Challenges and Developments for the Alignment of the Future Circular Collider at CERN

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1 Introduction

The European Organisation for Particle Physics (CERN) is the leading institute for particle physics based in Geneva, Switzerland and hosts a full particle accelerators complex. The Future Circular Collider (FCC) at CERN is the next generation particle accelerator advancing our understanding of the universe. High-precision alignment of thousands of components along the 90.7 km long tunnel is critical for the success of the project. Ensuring the accurate positioning of the accelerator components is crucial for achieving the desired beam quality and physics performance of the collider. This unprecedented scale introduces new challenges for the Geodetic Metrology Group, as existing alignment techniques used in accelerators like the Large Hadron Collider (LHC) are insufficient to meet the even stricter tolerances and scalability demands. This paper reviews key steps, current practices and developments in large-scale accelerator alignment.

The footprint of the FCC is visible in figure 1 and straddles the Franco-Swiss border and covers an area of 1000 km^2. The access to the tunnel is planned from eight access points, which leads to tunnel segments of 11 km between access shafts. The depth of the access shafts varies between 180 m and 400 m. For the tunnel construction the simultaneous use of eight TBM's is expected, which should start in both directions from the four large access points that will house the experiments. The tunnel boring will be executed mainly in molasse, but areas of limestone cannot be avoided. Investigations to identify critical areas and geological faults are on-going (REW et al. 2025). The FCC is scheduled as a two-step project sharing the common civil engineering and technical infrastructure. An electron-positron collider called FCC-ee, a precision machine and Higgs factory, will be followed by an FCC-hh machine to explore for new physics with a start of operation in the 2070s. The FCC feasibility study (BENEDIKT et al. 2025) has been published recently. The pre-Technical Design Report (pre-TDR) phase of the FCC-ee runs up to the end of 2027 and should precede the approval of the project by the CERN council. After the following Technical Design Report phase, the construction is planned for 2033 and accelerator operation beginning in the 2040s. This contribution summarizes the innovative approaches under investigation during the pre-Technical Design Report (pre-TDR) phase, aiming to establish robust and scalable solutions for the FCC's precise alignment.

