ISTITUTO NAZIONALE DI FISICA NUCLEARE

Laboratori Nazionali di Frascati

INFN-23-10-LNF
27 Marzo 2023

PROGRESS ON THE MECHANICAL DESIGN OF FCC e+e- INTERACTION REGION

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Abstract

We present the progress made in terms of the mechanical design of the vacuum chamber, the supporting structures and bellows of the Future Circular Collider e^+e^- FCC-ee. We also present the preliminary assembly procedure for the Interaction Region (IR) components and the preliminary technical solutions proposed for the insertion of all components into the main detector.

PACS:11.30.Er,13.20.Eb;13.20Jf;29.40.Gx;29.40.Vj

Published by
Laboratori Nazionali di Frascati

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[*] *This project has received funding from the European Union's Horizon 2020 research and innovation programme under the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754.*

1 Introduction

The FCC design study is at the feasibility study level, which followed the CDR published in 2019.
The interaction region (IR) is one of the key issues of a collider, it determines its success. It has to provide high luminosity that can be used for physics studies in the detectors with tolerable backgrounds and radiation. For this reason it requires a careful design, balancing the requirements from the accelerator and detector sides.

The mechanical design of the FCC-ee interaction region is a crucial task for the MDI study [1, 2]. In order to ensure an optimal and feasible engineered design, it is necessary to take into account novel technologies and evaluate every aspect, including the manufacturing process and the assembly strategy for all the MDI components (see Figure 1).

The LNF Accelerator Division Mechanical Engineering group is involved in designing the vacuum chamber of the FCC e+e- interaction region, the supporting structures and the assembly procedure for all components of the IR.

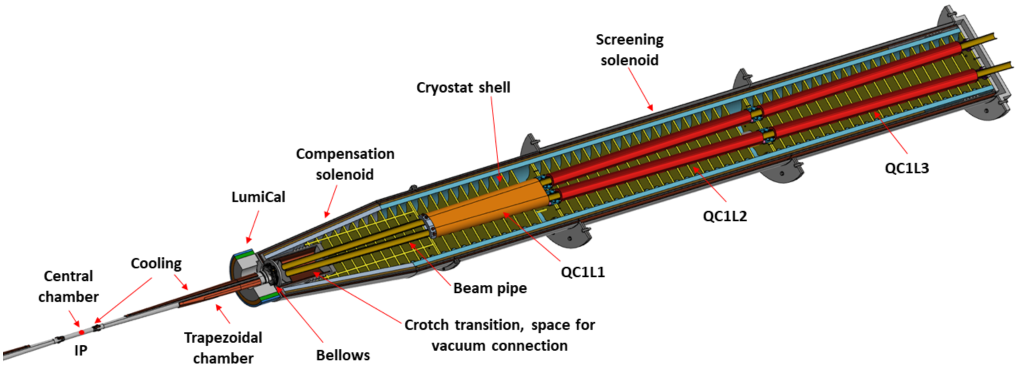


Figure 1: *FCC IR layout*

This activity is included in the activity RD_FCC funded by CSN1 of INFN, and funded by the EU-H2020 project FCC-IS. All the activities have been made the synergy with all groups involved and the results have been presented in more than ten international conferences and workshops.

2 Mechanical Model of the Beam Pipe

The mechanical model of the IR vacuum chamber has to fulfill conflicting requirements: it must have a smooth shape to provide low impedance, it has to be as thin as possible to minimize the material budget as required by the physics performance and at the same time rigid enough to resist stresses, it has to be cooled to control the beam heat loads and possible losses and heat due to synchrotron radiation.

The impedance was minimised by carefully designing the transverse section of the beam pipe, with a smooth transition from a circular to an elliptical transverse shape, as discussed in Refs. [1, 3]. The central chamber extends for ±90 mm from the IP. It will be composed by a double layer of AlBeMet162 with liquid cooling inside through a copper inlet and outlet channel system, as shown in Figure 2. The double layer structure is made of two concentric cylinders, each with a thickness of 0.35 mm and assembled with 1 mm gap for the paraffin flow. This brings the effective diameter of the central beam pipe and its cooling layer to 23.4 mm.

