Chapter 34

Focusing and Steering Magnet for a 10 MeV Industrial Linac – Post Accelerating Section

– *Sonali Parasher*

High-energy (5-10 MeV) electron accelerators are used for wide industrial applications. Two main parameters that impact product irradiation using an accelerator are beam energy and the output power of the beam. Beam energy determines the beam penetration inside the material surface, while the power determines the radiation dose given to the material [160–162]. Various accelerator subsystems such as focusing and steering magnets play an important role for effective beam transmission and prevention of beam misalignment if any. Accelerators require high vacuum of the order 10^{-7}-10^{-8} mbar and degradation of this vacuum is a concern commonly caused due to beam misalignment which in turn can cause beam hitting the beam pipe and that can sputter the material from the beam pipe as well. As part of an indigenous accelerator development program for societal applications, an existing 10 MeV linear accelerator (Linac) with power output of 3 kW is proposed to be upgraded to 5-6 kW. Electron beam is generated from LaB_6 based thermionic gun operated at 50 kV the produced electron beam is then injected into a $\pi/2$ mode operaed standing wave bi-periodic structure operating at 2856 MHz, power is getting coupled into the structure through a kystron power source.

34.1 Design of Focussing Magnet

34.1.1 Focusing Magnets

Solenoid magnets are designed and employed to focus charge particle beam. These magnets provide symmetric radial and axial magnetic fields produced by axicentered coils carrying azimuthal current. Solenoid lens are the only possible magnetic lens geometry consistent with cylindrical paraxialbeams resulting in it being best suited for electron focusing.

34.1.2 Magnet Design

The process of focusing magnet design comprises of identifying various magnet characteristics:
Magnet type: Different types of magnets exhibit different longitudinal and transverse magnetic field profiles. In this analysis, we consider full-length solenoid and solenoid with various pole gap configurations.

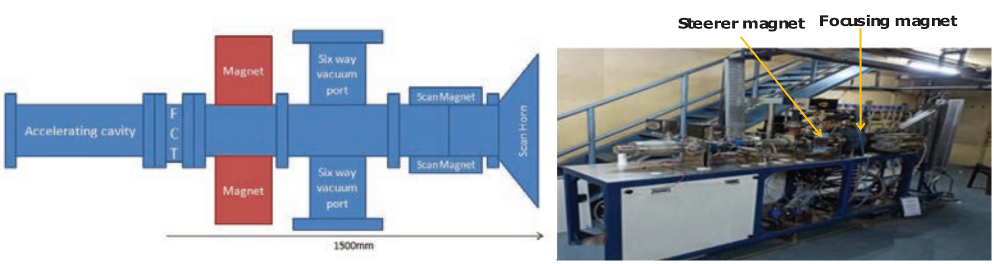

Figure 34.1: Schematic of the 10 MeV horizontal linac and steerer (left) and actual system assembly (right).

Magnet parameters: These include magnet material, maximum allowable current and the design value of solenoid yoke and the number of turns in the magnet.
Magnet length and location: Given the schematic of the accelerator shown in Fig. 34.1, we also determine what is the required length of the magnet and where should it be placed along the beam line. In our study, we were constrained by the available space and thus chose magnet length to be 190 mm, located right after the fast current transformer (FCT) following the accelerating cavity. A broad schematic for designing magnetic element is shown in Fig.

