Chapter 6

MAGNETS

6.1 Introduction

The magnets within the lattice of SESAME (half-cell) are given in figure (6.1). The specifications of the magnets are compiled below the figure.

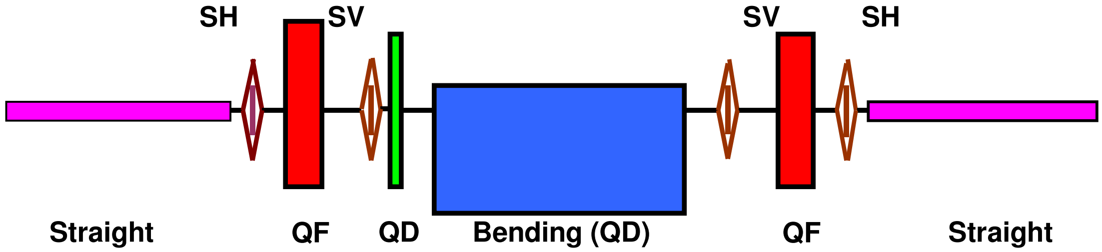


Figure 6.1:The arrangements of magnets within the half-cell of the SESAME storage ring.

Bending magnet:

Flux density	1.425 Tesla
Radius	5.85193 m
Deflection angle	22.5 degree
Magnetic length	2.29805 m
Iron length	2.233 m
Total length	2.3609 m
Strength (k-value)	0.285 $1/m^2$
Gradient	2.377 T / m
Gap height	40 mm

Quadrupole QF (Q1 and Q3):

Strength (k-value)	2.261 $1/m^2$
Gradient (max.)	18.9 T/m
Magnetic length	0.260 m
Iron length	0.225 m
Total length	0.327 m

Quadrupole QD (Q2):

Strength (k-value)	2.078 $1/m^2$
Gradient (max.)	17.3 T/m
Magnetic length	0.110 m
Iron length	0.090 m
Total length	0.192 m

Sextupole:

Strength (m-value)	43 $1/m^3$
Differ. Gradient	350 T/m^2
Magnetic length	0.14 m
Iron length	0.10 m
Total length	0.154 m

In the following sections the different magnets will be described.

6.2 Bending Magnet

According to the lattice of SESAME, the bending magnet has to perform also vertical focusing, which means that the shape of the pole profile has to be like a defocusing quadrupole. This pole profile is given by the equations:

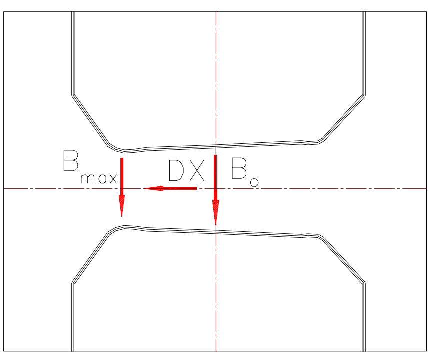
$$h(s) = h(0)\frac{1}{1+(s/X_0)} \tag{6.1}$$

and

$$X_0 = B_0 / G \tag{6.2}$$

B_0 is the nominal field at the orbit and G is the required gradient within the bending magnet.

The nominal magnetic flux density is given by the maximum allowed flux density in the bending magnets. The pole profile of a defocusing bending magnet is given in figure (6.2). The largest flux density (B_{max}) exists at the position at which the poles have the smallest distance. This B_{max} is given by the nominal field B_0, the gradient G, and the pole width (2*DX). For DX a value of 60 mm has been chosen. B_{max} for the different light sources is given in the table below with a value of a round 1.6 Tesla. The characteristics for the SESAME bending magnet fulfils this requirements.



Source	Energy (GeV)	B_o (T)	G (T/m)	B_{max} (T)
ALS	1.9	1.279	5.133	1.58
Elettra	2.3	1.38	3.303	1.58
Boomerang	3.0	1.30	3.335	1.50
CLS	2.9	1.354	3.867	1.586
SPEAR III	3.3	1.4	3.60	1.62

Figure 6.2: The shape of the pole profile within a defocusing bending magnet. The table presents the corresponding values of existing synchrotron light sources.

With the values for SESAME (B_0 = 1.425 T, G = 2.377 T/m and B_{max} = 1.57 T) , X_0 (see section 6.2) has a value of 599.49 mm. The profile given by equation 6.1 is correct, if the pole profile goes at infinity. Because the pole width is finite, magnet codes (Poisson, Mafia, etc.) have to be used for the right calculations of the pole profile. To reach the required field in a special area (-30 mm < x < +30 mm), so-called shims have to be added at the end of the poles.

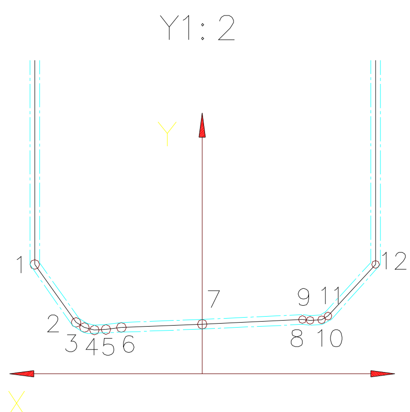


Figure 6.3: Pole profile for the SESAME bending.

Table 6.1: Coordinates for the pole profile of the bending magnet for SESAME

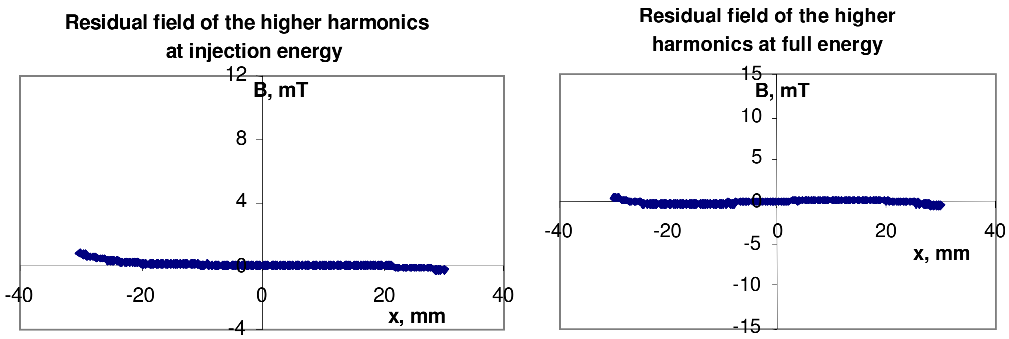
Point	X[mm]	Y[mm]
1	-87	51
2	-65.5	20.96
3	-61.2	18.3
4	-56	16.99
5	-50	17.3
6	-42	18.39
7	0	20
8	52	22.45
9	56	22.02
10	62	22.34
11	65.3	24.25
12	90	51

Table 6.2: Detailed coordinates for the pole profile of the SESAME bending magnet.

X[mm]	Y[mm]	X[mm]	Y[mm]	X[mm]	Y[mm]
-66.5	22.26	-18	19.2602	30	21.3608
-65.5	20.96	-16	19.3398	32	21.4578
-64	19.66	-14	19.4201	34	21.5557
-61.2	18.3	-12	19.5009	36	21.6544
-58.5	17.39	-10	19.5825	38	21.754
-56	16.988	-8	19.6646	40	21.8545
-54	16.947	-6	19.7475	42	21.9558
-52	17.026	-4	19.831	44	22.0581
-50	17.3	-2	19.9151	46	22.1613
-48	17.54	0	20	48	22.2654
-46	17.84	2	20.0855	50	22.3704
-44	18.12	4	20.1718	52	22.4464
-42	18.391	6	20.2587	54	22.2284
-40	18.514	8	20.3464	56	22.0163
-38	18.567	10	20.4348	58	22.0253
-36	18.571	12	20.524	60	22.1352
-34	18.6451	14	20.6138	62	22.3462
-32	18.7199	16	20.7045	63.85	23.1332
-30	18.7953	18	20.7959	64.6	23.6
-28	18.8713	20	20.888	65.3	24.25
-26	18.9479	22	20.981	66.05	25.05
-24	19.0251	24	21.0747	66.7	25.85
-22	19.1028	26	21.1693		
-20	19.1812	28	21.2646		

The right shape of this shims are calculated also by the magnet codes. The size of the shims is optimised to reduce the residual of the higher field components. The pole profile for the SESAME bending magnet after this optimisation process is given in table (6.1) and shown in figure (6.3).

The deviations from the nominal field at injection and full energy are given in figure (6.4). It is less than 0.1% with ±30 mm of the reference orbit. The width of the pole is chosen to keep the field in the iron yoke below 1.65 T.



(a) **(b)**

Figure 6.4: Residual field of the higher harmonics, (a) at injection energy (b) at full energy

The nominal flux density at the nominal orbit is 1.4 Tesla and the gap height at this location is 40 mm. These two factors determine the required excitation of the magnet:

$$N*I = B_o * gap / \mu_o = 1.4 * 0.040 / (4\pi*10^{-7}) = 45\,7359 \text{ Ampere-windings}$$

At 1.4 Tesla the magnet is already going into saturation and additional 10 % of current is needed in order to reach the nominal field. The nominal excitation for the bending magnet is 51500 Ampere-windings (A-Wdgs). This was also needed for the ANKA bending magnets and the engineering of the magnet is similarly to the ANKA ones. The excitation curve for the ANKA bending magnet is given in figure (6.5). The green line in this figure presents the

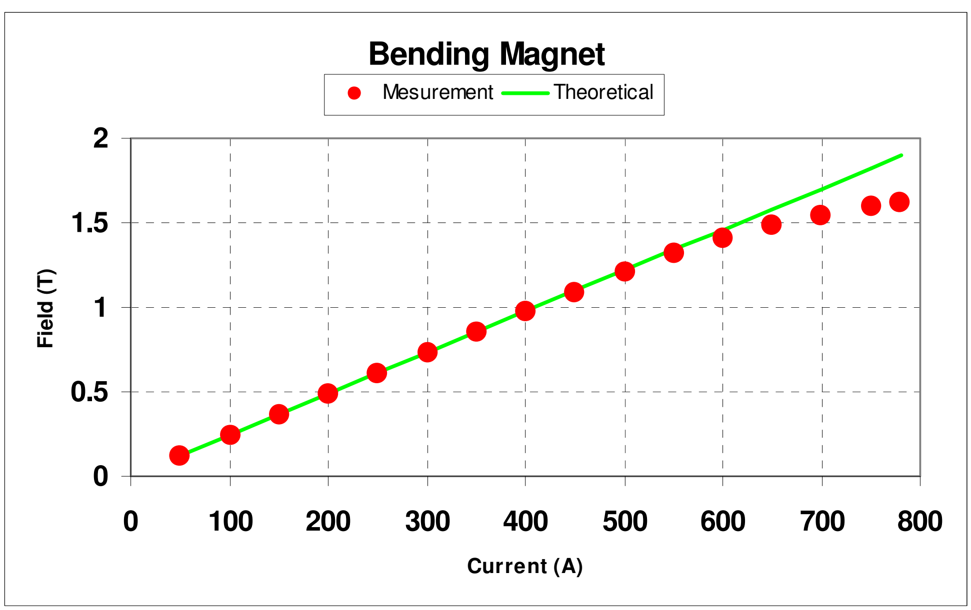


Figure 6.5: Excitation curve of the ANKA bending magnet

Table 6.3: Parameters of the SESAME bending magnet.

