STATUS OF GEODETIC STUDIES AND ALIGNMENT PERSPECTIVES FOR THE CERN FUTURE CIRCULAR COLLIDER

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Abstract

The ongoing feasibility study for the Future Circular Collider (FCC-ee), which is planned to be built at CERN, raises survey and geodetic challenges. Developing an alignment strategy for the 8832 magnets within the 91.2 km circular tunnel, associated transfer lines, and up to four experiments is critical. A robust geodetic infrastructure, including the definition of coordinate reference systems and the implementation of associated reference frames, must be created together with the development of a local geoid model. Concurrently, automated methods for the fiducialisation of equipment and their precise alignment in the tunnel and experimental caverns must be devised. Furthermore, the maintenance of the alignment must be anticipated over the 20 years of foreseen operation with permanent or periodic monitoring and readjustment systems. The new methods will have to respect strict alignment tolerances for the different parts of the accelerator, such as the straight sections, interaction regions, and machine-detector interfaces. Given the size of the machine, these methods should also enable survey operations to be completed within a reasonable timeframe and with minimal human workforce.

This paper presents the current status of the study and gives perspectives for additional research and development to be carried out in the coming years to prepare the final feasibility study report and the technical design report.

INTRODUCTION

The Future Circular Collider (FCC) is a proposed next-generation particle accelerator designed to exceed the research capabilities of the current Large Hadron Collider (LHC) at CERN. It will be a circular collider with a circumference of 91.2 km, capable of pushing the energy and intensity frontiers by an order of magnitude beyond the present values. Two or four experimental sites will be installed along its circumference. From 2021 to 2026, a feasibility study is investigating the technical and financial viability of such a facility [1].

The Geodetic Metrology Group at CERN is in charge of studying the geodesy, survey, positioning and alignment aspects of the FCC. New techniques must be studied, tested, and implemented to propose a solution compatible with the characteristics of the accelerator. The developments are guided by factors such as the size and lifespan of the infrastructure, the number and design of the equipment, their accessibility, and the alignment tolerance and beam requirements. Cost and resource constraints are also considered in choosing the optimal solution.

This article presents the current status of the development of the geodetic infrastructure and describes the alignment concepts established for the FCC, focusing on the Machine Detector Interface (MDI) and simulations of error propagation over long distances.

AN ENHANCED GEODETIC INFRASTRUCTURE

Each major extension of the CERN complex, like the construction of the Super Proton Synchrotron (SPS) and the Large Electron–Positron Collider (LEP), led to modifications of the geodetic reference system following the increasing need for accuracy and improvements to geodetic knowledge and practices [2]. The most recent update, which dates back to 2003, involved the implementation of a new geoid model for the CNGS (CERN Neutrinos to Gran Sasso) project [3].

For the FCC project, the definition of the geodetic system, the CERN reference network, and the geoid model must be adapted and upgraded due to the large area covered and to be in line with the latest geodetic best practices. A robust geodetic foundation for the planning, construction, alignment and operation of the FCC is therefore being developed to support the various levels of accuracy required. The geodetic infrastructure must be compatible with each phase of the project, from the initial coarse placement to the final, continually refined, sub-millimetre alignment.

Creation of new coordinate reference systems and frames

Figure 1 depicts the connection amongst the different components of the reference systems for the FCC. A core element is the static Coordinate Reference System (CRS), which will be established through a CERN Terrestrial Reference Frame (CTRF) along with a kinematic model (CKM) representing the temporal change in the coordinates of the CTRF's reference points. This frame will allow CERN's existing reference frames (legacy frames) to be connected to international, national and other local reference frames. It will also create a stable reference to be used as the basis for analyzing crustal deformations. For the civil engineering works, a compound CRS, comprising a projected CRS and a vertical CRS, will be used. The horizontal coordinates are expressed using an implementation (Projected Frame, CPF) of the projected system, and the Vertical Reference Frame (CVF) will allow gravity-related heights to be determined. For the alignment, the existing CERN Coordinate System (CCS), currently used for all machines at CERN, will remain valid, ensuring a consistent link with the existing facilities.

