multiple interferometers to be measured and a reference interferometer. As the optical frequency is scanned, a phase shift is induced in all interferometers, at a rate that is proportional to the length of each interferometer. The phase shifts in the interferometers are compared to determine the ratio of interferometer lengths.

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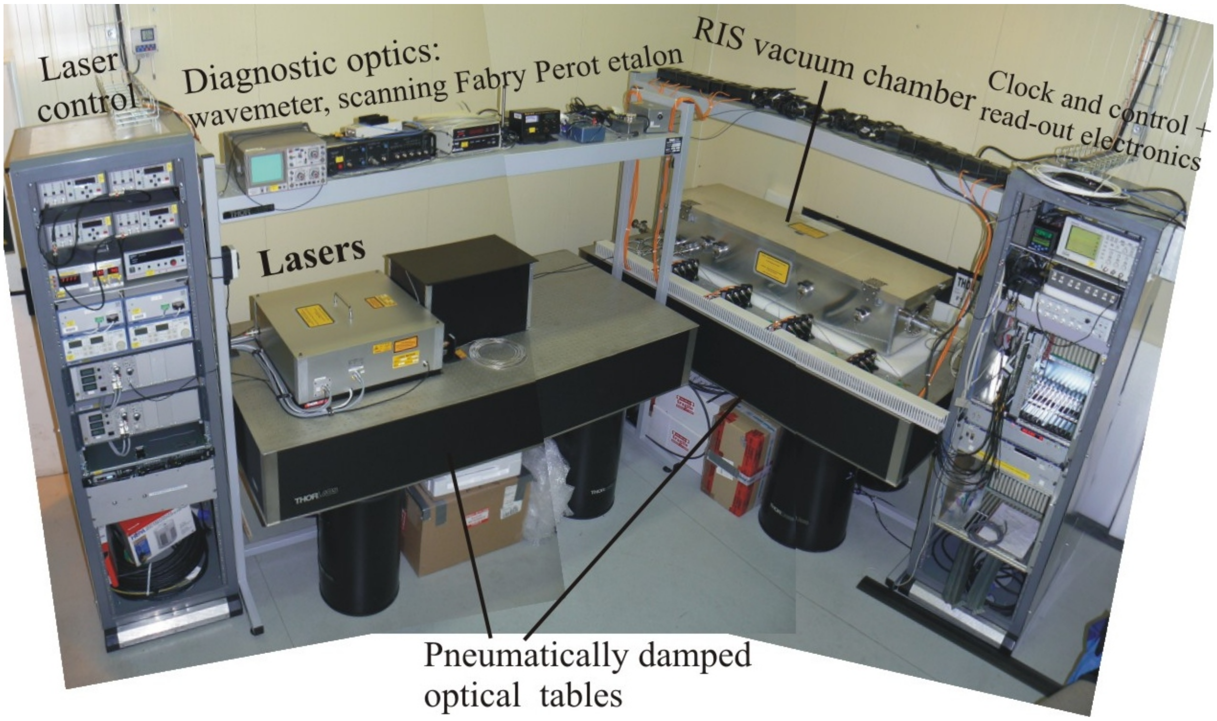

Figure 3: The FSI laser room at CERN houses the amplified two-colour laser, diagnostic optics and the evacuated reference interferometer system, with associated control and read-out electronics.

In the ATLAS FSI system, the Reference Interferometer (RI), is located away from the particle detector in a thermally stabilised room and inside an evacuated chamber. The lengths of the 842 grid line interferometers (GLIs) inside ATLAS are measured with respect to RI, which acts as a reference length. The optical path length in each GLI can be computed by comparing its phase shift to that in the RI. The stability of the reference length is critical to the long term repeatability of the FSI measurements.

In practice, any drift in the optical path difference of an interferometer, induces a large error on the phase ratio estimate, for small frequency scans. The error can be greatly reduced by tuning the frequency of two lasers in opposite directions, so that the drift errors cancel to first order. The precision can be further improved by extending the interval of the frequency by linking the phase of several fine tuning subscans, interspersed by periods of rapid coarse tuning. The phase shift between subscans is determined using a pair of Vernier Etlaons. An auxiliary short reference interferometer is used to verify the linking procedure. The details of obtaining precise length measurements using the FSI technique can be found elsewhere [2, 5].