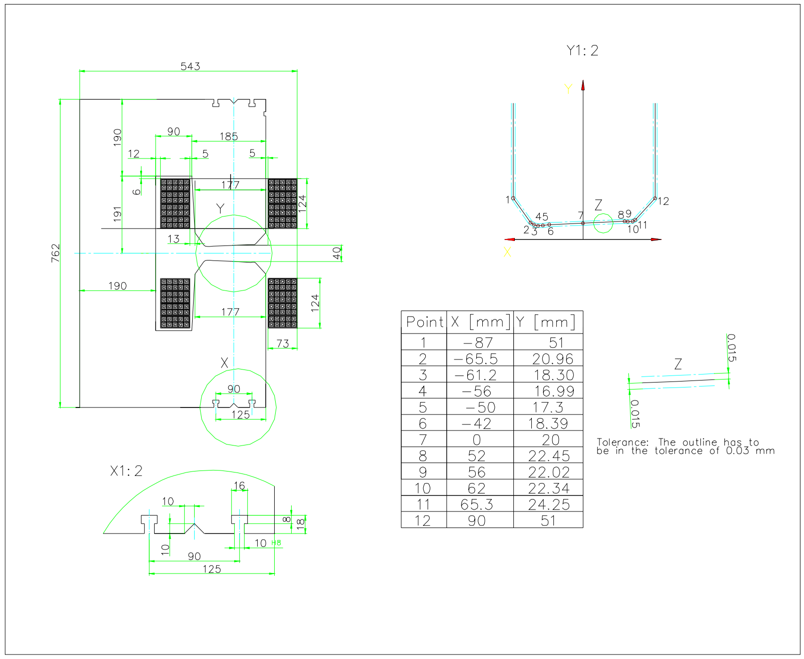
Parameter	Unit	Value
Number of magnets	-	16
Bend angle	*Degree*	22.5
Energy	*GeV*	2.5
Magnetic flux density	*T*	1.425
Bending radius	*m*	5.85193
Magnetic length	*m*	2.29805
Iron length	*m*	2.233
Total length	*m*	2.377
Gap height	*mm*	40
Pole width	*mm*	177 - 185
Iron weight	*kg*	5800
Copper weight	*kg*	820
Total weight	*kg*	6620
Gradient	*T/m*	2.377
Ampere turns	*A*	51 500
Number of turns	-	80
Nominal current	*A*	643
Number of pancakes	-	8
Conductor dimensions	*mm*	13*13, ∅=5.0
Conductor area	mm^2	196 / 20.5
Conductor length	*m*	465
Current density	A/mm^2	3.13
Total resistance	mΩ	50.6
Total inductance	*mH*	80.0
Time constant	*sec*	1.65
Voltage drop	*V*	32.6
Power	kW	21.0
Number of cooling circuits	-	8
Temperature rise	^{0}C	15
Cooling water flow	m^3/sec	$41.7\text{x}10^{-6}$
Cooling water speed	m/sec	2.12
Pressure drop	bar	8.17
Reynold number (>1160)	-	5310

excitation curve without saturation. Hence the saturation takes place at a field of 1.3 T, which corresponds to an energy of 2.3 GeV. The measured gradient of the green line is 0.002435 and the theoretical one is 0.002453, which means a difference of 7E-03.

Slight differences exist concerning the cooling, now the magnet is 0.4m longer and with the same dimensions for the coils and the cooling the needed pressure for a temperature drop of 15 degree would increase to 13 bar, which is unacceptable. Therefore the number of cooling circuits has been increased to 8 (each pancake has now its own cooling circuit) and the cooper dimensions have been change to 13 * 13 mm^2 with a cooling hole of 5 mm.

Turbulent flowing within the cooling channels is required for an active cooling. The "Reynolds Number" and the critical water speed give this. Both criteria are fulfilled with the proposed design. The specifications of the bending magnet are compiled in table (6.3).

Figures (6.6) to (6.10) presents the detailed design of the bending magnets. Figure (6.6) and (6.7) give the cross section, the pole profile of the magnet and the dimensions for the end plate. Figure (6.8) gives the top and the side view. The details of a pancake of the coils are presented in figure (6.9). Figure 6.10 gives the side view of the magnet.



Point	X [mm]	Y [mm]
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3	−61.2	18.30
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7	0	20
8	52	22.45
9	56	22.02
10	62	22.34
11	65.3	24.25
12	90	51

Figure 6.6: The cross section with pole profile of the SESAME dipole magnet.

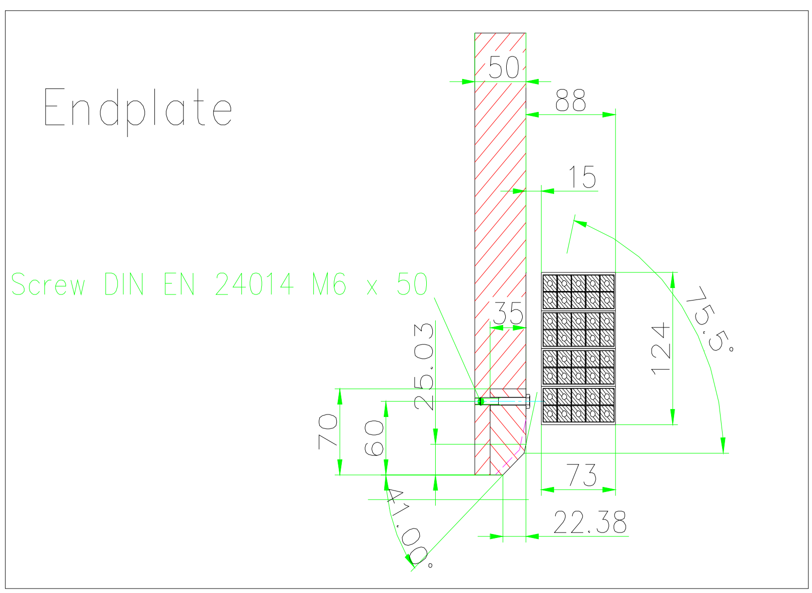


Figure 6.7: Dimensions of the end plate and the coil at the endplate of the SESAME dipole magnet.

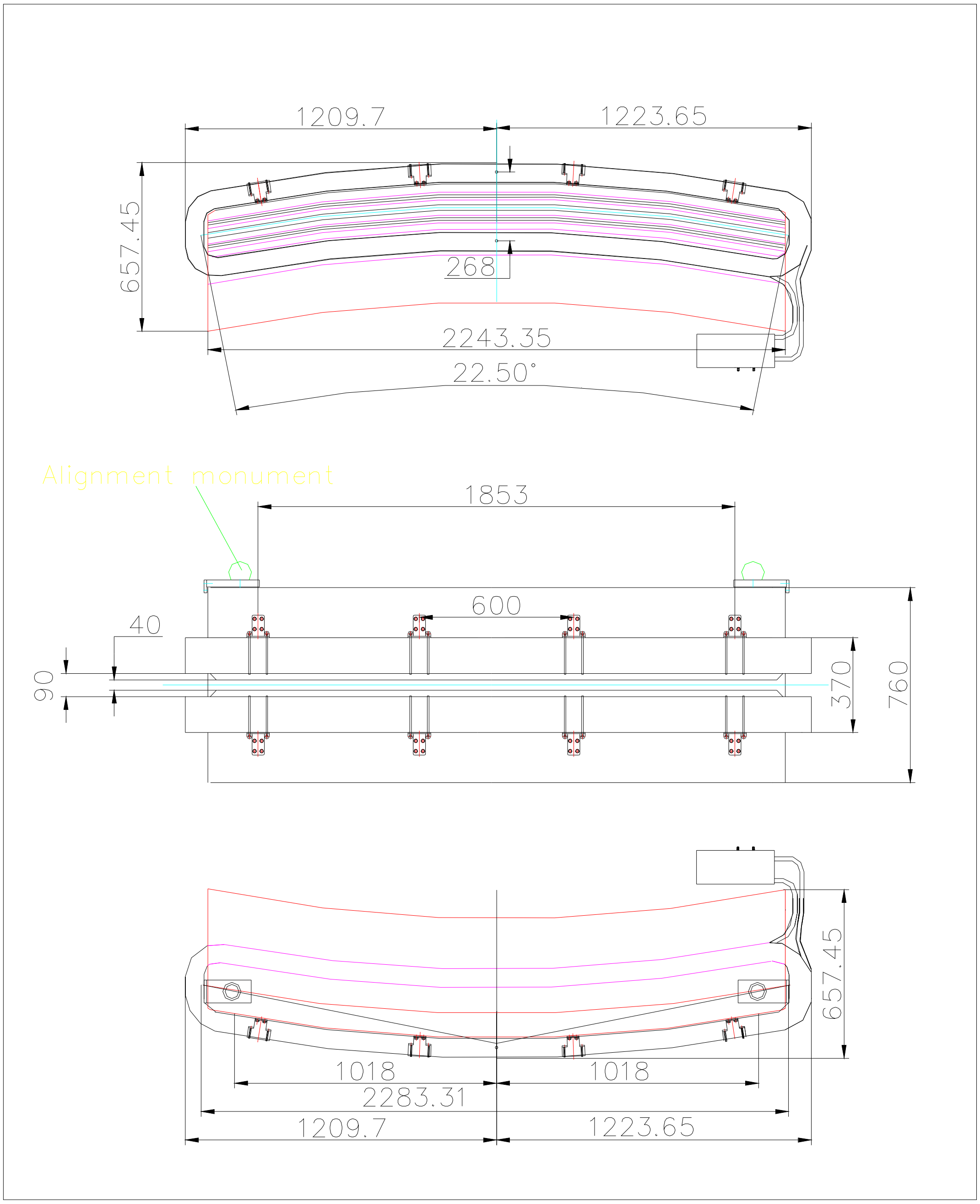


Figure 6.8: The top and the side view of the SESAME dipole magnet with dimensions.

