# MAGNETS FOR THE ESRF-EBS PROJECT

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*Abstract*

The ESRF-EBS (Extremely Brilliant Source) is an upgrade project planned at ESRF (European Synchrotron Radiation Facility) in the period 2015-2022. The actual storage ring will be replaced by a new one in the existing complexes. Based on innovative magnet solutions, the ESRF-EBS project aims to decrease the horizontal emittance and to improve the brilliance and coherence of the X-ray beams. Demanding specifications magnets have been designed for this project including dipoles with longitudinal gradient (field ranging from 0.17 T up to 0.67 T), High gradient quadrupoles (up to 90 T/m), combined function dipole-quadrupoles with high gradient (0.57 T and 37 T/m), strong sextupoles and octupoles. The dipoles with longitudinal gradient are based on permanent magnets, they will be assembled and measured in house. The design phase is finished and the procurement phase is under progress. Prototypes of longitudinal dipoles and high gradient quadrupoles have been built and measured. In this contribution the design of the magnets, the prototype results and procurement status will be presented.

## INTRODUCTION

The European Synchrotron Radiation Facility (ESRF) is an intense X-ray source located in Grenoble, France. It is a centre of excellence for fundamental and innovation-driven research. ESRF owes its success to the international cooperation of 21 partners, of which 13 are members and 8 are scientific associations.

The X-rays, endowed with exceptional properties, are produced by the high energy electrons (6 GeV) that race around the storage ring, a circular tunnel with 844 m in circumference.

A major upgrade project known as ESRF-EBS has been launched in 2015. It aims to reduce the horizontal emittance from 4 nm.rad down to 135 pm.rad. The brilliance of ESRF-EBS will be increased by a factor of 30 compared to the present brilliance, mainly due to this drastic decrease of the horizontal emmitance. The present Double Bend Achromat lattice will be replaced with a Hybrid Multi Bend Achromat one [1], increasing the number of dipoles per cell from two to seven. The new lattice will keep the same length and the same periodicity as the present one. The beamline source points including insertion devices and bending magnets will be also kept at the present positions.

## MAGNETS DESIGN

The magnets (Fig.1) represent one of the main challenges of the new lattice. The reduction of the beam size allows a significant reduction of the magnet apertures. The beam size is smaller in the central part of the cell than in the outer parts, resulting in two different magnet apertures and Good Field Region (GFR). The vertical distance between the poles of the magnets has been limited to at least 11 mm to allow the installation of the X-rays beam ports. A significant effort was placed on the optimisation of the power consumption of the magnets to reduce the operation costs. All the magnets have been designed using Radia software [2].

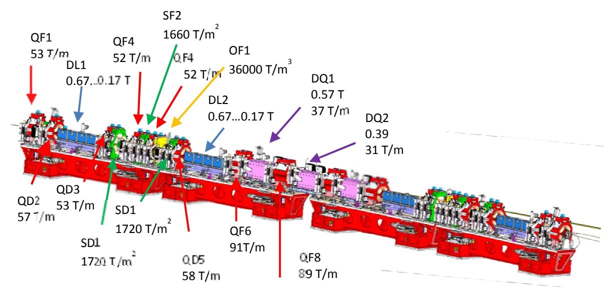


Figure 1: Schematic view of one cell magnets; Longitudinal gradient dipoles (DL), combined dipole quadrupoles (DQ), quadrupoles (QF, QD), Sextupoles (S), Octupoles (O), correctors are not represented in this figure.

### *Longitudinal Gradient Dipoles (DLs)*

A permanent magnet design has been selected for the DL magnets [3]. The DL with a total length of 1788 mm is based on five permanent magnet modules, all the modules have the same gap of 25.5 mm excepted the low field one which has a gap of 30.5 mm because of the integration of an absorber (Fig. 2a).

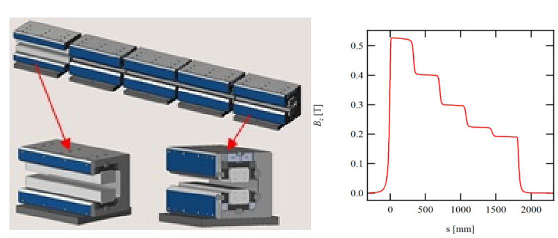


Figure 2: a) DL design of the modules with the two types of mechanical parts, b) Field versus longitudinal position.

Every module is magnetised by a different amount of permanent magnet in a way that the DL produces a longitudinal gradient magnetic field as shown in Fig.2b. The permanent magnet used for the DLs is $Sm_2Co_{17}$ due to its

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resistance to radiation damage [4] and its temperature stability. The DL design is dominated by iron, the tolerances on the magnetic proprieties of the magnet blocks are less strict than for undulators leading to chipper prices. Low carbon steel is used for the yoke, and pure iron for the pole. The pole shape is designed to reach the required field quality ΔB/B of $10^{-3}$ in the GFR of 13 mm. Fe-Ni material [5] will be used for the thermal compensation of the DLs.

