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.
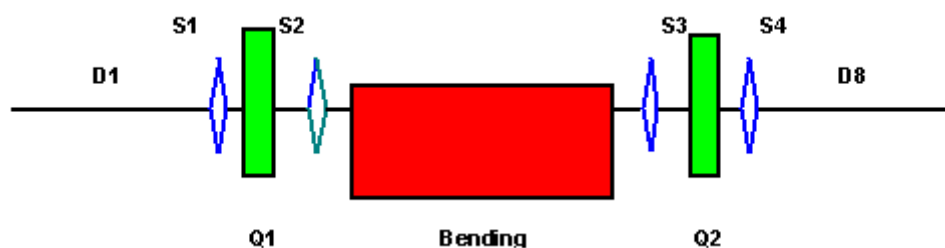

Figure 6.1: The arrangements of magnets within the half-cell of the SESAME storage ring.

Bending magnet:

Flux density	1.40 Tesla
Radius	5.95643 m
Deflection angle	22.5 degree
Magnetic length	2.3391 m
Iron length	2.274 m
Total length	2.467 m
Strength (k-value)	0.341 $1/m^2$
Gradient	2.84 T / m
Gap height	42 mm

Quadrupole:

Strength (k-value)	2.28 $1/m^2$
Gradient (max.)	19 T/m
Magnetic length	0.265 m
Iron length	0.23 m
Total length	0.332 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:

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

and

$$X_0 = B_0 / G \qquad (6.2)$$

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 fulfills this requirements.

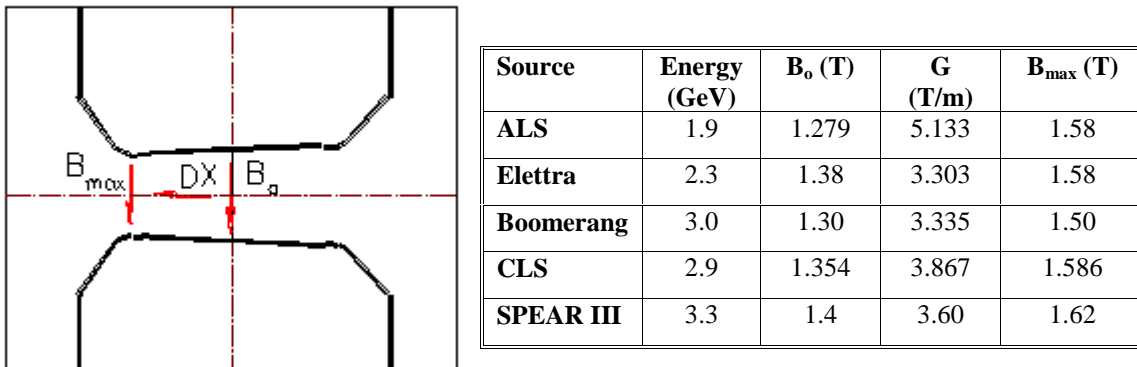| Source	Energy (GeV)	B_o (T)	G (T/m)	B_{max} (T)
ALS	1.9	1.279	5.133	1.58
Elettra	2.3	1.38	3.303	1.58
Boomerang	3.0	1.30	3.335	1.50
CLS	2.9	1.354	3.867	1.586
SPEAR III	3.3	1.4	3.60	1.62

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 = 1.4 T, G = 2.84 T/m and B_{max} = 1.57 T) , X_0 (see section 6.2) has a value of 492.96 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. 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).

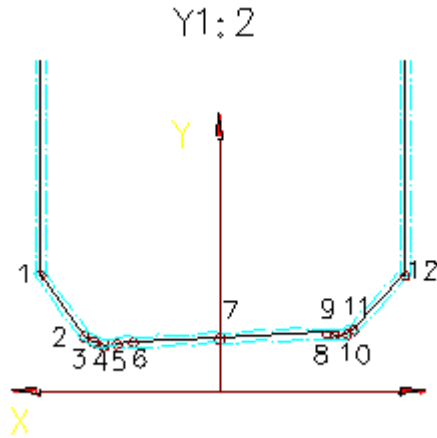**Table 6.1: Coordinates for the pole profile of the bending magnet for SESAME**

Point	X[mm]	Y[mm]
1	-87	52
2	-65.5	21.96
3	-61.2	19.3
4	-56	17.99
5	-50	18.3
6	-42	19.39
7	0	21
8	52	23.45
9	56	23.02
10	62	23.34
11	65.3	25.25
12	90	52

Y1:2

Figure 6.3: Pole profile for the SESAME bending.

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	23.26	-18	20.2602	30	22.3608
-65.5	21.96	-16	20.3398	32	22.4578
-64	20.66	-14	20.4201	34	22.5557
-61.2	19.3	-12	20.5009	36	22.6544
-58.5	18.39	-10	20.5825	38	22.754
-56	17.988	-8	20.6646	40	22.8545
-54	17.947	-6	20.7475	42	22.9558
-52	18.026	-4	20.831	44	23.0581
-50	18.3	-2	20.9151	46	23.1613
-48	18.54	0	21	48	23.2654
-46	18.84	2	21.0855	50	23.3704
-44	19.12	4	21.1718	52	23.4464
-42	19.391	6	21.2587	54	23.2284
-40	19.514	8	21.3464	56	23.0163
-38	19.567	10	21.4348	58	23.0253
-36	19.571	12	21.524	60	23.1352
-34	19.6451	14	21.6138	62	23.3462
-32	19.7199	16	21.7045	63.85	24.1332
-30	19.7953	18	21.7959	64.6	24.6
-28	19.8713	20	21.888	65.3	25.25
-26	19.9479	22	21.981	66.05	26.05
-24	20.0251	24	22.0747	66.7	26.85
-22	20.1028	26	22.1693		
-20	20.1812	28	22.2646		

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. The corresponding deviations for a gradient of plus and minus 5% at full energy are given in figure (6.5)
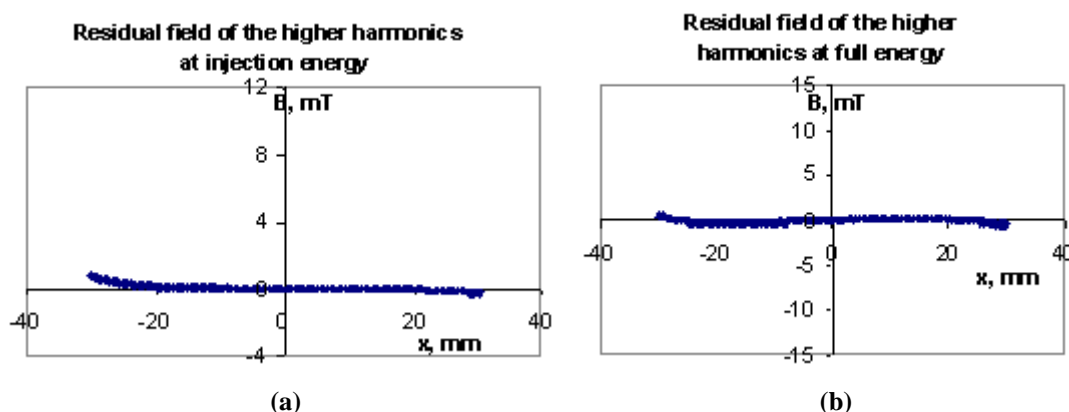
Figure 6.4: Residual field of the higher harmonics, (a) at injection energy (b) at full energy

According to figure (6.1), the bending magnet is the only one which performs the focusing in the vertical direction. The gradient in the bending is fixed and so the vertical focusing too. Of course for the operation of the machine one needs a knob for changing the vertical focusing. The installation of a separated quadrupole needs extra space, which reduces the length of the straight section, so the decision was made, to use pole face windings to change the focusing in the vertical direction.