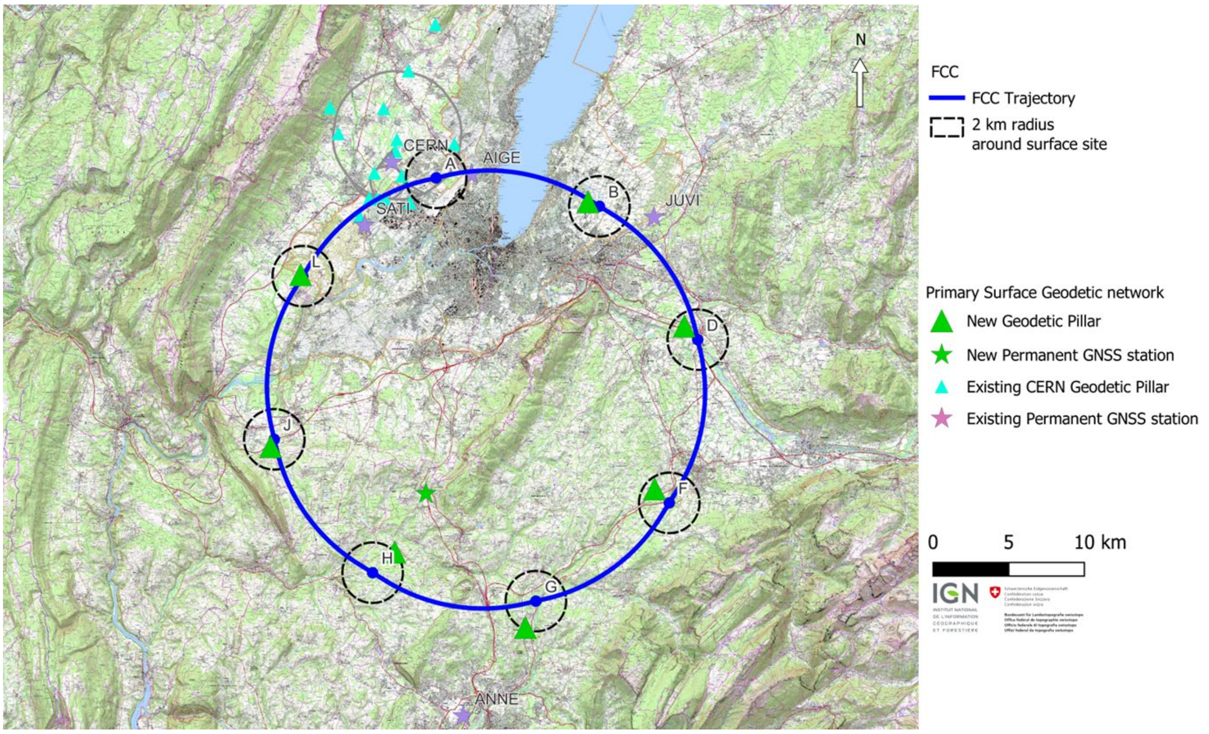

Fig. 1: Layout of the FCC in the Franco-Swiss border region and geodetic network.

2 Challenges for Alignment

The challenges of the FCC for the alignment are partly linked to the pure dimension and the associated logistics of the installation as to the number of components that have to be aligned. To the existing ~ 60 km of beam lines at CERN further 90 km beam line of the FCC-ee, additional 90 km for the booster in the same tunnel, transfer lines and a new injector complex will be added. The manual operation of surveying and alignment tasks reaches its limits, and the key for the successful installation and operation of the facility should be the automation of most tasks, which includes the surveying measurements. The distance in between shafts increases from 3.8 km for the LHC to 11 km for the FCC and the accelerator plane is inclined by 0.5°. In addition, beam physicists have significantly stricter accuracy requirements for the installation compared to previous projects at CERN. The alignment tolerances for the FCC-ee based on physics simulations are shown in table 1 for the critical elements.

The alignment tolerances as specified in Tab. 1 correspond to the applied misalignments used in physics simulations based on a gaussian distribution truncated at 2.5 σ and the values evolve with the project progress. They include all steps from the design, production, assembly, calibration, fiducialisation, alignment and operation. The tolerances should be considered as 1σ with respect to components in a sliding window of 100-200 m. For the alignment of the Interaction Region (IR) and the Final Focussing (FF) doublet section, specific permanent monitoring and alignment systems need to be developed.

Table 1: Alignment tolerances for FCC-ee at 1σ as used for physics simulations.

Element type	**Δx (hor.) µm, Δy (ver.) µm**	**Δz (long.) µm**	**Roll angle µrad**
Girders	150	500	150
Arc magnets on the same girder	50	100	50
IR section without sextupoles	50	50	100
IR section with sextupoles	30	100	30
FF-doublets section	10	100	10
All dipoles	1000	500	1000

3 Developments

3.1 Geodetic Infrastructure

For each new generation of particle accelerators at CERN, it has been necessary to modify and extend the geodetic infrastructure and to adapt it to the project needs with improving demand for accuracy. Currently, the CERN Coordinate System (CCS) is the reference system at CERN, associated with the CERN Geodetic Reference Frame (CGRF) and a local gravity field model. The CCS originates from the Proton Synchrotron in the 1950s and has evolved with CERN's major extensions and successive projects. It is a 3D cartesian local astronomic coordinate system, limited to the current CERN area and is adapted for local survey and alignment of the machines within CERN, but not for mapping and large civil engineering works. The geodetic reference network covers only the current CERN area.

For the FCC, the geodetic infrastructure must be extended and adapted to align with the current best geodetic practices, and serves the different phases of the project

- Connecting the CERN facilities to local, national and international facilities,
- Civil engineering works that include tunnel boring,
- Installation and maintenance of the infrastructure above and below ground,
- Installation and alignment of the accelerator components,
- Maintenance and upgrade of the alignment.

The major task is to define new coordinate reference systems, to establish the necessary geodetic reference frames and to determine a high-precision gravity field model for the FCC area. These works are conducted in the collaboration with expert institutes as Swisstopo, ETH Zürich, IGN and HEIG-VD.

A new static CERN Terrestrial Reference Frame (CTRF) is defined. The CTRF will be connected to existing local, regional, and global reference frames by geodetic transformations. Additionally, a CERN Projected Reference Frame (CPF) and a gravity-based CERN Vertical Frame (CVF) will be employed, mainly for planning and carrying out construction works. Figure 2 outlines the link between the coordinate reference systems for the FCC.

