

OVERVIEW OF THE FUTURE CIRCULAR COLLIDER AT CERN FROM SURVEY AND ALIGNMENT PERSPECTIVE

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Abstract

The Future Circular Collider (FCC) represents CERN's flagship future project. Following the Feasibility Study Report published in 2025 and the Reference Design Phase (RDP) concluding at the end of 2027, the project faces unprecedented engineering challenges. The proposed 90.7 km tunnel requires the high-precision alignment of approximately 23,000 magnets, pushing existing geodetic and metrological techniques, including those currently validated at the Large Hadron Collider, to their limits regarding tolerance and scalability.

This contribution introduces the FCC-ee project with current alignment requirements and addresses three key surveying challenges: extending the surface geodetic reference network to cover the FCC site; refining fiducialisation procedures; and optimizing data analysis methodologies. We provide an overview of the critical steps in the alignment process for large-scale accelerators and discuss the associated survey aspects. Furthermore, we highlight ongoing preparatory efforts currently under investigation within the RDP framework, aimed at validating solutions to meet the FCC's positioning requirements.

INTRODUCTION

The European Organisation for Nuclear Research (CERN) is the leading institute for particle physics based in Geneva, Switzerland and operates the most sophisticated particle accelerators complex in the world. The Future Circular Collider (FCC) at CERN is the proposed next generation particle accelerator to push the frontiers of fundamental physics beyond the Large Hadron Collider (LHC) with two large and two smaller experiments. 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 manual alignment techniques used in accelerators like the (LHC) are insufficient to meet the even stricter

requirements and scalability demands. This paper reviews key steps, current practices and developments in large-scale accelerator alignment.

The layout of the FCC spans an area of 1000 km² across France and Switzerland as visible in Figure 1. The Euclidean plane of the accelerator will be slightly inclined to fit best to the topography to optimize the construction costs and risk. The final inclination value still needs to be defined by the civil engineering team. Access to the underground tunnel is provided by eight surface sites, resulting in 11.3 km tunnel segments between adjacent access shafts, which is nearly three times the 3.8 km shaft spacing of the LHC. Shaft depths range between 180 m and 400 m. Civil engineering anticipates the simultaneous operation of eight Tunnel Boring Machines (TBMs), which should start in both directions from the four large access points that will house the experiments. Investigations to identify critical areas and geological faults are on-going. The tunnel boring will be executed mainly in molasse rock, but areas of limestone are unavoidable [1].

The electron-positron collider called FCC-ee is a precision electron-positron machine operating as a Higgs and electroweak factory at centre-of-mass energies from 91 GeV (Z) to 365 GeV ($t\bar{t}$) that could be followed by an FCC-hh a subsequent 100 TeV proton-proton collider designed to explore new energy scales planned for operation in the 2070s sharing the common civil engineering and technical infrastructure.

The FCC feasibility study [2] has been published in 2025, and the study entered the Reference Design Phase (RDP) of the FCC-ee that runs up to the end of 2027. This should precede the approval of the project by the CERN council in 2028. After the following Technical Design Report phase, the construction start is planned for 2033 and accelerator operation in the mid-2040s. This contribution gives the status of certain aspects of the preparation of the alignment strategy during the RDP, aiming to establish robust and scalable solutions for the FCC's precise and efficient alignment.

