

# JOINT DEVELOPMENT OF SUPERFERRIC CORRECTOR MAGNETS FOR HL-LHC

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## Abstract

The HL-LHC project is a major upgrade of CERN's LHC, aiming to enhance the collider's integrated luminosity by a factor of ten within ten operational years. Endorsed as top priority for the European Strategy for Particle Physics in 2013, the project was formally approved by CERN's Council in 2016. To achieve its performance goal, HL-LHC relies on several technology drivers. Among the new magnets for the interaction regions, the superferric – named so, because they combine superconducting NbTi coils with iron pole pieces to enhance the magnetic field near the aperture – high-order mode correctors are key in ensuring beam quality and stability, correcting field errors and compensating non-linearities in the magnet lattice. These magnets were the object of a collaboration between CERN and INFN-LASA Milan, first joint project to deliver its full scope to HL-LHC. INFN-LASA was tasked with design, prototyping, and industrialization. Key to the delivery of 54 correctors by 2023 was the early initiation via the INFN MAGIX project, followed by two agreements for prototyping and series production. The collaboration spanned over a decade and benefited from the early involvement of the industrial partner SAES-RIAL. The paper reviews the collaboration, detailing cost structure, schedule adherence, and industrialization process. Focus is on key factors that contributed to the success of the collaboration and lessons applicable to large-scale partnerships for future accelerator projects.

## INTRODUCTION

The High-Luminosity LHC project (HL-LHC) aims to increase the collider's integrated luminosity by a factor of ten beyond its original design, in 10 years of operation. The project was endorsed as top-priority at the 2013 update of the ESPP, paving the way for the project's TDR approval by CERN's Council in June 2016. The upgraded LHC was initially scheduled to deliver first beams around 2026, after a 2-year installation shutdown.

A defining feature of the HL-LHC project is its collaborative model: about 10% of the project's core value is delivered through in-kind contributions. These collaborations are essential not only for CERN budget, infrastructure and expertise leverage, but also to enlarge the know-how and production and testing capabilities in the accelerators community and the industrial partners. To avoid disparity in the Member's States contributions, the

deliverables from institutes amongst CERN Member States are co-financed by CERN to 50%.

To achieve its performance goals, the HL-LHC relies on several accelerator technology drivers, including superconducting magnets in Nb<sub>3</sub>Sn, superconducting crab cavities, high-current power transmission link based on MgB<sub>2</sub> and low-impedance collimators. Among the new magnets for the interaction regions, the superferric multi-pole corrector magnets ensure beam quality and stability, correcting field errors and compensating non-linearities in the magnet lattice. These superconducting magnets are called superferric, because they combine superconducting NbTi coils with iron pole pieces, enhancing the magnetic field near the aperture. Together with one nested orbit corrector, the multi-pole correctors are integrated in the so-called Corrector Package cryoassembly.

The superferric high-order mode correctors (quadrupole to dodecapole, see Fig. 1) for the HL-LHC work-package WP3 were the object of a collaboration between CERN and INFN-LASA Milan, Italy, the first collaborative sub-project to deliver its full scope to HL-LHC. This partnership, seeded by the INFN MAGIX project and formalized in the KE2291 (for prototypes) and KE3085 (for the series magnets) agreements, spanned over eight years and involved R&D, prototyping and series production, together with the industrial partner SAES-RIAL. The delivery of 54 corrector magnets was completed in November 2021 and fully validated at CERN in 2022.

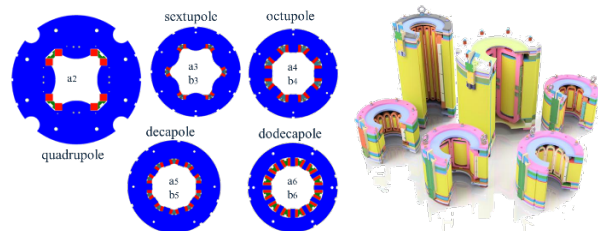


Figure 1: The high order correctors of HL-LHC.

This paper reviews the CERN-INFN collaboration, focusing on the industrialization process, cost structure, schedule adherence. It aims to identify the key factors that contributed to the success of the project and to extract lessons applicable to future large-scale scientific collaborations.