A densification of the French and Swiss static reference networks was conducted recently in the vicinity of the planned FCC surface sites to create a Primary Surface Geodetic Network (P-SGN). The criteria for the site selection have been the optimal GNSS environment, the durability and operational parameters. The pillars have a forced centring system that is adapted for different instrument types. The coordinates of the markers will be calculated in the ETRF using simultaneous GNSS observations. The first measurement campaign is planned in 2026. One of the pillars is equipped with a continuously operating reference station, supplementing the Réseau Géodésique Permanent operated by the IGN. The P-SGN will serve different purposes as i.e. the civil engineering and surveying works required for the construction of the FCC tunnel, provide a long-wavelength basis for the alignment works of the accelerator and provide the reference for the geo-kinematic monitoring of the FCC area.

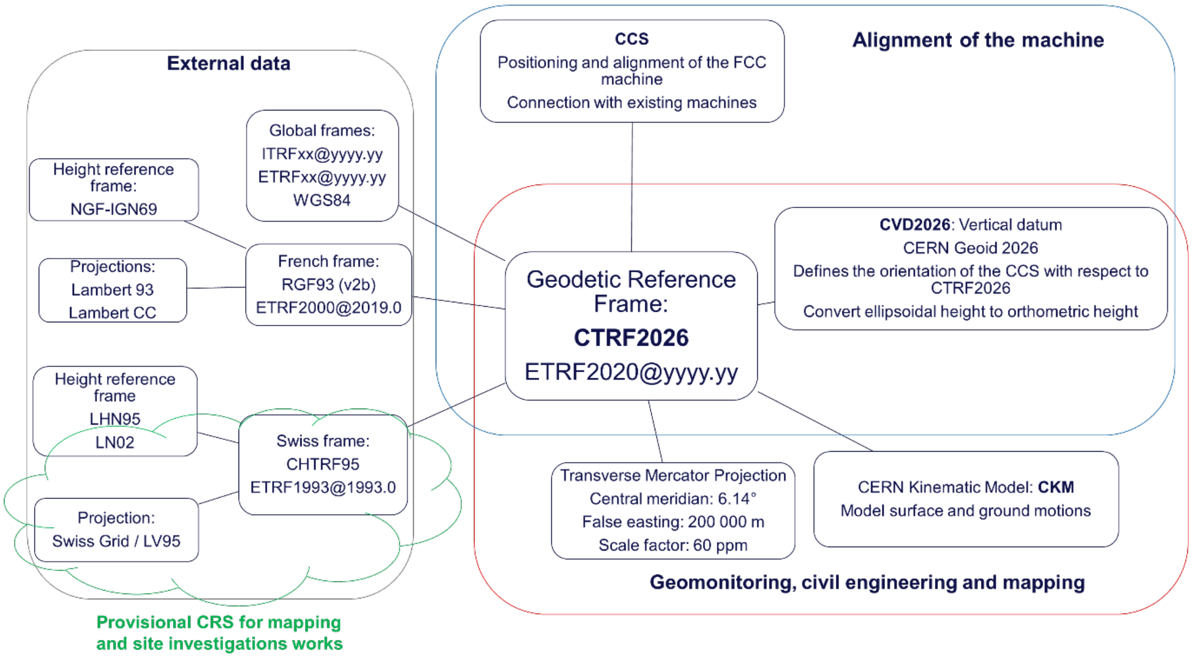

Fig. 2: Graphical outline of the coordinate reference systems for the FCC.

To align accelerator components in a Euclidean plane, all survey observations need to be corrected to consider variation of the direction of the plumbline – deflection of the vertical. Precise knowledge of the deflection of the vertical is also mandatory for the reduction of gyroscopic observations to guide and control the orientation of the TBM. In this context a comparison of existing geoid models for the FCC region has shown a standard deviation in the order of 5 cm (KOCH et al. 2023). It is above the accuracy demanded for the precise alignment of the FCC components. A geodetic control profile over 40 km has been created with measurements using GNSS and levelling, relative gravity observation and measurements of the deflection of the vertical (KOCH et al. 2022). It is used as a validation dataset for all gravity related studies of the FCC project.