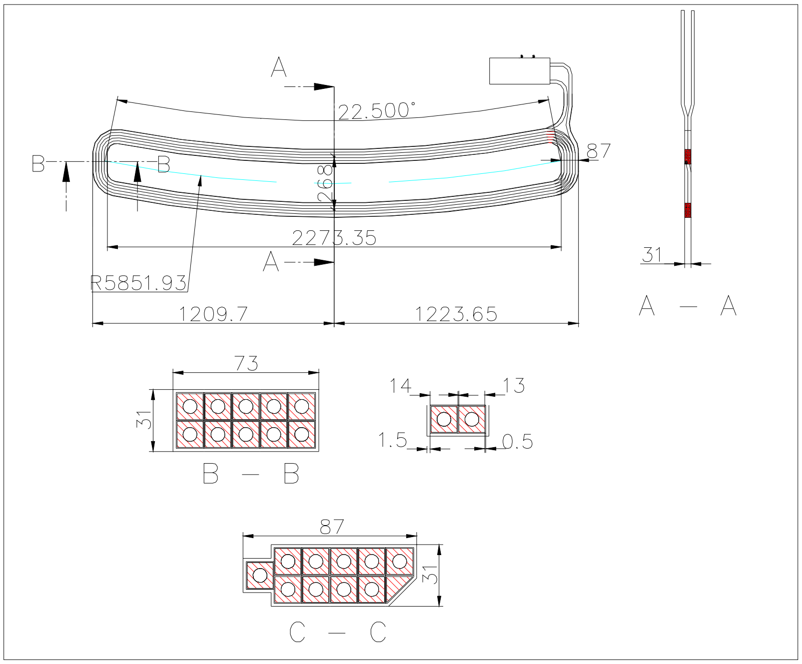


Figure 6.9: The shape of the coils for the SESAME dipole magnet

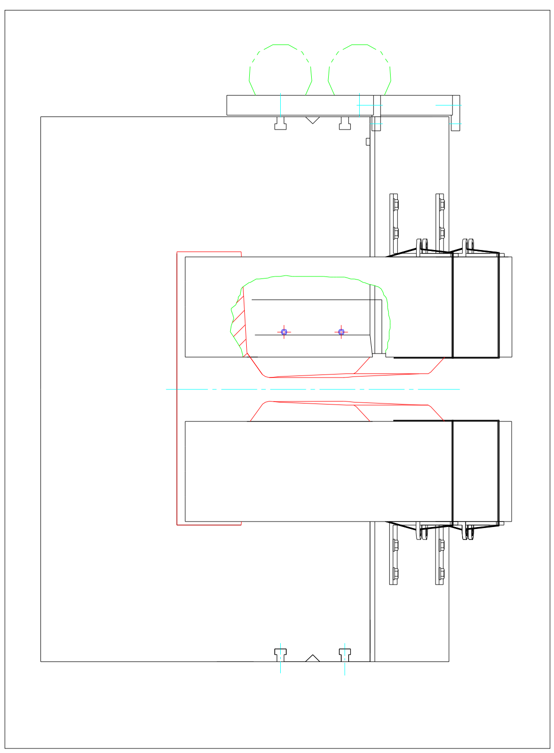


Figure 6.10: Side view of the SESAME dipole magnet

6.3 Quadrupole

The specifications of the quadrupoles are given by the maximum allowable gradient (g), which is given by the design. At present gradients of 19 T/m are useable. The calculations of the magnet optics result in a quadrupole strength k by a given length of the quadrupole. The strength is determined by the gradient of the quadrupoles and the radius (ρ) and field (B) of the bending:

$$k_{max} = g / (\rho * B) = 19 / (5.85193 * 1.425) = 2.28 \text{ m}^{-2}$$

With a k_{max} of 2.20 m^{-2} the maximum gradient is g = 18.35 T/m.

So far we have a k value of 2.04, hence this number can be increased, which means a reduction of the quadrupole length. Taking a length of 265 mm, the k-value would increase to 2.19 m^{-2} and the gradient would be g = 18.26 T/m. So the hard edge length of the quadrupoles will be 265 mm. The corresponding iron length will be 230 mm. To reach the required gradient in the quadrupoles the following excitation is needed:

$$N*I = (g*R^2) / (2*\mu_0) = 19*(0.035)^2 / (2*4*\pi*10^{-7}) = 9261 \text{ A*Wdg}$$

With N=26 turns the current is I = 356 A.

The magnetic flux at the pole tip B_{pol} is given by the formula:

$$B_{pol} = g*R = 19*0.035 = 0.665 \text{ T}$$

The overall magnetic flux is given by the formula.

$$\Phi = 2*B_{pol}*A_{pol} = 2*0.6655*0.23*0.088 = 0.108 \text{ Tm}^2$$

The parameters of the quadrupoles are summarized in the following table (6.7); a drawing of the ANKA quadrupole is presented in figure (6.12). As an example, the excitation curve for the ANKA-Quadrupole is given in the figure (6.11).

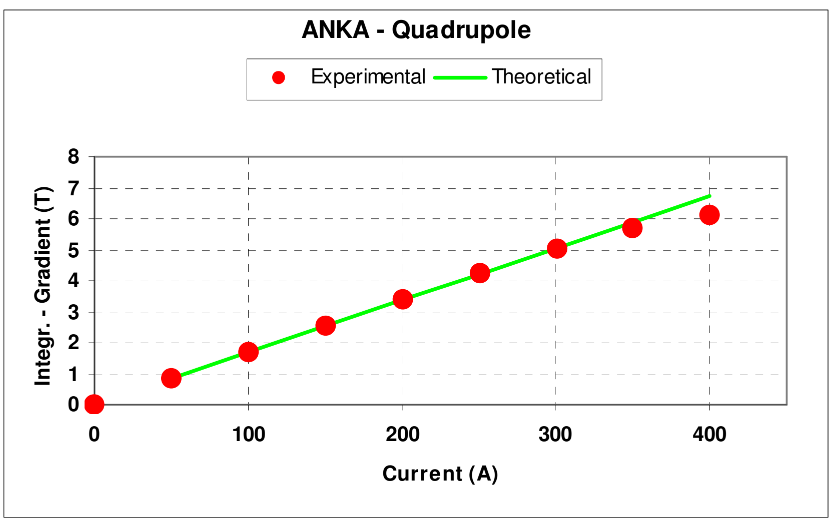


Figure 6.11: Excitation curve of the ANKA quadrupole

The slope of the curve should be 0.01707, and the measured value is 0.01684. The length of the quadrupole determines the difference; instead of 320 it is 316 mm. The saturation starts with a current of 350 A, which corresponds to a gradient of 18 T/m. The maximum reachable gradient of this quadrupole is 20. 5 T / m

The specifications of the quadrupoles Q2, Q3 and Q2 are compiled in table (6.4). Drawings of the detailed design are presented in figure (6.12) to (6.16).

Table 6.4: Parameters of the SESAME Quadrupole Q1,Q3 and Q2.

Parameter	**Unit**	**Type Q1 &Q3**	**Type Q2**
Number of magnets		32	16
Energy	GeV	2.5	2.5
Gradient	T / m	19.0	19.0
Magnetic length	m	0.265	0.110
Iron length	m	0.23	0.09
Total length	m	0.332	0.192
Aperture radius	mm	35.0	35.0
Pole width	mm	60.0 – 88.0	60.0 – 88.0
Iron weight	kg	235	97
Copper weight	kg	62	32
Total weight	kg	297	129
Ampereturns per pole	A	9261	9258
Windings per pole		26	26
Nominal current	A	356.0	356.0
Conductor dimensions	mm	10*10,∅=4.0	9*9,∅=3.0
Conductor / Cooling area	mm^2	87.4 / 12.6	81 / 7.07
Conductor length	m	80.0	52
Current density	A/mm^2	4.07	4.82
Total resistance	mΩ	16.4	12.6
Total inductance	mH	7.9	2.7
Time constant	s	0.48	0.22
Voltage drop	V	5.80	4.5
Power	kW	2.08	1.6
Number of cooling circuits		2	2
Temperature rise	^oC	15	15
Cooling water flow	m3/s	$16.5*10^{-6}$	$12.7*10^{-6}$
Cooling water flow	l / h	59.3	45.6
Cooling water speed	m / s	1.31	1.79
Pressure drop	bar	3.19	5.13
Reynold number (> 1160)		2620	2620
Critic. Veloc.	(m/s)	0.625	0.833

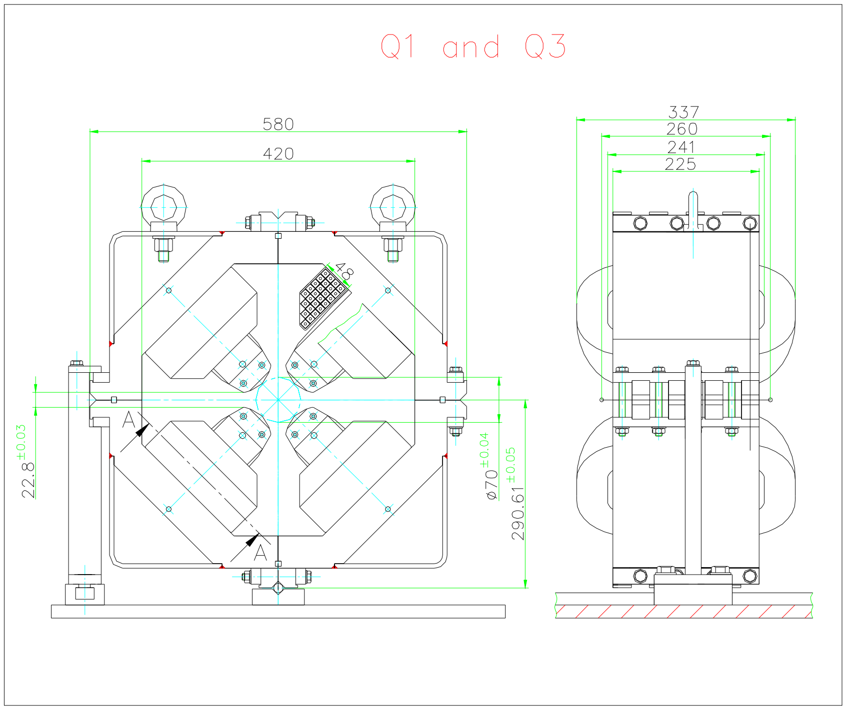


Figure 6.12: Layout of the SESAME quadrupoles Q1 and Q3.

