SESAME Technical Note

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Note: **M-1**

DIPOLE MAGNET DESIGN FOR SESAME

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I Introduction

In this note, the updated design (magnetic and electrical) of the dipole magnet for the main storage ring is presented. However, the final mechanical details of the magnets will be decided in collaboration with the manufacturer.

In SESAME, the electrons are injected from a 20 MeV microtron into an 800 MeV booster synchrotron, with a repetition rate of 1 Hz. The 800 MeV beam is transported through the transfer line to the main storage ring and after accumulation, accelerated at 2.5 GeV [1, 2].

The SESAME storage ring will have 16 dipole magnets with the maximum magnetic field of 1.455 T and a vertical gradient of 2.79 T/m. The dipole is a 'C' type magnet, with parallel end and with the yoke laminations stacked parallel according to the nominal bending radius; the full gap is 40 mm at the transverse magnetic center.

The magnetic properties of dipoles have been modeled using 2D POISSON code. For the yoke material, the commercial laminated Cockerill steel was used. From this analysis, the electrical requirements were determined.

II Specifications

The dipole magnets are gradient magnets with a bending angle of 22.5^0. The field strength of 0.4657T and 1.4554T are required for injection and full energy. The "C" type configuration is used to make simple the beam line ports design. For the magnetic analysis, the iron permeability of Cockerill steel was used. Figure.1 shows the B-μ curve of two type of steel that can be used for the dipole yoke.

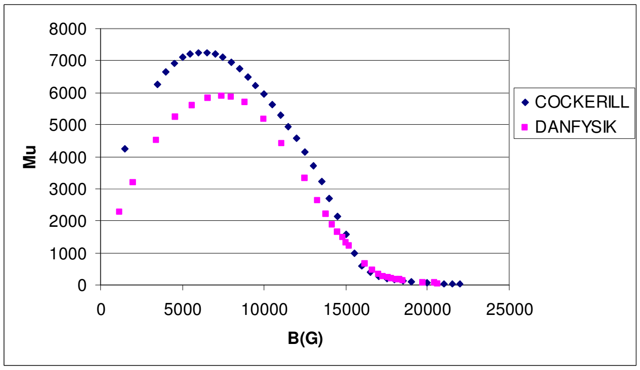

Figure1. The B-μ curve of two types of magnet yoke steel.

At full energy, the iron saturation effects cause the field strength to be non-linear with the excitation current. The calculated ampere-turn of 52266 is required for the 2.5 GeV operation.

We assume the coil made of 8 pancakes; each one with 10 turns; this gives a maximum excitation current of 654A for the power supply.

The output of POISSON is shown in Fig.2, while the cross section of lamination is shown in Fig. 4.

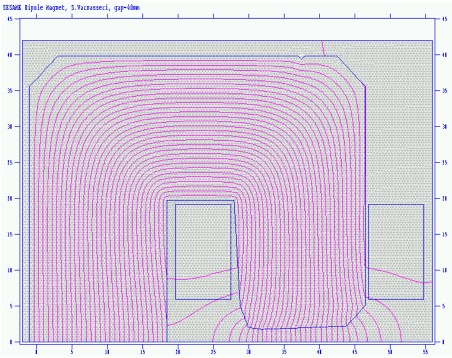

Figure 2. SESAME dipole magnet top-half cross section for POISSON code.

III Harmonic Analysis

In a storage ring usually one need a good field region in the transverse direction (few cm) in which the field is uniform (ΔB/B ~ few units in 10^{-4}) in order to have a good dynamic aperture. Furthermore is not only the absolute value of ΔB/B, which is important, but also the multiple content that is affected by the pole profile, iron saturation etc. This task of pole profile optimization and harmful harmonic reduction has been carried out in an iterative way by looking at the dynamic aperture.

Harmonic analysis has been used to estimate the multipole content of the magnetic field.