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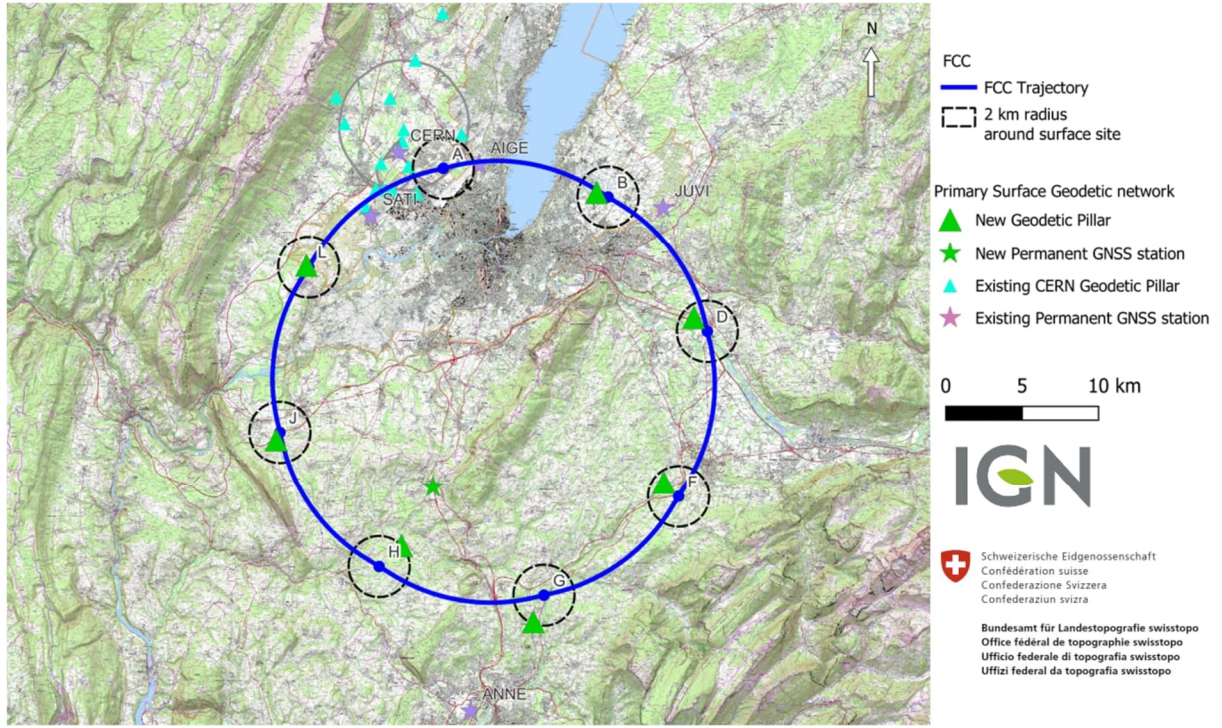


Figure 1: Layout of the FCC in the Franco-Swiss border region and geodetic network.

CHALLENGES FOR ALIGNMENT

From a survey and alignment perspective, the FCC requires a huge technological jump. To the existing ~60 km of beamlines across the CERN accelerator complex with approximately 7500 components, the FCC adds 90.7 km for the collider, 90.7 km for the booster ring co-located in the same tunnel, an entirely new injector complex composed of three linacs, a damping ring, a polarizer ring, and over 5 km of beam transfer lines. This at least multiplies by a factor of four the number of components to be aligned to sub-millimetric and micrometric relative tolerances, as well as the length of beam lines at CERN adding 190 km for the FCC and its injector complex. 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 need to be aligned. The tunnel segments of over 11 km length impose challenges for the uncertainty propagation, and the high number of components demands implicitly a transition from traditional manual alignment to automated, robotized, and remotely monitored metrology workflows.

The manual operation of surveying and alignment tasks reaches its limits and would be incompatible with the FCC schedule. The key for the successful installation, operation and maintenance of the facility should be the optimisation and automation of a maximum number of tasks, which includes all stages of the surveying and alignment. This applies to the surface works as the fiducialisation measurements and adjustments on girders, the installation and measurement of the geodetic reference network in the accelerator tunnel, the tracing of component positions in the tunnel, and continues with the measurement and

adjustment of the components during installation and maintenance of the machine.

The concept for the FCC arc measurements is mainly based on automated laser tracker measurements, which include instruments like the Leica ATS800, long-distance metrological scanner allowing higher level of automation associated with low-cost permanent targets. These instruments can be combined advantageously with the Ecartometry Measurement by Automatic Photogrammetry Survey (EMAPS) as shown in [3,4,5,6].

Alignment requirements for CERN accelerators have progressively tightened over the decades, which continues for the FCC-ee. The alignment requirements specified in Table 1 for the magnets, girder and beam positioning Monitors (BPMs) correspond to the applied misalignments used in physics simulations based on a gaussian distribution truncated at 2.5σ . The values evolve with the project progress. They are especially challenging in the Final Focus (FF) doublets section and in the Interaction Region (IR), which implies that specific permanent monitoring and alignment systems need to be studied in these areas as described in [7] for the Machine Detector Interface (MDI), which includes the FF. The alignment requirements are defined for the positioning of the functional axis and should be considered as a relative uncertainty (1σ) in a sliding window of 100-200 m. They include all steps from the design, production, assembly, calibration, fiducialisation, alignment and operation. Which is quite different from earlier CERN machines where requirements had been specified relative to external fiducial marks. Modern colliders evaluate alignment quality directly on the component's functional axis (i.e., magnetic axis or the electric centre of the beam position monitor).