For SESAME the pole face winding consists of two strips of a flat cooper (1.5x40 mm^2) distributed evenly over each pole. The coordinates of this stripes within the pole profile region is given in table (6.3). A picture of the arrangement of the pole face windings is given in figure (6.6). To change the gradient of ±5% while keeping a constant field in the center, this will reduce the magnet half gap to 19mm, the strip parameters are given table (6.4), the field quality in table (6.5).
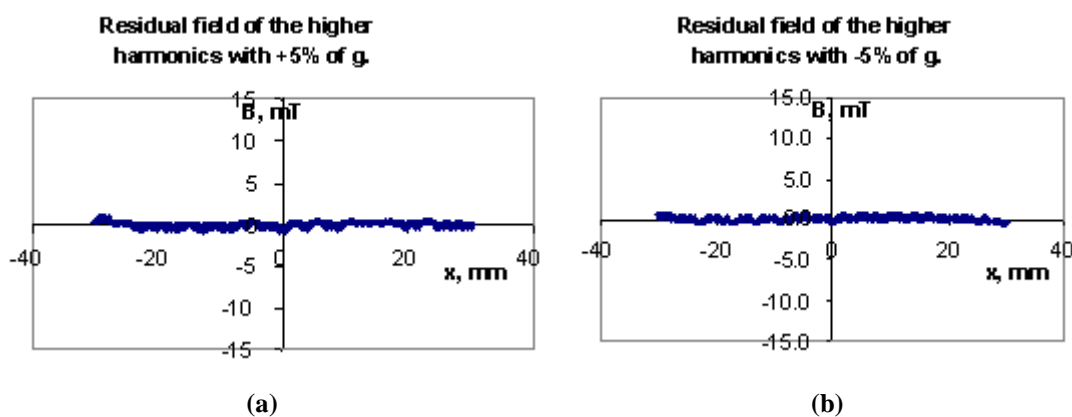

Figure 6.5: Residual field of the higher harmonics, (a) at full energy with +5% of the gradient (b) at full energy with -5% of g.

Tabel 6.3: Pole face windings coordinates.

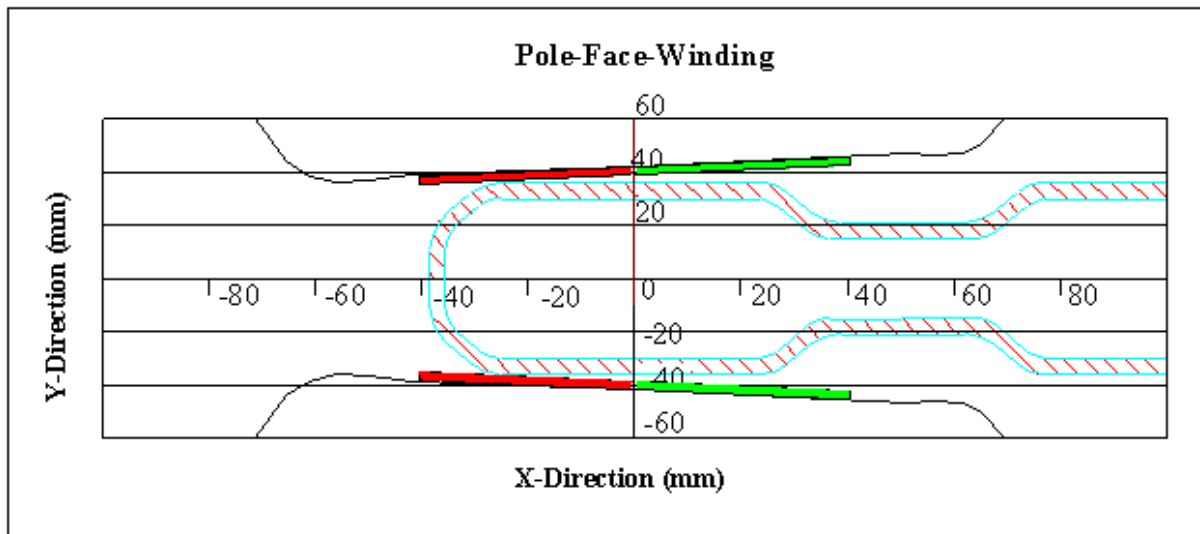| Left Strip		Right Strip	
X [mm]	Y[mm]	X[mm]	Y[mm]
-40.45	18.68	40.45	20.73
-40.38	17.18	40.38	22.22
-0.42	18.93	0.42	20.48
-0.49	20.42	0.49	18.98

Figure 6.6: Arrangement of the 4 pole face windings within the bending magnets of SESAME.

Table 6.4: Pole face windings parameter.

Parameter	Value
Number /magnet	4
Area [mm^2]	60
Length [m]	5
Resistance [mΩ]	1.6
Current [A]	100.2
Voltage [V]	0.16
Power [W]	16

Table 6.5: The quality of the field produced with the pole face windings.

	B [T]	g [T/m]	$\Delta B/B$	$\Delta g/g$
g	1.4	2.84	$<10^{-4}$	1×10^{-3}
g+5%g	1.4	2.982	1×10^{-4}	1.1×10^{-3}
g-5%g	1.4	2.698	1×10^{-4}	1.2×10^{-3}

The coils will be manufactured from a hollow and insulated copper conductor, each coil consists of 40 turns, the coils are subdivided into 2 turns x 5 turns pancakes to allow the placement of the coils, through the gap, onto the yoke, the coils were designed to be fabricated from 15x15 mm^2 hollow copper conductor with 7 mm diameter cooling channel, this result in ~465 meters of conductor per magnet with total resistance of 47.4 mΩ at an excitation current of 612 A with power consumption of 17.75 KW, the coils will be cooled with low conductivity water, the design temperature rise 15°C resulting in 8.28 bar pressure drop.