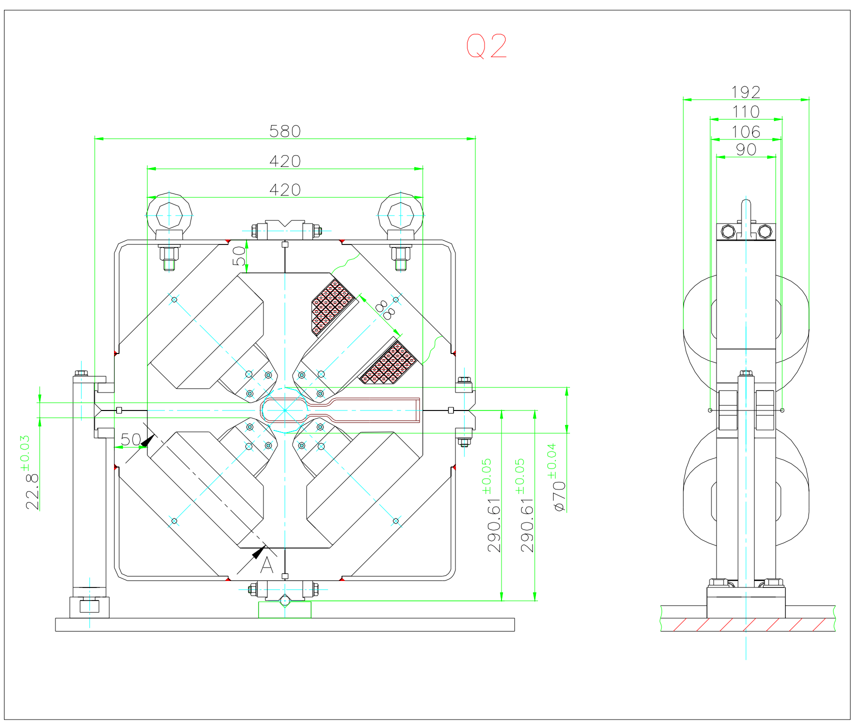


Figure 6.13: Layout of the SESAME quadrupoles Q2.

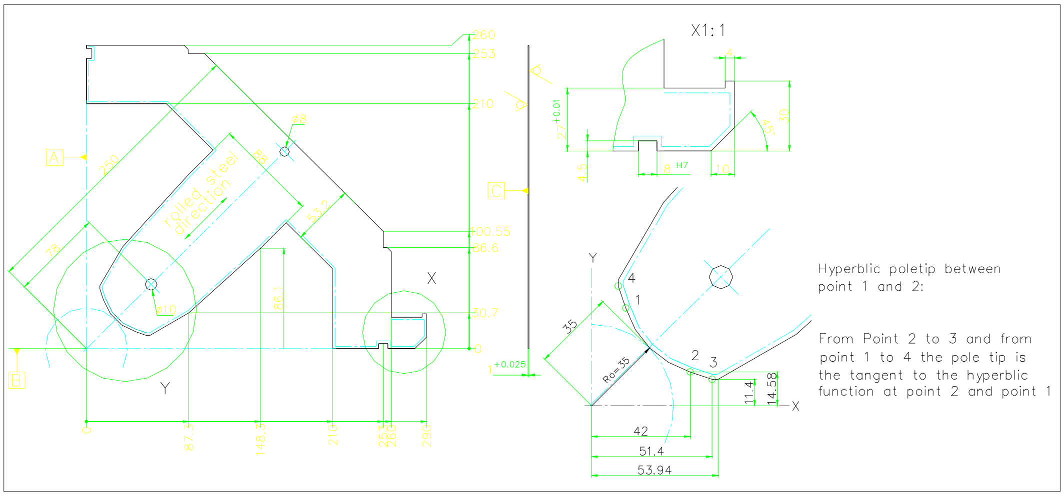


Figure 6.14: The shape of the lamination of the SESAME quadrupole, which is the same as for ANKA.

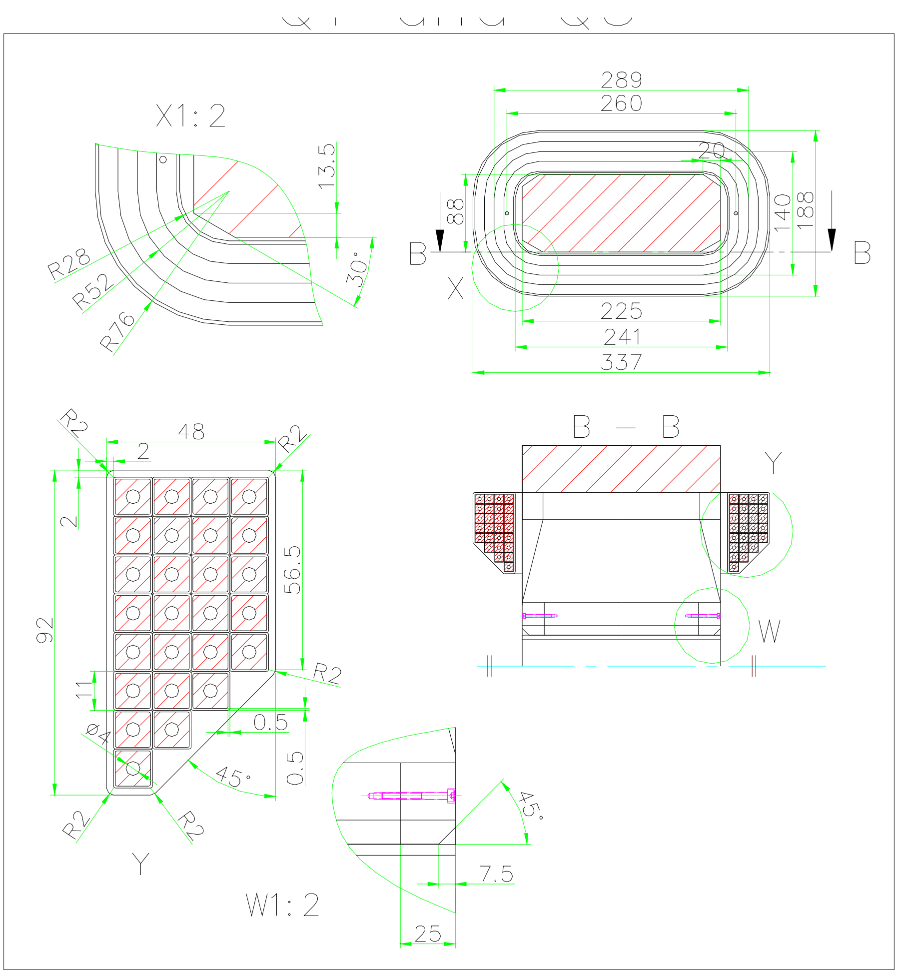


Figure 6.15: The shape and dimensions of the coil for the SESAME quadrupole Q1 and Q3

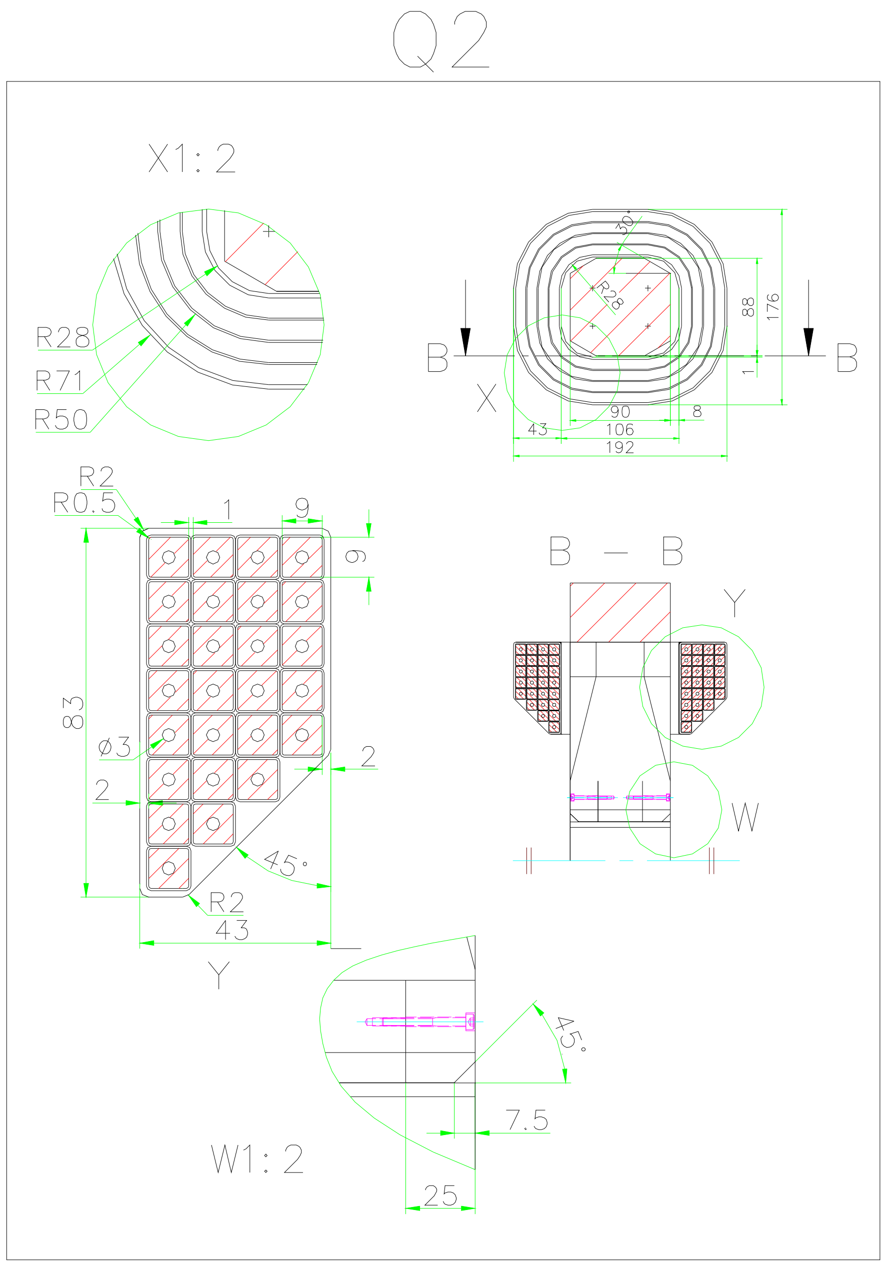


Figure 6.16: The shape and dimensions of the coils for the SESAME quadrupole Q2

A cross section of the quadrupole with the vacuum chamber at different locations is shown in figure (6.17) and (6.18). According to these figures the so called "closed magnet" can be used.