The mathematical theory is based on the idea that the vector potential A(x, y) can be thought of as the real part of a potential function F (z) where Z=x+jy [3]. The function F (z) can be expressed in a power series as:

$$F(z) = A(x, y) + jV(x, y) = \sum_{n=0}^{\infty} \frac{C_n}{r_{norm}^n} z^n .$$

where r_{norm} is the normalization radius around the analyzed point in the gap. If we let:

$$z = re^{j\varphi}$$

and the coefficient C_n by the formula:

$$C_n = |C_n| e^{j\alpha_n} = |C_n| (\cos\alpha_n + j\sin\alpha_n)$$

By substituting these relations into the formula for the vector potential, one obtains:

$$A(r,\varphi) = \mathrm{Re}\left[\sum_{n=0}^{\infty} \left(\frac{r}{r_{norm}} \right)^n |C_n| e^{j\alpha_n} e^{jn\varphi} \right]$$

$$= \sum_{n=0}^{\infty} \left(\frac{r}{r_{norm}} \right)^n |C_n| \cos(\alpha_n + n\varphi)$$

$$= \sum_{n=0}^{\infty} \left(\frac{r}{r_{norm}} \right)^n (a_n \cos n\varphi - b_n \sin n\varphi).$$

The above equation has the form of a Fourier series in the variable φ. Fourier analysis give us the coefficients a_0, a_n and b_n.

The harmonic analysis of the magnetic induction also starts with the series relation:

$$B_x - jB_y = j\frac{dF}{dz} = \sum_{n=1}^{\infty} jn \left(\frac{r}{r_{norm}} \right)^{n-1} \frac{C_n}{r_{norm}} e^{j(n-1)\varphi} .$$

which can be equated to Fourier series for the induction written in the form of:

$$B_x - jB_y = \sum_{m=0}^{\infty} B_m e^{jm\varphi}$$

The strengths B_m of the harmonic components of the magnetic induction are directly related to the coefficient a_n and b_n found in analyzing A(x,y). The relationship is:

$$B_m = -\frac{(m+1)}{r_{norm}}\left(\frac{r}{r_{norm}}\right)^m (b_{m+1} - ja_{m+1})$$

$$B_x - jB_y = j\sum_{n=0}^{\infty}\frac{n(A_n + jB_n)}{r}.\left(\frac{z}{r}\right)^{n-1}$$

The calculated SESAME magnetic Fourier coefficients for the geometry of the optimized pole profile (see Fig.2) at 2.5 GeV are given in Tab.1.

Teble.1. SESAME dipole magnetic Fourier coefficients

n	$n(A_n)/r$	$n(B_n)/r$
1	-14554	0
2	530.30	0
3	-3.1747	0
4	-0.586	0
5	0.3668	0
6	0.1533	0
7	1.2536	0
8	-0.01357	0
9	-0.7428	0
10	0.1689	0
11	-0.9079	0

Considering a *good field region* of ±2cm, the calculated multipole field components, B_n/B_0 for SESAME dipole design, are given in Tab.2.

Table.2. Multipoles within ±2cm

Multipole	At 2.5 GeV	At 800 MeV
X^2	$+2.42\times10^{-4}$	$+6.65\times10^{-4}$
X^3	$+4.7\times10^{-5}$	$+1.36\times10^{-5}$
X^4	-3.09×10^{-5}	-2.63×10^{-5}
X^5	-1.36×10^{-5}	-1.1×10^{-5}
X^6	-1.17×10^{-4}	-1.169×10^{-4}

The predicted homogeneity in vertical field along the x-axis in terms of $\Delta B_y/B_{y0}$ is shown in figure.3.

