

ELECTRO-MAGNETIC SEPARATOR TOPOLOGY CONCEPT FOR FCC-ee

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Abstract

The layout of the FCC-ee collider requires the separation of the electron and positron beams, which are circulating in opposite directions, on either side of the RF system. Only one of the two beams must be deflected, while the other one (the beam circulating in the direction of the RF) shall remain untouched to avoid synchrotron radiation being emitted toward the RF section. This functionality is achieved using a combination of an electric field and a perpendicular magnetic field, which must be matched to each other along the entire length of the separator to avoid synchrotron radiation (SR) emission toward the superconducting RF cavities. In order to satisfy the matching condition $B = E/c$ for relativistic particles, an extremely weak magnetic field (5 mT) is required for a given achievable static electric field (1.5 MV/m). This article presents a concept that combines an under-vacuum electrostatic system with a low-field large-aperture outside-vacuum dipole magnet to achieve the main separation functionality while providing excellent field matching and low SR production. In addition to the concept development, three critical aspects have been identified and are the subject of ongoing studies to assess feasibility by end of 2027: high-voltage (HV) breakdown, beam coupling impedance and machine protection.

INTRODUCTION

The Future Circular Collider electron-positron (FCC-ee) [1] is a high-luminosity lepton collider proposed at CERN, designed to operate at four centre-of-mass energies: the Z (45.6 GeV), WW (80 GeV), H (120 GeV) and $t\bar{t}$ (182.5 GeV) modes. At the two highest energy modes, the collider RF system, located in the long straight section at Point PH, is shared between both counter-rotating beams. In this common-RF scheme, the electron and positron beams traverse the RF cavities on a common trajectory, but at different times. This arrangement avoids the need for two dedicated RF systems and maximises the use of the RF infrastructure. This configuration requires a specific beam separation system at each end of the RF section and involves a new type of equipment: the Electro-Magnetic Separator (EMS) [2]. Downstream of the EMS, septa magnets will support beam separation and add to the integration challenge at Point PH, where space is constrained despite the kilometer-scale straight section. The EMS must deflect the beam leaving the RF section toward the arc (outgoing beam), while leaving the beam circulating in the direction of the RF system (incoming beam) entirely unperturbed. This constraint is critical since any deflection of the incoming beam

would produce synchrotron radiation (SR) toward the superconducting RF cryomodules, risking thermal perturbation.

The EMS concept is currently developed by CERN's Beam Transfer group (SY-ABT). The present article introduces the electromagnetic topology concept, the preliminary specifications, and the key technical challenges under investigation in the framework of the Reference Design Phase.

OPERATING PRINCIPLE

The EMS separates the beams trajectories by exploiting (i) the Lorentz-force contributions from the electric and magnetic fields and (ii) the reversal of both charge sign and propagation direction between the two counter-rotating beams. Given the Lorentz force $F_x = q(E_x - v_z B_y)$ and considering the left side EMS in Fig. 1, the transverse horizontal forces on the electron beam (charge $-e$, incoming with velocity c_z) and on the positron beam (charge $+e$, outgoing with velocity $-c_z$) are respectively:

$$F_{x,e^-} = (-e)(E_x - c_z B_y) = -eE_x + e c_z B_y, \quad (1)$$

$$F_{x,e^+} = (+e)(E_x + c_z B_y) = eE_x + e c_z B_y. \quad (2)$$

When the fields amplitudes satisfy the matching condition in Eq. (3), the contributions of E_x and B_y cancel for the electron beam (incoming), which sees a zero net force, while they add up for the positron beam (outgoing), which experiences a net deflection. Following similar principle, the same but opposite situation occurs in the right-side EMS of Fig. 1.

$$B_y = E_x/c \quad (3)$$

Satisfying condition in Eq. (3) pointwise along the full device length, including in fringing regions, is the central design challenge addressed in the following section.

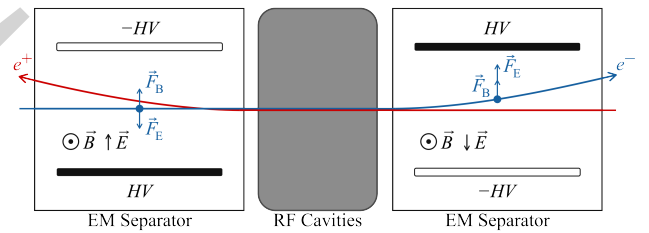


Figure 1: Lorentz force vectors acting on the e^- beam at two locations: as the incoming beam (zero net force) and as the outgoing beam (superimposed deflecting force).