The AlBeMet162 is an alloy of 62 % of Beryllium and 38 % of Aluminium; it has been chosen for its high modulus and low-density characteristics with the fabrication and mechanical properties characteristics of the aluminium. The cooling channels will be in copper, and they will be embedded on the AlBeMet162 by using the additive technique called *thick copper deposition*. The section of the beam pipe smoothly changes from a circular shape to an elliptical shape. The central chamber is merged with two symmetric beam pipes with 15 mm radius at 1.28 m from the IP.

The geometry is optimized to minimize the material budget and to guarantee a proper coolant flow to remove the heat generated by wakefields; the thickness of 0.35 mm of AlBeMet162 is the minimum limit for the mechanical resistance.

Table 1: Composition of the central chamber wall.

	Thickness [mm]	**Material**	X/X_0 (%)
	0.005	Gold	0.15
	0.35	AlBeMet162	0.14
	1	Paraffin	0.18
	0.35	AlBeMet162	0.14
Total	**1.705**		**0.61**

Figure 2: Central chamber in AlBeMet162 including cooling inlets and outlets for the Paraffin cooling circuit housed in a double layer, 180 mm long.

The vacuum chamber starting from 90 mm from the IP to the bellows is shown in Figure 3, and is called *trapezoidal chamber*. After a short transition from the central chamber, the thickness of the trapezoidal chamber remains to a constant value of 2 mm. It will be in AlBeMet162 as for the central pipe. For this region the AlBeMet162 pipe will not be in a double layer to provide the necessary cooling, but there will be copper cooling channels deposited on the AlBeMet162 with the same *thick copper deposition* technique described for the central chamber. In this case the cooling channels on the beam pipe will be asymmetric, as shown in Figure 3 to allow for the required acceptance of the luminosity calorimeter. A cone of 50 mrad was used as the cutting profile.

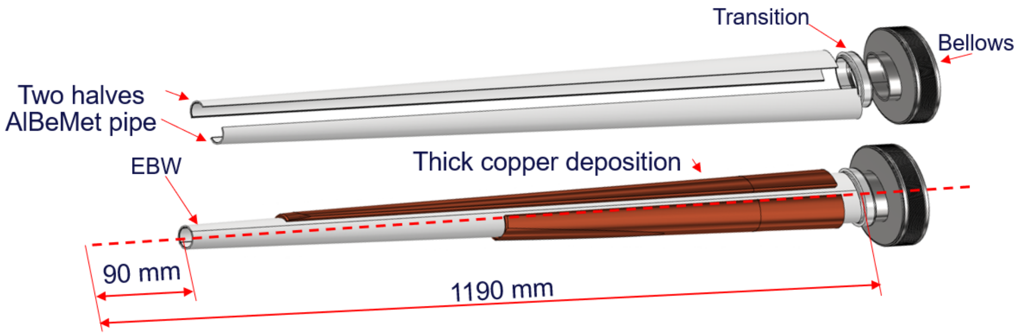


Figure 3: AlBeMet162 vacuum chamber from 90 mm from the IP to the bellows, named trapezoidal chamber for its shape, with asymmetrical copper cooling channels.

The vertex tracker detector will be mounted on top of the central chamber and held by a support placed on top of the trapezoidal chamber.

A thermo-structural analysis has been performed to calculate the temperature distribution, stress, strain and displacement, using the characteristics for paraffin and water flow reported in Table 2 as input.

The temperature distribution for the two chambers is shown in Figure 4, where about 50 W of deposited power was assumed over the central chamber and 130 W over the trapezoidal chamber, and in case of a perfect thermal contact between the materials. This study shows that with paraffin as liquid coolant the maximum temperature of the central chamber will be 33.1 °C, and 47.6 °C for the trapezoidal chamber cooled with water. The paraffin will reach 20.1 °C, and the water 20.5 °C, respectively. This cooling system can tolerate an increase of about 15% of heat load, to sustain higher values it will be necessary to adapt the velocity and flow rate of the coolant flow.

We have performed the structural analysis of the vacuum chamber and estimated its maximum stress and displacement for two constraint configurations: fixed ends or cantilevered-simply support. For this study we considered the earth gravity, the vacuum load and we assumed the vertex detector attached to the chamber; we have also used the temperature distribution along the chamber as input. Results are summarised in Table 3. The stresses and strains are acceptable; the estimated safety factor is about 5, considering that the yield strength of AlBeMet162 is 193 MPa. In any case the buckling behaviour

Table 2: Liquid cooling properties for paraffin and water, used as input for the thermo-structural analysis of the vacuum chamber.

