

MAGNETS DEVELOPMENT FOR THE ESRF-EBS INJECTION UPGRADE

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Abstract

Projects to improve the injection performance of the storage ring and to reduce the equilibrium emittance of the booster are currently in progress at the ESRF. The booster light upgrade involves replacing 18 existing quadrupoles with 3 families (6 magnets per family) of quadrupoles featuring different yoke lengths. An upgrade of the injection zone includes the installation of a Non-Linear Kicker and the replacement or modification of several electromagnets, as well as the septum S3. In this paper, we present the magnetic design of the booster electromagnet quadrupoles and the TL2 transfer-line permanent-magnet quadrupoles. A preliminary design of a permanent magnet septum S3 is also presented.

INTRODUCTION

The ESRF booster was constructed over 30 years ago as the injector for the original ESRF storage ring and remains in use today for injection into the Extremely Brilliant Source (EBS). While several of its components have been upgraded over time, and it is now operated off-energy with emittance exchange at extraction, the lattice itself has not been modified since the 1990s. A proposed upgrade aims to reduce both the equilibrium emittance and the bunch length by replacing 18 quadrupole magnets [1]. The booster is based on a FODO lattice with three straight sections featuring dispersion suppression. It currently includes 39 focusing quadrupoles, 39 defocusing quadrupoles, and 66 dipoles, all powered in series by independent channels of the Ramped Injector Power Supply (RIPS). This upgrade is relatively cost-effective, as it reuses the existing ramped power supply and requires only the replacement of 18 quadrupole magnets. The new lattice design achieves lower horizontal emittance and shorter bunch length (Table 1). An additional benefit of replacing these magnets is the recovery of 18 old quadrupoles that can be kept as spares, addressing the current limitation of having only two spare units available.

Table 1: Main Booster Parameters

	Present Booster	Light Upgrade
ϵ_x (nm rad)	83.1	59.6
BL (mm)	22.6	19.9
Quad families	2	5
Sext families	2	2

The ESRF-EBS injection scheme currently relies on a conventional off-axis injection using four kickers. In user

service mode (USM), this approach achieves an injection efficiency of up to 80%. However, during injection, some beamlines are perturbed and data acquisition must be temporarily halted. The existing system is now reaching its limits in meeting the objective of fully transparent injection, making it necessary to explore alternative schemes.

A new approach based on non-linear kickers (NLK) has therefore been considered. Preliminary studies indicate that this scheme could enable fully transparent injection while preserving high injection efficiency [2]. To implement this solution, modifications to both the storage ring and transfer line optics, as well as to the lattice layout, were required. These changes ensure the integration of the non-linear kickers within the injection cells and the replacement or modification of several electromagnets, as well as the septum S3.

DESIGN OF BOOSTER QUADRUPOLE MAGNETS

The magnets will be laminated to limit the eddy currents generated by the energy ramp. Table 2 presents the main parameters of the booster quadrupole magnets. The magnetic design of the 18 booster quadrupoles magnet has been done using Radia Software [3] (Fig.1).

Table 2: Booster Quadrupole Parameters

Description	Parameter	Unit
Gradient	15	T/m
Bore radius	30	mm
Current	481	A
Magnet length	500-575	mm
Ramping rate	4	Hz

The design of the new quadrupole is based on the existing magnet geometry, with a limited number of targeted modifications. In particular, the previously implemented multi-step chamfer with a specific contour has been removed in favour of a simplified pole profile. This change reduces manufacturing complexity while maintaining the required magnetic performance. The 18 quadrupoles are divided into three families, with six magnets in each family. All magnets share the same two-dimensional cross-section; the only difference lies in their length along the longitudinal (beam) axis. The integrated multipoles are reduced to few units for all the current range from 15 A to 481 A.

Figure 2 shows the mechanical design of the booster quadrupole. The main differences from the current design lie in the pole profile, as well as in the electrical and hydraulic connections.

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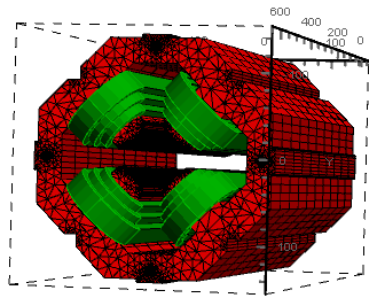


Figure 1: 3D Radia model of the booster quadrupole.