THE INSTALLED FSI SYSTEM

Overview

The FSI grids within the ATLAS SCT are illuminated from a common laser source housed in remote surface room, shown in Figure 3. The laser source is an amplified two-colour laser system [9], providing up to 600 mW of tunable, high spectral characteristic light, which is distributed via a fibre-splitter-tree to power the on-detector grid. A small fraction of the optical power is diverted into the diagnostic optics and Reference Interferometry System (RIS), which precisely monitor the frequency tuning of the laser during a scan. The RIS and lasers are mounted on pneumatically damped optical tables to isolate from extraneous vibration. The room is air conditioned to thermally stabilize the reference interferometer and to provide humidity control to prevent condensation on the laser diodes, which are cooled by peltier elements (TECs) to a few degrees below the ambient room temperature. The laser control and RIS read-out electronics are synchronised via a 250 m optical link to the multi-channel read-out system which is in the underground counting room adjacent to the ATLAS detector. The multiplexed read-out system uses APDs to register pW return signals from the 842 on-detector grid line interferometers.

Evacuated Reference Interferometry System

The Reference Interferometry System (RIS) consists of a thermally insulated, evacuated chamber containing two fibre-coupled Michelson inteferometers and a pair of vernier etalons. The RIS provides the essential frequency measurement of the tunable lasers and the reference length against which all SCT grid line interferometers are compared. The stability of the optical path length is paramount to the repeatability and precision of the FSI measurements, and is designed to remain stable to $10^{-7}K^{-1}$ over several years.

Figure 4: An evacuated chamber contains the Reference Interferometry System, which is read-out by fibre-ribbons routed through custom vacuum feedthroughs to an external array of photodiodes.

The evacuated chamber is shown in Figure 4 and was pumped down in situ to an order of magnitude below the 1 mbar vacuum pressure required. The purpose of the low vacuum is threefold:

- To reduce the systematic errors caused by refractive index differences between the gas in the RIS and the dry N_2 environment of the ATLAS SCT.
- To eliminate systematic drift errors caused by refractive index changes within the RIS during an FSI scan. Evacuation of the gas removes this source of error.
- To thermally isolate the RIS from external temperature variations. The vacuum decouples the RIS from heat exchange by conduction and convection currents with the surrounding environment.

Any thermal expansion which changes the interferometer physical path difference during a scan can create systematic drift errors. Changes in length of the RI on longer timescales can affect the overall scale and repeatibility of the measurements, which could lead to errors in the FSI grid reconstruction. The RIS was therefore designed to combat these effects using a combination of methods as follows.

Both RIs are designed to be extremely thermally stable. As in Figure 5, the RIS is built onto a frame of 6 Super-Invar rods, salvaged from a pair of old Coherent Innovar 90 lasers. Those particular Super-Invar rods were chosen for their documented, ultra low coefficient of thermal expansion (CTE) of 350 ppb K^{-1}. A thermal compensation scheme was developed to use short lengths of materials with larger CTEs to counter the expansion of the long rods. The scheme aims to minimise thermally induced changes in the physical path difference between the two interferometer arms. This requires matching the ratio of lengths of the interferometer arms to the inverse ratio of average CTE of each arm: $C_1/C_2 = L_2/L_1$. A change in temperature, ΔT should then produce the same physical change in length of each interferometer arm, so that the physical path difference between the two arms remains constant, $\Delta T(C_1L_1 - C_2L_2) = 0$. If this requirement is met, the measured optical path difference is to first order, independent of temperature changes, for a system in vacuum.