The nominal flux density at the nominal orbit is 1.4 Tesla and the gap height at this location is 42 mm. These two factors determine the required excitation of the magnet:

N*I = B$_o$ * gap / μ_o = 1.4 * 0.042 / (4π*10^{-7}) = 46 792 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 (6.7). The green line in this figure presents the 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.
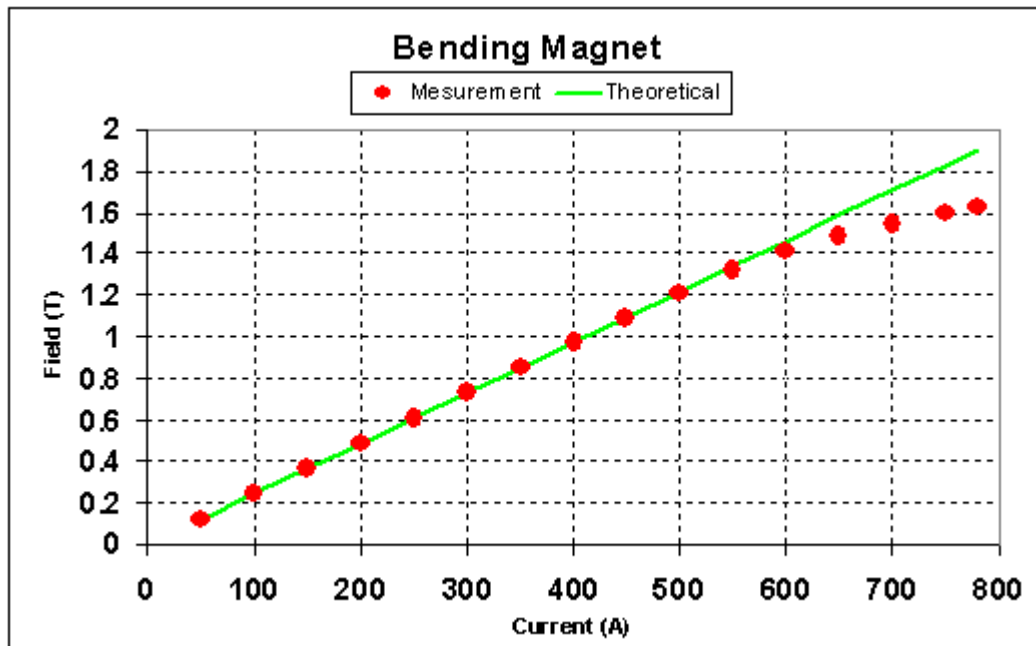
Figure 6.7: Excitation curve of the ANKA bending magnet

Table 6.6: 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*	1.4
Bending radius	*m*	5.95643
Magnetic length	*m*	2.3391
Iron length	*m*	2.274
Total length	*m*	2.467
Gap height	*mm*	42
Pole width	*mm*	177 - 185
Iron weight	*kg*	5800
Copper weight	*kg*	820
Total weight	*kg*	6620
Gradient	*T/m*	2.84
Ampere turns	*A*	51 500
Number of turns	-	80
Nominal current	*A*	643
Number of pancakes	-	8
Conductor dimensions	*mm*	13*13, $\varnothing$=5.0
Conductor area	*mm²*	196 / 20.5
Conductor length	*m*	465
Current density	*A/ mm²*	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	m³/sec	41.7×10^{-6}
Cooling water speed	m/sec	2.12
Pressure drop	bar	8.17
Reynold number (>1160)	-	5310

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 mm² 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 (6.6).

Figure (6.8), (6.9) and (6.10) presents the detailed design of the bending magnets. Figure (6.8) gives the cross section and the pole profile of the magnet. Figure (6.9) gives the top and the side view. The details of a pancake of the coils are presented in figure (6.10).
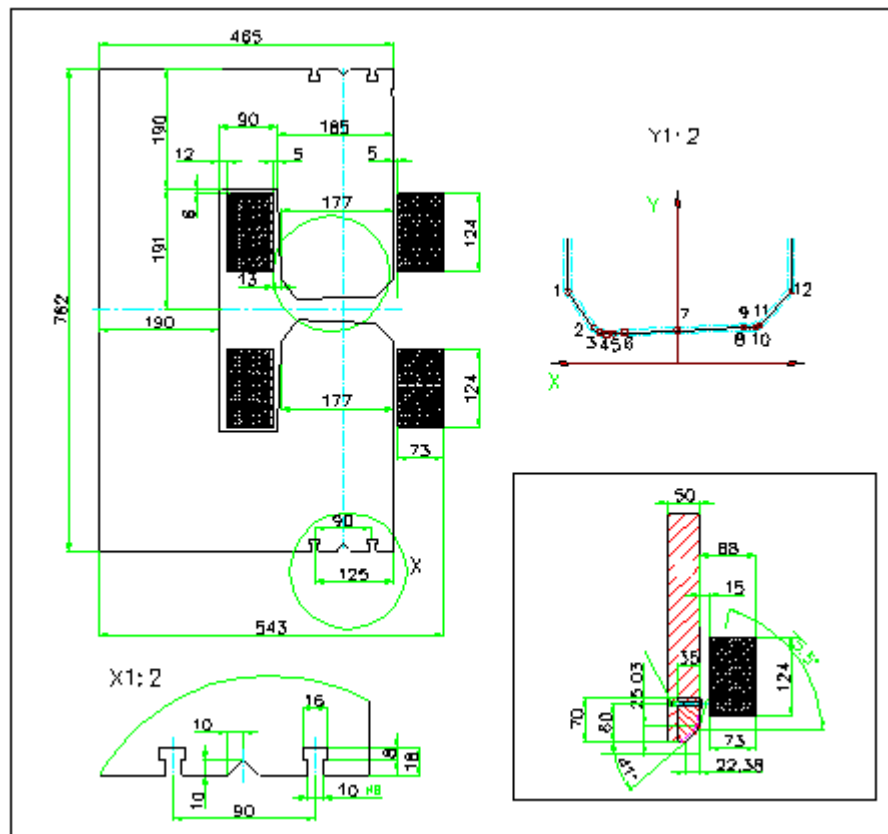
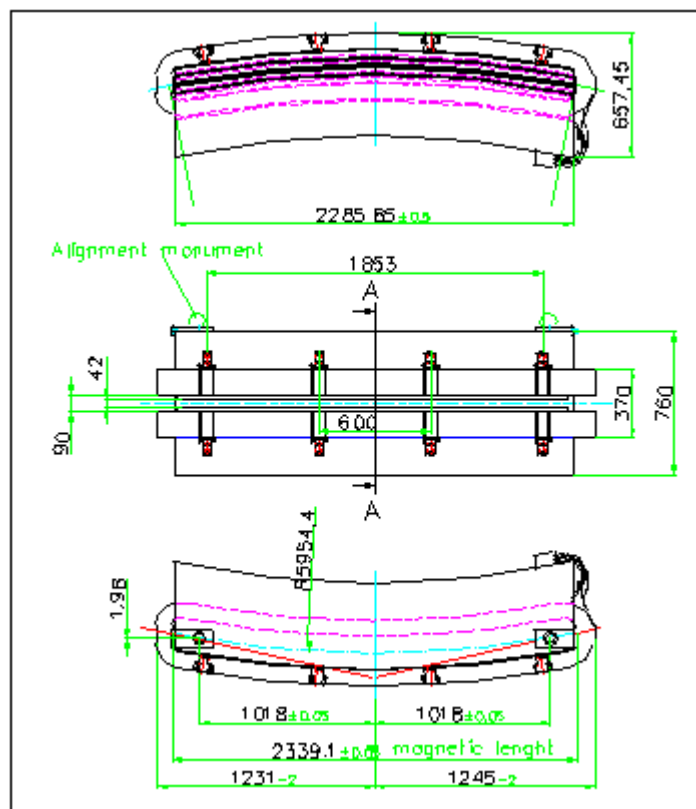**Figure 6.8: The cross section with pole profile of the SESAME dipole magnet.**

