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Léonard Watrelot, Andreas Herty, Stéphane Durand

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# CHALLENGES FOR THE FCC-EE MACHINE DETECTOR INTERFACE ALIGNMENT

L. Watrelot, CERN, Geneva, Switzerland, CNAM/GeF, Le Mans, France  
A. Herty, CERN, Geneva, Switzerland  
S. Durand, CNAM/GeF, Le Mans, France

## Abstract

The Future Circular Collider (FCC), a 93 km long circular collider, is one of the projects under study at CERN for the post Large Hadron Collider (LHC) era. Its goal will be to search for new particles while confirming and refining measurements on known ones, such as the Higgs Boson. In order to reach the designed luminosity and the requested accuracy of the collider, the Machine Detector Interface (MDI), and more precisely the components inside, such as the final focusing quadrupoles, the Luminosity Calorimeter (LumiCal), screening and compensation solenoids, will need to be extremely precisely aligned and monitored. The alignment of the accelerator components of the MDI is always difficult due to the detector components around the interaction point. This non continuity in the accelerator also creates an inevitable hole in the alignment system. One needs to design a system around the detector in order to align both sides of the accelerator as no space is available through the detector and therefore no line of sight through the detector is allowed. Though, the MDI currently designed is an innovative and elegant solution, having the final focus components of the accelerator, such as quadrupoles or Beam Position Monitor (BPM) and the LumiCal supported by a skeleton to hang in cantilever configuration inside the detector. This design raises additional challenges as it will limit the type of sensors usable in these confined conditions due to the lack of space, radiations, cryogenic cold and magnetic fields. Today, preliminary known alignment requirements for the inner components are extremely tight and current alignment systems cannot reach these values. This paper will underline these complexities and show why they represent challenges for the FCC-ee MDI alignment. Design, sensors, technology, and alignment tolerances will be discussed.

## INTRODUCTION

The Future Circular Collider is one proposal to be the next generation collider at CERN after the High Luminosity Large Hadron Collider (HL-LHC). This project is planned in two different stages, first a lepton collider, the FCC-ee, and then a hadron collider, the FCC-hh, both fitting in a 93 km long tunnel. The alignment of such a machine is crucial in order to reach the design luminosity, especially the MDI, the area near the interaction point where the circulating beams are finely focused to collide in the center of the physics detector, forming the Interaction Point (IP). Therefore, alignment requirements are extremely stringent for the components of the machine detector interface, which,

for the FCC-ee, are part of a very elegant but complex design. Although some existing accelerators or accelerator projects have MDI similar to the FCC-ee one, the reasons preventing the use of their alignment system for the FCC-ee have never been explained so far, and this is also the case for most of the available sensors. The objective of this paper is to compare the existing accelerators and accelerator projects MDIs to the FCC-ee one, to study eventual limitations preventing the use of existing systems and sensors for the alignment and monitoring of the FCC-ee MDI.

## SITUATION AT THE FCC-EE

### Machine detector interface design

In order to reach the designed luminosity, the FCC-ee will implement a crab-waist configuration at the interaction points. This is done by having a big Piwinski angle, which is obtained thanks to a large crossing angle, and a small horizontal beam size [1]. These requirements translate into having a complex machine detector interface: the final focusing quadrupoles will be placed close to the interaction point in order to lower the distance between the interaction point and the closest final focusing quadrupole,  $L^*$ , stated to be 2.2 m in the FCC-ee conceptual design report [2]. With this requirement and as can be seen on Fig. 1, the six final focusing quadrupoles of each side will need to sit inside the detector, which implies additional components. In order to protect the final focusing quadrupoles and the beam from the detector solenoid's magnetic field, a set of solenoids must be added around them. The screening solenoid will have a 3.6 m long cylindrical shape going from outside to inside the detector with a radius of 0.25 m. At the end, the

