Design of a Steering Magnet for a Scanning Electron Microscope

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Abstract

The PBP-CMU Electron Linear Laboratory (PCELL), Chiang Mai University, in collaboration with the National Astronomical Research Institute of Thailand (NARIT), is developing in a scanning electron microscope (SEM) system. PCELL is responsible for the design and development of electron gun, condenser magnetic coils, and a steering magnet for beam alignment. This work focuses on the design and electromagnetic simulation of the steering magnet required to deflect a 20 keV electron beam by 85.63°, corresponding to steering the beam from the vacuum-tube wall edge toward the tube center. The magnet was designed under mechanical and electrical constraints such that the overall frame (including coil windings) must not exceed a 40 mm tube radius, and the available power supply limits the coil current to 1 A. CST Studio Suite 2025 software was used to optimize the magnet geometry and field distribution to meet the deflection requirement within these constraints. Simulation results indicate that the proposed steering magnet provides the required beam deflection and is suitable for integration into the NARIT SEM system. The design approach can also be adapted for beam-steering applications in other electron microscope platforms.

Theories

Introduction of Steering coil in Scanning Electron Microscope;SEM

Scanning Electron Microscopy (SEM) is a type of microscope that uses an electron beam instead of light to observe the surface structure of a specimen. The electron beam scans across the sample surface to generate high-resolution images. One of the key components in the SEM system is the steering magnet, which uses an electromagnetic field to deflect the electron beam and sweep it across specimen' s surface

In this project, the research is conducted through the collaboration between NARIT and PCELL, in which aim to the design the steering magnet component to steer electron beam to the angle of 85.63 Degree

Dipole Magnet

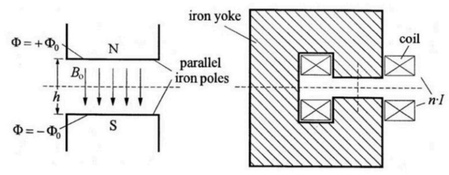


Figure 1: Magnetic field lines, magnetic scalar potential and the cross-sectional view of a C-shaped dipole magnet.

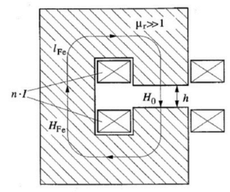


Figure 2: Integration path used to determine the magnetic field in a C-shaped dipole magnet.

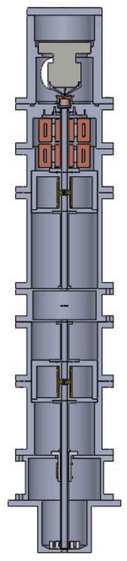


Figure 3: Components of the SEM system jointly designed by NARIT and PCELL, with the steering magnet developed in this study.

- **A dipole electromagnet with flat and parallel pole faces produces a uniform magnetic field (B_0) in an air gap of height h.**
- **The magnetic field is assumed to be directed along the z-axis, with the pole faces acting as equipotential surfaces**
- **Using Ampère's law for a C-shaped dipole magnet:** $\oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 n I \;\Rightarrow\; B_0 \approx \frac{\mu_0 n I}{h}$

Fringe Field and Effective Length

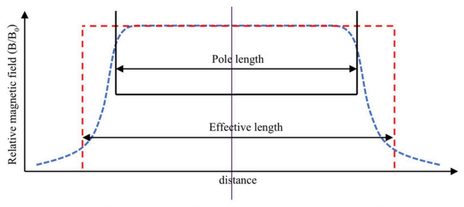


Figure 4: Magnetic field distribution of a dipole magnet along the direction of motion, showing the fringe field (blue dashed line) and the effective magnetic length.

