First Considerations on the Supporting Structures of FCC-ee Booster and Collider in the Arc Regions

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ABSTRACT: In 2022, the FCC Feasibility Study management mandated a working group to analyse the best configuration of the FCC-ee tunnel in the arc regions, in view of the construction of a mock-up of the arc half-cell. One of the main and most challenging goals of the study, named FCC-ee Arc Half-Cell Mock-up Project, was to perform a preliminary investigation on the principles of supporting the Short-Straight Sections and dipoles of the half-cells, both for the booster and for the collider machines. This is an important input needed for the choice of the best configuration of the relative placement of the booster with respect to the collider. The structural stiffness, mass and stability of the supporting structures must be optimized to minimize the vibrations transmitted/transferred to the magnetic system of the accelerators by elements such as pumps, water cooling system, beam thermomechanical stresses, powering elements, etc. To perform the study, tools such as CAD software, FEM and analytical techniques were employed. This paper summarizes the preliminary design concepts and the results of the simulations performed.

KEYWORDS: FCC-ee, mock-up, arc, cell, supports, vibrations, FEM.

Contents

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1. Introduction

An arc half-cell is the most recurrent assembly of mechanical hardware in the accelerator. The *Zh* and $t\bar{t}$ FCC-ee configurations count 3 000 of such half-cells. Building a mock-up of this tunnel section allows optimizing and testing aspects related to fabrication, integration, assembly, transport, installation, alignment, stability and maintenance.

The FCC Feasibility Study (FCC FS) management mandated a working group to develop such mock-up [1]. The first phase of the project, completed at the end of 2022, aimed at the integration of the different elements and supporting systems in the arc region. In this phase, one of the main challenges was to perform a preliminary investigation on the principles of supporting the Short-Straight Sections (SSS) and dipoles of the half-cells, both for the booster and for the collider. This input is important for the choice of the best configuration of the relative placement of the booster with respect to the collider. The stability of the supporting structures must be optimized to minimize the vibrations transmitted to the structure by pumps, water cooling system, beam thermomechanical stresses, powering equipment.

2. Configurations of the arcs

The length of the booster half-cells in all phases of FCC-ee is 26 m, whereas the collider will feature long half-cells (52 m) in the *Z* / *W* phase, and short half-cells (26 m) in the later *Zh* /$t\bar{t}$ phase. In the FCC-ee CDR [2], the booster and the collider are positioned at a similar vertical position, radially shifted one with respect to the other. Studies performed in 2022 have shown that, on the other hand, a positioning of the booster on top of the collider, at the same radial position, present significant advantages [3], especially from the integration and radiation points of view [4]. This second, vertical configuration is however more problematic for the stability of the booster magnets in the SSS, since the lever arm beam-ground is larger, and longer support is intrinsically less stiff. **Figure 1** shows the two configurations in the cross-section of the tunnel, assuming a diameter of 5.5 m.

While a choice between the horizontal and vertical booster-to-collider configurations has not been formally taken yet, the efforts around the stabilization of the supporting system were directed at the vertical case, which is the most demanding one. We will thus focus in this paper on the supporting of the vertical configuration.

