3.7 Storage Ring Magnets

3.7.1 Dipole Magnets

The lattice of CANDLE storage ring contains 32 gradient dipole magnets, 2 magnets per double bend achromatic (DBA) type standard cell. Those C-type Gradient Dipole magnets perform 3 functions. Each magnet bends 3 GeV electron beam by 11.25° providing one circle over 46.4 m of total magnetic length that corresponds to bending radius of $\rho = 7.385m$. This is accomplished by 1.345 T magnetic field in the dipoles and the single dipole length of 1.45m. The second function of dipoles is to focus the electron beam in the vertical plane with the quadrupole strength of $0.33m^{-2}$, which provides some considerable benefits [1-3]:

- It replaces substantial part of the integrated strength of the vertical focusing quadrupoles;
- Keeps beta functions under the control in the straight sections lowering lattice sensitivity to magnet errors and misalignment;
- Reduces the emittance by increasing the horizontal damping partition number;
- Shifts the peak of vertical beta function toward the cell center improving the separation of beta functions at sextupole positions.

Finally, the shapes of pole and magnet yoke allow the synchrotron radiation produced by bended beam in dipole to exit the ring thus utilizing the most straightforward source of the synchrotron radiation via the corresponding beam-lines channel. All three functions of the dipole magnet play the major role in the storage ring capability and in its stable operation. The main parameters of gradient dipole magnets are shown in Table 3.7.1.

Table 3.7.1 Gradient Dipole Magnet Parameters

Number of magnets	32
Bending Angle [Degree]	11.25
Field at pole center [Tesla]	1.35
Magnet Length [mm]	1450
Orbit Arc Length [mm]	1452.3
Orbit Arc half sagitta [mm]	17.81
Bending Radius [m]	7.39667
Quadrupole Strength [m^{-2}]	-0.33
Field Gradient at center [T/m]	-3.3
Horizontal Region with $\Delta B/B \le 5\times10^{-4}$ [mm]	±48
Vertical Region with $\Delta B/B \le 5\times10^{-4}$ [mm]	±11
Rigidity ($B\times\rho$) [T-m]	10
Excitation Current [Ampere-Turns]	24120
Trim Coil Current [Ampere-Turns]	482
Lamination thickness [mm]	0.5

Construction Features. Due to construction technical difficulties and high assembly cost of curved yoke magnets the straight yoke magnets are preferable to the magnets with curved yoke. Pole reference line coincides with orbit arc half sagitta. “Good Field Region” has to include ±30 mm area along the orbit arc (i.e. it occupies ±47.8 mm region with respect to magnet pole reference line). The construction is similar to SPEAR3 full-length gradient dipoles with reduced gaps from 50 mm to 44 mm at pole center. That gap provides enough room for vacuum chamber and coil assembly. Magnet front view with vacuum chamber cross section is shown in Fig. 3.7.1.

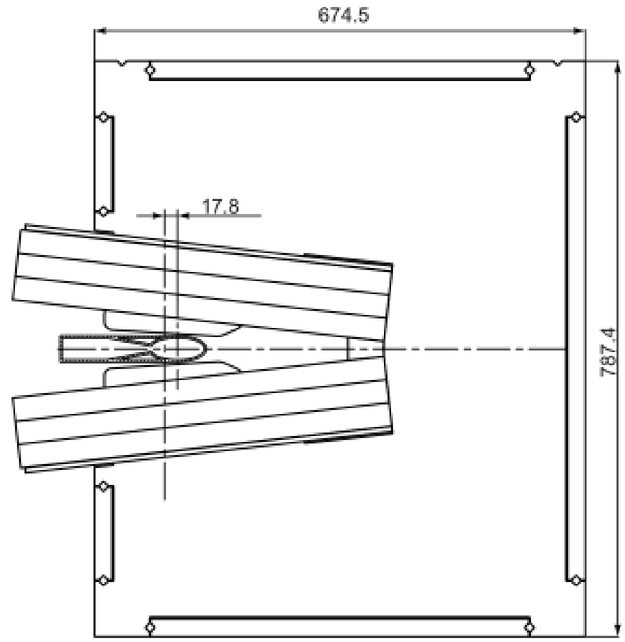

Fig. 3.7.1. Dipole magnet front view. Vacuum chamber position between the magnet poles is shown.

Magnet yoke will be assembled from one-piece magnetic steel laminations with 0.5 mm thickness. One-piece lamination is a good choice to minimize the assembling technical difficulties and the random errors. Laminations are pressed into pack, which are covered by squeezing plates on 4 sides and those plates are joined together by bolts. Yoke length will be 1450 mm with chamfering at the ends to correct the end fields. Magnet lamination contour is presented in Fig. 3.7.2.

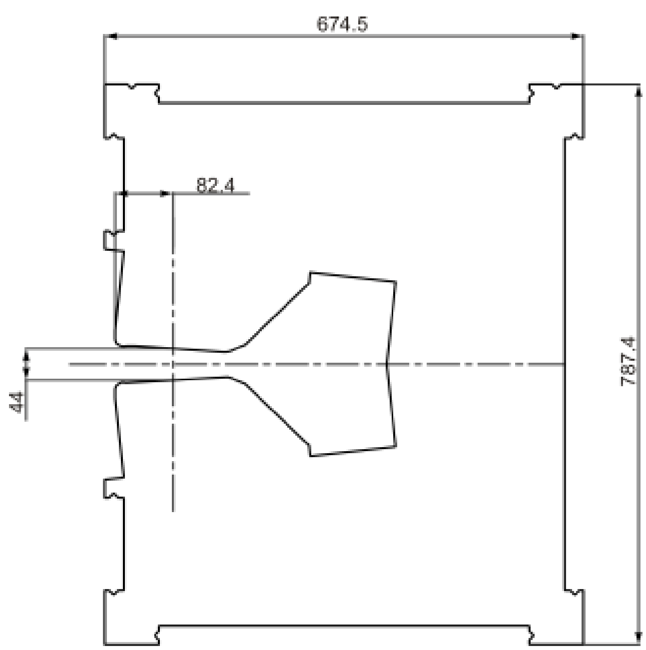

Fig. 3.7.2 Gradient dipole magnet core lamination contour

Coils will be assembled from 3 “pancakes” of conductors each containing 42 turns of 13.5mm × 13.5mm rectangular cross section conductor with inner 8mm diameter hole for water-cooling. The thickness of the “pancake” including the insulation is small enough to slide in through the inter-poles gap. Magnet cross section with coils is depicted in Fig. 3.7.3.

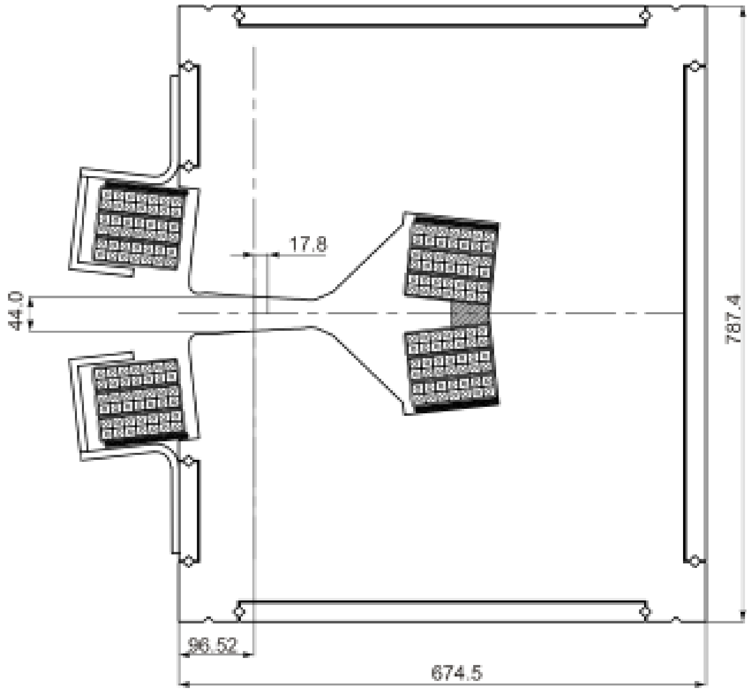

Fig.3.7.3 Dipole magnet cross section. Excitation coils’ positions are shown.

Pole Design.

We started from SPEAR3 gradient dipole magnet pole shape. The task was to reduce the inter-pole gap from 50 mm to 44 mm while keeping “good field region” essentially the same (±48 mm in horizontal direction and ±11 mm in vertical direction).

We followed the procedure depicted by J. Tanabe in his lecture B-1 [2]. Some important parameters in comparison with those of SPEAR3 gradient dipole magnets are presented in Table 3.7.2.