Table 1: Misalignment values at 1σ level as used for optics simulations of the FCC-ee (distribution truncated at 2.5σ).

Element type	Δx (hor.) μm	Δy (ver.) μm	Δz (long.) μm	Roll angle μrad
Girders in arcs	150	150	500	150
Quadrupoles on girder	50	50	100	50
Sextupoles on girder	50	50	100	50
IR section without sextupoles	50	50	100	100
IR section with sextupoles	30	30	100	30
FF-doublets section	30	30	100	30
All dipoles	1000	1000	500	1000
BPM stability	10	10	---	10

Geodetic Infrastructure

For each new generation of particle accelerators at CERN, it has been necessary to modify and extend the geodetic infrastructure 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.

For the FCC, the geodetic infrastructure must be extended and adapted to align with the current best geodetic practices, and to satisfy the requirements imposed by the different stages of the project:

- Connecting the CERN facilities to local, national and international facilities,
- Supporting civil engineering works that include tunnel boring and surface motion kinematic monitoring,
- Installing and maintaining the infrastructure above and below ground,
- Installing and aligning the accelerator components,
- Maintaining and upgrading the alignment.

The first tasks are 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 collaboration with expert institutes Swisstopo, ETH Zürich, IGN and HEIG-VD.

Being a cross-border project, using a dedicated reference frame for the project is the best solution. A new static CERN Terrestrial Reference Frame (CTRF), aligned with the latest European Terrestrial Reference frame (ETRF) realization 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 mapping 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 the Primary Surface Geodetic Network (P-SGN). The P-SGN will serve different purposes including the civil engineering and surveying works required for the construction of the FCC tunnel, providing an absolute reference for the alignment works of the accelerator and providing the reference for the geo-kinematic monitoring of the FCC area. Eight concrete geodetic pillars were built to materialize it. 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. One of the pillars is equipped with a continuously operating GNSS reference station, densifying the Réseau Géoésique Permanent operated by the IGN.

The coordinates of the markers will be calculated in the ETRF using simultaneous GNSS observations. The first measurement campaign has been carried out in June 2026, and a control campaign is planned before the end of 2026. The computation of the coordinates is ongoing.

To align the accelerator components in a Euclidean plane, all survey observations need to be corrected for the variation of the 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 [8]. It is above the required absolute accuracy for the 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 [9]. It is used as a validation dataset for all gravity related studies of the FCC project.

Coordinate Reference Systems for FCC

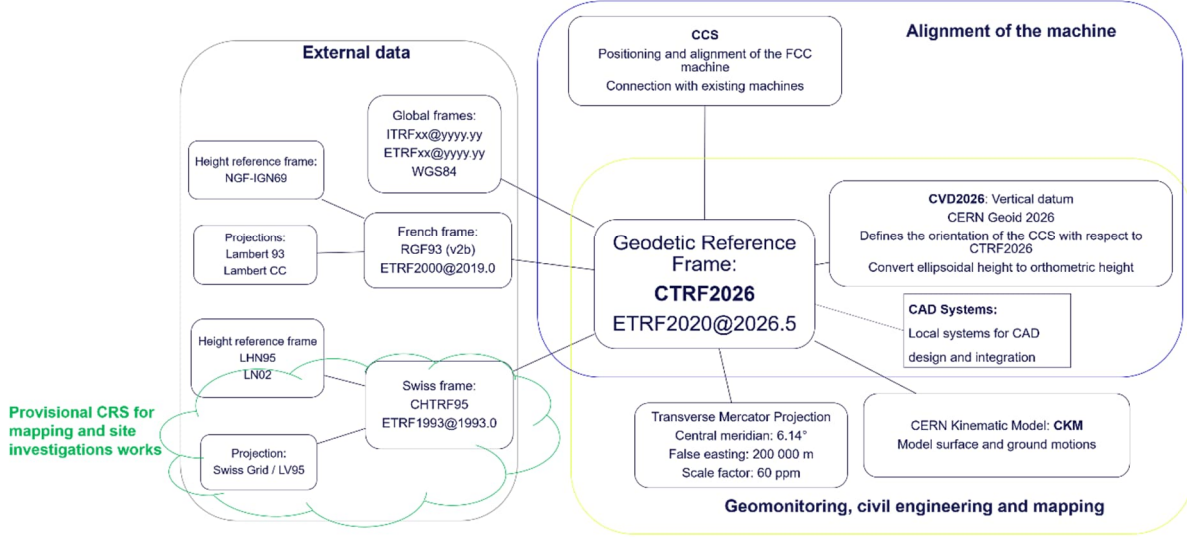


Figure 2: Graphical outline of the coordinate systems for the FCC.