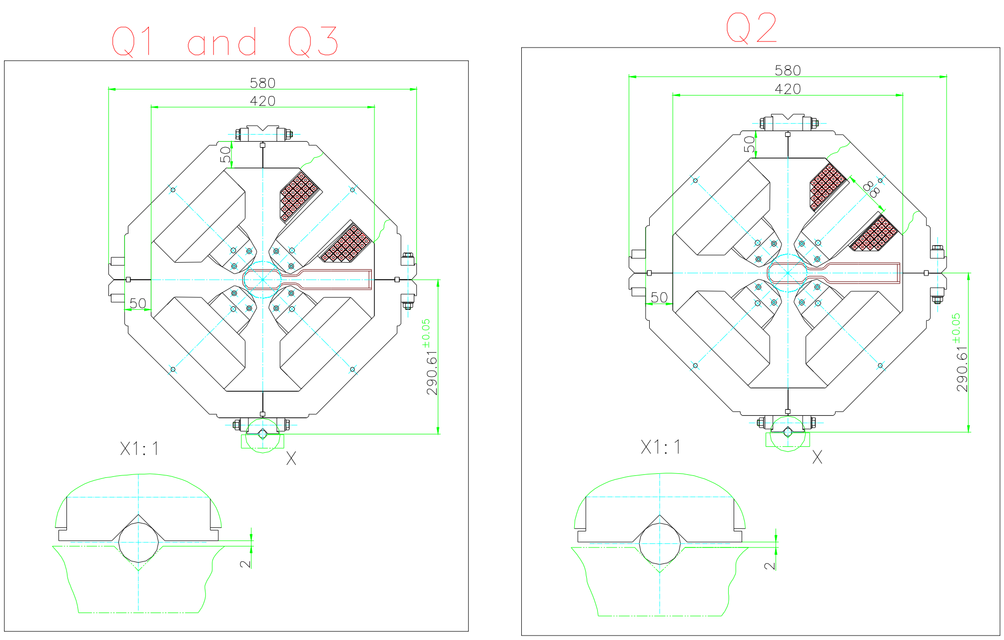


Figure 6.17: The maximum needed space for the vacuum chamber in the quadrupoles Q1, Q2 and Q3

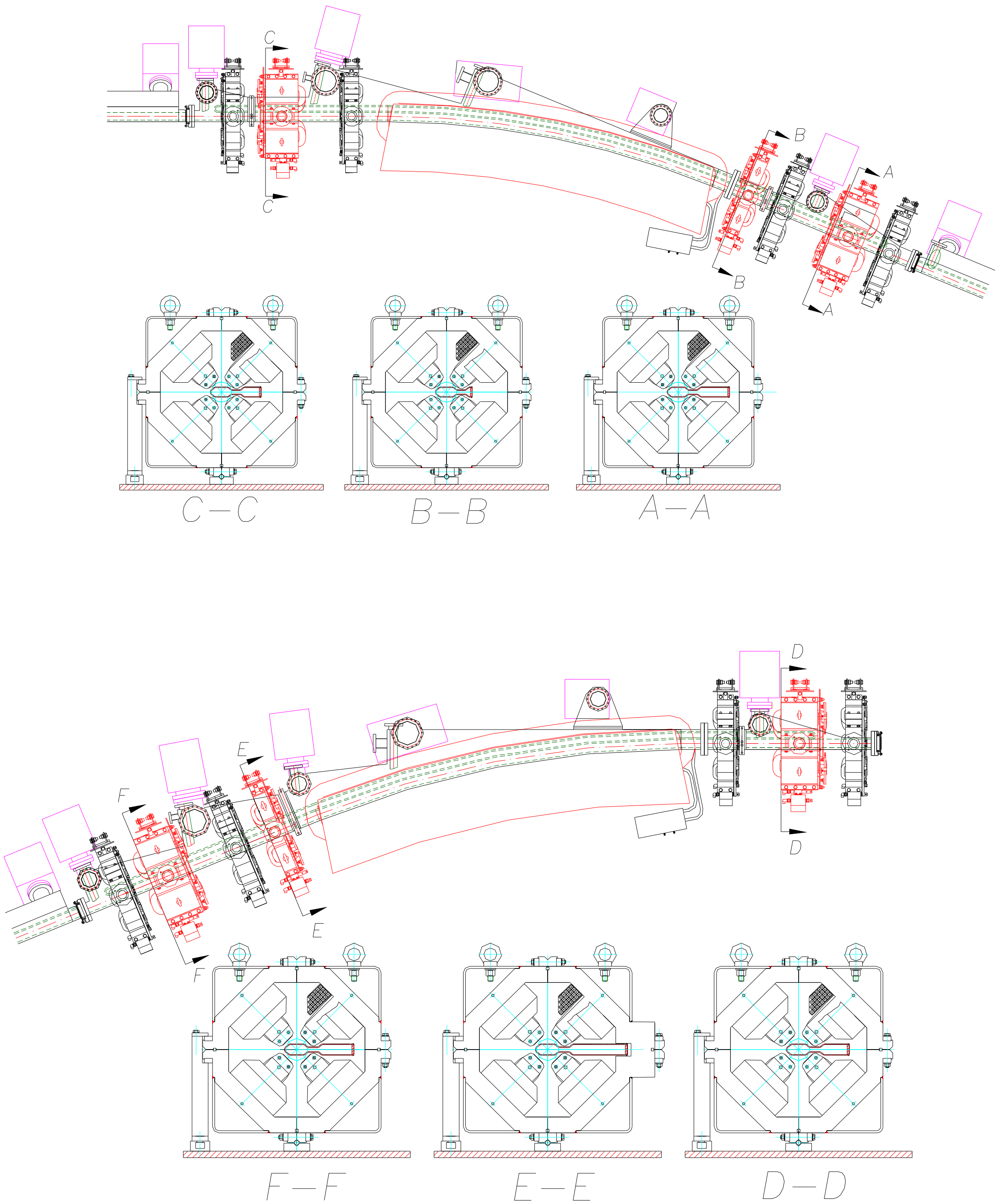


Figure 6.18: The needed space for the vacuum chamber in the quadrupoles at different locations

6.4 Sextupole

SESAME could be operated with the two extreme optics: without wigglers and with 8 wigglers. The wigglers have a field of 3.5 T and a period length of 60 mm. For both optics the defocusing sextupoles (S1 and S4 in Fig.6.1) have the highest value, the following settings are required:

Without wigglers: $m*l_{max} = 3.60\ m^{-2}$ and $B''*l_{max} = 29.9$ T/M.
With 8 Wigglers. $m*l_{max} = 3.75\ m^{-2}$ and $B''*l_{max} = 31.3$ T/M.

The vertical chromaticity is equal –9.5 and the corrected is zero. At least one should run the machine with a positive chromaticity of 2. This increases the settings by a factor 1.2, but for safety reasons a factor 1.4 should be taken which results in the following settings:

$m*l_{max} = 3.80\ m^{-2} * 1.4 = 5.32\ m^{-2}$ and,

$B''*l_{max} = 29.9\ T/M * 1.4 = 43.82\ T/m.$

The iron length should be 100mm. The fringe field give a farther contribution which results in a hard edge length of 140 mm. Therefore the m-value and the differential gradient of the sextupole have to meet the requirements:

$m_{max} = 5.32\ m^{-2} / 0.14 = 38.0\ m^{-3}$ and,

$B''_{max} = 43.8\ T/M / 0.14 = 313.0\ T/m^2$.

The m-value is connected with the radius and field in the bending magnets:

$$m = B'' / (\rho*B)$$

With B=1.425 T and ρ = 5.85193 meters, the m-value corresponds to a differential gradient of

$$g' = B'' = 317\ T/m^2$$

This is in agreement with the above given value. In order to have some more margin for the engineering a differential gradient of **$g' = B'' = 350\ T/m^2$** is chosen. To reach the required field in the sextupoles the following excitation is needed:

$$N*I = (B''*R^3) / (6*\mu_0) = 350*(0.0375)^3 / (6*4*\pi*10^{-7}) = \mathbf{2448\ A*Wdg}$$

With **N=18** turns the current is **I = 136.0 A.**

The magnetic flux at the pole tip B_{pol} is given by the formula:

$$\mathbf{B_{pol}} = (1/2) * B''*R^2 = (1/2)*350*0.0375^2 = \mathbf{0.246\ T}$$

The overall magnetic flux is given by the formula.

$$\mathbf{\Phi} = 2*B_{pol}*A_{pol} = 2*0.246*0.08*0.14 = \mathbf{0.0055\ Tm^2}$$

The parameters of the sextupoles are summarized in table (6.5) and a drawing of the SESAME-sextupole is given in figure (6.20). This is more or less the same as for ANKA. As an example; in figure (6.19) is presented the excitation curve of the ANKA-Sextupole.

The slope of the curve in figure (6.19) should be according to the design 0.415, a value of 0.141 has been measured. An altered length gives the difference. Instead of 0.145 the length is 0.141m. the saturation starts at a current of 275 A, which results in an integrated differential gradient of 110 T/m or a differential gradient (B'') of 780 T/ m^2.