Prototype modules have been built and measured using a stretched wire magnetic bench [6]. Figure 3a shows two prototype modules with a field of 0.6 T and 0.4 T, separated with a gap of 5 mm. The comparison between the measurement and predicted results are presented in Fig. 3b. The sextupole end effect will be improved with the assembly of the additional modules.

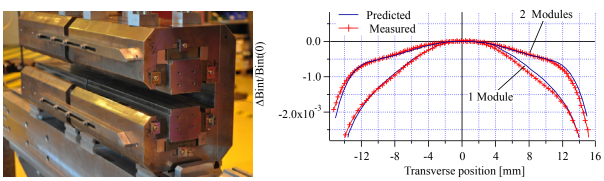


Figure 3: a) Two prototype modules, b) magnetic measurement of the modules.

### *Combined Dipole Quadrupoles (DQs)*

The combined dipole quadrupole has a high gradient field that cannot be obtained with a tapered dipole design. The design of the DQs is a combination of a transverse offset quadrupole which allow high gradient field and a single side magnet. The final design of the DQ is a single sided quadrupole [7]. The main parameters of the DQs are shown in table 1 and the 3D model in Fig 4a.

Table 1: Main Parameters of the DQs Magnet

| **Parameters** | **DQ1** | **DQ2** |
|---|---|---|
| Field B | 0.56 T | 0.39 T |
| Gradient G | 36.8 T/m | 31.2 T/m |
| Length | 1028 mm | 800 mm |
| GFR | 7 mm | 7 mm |
| ΔG/G | $<10^{-2}$ | $<10^{-2}$ |

The non-used side of the qudrupole has been removed to reduce the power consumption, to lighten the magnet weight and simplify the vacuum chamber design. The dimensions of the pole and the coil have been reduced on the low field side of the magnet.

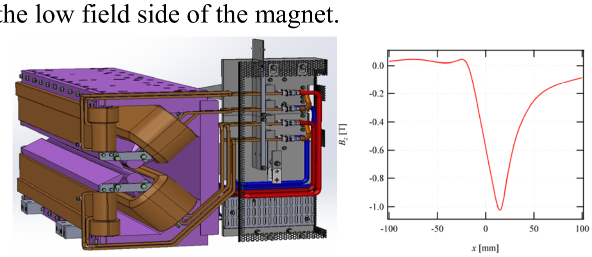


Figure 4 [7]: a) 3D model of DQ1, b) magnet field and gradient.

Figure 4b presents the magnetic field and gradient of the DQ1. The field is close to zero on the non-used side and offset quadrupole like on the used side. Correction coils are used to tune independently the field and the gradient. These coils allow ±2.5 % of the gradient with a constant field in the centre of the magnet.

### *Quadrupole Magnets*

The ESRF-EBS lattice includes two types of quadrupoles; high gradient (HG) quadrupoles (Table 2) and moderate gradient (MG) quadrupoles (Table 3). All the quadrupoles are iron dominated normal conducting magnets. The moderate gradient quadrupole works below the saturation and its field quality is independent from the current, however the high gradient quadrupole working point is closer to saturation the field quality has been optimised at this working point.

Table 2: Main Parameters of HG Quadrupoles

| **Parameters** | **QF6** | **QF8** |
|---|---|---|
| Bore radius | 12.6 mm | 12.6 mm |
| Gradient G | 89 T/m | 87.6 T/m |
| Length | 388 mm | 484 mm |
| GFR | 7 mm | 7 mm |
| ΔG/G | $<10^{-3}$ | $<10^{-3}$ |

Table 3: Main Parameters of MG Quadrupoles

| **Parameters** | **QF1** | **QD2-QF4-QD5** | **QD3** |
|---|---|---|---|
| Bore radius | 16.4 mm | 16.4 mm | 16.4 mm |
| Gradient G | 50.4 T/m | 53.9 T/m | 47.9 T/m |
| Length | 295 mm | 212 mm | 162 mm |
| GFR | 13 mm | 13 mm | 13 mm |
| ΔG/G | $<10^{-3}$ | $<10^{-3}$ | $<10^{-3}$ |

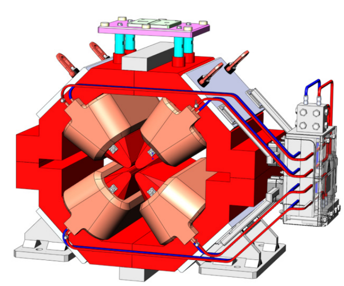

Figure 5: 3D model of the high gradient quadrupole.

A high gradient prototype quadrupole (Fig. 6a) has been built and machining to a very tight tolerances of ±0.020 mm. This tolerance has been increased to ±0.040 mm on the series production for time and cost optimisation. The measured gradient of 87 T/m at 90 A is very close to the design value of 86 T/m. Figure 6b shows a good agreement between the measured and designed high harmonics.