ELECTROMAGNETIC TOPOLOGY CONCEPT

Topology and Design Choices

The EMS topology combines two co-axial static devices: an *under-vacuum electrostatic separator* providing the electric field, and an *outside-vacuum dipole magnet* surrounding

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the vacuum vessel and providing the magnetic field. Based on previous operational experience of electrostatic separators in the Large-Electron-Positron collider (LEP), a conservative static electric field magnitude of 1.5 MV/m has been selected to minimise electrical breakdown during operation. A nominal electric field of $E_x = 1.5$ MV/m results in a weak magnetic field of only $B_y = 5$ mT. Achieving and maintaining such a low magnetic field with precision is part of the identified challenges. The estimated required length for the EMS system is 44 m per side. The current specifications propose a system segmentation into 11 units to ensure mechanical feasibility and allow independent field trimming per unit. Segmentation is also anticipated to limit the impact of a breakdown fault in an individual unit w.r.t. machine protection. Space reserved between consecutive units is accounted for in the total system length, allowing placement of possible SR masks and vacuum-related equipment. The preliminary specifications are summarised in Table 1.

Table 1: Preliminary EMS Specifications

Parameter	Value	Unit
Total deflection	0.44	mrad
Number of units	11	–
Deflection per unit	40	μrad
Total system length	44	m
Unit length (flange to flange)	3	m
Electrode gap	120	mm
Nominal electric field ($\bar{t}\bar{t}$)	1.5	MV/m
Electrode voltage ($\bar{t}\bar{t}$)	± 86.4	kV
Nominal magnetic field ($\bar{t}\bar{t}$)	5	mT
Coil current ($\bar{t}\bar{t}$)	87	A
Coil turns (2 coils in series)	10	–

Electric and Magnetic Fields Matching

Defining the local field error $\Delta(z) = B_y(z) - E_x(z)/c$, two integrals with distinct consequences must be considered. $\int \Delta(z) dz$ governs the net deflection and can be zeroed by slightly trimming the power supplies. By contrast, the integral $\int |\Delta(z)| dz$ is irreducible: wherever $\Delta(z) \neq 0$ locally, the incoming beam acquires a transient deflection angle and emits SR toward the RF cryomodules. Its magnitude, set by the EMS topology and manufacturing quality, is the primary design figure of merit: better local matching reduces residual SR production, and can also benefit equilibrium emittance preservation by minimising beam disturbances.

Achieving good local matching is particularly challenging in the fringing regions, where the electric and magnetic field profiles naturally differ due to the large aperture difference between the electrodes and the dipole magnet. Following an initial phase of conceptual research, the best results were obtained using a novel topology presented in Fig. 2, which combines curved electrode shapes, precise positioning of the dipole magnet relative to the electrostatic system, and shielding components that sharply cut both B and E fields in the fringing regions, ensuring synchronised field transitions.

As shown in Fig. 3, the peak amplitude of $\Delta(z)$ in the fringing regions is less than $4 \cdot 10^{-2}$ of the main field, which represents less than $200 \mu\text{T}$ at the $\bar{t}\bar{t}$ operating point and yields to an integrated error of $\int |\Delta(z)| dz = 0.045 \text{ mT}\cdot\text{m}$ per unit. In terms of SR production, a preliminary study indicates that this translates to less than 10 mW produced by the 11 consecutive EMS, and that SR are emitted in a narrow cone with an half-opening angle of approximately $15 \mu\text{rad}$. The potential consequences of X-ray photons impacting the cavity walls and the requirements for potential protection elements must still be studied.

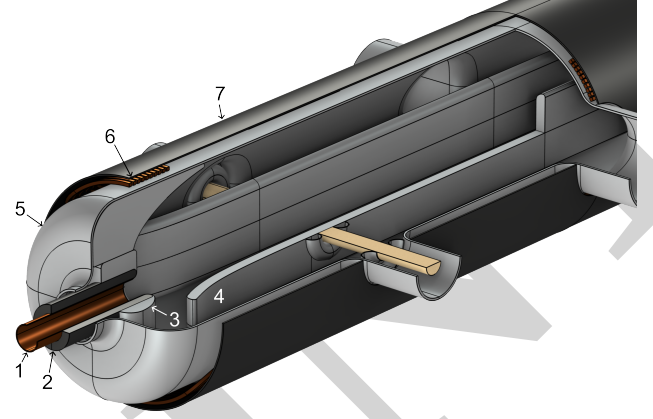


Figure 2: EMS concept model: 1) Beam screen 2) B-field shield 3) E-field shield 4) Electrode 5) Vacuum vessel 6) Multi-turn coil 7) Thin iron yoke. Auxiliary and structural components are not shown.

Dipole Magnet Topology

A specific large-aperture and low-field dipole magnet concept compatible with the EMS requirements is shown in Fig. 2. The most important aspect of this magnet is the ability to gradually reduce the magnetic field amplitude at both ends of the EMS by a proper distribution of the coil end-turns. By optimising the placement of those end-turns to locally reduce the magnetic field, it is possible to ensure a sufficient distance between the electrodes and the E-field shield to avoid high electric field enhancement.

The proposed magnet features a circular yoke surrounding the vacuum vessel, offering greatly reduced mass and space requirements compared to a standard H-frame topology of the same aperture. The thin yoke structure enhances the magnetic flux density within the iron, enabling operation in a predictable region of the B-H curve. To allow the passage of HV feedthrough and electrode supports through the vacuum vessel, the yoke features large side openings that locally disturb the magnetic field uniformity; this is corrected by longitudinal yoke shimming. Two multi-turn coils in series are designed for low current density, requiring only indirect cooling and providing a balance between voltage and current that is compatible with standard power supplies.