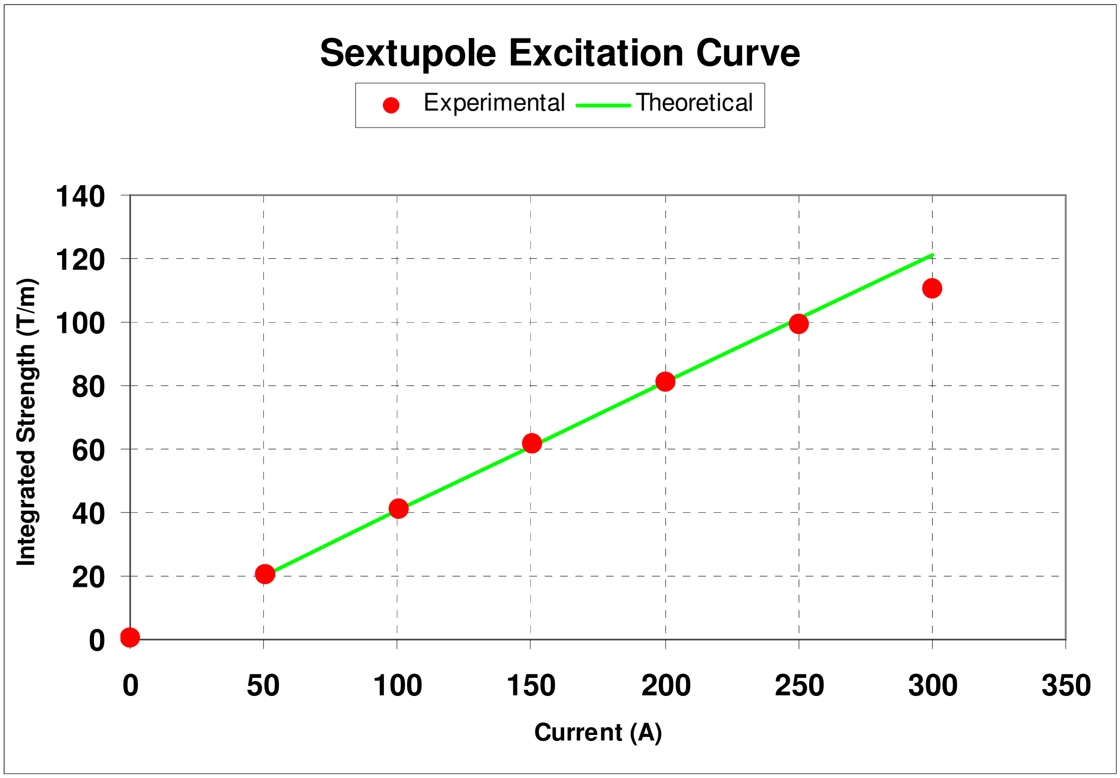


Figure 6.19: Excitation curve of the ANKA sextupole

A compilation of the specifications of the sextupole magnet is given in table (6.5). The detailed design is presented within the figures (6.20) to (6.25). The cross section of the sextupole with the vacuum chamber at different locations in the storage ring are presented in figure (6.26), according to section C-C in this figure, 16 of the 64 sextupoles have to be modified, but all other sextupoles are "closed" ones.

Table 6.5 Parameters of the SESAME-Sextupoles.

Parameter	**Unit**	**Type 140**
Number of magnets		64
Energy	GeV	2.5
Diff. gradient (g’’)	T / m^2	350.0
Magnetic length	m	0.140
Iron length	m	0.100
Total length	m	0.154
Aperture radius	mm	37.5
Pole width	mm	80.0
Magnet weight	kg	
Ampere turns per pole	A	2448
Windings per pole		16
Nominal current	A	138.6
Conductor dimensions	mm	6.*4.,∅=2.5
Conductor / Cooling area	mm^2	19.0 / 4.9
Conductor length	m	45
Current density	A/mm^2	7.35
Total resistance	mΩ	37.8
Total inductance	mH	3.5
Time constant	S	0.09
Voltage drop	V	5.22
Power	KW	0.72
Number of cooling circuits		2
Temperature rise	^{o}C	15
Cooling water flow	m3/s	$5.8*10^{-6}$
Cooling water flow	L / h	20.7
Cooling water speed	m / s	1.17
Pressure drop	Bar	2.38
Reynold number (>1160)		1470
Critical velocity	(m/s)	1.00

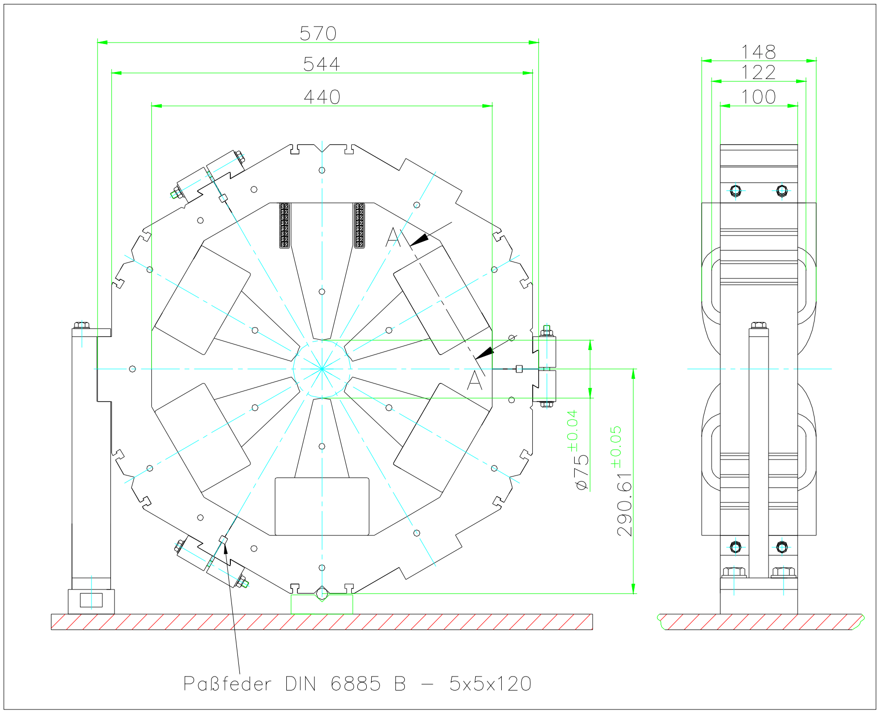


Figure 6.20: Layout of the SESAME sextupole

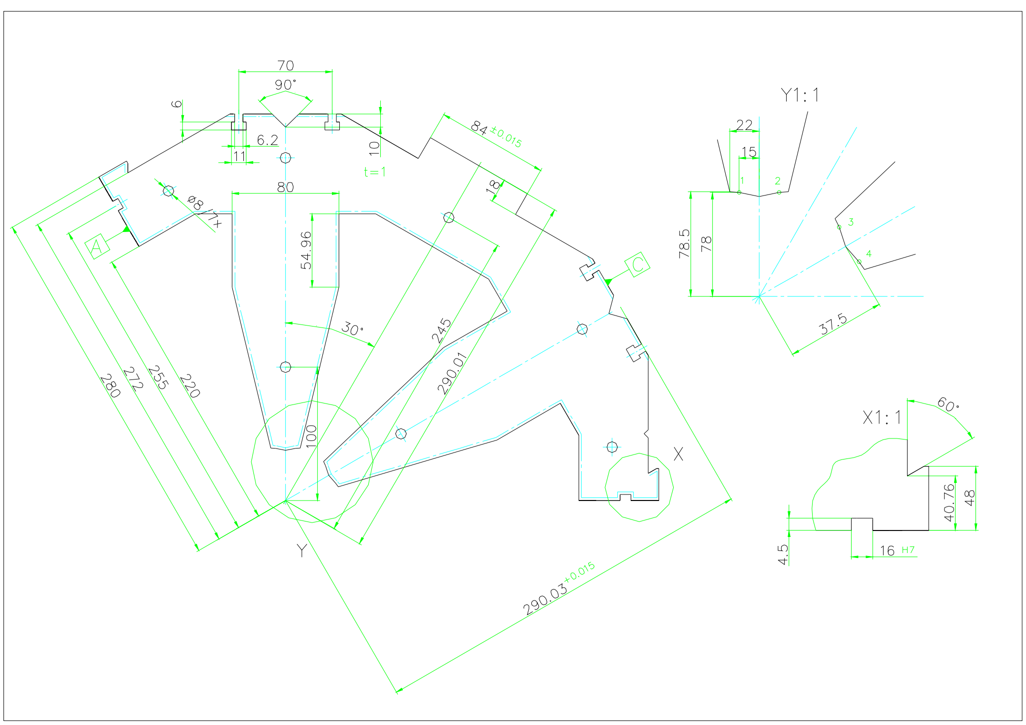


Figure 6.21: The shape of the lamination of the ANKA Sextupole, which will be used for SESAME.

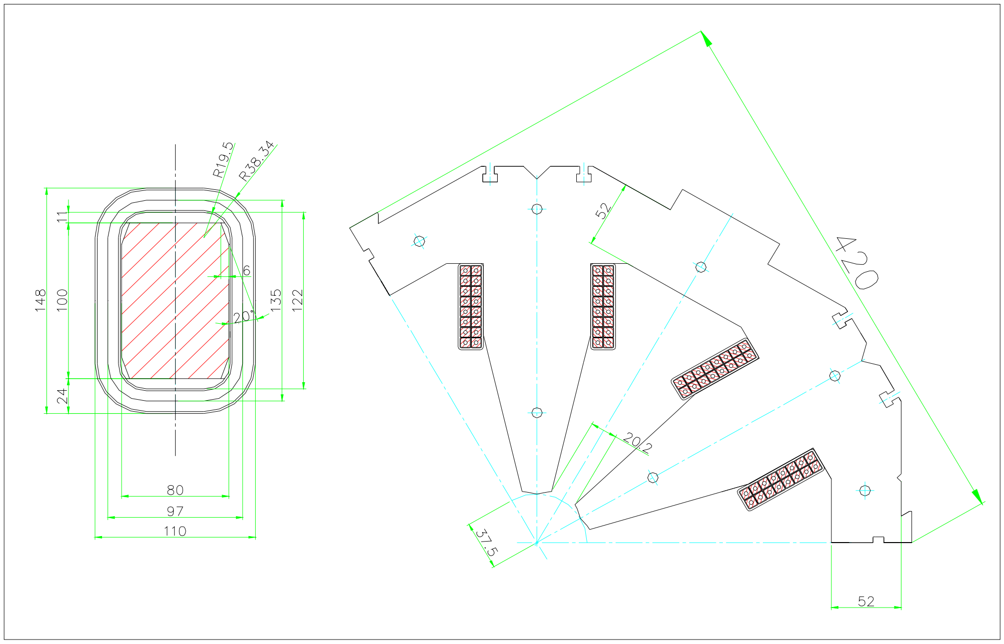


Figure 6.22:Arrangements of coils for the SESAME sextupoles.

