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INTEGRATION OF FCC-EE RF SYSTEMS TARGETS AND CHALLENGES

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Abstract

Following the progress on the study of the FCC-ee radiofrequency (RF) systems (i.e. length of the cryomodules (CMs)), general services infrastructure (i.e. electrical, cooling, ventilation), transport and handling volumes, and alignment requirements, the 3D integration has evolved with a new configuration scenario. This paper describes the new proposal to locate the collider RF elements (400 MHz and 800 MHz CMs) at point H, and the booster RF elements (800 MHz CMs) at point L, without changing the 5.5 m inner diameter tunnel (see Fig. 1).

INTRODUCTION

The Future Circular Collider (FCC) is planned as the next-generation particle accelerator at CERN, which allows the scientific community to expand their knowledge of the standard model using particle collisions at high energies. The FCC will require extensive civil underground infrastructure in shafts, caverns, tunnels, and surface buildings to achieve this goal.

The FCC electron-positron collider (FCC-ee) design is still being optimised for the feasibility study, even if many improvements have been implemented [1]. The machine optics have been adapted to the new layout with eight surface sites instead of twelve surface sites [2], a circumference of 90.7 km and a four-fold super-periodicity, which allows four collision points and experiments (see Fig. 1). The main ring optics and RF configurations have been refined to simplify operation across the energy range.

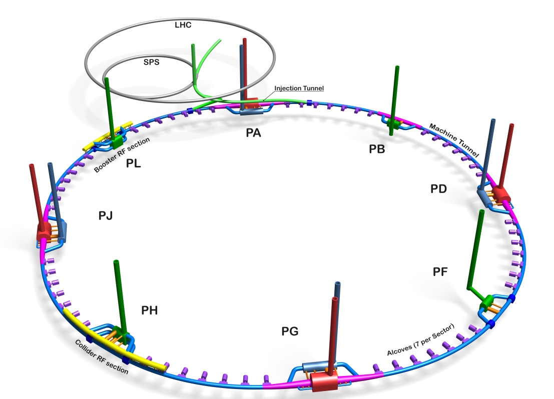

Figure 1: FCC schematic layout - 2023

TARGETS IN RF SYSTEM INTEGRATION

RF System Configuration Study

The RF system for the FCC-ee is composed of elliptical SuperConducting (SC) cavities operating at 400 MHz and 800 MHz housed in segmented CryoModules (CM) and powered by high-power klystrons and solid-state RF amplifiers. The overall system serves the crucial function of accelerating the particle beams from an injection energy of 20 GeV to the final energy of the chosen operation mode *Z*, *W*, *H* and $t\bar{t}$ going from 45.6 to 182.5 GeV. It also compensates for energy losses due to synchrotron radiation at a power level of 50 MW per beam in a continuous wave. During the Conceptual Design Report (CDR) phase of the FCC study, a RF system concept was proposed based on the experiences of previous machines like the Large Electron-Positron (LEP) and the Large Hadron Collider (LHC), and is oriented toward both niobium thin film and bulk niobium technology for the superconductor.

Integration Configuration Study

In the CDR study, the proposed layout was equally splitting the SC cavities, and for them to be housed at two opposite straight sections of the circumference, at point D, and point J.

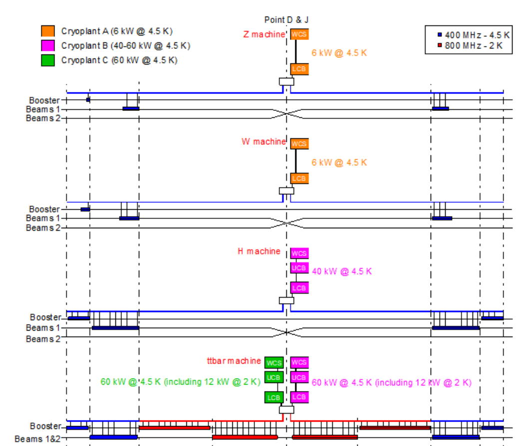

Figure 2: RF and Cryogenic layout - CDR

The number of cavities increases progressively with the different physics modes. Table 1 and Table 2 summarize the quantity of CMs required according to the physics configuration mode.

Table 1: Number of CMs Required for the Collider (CDR)

Configuration	400 MHz	800 MHz
Z mode	26	0
W mode	26	0
H mode	93	0
$t\bar{t}$ mode	68	0

The first integration proposal of the SC cavities was to start from the extremity of the straight section to the center. In the

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Table 2: Number of CMs Required for the Booster (CDR)

Configuration	400 MHz	800 MHz
Z mode	0	3
W mode	0	13
H mode	34	0
$t\bar{t}$ mode	34	120

first three physics modes, *Z* to *H*, the machine had separated collider beams (e+ and e-), and in $t\bar{t}$ machine operation both collider beams were converged in a single beam pipe (see Fig. 2). The total length of the RF sections at point D, and point J, were 2.2 km.