An initial local gravimetric geoid model was computed using the GROOPS software toolkit (MAYER-GÜRR et al. 2021) aiming to reach a centimetric accuracy over the FCC area. It raised challenges linked to the gravity data coverage or the impact of the choice of the digital terrain model (Koch et al. 2025). The model will be refined in collaboration with SwissTopo and the same methodology will be applied for the computation of quasi-geoid required by the new Swiss height system. To overcome the challenges, a densification of observation data and the development of a gravity simulation tool are foreseen.

3.2 Software and Simulations

At CERN, the LGC software (Logiciel Général de Compensation) is a geodetic least-square adjustment software package developed at CERN to compute position estimates and related statistics from surveying observation. LGC has evolved since the mid-1980s and it is used intensively for the 3D analysis of acquired data for the alignment at CERN. In late 2025, the first open-source version of LGC has been released (KAUTZMANN et al. 2024).

The software supports over 20 different observation types and allows the definition of local coordinate systems associated with structural assemblies, such as magnets or girders, to realistically model points that are geometrically linked to the same object. These local coordinate systems are organised in a hierarchical tree, in which individual systems are related by Helmert transformations that may either be estimated as part of the adjustment or assumed to be fixed, thereby ensuring a consistent connection between local measurement frames and the global reference system. The supported observation models include horizontal and vertical angles, distances, levelling information, various types of offset measurements, as well as inclinometer, HLS, and WPS sensor observations. In addition, the software can consider local geoid information, allowing the correct handling of verticalized instruments and height-related observations adapted to local site conditions.

For the FCC, the evaluation and comparison of different alignment strategies is a central aspect of the overall alignment concept. These studies are performed using the LGC software, which provides the necessary simulation capabilities to assess achievable precision, reliability, and robustness through error propagation studies. Compared to previous use cases, the size of the resulting parameter estimation problems increases by several orders of magnitude, potentially involving more than one million variables and several million observations. Significant computational improvements have already been implemented in LGC for the FCC-ee study. The software has been adapted to exploit sparse linear algebra methods, enabling the efficient treatment of large-scale least-squares problems. In addition, the evaluation of the mathematical observation models has been significantly accelerated by exploiting the sparsity of the models and the underlying matrix structure. A substantial reduction in memory requirements has been achieved through the simultaneous computation of the parameter covariance matrix columns and the diagonal of the residual covariance matrix, which is required for reliability analysis. This approach eliminates the need to store the full parameter covariance matrix, thereby making reliability computations feasible even for large-scale problems. In parallel, a dedicated interface for the evaluation of mathematical observation models and their derivatives has been introduced. This decoupling of the mathematical core from the classical least-squares formulation enables rapid prototyping of alternative estimation approaches, such as L1-norm, Huber-based objectives or iterative reweighting schemes for blunder detection. Finally, the solution of nonlinear least-squares problems has been strengthened through the introduction of a globalisation strategy based on the Levenberg–Marquardt algorithm, allowing robust convergence even in cases where the initial approximate coordinates are only poorly known. Together, these developments enable large-scale simulation studies involving several million observations and more than one million unknowns. Among the future developments are several key areas. One of them is the integration of an Optimum Experimental Design (OED) approach within LGC. The goal of this approach is to optimise the achievable parameter precision by selecting an optimised layout of reference marks and measurement configurations. This is particularly relevant given the large number of components and sensors to be fiducialised and the very stringent alignment tolerances required for the FCC. The OED functionality is expected to build upon the recently introduced interface for the evaluation of observation models and their derivatives, providing a flexible framework for design optimisation. Another development focus is the strengthening of the already existing file-less monitoring interface (GUTEKUNST et al. 2024), which is tailored to continuous monitoring and alignment applications. In this context, the emphasis is on computational efficiency in order to guarantee short estimation cycles, a key requirement for automated alignment and monitoring workflows. A further area of development concerns the extension of the estimation framework to include component deformations. This may involve the integration of novel types of observations, such as in-fibre-based length measurements using frequency-scanning interferometry (FSI) and is expected to become particularly important in highly sensitive areas, for example the Machine–Detector Interface (MDI) region.

3.3 Fiducialisation

Fiducialisation at CERN is the process of precisely determining and transferring the functional axis of a component, most commonly the magnetic axis, corresponding to the trajectory of the particle beam with respect to external reference points, known as fiducials. This process is critical, as it directly impacts the achievable alignment accuracy of accelerator components during installation and subsequent maintenance.

