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Mechanical design of the interaction region of the Future Circular Collider e^+ e^- and support structural optimization(*)

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Summary. — We describe the vacuum chamber of the Future Circular Collider e^+ e^- interaction region, the conceptual design of the bellows and the lightweight structure called Support Tube. We also present a study on the structural optimization of the support structure. The aim is to optimize the structure to reduce the mass, maintaining the stiffness needed. Finite element analysis is used to develop a detailed numerical model considering complex geometries, material properties, and loading conditions. The study seeks to identify design improvements using optimization algorithms, such as Solid Isotropic Material with Penalization, Generative Design and Lattice approach.

1. – Introduction

The Future Circular Collider e^+ e^- represents a significant challenge for the global scientific community. The high level of the project demands an equally high level of design and scenario anticipation from the current feasibility study phase to the realization of the machine. The FCC project is a precious opportunity to use the most innovative techniques in mechanical design, such as structural optimization.

2. – Mechanical design of the vacuum chamber

The vacuum chamber (fig. 1) design starts from the IP (Interaction Point), extends up to the bellows (1.2 meters from the IP), and is divided into two parts. The Central Chamber, from 0 to 90 mm, consists of two concentric cylinders with a thickness of 0.35 mm, spaced 1 millimetre radially to create a gap for the paraffin flow.

The second part, called the Trapezoidal Chamber, extends up to the bellows and is created in two halves welded with EBW (Electron Beam Welding) and it is water cooled.

The design is asymmetric due to Luminometer requirements.

A thermo-structural analysis of the chamber has been performed using thermal loads derived from impedance calculations with CST [1] and project loads and constraint conditions.

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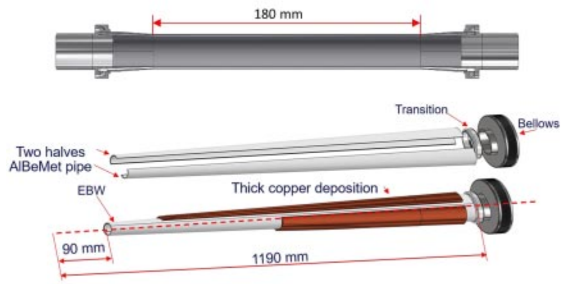

Fig. 1. – Vacuum chamber of FCCee IR from 0 to 1.2 mm from the IP.

3. – Bellows mechanical design

The bellows is particularly important to prevent misalignments during assembly and compensate for thermal elongation. Specifically, the one depicted in the figure is a bellows with two sets of convolutions: the smaller set is responsible for compensating for thermal deformations of the chamber, while the larger set will compensate for misalignments during assembly and operation. The bellows will be supported in the central part between the two sets of convolutions (fig. 2).

4. – Support tube mechanical design

In order to support the components of the interaction region, a cylinder has been designed in two halves with reinforcing ribs and two endcaps. This cylinder will be inserted inside the main detector.

The cylinder structure consists of layers of carbon fibre arranged appropriately with a layer of honeycomb in the centre (fig. 2). The disks, medium, and outer trackers will be anchored to the reinforcing ribs, while the luminometer and the chamber will be attached to the endcaps. A structural analysis has been performed on the carbon cylinder to assess deformations and stress caused by the loads and demonstrate full compliance with the stiffness requirements of the structures.

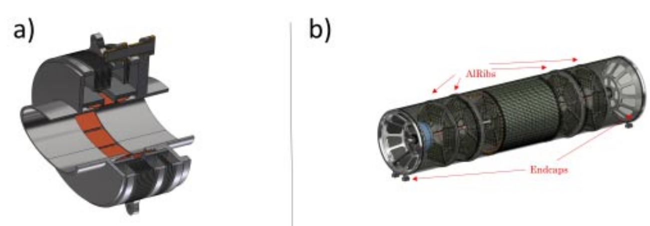

Fig. 2. – a) Section of the bellows with two series of convolution; b) Support Tube with the all components mounted.