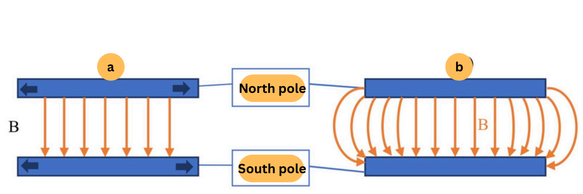


Figure 5: Magnetic field (B) of a two-pole electromagnet: (a) an ideal case with infinitely long pole length, and (b) the magnetic field distribution of a practical magnet.

- **The fringe field decreases with distance from the pole edge and its distribution is non-linear.**
- **To account for this effect, an effective magnetic length L_{eff} is defined as the equivalent length of a uniform field B_0 producing the same integrated magnetic effect.**

$$L_{\text{eff}} = \frac{\int_{-\infty}^{\infty} B(z)\, dz}{B_0}$$

Lorentz Force

- **The deflection of the electron beam is governed by the Lorentz force, which acts on a charged particle moving in a magnetic field**

$$\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}$$

- **This force causes the electron beam to bend when passing through the magnetic field generated by the steering magnet. Therefore, the magnetic field strength and the effective magnetic length determine the magnitude of the beam deflection.**

Bending Electron in SEM

- **This Lorentz force causes the particle trajectory to bend into a curved path, which is the fundamental principle used to steer electron beams in systems such as SEM.**
- **In a dipole magnet, the total deflection depends on the magnetic field strength B_0 and the effective magnetic length l_{eff} that includes the fringe-field contribution.**
- **The resulting deflection angle of the particle beam can be expressed as** $\theta\ [\text{rad}] = 0.2998\, \frac{B_0\ [\text{T}]\ l_{\text{eff}}\ [\text{m}]}{\beta\, E_{\text{total}}\ [\text{GeV}]}$

Methods

- **Define initial parameters: electron energy of 20 keV and required deflection angle to obtain the target magnetic rigidity. $B_0 \cdot L_{eff}$ = 7.41 · 10^{-4} T·m for bending angle 85.63 Degrees.**
- **Design the steering coil configuration according to the geometry constraints (Fig. 6).**
- **Model the yoke and coil using CST Studio Suite 2025, implementing predefined parameters for easier adjustment and optimization.**
- **Perform parameter sweep by fixing the gap h and magnet length L while varying the number of coil turns (N) to analyze B_0 ,L_{eff} and $B_0 \cdot L_{eff}$**
- **Optimize other parameters N, h, or L. until $B_0 \cdot L_{eff}$ approaches the target value**

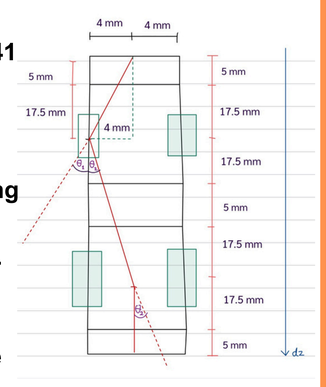


Figure 6: Schematic layout of the steering coil design in the 85 mm along z assigned chamber section.

Results

Parameters

h = The pole gap distance between yokes [m]
I_x = Current in x-axis is 1 A [A]
cx = Coil conductor thickness [m]
cy = Length of coil conductor [m]
A = Cross-section area of coil conductor [m^2]
N = Number turn of coil (1.5)(A)/(I_x) [Turn]
by J is current density 1.5 [A/m^2]
L = Length of magnet [m]

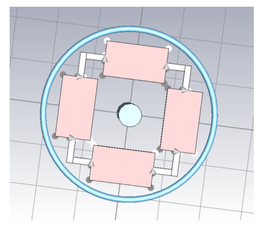


Figure 7: The outer blue circle represents the chamber diameter limit (80 mm), indicating that the designed steering magnet must remain within this boundary.