Table 3.7.2 Parameters defining pole design

	SPEAR3	**CANDLE**	
B_0 [T]	1.4242	1.354	The field at half sagitta
B' [T/m]	3.6305	3.3	The field gradient
h [mm]	25	22	The half gap at half sagitta
x_c [mm]	392.29	409.091	Quadrupole center coordinates are ($-x_c$,0)
H [mm]	140.05	134.164	The pole tip radius of the quadrupole
x_1, x_2 [mm]	± 50	± 48	Good Field Region, Horizontal
y_1, y_2 [mm]	± 11	± 11	Good Field Region, Vertical

Since these gradient dipole magnets have constant gradient of the field they can be considered as quadrupole magnets with the center at $x = -x_c$, where $x_c = B_0 / B'$ taking into account the fact that the field is 0 at quadrupole center. The quadrupole pole shape is given by the equation of the hyperbola

$$(x + x_c)y = \frac{1}{2}H^2, \qquad (3.7.1)$$

with $H = \sqrt{2x_c h}$ pole tip radius.

Conformal transformation by formula $w = z^2 / H$, where $z = x_c + x + iy$ and $w = u + iv$ are complex numbers, maps quadrupole pole into a convenient dipole magnet pole given in (u, v) coordinate space

$$u = \frac{1}{H}\left[(x_c + x)^2 - y^2\right]$$

$$v = \frac{1}{H}\left[2y(x_c + x)\right] = H \quad . \qquad (3.7.2)$$

Provided that half sagitta of the trajectory inside the magnet is 17.8611 mm and the magnet is straight we require the horizontal good field region to be from $x_1 = -48mm$ to $x_2 = 48mm$ (vertical good field region is ± 11mm), i.e. $\Delta B / B \le 5\times 10^{-4}$ in that region.
In the w space, the horizontal good field region endpoints are

$$u_1 = \frac{1}{H}(x_c + x_1)^2 = \frac{(409.091 - 48)^2}{134.164} = \quad 971.846 \text{ mm;}$$

$$u_2 = \frac{1}{H}(x_c + x_2)^2 = \frac{(409.091 + 48)^2}{134.164} = 1557.29 \text{ mm;} \qquad (3.7.3)$$

The corresponding values for SPEAR3 magnets are 837.0 mm and 1397 mm.
One can calculate the “pole overhang” in the w (dipole) space [1]

$$\frac{a}{H} = -0.14\ln\frac{\Delta B}{B} - 0.25 = -0.14\ln(5\times 10^{-4}) - 0.25 = 0.8141; \qquad (3.7.4)$$

Thus, the pole corner coordinates in the w space are

$$u_{1p} = u_1 - a = 971.846 - 0.8141\cdot 134.164 = 862.623 \text{ mm}, \; v_{1p} = H = \; 134.164 \text{ mm;}$$

$$u_{2p} = u_2 + a = 1557.29 + 0.8141\cdot 134.164 = 1666.51 \text{ mm}, \; v_{2p} = H\,; \qquad (3.7.5)$$

and for the SPEAR3 gradient dipole these numbers are 723.0 mm and 1514.8 mm respectively.
In an attempt to take an advantage of SPEAR3 gradient dipole pole corners known shape, we tried to keep the chamfering and shimming shapes. The coordinates v are reduced by $\Delta H = 140.05\text{-}134.164\text{=}5.886$ mm, while the coordinates u are transformed in a way that pole corners u coordinates coincide with those found in equations (3.7.1) and (3.7.2), namely

$$u = c_v u_0 + \Delta u \,,$$

with

$$c_v = \frac{(u_{2p} - u_{1p})_{CANDLE}}{(u_{2p} - u_{1p})_{SPEAR3}}, \qquad \Delta u = u_{1p\,CANDLE} - u_{1p\,SPEAR3} \tag{3.7.6}$$

The numerator in c_v contains pole tip corners coordinates for CANDLE gradient dipole magnet, while the denominator contains those for SPEAR3 magnet ($c_v = \frac{(1666.51-862.623)}{(1510.8-722.57)} = 1.0199$). The quantity Δu is the difference between the poles left corners u coordinates of CANDLE and SPEAR3 magnets (Δu = 862.623-722.57 = 140.053 mm).

Then, the conformal transformation should be reversed to find the pole shape for gradient dipole, which corresponds to obtained convenient dipole pole shape.

$$x = \sqrt{H|w|}\cos(\phi/2) - x_c ,$$

$$y = \sqrt{H|w|}\sin(\phi/2), \tag{3.7.7}$$

where $|w| = \sqrt{u^2 + v^2}$ and $\phi = arctg(v/u)$.

Obtained pole tip coordinates are presented in Table 3.7.3.

Table 3.7.3 Dipole Pole Tip Coordinates

X [mm]	Y[mm]	X [mm]	Y[mm]	X [mm]	Y[mm]
-77.091	44.034	-40.155	24.356	29.030	20.527
-76.780	33.719	-38.678	24.255	33.713	20.309
-76.602	32.416	-36.456	24.113	35.850	20.209
-76.231	31.153	-34.222	23.970	37.750	20.130
-75.675	29.955	-31.976	23.830	39.654	20.047
-74.944	28.851	-29.723	23.685	41.565	19.960
-74.054	27.866	-28.214	23.594	43.482	19.875
-73.025	27.021	-26.703	23.503	45.407	19.784
-72.271	26.546	-25.185	23.408	47.600	19.701
-70.717	25.599	-22.901	23.272	49.800	19.625
-69.039	24.912	-20.608	23.138	51.605	19.556
-67.264	24.550	-18.307	23.006	53.419	19.487
-65.457	24.523	-15.996	22.871	55.242	19.425
-63.666	24.689	-13.673	22.741	57.791	19.284
-61.861	24.886	-11.718	22.630	60.355	19.065
-60.050	25.057	-9.772	22.519	62.546	18.803
-58.225	25.177	-7.836	22.412	64.743	18.485
-56.384	25.238	-5.909	22.305	66.502	18.298
-54.533	25.233	-3.990	22.199	68.409	18.219
-52.662	25.171	-2.082	22.095	70.308	18.297
-50.788	25.076	-0.181	21.992	72.197	18.541
-48.903	24.964	4.829	21.727	74.086	18.943
-47.007	24.835	9.742	21.470	75.958	19.502
-45.112	24.698	14.674	21.222	77.013	19.885
-43.096	24.558	19.512	20.982	95.497	27.860
-41.625	24.458	24.297	20.751		

Magnetic Field Calculations. Magnet Design has been validated by field calculations with the help of POISSON [4] and MAGNET [5] codes. In the calculations the magnetic permeability table for AISI 1010 steel is used. It is expected that the laminations will be made of the Russian type 2212 electro-technical steel with magnetic properties close to those of AISI 1010 steel.

Fig. 3.7.4 shows the magnet field lines calculated by POISSON two-dimensional code.

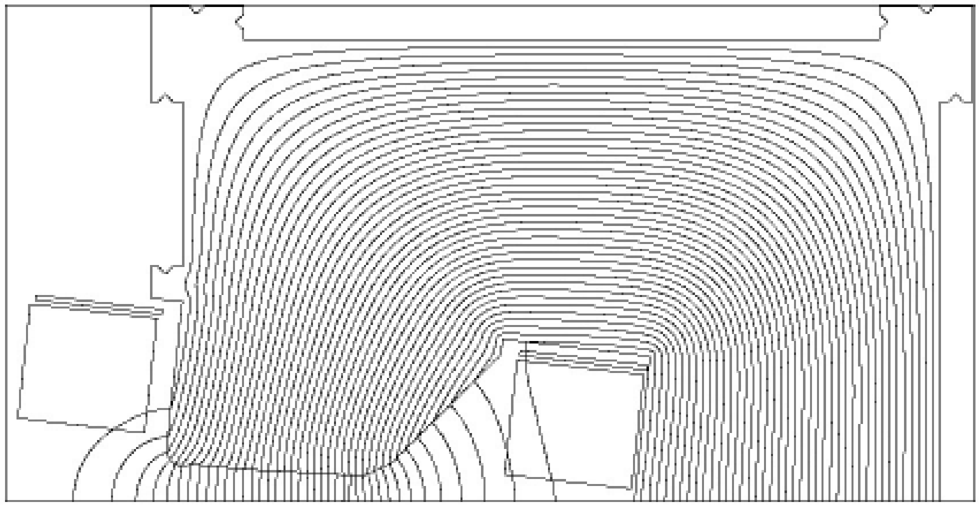

Fig. 3.7.4 Dipole field lines drawn by VGAPLOT program using POISSON output.

Calculations show that 24600 Ampere-Turns total excitation current is required to obtain the design values of field induction and gradient (Fig. 3.7.5 and Fig. 3.7.6).

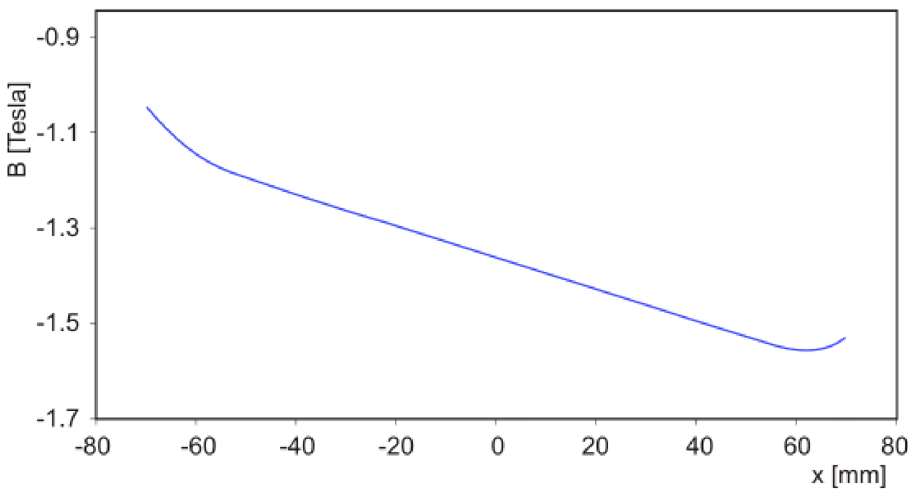

Fig. 3.7.5 Dipole centerline field plot.