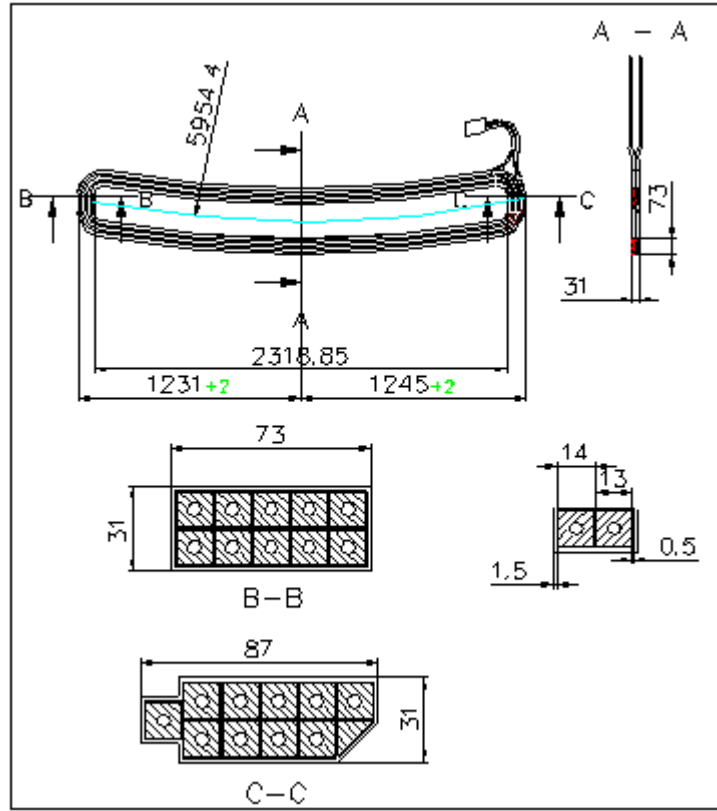**Figure 6.9: The top and the side view of the SESAME dipole magnet with dimensions.**

Figure 6.10: The shape of the coils for 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:

$$k_{max} = g / (\rho * B) = 19 / (5.957 * 1.4) = 2.28 \text{ m}^{-2}$$

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).
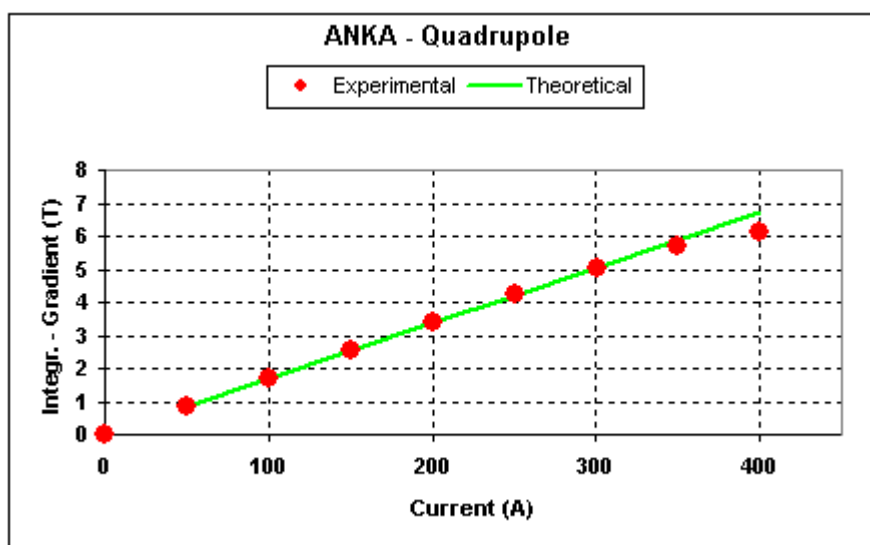

Figure 6.11: Excitation curve of the ANKA quadrupole

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 magnets are compiled in table (6.7). Drawings of the detailed design are presented in figure (6.12), (6.13) and (6.14). Figure (6.12) shows the dimensions of the quadrupole. The pole profile shape is given in figure (6.13) and the dimensions of the coil are presented in figure (6.14).

A cross section of the quadrupole with the vacuum chamber at different locations is shown in figure (6.15). According to these figures the so called "closed magnet" can be used.

Table 6.7: Parameters of the SESAME Quadrupole.