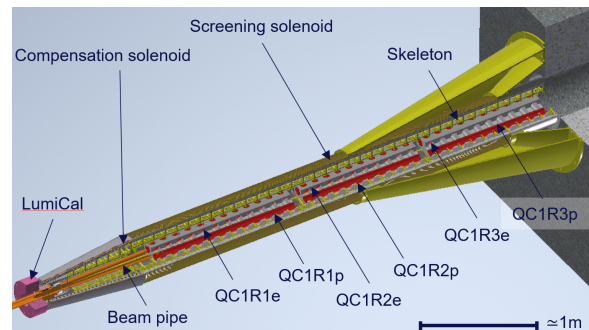


Figure 1: 3D drawing of the accelerator final assembly before the IP. The key components for machine performance in the MDI are supported by the skeleton in a cantilever configuration, held from outside the detector.

compensation solenoid will be installed, with a 0.77 m long truncated cone shape, going from 0.25 m radius to 0.1 m radius. The two solenoids and the final focusing quadrupoles will be surrounded by a thin, skin-like cryostat in order to reach a superconducting state. As the cryostat will not provide any support, the support will be done thanks to a skeleton placed between the final focusing quadrupoles and the solenoids and will support the assembly from outside the detector in a cantilever configuration [2].

### *Constraint implications for the alignment*

This configuration raises a lot of difficulties for the alignment of the components. First, as the assembly will be situated inside the detector, it needs to be as small as possible to avoid occupying too much space near the IP. This implies to have an extremely dense assembly, and so, very little space allocated for each system inside, including the alignment system. As the assembly is supported in a cantilever configuration, the weight will also be limited. Then, the assembly will be located deep inside the detector, access will not be easy and maintenance or repair will be almost impossible without opening the entire MDI. Moreover, the environmental conditions inside this assembly will be extremely harsh, with intense magnetic fields from the final focusing quadrupoles and the solenoids. Cryogenic temperatures are required to reach the superconductive state for all these elements and very high radiation doses are also expected [2]. In addition, mechanical constraints and vibrations will also be limiting factors for the design of an alignment system. Finally, a continuous alignment monitoring of the most important components of the MDI has been asked and the alignment requirements are extremely stringent in order to reach the required luminosity. Initial values for the alignment requirements are of the order of  $30\ \mu\text{m}$  ( $1\ \sigma$ ) for the final focusing quadrupoles and BPM,  $50\ \mu\text{m}$  ( $1\ \sigma$ ) for the Luminosity Calorimeter (LumiCal) and  $100\ \mu\text{m}$  ( $1\ \sigma$ ) for the solenoids [2] which is three times more precise than the precision reached for existing MDIs.

## **SIMILAR EXISTING MACHINE DETECTOR INTERFACES**

For each of the subchapters, a description of the MDI design is given, followed by a description of the alignment system of the MDI. Each section is then concluded by a discussion on the difficulties to adapt the alignment system to the FCC-ee MDI.

### *DAFNE/KLOE*

The DAFNE/KLOE machine detector interface has a similar situation as the FCC-ee MDI: final elements of the accelerator, namely the final focusing quadrupoles, are located deep inside the detector with an  $L^*$  of 0.3 m. In order to support these components, a girder support going through the entire experiment has been chosen, as it can be seen on Fig. 2. This girder is not only supporting the final focusing quadrupoles and accelerator components,

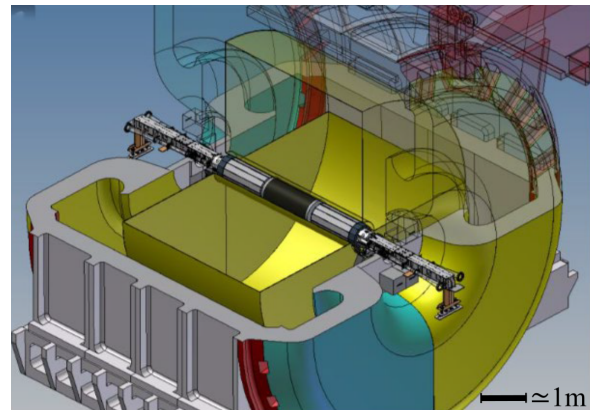


Figure 2: 3D drawing of DAFNE/KLOE machine detector interface. Here, the accelerator components inside the detector are supported by a girder going through the entire detector (gray assembly in the middle).

but also some detector components such as the inner tracker. Alignment requirements were  $100\ \mu\text{m}$  ( $1\ \sigma$ ) for most important components (final focusing quadrupoles) and done thanks to the support. The girder was articulated around the interaction point in two points thanks to two bellows. A set of screws and supports, located at each end of the girder, coupled with laser tracker alignment targets, allowed the alignment of the girder to the requested accuracy. Though, once aligned and entirely assembled, the alignment targets were not visible anymore due to cables and pipes blocking the lines of sight.