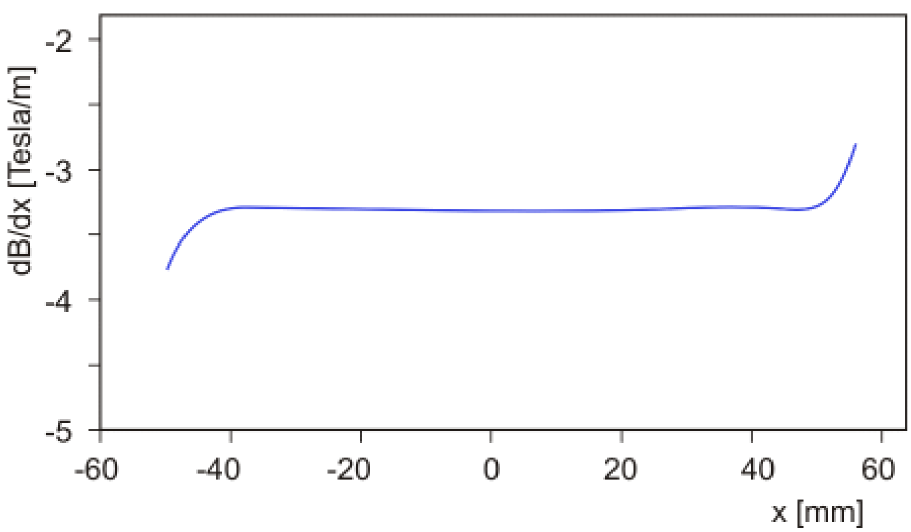

Fig. 3.7.6 Magnetic field gradient at dipole centerline.

3.7.2 Quadrupole Magnets

CANDLE storage ring contains 80 quadrupole magnets of 3 types that differ by their lengths and magnetic strengths. Their main parameters are listed in Table 3.7.4. Although the quadrupole magnets lengths and the excitation currents are different, they have identical cross-sections and are assembled from the same two piece laminations, simplifying the construction and the assembly to a great extent.

Table 3.7.4 Storage Ring Quadrupoles Main Parameters

	QF	QD	QFC
Number of Magnets	32	32	16
Number of Magnets per Cell	2	2	1
Magnetic Length [mm]	380	160	500
Quadrupole Strength [m^{-2}]	1.6497	-1.2896	1.70304
Nominal Field Gradient [T/m]	16.5	-12.9	17.0
Excitation Current [Ampere-Turns]	8157	6378	8404
Inscribed Radius [mm]	35	35	35
Turns per Pole	100	100	100
Current [A]	82	64	84

The cross section of storage ring quadrupole magnet yokes coincides with that of SPEAR3 quadrupole magnets and retains the same mechanical structure [1]. Fig. 3.7.7 shows the cross sectional view of the quadrupole magnets. Having a 35mm bore radius (Fig. 3.7.8), it accommodates the storage ring vacuum chamber. The lower and the upper halves of magnet yokes are assembled separately from the same identical laminations and are joined together being separated by non-magnetic spacers after the positioning of coils and vacuum chamber. AISI 1010 steel of 0.5mm thickness is chosen as lamination material, which are then stacked, glued and compressed axially by the rods. The magnet bore size and the coil shapes permit room for the vacuum chamber.
In comparison with SPEAR3 quadrupole magnets, those of CANDLE storage ring need to provide a lower field gradient (17 T/m versus 22 T/m) and thus they require lower excitation current reducing yoke saturation problems and increasing magnet efficiency. Coils are composed of two pancakes that can be inserted to their position separately. Individually powered shunting coil makes separate layer, which is positioned around the main coil. We use 100 turns of 4.76 mm square insulated copper conductor with 3.18 mm inner hole for water-cooling. The maximum current density is 6.0 A/mm^2.
Some parameters of coils are presented in Table 3.7.5.

Table 3.7.5 Quadrupole Magnet Coil Parameters.

	QF	QD	QFC
Turns per pole	100	100	100
Current [A]	82	64	84
Conductor Cross Section Area [mm^2]	13.86	13.86	13.86
Current Density [A/mm^2]	5.9	4.3	6.0

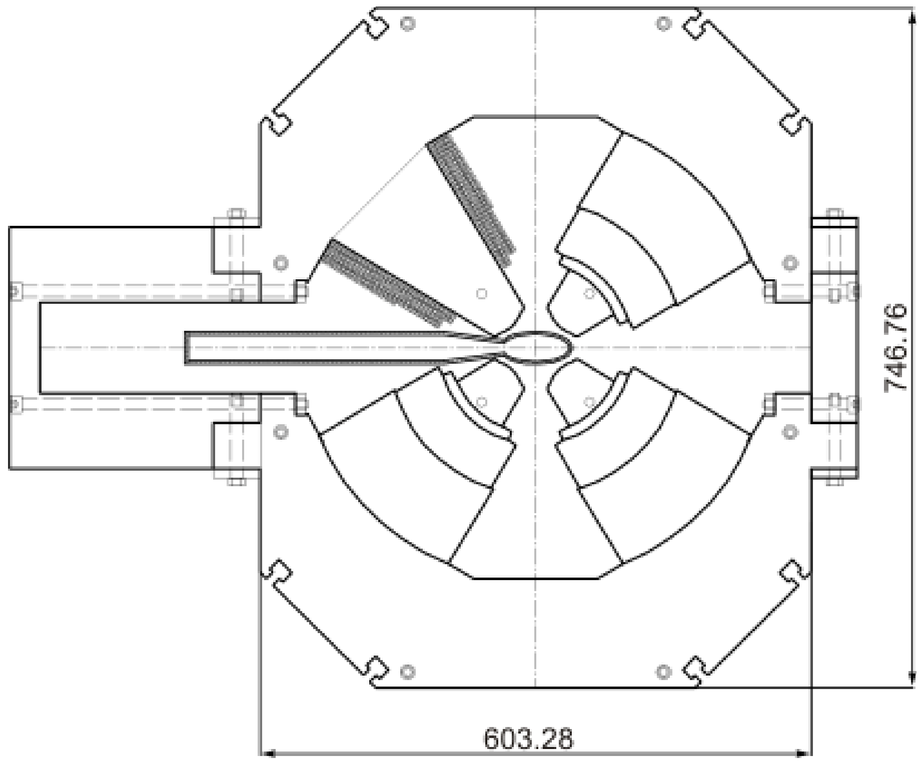

Fig. 3.7.7 Quadrupole magnet cross-section view. It is the same for all 3 types of the storage ring quadrupole magnets.

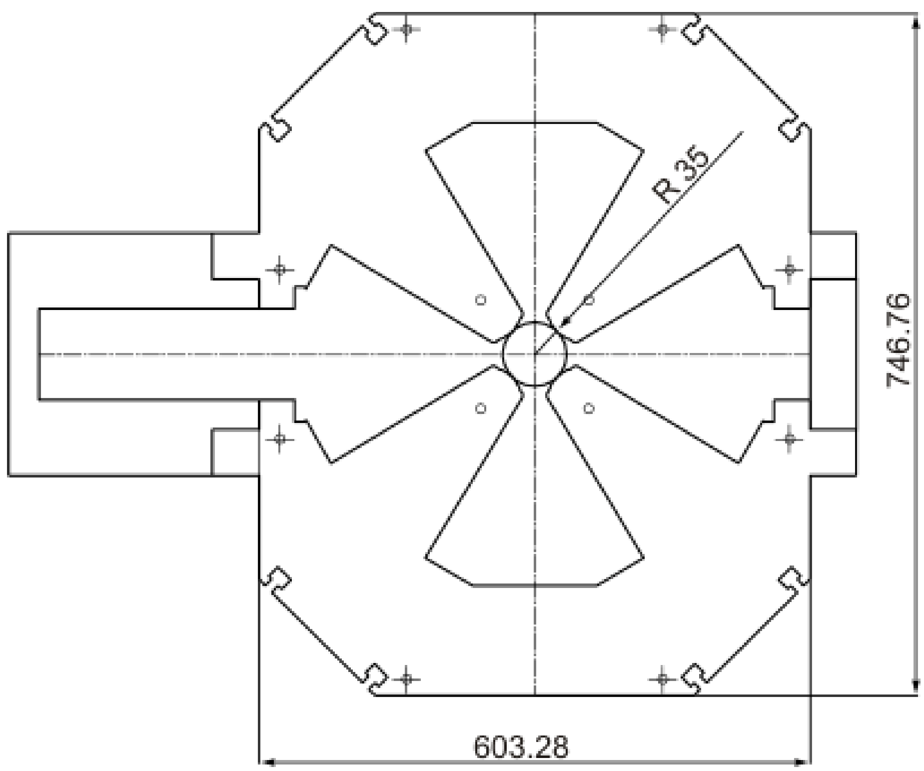

Fig. 3.7.8 Quadrupole magnet yoke cross section. Bore radius is 35 mm.