| Parameter	Unit	Type 265
Number of magnets		32
Energy	GeV	2.5
Gradient	T / m	19.0
Magnetic length	m	0.265
Iron length	m	0.23
Total length	m	0.332
Aperture radius	mm	35.0
Pole width	mm	60.0 – 88.0
Iron weight	kg	235
Copper weight	kg	62
Total weight	kg	297
Ampereturns per pole	A	9261
Windings per pole		26
Nominal current	A	356.0
Conductor dimensions	mm	$10*10, \varnothing=4.0$
Conductor / Cooling area	mm^2	87.4 / 12.6
Conductor length	m	80.0
Current density	A/mm^2	4.07
Total resistance	mΩ	16.4
Total inductance	mH	7.9
Time constant	s	0.48
Voltage drop	V	5.80
Power	kW	2.08
Number of cooling circuits		2
Temperature rise	^{o}C	15
Cooling water flow	m3/s	$16.5*10^{-6}$
Cooling water flow	l / h	59.3
Cooling water speed	m / s	1.31
Pressure drop	bar	3.19
Reynold number (> 1160)		2620
Critic. Veloc.	(m/s)	0.625
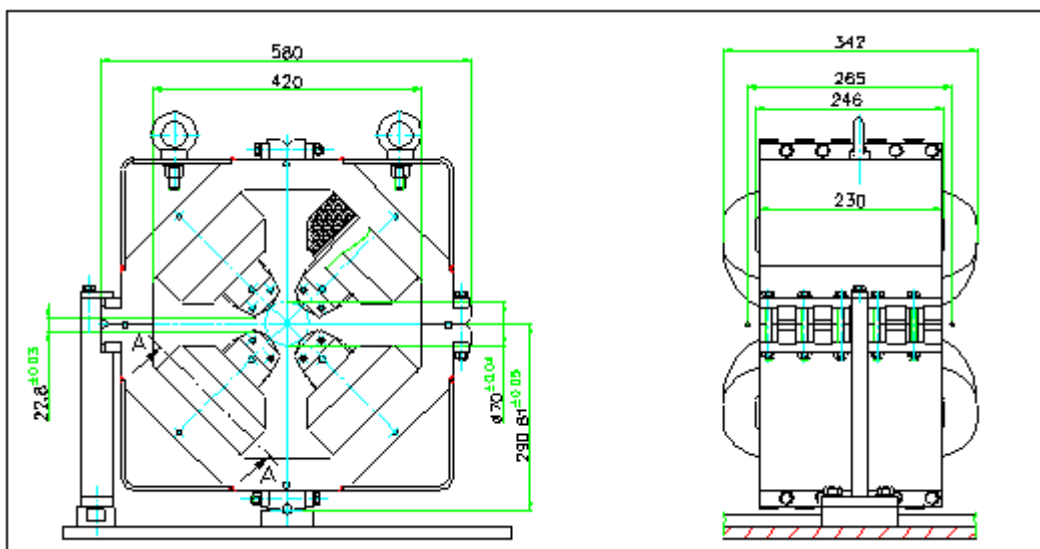
Figure 6.12: The ANKA quadrupole. By changing the length it is appropriate for SESAME.
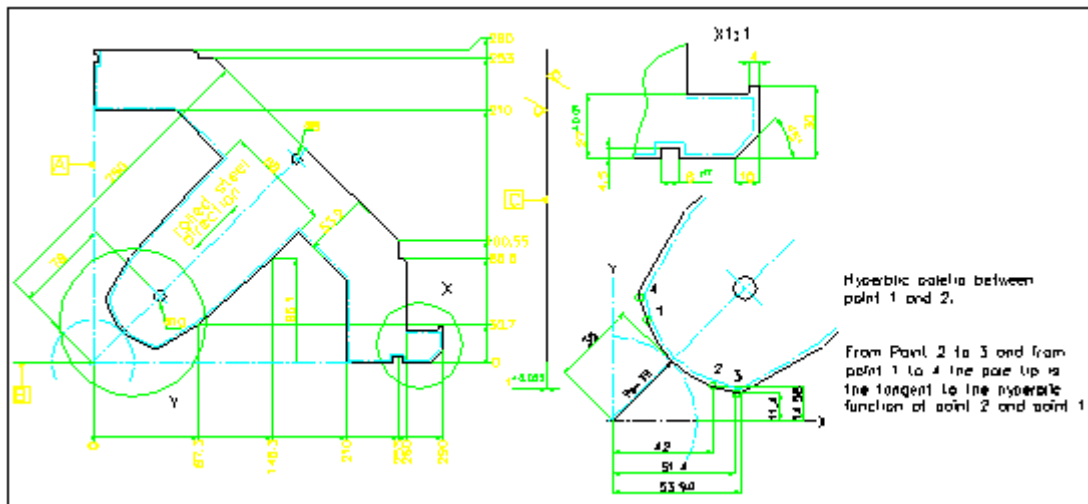
Figure 6.13: The shape of the lamination of the ANKA quadrupole, which will be used for SESAME.
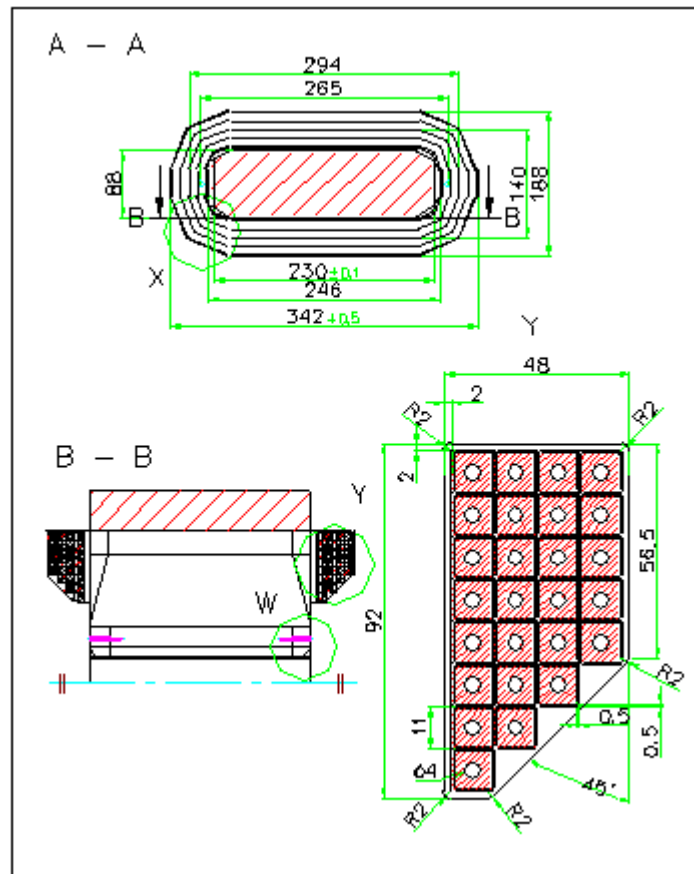

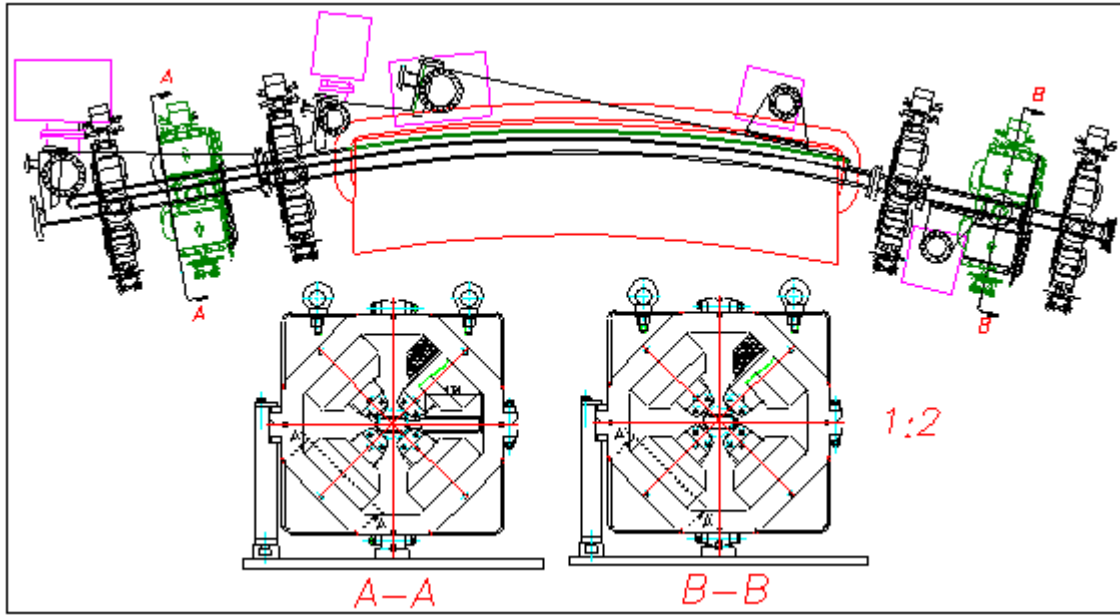**Figure 6.14: The shape of the coil for the SESAME quadrupole**

Figure 6.15: 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 sextupole has 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:

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

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

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:

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

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

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

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

With B=1.4 T and $\rho = 5.957$ meters, the m-value corresponds to a differential gradient of

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

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:

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

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.