Even though the situation is similar to the FCC-ee, the support of the accelerator elements, the alignment requirements and the absence of cryogenic cooling of the final focusing quadrupoles makes it too different from the FCC-ee MDI. Regarding the alignment strategy, it cannot be adapted to the cantilever configuration of FCC-ee as it is too complex and not accurate enough.

### *SuperKEKB/Belle II*

The SuperKEKB/Belle II, shown in Fig. 3, is extremely similar to the project FCC-ee MDI, with final accelerator

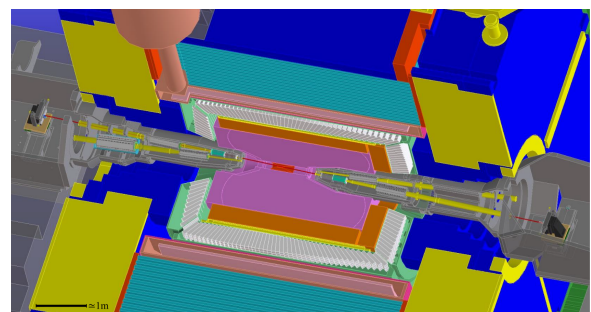


Figure 3: 3D drawing of the SuperKEKB/Belle II machine detector interface. The final focusing quadrupoles are held by the cryostats (grey assemblies on each side of the detector) in a cantilever configuration, as it is planned for the FCC-ee.

components deep inside the detector, supported in a cantilever configuration and cooled down to cryogenic temperatures. The main differences are the asymmetric MDI, as a result of the low energy ring and the high energy ring, and the supporting of the final accelerator components done by the cryostat itself. Alignment requirements were  $100\ \mu\text{m}$  ( $1\ \sigma$ ) for the final focusing quadrupoles and has been carefully fulfilled during assembly of the components inside the cryostat using a laser tracker. While assembling, reference points (fiducials) were installed outside the cryostat and measured with respect to the inner components, in order to know their position once the cryostat is closed. Once everything was assembled and the cryostat closed, the installation inside the detector was performed using the fiducials, measured with respect to a network of reference targets on the walls of the hall hosting the detector. Once the cryostats inside the detector, the alignment of the inner magnets was checked thanks to the single stretched wire system [3]: a conducting wire is passed through the magnets in order to monitor the magnetic fields and to determine precisely their coordinates. This measurement was carried out with magnets not energized and energized to nominal currents.

Even though the design is very similar to the one of FCC-ee, there is no continuous alignment and monitoring system in this MDI, as everything was aligned during the assembly and the position was checked during the installation. The procedure for the alignment during assembly could be used for the FCC-ee but an alignment system is required once the cryostat is closed, to follow the position of important components (and punctual checks are not enough as there will be transport, installation and cooling down that may introduce offsets to the components).

### *LHC/ATLAS, HL-LHC/ATLAS*

An accelerator providing an alignment, monitoring and re-adjustment system for the entire MDI that is remotely



Figure 4: Photo of the low-beta magnets before the physic detector. The alignment systems are highlighted: Hydrostatic Levelling System with water network, support pillars and sensors (light green) and the Wire Positioning System with sensors, stretched wire, wire protection system (light blue).

