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**Challenges of present and future $e^+e^-$ circular colliders**

# Geodetic, survey and alignment challenges of the FCC-ee

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Abstract: At CERN, each generation of particle accelerators led to the implementation of new geodetic, survey and alignment methodologies following the increasing accuracy requirements and the evolution of survey instruments. The Future Circular Collider (FCC), representing the next generation of particle accelerator, will in its turn require new development to ensure the accomplishment of the construction of the 91 km tunnel and the correct positioning of the machine components. Mainly because of larger size of the machine but also due to the design of its components, the existing geodetic infrastructure has to be extended and upgraded. The accelerator component alignment methodology currently used in not scalable, and the Machine Detector Interface alignment procedure must be revised including monitoring of the alignment. The article summarizes the different aspects of the geodetic, survey and alignment challenges that are currently investigated during the FCC feasibility studies.

Keywords: Accelerator Subsystems and Technologies; Detector alignment and calibration methods (lasers, sources, particle-beams)

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## Contents



# 1 Geodetic challenges

Geodetic challenges arise from the development of the FCC, from the construction of the tunnel to the final alignment of the accelerator components and experiments. The FCC will cover an area that is around ten times larger than the current CERN site, spanning over the Swiss and French borders and areas with different topographical and geological features. Therefore, an evolution and extension of the geodetic reference systems and geodetic infrastructure including reference frames and gravity field model currently available at CERN is needed. A solid geodetic foundation for the planning, construction, alignment and operation of the proposed FCC is developed to support the different levels of accuracy required, from the initial decametric coarse placement study to the final and perpetually refined submillimetric alignment. The geodetic infrastructure must be compatible with each phase of the project.

## 1.1 Geodetic Reference Frame

The geodetic infrastructure currently in place at CERN is based on developments dating from the construction of the LEP in the 1980's [1]. The Cern Coordinate System (the local 3D cartesian coordinate system used to express coordinates within the facility) is not adapted for such a large project and cannot be easily used with current survey techniques like GNSS [2]. Considering the needs for the entire lifecycle of the FCC, and the necessity of easy communication and collaboration with third party survey and civil engineering companies, a new geodetic reference system associated with a Transverse Mercator projection is defined and a dedicated coordinate reference frame covering the area of the future project is implemented.

Being a cross border project, existing georeferenced data useful for the feasibility study like geological maps, digital terrain model or aerial images are expressed in different geodetic horizontal and vertical datums. To be used together, they must be consolidated, and transformed to the project datum. To ensure consistency between the dataset the development of the appropriate transformation models and their associated uncertainties is a key task.

The studied area may be subject to geodynamic natural or anthropic horizontal and vertical displacements such as subsidence, due to, for instance, active geological faults. If such displacements

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exist, they may have an impact for the civil engineering works and on the stroke of the supports of the accelerator components to ensure that the range of the adjustment system is sufficient for the entire lifetime of the machine. Studies prior the start of the construction will be carried out to estimate the amplitude of these movements. Analysing existing data like levelling observations or doing InSAR studies will be used to get a first knowledge of the stability of the area. If local movements are identified, they will be monitored and quantified precisely by regular or continuous terrestrial observations.

Whereas a large reference surface geodetic network can be homogeneously and accurately determined and monitored using modern GNSS techniques, keeping a millimetric level of accuracy when transferring the coordinates and orientation underground through the shaft to a depth between 150 m and 400 m needs the development of specific methods.

### 1.2 Gravity field modelling

In order to align the machine in an Euclidean plane, the local variations of the gravity field must be known or modelled with a high accuracy at a very short wavelength. Variations of 30 µm per 225 m will ultimately be known for the fine vertical alignment of the components of the machine. The existing CERN geoid model is limited to the existing facilities and available global and regional geoid models covering the area of study are inconsistent and do not provide a sufficient level of resolution and accuracy.

Ongoing studies on current and future technologies are focusing on the development of local gravity field model, from the data acquisition instrument and methodology to the modelling approach to the control dataset (see [3] and [4]).