	Paraffin	Water
Flow rate [kg/s]	0.015	0.0019
Section [mm^2]	68.17	9.62
Velocity [m/s]	0.3	0.2
Inlet temperature [°C]	18	18
Convective coefficient[W/m^{2}K]	900	1200

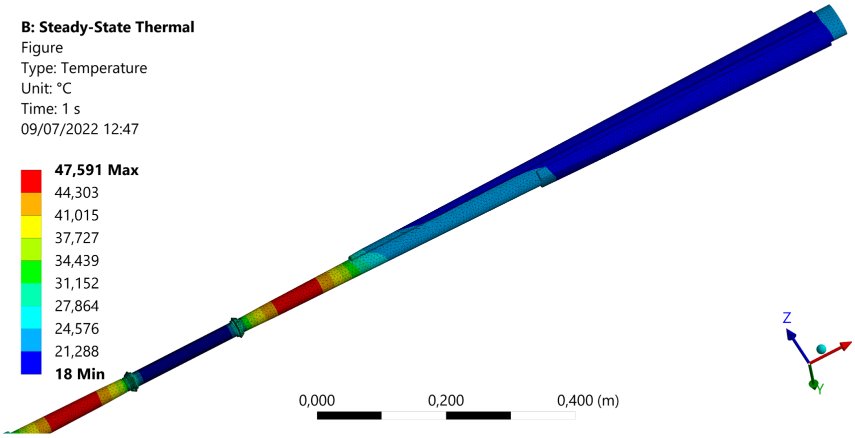


Figure 4: ANSYS [4] simulation of the temperature distribution along the trapezoidal chamber for about 50 W of deposited power over the central chamber and 130 W over the trapezoidal chamber.

is more critical than the static one, therefore some experimental tests would be extremely useful to check our analysis.

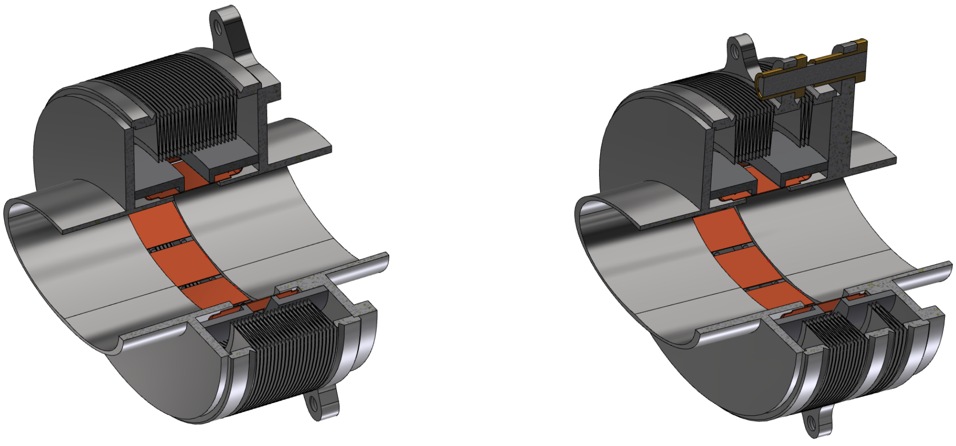
Table 3: Structural analysis in two constraint configurations.

Case	Max Von Mises [MPa]	Max displacement [mm]
Fixed ends	46	0.01
Cantilevered, simply supported	25	0.3

3 Mechanical Model of the IR Bellows

At either ends of the trapezoidal chamber there will be bellows to absorb chamber-to-chamber misalignments, and thermal expansions of the order of few millimeters. The IR bellows has to be as compact as possible due to the small space available, which is about 70 mm longitudinally. We discuss here how the proposed design of the bellows fits with our mechanical requirements.