An initial local gravimetric geoid model was computed using the GROOPS software toolkit [10] 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 [11]. 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.

Software and Simulations

The LGC software (Logiciel Général de Compensation) is a geodetic least-squares adjustment package developed at CERN since the mid-1980s to compute position estimates and related statistics from surveying observations; it was released as open source in late 2025 [12]. It supports over 20 observation types, including angles, distances, levelling, offset measurements and inclinometer, Hydrostatic Levelling Sensor (HLS) and Wire Positioning Sensor (WPS) observations. It organises the local coordinate systems of assemblies such as magnets or girders in a hierarchical tree related by Helmert transformations, estimated as part of the adjustment or held fixed.

Scaling to the FCC Different alignment strategies are compared for the FCC with LGC through error propagation studies, on problems exceeding one million parameters and several million observations, where memory becomes the binding constraint. The software has therefore been adapted to sparse methods, in the linear algebra as well as in the evaluation of the observation models, and a Levenberg–Marquardt globalisation ensures convergence from poor approximate coordinates. The columns of the parameter covariance matrix are computed after the adjustment together with the diagonal of the residual covariance

matrix required for reliability analysis, removing the need to store the full matrix.

The relative uncertainty between neighbouring components is the quantity from which the sliding-window alignment capability of a given network can be evaluated, as it expresses the magnet-to-magnet capability to which the requirements of Table 1 refer within a sliding window of 100 m to 200 m. Its evaluation requires off-diagonal elements of the covariance matrix, not standard at this scale, as the complete matrix exceeds any feasible memory or storage. They therefore have to be computed on demand, and an extension under development exposes them through a library interface returning the relative uncertainty of an arbitrary pair of points in a chosen frame.

An Extensible Estimation Framework A dedicated interface for the evaluation of observation models and their derivatives decouples the mathematical core from the least-squares formulation, so that alternative objectives such as L1-norm or Huber-based estimation and iterative re-weighting for blunder detection can be prototyped without touching the adjustment engine. The same interface carries an Optimum Experimental Design approach optimising the layout of reference marks and measurement configurations, the subject of a dedicated contribution to these proceedings [13].

Interchangeable Local Geoids Post-processing observations from gravity-linked measurements, such as levelling, the orientation of verticalized stations, hydrostatic levelling and GNSS heights, requires the knowledge of the deflection of the vertical in the form of a gravity field model. LGC today supports a small set of hardcoded models only. A flexible integration of generic grids is therefore needed, separating the model from the computations that use it. It will allow future gravity field models to be integrated, such as the one currently being developed for the

FCC region, and their effect on the estimated positions to be compared.

Coordinate Transformation CSGeo, the CERN coordinate transformation software and its associated shared libraries, is updated to include the coordinate reference systems implemented for the FCC and the related transformations. Having a unique coordinate transformation tool shared between different services (alignment, civil engineering, mapping, integration) ensures consistency and reduces the risk of blunders when data are shared and during the construction of the tunnel and installation of the infrastructure.

Modelling Component Deformations The estimation framework currently treats components as rigid bodies. However, certain components of the FCC-ee in very sensitive sections, such as the MDI, also require the modelling of small nonlinear deformations. Including them in the software calls for a generic deformation model, together with dedicated observation models determining its parameters. One example is the high-precision length measurement along a curved, deforming path, realised with in-fibre frequency scanning interferometry (FSI) and described in a further contribution to these proceedings [7]. Estimated within the adjustment, the deformation parameters propagate consistently into the coordinates of the attached points and their uncertainties.

Linking Alignment and Beam Dynamics The requirements expressed in Table 1 are derived from misalignments applied in beam dynamics simulations following a Gaussian distribution truncated at 2.5σ , which does not reproduce the spatial correlation structure of a survey network, in particular its long-wavelength component. A direct connection to the beam dynamics simulations carried out in the Xsuite framework would narrow this gap: misalignment scenarios generated from simulated network adjustments would be injected into the pipeline, the correction chain applied and dynamic aperture and beam lifetime evaluated over many seeds, the fraction of correctable seeds providing a metric from which the impact of the sliding-window tolerances can be analysed. A similar connection would benefit the smoothing workflow, currently performed with the PyRabot software, whose criteria should be formalised as a physically motivated optimisation objective agreed with the beam physicists and cross-validated against the simulated misalignment and smoothing campaigns.