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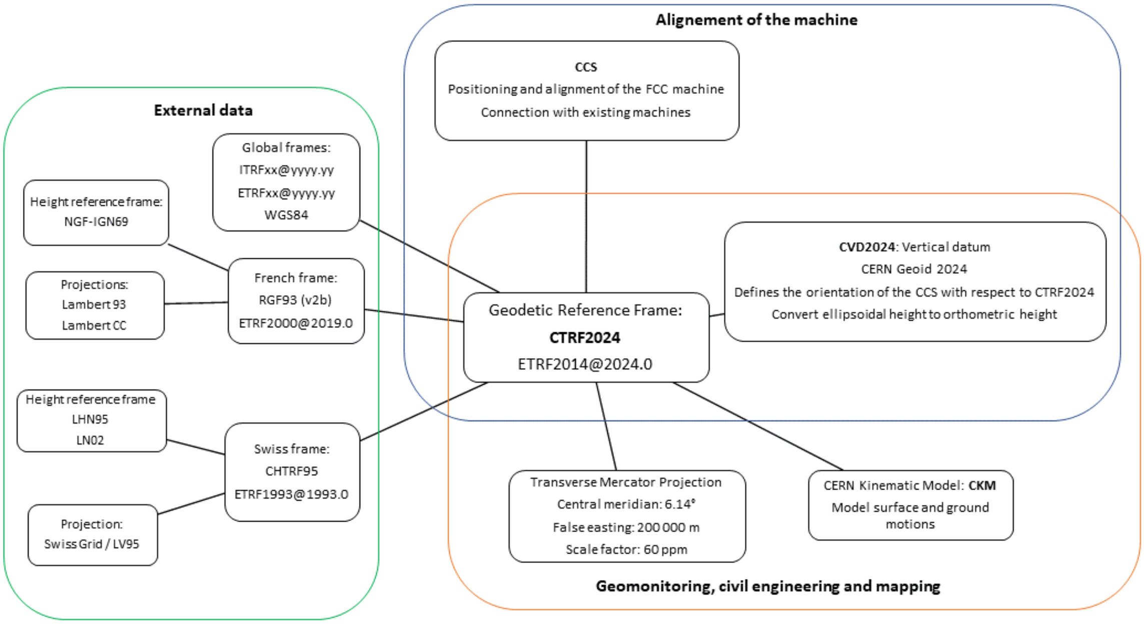

Figure 1: Graphical outline of the coordinate reference systems for the FCC.

Existing or newly acquired geo-referenced data, such as geological maps, digital terrain models, or aerial images, are expressed in various geodetic horizontal and vertical datums, as FCC is a cross-border project. They must be consolidated and transformed into the CTRF to be used together. The appropriate transformation models and their associated uncertainties will be computed, and geodetic transformation software will be developed and provided to the stakeholders, ensuring consistency through the dataset.

In the frame of this research, coordinate transfers from the surface to the underground were performed through four LHC shafts using mechanical plumbing. The goal was to control the current consistency of the underground coordinates with respect to the surface coordinates, since the latest measurements dated back to the construction of the LEP tunnel (that was repurposed for the LHC) in the late 1980's. The analysis of the results showed differences between the surface and the underground coordinates of less than 25 mm, indicating that there is no significant bias in the underground network introduced by the extensive measurements taken over the past 40 years. Results have to be confirmed for the four other LHC shafts and the SPS reference network. These measurements will then be used to calculate the coordinate transformation model between the CCS and the new CTRF.

Implementation of the surface geodetic network

A Primary Surface Geodetic Network (P-SGN) must be created as soon as possible to implement the CTRF, as it will serve as the reference for all survey work. The P-SGN will serve different purposes, including:

- Materialization of the CERN Terrestrial Reference Frame (CTRF);
- As a reference for the civil engineering and surveying works required for the construction of the FCC tunnel;
- Providing the long-wavelength basis for the later alignment work;
- Providing the reference for the geokinematic monitoring of the FCC area.