5. – Structural optimization

The structural optimization of the support structures of the interaction region is currently underway for the endcaps and the anchoring structure to the detector. The study is exploring various optimization methods that will be compared, evaluating the effectiveness of each. After selecting the most suitable method for the structures, a more detailed optimization will be carried out, considering the design variables that can be optimized. Currently, the SIMP algorithm, based on the concept of penalization, and the Generative Design method, capable of creating a structure from an initial shape and spatial constraints, have been used.

The Solid Isotropic Material with Penalization (SIMP) [2] aims to find lightweight and efficient structures by penalizing intermediate densities. The SIMP approach assigns varying material densities to different regions of a design domain, with lower densities representing void spaces and higher densities representing solid materials. Introducing a penalization factor, intermediate densities are discouraged, leading to designs with concentrated material distribution.

The Generative Design [3] has the opposite approach of SIMP; this type of design starts from the constraints and loads geometries and, imposing some particular constraint shape, it can progressively generate the optimal shape. This algorithm utilises techniques like genetic algorithms, neural networks, and machine learning to refine and improve designs iteratively.

The lattice structure with Field Driven design allows to create of an infill or some area using lattice structure linking the thickness of the lattice to a function created by a point map based on a structural optimization. For each point of the map, depending on the stress value calculated, is possible to associate a local value of the thickness that changes with the stress. In this way, it is possible to create a lattice structure with an ununiform thickness that follows the need in terms of resistance.

These methods have been used to optimize the interface between the Support Tube of the FCC interaction region and the detector. The first step made is a preliminary analysis to study the number and position of anchoring points for the Support Tube. After the choice of the best configuration has been performed three structural optimizations for each design, using two different SIMP algorithms and a Generative Design algorithm. After the comparison of these designs has been performed a study of the final flange of the support structure, using the SIMP algorithm, the Generative Design and the lattice structure with Field Driven design.

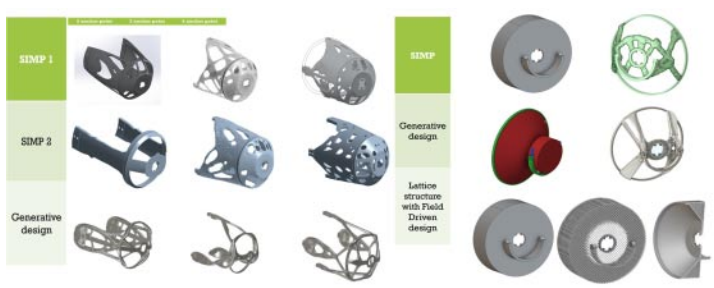

Fig. 3. – Result for support structure between Support Tube and Detector (left); result for the Support Tube endcap (right)

Table I. – *Structural optimization results of the support between Detector and Support Tube*

Method	Mass reduction	Max stress [MPa]	Max deformation	Nº anchoring point
SIMP1	65%	30	0.1	2
SIMP2	76%	12	0.1	2
Generative	69%	3.4	0.1	2
SIMP1	69%	10	0.05	3
SIMP2	61%	12.6	0.04	3
Generative	73%	2.5	0.1	3
SIMP1	44%	6	0.1	4
SIMP2	49%	7	0.02	4
Generative	68%	2.6	0.09	4

6. – Results

It is possible to compare the different results obtained using SIMP and Generative Design for the global support by looking at fig. 3 and table I. The mass reduction, the maximum stress and the displacement have been evaluated.

Analysing the results of SIMP (1&2) and Generative Design, the method that allows to minimize more efficiently the mass, respecting the constraint in terms of maximum displacement (0.1 mm) and maximum stress (3.4 MPa), is the Generative Design method, especially for the case with 3 and 4 anchoring points.

7. – Conclusion

The design of the components is in continuum evolution, but the conceptual design has been proposed, considering the fundamental constraints. The comparison of the different approaches of optimization is still in progress. It is necessary to highlight that the lattice method is still in study, and a comparison has not been performed yet. The Generative Design allows to obtain good values of the mass reduction, maintaining acceptable values of displacement and stress, pointing out the advantages of the method.

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