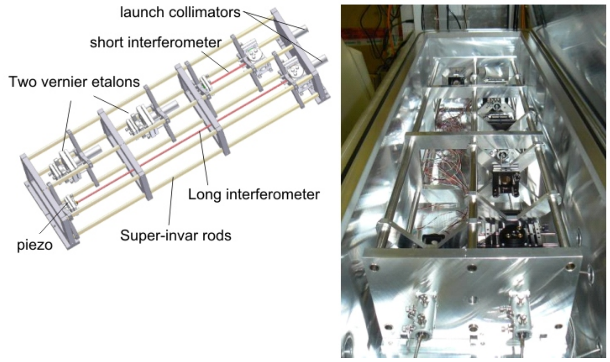

Figure 5: The Reference Interferometry System is built on a Super-Invar frame with a CTE compensation scheme to reduce thermal expansion.

Wherever possible in the layout, care was taken to localise the compensation scheme to reduce unbalanced expansion errors caused by temperature gradients between interferometer components. Achieving this requirement was aided by the Michelson layout, for which the expansion of the short arm counters the expansion of the long arm. The layout also minimises the total amount of higher CTE material required for CTE ratio:length ratio balancing.

Furthermore, the frame is supported on a kinematic mount that uses a knife-edge and ball bearings to reduce stiction and therefore decouples the frame from thermal expansion of the evacuated chamber. The contact points are also minimal and use thermally insulating plastics to slow down heat exchange by conduction.

The RIS is illuminated via a single mode fibres to provide circular, low M^2 beams, which do not suffer from the higher order modes that could be present with a free space beam input. Both RIs have 6 fibres for read-out, 4 of which are used in the new phase extraction method described below. The long RI also has a piezo mounted mirror for phase stepping, if required. The RIS is instrumented with precise PT100 platinum resistance thermometers.

Vernier Etalons

The RIS contains a pair of vernier Fabry-Pérot etalons to determine the frequency interval between subscans. An etalon produces a comb of peaks as the frequency is scanned. The two etalons have carefully chosen Free Spectral Ranges that produce a beating pattern over a large frequency range. The FSR choice is limited by the phase resolution of the reference interferometer and peak fitting errors. In previous studies, the phase resolution was estimated to be well below 50 MHz [4]. Therefore a pair of etlaons with FSR_1 = 10.00 GHz and FSR_2 = 10.05 GHz

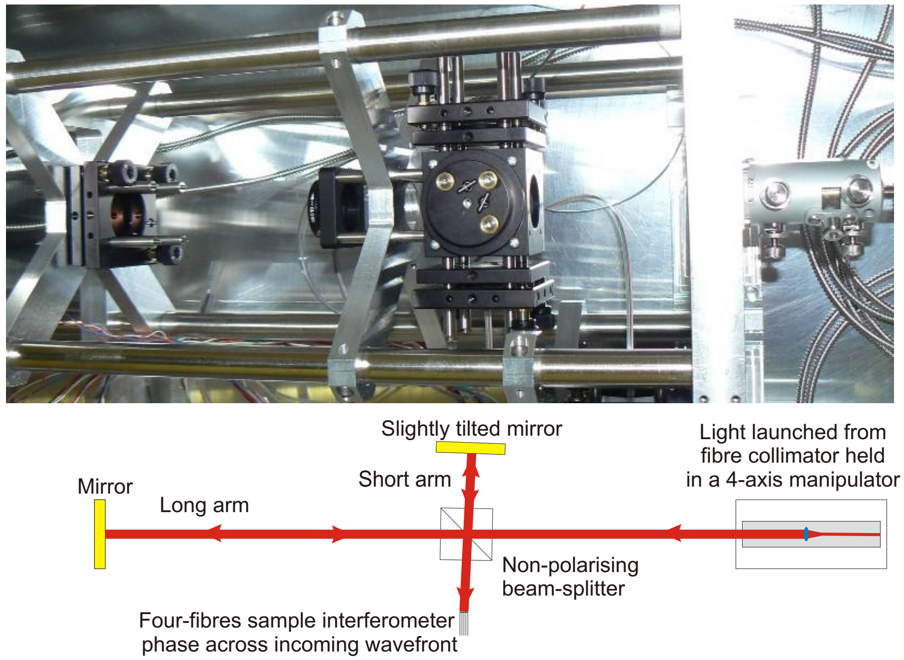

Figure 6: The reference interferometers use four parallel fibres to directly monitor the interferometer phase.