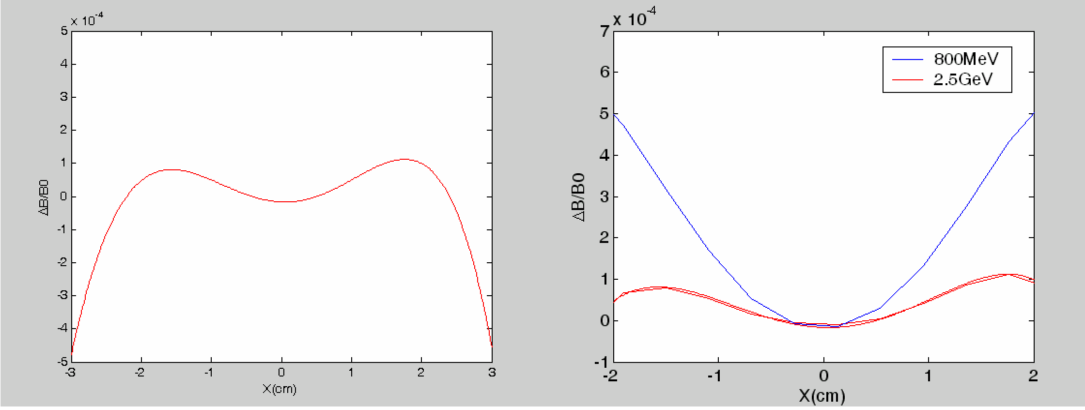

Figure.3. Transversal field quality prediction on y=0 axis at the field level 1.4554T, left within ±3cm region at 2.5 GeV, right for ±2cm at 2.5GeV and 800MeV.

IV Dipole Parameters

The coil design is based on copper conductors of square cross section and a central hole for water-cooling. Moreover, the electrical connections are assumed to be in the center of the magnet. There will be 8 pancakes, each pancakes consists of 2 layers of 5 conductors. Fig.4 and fig.5 give the detailed design of dipole coils, dipole lamination and pole profile.

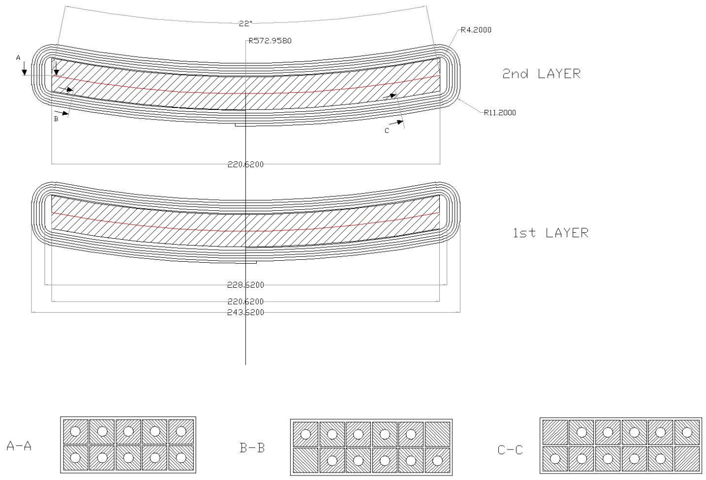

Figure.4. Top view of pancake and cross section.

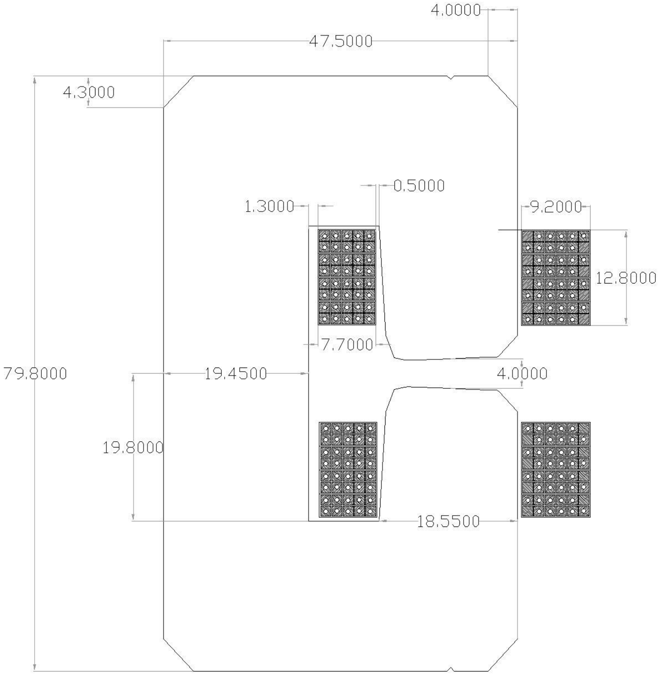

Figure.5. Lamination and coil cross section.

The conductor cross section is 14x14 mm^2 copper with a 6mm diameter hole for cooling water. In addition, there is 0.5mm insulation for each conductor.