With the help of POISSON code, a magnetic field simulation for QF magnets was implemented using AISI 1010 steel magnetic parameters. The good field region, defined by $\frac{\Delta B}{B_2} \leq 5\times10^{-4}$ is 30 mm. The field is zero at magnet center and rises linearly with radius at a constant gradient of 16.5 T/m within the good field region (Fig. 3.7.9 and Fig. 3.7.10).

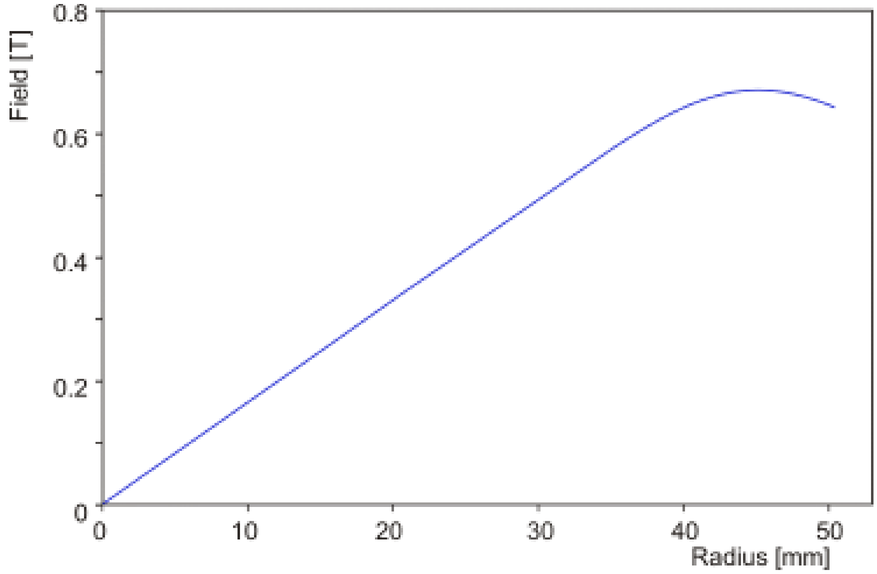

Fig. 3.7.9 Quadrupole magnet field plot.

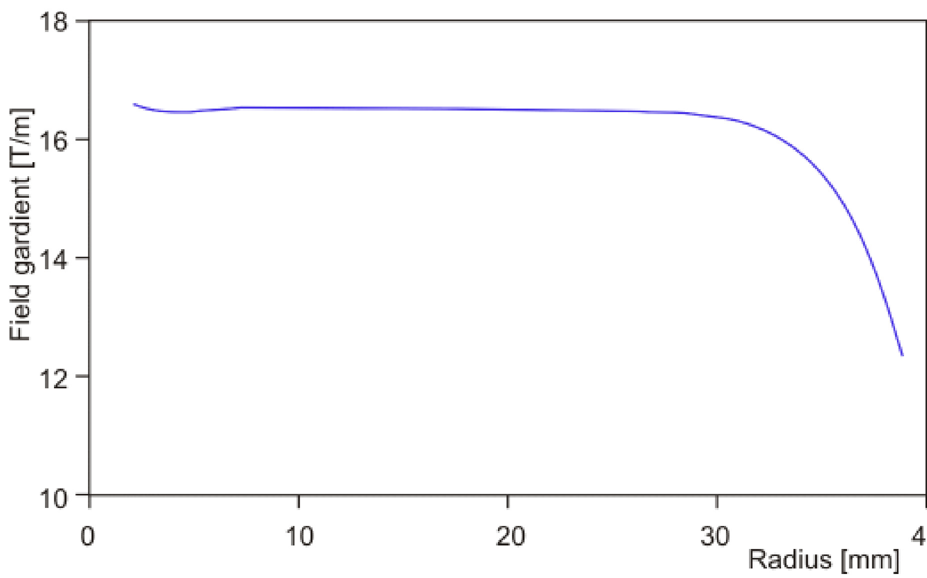

Fig. 3.7.10 Quadrupole field gradient plot.

Magnetic field harmonic analysis was performed to determine the field random errors in the multipole terms. The first 13 allowed multipole values are plotted in Fig. 3.7.11, while the field plot obtained from POISSON and plotted using WSFPLOT utility of POISSON/Superfish package is shown in Figure 3.7.12.

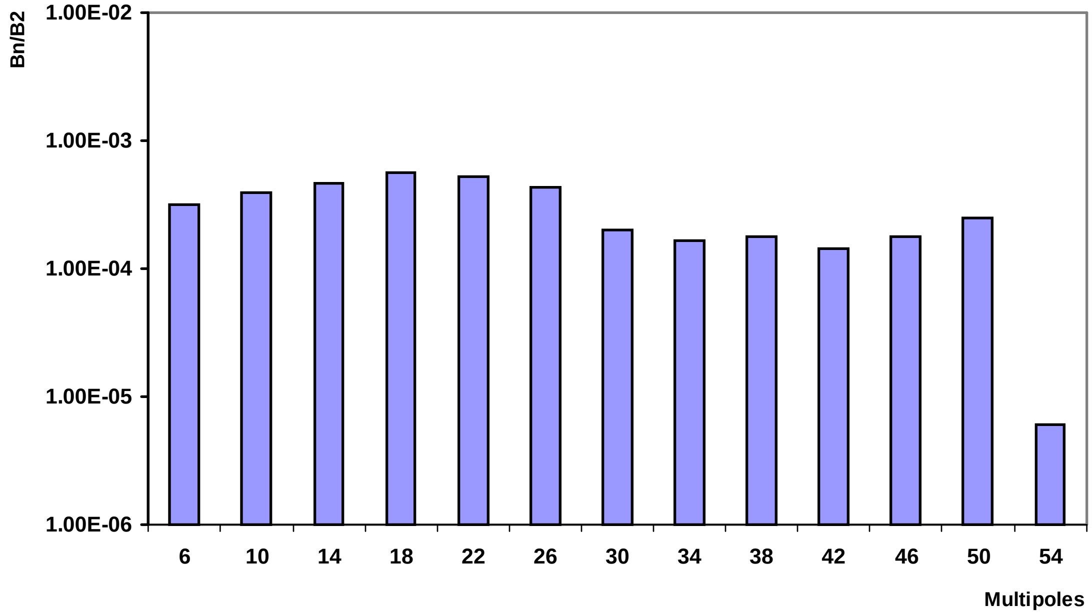

Fig. 3.7.11 Quadrupole magnet field normalized multipole errors. Normalization radius is chosen to be 32.5 mm.

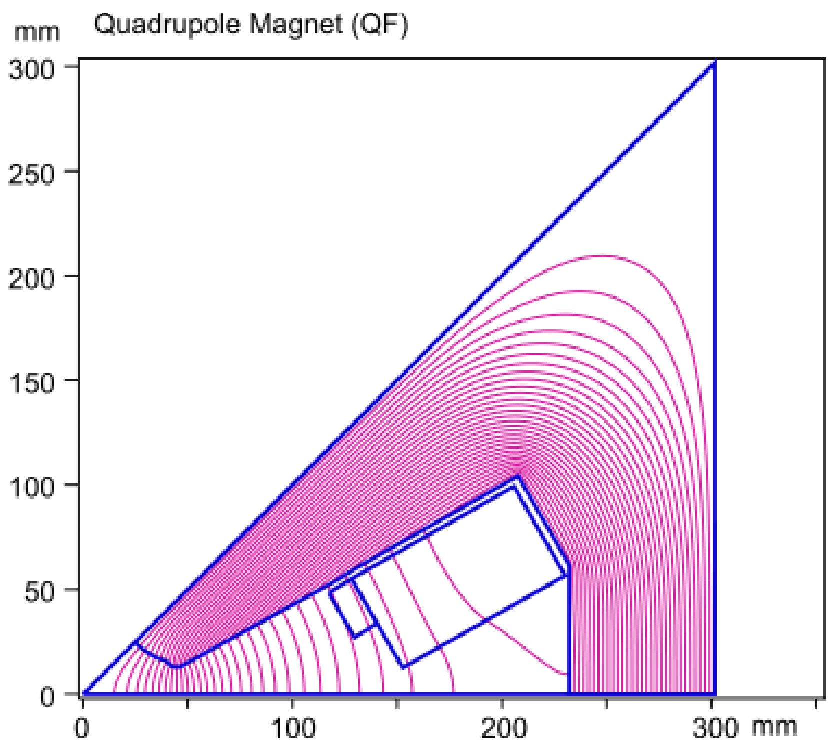

Fig. 3.7.12 Quadrupole magnet field-lines plot. Only a half pole is considered.

3.7.3 Sextupole Magnets

The storage ring sextupole magnets are of two types, both of them have the same cross sections but different lengths. The vertical Focusing (SD) magnets have strength of –35.11 m^{-3} and length of 25 cm, while the horizontal focusing magnets (SF) have strength of 29.7 m^{-3} and length of 21 cm.

