7 Magnets of the storage ring

Ch. Benabderrahmane, G. Le Bec, J. Chavanne and D. Einfeld

The specifications of the magnets according to the lattice (chapter 5) are presented in Table 7.1. The lattice of the SEE-LS is similar to that of the ESRF-EBS [7.1], so for the first step it is proposed to use the same layout for the magnets. Therefore the parameters have to be updated accordingly.

Table 7.1: Specifications of the magnets for the proposed storage ring of the SEE-LS

Element	Length (m)	Defl. angle (degrees)	Radius (m)	Field (T)	Gradient (T/m)	B'' (T/m^2)	B(pole) (T)
M11	1.15	3.7	17.8082	0.46827	4.3196	−90.562	0.468
M12	1.15	3.65	18.0521	0.46194	9.14788	126.419	0.462
MQ1	0.55	2.6	12.1203	0.68802	29.2085	−1805.9	0.75
MQ2	0.44	2.6	9.69621	0.86003	32.1468	1448.82	0.75
QF1	0.2				36.7686		0.603
QD2	0.15				−24.551		0.403
QF3	0.212				24.7695		0.406
QF4	0.212				25.8483		0.423
QF5	0.388				54.8623		0.697
QF6	0.484				48.7261		0.619
SH1	0.1					724.626	0.135
SD1	0.166					71.6921	0.013
SF2	0.2					1396.5	0.26
SD3	0.166					−2659.3	0.495

7.1 Bending magnets

The bending magnets M11 and M12 should be built in the same way as for ESRF-EBS [7.1], the upgrade of the ESRF. These are permanent magnets. In addition to the properties of the ESRF magnets, the proposed magnets will have a gradient too. According to Table 7.1, the magnets also have a sextupole component. In an upgrade of the lattice it should be possible to include separate sextupoles to eliminate this sextupole component. The layout of the dipole bending magnet is shown in Figs. 7.1–7.5.

The length of the ESRF-EBS magnet is roughly 1.8 m, while that of the SEE-LS magnet will be 1.15 m. Given the reduced length, the magnet will be composed of three modules. The bending magnet consists of three main components (see Fig. 7.2): the yoke, the permanent magnets, and the iron poles. For excitation of the magnetic field one needs six permanent magnets: four side magnets, one top magnet, and one bottom magnet. The dimensions of the magnet are given in Fig. 7.3 and the pole profile is displayed in Fig.7.4 according to the required gradient of up to 10 T/m. The gradient is quite high, but an expert at the ESRF [7.2] does not see it as a show-stopper in terms of the design.

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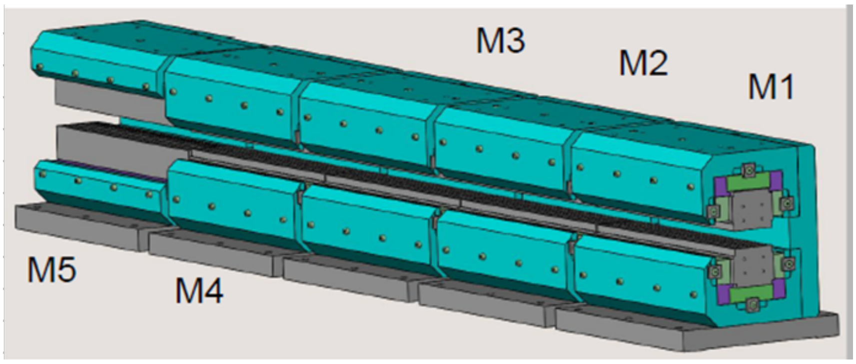

Fig. 7.1: The layout of the permanent bending magnets M11 and M12, according to that of the ESRF-EBS project. The SEE-LS magnets will be composed of three modules.