The bellows will be attached on one side to the trapezoidal chamber, on the other side to the remote vacuum flange, close to the superconducting IR magnet system, which will be embedded in a cryostat. For the moment we considered only the elongation due to the thermal expansion given by beam heat load and that due to the assembly. Two slightly different bellows geometries are proposed at each IP side to isolate the central chamber from external stresses and strain due to assembly and operation conditions. They will have the same axial length and the same RF contacts configuration, but with a different convolutions configuration, maintaining a symmetrical geometry. The study of the electromagnetic forces on the magnets in case of accidental quench has not been performed yet. This will give an additional specification to the possible elongation of the bellows.



(a) Single bellows (b) Double bellows

Figure 5: Bellows concepts of FCC IR

Since bellows can create a resonant cavity and lead to vacuum, stability and overheating problems, any geometrical discontinuity has to be avoided and electrical contact must be preserved. An adaptation of ESRF bellows design [5] has been considered as a starting point for our design. There are twelve CuBe blades lying around elliptical shape of vacuum chamber and the desired electrical contact is obtained by a blade pusher.

The first bellows, named *single bellows*, is shown in Figure 5 (left). It is properly anchored to the endcap of the support tube with a flange that will allow to align the beam pipe inside it. On the side toward the cryostat the bellows has convolutions to mitigate the thermal expansions that also provide the proper clearance during the assembly and the connection between the remote vacuum connection and the vacuum chamber.

The second bellows, named *double bellows* and shown Figure 5,(right) is a bellows with the same envelopes and dimension of the *single bellows* to keep a symmetrical geometry but with two set of convolutions, thus allowing to isolate the IR beam pipe from stress and strain coming from the assembly procedure and during the operation, i.e. thermal expansion, and to preserve the thin walled central chamber. On the side toward the IP the bellows is made up of few convolutions to absorb the thermal expansion of the IR beam pipe; a linear bearing system is used to allow only an axial degree of freedom. On the cryostat side the bellows has more convolutions to provide suitable clearance for the assembly. An intermediate flange is present and anchored to the support tube endcap.

The wakefields calculations to evaluate the impedance budget for these bellows are in progress with the simulation code CST [6] and are not subject of this paper.

4 The Support Tube and the MDI Assembly Strategy

4.1 IR Carbon-fibre Support tube

This section describes a novel concept for the FCC-ee MDI, the support tube, that has been developed to ease the integration of the accelerator and detector components into a single rigid structure. In particular, this structure will allow to provide a cantilevered support for the pipe, it will avoid loads on thin-walled central chamber during assembly, and it will support the LumiCal and the outer tracker. The support tube is an empty cylindrical structure made with a multiple layer structure, composed as described in Table 4.

Table 4: Composition of the multiple layers structure.

Thickness [mm]	Material	Orientation
0.25	Epoxy carbon woven (230 MPa)	45
0.25	Epoxy carbon woven (230 MPa)	-45
0.25	Epoxy carbon woven (230 MPa)	45
0.25	Epoxy carbon woven (230 MPa)	-45
4	Honeycomb	0
0.25	Epoxy carbon woven (230 MPa)	-45
0.25	Epoxy carbon woven (230 MPa)	45
0.25	Epoxy carbon woven (230 MPa)	-45
0.25	Epoxy carbon woven (230 MPa)	45

This support tube is longitudinally split in two halves, it is complemented by two aluminium flanges, and by two endcaps that will support the LumiCal and the beam pipe (Fig. 6). Six aluminum ribs are fixed inside the tube in order to support the outer tracker. It will be introduced inside the detector thanks to longitudinal rails fixed to its external surface.