## 2 Alignment of the components in the tunnel

### 2.1 Alignment of the accelerator components

The survey and alignment of components in a tunnel always follow the same sequence [5]. Once the tunnel is excavated, accelerator components need to be installed and aligned. Surveyors establish an underground geodetic network on the walls and floor while these are still empty. This network is used to install services and to mark of the adjustment solutions for the components on the ground floor. Once components are in place, an initial alignment is performed according to 6 degrees of freedom, followed by a smoothing (relative alignment of consecutive components). Reference points (named fiducials) on the components are defined and measured w.r.t. the component axis (mechanical axis, electro-magnetic axis, electric center) during the fiducialisation process on the surface as the reference axes are not later accessible in the tunnel. It is assumed that adjacent arc quadrupoles and sextupoles reference axes are pre-aligned at 50 µm accuracy with respect to a common $\sim$ 6 m long girder. In the tunnel, the alignment tolerances from girder to girder or between girders are 200 µm over 50 m and 500 µm over 200 m. In the interaction regions (IR), transverse misalignment errors for quadrupole and sextupole reference axes are taken to be ±100 µm ($1\sigma$) (±250 µm ($1\sigma$) longitudinally, and ±0.25 mrad in roll). Current requirements regarding the alignment are of 30 µm for the final focusing quadrupoles; the LumiCal will need to be aligned at 50 µm, and the screening and compensation solenoids at 100 µm (all values referring to $1\sigma$). But the work does not stop when the components are installed in the tunnel and aligned for the first time, the alignment needs to be maintained regularly. Settlement of the tunnel, seasonal variations and earth tides make the collider move and deteriorate the alignment. Temperature gradient, local heating can also have a huge impact on the alignment. Procedures for alignment maintenance are established, well known and shared all over the world [6]. But for the next generation of colliders as the FCC-ee, the size is so different that these procedures are not adapted anymore.

This collider is planned to be around 90 km circumference, which corresponds to three times the Large Hadron Collider. The FCC would not only considerably increase the length of beamline requiring to be aligned but will also introduce new challenges due to its size. Thousands of components will need to be fiducialized, transported, placed, and aligned in the tunnel. The maintenance of the alignment will also be more difficult in a brand-new tunnel in which the unstable area will not be known. The simple scaling of the time needed to perform these initial and maintenance tasks is not an option to reach the targeted integrated luminosity, but the scaling of the workforce is not possible either, as a huge number of well-trained technicians and engineers will be required for short periods of time. This well-trained workforce is already a challenge for the LHC alignment campaigns and seems to reach an impossible level for the FCC. All the alignment steps mentioned previously will need to be estimated, quantified and studied in order to propose adapted solutions. Innovative technologies such as remote controlled or fully automated robots, advanced 3D modeling, digital twins and augmented reality are tools that will have to be taken into account to face these challenges.

There will be also specific areas or components for which nonstandard (tighter) alignment tolerances will be required. Some solutions were developed for linear colliders but are not directly applicable to a circular collider [7]. Sustainable and affordable alignment solutions are under development for an application to the arcs and long straight sections of the FCC-ee, based on Frequency Scanning Interferometry [8] and Structured Laser Beam [9]. The alignment will be even more challenging in the Machine Detector Interface (MDI), combining stringent alignment tolerances, in a harsh and inaccessible environment.

### 2.2 Alignment of the Machine Detector Interface

The two main projects, the future circular collider (FCC-ee) [10] and the circular electron positron collider (CEPC), plan to implement a crab-waist collision scheme, as shown in figure 1. This implies to have a large crossing angle and a small beam-size at the interaction point (IP). For the FCC-ee, these conditions translate into having six independent final focusing quadrupoles, located inside and on each side of the detector. These final focusing quadrupoles will operate at cryogenic temperature, implying to have a cryostat around them. They will also be protected from the detector solenoid by a screening and compensation solenoid, which will sit in the same cryostat.