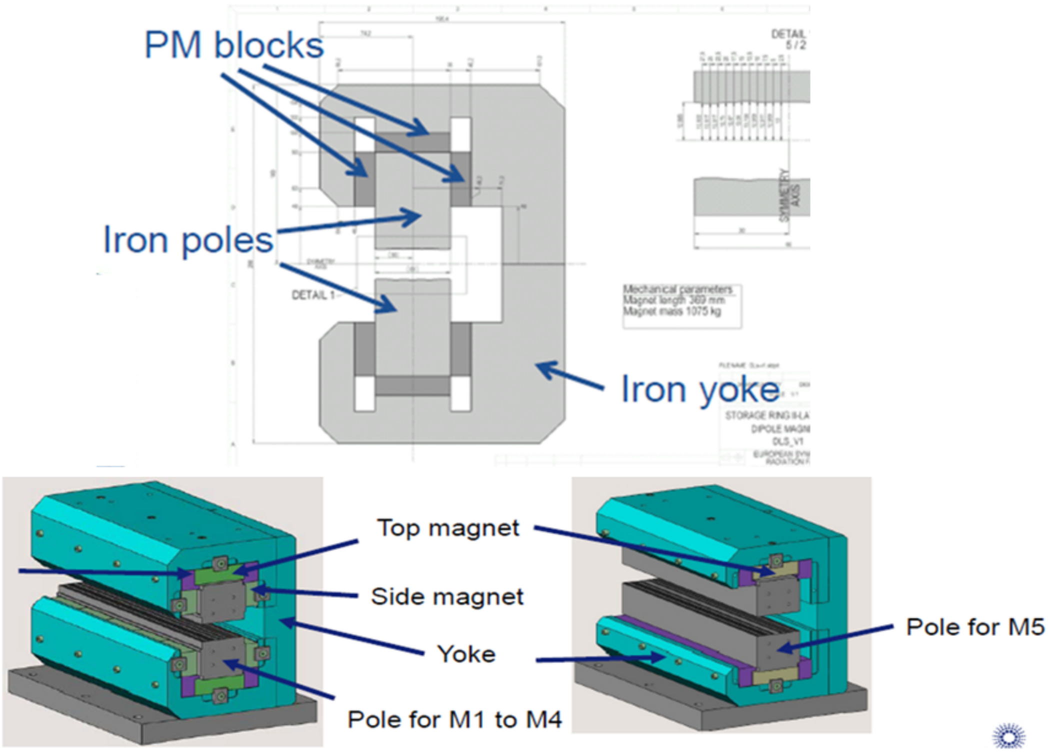

Fig.7.2: The different components used for the modules M1 to M4 and M5

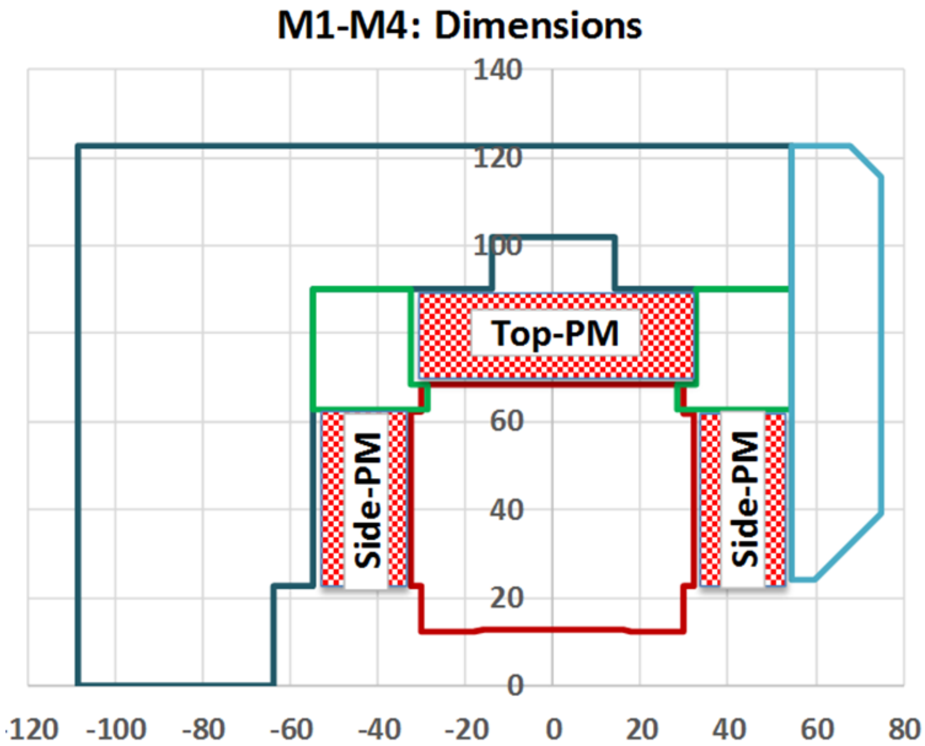

Fig. 7.3: Dimensions of the modules M1–M3 with the locations of the top and side permanent magnets. The contour of the pole is represented by a brown line.

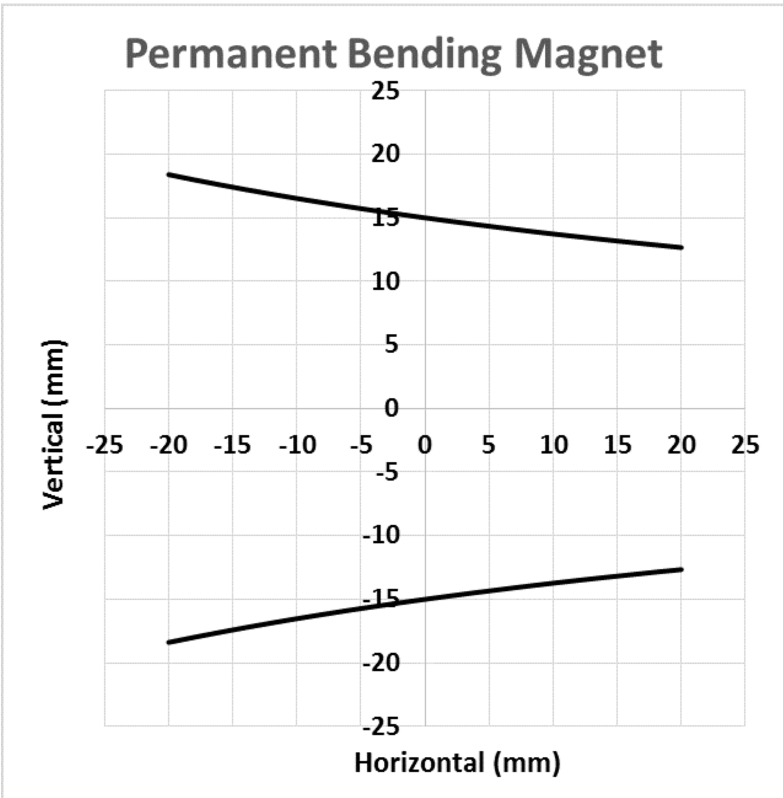

Fig. 7.4: The pole profile of the bending magnet according to the required gradient of 32 T/m

To fix the magnets on the girders a special support is needed; this support is shown in Fig. 7.5 along with the magnet. The modules are fixed on a so-called top plate, which is mounted on the base support. For the alignment procedure, the base support can be moved in the horizontal as well as the vertical direction.