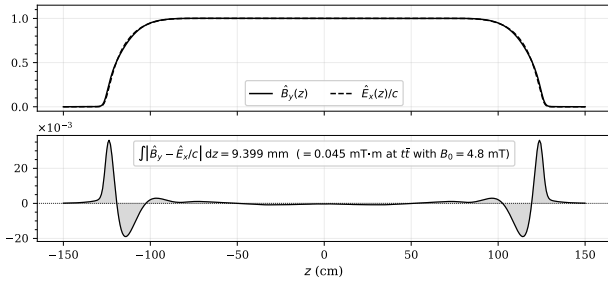


Figure 3: On-axis field matching along one EMS unit from FEA: normalised profiles $\hat{B}_y(z)$ and $\hat{E}_x(z)/c$ (top) and their local residual $\hat{B}_y - \hat{E}_x/c$ (bottom). The integrated absolute mismatch (9.4 mm) rescales linearly with B_0 to 0.045 mT·m at the $\bar{t}\bar{t}$ operating field (simulated at $B_0 = 4.8$ mT).

TECHNICAL CHALLENGES

Beyond the electromagnetic design challenges addressed in the previous sections, the following aspects require particular attention during development: integration of the electrostatic and magnetic sub-systems within the available space, integration of vacuum equipment and HV circuit, thermal management of magnet and electrodes, compatibility with bake-out, and, fundamentally, compatibility with the beam optics and the operational scheme. To date, three aspects are also considered as major feasibility uncertainties, for this reason the 3 studies presented below are given a high priority and are considered essential toward reaching a viable concept.

Beam Coupling Impedance

The EMS concept presents a concerning geometry from the perspective of beam coupling impedance. This has already been pointed out from the Circular Electron-Positron Collider (CEPC) study for a similar equipment [3]. A beam impedance study has been launched at CERN with 2 parallel approaches: (i) Simulation of the EMS concept model from Fig. 2; and (ii) Simulations, measurements, benchmarking and prototyping based on an former LEP electrostatic separator, with an emphasis on research of impedance mitigation techniques.

High-Voltage (HV) Breakdowns

HV equipment like the EMS are prone to electrical breakdown, a phenomenon leading to a temporary fault, and that must be contained in one single unit. The EMS will, in addition, be exposed to SR from the upstream arcs, which is expected to increase its breakdown rate. An experimental program is underway at CERN to investigate the dependency of breakdown rate on SR. For this, a pair of under vacuum electrodes are exposed to pulsed and DC electric fields up to 80 MV/m, while being irradiated with X-rays [4]. Breakdown rate and field emission are monitored on the system to study this dependency. Further studies and collaborations are already anticipated in an effort to improve the fundamental understanding of breakdown mechanisms.

Machine and Equipment Protection

Two type of failures can occur within the EMS units: (i) A HV breakdown leading to a complete loss of electric field in the EMS unit. (ii) A power outage affecting a magnet and leading to a reduction of the magnetic field. Both of these faults break the fields matching condition. If such failures occur at the entrance of the RF cavities, they may result in a non-zero incoming beam angle and non-rectilinear trajectory within the cavities. A major concern is the synchrotron radiation generated inside the RF cavities due to this oscillatory trajectory, potentially leading to radiation-induced damage or undesired heat loads on RF structures. Similarly, failures occurring at the exit of the RF cavities may reduce the deflection angle, leading to insufficient beam separation. This can lead to trajectory distortions in the arcs, potentially resulting in beam interception on arc components, increased synchrotron radiation and beam instabilities. System segmentation into independent units, with HV decoupling resistors, limits the impact of a single event [5]. Overall, EMS failures represent a source of fast trajectory excursions, and their impact will be carefully evaluated to define the required protections.

DEVELOPMENT AND VALIDATION PLAN

The EMS is a novel equipment type presenting a low level of maturity where requirements and specifications are subject to regular iteration. The current project phase (Reference Design Phase) aims to separately validate each critical aspect of the EMS concept in the laboratory or by relying on high-fidelity simulations. This must improve the project's maturity level by converging toward a stable concept architecture with a clear feasibility statement by the end of 2027. In addition, the integration requirements of the EMS system must be confirmed to allow the civil engineering procurement phase to begin in case of project approval. The Reference Design Phase also prepares the project for the next phase: the Technical Design Report, for which a full-scale prototype of the EMS is foreseen.

CONCLUSION

A novel electromagnetic separator topology concept for the FCC-ee common-RF scheme has been presented. The topology combines an under-vacuum electrostatic separator with an outside-vacuum dipole magnet in a segmented system architecture. The electromagnetic study of this topology demonstrates the possibility of ensuring the main functionality of separating the electron and positron beams while reaching excellent local field matching. Three key technical challenges have been identified as critical regarding feasibility and triggered ongoing experimental and analytical studies: HV breakdown, beam coupling impedance, and machine protection. The proposed topology provides a concept baseline for the Reference Design Phase, with a feasibility assessment targeted by the end of 2027.

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