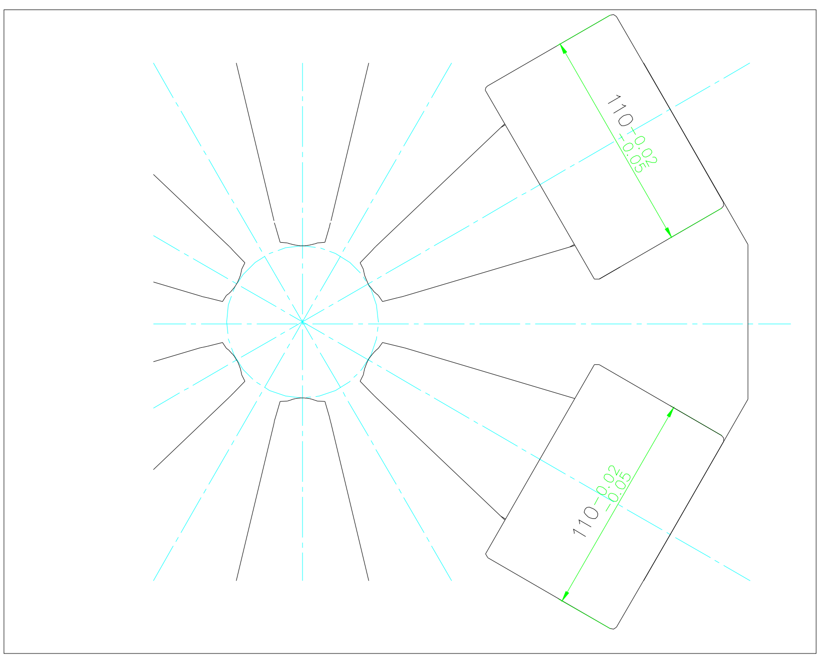


Fig.6.23: Dimensions of the sextupole coils

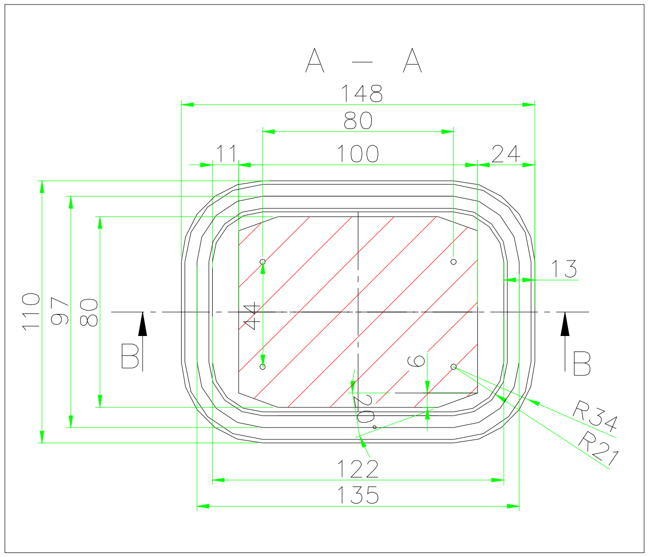


Fig.6.24: Dimensions of the sextupole coils

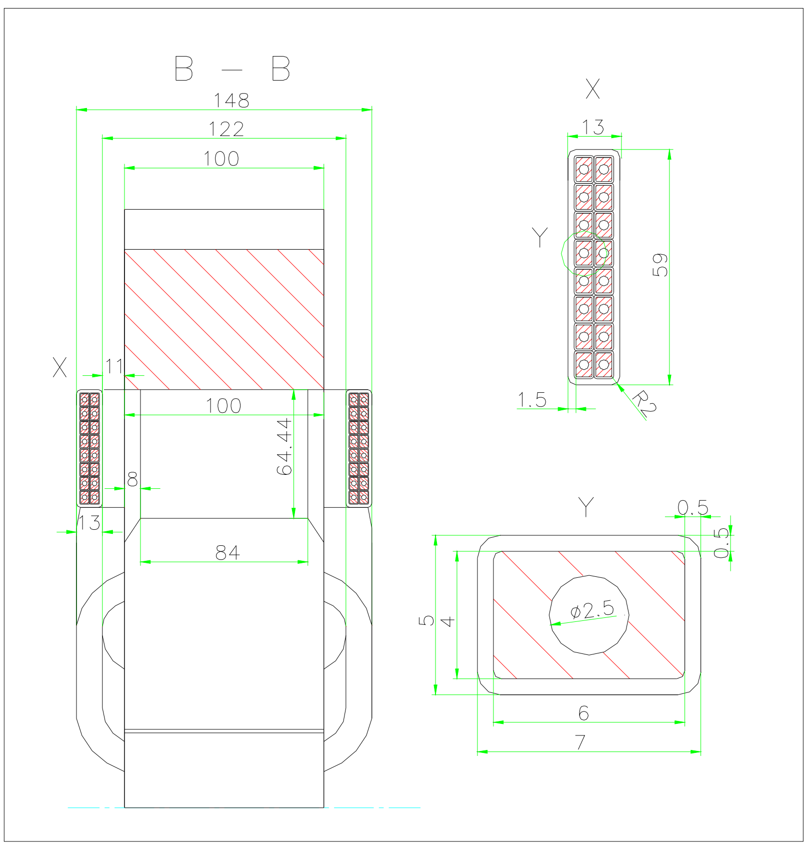


Figure 6.25 : The dimensions for the coils of the sextupoles.