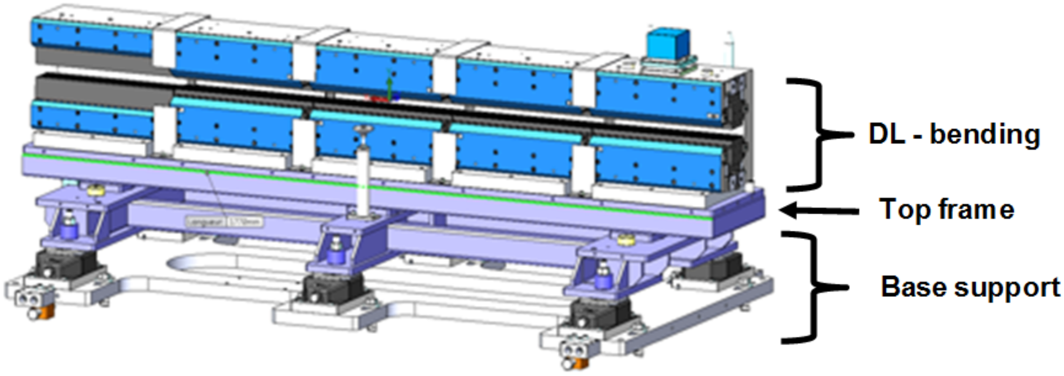

Fig. 7.5: The bending magnet M11 with the top plate and support

7.2 Combined bending magnets

The combined bending magnets MQ1 and MQ2 operate with a field of 0.7–0.9 T and a gradient of up to 32 T/m. These are special magnets, and the basis for the design is that used for the ESRF-EBS (see Fig. 7.6)

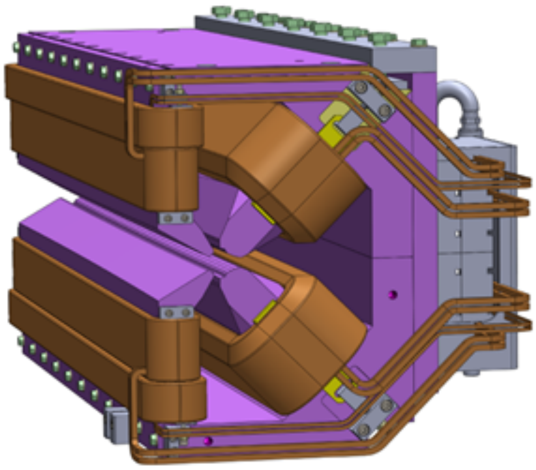

Fig. 7.6: Layout of the combined bending magnets MQ1 and MQ2

Because of the high gradient, there is a special arrangement of the poles, as shown in Fig. 7.7, and a special profile of the poles (see Fig. 7.8). To reach the required field homogeneity, a special setting of correction coils is needed (see Fig. 7.7). The parameters of the magnets are given in Table 7.2.

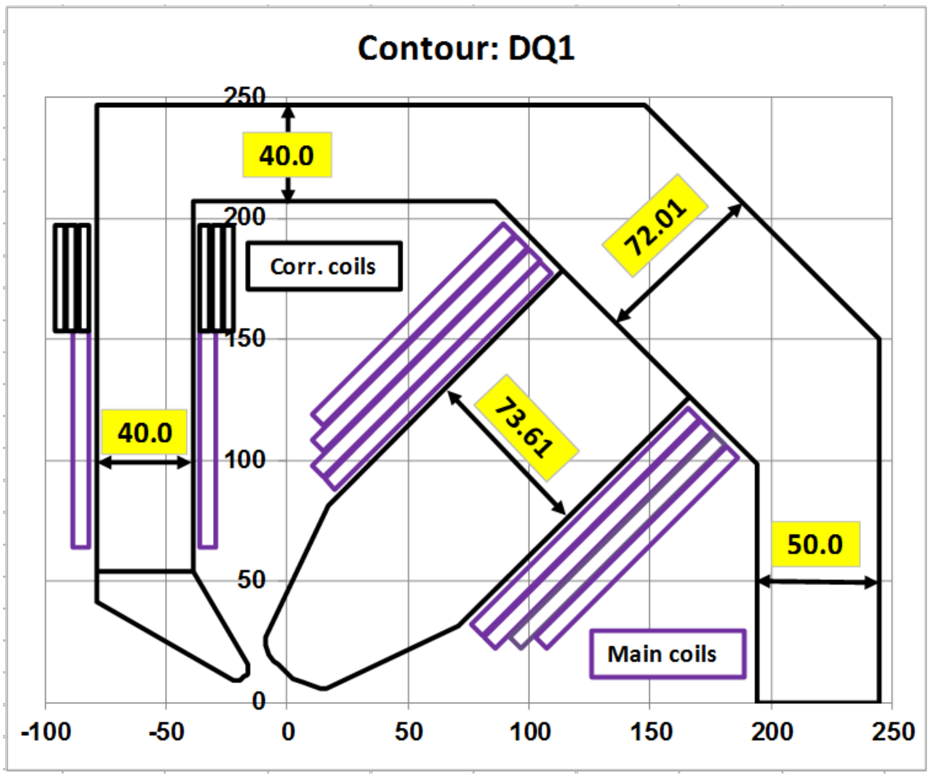

Fig. 7.7: Profile of the combined bending magnet MQ1 with the main and the correction coils

This magnet will be similar to bending magnet DQ1 of the ESRF-EBS.