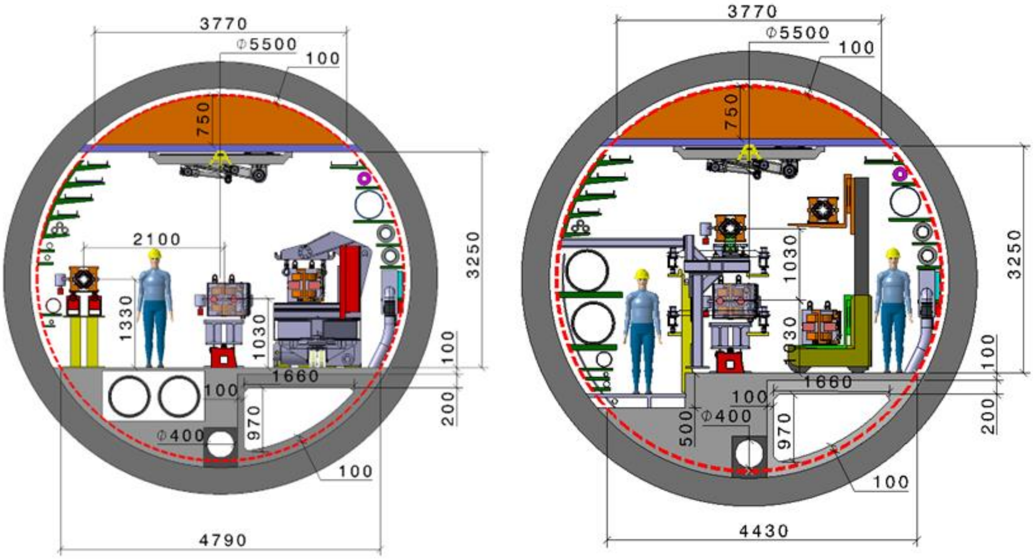

Figure 1. Configurations for the relative placement between booster and collider. Left: horizontal configuration. Right: vertical configuration.

The CDR also considered the booster SSS and the collider SSS at the same azimuthal coordinate, during the short half-cell phase. However, this presents significant disadvantages, as the SSS is, for both machines, the most demanding region from the integration point of view. In terms of volume, in fact, this region features the biggest magnets, as well as the beam instrumentation, alignment and support systems, especially when a girder is used to support the quadrupoles and sextupoles. A longitudinal shift between the SSS of the booster and the collider, maintaining intact their periodicity (*i.e.* booster and collider SSS are shifted by a delta which is maintained constant along the ring) is therefore proposed. See a scheme of this in **Figure 2**.

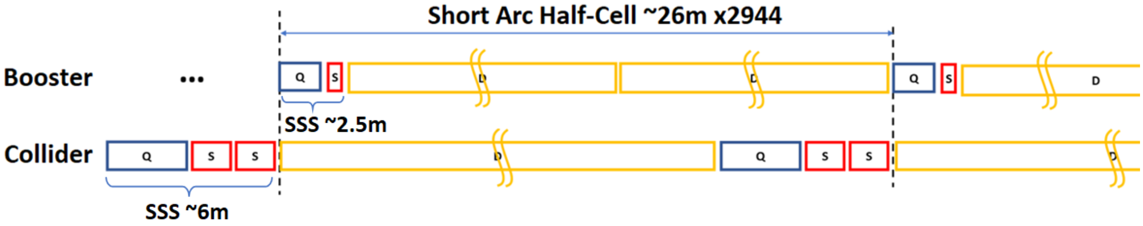

Figure 2. Azimuthal shift between booster and collider.

3. Optimization of the arc element supports

The application of a longitudinal shift of the SSS between the booster and the collider leads to an improvement of the compactness of the design of the booster supporting system. An evolution of the support design is shown in **Figure 3**. In a nutshell, a 46 cm radial dislocation of the booster position permits positioning its beam axis in correspondence of the vertical supporting rods, with beneficial effects on the stability. The lowering of the booster position reduces the lever arm, further increasing its stability. The combination of these two principles leads to a further improvement, in particular on the bending mode of the horizontal beam, as seen in **Figure 3**.