Taking the Future Circular Collider (FCC) girder, see figure 3 (BENEDIKT et al. 2025), multiple beam-line components are installed, fiducialised, and pre-aligned as a single assembly. These components include magnets (quadrupoles and sextupoles), beam pipes, and beam position monitors (BPMs), which are used to monitor the beam trajectory. Initially, the magnetic axes of the magnets are determined, and the functional axes are then related to external reference targets. Subsequently, each component mounted on the girder is aligned with respect to a common reference frame.

Although fiducialisation is traditionally performed using high-precision instruments such as laser trackers or coordinate measuring machines (CMMs), the FCC project requires the evaluation and validation of novel measurement systems. These include instruments with high-accuracy surface scanning capabilities and the ability to measure six degrees of freedom (6 DoF), such as next-generation laser trackers, laser radars, and structured light scanning systems. Furthermore, recent advances in Frequency Scanning Interferometry (FSI) offer opportunities to further improve measurement efficiency and accuracy during fiducialisation.

One of the primary challenges of fiducialisation is the extremely tight alignment tolerances required. Mechanical deformations arising from gravity, thermal variations, transport, and mounting stresses can introduce systematic errors if not properly modelled and compensated.

To address these challenges, the development of a virtual platform is essential to predict, optimise, and validate measurement results and alignment procedures both prior to and during physical measurements. Such a platform would incorporate unified metrology models to optimise measurement networks and strategies through the simulation of instrument configurations, fiducial layouts, lines of sight, and environmental effects. In addition, simulation environments and digital twin models leveraging advanced modelling techniques and machine learning can enhance the understanding and quantification of coupled structural - thermal effects at both the individual magnet level and the complete girder assembly. Error propagation tools are also required to identify and estimate dominant error sources associated with measurements, mechanical effects, assembly sequences, and alignment processes.

Another significant challenge for the FCC arises from the large number of components involved. It is estimated that more than 23,000 magnets will be constructed and installed across the collider and booster rings. Consequently, automation is essential for fiducialisation and alignment. Automated measurement systems must achieve the required precision while remaining efficient and scalable.

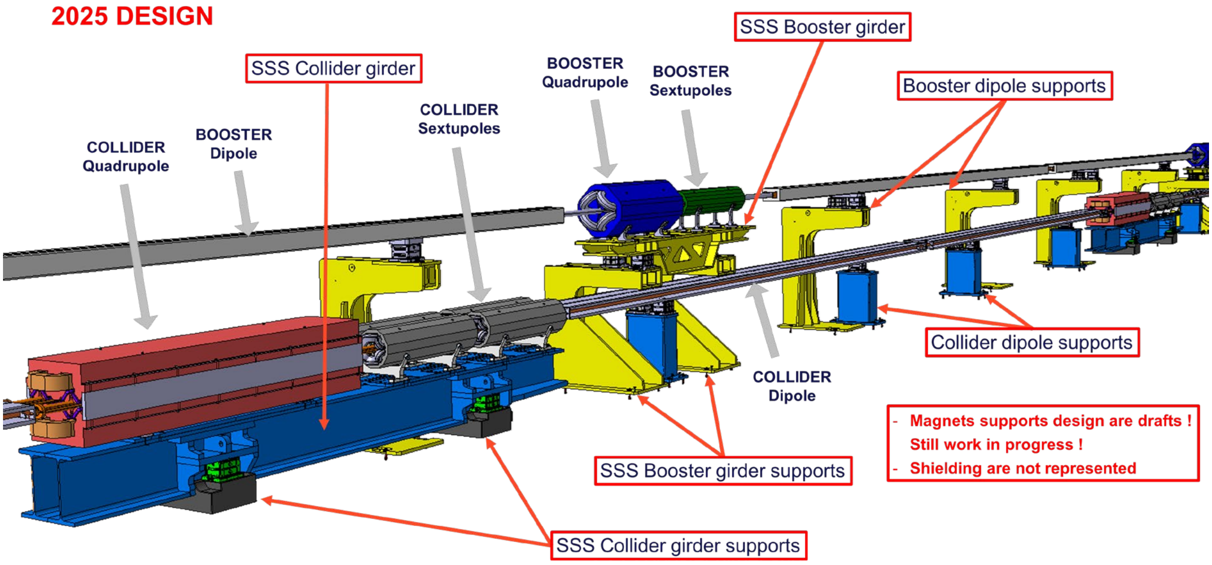

Fig. 3: Draft design of the FCC-ee beamline and girder assembly.