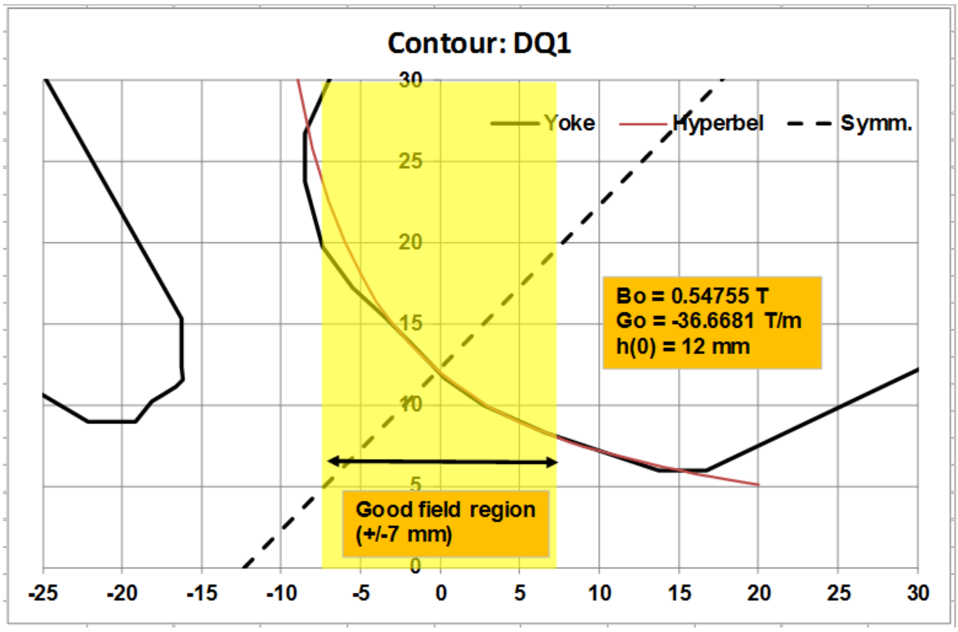

Fig. 7.8: Detailed contour of the MQ1 and MQ2 poles. For comparison, the hyperbolic contour also given. The good field region is ±7 mm.

Table 7.2: Parameters of the combined bending magnet MQ1

Parameter	Value	Unit
Field	0.86	T
Gradient	32	T/m
Current	87	A
Turns (main)	65	
Turns (aux.)	12	
Amp turns	6.7	kA turns
Coil dimensions	6.5 × 6.5	mm × mm
Pipe diameter	4	mm
Conductor area	28.67	mm^2
Resistance	221	mΩ
Voltage	19.2	V
Power (kW)	1.67	kW
Current density	3.04	A/mm^2
Cooling circuits	2	
Pressure drop	7.2	bar
Water flow	0.63	l/min
Water velocity	0.84	m/s
Temperature rise	19	K
Reynolds number	3350	

7.3 Medium-gradient quadrupoles

QF1, QD2, QF3, and QF4 are so-called medium-gradient quadrupoles, requiring a gradient of up to 30 T/m. The specifications are given for the QF4 quadrupole with the highest gradient, 25.9 T/m. The general layout of the quadrupole is given in Fig. 7.9.

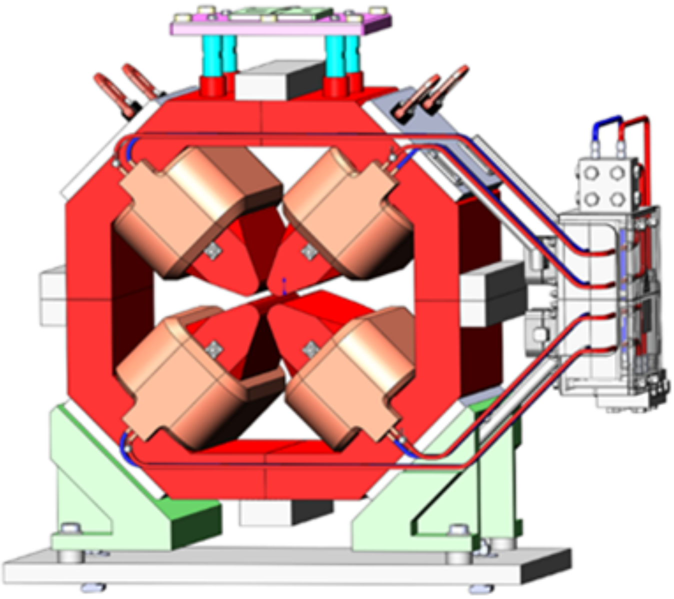

Fig. 7.9: Layout of medium-gradient quadrupole

The cross-section of a quarter of the quadrupole and the pole profile are displayed in Fig. 7.10. The parameters of the quadrupole are summarized in Table 7.3.