controllable is the LHC. Even though the LHC/ATLAS MDI is the only mentioned in the rest of the paragraph, the system is installed at each of the four LHC experiments : ATLAS, CMS, ALICE and LHCb. As shown in Fig. 4, in the LHC/ATLAS the situation is very different from the FCC-ee MDI, as the final focusing quadrupoles are located in the tunnel 25 m away from the IP. The monitoring is done thanks to a combination of systems allowing a position determination in three dimensions. This is performed using the Wire Positioning System (WPS), the Hydrostatic Levelling System (HLS) and the Distance Offset Measurement System (DOMS). These systems allow the monitoring of the relative position of the cryostats and thus the final focusing quadrupoles inside. The WPS uses a stretched wire going along all the components needing monitoring, providing a straight reference for the sensors to measure on. This wire requires two stable anchoring points and sensors at each side, strictly independent from the machine and the detector, to avoid any vibration. A wire protection, to avoid any disturbance or unintentional breaking of the wire and a clear line of sight between the two anchoring points, is needed to operate the system. The Hydrostatic Levelling System requires a stable water network along the measured components, linked to the sensors by water and air pipes. These two alignment monitoring systems also require remote validation and maintenance systems, such as a wire displacement system for the WPS and a filling/purging station for the HLS [4]. For the re-adjustment, a system is implemented that acts on the supporting jacks in order to re-align remotely the components.

All this infrastructure requires space that cannot be provided in the FCC-ee MDI. Furthermore, the actual network is not precise enough and is currently allowing a  $100\ \mu\text{m}$  ( $1\ \sigma$ ) alignment. This precision is not meeting the  $30\ \mu\text{m}$  ( $1\ \sigma$ ) required for the FCC, but a more dense network would improve the situation.

### *ILC and CLIC*

Regarding future accelerators, two projects are studied: the Compact Linear Collider (CLIC) and the International Linear Collider (ILC). Both are linear colliders with

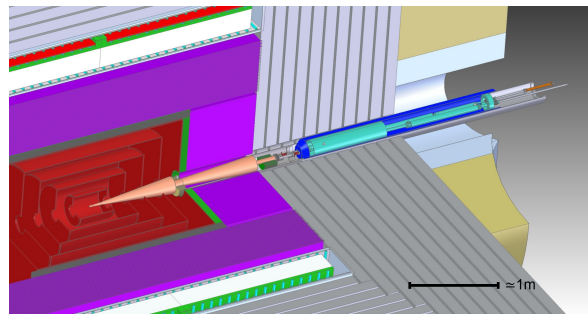


Figure 5: 3D drawing of the project ILC machine detector interface. The final focusing quadrupole (light blue) is inside the detector.

extremely constraining alignment tolerances, especially in the MDI. Both have their final focusing quadrupoles inside the detector, supported in a cantilever configuration. CLIC would not require cryogenic cooling for its final focusing quadrupoles whereas ILC does. This makes the MDI concept of ILC even more complex than the one of CLIC. Though, the major challenge is the exceptionally constraining alignment requirement, of better than  $20\ \mu\text{m}$  for the final focusing quadrupoles for CLIC [5] and ILC [6]. It is important to note that the design is not definitive for these two projects.

For the alignment, no solution has been found so far. Only propositions of exotic designs have been made, like an interferometric distance measurement network for ILC and a ZERODUR<sup>®</sup>-rods configuration monitored by optical sensors for CLIC. But none of these have been demonstrated to work, knowing that the constraints are extremely difficult to deal with. Therefore, these two future generation collider projects do not have the answer for the alignment of their MDI either. This also underlines the difficulty of the situation in the FCC-ee MDI, which is similar to these projects, even though requirements are less stringent.

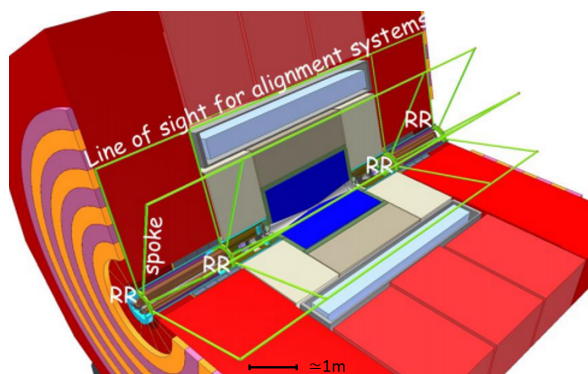


Figure 6: 3D drawing of the CLIC project machine detector interface and a proposed alignment system: ZERODUR<sup>®</sup>-rods touching metrology disks placed at the ends of the final focusing quadrupole. Displacement of the final focusing quadrupoles is then monitored at the other end of the rods with an optical alignment system. The system has never been demonstrated to work.