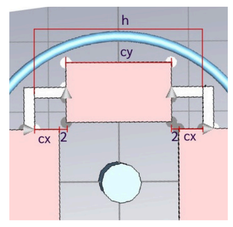
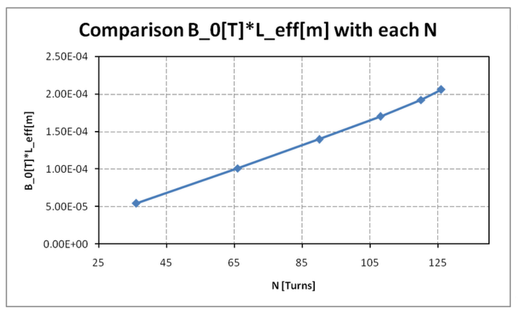


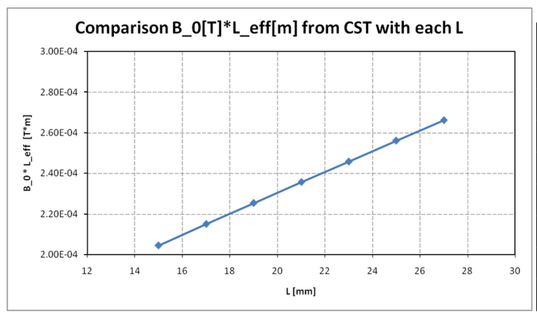
Figure 8: Illustration of the parameter conditions used in the steering magnet design.

Optimizing Coil Turn (N): Ix = 1A, h = 30 mm, L = 9 mm



cx * cy [mm * mm]	A [mm^2]	N [Turns]	L_eff [mm]	B_0 [T]	B_0 * L_eff from CST [T * m]	B_0 * L_eff from Theory [T * m]	Difference Percentage [%]	Bending [Rad]	Bending [Degree]
1 * 24	24	36	44.3	$1.23 * 10^{-3}$	$5.43 * 10^{-5}$	$8.02 * 10^{-4}$	93.22	0.110	6.27
2 * 22	44	66	44.4	$2.28 * 10^{-3}$	$1.01 * 10^{-4}$	$8.02 * 10^{-4}$	87.38	0.203	11.69
3 * 20	60	90	43.3	$3.16 * 10^{-3}$	$1.40 * 10^{-4}$	$8.02 * 10^{-4}$	82.56	0.282	16.16
4 * 18	72	108	44.2	$3.85 * 10^{-3}$	$1.70 * 10^{-4}$	$8.02 * 10^{-4}$	78.78	0.343	19.66
5 * 16	80	120	44.0	$4.37 * 10^{3}$	$1.92 * 10^{-4}$	$8.02 * 10^{-4}$	76.00	0.388	22.23
6 * 14	84	126	43.8	$4.70 * 10^{-3}$	$2.06 * 10^{-4}$	$8.02 * 10^{-4}$	74.29	0.416	23.82

Optimizing Magnetic Length (L): Ix = 1A, h = 30 mm, N = 108



cx * cy [mm * mm]	N [Turns]	L [mm]	L_eff [mm]	B_0 [T]	B_0 * L_eff from CST [T * m]	B_0 * L_eff from Theory [T * m]	Difference Percentage [%]	Bending [Rad]	Bending [Degree]
4 * 18	108	15	48.0	$4.26 * 20^{-3}$	$2.04 * 10^{-4}$	$7.41 * 10^{-4}$	72.39	0.412	23.63
4 * 18	108	17	49.2	$4.38 * 10^{-3}$	$2.15 * 10^{-4}$	$7.41 * 10^{-4}$	70.97	0.434	24.85
4 * 18	108	19	50.2	$4.49 * 10^{-3}$	$2.25 * 10^{-4}$	$7.41 * 10^{-4}$	69.58	0.454	26.04
4 * 18	108	21	51.5	$4.58 * 10^{-3}$	$2.35 * 10^{-4}$	$7.41 * 10^{-4}$	68.19	0.475	27.22
4 * 18	108	23	52.8	$4.65 * 10^{-3}$	$2.45 * 10^{-4}$	$7.41 * 10^{-4}$	66.83	0.496	28.40
4 * 18	108	25	54.4	$4.71 * 10^{-3}$	$2.56 * 10^{-4}$	$7.41 * 10^{-4}$	65.43	0.516	29.59
4 * 18	108	27	59.9	$4.76 * 10^{-3}$	$2.66 * 10^{-4}$	$7.41 * 10^{-4}$	64.08	0.536	30.74

After identifying the trend of the required $B_0 \cdot L_{eff}$ from the previous analysis, the parameters are optimized simultaneously to obtain a value that satisfies the target condition.