The geometrical parameters of the CANDLE storage ring sextupole magnets are similar to those of SPEAR3 sextupoles [1] but different excitations currents are required due to different focusing lattice. Table 3.7.6 presents the main parameters for the sextupole magnets.

Table 3.7.6 Storage Ring Sextupole Magnet main parameters.

	SD	SF
Number of Magnets	32	32
Magnetic Length [mm]	250	210
Strength [m^{-3}]	- 35.115	29.7
Sextupole Coefficient ($\frac{1}{2}\partial^2 B_y/\partial x^2$) [$T/m^2$]	175.58	148.5
Inscribed Radius [mm]	45	45
Excitation Current (Ampere-Turns per Pole)	4335	3662
Turns per Pole	33	33
Current [A]	132.6	111

Both magnet yokes are made of one type of lamination (Fig. 3.7.13) thereby reducing the number of parts and components in the magnet. The material of the laminations is AISI 1010 steel. 0.5mm thick laminations have non-symmetrical positioned ears and are stacked alternatively in packs in order to provide space for bolts. The laminations are assembled in three separate sections, which are then bolted to magnetic steel spacers. The pole leg shape is asymmetrical to provide enough space for vacuum chamber and yet the coil is far through from the pole tip to allow good performance (Figure 3.7.14).

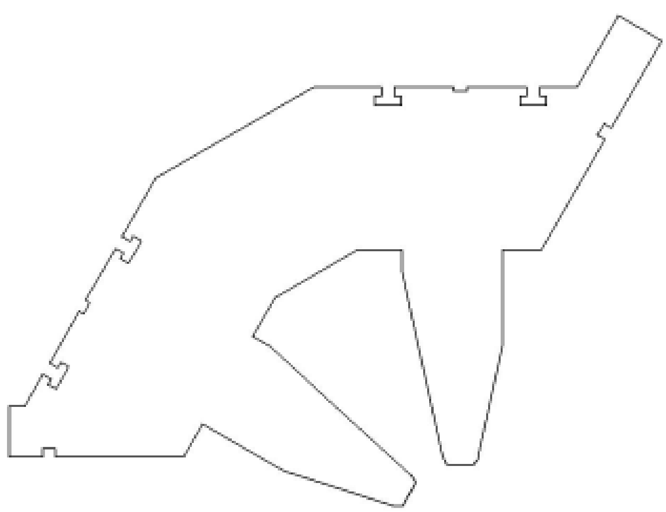

Fig. 3.7.13 Sextupole lamination.

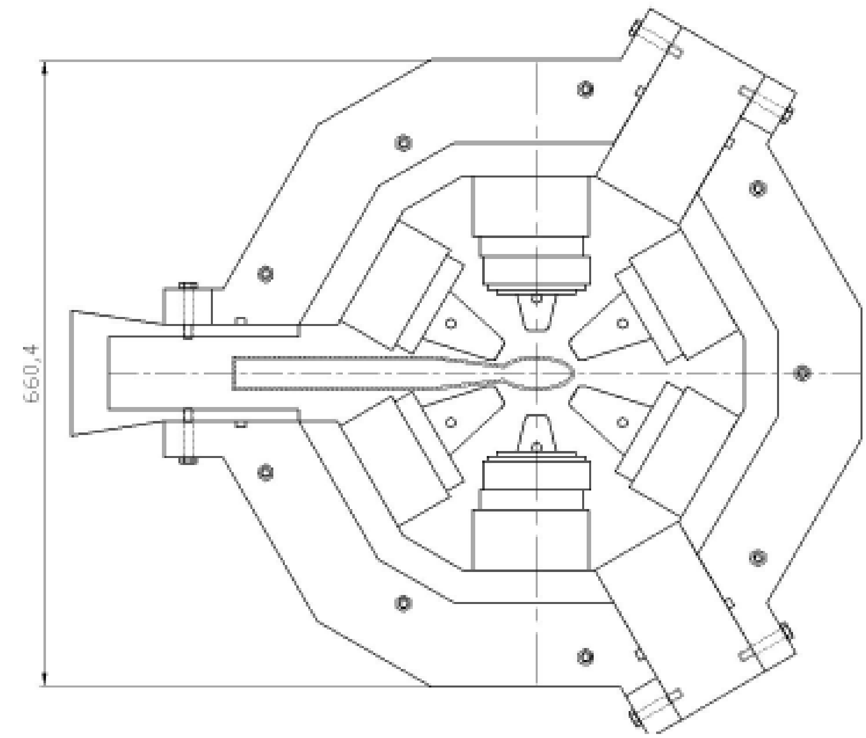

Fig. 3.7.14 Sextupole magnet (SD) cross section view.

The coil has 33 turns and is one pancake made of 6.35×6.35 mm^2 square cross section copper conductor with 3.15 mm diameter cooling hole. Each sextupole magnet is also provided with two auxiliary coils for excitation of correction skew quadrupole fields. Those additional coils will be placed on the top of the main coils (Fig. 3.7.15).

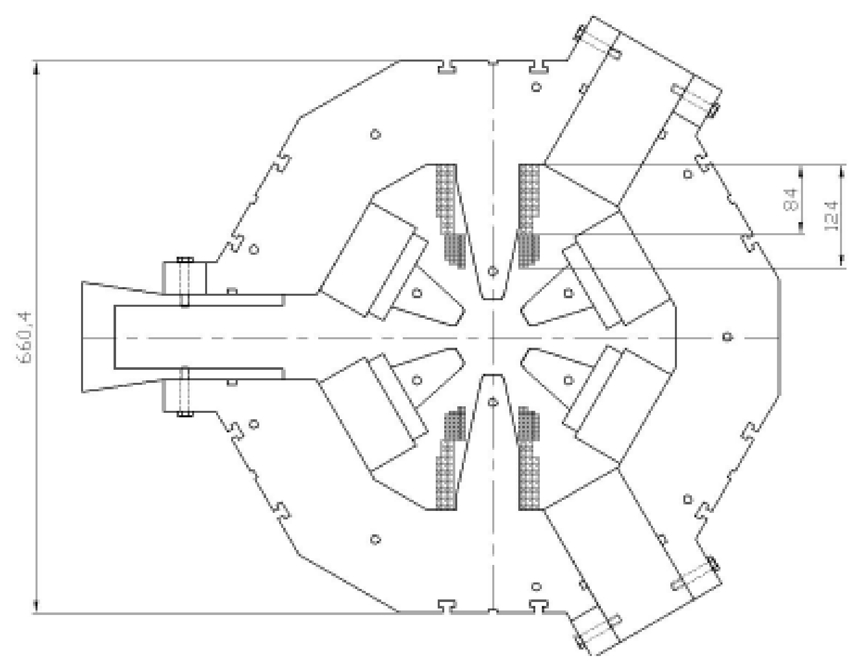

Fig. 3.7.15 Sextupole magnet (SD) cross section view with coil positions shown.

Magnetic field simulation and harmonic analysis was performed using the POISSON code [2]. Field lines distributions are illustrated in Fig. 3.7.16. Fig. 3.7.17 presents the results of the harmonic analysis. Harmonic analysis shows that in the middle plane $\Delta B/B < 3.47\times10^{-3}$ at a radius of 30mm at SD nominal excitation current of 4335Ampere-Turns.

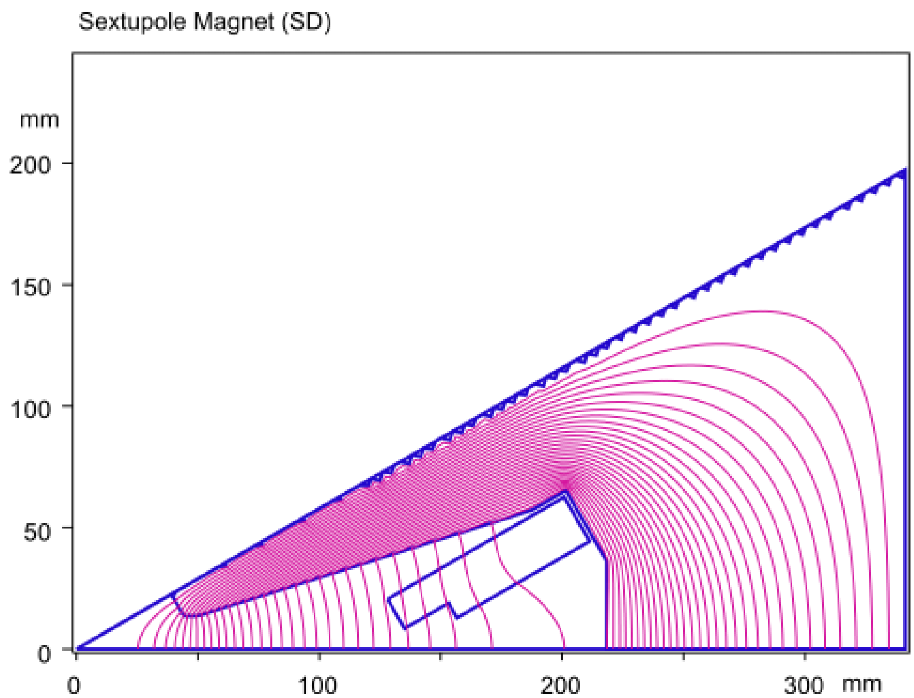

Fig. 3.7.16 Sextupole magnet fieldlines drawn by WSFplot utility using POISSON output.