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

The parameters of the sextupoles are summarized in table (6.8) and a drawing of the corresponding ANKA-sextupole is given in figure (6.17). As an example; in figure (6.16) is presented the excitation curve of the ANKA-Sextupole.
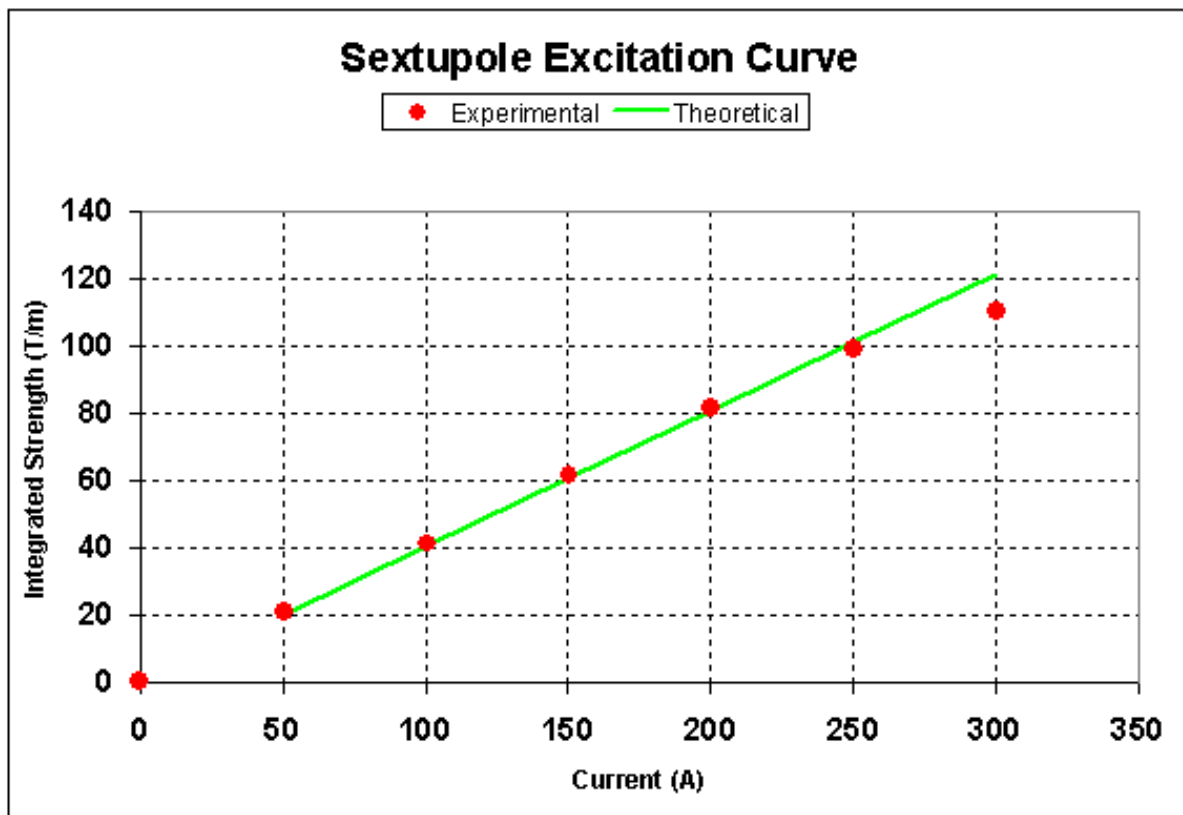

Figure 6.16: Excitation curve of the ANKA sextupole

The slope of the curve in figure (6.16) 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.

A compilation of the specifications of the sextupole magnet is given in table (6.8). The detailed design is presented within the figures (6.17), (6.18), (6.19) and (6.20). The dimensions of the sextupoles are shown in figure (6.17), figure (6.18) gives the dimensions of the lamination and the pole profile. The shape and the dimensions of the coils are shown in figure (6.20).

The cross section of the sextupole with the vacuum chamber at different locations in the storage ring are presented in figure (6.21), 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 6.8 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.,$\varnothing$=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
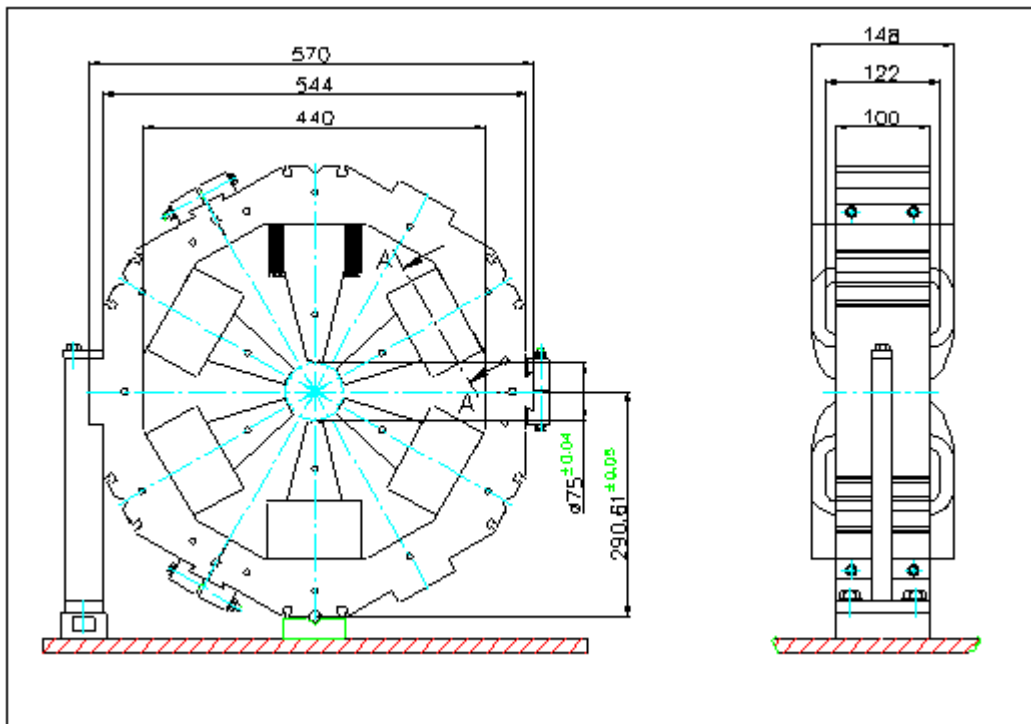
Figure 6.17: The ANKA sextupole. By changing the length it is appropriate for SESAME.

**Figure 6.18: The shape of the lamination of the ANKA Sextupole,
which will be use for SESAME.**

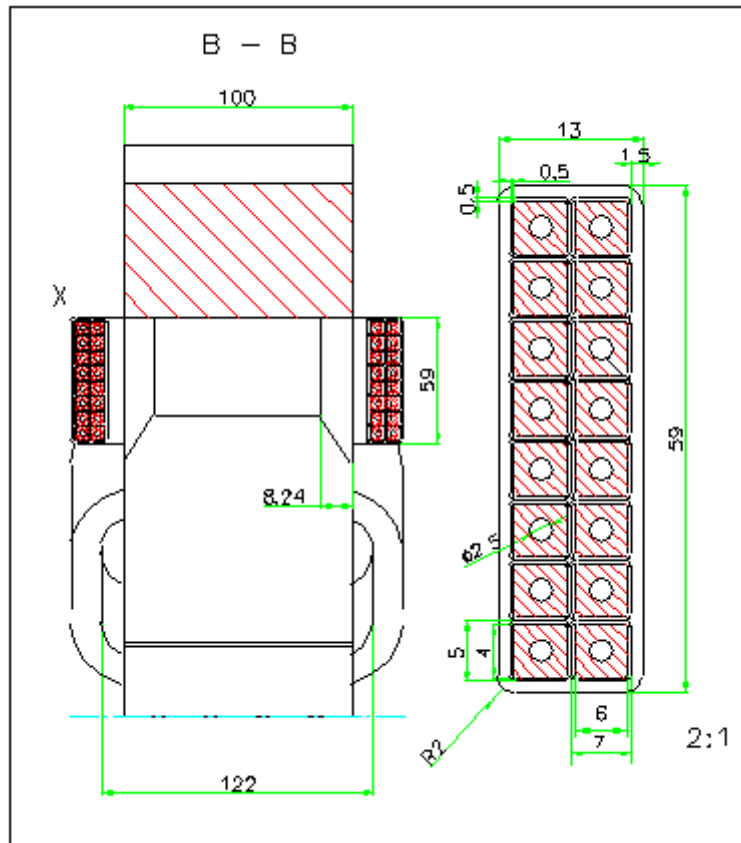**Figure 6.19:Arrangements of coils for the SESAME sextupoles.**