The French Institut national de l'information géographique et forestière (IGN) and Swisstopo are densifying their national geodetic network over the FCC area. The construction of eight new geodetic pillars is underway. Seven of them will be part of a passive network, while the central pillar will be equipped with a Continuously Operating Reference Station (CORS). These markers are necessary for the FCC but will also be available for the entire survey community, with the new CORS becoming part of the French RGP (Réseau Géodésique Permanent). Additionally, the P-SGN will incorporate existing CERN geodetic pillars, creating a unified network across the entire CERN complex (see Fig. 2).

The coordinates of the P-SGN markers will be calculated and tied into the latest realization of the European Terrestrial Reference Frame using simultaneous Global Navigation

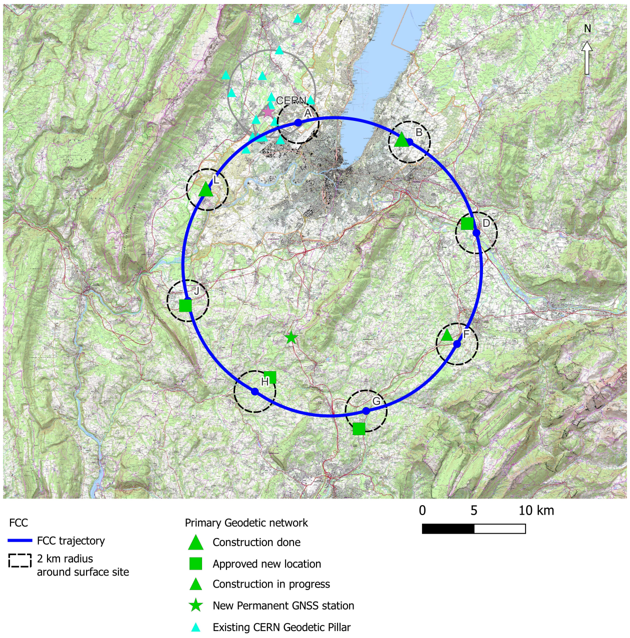

Figure 2: Primary Surface Geodetic Network (P-SGN) of the FCC. The existing and new geodetic pillars and CORS will form the CTRF.

Satellite Systems (GNSS) observations. Two GNSS observation campaigns for the entire network are foreseen: the first one starting in Spring 2025 and the second one more than a year later. Each campaign will consist of two 48-hour sessions, with IGN and Swisstopo conducting independent processing. The observation and processing strategy will ensure coordinate accuracy within 3 to 5 mm. The coordinates of the markers will also be determined in French and Swiss national reference frames (RGF93 and CHTRF95, respectively). IGN and Swisstopo will add these new markers to their national database, making them available for use in any local project by survey companies.

A surface levelling network will be created, linking the eight surface sites and access shafts. The normal height of the P-SGN markers will be determined by levelling combined with gravity observations.

During tunnel construction, the number of geodetic reference markers will be increased with auxiliary points. A portal network will be created at each shaft to determine and control the orientation of the tunnel.

New gravity field model

Like all CERN circular accelerators, the beamline of the FCC is defined in an Euclidean plane. However, the direction of the vertical (i.e. the direction of the gravity vector or the direction of the plumb line) varies along its path, primarily due to the distribution of the masses within the Earth. To meet the vertical alignment requirements and to overcome the differences between the French and Swiss altimetric systems, the local variations of the gravity field must be known or modelled with high accuracy and resolution.

A control profile, composed of astro-geodetic and GNSS-levelling observations, was measured at the beginning of the project to control the different geoid solutions that are computed [4]. This campaign measured a 48 km-long profile across the entire FCC region. It included deflection of the vertical (DoV) measurements at an average spacing of approximately 800 m using a COmpact DIgital Astrometric Camera (CODIAC) system, a levelling line with gravimetric observations (1 km spacing) along the same profile, and GNSS measurements to obtain accurate positions for all of the measurement points. The results of the campaign provided highly detailed and precise gravity information along the measured profile, allowing the quality of the computed gravity field models to be assessed and validated.

Different levels of accuracy are considered for the different phases of the project. The initial target is a 1 cm accuracy for the civil engineering and tunnelling works, which will also serve as a basis for computing the gravity field model at the tunnel level. A first attempt was made using the Stokes-Helmert method [5] and a finer solution is being computed using the GROOPS software toolkit [6].