The final focusing quadrupoles, solenoids, luminometers, beam position monitors and other components inside the detector will require an alignment to a micrometric level as shown in figure 2. This alignment will need to be clearly defined and performed between the MDI components on one side of the detector, but also with the rest of the machine upstream, and finally between the two sides of the detector. Even though the alignment during the assembly is challenging, multiple solutions exist to reach the required accuracy. Laser tracker, Coordinate Measurement Machine (CMM), micro-triangulation could be used in that situation (cf. PACMAN project) [11]. In addition, the monitoring of the alignment will be mandatory for some of the components of the MDI. This is



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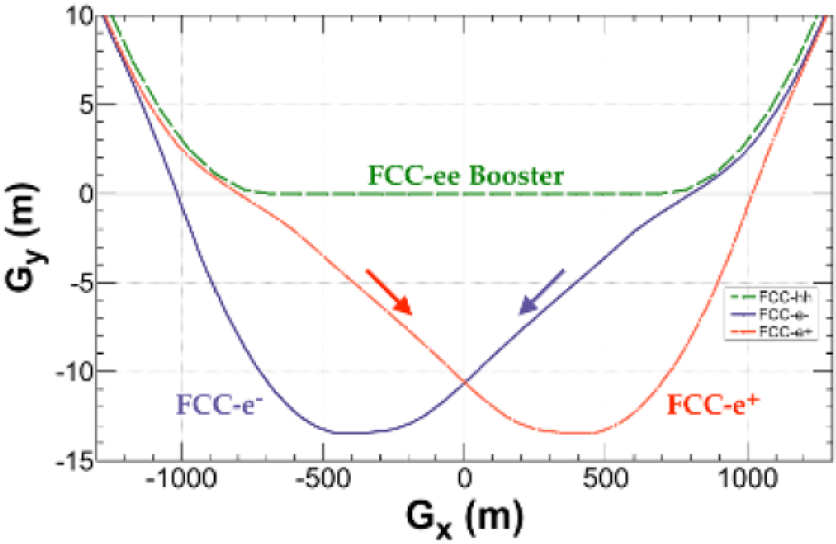


**Figure 1**. Crab-waist layout of the FCC-ee around the interaction point. Reproduced from [10]. CC BY 4.0.

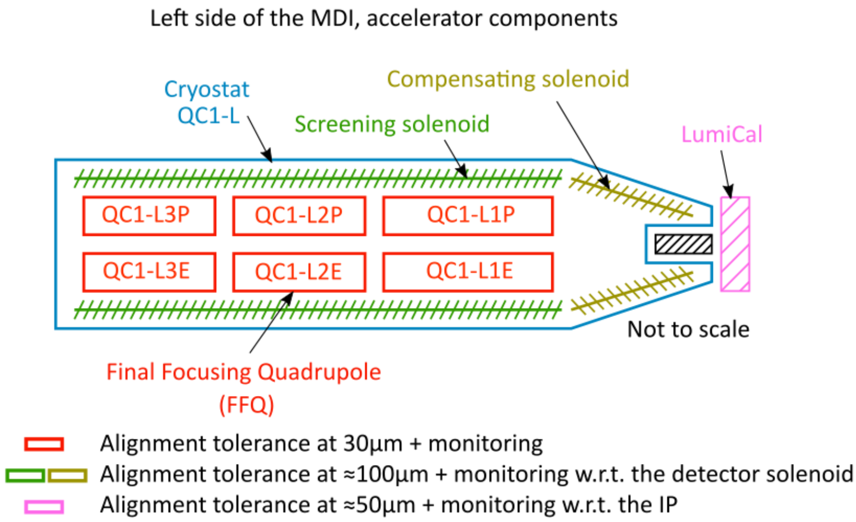


**Figure 2**. Current design of the FCC-ee MDI, with the inner components locations and initial alignment requirements [12].

a common request to all future colliders: CLIC, ILC and FCC. Though for now, this monitoring system is the greatest challenge for the alignment in the MDI [12]. No existing system could be adapted to the FCC needs as the rare monitored MDI (like the LHC) have a design too different from the FCC one. Projects MDI monitoring systems, such like in CLIC [13] or ILC are not mature enough to be implemented. Regarding other sensors, they would have a hard time working in the difficult conditions inside the detector: cryogenic temperatures, radiations, intense magnetic field etc. But new and innovative systems are currently under study [12].

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