Data Storage The data storage needs a revision with respect to the actual Geode model. The different types of data input would be i.e. raw observation data from measurement and monitoring systems acquired during the preparational metrology works on surface and in the machines, pre-calculated data from component and sensor fiducialisations in their functional frame, mechanical deformation models as for the MDI area, and the positioning data of all elements in the machines and experiments. The efficient access and use for the data analysis and interpretation is

considered as a key element for the installation and maintenance of the FCC and injector complex during their lifetime. It should be closely connected to the layout data of the machines.

Towards Automated and Continuous Alignment Automation of the measurement and adjustment workflow will be essential. The file-less monitoring interface developed for the Full Remote Alignment System (FRAS) of the High-Luminosity LHC [14] is being strengthened with emphasis on the short estimation cycles it requires, so that FCC solutions can build on experience already proven at a smaller scale.

Fiducialisation

Fiducialisation at CERN is the process of precisely determining and transferring the functional axis of i.e. a magnet, most commonly the magnetic axis, with respect to external visible reference points that are used for the positioning and alignment of the component, 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 FCC girder as an example, see Figure 3 [15], multiple beam-line components are installed, fiducialised, and pre-aligned as a single assembly. These include one dual-aperture quadrupole and two single-aperture sextupole magnets, beam pipes, and BPMs, which monitor the beam trajectory. The magnetic axes of the magnets are first determined using magnetic measurement techniques, such as rotating-coil or stretched-wire methods. These functional axes are then related to external reference targets and expressed in the girder reference frame. The quadrupole is aligned and secured to the girder first, serving as the reference for subsequent alignment of the sextupoles to its corresponding functional axes. The BPMs are mechanically attached to the quadrupole with a sub-millimetric alignment tolerance. The offsets of their electrical centres relative to the quadrupole's functional axes are determined during fiducialisation process. The relationships between the functional axes and the fiducials are documented, allowing the entire girder assembly to be accurately positioned in the tunnel using only the external fiducials.

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, photogrammetry and structured light scanning systems. Furthermore, recent advances in FSI as improved measurement stability, calibration procedure and updated software, offer opportunities to further improve measurement efficiency and accuracy during fiducialisation measurements.