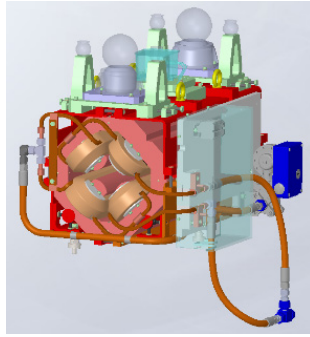


Figure 2: Mechanical design of the booster quadrupole.

A call for tender was launched in 2025 for the manufacturing of 21 quadrupole magnets, including 18 magnets for installation and 3 spare magnets. The company ELYTT Energy [4] has been selected, and production is currently underway. A prototype magnet will be manufactured and measured, and the number of laminations will be adjusted to achieve the required integrated gradient. Series production will begin following validation of the prototype.

DESIGN OF TL2 PERMANENT MAGNET QUADRUPOLE

To accommodate the modifications to the storage ring layout and the reduction of the injected beam horizontal offset from 15 mm to 8 mm, the downstream section of the booster-to-storage ring transfer line (TL2) was redesigned. The quadrupole layout was adjusted accordingly, with three electromagnetic quadrupoles replaced by two compact permanent magnet quadrupoles (Table 3) to prevent interference with nearby storage ring magnets.

Table 3: TL2 PM Quadrupole

Description	Parameter	Unit
Gradient	30	T/m
Bore radius	14	mm
PM material	Sm2Co17	
Remanence Br	1.14	T
Magnet length	250	mm

The magnetic design of TL2 quadrupole magnet is a dominated iron one (Fig.3), using Samarium Cobalt permanent magnet to avoid any risk of demagnetisation because of radiation.

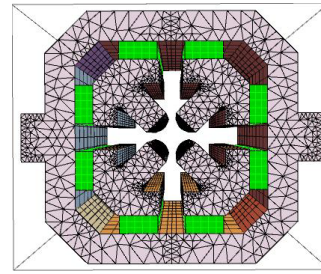


Figure 3: 3D Radia model of the TL2 PM quadrupole.

Figure 4 presents the magnetic performance of the quadrupole. The pole profile is designed without chamfers at the extremities of the quadrupole. The integrated multipole components are optimized to within a few units. The mechanical design has been completed and a prototype has been manufactured. The permanent magnet blocks are expected to be delivered by the end of May. The quadrupole will then be assembled using a dedicated tool and measured at ESRF in June.

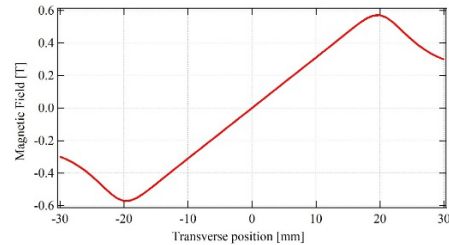


Figure 4: Magnetic field of TL2 PM quadrupole.

PRELEMENARY DESIGN OF PERMANENT MAGNET SEPTUM S3

The ESRF injection system relies on an in-vacuum pulsed septum magnet S3 located at the end of the transfer line TL2, providing the final deflection of the injected beam onto the storage ring orbit. The septum operates at high magnetic field with a thin septum blade to minimize the separation between injected and stored beams, while limiting the leakage field seen by the stored beam [5]. Its design represents a compromise between achieving sufficient deflection strength and preserving beam quality in the storage ring. Residual stray fields from the septum can induce orbit perturbations and require careful compensation through optics tuning and correction schemes. The performance of the septum S3 is therefore a critical element for injection efficiency and for minimizing disturbances to users during operation. It also presents several drawbacks, including strong mechanical stresses due to Lorentz forces, significant thermal loads, complex pulsed power supplies, and reliability constraints associated with repetitive high-current operation. In the new ESRF-EBS injection scheme, the septum must satisfy demanding parameters, including a high magnetic field of about 1.26 T, a 50 mrad deflection angle, and a length of 800 mm, while maintaining a small separation of only 17.5 mm between the injected and stored beams. Permanent magnet solutions were considered for the design of this septum [6].

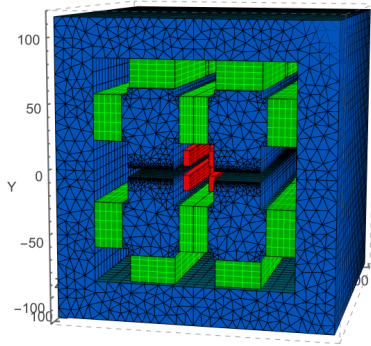


Figure 5: Radia model of permanent magnet septum S3.