Optimizing All parameters

cx * cy [mm * mm]	N [Turns]	L [mm]	L_eff [mm]	B_0 [T]	B_0 * L_eff from CST [T * m]	B_0 * L_eff from Theory [T * m]	Difference Percentage [%]	Bending [Rad]	Bending [Degree]
5 * 16	120	25	54.3	$5.36 * 10^{-3}$	$2.90 * 10^{-4}$	$7.41 * 10^{-4}$	60.74	0.586	33.60
9 * 26	351	17	69.2	$8.23 * 10^{-3}$	$5.75 * 10^{-4}$	$7.41 * 10^{-4}$	22.40	1.159	66.43
4 * 18	108	19	50.2	$4.49 * 10^{-3}$	$2.25 * 10^{-4}$	$7.41 * 10^{-4}$	69.58	0.454	26.04
4 * 18	108	21	51.5	$4.58 * 10^{-3}$	$2.35 * 10^{-4}$	$7.41 * 10^{-4}$	68.19	0.475	27.22
4 * 18	108	23	52.8	$4.65 * 10^{-3}$	$2.45 * 10^{-4}$	$7.41 * 10^{-4}$	66.83	0.496	28.40
4 * 18	108	25	54.4	$4.71 * 10^{-3}$	$2.56 * 10^{-4}$	$7.41 * 10^{-4}$	65.43	0.516	29.59
4 * 18	108	27	59.9	$4.76 * 10^{-3}$	$2.66 * 10^{-4}$	$7.41 * 10^{-4}$	64.08	0.536	30.74

Figure 9: Design table comparing the optimized parameters, with the values highlighted in red representing the current best optimization.

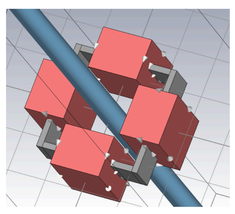


Figure 10: Optimized steering magnet model with the best performance obtained so far.

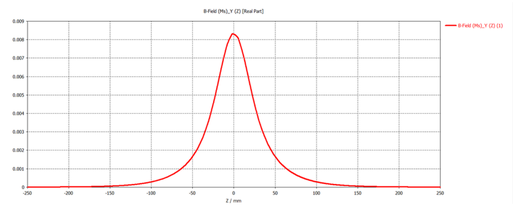


Figure 11: Magnetic field profile showing the relationship between B_0 and the z-position.

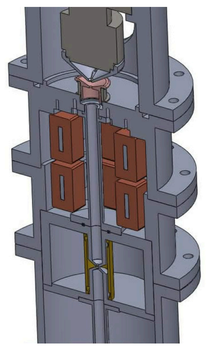


Figure 12: Optimized steering magnet in the SEM system jointly designed by NARIT and PCELL.

Conclusion

The optimization process resulted in a value of $B_0 \cdot L_{eff}$ = 5.75 · 10^{-4} T·m, corresponding to a deflect angle of 66.42 Degree the difference from the target value of 7.41 · 10^{-4} T·m is approximately 22.4%, while the desired deflection angle is 85.63 Degree. Nevertheless, further optimization is required to obtain a value closer to the target within the geometric constraints of the SEM chamber. This is result for situations where the electron beam approaches the chamber wall, where the magnetic field from the steering magnet must deflect the beam back to the desired trajectory at postion.