3.4 Machine Detector Interface Alignment Challenges and Deformation Monitoring for FCC-ee

The Machine–Detector Interface (MDI) is widely recognized as one of the most challenging areas of the FCC-ee accelerator. Its design is evolving rapidly, driven by the need to integrate an increasing number of functions within an extremely constrained and complex environment. The MDI plays a critical role in preparing and delivering the beams immediately upstream of the interaction point; its performance directly impacts on luminosity and overall machine stability.

While the fundamental role of the MDI has remained unchanged over time, its implementation within FCC-ee introduces unprecedented constraints. To achieve the required optics performance, the final focusing elements must be placed partially inside the detector volume. This configuration drastically increases the complexity of the assembly, leading to an exceptionally dense arrangement of components within a very limited spatial envelope. In addition, the MDI region is subject to strong magnetic fields, steep temperature gradients, and very high radiation doses, the precise levels of which continue to evolve as simulations and detector integration studies progress.

Among the most stringent constraints are those related to alignment. The final focusing doublets must be positioned with extremely high accuracy (see table 1), and their position, orientation, and potential deformations must be known not only during installation, but also throughout operation. The combination of limited accessibility, harsh environmental conditions, and tight tolerances renders conventional alignment and monitoring solutions unsuitable. Neither existing accelerator implementations nor commercially available sensor systems can meet the full set of requirements imposed by the FCC-ee MDI environment. This conclusion, supported by previous studies and experimental investigations (WATRELOT 2023), motivated the development of a dedicated alignment and deformation monitoring concept tailored specifically to this application.

Following a detailed analysis of the requirements and constraints, a novel monitoring strategy was proposed (WATRELOT 2023, WATRELOT et al 2023) and is currently under active development. The approach is based on Frequency Scanning Interferometry (FSI), a well-established optical measurement technique capable of providing micrometric distance measurements under controlled conditions, and, crucially, allowing for simultaneous monitoring of multiple measurement paths. Although FSI as a measurement principle has been known since the 1980s (KIKUTA 1987), its application to continuous deformation monitoring of accelerator components represents a significant innovation.

The core concept, developed and described in detail in (WATRELOT 2023, WATRELOT et al. 2023), consists of monitoring the optical fibre itself rather than discrete external targets. Semi-reflective interfaces are intentionally introduced along the fibre, for example by means of controlled imperfect splices that create localized reflective defects. Each of these interfaces acts as a partial reflector, enabling independent interferometric measurements of multiple fibre segments along a single optical path. By placing several such semi-reflective elements on one fibre, it becomes possible to monitor multiple distances simultaneously and independently, with micrometric precision (WATRELOT 2023).

To translate these distance measurements into a geometrical description of structural deformation, the fibres are arranged in helical patterns around the tube to be monitored. Changes in the measured fibre segment lengths reflect local and global deformations of the structure. A least-squares adjustment procedure is then applied, linking a deformation model of the tube to the analytical equations describing the helices. From this adjustment, the deformation parameters can be estimated efficiently, allowing reconstruction of the tube's three-dimensional shape with high accuracy.

This strategy forms the backbone of the proposed MDI alignment monitoring system. To date, the feasibility of simultaneous and independent multi-segment FSI measurements has been demonstrated experimentally. A series of progressively more complex prototypes has been developed, each validating key aspects of the concept and advancing the system toward realistic implementation conditions (WEYER et al. 2024).

Current efforts focus on the validation of the complete MDI alignment strategy using a dedicated deformation test bench. The objective of this bench is to reproduce, at half scale, the mechanical and metrological conditions of the MDI assembly, while integrating the monitoring system as close as possible to its final configuration. Controlled deformations are applied to the structure, and the reconstructed shapes obtained from the FSI system are cross-checked against reference measurements provided by conventional surveying instruments, typically a laser tracker.

The ongoing work includes the mechanical design, construction, and commissioning of the deformation bench, as well as the machining and preparation of the tube to be monitored. The latter represents a particularly demanding task, as nearly 100 m of bare optical fibre must be handled, routed, and glued without damage. The deformation bench has now been designed and built, using a Universal Alignment Platform as the deformation-inducing system. This 6 DoF platform, commonly employed for component realignment in accelerator tunnels, provides precise and accurate control of imposed displacements and rotations.