34.2. The first step involves finding the approximate peak magnetic field along the axis of the solenoid for a given beam energy. This is done by analytically solving the transfer matrix of the magnet and numerically solving the RMS envelope equation with Octave. Based on this study a 3-D model is constructed in CST particle studio. Number of turns, current, yoke dimensions are optimized to get required field. Evolution of beam envelope, beam size in x-y plane and transverse phase space are studied at different input conditions and at different location along the beam line. A scaled down model of solenoid magnet is designed, fabricated and tested. In the next few sections, we present details of the magnet design as explained

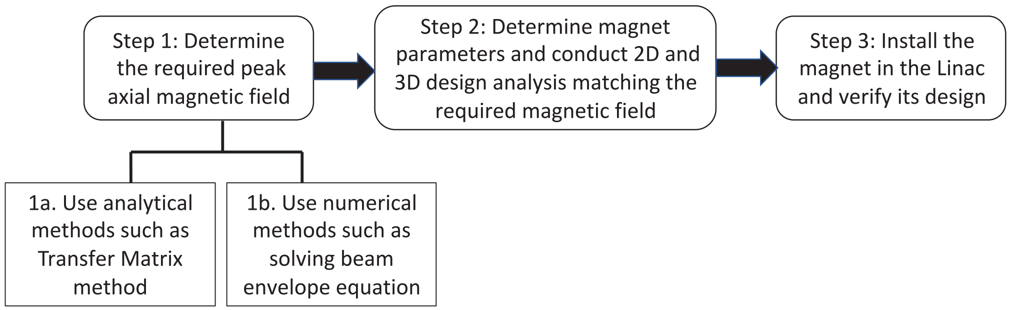

Figure 34.2: Industrial Accelerator magnet design steps.

in Fig. 34.2 Solenoid focussing magnet is designed to avoid beam spread after linac up to scan horn and it will also help to measure the exact beam size after the exit of the linac. Solenoid magnet is used when axial symmetry of the beam is desired at the output along with a focussed beam. Equations (34.1 & 34.2) represent the magnetic field inside the solenoid magnet having N number of turns.

$$B_z = \frac{\mu_0 N I}{L}, \tag{34.1}$$

$$B_r = -\frac{r}{2} B_z \tag{34.2}$$

Where B_z is axial magnetic field, B_r is radial magnetic field, and N/L is the number of turns per unit length. The analytical calculation for magnetic field is done by following methods:

Transfer Matrix Method

Analytical calculation of magnetic field is done by solving transfer matrix [162] for solenoid considering beam remain parallel through whole drift space after passing through solenoid magnet. This gives a value of magnetic field around which the CST simulation is done. The relation between beam deflection and its derivative at length L is given by

$$[x\ x'\ y\ y'].^T_{z=L} = M * \ [x\ x'\ y\ y'].^T_{z=0}$$

where M is the transfer matrix for a solenoid with strength B and length L which is represented as below:

$$M = \begin{bmatrix} c^2 & sc/k & sc & s^2/k & 0 & 0 \\ -ksc & c^2 & -ks^2 & sc & 0 & 0 \\ -sc & -s^2/k & c^2 & sc/k & 0 & 0 \\ ks^2 & -sc & -ksc & c^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & L/\gamma^2 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$c = coskL; s = sinkL; k = \frac{B_z}{2B\rho}; B\rho = p/q.$

Solving the equation for a 2-D matrix we get the equation in the below form.

$$r'_f = 0.01\left[-\sqrt{K}\sin(0.2\sqrt{K})\right] + 0.02\left[\cos(0.2\sqrt{K}) - 0.085\sqrt{K}\sin(0.2\sqrt{K})\right] \tag{34.3}$$

Here we assume a drift space of 85 mm before the magnet and solenoid length is considered to be 20 mm, Asumming a drift space of 700 mm post accelerator, If we desire a parallel beam at the target, then $r'_f = 0$. We can substitute $m = 9.1 \times 10^{-31}$ kg, $c = 3 \times 10^8$ m/s, and $q = 1.6 \times 10^{-19}$ C; furthermore, for a 10 MeV Linac, substitute the value of $\gamma = 1 + \frac{10}{0.511} = 20.57$, and $\beta = 0.98$. This equation gives us a value of approximate peak field of **0.21 T**.