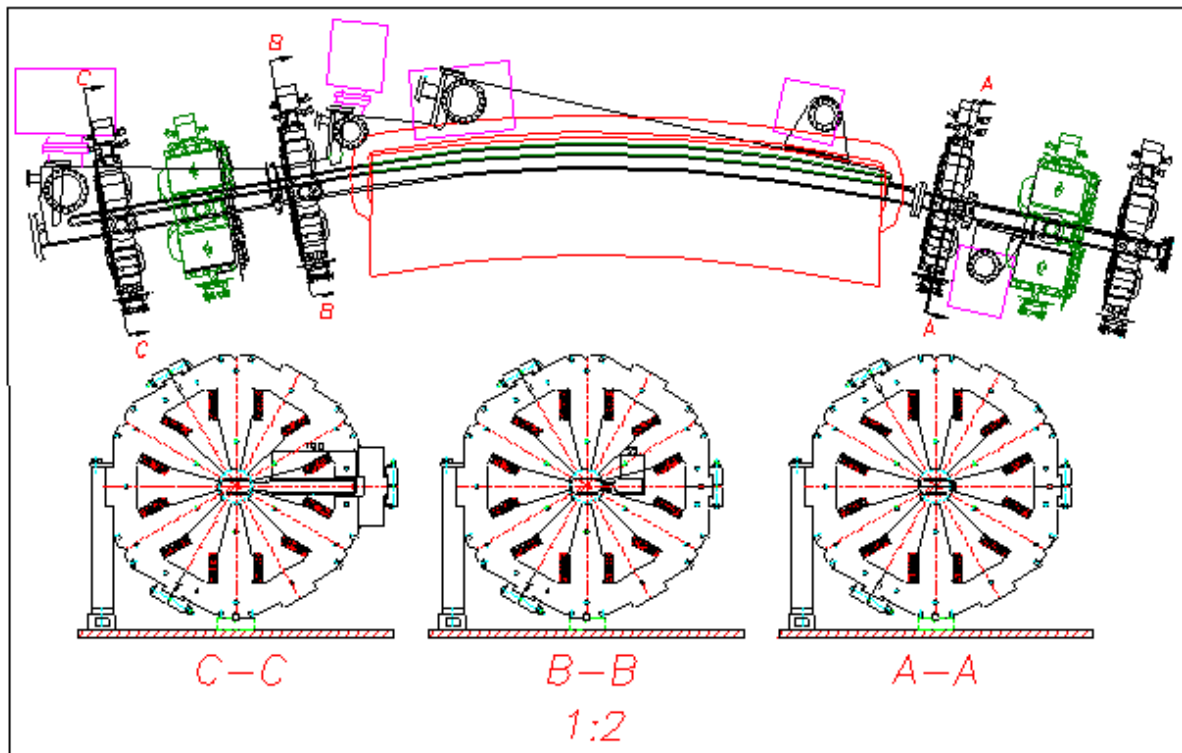**Figure 6.20 : The dimensions for the coils of the sextupoles.**

Figure 6.21: 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 (6.22), (6.23), (6.24) and (6.25) respectively.
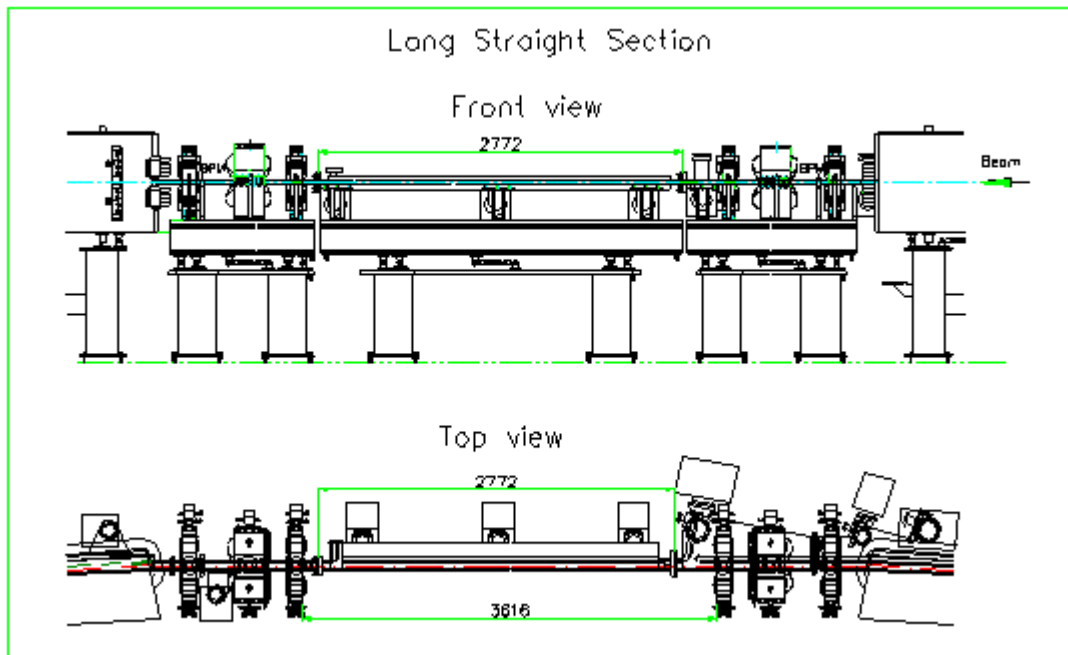
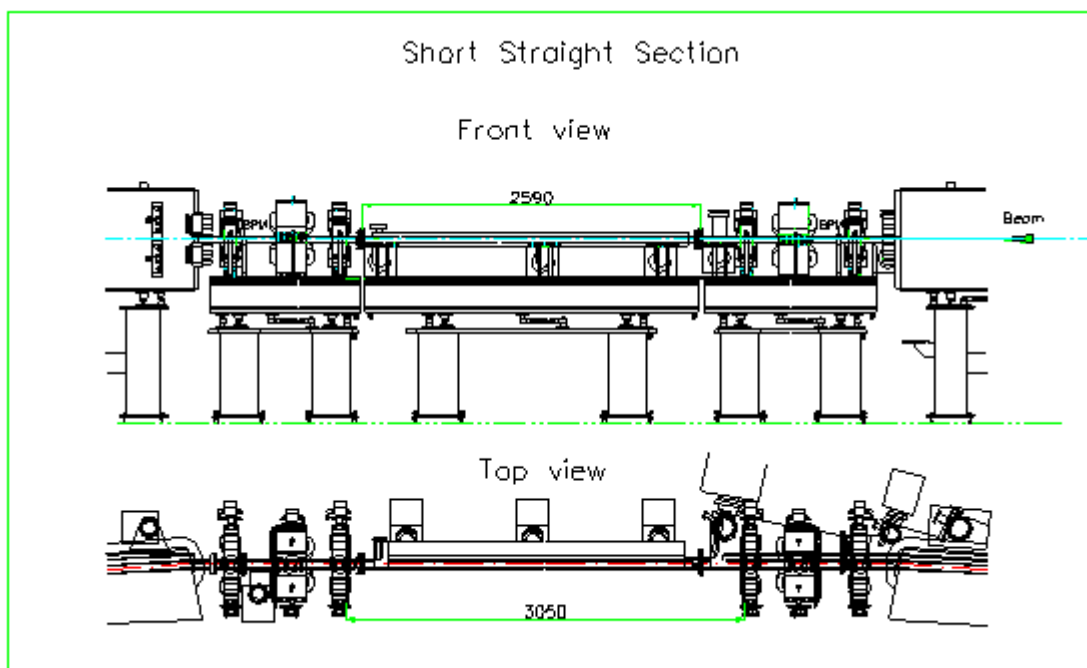**Figure 6.22: The long straight section girder system.**