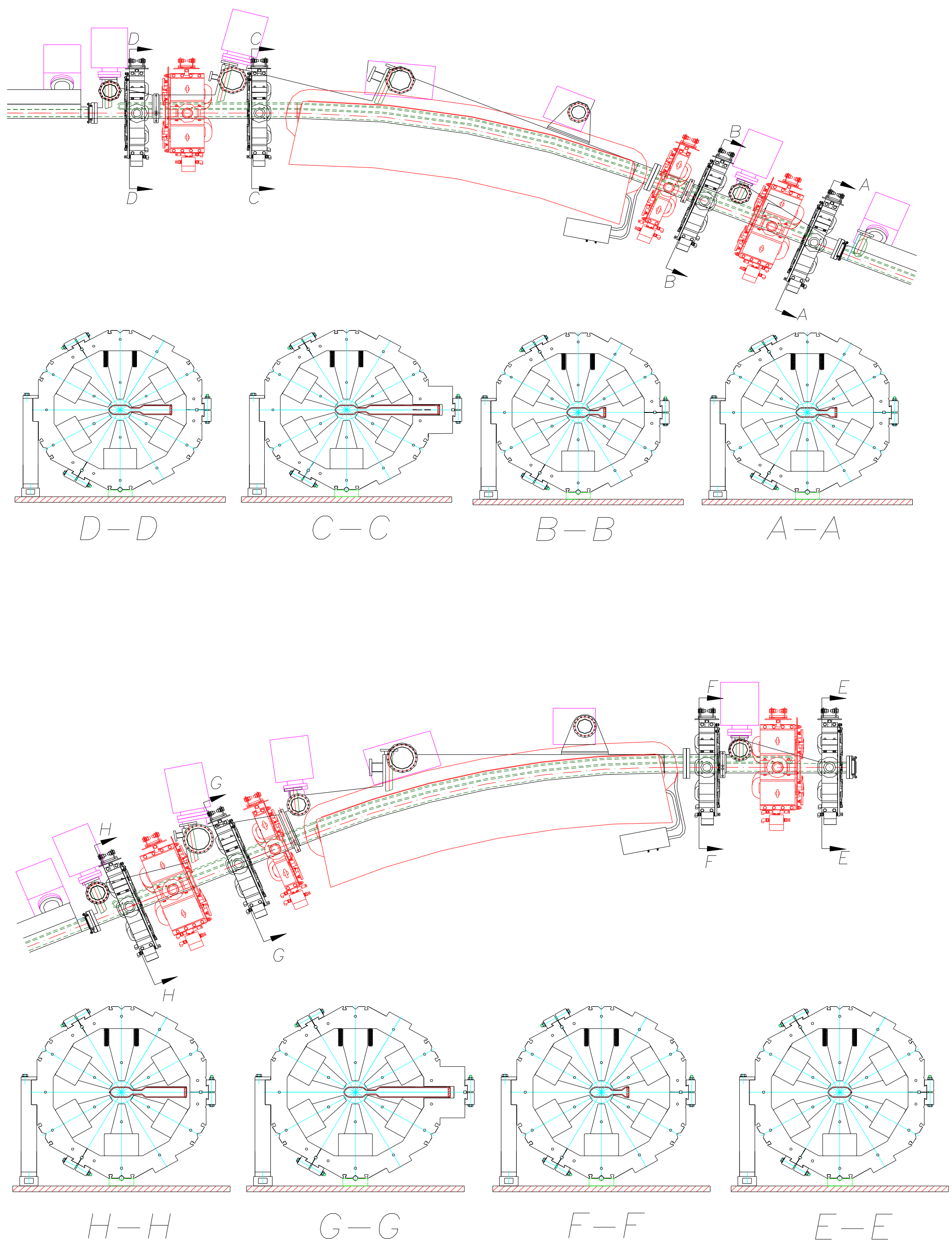


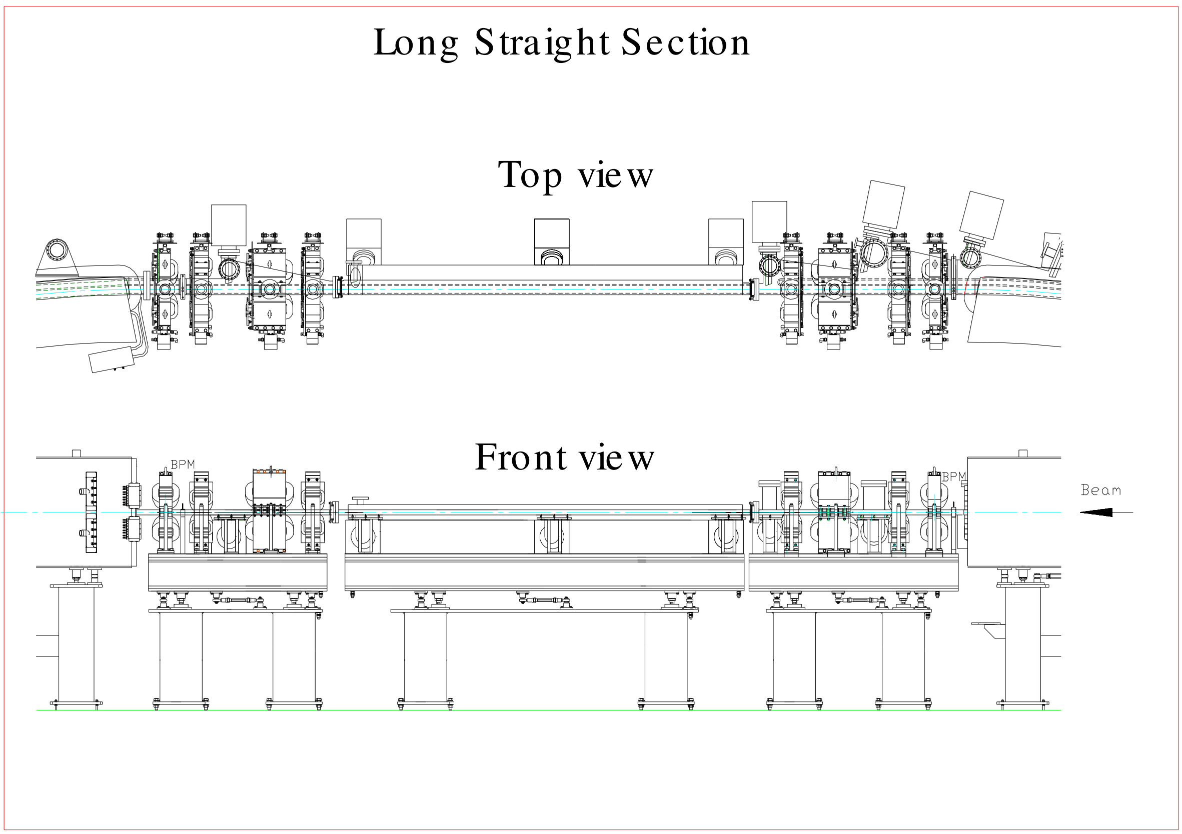
Figure 6.26: The needed space for the vacuum chamber in the quadrupoles at different locations.

6.5 Correctors

A detailed design of the correctors has not been made, the intention is to introduce the corrector function into the sextupoles, a design is underway.

6.6 Girder System

Draft design of the girder system for the long straight section, short straight section, the RF straight and the injection straight are shown in figures (6.27), (6.28), (6.29) and (6.30) respectively.



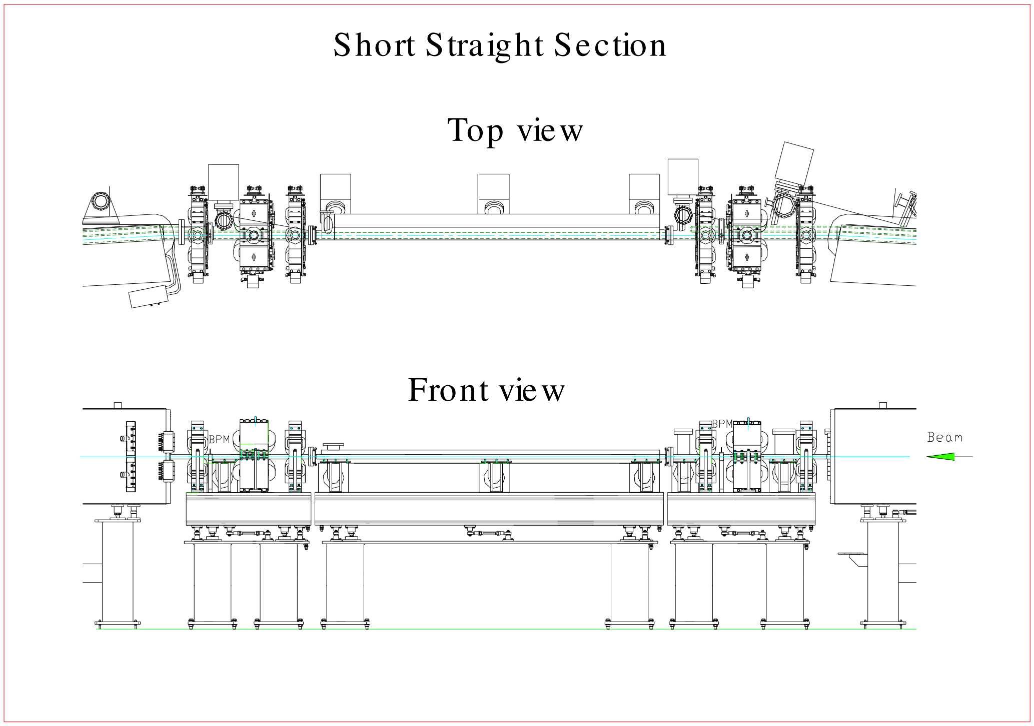


Figure 6. 28: The short straight section girder system.

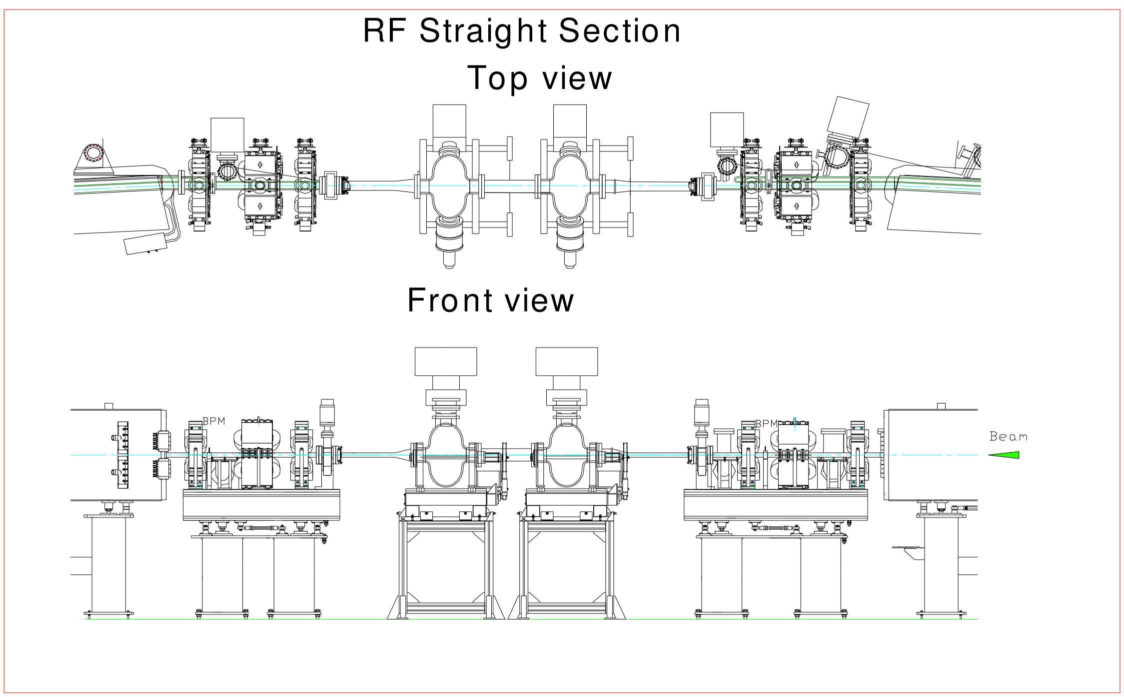


Figure 6.29: The RF straight section girder system.

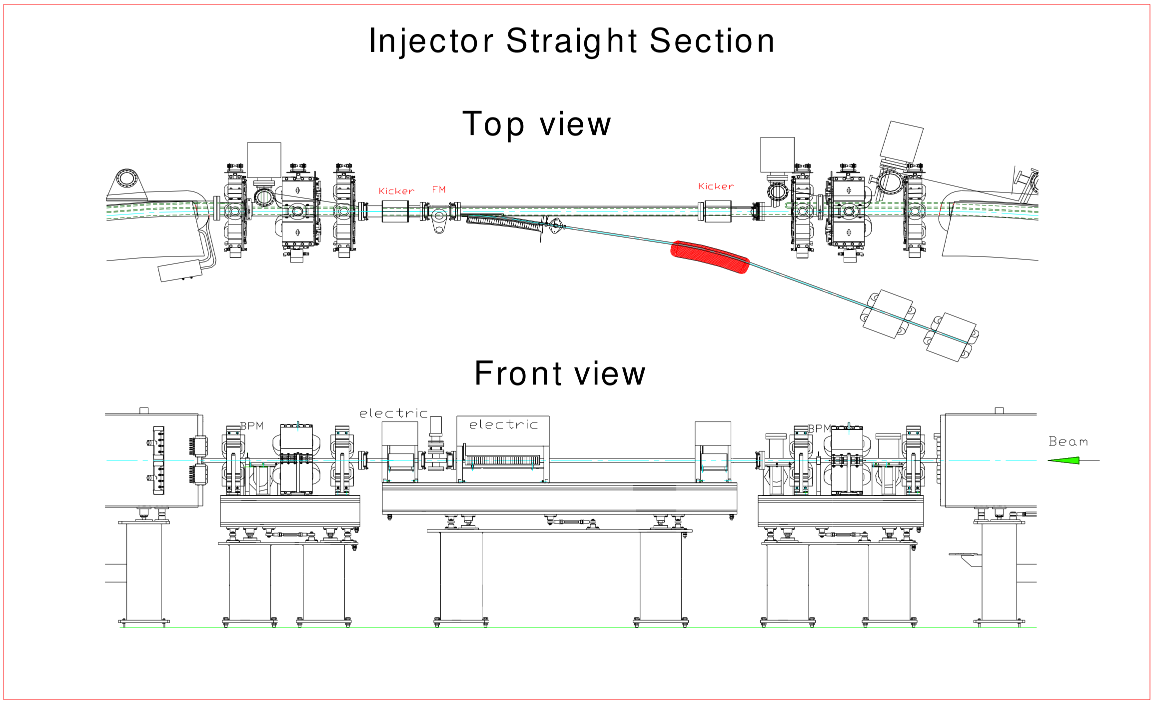


Figure 6.30: The injection straight section girder system.

References

[1] Å. Andersson et al, "*Design report for the MAX II ring*", NTMX-7019,(1992).
[2] David Meeker, "*Finite Element Method Magnetics*", (FEMM code) version 3.0.