## PRECURSORS

In the framework of FP7, grant agreement 284404, the EU commission financed 4.9 M€ of the 21 M€ of the Design study for HL-LHC from 2011 to 2016, when the

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project was approved and fully integrated in CERN's Medium Term Plan (MTP). One work-package concerned the development of superconducting magnets and involved also INFN-LASA [1]. The collaboration between CERN and LASA on the development of high-order corrector magnets benefited also from a preparatory effort by INFN, before the formal approval of HL-LHC. Recognizing the need to acquire competence in the technological challenges and opportunities posed by future accelerators, INFN launched the MAGIX project (2014–2017), a national initiative aimed at advancing superconducting magnet technologies and materials for next-generation accelerators, while improving INFN's infrastructure and competence in coil winding, cryogenic testing, and magnet diagnostics. MAGIX was intended as preparatory platform for INFN's participation in international collaborations. Within MAGIX, the CORRAL workpackage was specifically dedicated to the design, construction, and testing of 5 superferri-corrector magnet prototypes (from quadrupole to dodecapole), compatible with the HL-LHC requirements. With MAGIX grants, INFN-LASA acquired a coil-winding machine and an impregnation oven and developed a test cryostat. These early investments were decisive in enabling LASA to transition from a research-focused lab to a semi-industrial facility capable of supporting an industrial partner and later transfer knowledge to it.

The collaboration also benefited from prior work on superferri-corrector magnets, for which a sextupole demonstrator had been fabricated by CIEMAT Spain, for the EU program FP7-SLHC [2]. INFN proceeded to a technical review of the design of this prototype and identified no show-stopper.

## PROTOTYPING AND SERIES

### *Prototyping (2014-2019)*

The early initiative within FP7 laid the foundation for a formal collaboration with CERN, cast in the KE2291 agreement of June 2014, anticipating on the HL-LHC project official approval the following year. KE2291 defined a shared R&D program with a total estimated cost of 1.3 M€. CERN committed to 50% of the personnel, manufacturing and testing costs, and 75% of the raw material costs. INFN fully covered the infrastructure cost at LASA, including coil winding, impregnation, and single-coil cryogenic testing. The program of KE2291 defined milestones from 2015 to 2017, for five superferri-corrector prototypes, (quadrupole, sextupole, octupole, decapole, and dodecapole), including design, construction and cold testing.

After the CIEMAT sextupole design was modified at LASA to overcome some criticality and validated via an internal review, LASA underwent to build and test a full sextupole prototype, with components from industry. Qualified in February 2016, the sextupole served as a technical and procedural benchmark for the subsequent correctors, joined by an octupole and a decapole in 2017. The longer quadrupole and dodecapole required industrial fabrication, so a supply contract was signed in September 2017 with SAES-RIAL. The dodecapole was validated in September

2018, while a major non-conformity appeared upon testing the skew quadrupole in early 2018. The prototype showed a short circuit in one coil after several quenches. Reinforcements of the electrical insulation was integrated in the coil design, and specific diagnostics tools were added to the quality control procedures. Additional quenches after the thermal cycle were also questioned, and the specification was modified to ensure that after thermal cycle the magnets should require no additional training to recover nominal performance. Meanwhile, LASA had commissioned a new cryostat for testing the longer dodecapole and quadrupole as well as the series magnets, allowing for parallel testing of up to 4 magnets. The collaboration also pioneered diagnostic tools to detect coil defects and residual magnetization after quenches.

Two more coils were produced, the damaged coil was replaced, and the refurbished skew quadrupole corrector prototype was validated in June 2019, completing the 5 prototypes in the scope of the agreement [3-11]. With one magnet per type – treating normal and skew as a single type – a minimum number of prototypes was sufficient to validate and conclude the R&D phase [12].

### *Series production (2019-2023)*

Even if not yet completed by the moment when the series agreement was established, the prototyping phase not only delivered essential technical insight, but also established the collaborative framework, setting the scene for industrialization and series production under the series agreement, KE3085. The contract covered the delivery of 54 magnets: 6 skew quadrupoles; and 12 each (6 normal and 6 skew) of sextupoles, octupoles, decapoles, and dodecapoles—yielding 24 normal and 30 skew units in total. Magnets were to be delivered in six batches, each consisting of nine magnets (one per type), to be tested at INFN-LASA before shipping to CERN. The agreement also included the development of specific tooling, magnetic measurement equipment, and cryogenic test infrastructure. CERN was to provide the magnet specifications, iron raw material for yoke laminations, and the equipment for magnetic measurements. Further, CERN was to make a financial contribution to INFN-LASA, staged in 4 phases at each of 4 project milestones. INFN was responsible for engineering, tendering, contract follow-up, quality assurance, and testing in operative conditions at LASA, as well as delivery. The total cost of the KE3085 collaboration was approximately 5.76 M€, equally shared between CERN and INFN.