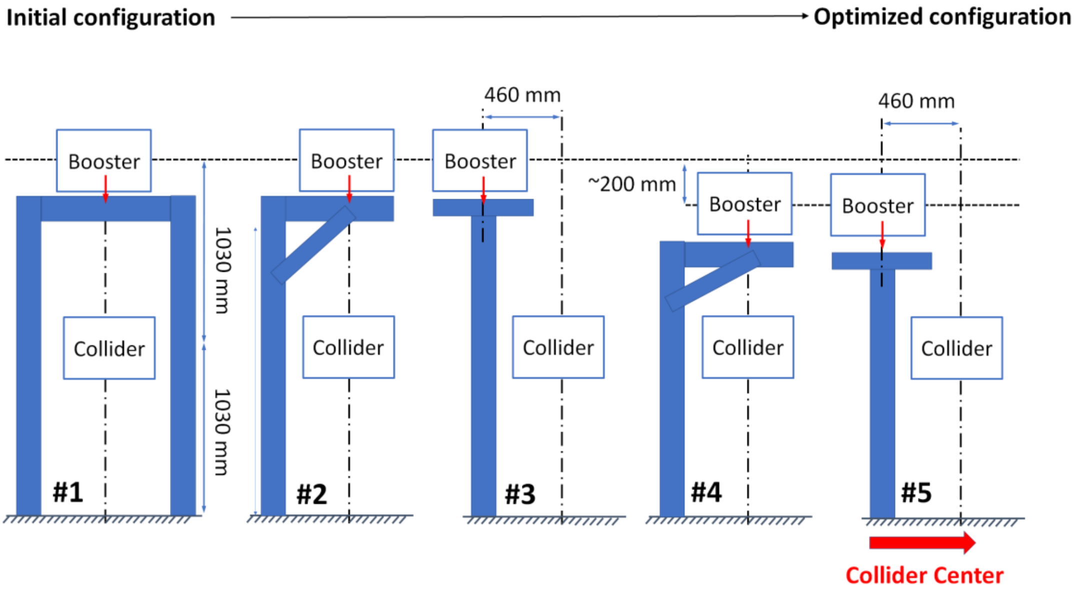

Figure 3. Principles of optimization of the booster supporting system and placement, in case of a vertical configuration.

Two types of FEM simulations were performed: static structural analyses to evaluate the deformation of the system under the weight of the booster SSS, as well as modal analyses to estimate the improvements in terms of stiffness. Results are reported in **Figure 4** and **Figure 5**.

Mode Shape	**FCC Week '22** Frequency [Hz]	**First Iteration** Frequency [Hz]	**Shifted Horizontally** Frequency [Hz]	**Shifted Vertically** Frequency [Hz]	**Shifted Vertically & Horizontally** Frequency [Hz]
Longitudinal	*7*	*18*	*24*	*21*	***29***
Bending Cantilever Arms/ Torsion Horizontal Beam	7	19	23	29	**29**
Bending Horizontal Beam	14	36	41	40	**54**

Figure 4. Natural frequencies of the booster SSS under different supporting concepts.

The longitudinal mode is reported for reference, even though it is not particularly relevant for this study, as it does not generate vertical/horizontal displacements which are detrimental to the beam. The results show a significant improvement of the system stability along the different iteration. The stiffness of the system is increased by almost one order of magnitude, with a gain on the natural frequencies of a factor of four. We aim for this preliminary study at having at least

~30 Hz for the first bending mode, based on past results obtained on systems such as the PETRA IV girder (46 Hz) [5]and the PSB-LIU girder (29 Hz) [6].