Perspectives for future development

The overall vertical requirement for the alignment of the machine is to within a few millimetres, with a relative placement tolerance of the girders of 150 µm over 100 m. To meet these tolerances, new methodologies and instruments must be developed to precisely measure the variation of the deflection of the vertical inside the FCC tunnel.

Numerical and instrumental approaches, such as Gravity Forward Modelling and the Differential Geodetic Deflectometer, were explored during the Compact Linear Collider study [7]. However, these methods did not provide results with a sufficient confidence level or were not directly applicable for a machine of the size of the FCC. Therefore, further research efforts are required to find the most suitable solutions.

The stability of the FCC area must also be considered. The area may experience natural or human-induced horizontal and vertical displacements, such as subsidence due to active geological faults. If such displacements exist, they could impact civil engineering work, affect the accelerator component design (ensuring the adjustment system's range is adequate for the machine's lifetime), and lead to an increased need for alignment. Studies are planned to estimate the extent of these movements. Existing data, such as levelling observations or InSAR (Interferometric Synthetic Aperture Radar) studies, will be analyzed to assess the area's stability. If local movements are detected, they will be closely monitored and measured through regular or continuous terrestrial observations.

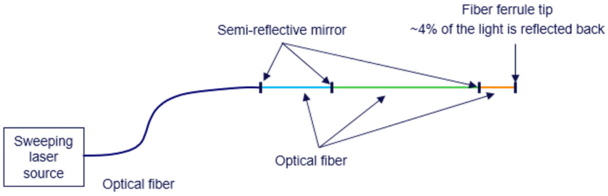

Figure 3: FSI deformation monitoring system declination.

UPDATE ON THE ALIGNMENT MONITORING OF THE MACHINE DETECTOR INTERFACE (MDI)

The alignment and monitoring of the MDI present significant challenges due to its complex and dense design, tight alignment constraints (micrometric level for the final focusing quadrupoles), and harsh operating conditions (radiation, cryogenics, vacuum) [8]. In order to tackle these challenges, an alignment and monitoring system was proposed based on three subsystems: a deformation monitoring system, a short-distance measurement system, and a long-distance measurement system [9], all based on Frequency Scanning Interferometry (FSI). In this system, illustrated in Fig. 3, FSI measures the length of a fibre segment using the entry and exit refractive index changes of the fibre. Multiple segments can be put in series and measured independently but simultaneously by the system, allowing for precise deformation calculations of the supporting medium. The helical placement of fibers has been studied [9], offering several advantages. This configuration minimizes stress on the fibers during contraction and expansion of the support structure due to temperature variations, such as between installation at room temperature and operation at cryogenic levels. Additionally, the fibers can deform during operation while remaining precise enough to monitor the various deformations of the support cylinder. By using such helical arrangement, the fiber captures all deformation simultaneously. To fully assess the deformations, a network of fibers with varying helical pitches and orientations is required, providing both comprehensive data and high redundancy [9].Since the last update, four prototypes have been constructed in order to validate, step by step, the measurement principle, the multiple and simultaneous measurements and assess difficulties that may be encountered during assembly. These small scale models, cheap and studying specific aspects of the system, are paving the road to the final validation of this deformation monitoring system, thanks to a fifth prototype currently under construction.

Validation of the System's Deformation Sensitivity

The first prototype, shown in Fig. 4, aimed to confirm that the sensing system was sensitive enough to measure deformations. To achieve this, four fibres composed of six spliced, and therefore, measuring sections were glued to a steel plate. The plate was then bent at one or multiple locations, and the fibre sections were able to record these deformations, as illustrated in Fig. 5. The graph displays the evolution of the distances measured by the different fibre sections, showing the offset from the initial value due to deformation. The different deformation stages are evident, validating the sensitivity of the fibres to the deformation of the steel plate.

Figure 4: Steel plate, with 4 fibres glued on it. Each fibre has 6 splices and therefore measured sections.