The industrial partner selected for series production was SAES-RIAL, the fabricant which had already collaborated with INFN during the prototyping phase. Coils were produced at SAES Getters, magnets were assembled at SAES-RIAL Vacuum. INFN-LASA transmitted the procedures which it had developed in coil winding and impregnation, mechanical assembly, PCB-based electrical splicing, as well as pioneering diagnostic techniques for quality control and post-quench residual magnetization measurement. It also transferred key tooling to RIAL, including the custom winding and impregnation machines and diagnostics tools, and provided training and documentation to ensure that

RIAL could meet the stringent quality and performance standards required for HL-LHC magnets. Each batch of magnets was tested at LASA using the dedicated cryostat for handling four magnets simultaneously, which significantly reduced testing time and helium consumption. The magnets were then shipped to CERN in six batches between 2020 and 2023. This laid the foundation for the successful delivery of 54 corrector magnets, an example of how a research institution can bridge the gap between laboratory-scale innovation and industrial-scale production.

Following the prototyping experience, a fine tuning of design (nominal current, iron yokes, integrated field and length of some magnets) was implemented after the signature of the agreement. The industrial contract for the fabrication of the series was awarded in February 2019, but signed only in June that year, due to administrative delays. These two factors determined some initial shift of the KE3085 milestones. While the initial wording of the agreement foresaw test and delivery of the magnets in batches of 18 (2 per type), it was later recognized that this implied too high risks of late discovery of issues, and the milestones schedule was changed to introduce a more staged test schedule, with 9 magnets per batch.

The NbTi superconducting wire was procured by INFN LASA with Bruker: the contract was placed in September 2018 and by March 2020 most of the wire was delivered. The raw material for the laminations was supplied by CERN directly to the industrial partner SAES RIAL. A production readiness review was held in December 2019: the reviewers deemed the series production plan compliant with the project needs and not on the project's critical path.

Covid-19 impacted Italy in early 2020, first amongst all European countries. The company could continue production, as the work was classified under essential scientific infrastructures, allowing continuity under the Covid-adapted Italian regulations. Under the pandemics, the bottleneck appeared to be the testing capability at LASA, since the lab was submitted to presence limitation since February 2020. Re-start occurred in May, albeit limited to 50% of staff.

The milestones trend at the end of the series production is presented in Fig. 2. By June 2020, 129 coils had been produced, with 19 non-conformities. The main non-conformity was observed in the resin impregnation procedure, where the thermal cycle specified by CERN had not been respected for 6-pole, 8-pole and 10-poles; all coils were accepted, since the NC did not modify their mechanical properties. Further, early quality check points were introduced, and the problem did not repeat. All coils were later accepted. While the 1st batch featured 3 months delay by then, mainly due to engineering changes and non-conformities assessment, Covid had introduced an additional 2-months. A further NC was detected in December 2020, where after powering at cold, several wedges had moved in 8-pole and 12-pole without effect on performance. A change of the torque applied to load the wedges were introduced on the already produced 9 magnets of the first half-batch.

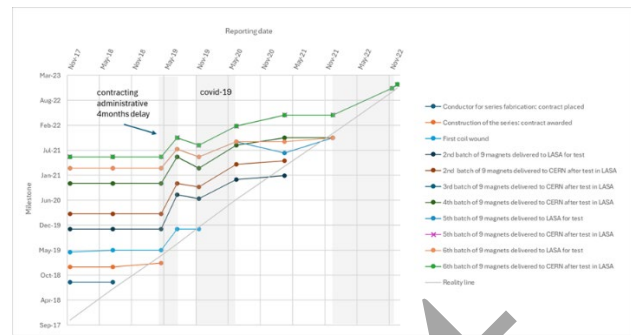


Figure 2: Milestones trend analysis for series production.

The first 2 magnets reached LASA in early July 2020 and were tested compliant. By November, 4 more magnets had been tested and validated, amongst which the first long 12-pole. The first test of a skew quadrupole was performed in March 2021. By then, 26 out of the 54 magnets had been delivered to LASA, 2 had been tested at CERN, while 8 more had to be tested at CERN on short track to ensure proper risk mitigation of late detection of NCs. The test rate at LASA equalled the production rate in industry; schedule remained under scrutiny.

The first complete batch was delivered to CERN by May 2021, followed by the second in February 2022. The last 10 magnets were delivered to LASA in October 2021. By December 2022, 46/54 magnets were at CERN, two magnets had to be retested. Tests were completed in February 2023, and the delivery to CERN, started mid-2020, was completed in March 2023 [13-16].

Overcosts were recorded all along the project. At completion, the contract collaboration, initially established at 5.76ME, featured 372k€ 10% of extra costs, or 6% of the initial value. This included additional tests and design iterations (54%), a correction of the wedges design and the related fabrication and tests (32%) and additional spare coils (14%). This additional cost was equally shared amongst the 2 partners. At its completion, the collaboration agreement had featured a remarkable adhesion to schedule in spite of design tuning, administrative delays in procurement, the effect of non-conformities, and the impact of Covid-19. This was made possible by an anticipated start of prototyping and engineering before project approval, the uninterrupted partnership with industry since the early phases and the full completion of prototyping before series production.

## ACKNOWLEDGEMENT

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