was chosen to provide a beating pattern that can be resolved unambiguously over a cycle of 2010 GHz (Repeat cycle = N_2 FSR_1 = N_1 FSR_2). This choice is a trade off between maximising the beat cycle interval and minimising the necessary frequency interval that must be sampled to obtain a peak from each Etlaon (in this case, 10.05 GHz). The beat cycle of 2010 GHz is smaller than the $\approx$ 10 THz coarse tuning range of the lasers, but is sufficient to be easily resolved using a wavemeter. The FSR is small enough to permit corrections within a subscan in the event of a laser mode hop during fine tuning.

IMPROVEMENTS TO THE TECHNIQUE

Reference Phase Measurement

A Frequency Scanning Interferometry measurement relies on precise information about the change in frequency of the laser during a scan. In practice it is not necessary to measure the absolute frequency. Rather is it sufficient to measure the change in phase of the fringes generated in a Reference Interferometer (RI), as the frequency is scanned. If the interferometer length, L, is fixed, then the phase change, $\Delta\Phi$, is related to the frequency change, $\Delta\nu$, by: $\Delta\Phi = (2\pi/c)L\Delta\nu$. A direct measure of the reference phase enables corrections of the non-linearities in frequency tuning of the laser with time.

Four-fibre Phase Extraction

In the prototype ATLAS FSI system, the reference interferometer phase was measured by stepping the position of a mirror mounted on a piezo-actuator. Four intensity measurements at equi-spaced mirror positions (ideally 108° apart in phase) were required for one phase measurement. The local phase value was extracted by a modified Carré algorithm and a series of measurements of the local phase were unwrapped to obtain a tuning curve for the lasers. [4, 5]

The phase stepping works reliably, but is limited by the maximum driving frequency of the piezo and four acquisition cycles are required for each phase measurement. These limitations are overcome by use of a four-fibre read out system, which permit a direct measurement of the phase in one data acquisition cycle. The optical layout is shown in Figure 6, which uses four equi-spaced parallel fibres to sample the wavefront across the interferometer beam. By slightly

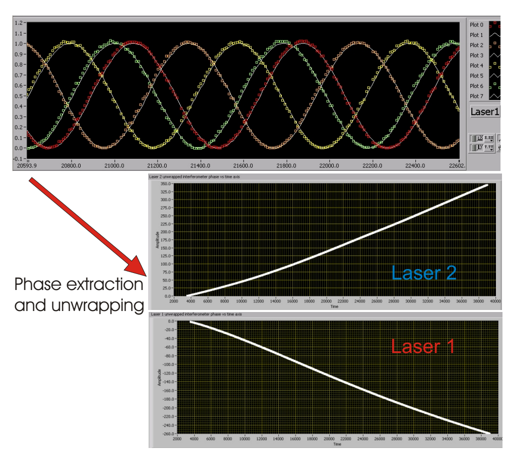

Figure 7: The simultaneous intensity signals from four parallel fibres are used to extract the interferometer phase.

tilting the mirror, the phase difference across the four fibres can be adjusted to closely match the 108° required for optimal phase extraction by the modified Carré algorithm. An example of the normalised sinusoidal interferometer fringes sampled by four fibres is shown in Figure 7. These signals were used to extract the phase for two lasers, which were tuning in opposite directions in frequency. The key advantage of the method is that faster scans are possible, which reduces interferometer drift errors and therefore improves the measurement precision.

Dual Interferometer Phase Extraction

A new feature of the installed RIS is that both interferometers have four fibre read-out for direct phase extraction, which was not the case in the prototype FSI system. First commissioning data from the RIS are shown in Figure 8. In this test a single laser simultaneously illuminated both interferometers as the frequency was scanned over $\approx$ 190 GHz. After fringe normalisation, the four-fibre technique is used to extract the phase. The residuals from the best line fit show that both RIs successfully extract the same non-linear frequency tuning curve of the laser.