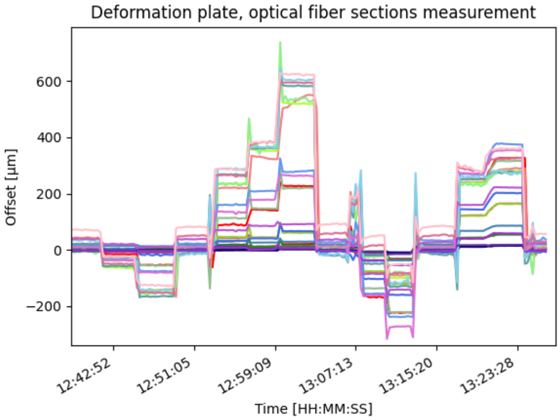

Figure 5: Deformation measurements of the fibre sections from the steel plate prototype.

First helical installation of fibres on a tube

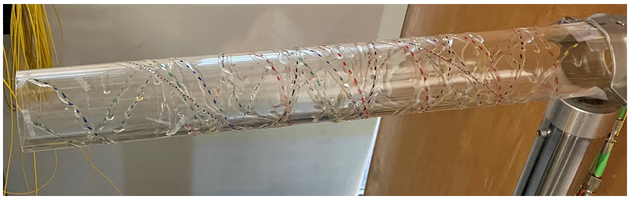

Figure 6: fibres glued on the surface of a Plexiglas tube.

The second prototype, shown in Fig. 6, used a helical installation of fibres. The goal was to detect potential obstacles that could be encountered in more complex future prototypes. The fibre placement, data acquisition and interpretation were also studied. Six fibres were installed on this tube, with 5, 8, 11, 15, and two times 9 sections. The measurements of all sections are plotted in Fig. 7, sorted by the length of the section measured. Once again, the measurement is of the

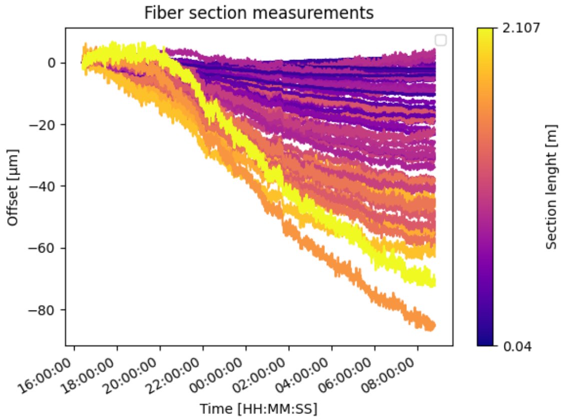

Figure 7: fibre section measurements on the first tube prototype.

offset between the first measured length and its evolution over time. An overall shortening of the fibre sections, up to 80 μm, can be seen in the figure. This phenomenon is due to the long curing time of the glue (several days), which had not finished before the acquisition period. Despite this issue, this prototype effectively validated the fibre installation and the data acquisition process.

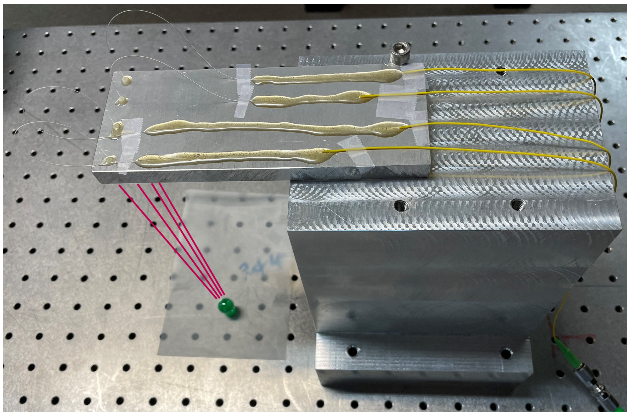

Figure 8: fibres glued on an aluminium plate, terminated with a ferrule allowing a measurement on glass beads.

Validation of multiple and simultaneous measurement methods

The third prototype, shown in Fig. 8, was assembled in order to highlight the versatility of the FSI system by simultaneously conducting in-fiber and in-air measurements. Four fibres with multiple sections were glued to an aluminium piece with one extremity in a hole, allowing for a distance measurement between the fiber end and a glass bead positioned below.