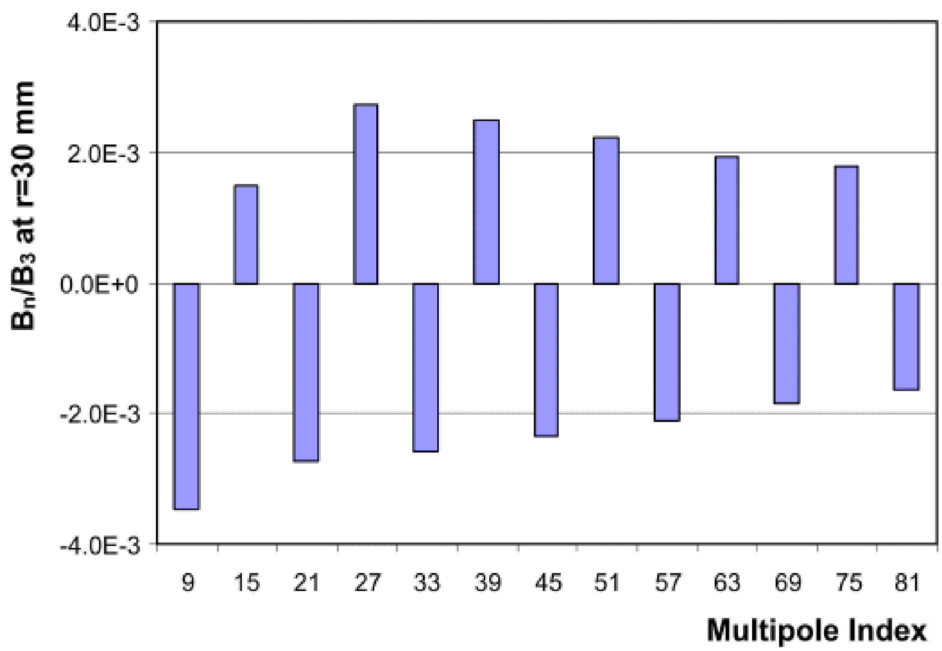

Fig. 3.7.17. Random multipoles at 30 mm. Normalization Radius is equal to 30 mm.

3.7.4 Corrector Magnets

For the beam steering purposes it is intended to install 32 combined horizontal/vertical corrector magnets in the storage ring, 2 per standard cell. In addition, each cell will also have one horizontal and one vertical corrector magnets. All the magnets are of the same type. Simulation studies show that corrector magnet maximal angle 1mrad is sufficient for both vertical and horizontal orbit corrections. The vacuum chamber defines corrector magnet internal sizes, while the adjacent magnets and the vacuum pump limit its external sizes. Fig. 3.7.18 illustrates the configuration chosen for corrector magnet.

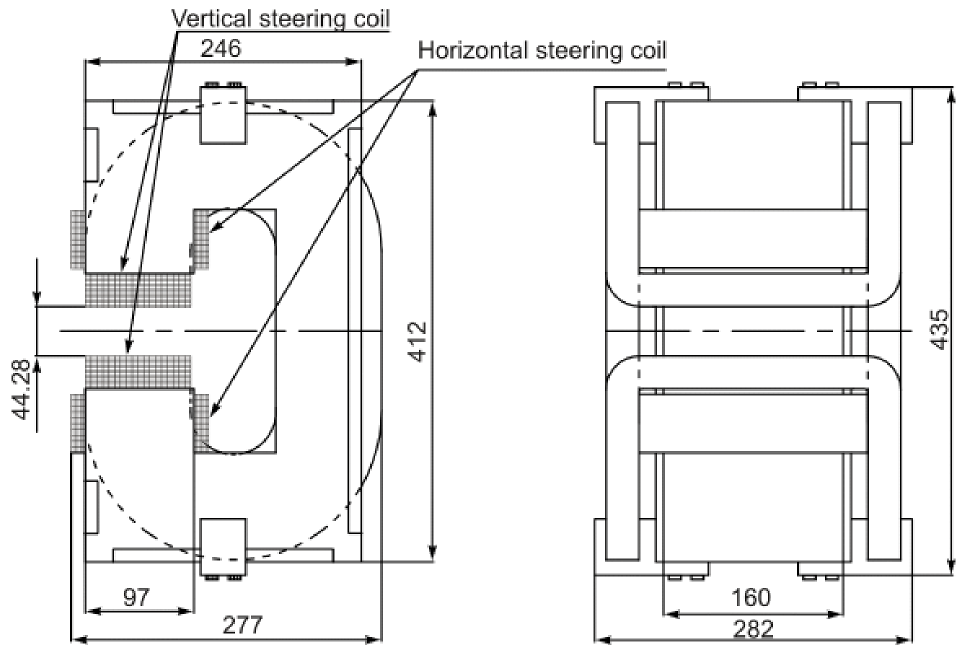

Fig. 3.7.18 Corrector magnet design.

It has convenient C-type dipole magnet design producing vertical field for the horizontal steering, and the vertical steering coil is wound on the pole faces returning over horizontal steering coils on the front-end faces of the magnet thus extending significantly the magnets physical length. C-type design is preferable to rectangular frame design because of space constraints imposed by beam chamber large horizontal size. Table 3.7.7 lists corrector magnet main characteristics.

The two type coils installed on the same yoke are powered individually so that both horizontal and vertical corrector magnets can operate independently. The same type of magnet will be used for separate horizontal or vertical correctors installing either horizontal or vertical steering coil on the same type of yoke. Yoke is made of 0.5 mm tick laminations. The kick strength required to produce an angle of $\theta = 1mrad$ for the momentum $p = 3GeV/c$ is $K = Bl = \theta p/0.3 = 0.01T \cdot m$ with B field induction and l magnetic length. For both the horizontal and the vertical steering $l = 0.284m$, and $B = 0.0352T$. Magnet yoke will be made of 0.5mm tick laminations with 0.412 m height and 0.246m width.

Table 3.7.7 Corrector magnet parameters.

	Horizontal Steering	Vertical Steering
Number of Magnets	16 + 32combined	16 + 32combined
Deflection Angle [mrad]	1	1
Integrated Field [T-m]	0.01	0.01
Length [m]	0.284	0.284
Magnetic Field [T]	0.0352	0.0352
Ampere-Turns	1320/pole	2470
Turns per Coil	120	252
Current [A]	22	9.8
Conductor Width/Height[mm]	4.93/1.8	4.93/1.8
Current Density [A/mm^2]	2.5	1.1
Conductor Length [m]	82.9	410
Core Length [m]	0.16	0.16
Pole width [m]	0.0884	0.0884
Gap Height [m]	0.09468	0.09468
Magnet Resistance [Ohm]	0.696	1.381
Voltage [V]	14	6
Power [kW]	0.308	0.058

3.7.5 Kicker Magnets

Four kicker magnets are included in CANDLE storage ring magnet system to produce closed bump during the injection of the beam from the booster-to-ring transfer line [Section 3.2.1]. The closed bump of the orbit is slow, thus 2 μs kicker rise time is set, which corresponds to less than three beam turns in the ring (the revolution time is 0.72 μs). The bump magnets are then turned off for a time corresponding to about three orbits of the ring to prevent the injected particle loss due to colliding with the septum. Parameters of CANDLE storage ring bumpers are listed in Table 3.7.8.

Table 3.7.8 Parameter list of storage ring injection kicker magnets.

Magnetic Length	0.4 m
Magnetic Field	0.3 T
Bending	0.687 degree
Aperture	40 mm $\times$ 35 mm
Peak Current	3.6 kA
Magnet Technology	H-frame with ceramic chamber inside
Conductor sizes (H×V)	62mm $\times$ 35mm
Inductance	~6 μH
Pulse Waveform	2 μs half-sine

Magnet inductance was estimated by the formula for the inductance of the iron cored dipole [8]

$$L = \mu_0 N^2 l(b + 2g) / g \ ,$$

where $N = 2$ is the turns number, $l = 0.5m$ is the magnetic length, $b = 40mm$ is the pole breath, $g = 35mm$ is the pole gap and μ_0 is the vacuum permeability. We preferred H-frame dipole type to windows frame type since more space was available for tick conductor in that case and, besides the experience showed that there was a problem of ceramic chamber overheating by the circulating electron beam [9]. In addition, the H-frame design permits forced air cooling in case of necessity. Metallised ceramic vacuum chamber will have large aperture (40 mm × 35 mm) not to reduce the storage ring chamber acceptance. Closed design ferrite yoke ensures the confinement of magnetic field inside the magnet frame. Cross-sectional view of the magnet is given in Fig. 3.7.19.