Envelope Equation Method

When a group of particles are introduced together, we can track the evolution of the ellipse representing the particle by tracking the normalized beam radius as a function of distance z. Envelope equation [162] is used to model the radial trajectory using the equations of motion [163]. This equation takes into account the effect of space charge divergence and focusing forces and do not account for fringe of the magnet The envelope equation is given by:

$$A'' = K_{r,\beta}A - \frac{\beta\gamma Q}{A} - \frac{\epsilon_n^2}{A^3} = 0 \tag{34.4}$$

where $Q = \frac{I_b}{\beta^3\gamma^3 I_0}$, $\epsilon_n = \beta\gamma\epsilon$, $A = \sigma_r(\beta\gamma)^{1/2}$,
$K_{r,\beta} = \left[\frac{eB_z(z)}{\beta\gamma m_0 c}\right]$, and $I_0 = \frac{ec}{r_0} = 17000$ kA.
In the above equation A is the normalized beam radius, I_b is the beam current, σ_r is the RMS radius, r_0 is the classical electron radius ϵ_n is the normalized beam-emittance $K_{r,\beta}$ is the strength of the magnet, and $\beta = v/c$. The derivatives are defined relative to distance along the axis (z). Solving beam-envelope analytically is difficult and thus numerical approximation

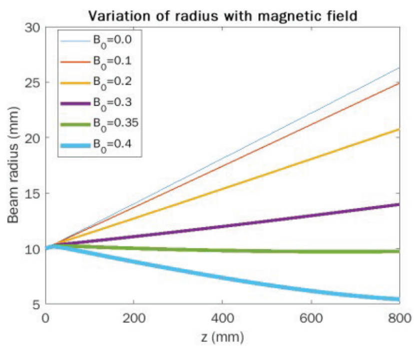

Figure 34.3: Beam envelope equation solved with MATHEMATICA showing 0.35 T field required for parallel beam and withour field beam size grows to 10 mm to 25 mm at 800 mm distance.

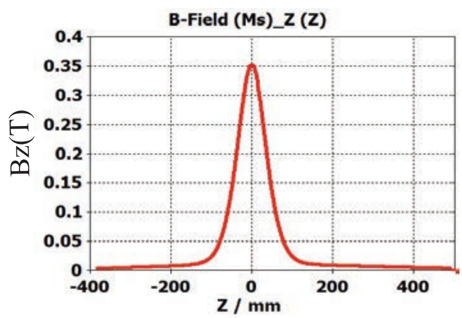

Figure 34.4: Magnetic field value plotted in MATHEMATICA with solenoid magnetic field equation.

methods are commonly used. These approximation methods include Runge-Kutta method which considers a fourth-order approximation to the derivative terms. A beam envelope equation for the trajectory of particle is solved using MATHEMATICA. Estimation made by analytical calculations is verified by simulating a 3-D model in CST particle studio. Particle trajectory is analysed at various values of focussing field. It is found that for single pole gap

magnet of magnetic field of 0.35 T is required for this beam energy. The equation helps to verify the magnetic field value required by required by 10 MeV beam energy. Figure 34.4 shows the field of 0.35 T is needed for our design consideration for a parallel beam at distance of 800 mm. This figure also shows that without magnetic field at the distance of 800 mm beam size grows from 10 mm to 25 mm considering initial beam divergence of 20 mm-mrad. Figure 34.4 shows the magnetic field plotted in MATHEMATICA.
The coils are winded on MS frame. Thickness of the winding coil is decided by the maximum current required to pass through the coil. Figure 34.9 shows a 10 MeV beam deflection by an O-type steerer. Here the beam enters inside the magnet from right side of the figure and is getting deflected after exiting the magnet. This can also be seen as if there is an inbuilt deflection in the beam it will automatically get corrected while passing through the magnet. Figure 34.10 represents the design of steerer of 150 mm with deflection of 30 mm in x and y plane and Figure 34.11 displays the focusing and steerer magnet installed in the beam line of the horizontal Linac. Table 34.1 shows the value of NI and corresponding field with achieved steering with the same.