Measurements can be seen in Fig.9, where the measurement of the fibre sections are plotted in addition to the measurements on the glass bead. This validated the measurement capability of the FSI to perform simultaneous measurements both in fiber and in air.

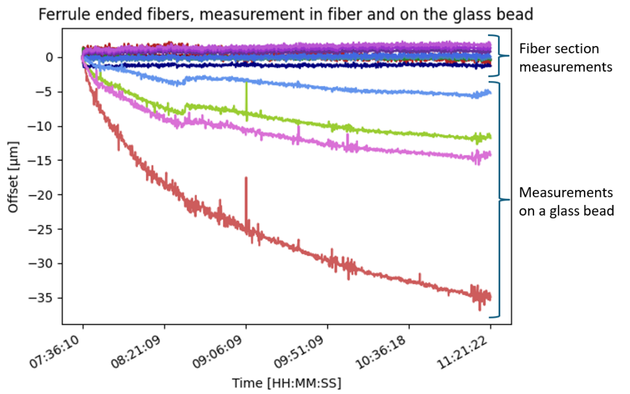

Figure 9: Measurements from the fibres with ferrule installed on the aluminium plate.

Tests of the complete installation

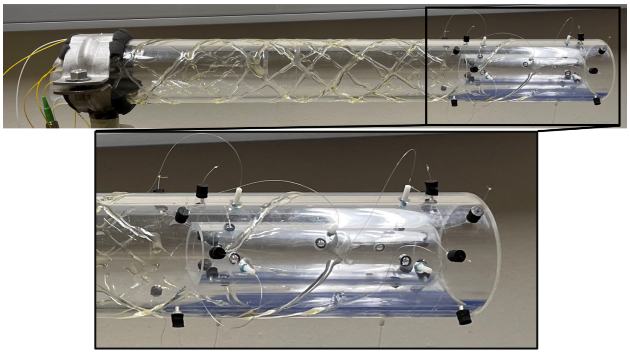

Figure 10: Plexiglas tube with glued fibre, terminated by ferrules allowing for measurements to a smaller cylinder equipped with glass beads inside.

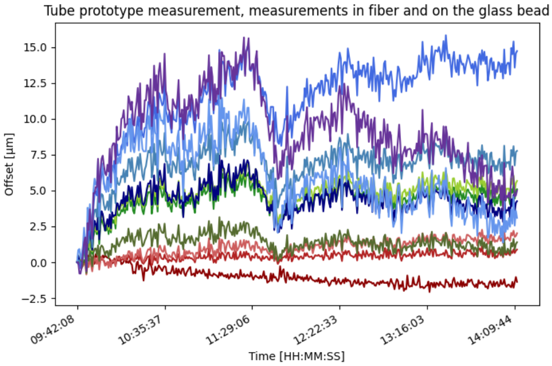

Figure 11: Example of measurements performed by a fibre on the fourth prototype composed of 10 fibre section measurements and a measurement on the glass beads of the smaller cylinder.

The fourth prototype, shown in Fig.10, combined the fibres installed on the tube and the distance measured from the ferrule end toward glass beads. The aim was to assess the difficulty of building and assembling a more realistic prototype, implementing for the first time the different sensor systems in the wanted shape, while assessing their performances. A smaller tube was installed in the larger one and suspended using fishing wire. Nine glass beads were placed on the inner tube and nine corresponding holes were drilled in the larger tube to glue the ferrules. An example of measurements performed by one of the nine fibres installed is shown in Fig. 11. This graph shows the simultaneous recording of outer tube measurements and measurements to the inner tube, validating the installation and the operation of the different measurement systems. Some difficulties were identified, including the fragility of the fibres, particularly at the ferule end, where the radius of curvature of the optical fibre must be respected. Moreover, precise alignment between the hole in the large cylinder and the beads on the small cylinder is crucial, as the visibility cone given by the ferrule provides only about a millimetre measurement range.