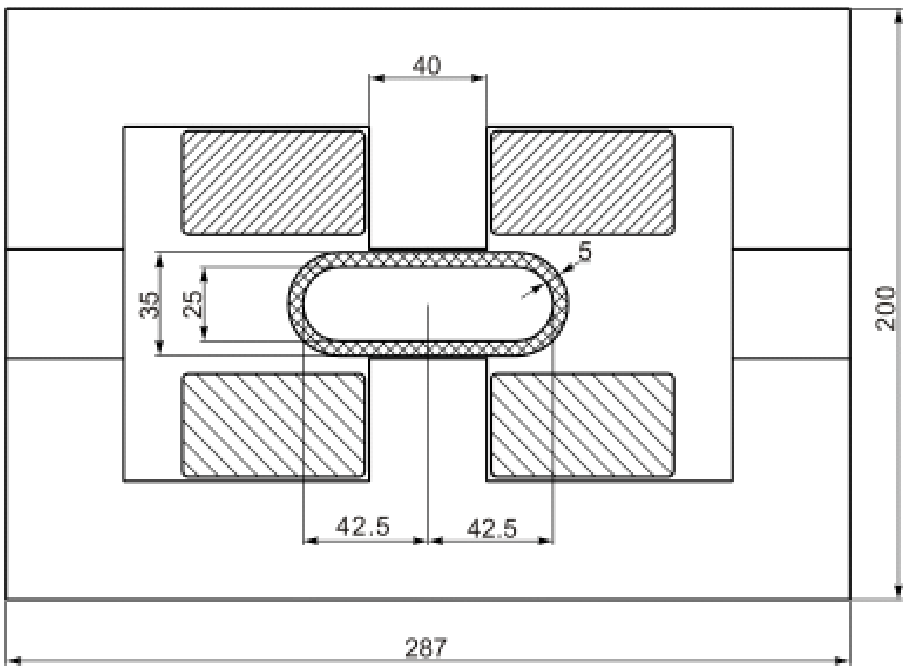

Fig. 3.7.19 Storage ring injection kicker magnet cross section

3.7.6 Septum Magnets

Storage ring septum magnets parameters are given in Table 3.7.9.
Two passive (Eddy Current) septum magnets will be placed at the end of booster to storage ring transfer line. Septum 1 will be positioned parallel to stored beam bumped orbit 12 mm apart and will deflect 3 GeV electron beam by 3 degree angle while leaving stored beam undisturbed. Septum 2 magnet, consisting of two halves, will be placed on the transfer line itself and its role is to curve injected beam by the angle of 8 degree.
A survey of previous septum designs [9] indicate that in spite of the fact that Eddy Current designs showed typically greater leakage fields (that reach their peak value at the end of current pulse [10]) than conventional front-end designs they have some great advantages making them designers choice for new machines, particularly septum thickness can be made small, cooling problems are eliminated, less insulation problems etc.
Copper screen will surround C –shape core at the front, top, bottom and ends. Providing the thickness of that high conductivity material screen is much greater than skin depth magnetic field will be effectively constrained within the magnet gap and uniform field can be obtained up to septum face [8].

Table 3.7.9 Parameters of storage ring septum magnets.

	Septum 1	Septum 2
Magnet Technology	Eddy current septum	Eddy current septum
Septum Thickness	3 mm	3 mm
Deflection Angle	3 degrees	8 degrees
Stored Beam Aperture (H×V)	+30/-12 mm × 30mm	Not restricted
Injected beam aperture (H×V)	28mm × 6mm	36mm × 6mm
Magnet Length	0.5 m	2 × 0.6m
Magnetic Field	1.01 T	1.14 T
Peak Current	4821 A	5430 A
Pulse Waveform	Half-sine 25 μs	Half-sine 25 μs
Inductance	2.6 μH	6.2 μH
Pulse Repetition Rate	2 Hz	2 Hz

Figure 3.7.20 presents Septum1 cross-sectional view. The septum magnets will be housed in the vacuum tanks. To cope with stray fields magnetic screen will be used. To keep magnet pole breath small it is a good idea to split Septum 2 magnet in two halves with 0.6 m length each. We learnt that idea from SOLEIL storage ring injection septum design [11].

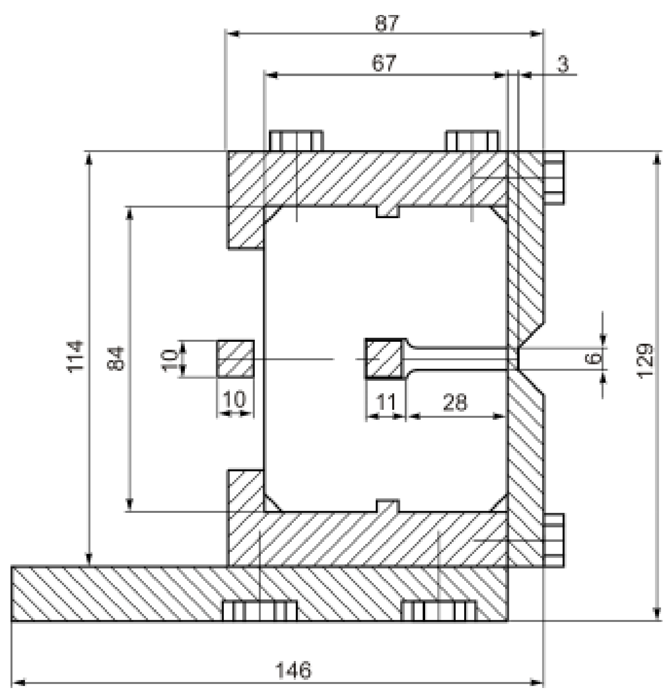

Fig. 3.7.20 Cross-sectional view of storage ring injection Septum1 magnet.

Magnet will be powered by 25 μs half–sine pulse, which corresponds to 20 kHz frequency with 2 Hz repetition rate. That reduces the heat load by the factor of duty-cycle of the magnet (which is equal to 3.5 × 10^{-5}). Skin depth in material is defined by the formula $\delta = \sqrt{2\rho / \omega\mu\mu_0}$, where ρ is the resistivity, μ is the permeability, ω the is frequency. For the copper ($\rho = 1.75\times10^{-8}\,Ohm.m$, $\mu \approx 1$) one finds $\delta = 0.46mm$. Hence both CANDLE storage ring injection septum magnets have septum thickness equal to 6.5

skin depth. The pulse length of 25 μs provides flattop (2×10^{-4}) during 640 ns revolution time of the booster beam at 3 GeV.
Calculations using Halbach's model [12,13] show that leakage field maximum is at the level of 0.2% of the field magnet within magnet gap. Septum magnet final design is being carried out employing simulations with the help of OPERA code [14].

3.7.7 Magnets Support System

The magnet support system for the storage ring is based on the girder approach. One standard cell of the magnetic system is mounted on three girders: two identical girders for the dipole composed section (1 dipole, 2 quadrupoles, 1 sextupole) and one girder that support the central quadrupole with two focusing sextupoles. The girder lengths are 3.4m and 2 m for the dipole and central quadrupole composed sections respectively.
The general layout of the girders in one standard cell is shown on figure 3.7.21.

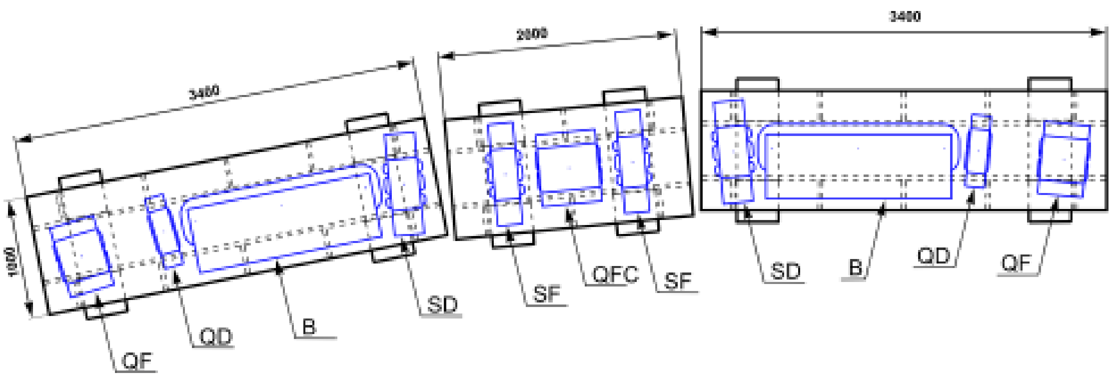

Fig. 3.7.21. General plan-view layout of the girders.

The reference orbit of the storage ring is fixed at the level of 1.5m from the floor. Each girder is based on four metallic pedestals – two pedestals on each side of the girder, which in turn fixed with anchor bolts to concrete piers, which are placed along the whole ring. There are 96 concrete piers along the ring circumference.
The main parameters of the girders are given in Table 3.7.10.

Table 3.7.10 Main parameters of the girders.

	Long Girder	Short Girder
Length (mm)	3400	2000
Width (mm)	1000	1000
Height (mm)	500	500
Wight (kg)	2000	1200
Quantity in one cell	2	1
Thickness of the sheet (mm)	25	25

Girders are mounted on the metallic pedestals (Fig.3.7.22). After the positioning, the girders are doweled and tightened by bolts. Screws that are shown in the figure 3.7.22 (A) perform the girders positioning. To the claws of the girders the bushes are fastened, which have trapezoidal threading for screwing the positioning screws.