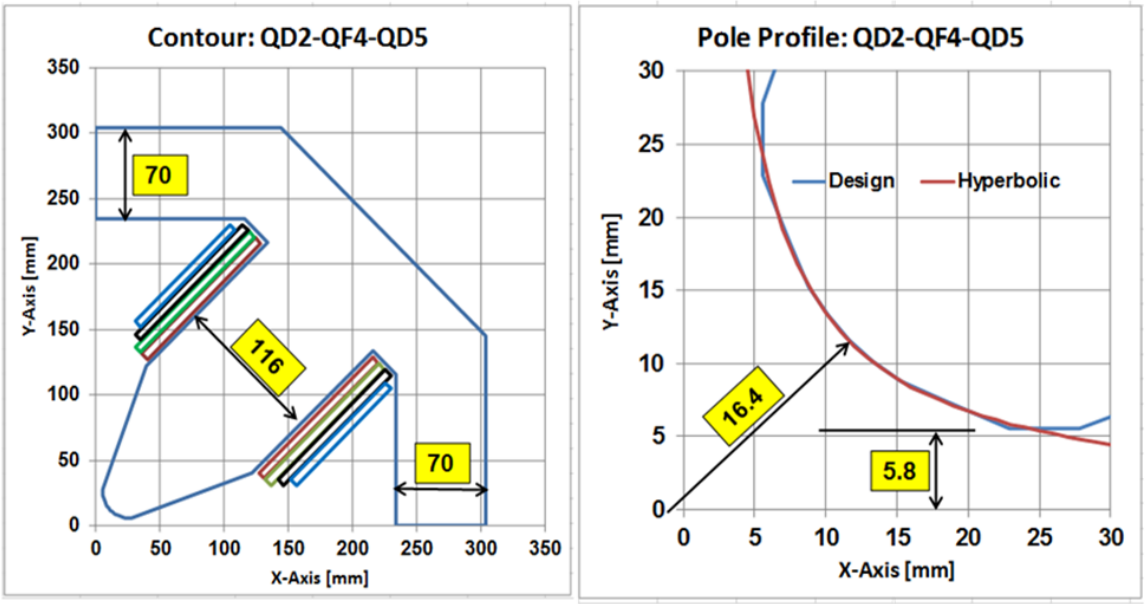

Fig. 7.10: Lamination and pole profile for the medium-gradient quadrupoles

Table 7.3: Parameters of the medium-gradient quadrupole QF4

Parameter	Value	Unit
Gradient	26	T/m
Bore radius R_o	16.4	mm
B(pole)	0.426	T
Current	45	A
Turns	68	
Amp turns	3.00	kA turns
Coil dimensions	6 × 6	mm × mm
Pipe diameter	3	mm
Conductor area	28.07	mm^2
Resistance	143	mΩ
Voltage	6.32	V
Power (kW)	0.278	kW
Current density	1.57	A/mm^2
Magnet inductance	129	mH
Time constant	0.9	s
Cooling circuits	2	
Pressure drop	7.0	bar
Water flow	0.37	l/min
Water velocity	0.872	m/s
Temperature rise	5.4	K
Reynolds number	2620	

Because of the low power and low temperature rise, the number of turns can be decreased and will have to be optimized.

7.4 High-gradient quadrupoles

QF5 and QF6 are so-called high gradient quadrupoles, requiring a gradient of up to 55 T/m. The specifications are given for the QF5 quadrupole with the highest gradient, 55 T/m. The general layout of the quadrupole is given in Fig. 7.11.