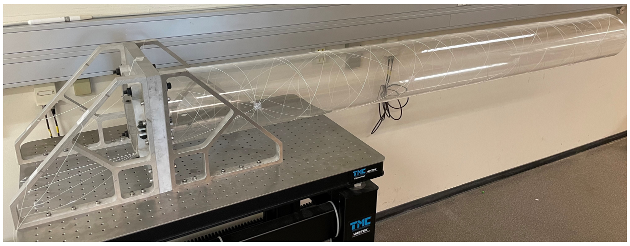

Figure 12: Future prototype in construction

The ongoing prototype, shown in Fig. 12, will incorporate all this data to be as close as possible to the final system. The objective is to use this 2 m-long Plexiglas tube to install a working system capable of simultaneously measuring the tube's deformation and the position of inner elements. It is planned to install six smaller tubes inside a 2 m-long outer tube, with ferrule-ended fibers carefully positioned to monitor them. This prototype will also facilitate a comparison with laser tracker measurement.

TOWARDS AN ALIGNMENT STRATEGY FOR THE ARCS OF THE FCC

The study of an arc alignment system for the FCC has begun. The initial step involved evaluating all the challenges that need to be addressed to meet the alignment requirements. These challenges include size constraints, available space, and strict alignment tolerances. At this stage, as the FCC-ee is still being designed, much of this data is preliminary. The primary datasets include survey files from the optical layout computations and some drawings of the tunnel and components from the integration study. Given the tunnel's vast size, the main requirement for the alignment system is to maintain low positioning measurement uncertainty over long distances within a narrow cylindrical tunnel, typically 11 km between two pits for a tunnel of 5.5 m diameter. The first step towards achieving this objective was to generate a geometrical network simulation of the tunnel and its components within the same coordinate system, utilizing the survey file and the data from the integration plans, as shown in Fig. 13. Using this data, various alignment systems can be simulated to assess their performance over long distances. The computing tools used include Python for generating the tunnel model and simulating measurements, and LGC++ (Logiciel Général de Compensation), a CERN-developed least squares adjustment software for surveyors, for resolution and uncertainty computation.

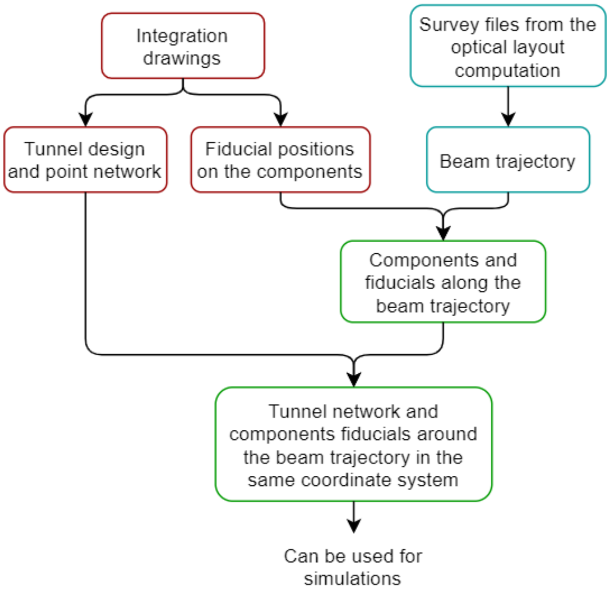

Figure 13: Process used to generate the setup to perform the simulations

The initial simulations are conducted using laser trackers to validate the process of generating network and measurement simulations, since these are more commonly employed than hydrostatic levelling systems or wire offset measurement networks. These initial simulations also contribute to improving LGC++, which is currently only used for smaller tunnel sections. Computation for tunnels ranging from 10 km to 90 km is ongoing.

CONCLUSION

The alignment of the FCC-ee components remains a significant surveying challenge, from defining the surface geodetic infrastructure to monitoring the deformation of the inaccessible machine detector interface region. Ongoing studies aim to address these challenges, with development underway for a new coordinate reference systems, the implementation of the surface geodetic network, and the definition of a new gravity field model. In parallel, prototypes have been constructed to validate a possible alignment monitoring system for inaccessible components. Promising results with these initial prototypes have encouraged further development of such a system to validate the entire monitoring capability, from technical aspects to the mathematical resolution. Simulations have also been initiated to start designing and optimizing the alignment strategy for the arcs.

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