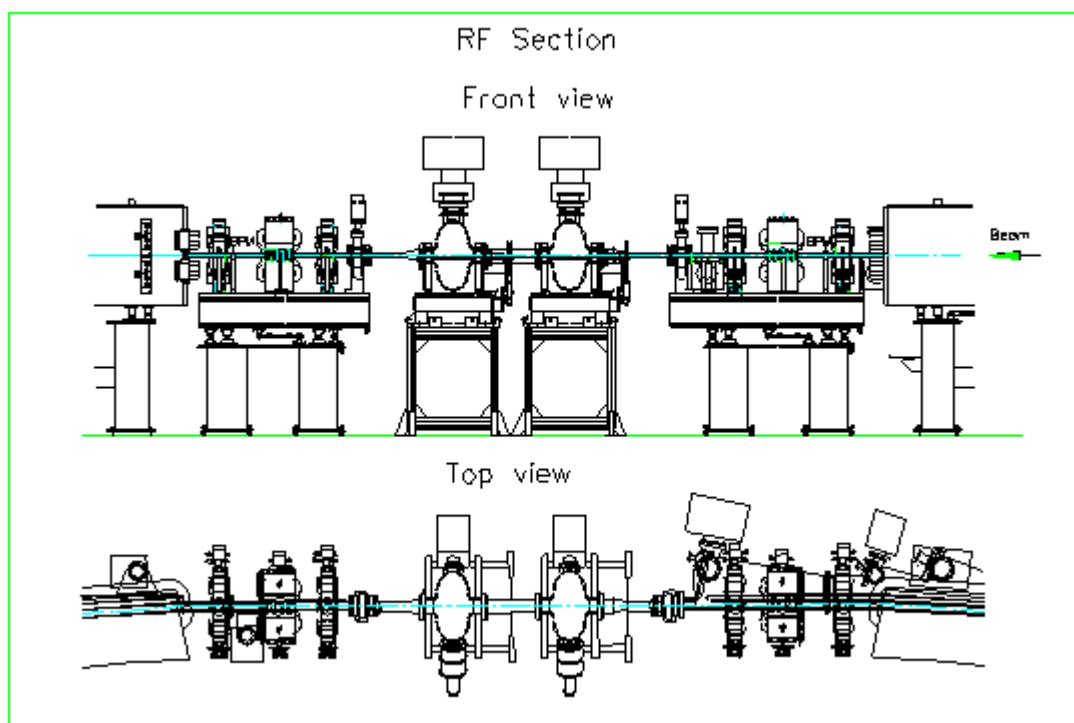**Figure 6. 23: The short straight section girder system.**

Figure 6.24: The RF straight section girder system.
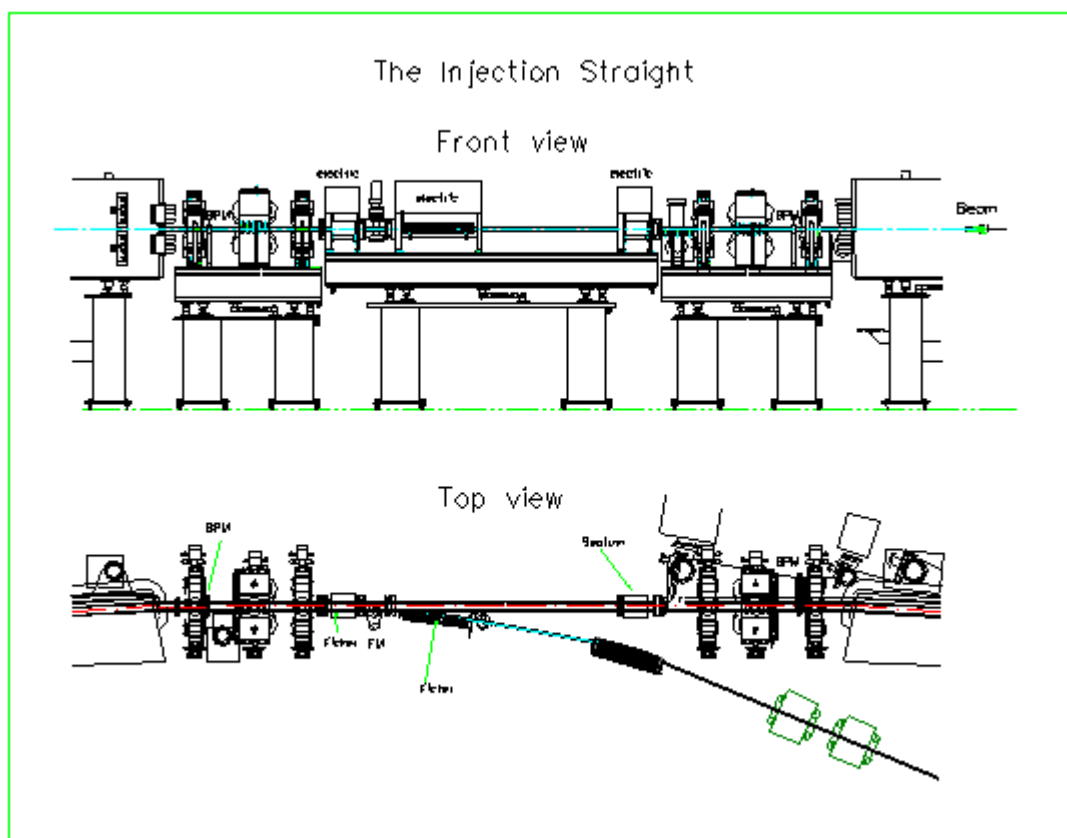

Figure 6.25: The injection straight section girder system.

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.