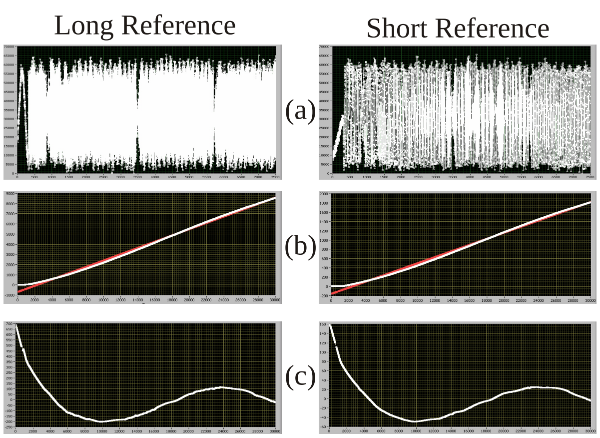

Figure 8: Simultaneous phase extraction from two reference interferometers as a common laser source is frequency scanned. The plots show for each interferometer: (a) the interference pattern recorded by one read-out fibre vs time, (b) the phase extracted from the four fibre measurements vs time, and (c) the residuals from a straight line fit to (b). Importantly the non-linear frequency tuning curve is extracted identically in both interferometers.

Preliminary Result with Commissioning Data

Dual interferometer phase extraction allows the length ratio of the short and long reference interferometers to be determined directly. The phase change in the short RI, $\Delta\Theta = (2\pi/c)D\Delta\nu$, and the long RI, $\Delta\Phi = (2\pi/c)L\Delta\nu$, are compared to give the phase ratio, $\frac{\Delta\Theta}{\Delta\Phi} = \frac{D}{L}$. Thus the gradient, $\frac{D}{L}$ in a plot of Figure 9 is the length ratio of the RIs. The length ratio was calculated repeatedly

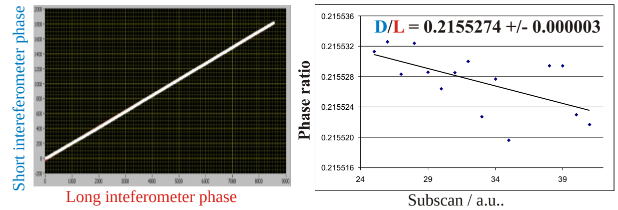

Figure 9: The measured length ratio is determined directly from the gradiant of the phase changes extracted from two reference interferometers.

for 15 partial subscans to given a preliminary result of, $D/L = 0.2155274 \pm 0.000003$. This is equivalent to a 3 μm measurement precision on the SI length, which is reasonable for a single laser. The resolution is currently limited by several mode hops in the laser data, which restrict the useful frequency interval to only 34 GHz of the 190 GHz subscan. This is thought to be due to a misalignment of the internal laser cavity, after recent shipping. When the laser is realigned and commissioned, the available 190 GHz will improve on this result. Ultimately a reference measurement precision of order a few nanometers is expected by using two laser drift correction technique with multiple subscan linking over a 10 THz coarse tuning range, as demonstrated previously [5].

LIGHT DISTRIBUTION AND READ OUT

Fibre Splitter Tree Installation

The fibre coupled light from the lasers must be split between the 842 delivery fibres of the on-detector grid line interferometers (GLIs). A fibre-splitter-tree based on biconic, fused taper couplers was originally envisaged [9]. However a more compact and cost effective solution was identified in the form of Planar Lightwave Cicuits that were mode matched to the required 830nm SM fibre. This technology permits high multiplicity coupling ratios of 1x8, 1x16 or even 1x32 to be created using ion-exchange in glass, in devices of a similar size to a 1x2 bi-conic coupler and with better overall insertion losses. The devices were assembled in to 15 splitter tree modules, one of which is shown in Figure 10. Each 1U module distributes light to upto 64 GLIs via a matrix of interwoven fibres and also conveys the pW return signals to read-out system. The fibre matrix is necessary to deal with the many constraints imposed by optical multiplexing, connectivity and the grid topology.