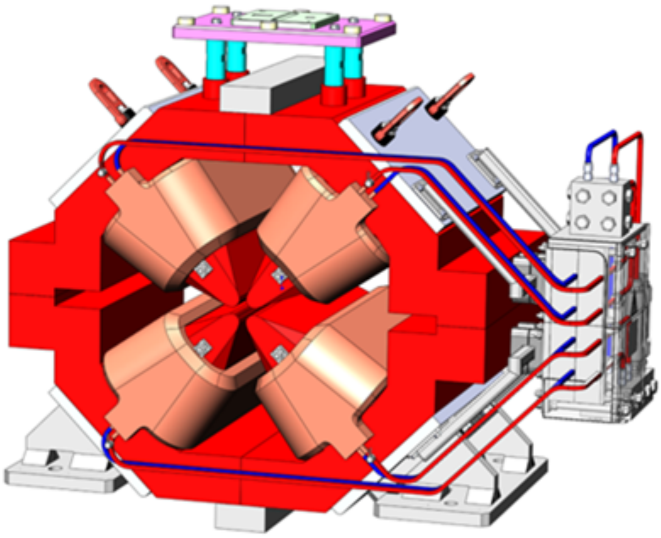

Fig. 7.11: Layout of high-gradient quadrupole

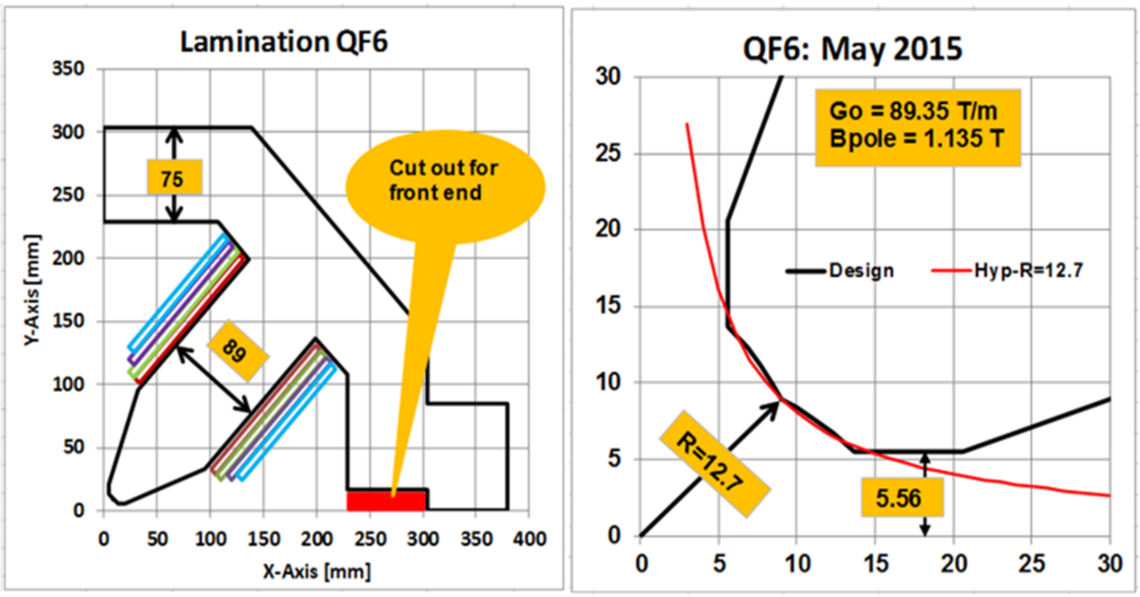

Fig. 7.12: Lamination and pole profile for the high-gradient quadrupoles

The cross-section of a quarter of the quadrupole and the pole profile are shown in Fig. 7.12. The parameters of the quadrupole are summarized in Table 7.4.

Table 7.4: Parameters of the high-gradient quadrupole QF5

Parameter	Value	Unit
Gradient	55	T/m
Bore radius R_o	12.7	mm
B(pole)	0.625	T
Current	54.7	A
Turns	77	
Amp turns	3.53	kA turns
Coil dimensions	6 × 6	mm × mm
Pipe diameter	3	mm
Conductor area	28.07	mm^2
Resistance	204.2	mΩ
Voltage	11.17	V
Power (kW)	0.611	kW
Current density	1.95	A/mm^2
Magnet inductance	272	mH
Time constant	1.33	s
Cooling circuits	2	
Pressure drop	7.05	bar
Water flow	0.303	l/min
Water velocity	0.714	m/s
Temperature rise	12	K
Reynolds number	2140	

Because of the low power and low temperature rise, the number of turns can be decreased and will have to be optimized. Furthermore, it is possible to decrease the length of the quadrupole.

7.5 Sextupoles

The largest sextupole component B is around 2700 T/m^2, this value can be reached with the design used for the ESRF-EBS. The layout of the sextupole is presented in Fig. 7.13, and the lamination and pole profile are given in Fig. 7.14. The pole profile perhaps still needs to be optimized.

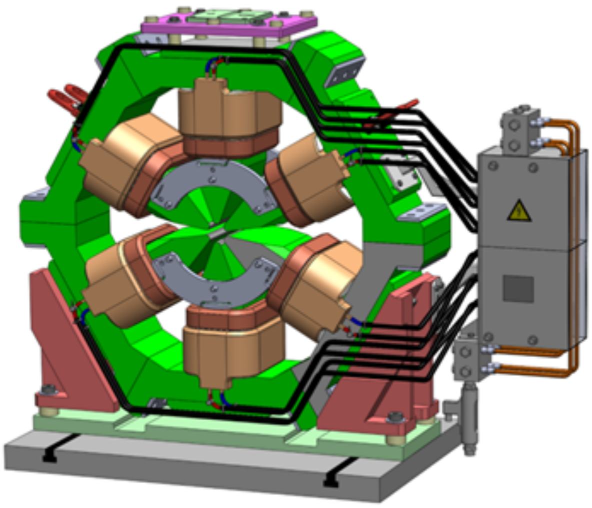

Fig. 7.13: Layout of the sextupole

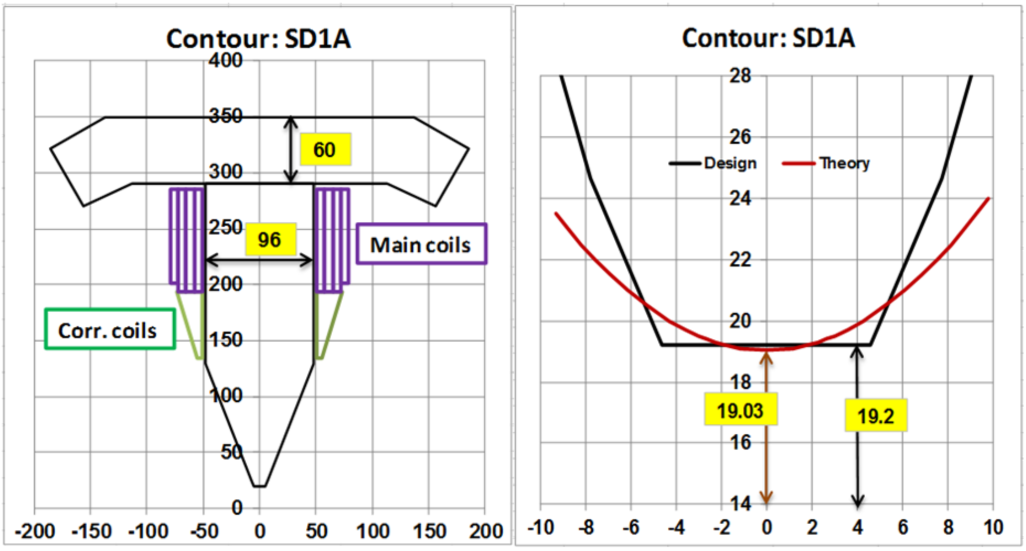

Fig. 7.14: Lamination and pole profile of the sextupole

Table 7.5: Parameters of the sextupole SD3

Parameter	Value	Unit
Diff.-Gradient	2700	T/m^2
Bore radius R_o	19	mm
B(pole)	0.49	T
Current	48.2	A
Turns	51	
Amp turns	2.46	kA turns
Coil dimensions	6 × 6	mm × mm
Pipe diameter	3	mm
Conductor area	28.07	mm^2
Resistance	122.1	mΩ
Voltage	5.88	V
Power (kW)	0.283	kW
Current density	1.716	A/mm^2
Magnet inductance	79.3	mH
Time constant	0.65	s
Cooling circuits	2	
Pressure drop	7.0	bar
Water flow	0.41	l/min
Water velocity	0.98	m/s
Temperature rise	4.9	K
Reynolds number	1477	

The sextupole has correction coils so that there is the possibility of making a beam correction in the horizontal as well as the vertical direction. The parameters of the sextupoles are summarized in Table 7.5. The number of turns can still be reduced in order to increase the temperature rise.