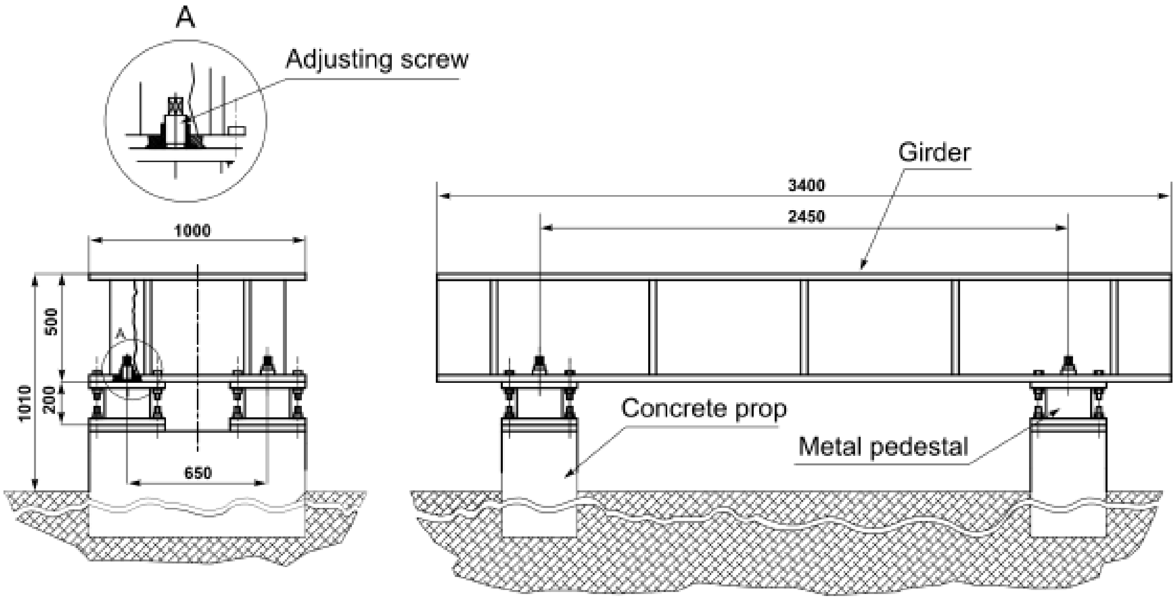

Fig. 3.7.22. Girder design.

The girder's construction is welded. Its components are 25mm thick steel sheets. On the two longitudinal placed sheets the bottom and upper sheets are welded. The ribs are placed on each side of the girder under the magnet to increase the rigidity of the construction. Given design of the girders allows the girder vertical alignment with rms value of 150 μm within the range of 2 cm displacement.

The magnets alignment is performed individually. The positioning device is placed under each magnet. The general view of the magnets with positioning devices is shown on figure 3.7.23. The positioning device (Fig.3.7.23 A) is the rod connected with the magnet and girder by hinges. A regulating bush with an inner screw socket is placed on the rod. The bush threading has a step of 0.5 mm with right and left orientation at the ends. There are five rods on one magnet, which allow align magnets in all three directions including the rotation. The precision of the positioning is $50\,\mu m$ in vertical direction and 160 μm in horizontal plane. The alignment device allows the displacement of the magnets in particular direction at least 5 mm. The summary of the magnet support alignments are given in Table 3.7.11

Table 3.7.11 The magnet support alignments.

System	**Rms alignment**	**Displacement**
Girder (vertical positioning)	0.15 mm	2 cm
Magnets (vertical positioning)	0.05 mm	5 mm
Magnets (horizontal positioning)	0.16 mm	5 mm

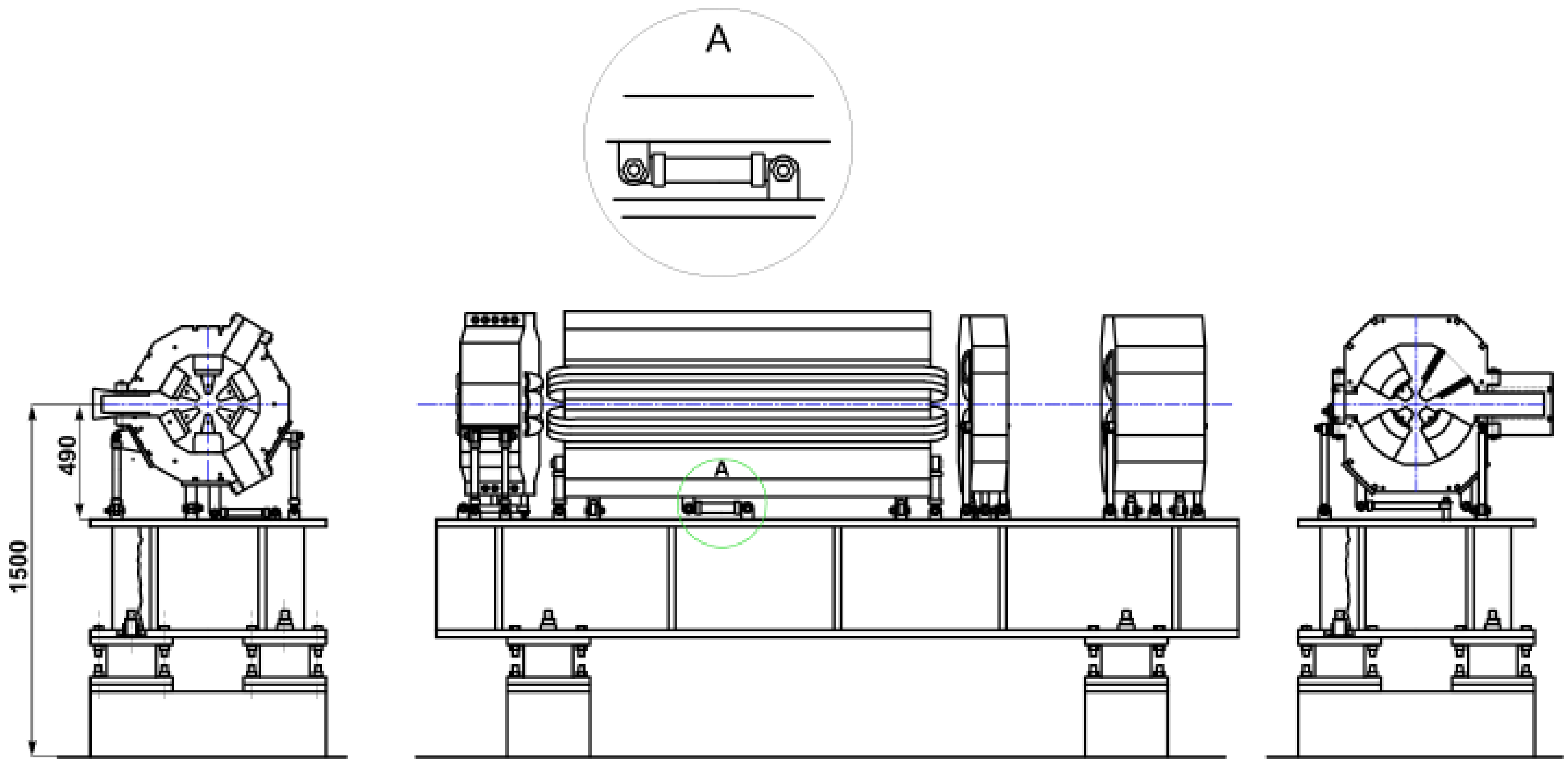

Fig. 3.7.23. General view of the magnets with positioning devices.

References

1. ”SPEAR3 Design Report”, Stanford Synchrotron Radiation Laboratory, 1999.
2. J.Tanabe, Lectures-Yoke Design, Dipole Field Quality, Conformal Mapping, Jan., 2001.
3. ”Spravochnik Po Elektotekhnicheskim Materialam” (in Russian), v.3, Energoatomizdat, Leningrad, 1988.
4. Programs available from LANL Accelerator Code Group; LA-UR-90-1766.
5. H. Wiedeman, “Particle Accelerator Physics”, Springer Verlag, Berlin, 1993.
6. K.Halbach, “Special Topics in Magnetics” in Handbook of Accelerator Physics and Engineering, Singapore, 2000.
7. K.G. Steffen, “High Energy Beam Optics”, New York, 1965.
8. Neil Marks, “Conventional Magnets” in CERN Accelerator School Proceedings, CERN 94-01 v2, 1994.
9. SLS Handbook, CERN, 1998.
10. H. Kim, “Direct-Drive and Eddy-Current Septum Magnets” in Proceedings of the 2001 Particle Accelerator Conference, Chicago.
11. SOLEIL- Rapport d’APD, 1999.
12. K.Halbach,”Some Thoughts on an Eddy Current Septum Magnet”, Light Source Note LS-244, Argonne National Laboratory, 1994.
13. S. H. Kim, “Direct-Drive and Eddy-Current Septum Magnets” ”, Light Source Note LS-292, Argonne National Laboratory, 2001.
14. OPERA-2d, OPERA-3d, Vector Fields Ltd., Oxford, UK.