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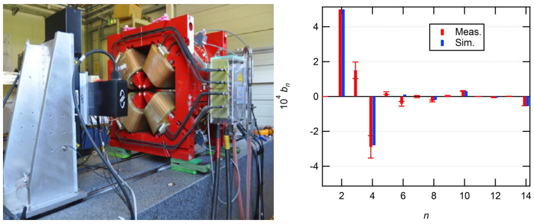


Figure 6: a) High gradient quadrupole prototype [8], b) measured and designed high harmonics.

### *Sextupole Magnets*

In addition of their main function the sextupoles (Fig. 7) are able to produce correction magnetic field (horizontal and vertical dipoles and skew quadrupole) which is created by additional coils.

Table 4: Main Parameters of Sextupole Magnets

| **Parameters** | **SD1** | **SF2** |
|---|---|---|
| Bore radius | 19.2 mm | 19.2 mm |
| Strength S | 1716 T/m2 | 1716 T/m2 |
| Length | 166 mm | 200 mm |
| GFR | 13 mm | 13 mm |
| ΔS/S | $<10^{-2}$ | $<10^{-2}$ |

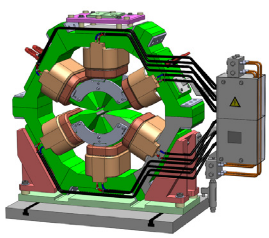

Figure 7: 3D model of the sextupole magnets.

### *Octupole Magnets*

The octupole (Fig. 8a) magnet is constituted by four yokes and four coils, each yoke has two poles and equipped with a coil. There is a large margin on the octupole strength, and the nominal value of 36000 T/m$^3$ can be doubled if needed. The radius bore of the octupole is 18.6 mm and the iron length is 90 mm.

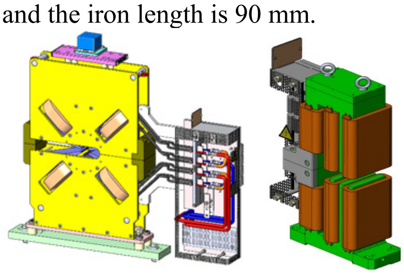

Figure 8: a) 3D model of octupole magnet on the left and b) 3D model of the corrector magnet on the right.

### *Corrector Magnets*

The corrector magnet (Fig. 8b) is C- type structure compatible with the stay clear for the vacuum chamber. It has an iron length of 100 mm and a gap of 25 mm. It can be simultaneously used for horizontal and vertical steerers (0.6 mrad) and skew quadrupole corrector. The corrector operates for both AC and DC modes.

## PROCUREMENT

The procurement of the magnets has started. A Pre-Qualification Exercise (PQE) has been performed to select a short list of electromagnets suppliers. This selection is based on a technical questionnaire, administrative document and plant visits. A short list of six companies has been selected over 19 participants to this PQE.

All the Call For Tenders (CFTs) of the magnets have been launched and the documents sent only to the short list. Four companies have been selected to produce all the magnets. All the contracts have been signed. The contract is divided in 3 main phases. Phase 1 is dedicated to the engineering design, detailed drawing and quality control document. Phase 2 is dedicated to the production of the pre-series magnet and phase 3 to the production of the series magnets delivered in several batches. Actually all the magnets are in the phase 1 of the procurement. All the magnets will be machined from solid low carbon steel blocks, except the moderate gradient quadrupoles and correctors which will be laminated magnets.

The DLs will be assembled in house in order to keep a full control on the production and to take benefit from the in house experience in terms of permanent magnet assemblies, magnetic measurement and magnetic tuning. The CFTs for the permanent magnet blocks and mechanical parts have been launched and all the companies selected. Three different CFTs have been launched for the mechanical parts, one CFT for the row material procurement, one CFT for the flame cut and annealing of the row blocks and one CFT for the machining of the modules.

A dedicated area at ESRF has been prepared for the DLs assembly. This area is equipped with workshops for the mounting of permanent magnet blocks on the modules, and the assembly of modules on the DL supports. Several stretched wire magnetic benched have been installed in this area to perform the magnetic measurement, tuning and fiducialization of the DLs. One magnetic bench will be used for the measurement of some electromagnets received from the suppliers.

## CONCLUSION

The magnets of the ESRF-EBS project have been designed. Innovative solutions have been used for the longitudinal gradient dipoles and combined dipole quadrupoles. DL modules and high gradient quadrupole prototype magnets have been build and characterised.

All the CFTs have been launched, the suppliers selected and the contracts signed. The DLs will be assembled in house in a dedicated area at the ESRF. All the CFTs for the permanent magnets blocks and the mechanical parts has been launched, the suppliers selected and the contract signed. The production is under progress.

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