Table 34.1: Steering value with magnetic field and attained steering.

NI	**Magnetic field (Gauss)**	**Steering offered (mm)**
1000	100-120	28 × 28
750	80-100	21.1 × 21.0
500	40-60	14 × 14
375	30-48	10.5 × 10.5
250	18-32	7 × 7
175	13-22	5 × 5
100	12-20	4.2 × 4.2

34.2 Simulation Results

With the help of CST studio suite, the simulation is done in particle studio with maximum mesh size of 10^6 or higher order, the magnetic field calculated by analytical method is verified with CST and it is found that $NI = 15000$ is required to achieve a magnetic field value of 0.35 T. Yoke thickness and pole gap are optimised in the similar manner [131]. Where N is number of turns and I is current flowing through the conductor. Beam RMS evolution is also plotted along the z axis Fig. 34.5 shows the same here z is measured in meters. The magnetic field B_z along z axis is plotted with the help of CST studio for different NI values in Fig. 34.5 z is given in m. Figure 34.7 represents the beam size in X and Y plane for

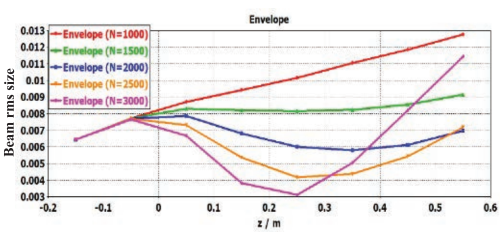

Figure 34.5: Beam envelope equation as achieved by CST.

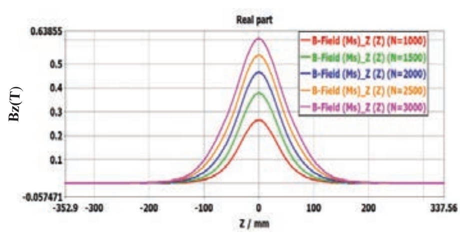

Figure 34.6: Magnetic field for different NI values, with I = 10 A.

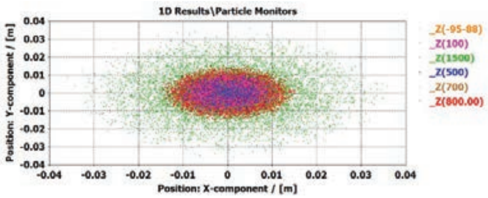

Figure 34.7: Beam size in X and Y plane at different Z values.

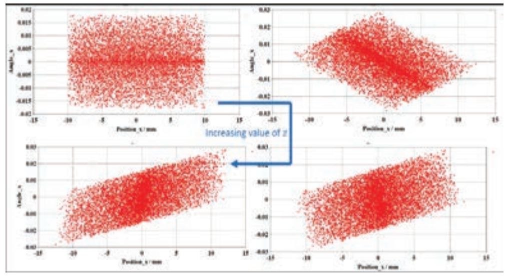

Figure 34.8: Beam inside magnet in x-x´ plane.

incoming beam size of 10 mm; it shows that upto 800 mm the beam remains nearly same in size relative to the origin, however, after that its size increases.It is also been noticed that while the beam goes inside the magnet there is the twisting of the angle with respect to z, and this can be seen in x-x´ phase plane diagram. Same is shown in Fig. 34.8. This figure shows that beam size at the end of 700 mm remains same as beam size while entering the magnet, this also matches with the design criteria.