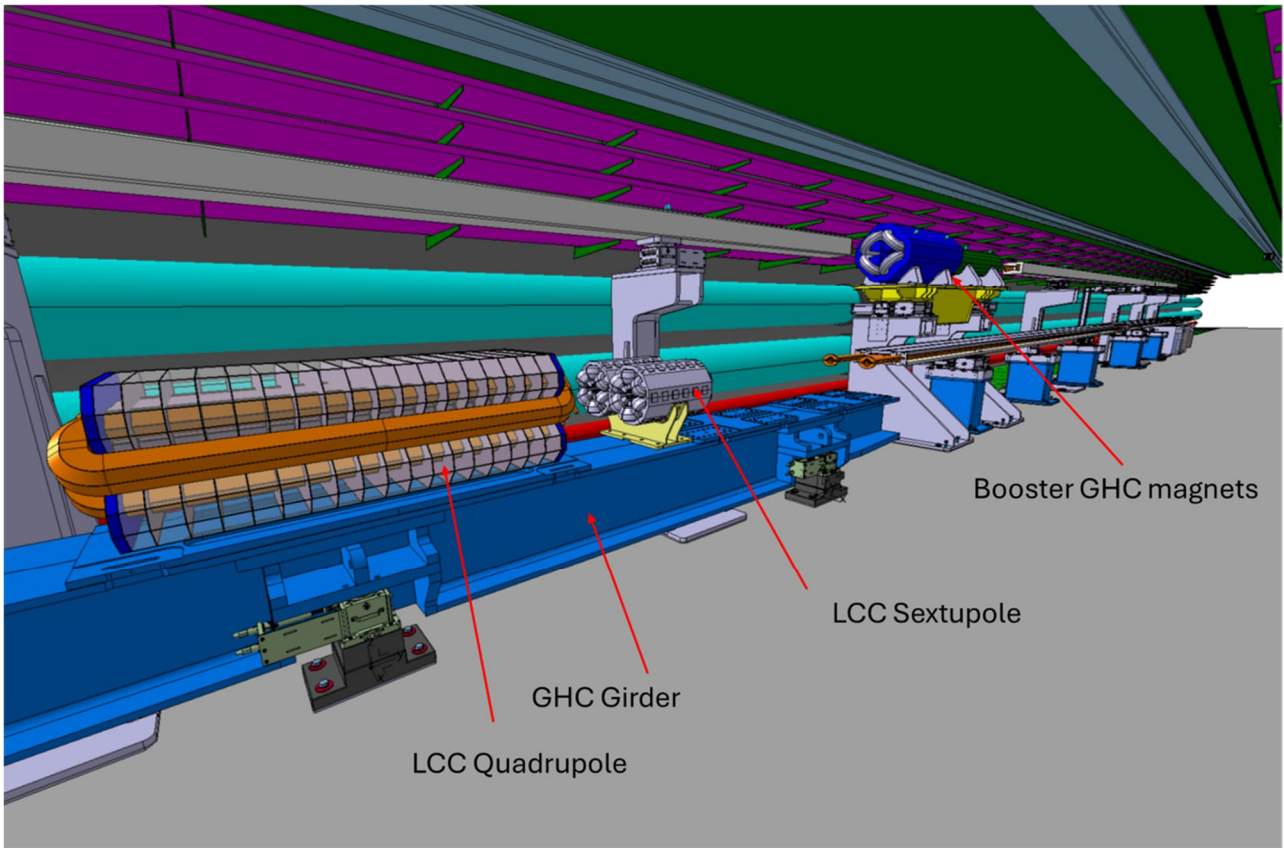


Figure 3: FCC-ee Half Cell 3D model under migration to Local Chromaticity [15].

One of the primary challenges of fiducialisation are the tight alignment tolerances required. Establishing a precise and stable relationship between the magnetic axes of multiple components and their fiducials is technically demanding, particularly when integrating magnetic, mechanical, and optical measurement techniques. Mechanical deformations arising from gravity, thermal variations, and mounting stresses can introduce systematic errors if not properly modelled and compensated. Long-term stability represents an additional challenge, as the structural integrity of components, support systems, jacks, and fiducials must be maintained throughout installation, transport, and operation in a highly radiation environment. To address these challenges, the development of a virtual simulation environment is critical for modelling, refining, and verifying alignment protocols and measurement data both before and during physical execution. 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. Consequently, automation is essential for fiducialisation and alignment. Automated measurement systems must achieve the required precision while remaining efficient and scalable. Robotic handling systems, automated adjustment mechanisms, and autonomous guided vehicles (AGVs) can ensure consistent placement of sensors and fiducial targets, enable automated re-alignment, reduce human intervention, and improve process repeatability. Furthermore, seamless integration of data acquisition, processing, and communication systems is required to support real-time coordinate transformations, uncertainty propagation, and validation of measurement results.

Conclusion

Meeting the stringent micrometric sliding-window alignment requirements across the 90.7 km FCC requires a structural shift from traditional manual metrology towards fully automated, scalable workflows. Progress achieved during the RDP has established a solid geodetic foundation, marked by the definition of the CTRF2026, the deployment of the P-SGN, and high-precision gravimetric geoid modelling required for vertical reductions across complex terrain.

To manage the unprecedented scale of over 23,000 components across nearly 190 km of beamlines, ongoing

technological advancements are successfully bridging the gap between geodetic metrology and beam dynamics. Modernized computation packages like the open-source LGC handle large-scale sparse adjustments and relative error propagation, while state-of-the-art instruments—including automated laser trackers, EMAPS, and FSI in high-precision areas like the MDI and the IRs—provide the precision necessary for tunnel and surface operations. Digital twin modelling and automated fiducialisation frameworks are proposed to enable full optimization and monitoring of complex girder assemblies before and during beam operation.

Together, these integrated developments in geodesy, instrumentation, and computational modelling pave the way for a continuous, robotized alignment that meets the demanding operational requirements of the FCC-ee. As the Reference Design Phase continues through 2027, these metrological solutions will remain central to establishing technical feasibility, risk mitigation, and cost-efficient maintenance strategies in preparation for the CERN Council’s formal project approval decision in 2028.

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