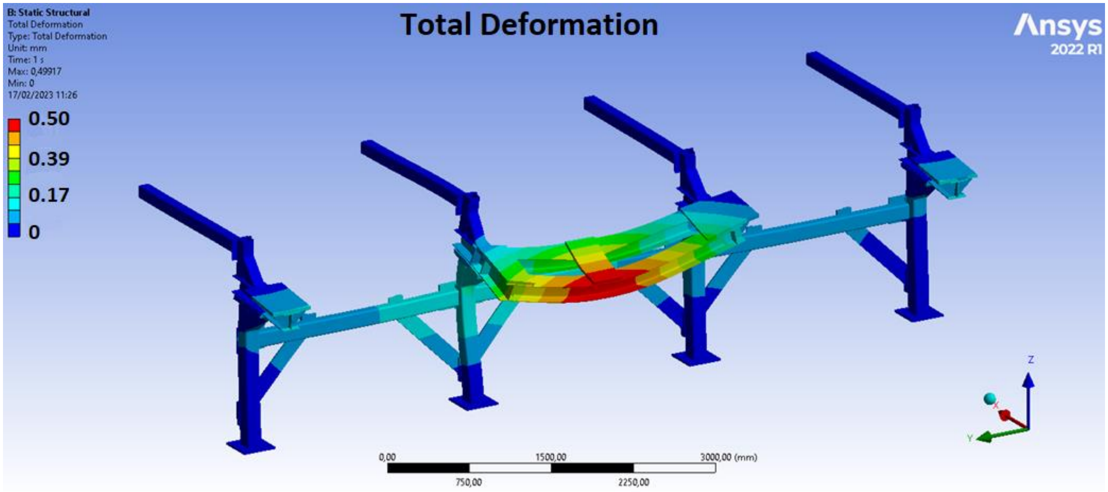

Figure 5. Static deformation of the booster supports under the weight of the SSS. Maximum in this configuration is 0.5 mm.

As a result of the iteration between design and simulations, a first layout of the arc half-cell with preliminary supporting systems was prepared, and is shown in **Figure 6**.

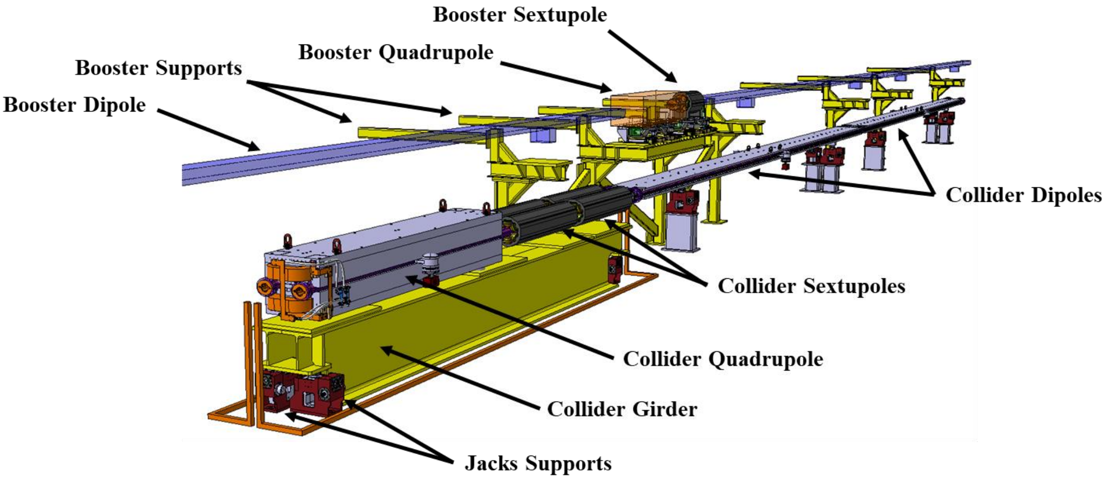

Figure 6. CAD model of arc cell short straight section.

4. Conclusions and perspectives

As a result of an iterative work involving integration studies, design and simulations, a preliminary version of the supporting system for the FCC-ee booster and collider elements in the arc regions has been defined. The study will be completed by random vibration analyses including a reasonable footprint of the expected ground motion [7], as well as adding the collider to the FEM model, to evaluate the vibrational crosstalk. The oscillation at the level of the beam axis can then be evaluated and compared with the demanding specification, in terms of stability, of the FCC-ee magnets (See **Table 1**). In the scope of a collaboration with the Laboratoire d'Annecy De

Physique Des Particules (LAPP), the effect of vibrations on the beam emittance and luminosity will also be analyzed through beam optics simulations, as described in [8].

Table 1. Dynamic stability requirements.

Frequency Range [Hz]	Tolerance [nm]	Correlation*
100 ÷ 400	1	None
10 ÷ 100	5	None
1 ÷ 10	20	None
0.01 ÷ 1	100	None
0.01 ÷ 1	1000	10 km

* correlation between the movement of all the quadrupoles within a given distance

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