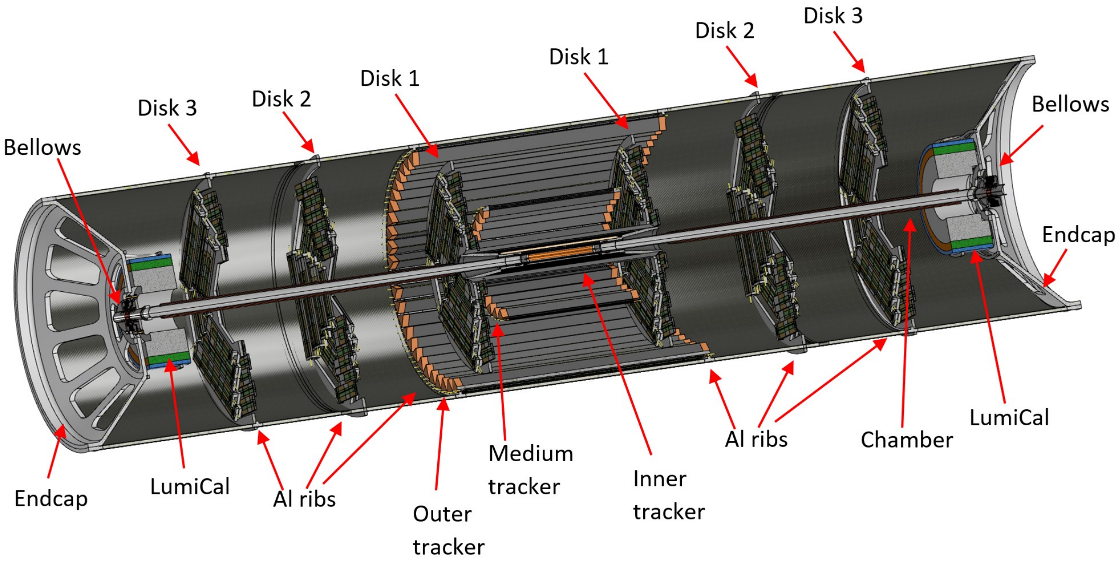


Figure 6: Carbon-fibre cylindrical support tube.

A structural analysis has been performed to calculate the stress and displacement in each part of the support tube, namely the reinforcement, carbon-fibre, and the honeycomb. The double fixed ends case has been considered as constraint configuration. The loads that have been considered are listed in Table 5.

Table 5: Loads considered over the support tube for the structural resistance analysis. For the disks, medium and outer barrel a safety margin of a factor 3 has been considered to account for the services.

Component	**Value [kg]**
Vacuum Chamber	51
LumiCal	2×70
Disks	18
Medium Barrel	3
Outer Barrel	11

The analysis was performed using overestimated values, which take into account estimated weights of the additional services material (such as the water ducts and the power cables that run from the detection region to the end of the support tube) finding that the structural resistance is safely respected.

The results of the analysis are summarized in Table 6, they show the small stress and displacement values.

Table 6: Structural analysis of the support tube, results of the maximum stress and maximum displacement.

Support tube	**Maximum stress [MPa]**	**Maximum displacement [μm]**
Aluminium flanges	2.70	13
Aluminium ribs	0.09	14
Honeycomb	0.001	15
Carbon fiber	0.30	