The defined RF equipment integration was in a horizontal plane configuration following the FCC-ee regular tunnel integration study [2] , where the collider main ring was sitting next to the booster ring.

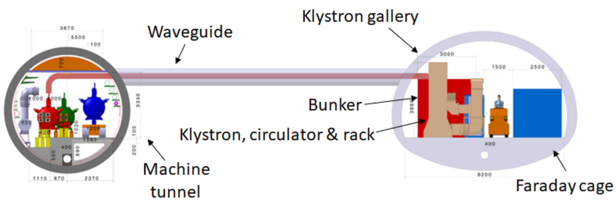

Figure 3: Tunnel and klystron gallery RF 400 MHz-CDR

The klystron gallery was next to the machine tunnel in a horizontal plane and the waveguide was routed to pass over the CMs, and below the smoke/He extraction duct. The diameter of the cryogenic distribution line (QRL) is 0.65 m, and 1.14 m for the 400 MHz CMs. With that configuration the machine tunnel remained at 5.5 m in diameter but the access of the robot system on the ceiling in the RF sections became impossible.

Looking for better integration of the RF equipment and following the FCC-ee RF study, for which dynamic losses had to be optimized, the number of the 400 MHz CMs and 800 MHz CMs in the different operation modes had to be adapted. Additionally, modifying the collider and booster integration configuration in the arc [3]. A new integration solution for the RF section was then studied (see Fig. 2).

CHALLENGES IN RF SYSTEM INTEGRATION

RF Feasibility Study

During the past three years, critical challenges were addressed and detailed designs of the main RF components were performed, allowing the refinement of the RF parameters [4]. The design effort of new types of high efficiency klystrons and RF power couplers confirmed the possibility of providing up to 1 MW of RF power per cavity to the beam. Thanks to a careful optimization of the cavity shapes, a trade-off was found between lowering the electromagnet surface fields and limiting the risk of parasitic beam-cavity interactions. The accelerating gradient of 10 MV/m at 400 MHz and 20 MV/m at 800 MHz was confirmed. However, it was chosen to switch from 4-cell to 2-cell cavities for the *W* and *Z*/*H* modes to favour the damping of higher-order modes thus reducing the risk of beam instability. Some changes in the total RF voltage and the beam intensity were also done for beam dynamic constraints, leading to an increase of the number of cavities for some operating modes [5]. This is compensated by the fact that the RF system is now common for the Z/H mode in addition to the $t\bar{t}$ mode, and that the booster is now running at 800 MHz instead of 400 MHz allowing to reach a higher accelerating gradient.

A priority in key challenges for the next years, will be the limitation of liquid helium quantities and cryogenic consumption at the temperature of 4.5 K and 2 K. A special R&D program oriented towards new surface treatments of the SC material technology is being launched and it will confirm whether the aggressive target values of dynamics losses can be reached.

Integration Feasibility Study

One of the big challenges for integration was to keep the tunnel size to 5.5 m in diameter at RF sections. The main constraints are the vertical configuration of the collider and booster rings with a distance of 1.03 m, and the size of the QRL which increased with the number of the 400 MHz and 800 MHz CMs. The safety requirement for personnel is to provide passage for the robotic systems at the RF sections for better monitoring and evacuation of people from the machine tunnel in case of an accident. To keep the tunnel diameter at 5.5 m to house all the RF elements in the Long Straight Sections (LSS), a solution separating the RF elements for the collider ring at point H, and RF elements for the booster ring at point L is proposed [6].

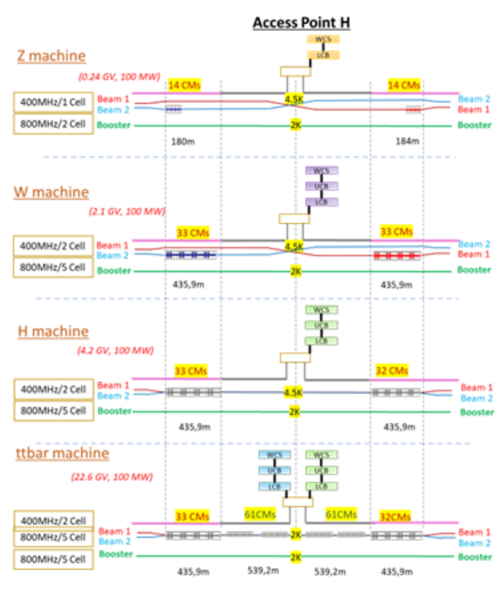

Figure 4: RF and Cryogenic Layout point H - 2023

The number of collider CMs at point H (see Fig. 4) for the different physics configuration modes is shown in Table

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3. The total length of the RF straight section is 1.95 km.