7.6 Correctors

The correctors have to make a kick in both directions of roughly 0.5 mrad. The layout of the corrector is given in Figs. 7.15–7.17, and the corresponding parameters are presented in Table 7.6.

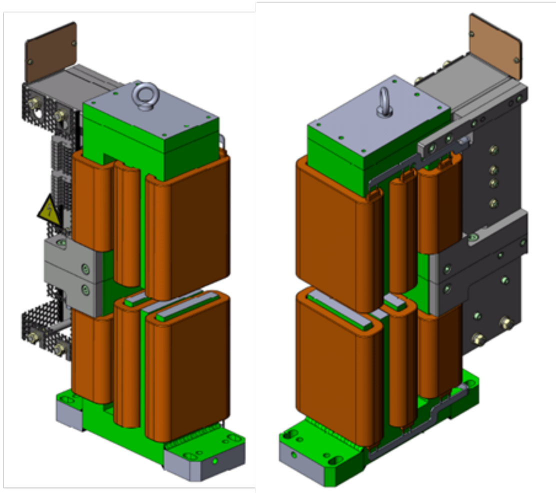

Fig. 7.15: Layout of the correctors

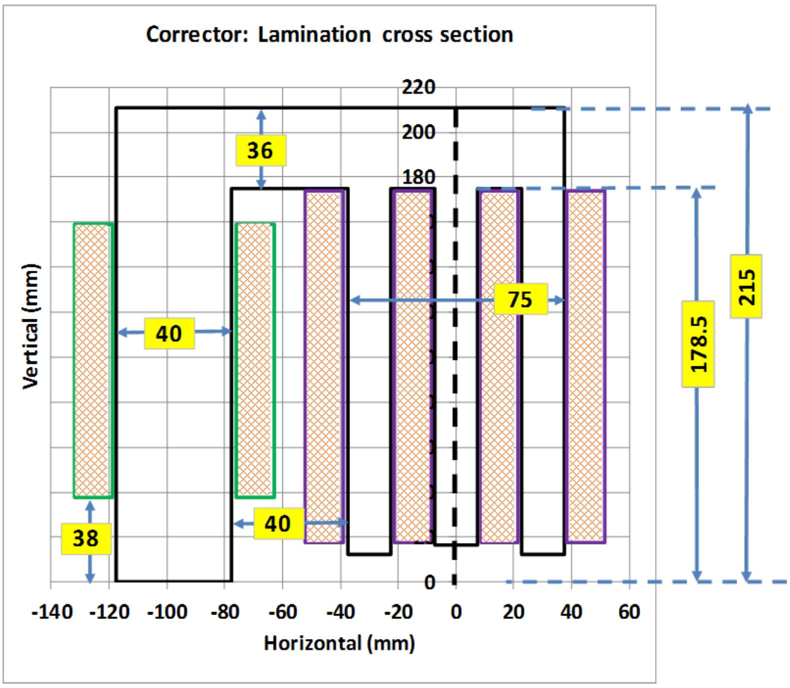

Fig. 7.16: Lamination and pole arrangement of each corrector

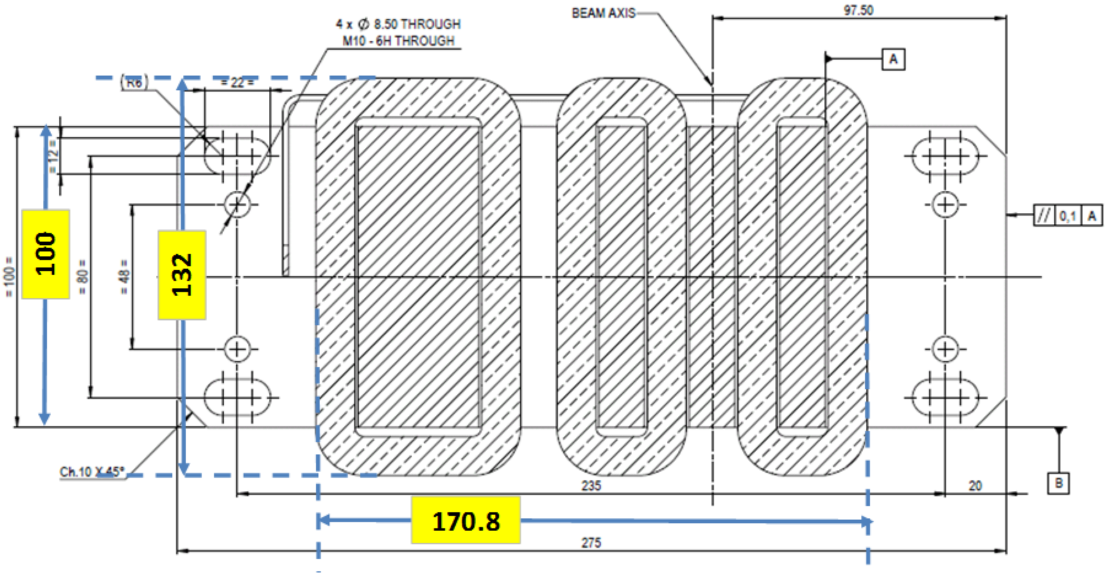

Fig. 7.17: Dimensions of each corrector

Table 7.6: Parameters of the correctors

Parameter	Value	Unit
Vertical integrated dipole	10	T mm
Horizontal integrated dipole	10	T mm
Skew integrated quadrupole	0.12	T
Mechanical length	100	mm
Gap	25	mm
Overall width	450	mm
Overall height	523.2	mm
Overall length	150	mm
Nominal current	2	A
Electrical resistance coil1	2,5	W
Voltage coil1	5	V
Inductance coil1	0.98	H
Electrical resistance coil2	2	W
Voltage coil2	4	V
Inductance coil2	0.94	H
Power loss per coil1	10	W
Power loss per coil2	8	W
Copper conductor size	2x0.9	mm^2
Corner radius	2	mm
Number of turns for coil1	900	turns
Number of turns per coil2	620	turns
Number of pre-series magnets	2	
Number of series magnets	96	

7.7 Octupoles

The layout of the octupoles, the size of the lamination, and the pole profile are presented in Figs. 7.18–7.20. The parameters are given in Table 7.6.

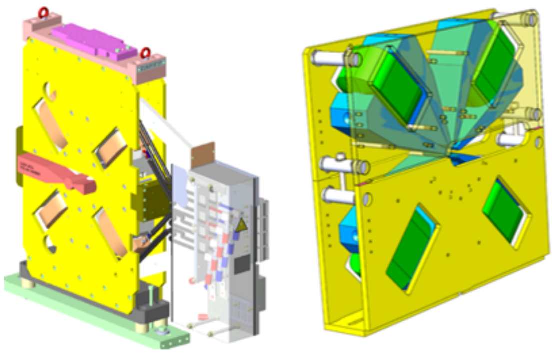

Fig. 7.18: Layout of the octupoles

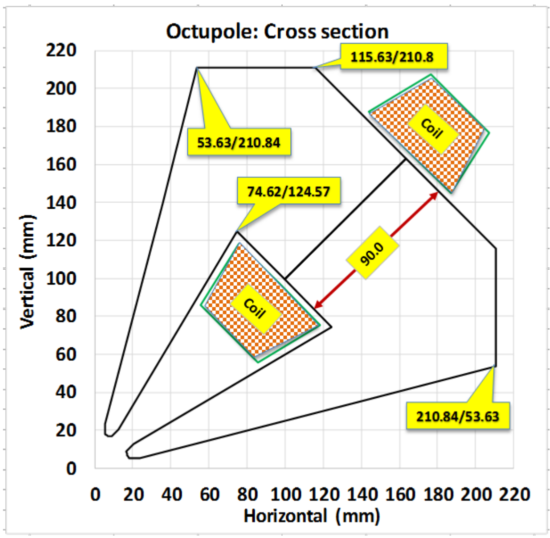