Read-out System Commissioning

The 15 splitter tree modules are assigned to 15 FSI readout cards (FROC). The FROCs use 32 Avalanche Photodiodes to register pW signals from upto 64 multiplexed, optically switched interferometers, as detailed elsewhere [9]. Commissioning tests have shown that after installation, the pedestal data transfer rate is acceptable, as in Figure 11.

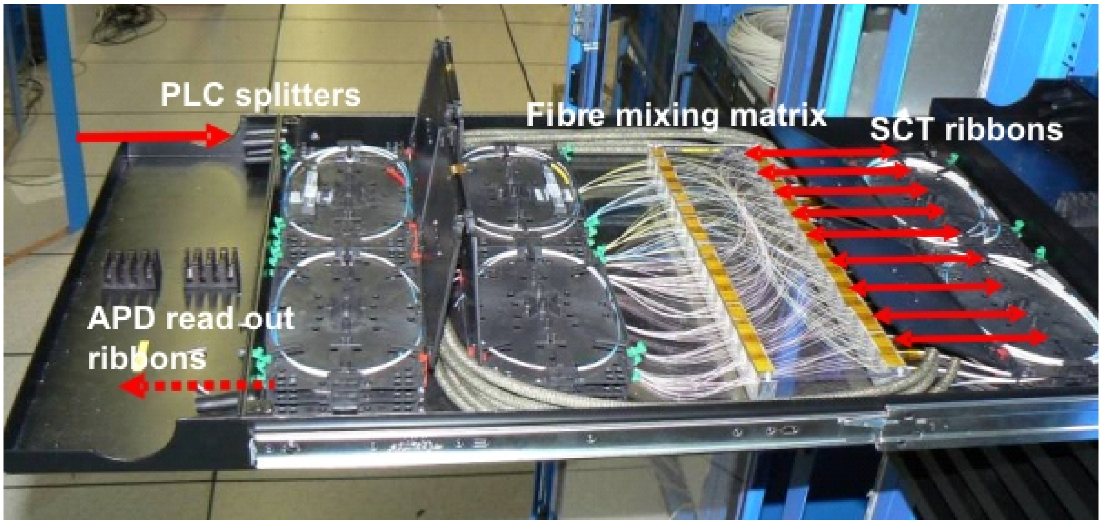

Figure 10: One of 15 fibre-splitter-tree modules that convey light from the laser to the 842 SCT fibre-coupled grid line interferometers and route the signals to the read-out cards.

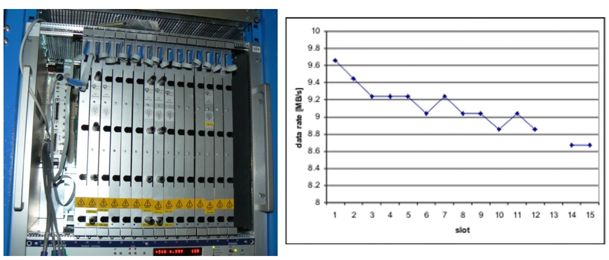

Figure 11: The 15 FSI Read Out Cards (FROCs) and the measured transfer rate of commissioning data.

CONCLUSION

The ATLAS Inner Detector FSI alignment system is in place at CERN and the commissioning phase has started. Several improvements have been made to the installed system that were not present in the prototype. A four-fibre phase extraction technique has been developed to improve the precision and the thermally stable Super-Invar dual reference interferometers provide simultaneous phase extraction. First data from the installed reference interferometry system indicate improved performance is possible using these new analysis techniques and extended frequency tuning capabilities of the new lasers. The multi-channel read-out system and fibre-splitter-tree are now being commissioned. We look forward to first measurements of the ATLAS FSI geodetic grid in the coming months, which will reveal the alignment stability of particle tracker.

ACKNOWLEDGEMENTS

We are grateful for the invaluable, excellent support of technical staff from Oxford Physics Central Electronics and Mechanical Groups.

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