Table.3. SESAME dipole parameter list at 2.5 GeV

Number of magnets	16
Bend angle	22.5
Energy (GeV)	2.5
Magnetic flux density (T)	1.4554
Gradient (T/m)	2.79
Bending radius (m)	5.72958
Magnetic length (m)	2.25
Iron length (m)	2.22
Central Gap height (mm)	40
Pole width (mm)	177÷186
Iron weight (kg)	5660
Copper weight (kg)	622
Total weight (kg)	6282
Packing factor	> 97%
Ampere turns (Total)	52260
Number of turns (Total)	80
Nominal current (A)	654
Number of pancakes (2 layers)	8
Conductor dimensions (mm)	14*14
Cooling hole diameter (mm)	6
Conductor area (mm^2)	167.7
Conductor length (m)	413.72
Current density (A/mm^2)	4.02
Resistance (mOhm)	41.5
Inductance (mH)	90
Voltage drop (V) per magnet	27.2
Power (kW) per magnet	17.75
Number of cooling circuits	8
Temperature rise (C)	10
Cooling water flow (l/s)	5.43E-2
Cooling water speed (m/s)	1.92
Pressure drop (bar)	6
Reynolds number	13634

The overall conductor length is 413.7m, with the total resistance of 41.5mΩ and total inductance of 90mH. The nominal current to have the maximum field of 1.4554T is 654A, which results in 27.2 V voltage drop, and 17.75 kW thermal power dissipation in the conductors. The coils are cooled with low conductivity water, with 6 bar pressure drop for 10^{o}C temperature rise.

3D calculation gives a yoke length of 2.22 m for a magnetic length of 2.25m. Table.3 gives the magnetic, electric and hydraulic parameters of SESAME dipole magnets.

V References

[1] G.Vignola et al. "SESAME in Jordan", PAC 2005, May 2005, USA

[2] G.Vignola, M. Attal "SESAME Lattice" - SESAME Tech. Note **O-1**, Dec. 2004

[3] "Poisson Superfish Manual" LANL document server

[5] M. Attal – SESAME Tech. Note **O-4** – August 2005

[4] M.Hildred Blewett, "Magnet Design in High Energy Accelerators", IEEE Trans. on Nuclear Science 1965, p317-326.

Appendix

The resulted field quality and multipole components of dipole magnet for different type of steel has also been carried out. The material EBG-1200-100A which is widely used for Danfysik magnets gives almost the same distribution of multipoles, but the effects of new multipole components on dynamic aperture should be evaluated; or the pole profile slightly be modified.

Considering a good field region of ±2cm, the calculated multipole field components, B_n/B_0 for SESAME dipole design, are given in Table.A.1

Table.A.1. Multipoles within ±2cm for Danfysik-type yoke material.

Multipole	At 2.5 GeV	At 800 MeV
X^2	$+3.1\times10^{-4}$	$+6.65\times10^{-4}$
X^3	$+6.66\times10^{-5}$	$+1.37\times10^{-5}$
X^4	-3.46×10^{-5}	-2.63×10^{-5}
X^5	-2.41×10^{-5}	-1.11×10^{-5}
X^6	-1.148×10^{-4}	-1.169×10^{-4}

The predicted homogeneity in vertical field along the x axis in terms of $\Delta B_y/B_{y0}$ is shown in figure.A.1. The gradient of dipole is changed from -2.791 T/m to -2.8109 T/m. The overall exciting current to have a 1.4554 T and 0.4657 T for the full energy and injection are 51436 A and 14938 A respectively.

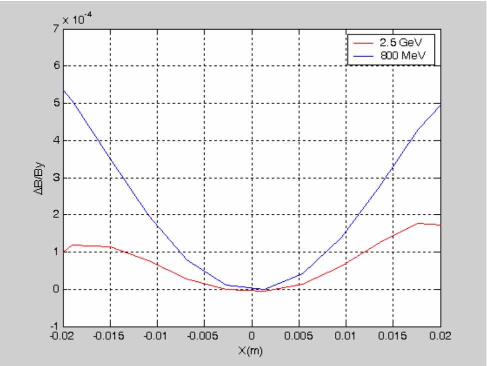

Figure.A.1. Transversal field quality prediction on y=0 axis, for ±2cm at 2.5GeV and 800MeV.