Initial tests, shown on left part of figure 3, are currently being conducted using a polymethyl methacrylate (PMMA) tube, selected for its lower stiffness compared to aluminium, allowing larger and more easily measurable deformations during early validation phases. A network of reference points placed on the tube surface is monitored independently to provide external validation data. In parallel, the aluminium tube intended for the next phase of testing has been manufactured, including precisely machined grooves designed to host the optical fibres.

Fig. 4: Assembled deformation test bench with laser tracker (left) and groove measurement (right).

These grooves are presently being inspected, as shown in figure 4 (right), to identify any systematic offsets or machining imperfections. Such deviations can be incorporated directly into the helix equations used in the deformation model, thereby preventing loss of precision in the final reconstruction. The forthcoming steps include final integration of machining imperfections into the model, preparation and qualification of the fibres, gluing of the fibres into the grooves, and full system testing. Although the remaining tasks are well defined, they are expected to be particularly demanding and time-consuming.

In parallel with this work, additional R&D activities are being pursued to extend the capabilities of the FSI system. These include long-range FSI measurements for applications around the detector, monitoring of the vertex detector shape, and tracking of detector opening and closing motions. Together, these developments contribute to a coherent metrology strategy for future collider experiments, with the FCC-ee MDI serving as a primary and particularly challenging use case.

3.5 Automated Offset Measurement

To guarantee sufficient alignment accuracy, wire offset measurements are essential at CERN, particularly for large accelerators. This method consists of measuring, using a large calliper gauge, the horizontal offsets between a magnet's fiducial and a reference wire stretched over distances up to 120 m. By repeating this operation with a 50% overlap, it is possible to determine the alignment of the machine's arcs with a high degree of precision. In addition, offset measurement is employed in monitoring systems such as the Full Remote Alignment System (FRAS) (BIEDRAWA et al. 2022). Developed for the HL-LHC, FRAS is a powerful installation comprising multiple sensors like Wire Positioning System (WPS); however, due to its system complexity and cost, it is not suitable for deployment along the entire accelerator, such as the FCC-ee.

With the upgrade of the LHC, several constraints - including increased radiation levels and the time required for measurements - have led the Geodetic Metrology Group to develop an innovative vision-based measuring prototype. This system is a promising tool, intended to partially replace the labour-intensive, manual wire offset measurements and to provide a link between FRAS and the rest of the accelerator. Mainly based on photogrammetry, this prototype called Ecartometry Measurement by Automatic Photogrammetric Survey (EMAPS) allows contactless horizontal offset measurements between a referenced stretched wire and one or multiple photogrammetric targets installed or engraved on the accelerator components. The offset measurement is performed with an automatic pipeline based on the open-source software MicMac adapted through a CERN and IGN collaboration.

The current prototype features four 24 MP Nikon D5600 cameras integrated on a rigid carbon beam measuring 800 mm × 200 mm. It also includes four Wyler Zerotronic inclinometers installed on two individual aluminium cubes. A studio flash with a green filter and a triggering microcontroller are integrated on the beam to complete the prototype. For the development phase, the system is installed on a manual trolley to facilitate handling and mobility. A ball-joint interface was positioned on the trolley and connected to the EMAPS via a steel bar. On the opposite side, a handle, and a counterweight were added to ensure balanced and ergonomic operation (see figure 5).

To measure the offset, a preliminary calibration phase is required to determine the cameras parameters and the boresight matrix between the inclinometers and the cameras (BARCET et al. 2024). After this phase, the reference wire can be manually tensioned between two anchor points. The EMAPS has the flexibility to measure WPS sensors of the FRAS with engraved photogrammetric targets or alternatively to measure in the arcs of the accelerator temporarily installed photogrammetric targets on the 3.5-inch interface of the magnet fiducials. For the prototype operation, reference targets are installed manually on the magnet’s fiducial in the arcs. For the FCC-ee, it is feasible to consider engraving the photogrammetric targets directly on the magnets during the manufacturing process, followed by a fiducialisation.

Fig. 5: Photo of the EMAPS prototype during validation measurements

The results of numerous test campaigns are very encouraging, and repeatability tests showed 15 µm standard deviation while adjusted redundant measurements in the LHC with ~500 measurements can still reach standard deviations of less than 20 µm for individual measurements. First comparisons with manual offset measurements and a FRAS test setup indicate an accuracy of ~ 40 µm. The future developments of the EMAPS concentrate on the automation and the replacement of the cameras by industrial cameras with a redesign of the mechanical fixation to improve the mechanical stability of the relative orientation.