Table 3: Number of CMs required for the collider (Feasibility Study phase)

Configuration	400 MHz	800 MHz
Z mode	28	0
W mode	66	0
H mode	66	0
$t\bar{t}$ mode	66	122

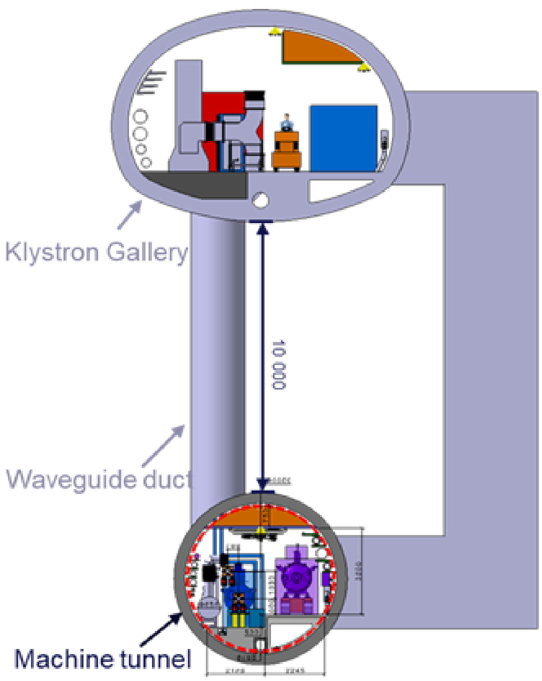

Figure 5: Tunnel and klystron gallery RF 400 MHz point H - 2023

The klystron gallery has been proposed to be above the machine tunnel with vertical waveguides passing through with a duct of 1 m in diameter, as already done for other projects (LINAC4, HL-LHC). This solution eases the cavities integration in the tunnel. Thanks to the relocation of the booster 800 MHz CMs, the tunnel diameter of the LSS can be the same as the arc 5.5 m in diameter. The stairs connecting the machine tunnel and Klystron gallery were added every 280 m to ease the evacuation, and maintenance and commissioning work. The klystron gallery will also house power supplies of quadruple magnets, survey equipment, and beam instrumentation racks. The cables will go through the waveguide ducts from the klystron gallery to the machine tunnel (see Fig. 5). This solution will give more space in the machine tunnel by reducing the number of the cables and water pipes attached to the wall.

The number of booster CMs at point L (see Fig. 6) for the different physics configuration modes are shown in Table 4. The total length of the RF straight section is 1.3 km.

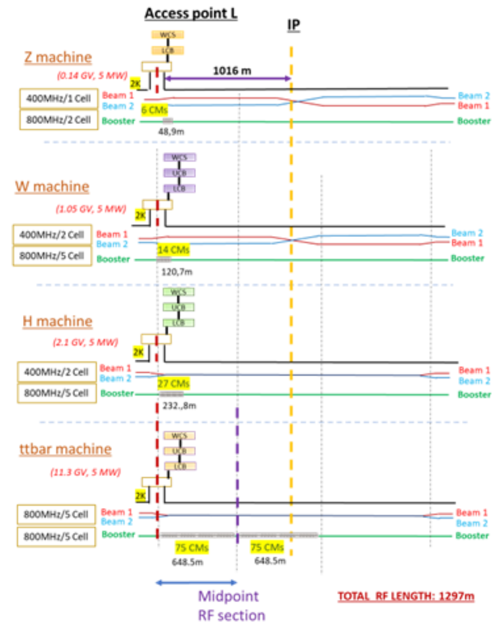

Figure 6: RF and Cryogenic Layout point L - 2023

Table 4: Number of CMs required for the booster (Feasibility Study phase)

Configuration	400 MHz	800 MHz
Z mode	0	6
W mode	0	14
H mode	0	28
$t\bar{t}$ mode	0	150

Due to surface constraints, the access shaft at point L should be located few hundred meters anticlockwise from the center of the LSS. The center of the RF section in the offset to the center of the LSS, and the final 800 MHz CMs starts 100 m before the end of the LSS. This non-symmetric arrangement of the RF elements lead to an increase in the QRL size to 0.8 m in diameter compared to 0.65 m in diameter at point H [6]. The klyston gallery is also placed above the machine tunnel, as for point H .

CONCLUSION

The 3D configuration layout of the RF section is a key part of the FCC feasibility study and was presented at the midterm review [1]. Its integration is still at a conceptual level and needs to be regularly updated with the evolution of the design of the CMs, the cryogenic lines, and other machine elements. The layout of the klystron galleries will further evolve with the technical design of all services. Lastly, the service caverns need to be designed, considering the requirements of the hadron machine (FCC-hh). The main result of this work is the validation of a 5.5 m tunnel diameter for both RF sections, which is identical to the arc tunnels. This will ease the civil engineering work and minimise the cost. The integration works will continue towards a Technical Design Report.

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