## CHALLENGES FOR THE FCC-EE MDI

The complex FCC-ee MDI prevents the use of existing systems. The absence of solutions for future colliders project underlines the limits of all existing sensors to reach the alignment requirements, as even exotic system proposals could not meet the requirements of these MDIs. Each technology encounters difficulties in such complex situation.

Optical sensors are very sensitive to radiations and require lines of sight to see the targets they are measuring on. The high radiation doses and the lack of space in the assembly of the FCC-ee MDI prevent the use of this type of sensors.

Capacitive sensors provide micrometric precision and can work in harsh conditions. To combine their individual

measurements in a network covering the elements required to be aligned, they need to be integrated in an infrastructure allowing to precisely measure two or more distinct components separated by long distances without a loss in precision. These networks can range from some centimeters to multiple hundreds of meters. All this infrastructure, like wires, water network or support pillars, that are installed in the LHC MDIs requires a lot of space and cannot fit inside the detector of the FCC-ee. Moreover, a simple scaling of the LHC alignment system to the FCC-ee MDI would require at least four times the amount of sensors for the same amount of components, so even more space would be needed.

Current interferometry sensors are mainly used for in-air measurement, which require a line of sight towards the target and thus some free space. The high required accuracy also implies to have a rather dense network. The space requirement prevents the use of these sensors in the FCC-ee MDI.

Other sensor technologies, for example ultrasound or inductive, are subject to similar problems as most of them are also using infrastructure similar to the capacitive sensors. The fact that even these sensors could not be used in the FCC-ee MDI is once again underlined by the fact that no solution has been found for CLIC and ILC MDIs. Moreover, the access to the sensors will be extremely difficult and possible maintenance will be limited to the extreme minimum.

Finally, it is important to note that the technical considerations mentioned before ignore the considerable challenge to design an alignment system when the MDI design is constantly evolving with regard to component shapes, size, and position.

## CONCLUSION

This paper presents the challenges encountered for the alignment of the FCC-ee MDI and identifies the reasons why they cannot be solved by measurement and alignment concepts currently in use in similar MDI configurations in other accelerators. The main technical limitations are the available space, the operation conditions inside the MDI (cryogenic temperature, radiations, magnetic fields). From the conceptual point of view, the evolving design ideas and the quantification of the alignment requirements leave uncertainties on how to establish such a system. Existing MDI either do not have an alignment and monitoring system,

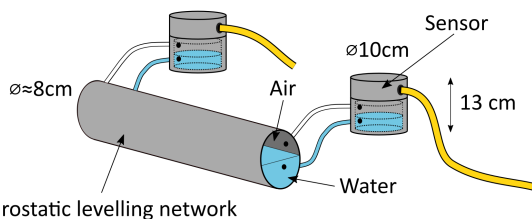


Figure 7: Drawing of a hydrostatic levelling system, composed of a sensor linked to a water network. Filling/purging stations and support system are not represented.

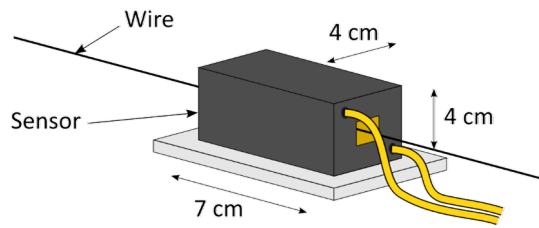


Figure 8: Drawing of a wire positioning sensor, composed of a sensor and a straight wire going through it. Wire protection and wire stretcher are not represented.

as they were aligned during assembly or they have alignment systems adequate for their needs, unfeasible to be adapted to deal with the FCC-ee MDI limitations. These found issues are not unique to this project, as for CLIC or ILC MDI no alignment solution has been published either. The limiting factors are mainly existing sensors and their measurement principles that are unsuited for such alignment. Years of studies on the concepts for other projects, finally lead to proposals for new MDI alignment systems with exotic concepts that lack of adequate sensors and are therefore predestined not to work. The need for such alignment and monitoring system is though identified right from the very first stage of studies for next generation colliders. From the high luminosity upgrade of the LHC to the CLIC, ILC and of course the FCC, all clearly asked for such alignment and monitoring system for their MDI. Studies on new and innovative systems for the FCC-ee MDI are ongoing to face these challenges.

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