4 Conclusion

The specified alignment tolerances for the FCC-ee are extremely challenging and several tasks are above the state of the art. A research program has been initiated in the Geodetic Metrology Group for the pre-TDR phase to address several of these challenges. The geodesy preparation is most advanced, and major challenges have to be solved using innovative solutions based on FSI for the MDI area and for the monitoring of the beam delivery system. The EMAPS paves the way for the automation of measurement tasks in the tunnel that will be a key element for the establishment of cost-efficient solutions for the installation and maintenance of the FCC-ee alignment. The approval of the FCC study by the CERN Council is expected in 2028.

Literature

BARCET, F., BESTMANN, P., & MERGELKUHL, D. (2024): Direct wire offset measurement by photogrammetry including gravity link. Proceedings of IWAA 2024, SLAC National Accelerator Laboratory, Menlo Park, CA, USA.

BENEDIKT, M., ZIMMERMANN, F., AUCHMANN, B, ET ALL (2025): Future circular collider feasibility study report: Volume 2 Accelerators, technical infrastructure and safety. In: The European Physical Journal Special Topics 234 (19).

BIEDRAWA, P., BLANCO VINUELA E., CALA FRANCO, C. et al (2022): Full remote alignment system for the High-Luminosity Large Hadron Collider HL-LHC. Proceedings IWAA 2022, CERN, Geneva, Switzerland.

GUTEKUNST, J., KAUTZMANN, G., KLUMB, F., MAINAUD DURAND, H. & SOSIN, M. (2024): Continuous position estimation for the full remote alignment system of the High Luminosity LHC upgrade. In: Proc. IPAC'24, Nashville, TN, May 2024, pp. 3337-3340.

KAUTZMANN, G., GUTEKUNST, J. KLUMB, F., & ELSON, P. (2024): LGC Open-Source: A Strategy to Share Adjustment Software and Algorithmic Development. Proceedings IWAA 2024, SLAC National Accelerator Laboratory, Menlo Park, CA, USA.

KIKUTA, H., IWATA, K. & NAGATA, R. (1987): Absolute distance measurement by wavelength shift interferometry with a laser diode: some systematic error sources. In: Applied Optics Vol.26, 1987

KOCH, J. A., MARTI, U., ROTHACHER, M., & WILLI, D. (2022). High-precision profile for geoid validation in the FCC region at CERN. In: Gravity, Geoid, and Height Systems 2022 Symposium (GGHS 2022). ETH Zurich.

KOCH, J. A., MARTI, U., HERRERA PINZÓN, I. D., WILLI, D., SOJA, B., & ROTHACHER, M. (2023). Geoid Computation for the Future Circular Collider at CERN. In: International Union of Geodesy and Geophysics General Assembly (pp. 235-243). Cham: Springer Nature Switzerland.

KOCH, J.A., SOJA, B., ROTHACHER, M. (2025). Impact of Different DEMs on High-Precision Geoid Modeling in the Region of CERN. In: International Association of Geodesy Symposia. Springer, Berlin, Heidelberg.

MAYER-GÜRR, T., BEHZADPOUR, S., EICKER, A., et al. (2021): GROOPS: A software toolkit for gravity field recovery and GNSS processing. In: Computers & geosciences, vol. 155, p. 104864.

REW, L., VOIRON, J., CUNNINGHAM, R., & OSBORNE, J. (2025). Site characterisation for a deep, 91 km long tunnel: A case study of CERN's FCC. In: Tunnelling into a Sustainable Future–Methods and Technologies (pp. 1140-1147). CRC Press.

WATRELOT, L., SOSIN, M. & DURAND, S. (2023): Frequency scanning interferometry-based deformation monitoring system for the alignment of the FCC-ee Machine Detector Interface. In: Measurement Science and technology 34(075006)

WATRELOT, L. (2023): FCC-ee Machine Detector Interface Alignment System Concepts. HESAM Université, France.

WEYER, B., WATRELOT, L. & NIEWIEM, W. (2024): Status of geodetic studies and alignment perspectives for the CERN future circular collider. Proceedings IWAA 2024, SLAC National Accelerator Laboratory, Menlo Park, CA, USA.