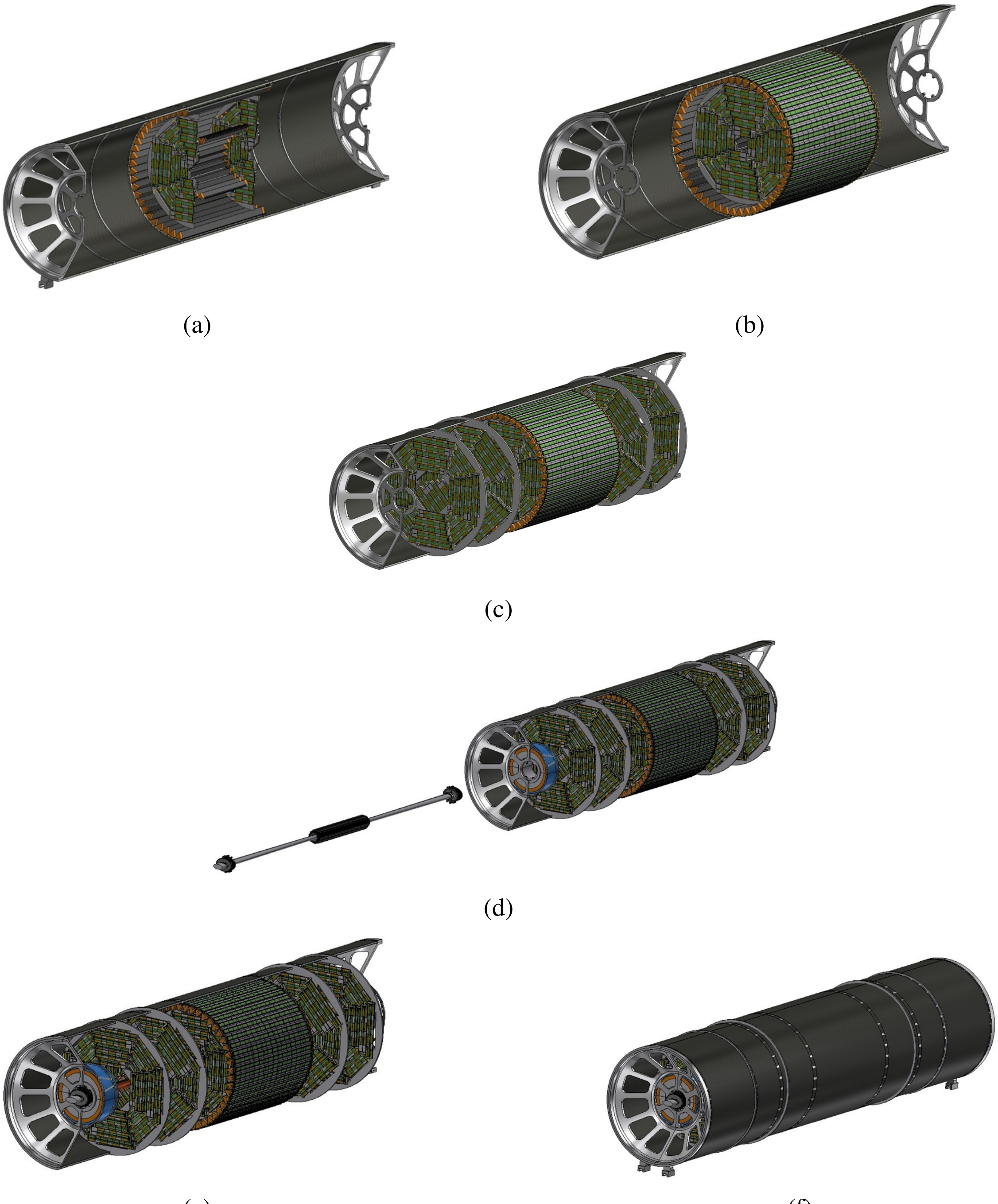
4.2 Assembly sequence and alignment

Thanks to the design of the support cylinder, the assembly of the entire system can be implemented in a modular way allowing a careful alignment of all the MDI components.

The assembly sequence has been careful studied and is schematically described in Figure 7. We do plan to model the assembly sequence both with CAD as well as with dedicated tools using a mock-up of all components.

One of the two halves of the cylinder is taken as a base for the mounting the detector components and the vacuum chamber. It will be mounted on a cradle which will sustain it rigidly.

The first step consists of assembling the Outer Barrel, the Medium Barrel and the innermost disks (disks 1) as a single mechanical structure in the laboratory. This assembly



(a) (b) (c) (d) (e) (f)

Figure 7: MDI assembly sequence

will then be fixed to the half cylinder (a). Successively, the other disks will be positioned and installed over the reinforcement ribs of the support tube (b).

After the positioning of the Outer tracker parts, the LumiCal will be mounted in a centered position on the endcaps of the support tube, and it will then be fixed to it (c).

The vacuum chamber, together with the vertex detector mounted on top, will be then slid inside, using a dedicated tool, and the Lumical can be aligned in its final position (d).

Finally, the second half of the support tube will be installed, concluding the assembly procedure (e).

5 Conclusion

This work it is necessary to evaluate the feasibility of the IR design; everything is still in progress and more versions of the design will come, therefore it is important to adopt a flexible way for designing and evaluate the new technologies that will be developed in the next years. This progress report is going to be presented during the mid-term review in the middle of 2023 and during the FCC week 2023 in London.

6 Acknowledgements

The results have been obtained in synergy with the LNF group, especially with Manuela Boscolo, in charge of the MDI coordination and Luigi Pellegrino as former head of the Mechanical Department of the Accelerator Division at LNF and recently with Enrico Di Pasquale, the new group leader of the Mechanical Department. A special thanks to Pisa-INFN group, specifically to Fabrizio Palla and Filippo Bosi for the design of Vertex Detector, medium tracker, outer tracker and disks. Thanks for the support from FCC project in its entirety.

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