A novel septum S3 concept based on permanent magnets operating without a conductive shielding blade has been investigated. Figure 5 presents the design of this septum. It consists of two identical dipoles, positioned on either side of the stored beam. One dipole generates the magnetic field required to deflect the injected beam, while the other cancels the magnetic field along the stored beam trajectory and produces a quadrupole field in the good field region of the stored beam. This field configuration is easier to correct than the non-linear magnetic field that would otherwise be generated in its absence. This concept eliminates the need for high-current pulsed systems and reduces mechanical and thermal constraints. In addition, it offers improved magnetic stability, zero power consumption, and simplified operation, making it a promising solution for future synchrotron injection systems.

The magnetic field in the stored beam region is corrected using magic blocks. A first set of magic blocks (Fig.6, left) is used to compensate for the quadrupole and octupole components generated by the septum S3. A second set (Fig.6, right) is employed to correct residual field errors within the good field region.

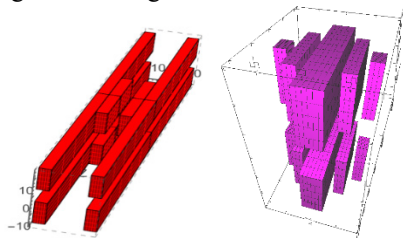


Figure 6: Magic blocks for field correction.

Figure 7 shows the integrated magnetic field as a function of the transverse position. The stored and injected beam positions are located at 0 mm and -17.5 mm, respectively. The black curve represents the field integral without correction, while the red curve corresponds to the corrected field integral. Figure 8 presents a zoomed-in view of Figure 7, highlighting the correction of the field integral within the good field region of ± 7 mm around the stored beam position.

Beam dynamics simulations are currently in progress, based on the magnetic simulation results, to evaluate the behaviour of both the injected and stored beams with the permanent magnet septum S3. A prototype will be

constructed and tested, provided that the simulations do not reveal any critical issues.

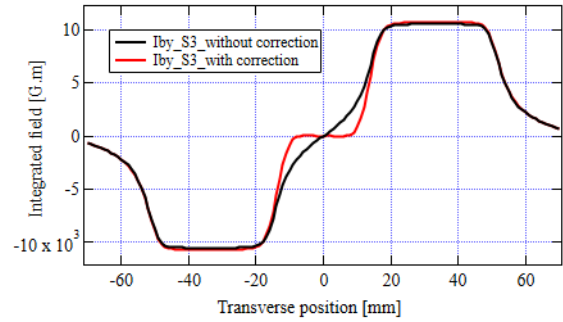


Figure 7: Integrated magnetic field of septum S3.

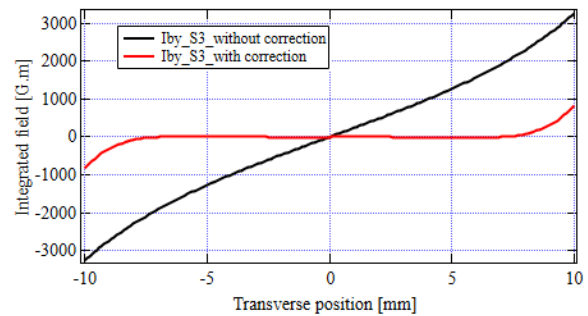


Figure 8: Integrated magnetic field of septum S3 at the stored beam good field region.

CONCLUSION

The proposed upgrade of the ESRF booster, which includes the replacement of 18 quadrupole magnets, aims to reduce the horizontal emittance from 85 nm to 59 nm and the bunch length from 22.6 mm to 19.9 mm. The quadrupole magnets have been designed, and their production is currently in progress. A first prototype will be measured, and its magnetic length adjusted to achieve the required integrated gradients before the start of series production. The current injection scheme at ESRF-EBS impacts several beamlines. A new injection scheme based on a non-linear kicker is therefore being considered. In this context, a compact permanent magnet quadrupole has been designed to replace the existing TL2 electromagnetic quadrupoles; it will be assembled and tested in June. In parallel, a preliminary design of a permanent magnet septum S3 has been proposed to replace the current pulsed septum. A prototype will be manufactured and measured to validate the simulation results.

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