Fig. 7.19: Dimensions of the octupoles with the arrangements of the coils

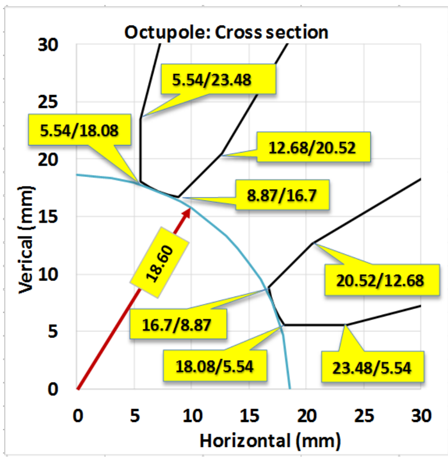

Fig. 7.20: Dimensions of the octupole pole profile

Table 7.7: Parameters of the octupoles

Parameter	Max. curr.	Nom. curr.
Bore radius [mm]	18.6	18.6
Yoke length [mm]	90	90
Total length [mm]	114	114
Current [A]	104	53.4
Integrated B'' [T/m^2]	7013.5	3598
Centre field gradient B'' [T/m^3]	71795	36868
Magnetic length [mm]	97.69	97.59
Gap between poles [mm]	11.08	11.08
Number of A-turns/coil	3744	1922.4
Number of turns/coil	36	36
Conductor length/coil [m]	12.8	12.8
Total electrical resistance [mΩ]	31.04	31.04
Total inductance [mH]	21.61	11.11
Input voltage [V]	3.23	1.66
Power [W]	335.73	88.51
Current density in copper [A/mm^2]	3.70	1.90
Conductor width [mm]	6	6
Conductor height [mm]	6	6
Hole diameter [mm]	3	3
Corner radius [mm]	1	1
Copper cross-section [mm^2]	28.07	28.07
Pressure drop [bar]	7.2	7.2
Number of coils in series	4	4
Water speed [m/s]	1.57	1.57
Water flow per circuit [l/min]	0.7	0.7
Water flow per magnet [l/min]	0.7	0.7
Temperature elevation per circuit [K]	7.4	1.9

References

[7.1] ESRF-EBS project, EBS storage ring technical report (ESRF, Grenoble, 2018), https://web.archive.org/web/20190506105503/https://www.esrf.eu/files/live/sites/www/files/about/upgrade/documentation/Design Report-reduced-jan19.pdf

[7.2] J. Chavanne, ESRF, private communication.