34.3 Steerer Magnet Design

34.3.1 Design of Steerer Magnet

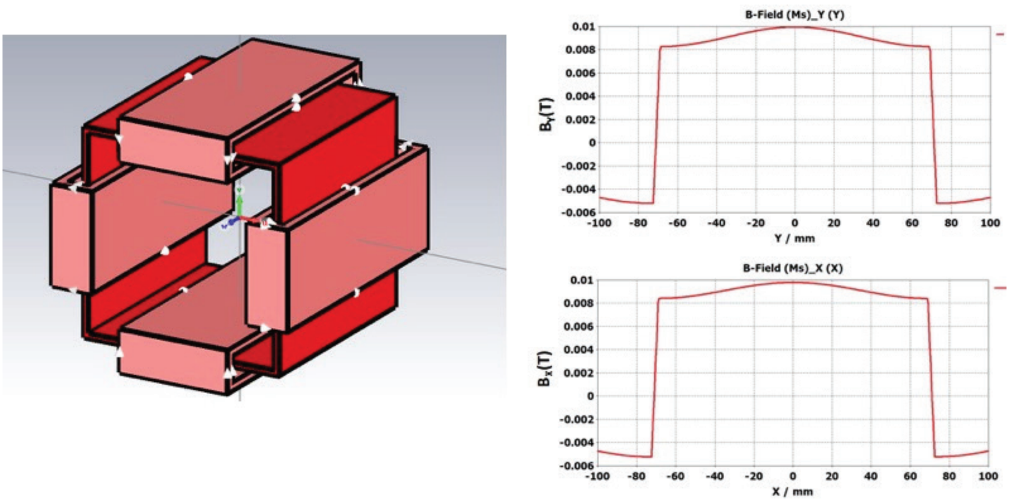

Figure 34.9: Steerer magnet design in CST particle studio.

Steerer magnet plays an important role in correcting the beam misalignment. If the misalignment is present at the entry side of the Linac it will grow as the beam progress through the Linac structure. Steerer magnet gives a required deflection to the beam in X and Y plane. Given design is an O-type steerer which have two X coils and two Y coils. Number of turns is decided by the input energy of the beam and maximum deflection correction required in X and Y plane.

The design of a 150 mm-long steerer magnet, which is used for skew correction of the beam after the accelerator section, is done in CST Particle Studio. The schematic of the steerer magnet and the magnetic field profiles (perpendicular to the axis) are shown in Fig. 34.9. This field corresponds to $NI = 1000$ and gives the skewness correction of 21 mm in the x and y beam directions. There are two coils each in the x and y directions. These coils are joined in series and are winded on a 3 mm MS1010 core of length 150 mm. The field is measured using a gauss meter with coil energized using a 32 V, 10 A power supply. The

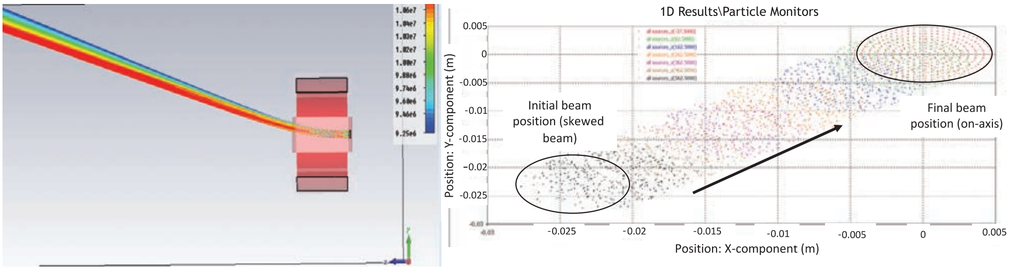

Figure 34.10: (Left) Steerer magnet design in CST particle studio; (Right) When the steering magnet is used, we observe that beam skew is reduced from (-25 mm, -25 mm) to (0, 0).

coils are winded on MS frame. Thickness of the winding coil is decided by the maximum current required to pass through the coil. Figure 34.10 shows a 10 MeV beam deflection by an O-type steerer. Here the beam enters inside the magnet from right side of the figure and is getting deflected after exiting the magnet. This can also be seen as if there is an inbuilt deflection in the beam, it will automatically get corrected while passing through the magnet. Figure 34.10 represents the design of steerer of 150 mm with deflection of 30 mm in x and y plane and Fig. 34.11 displays the focusing and steerer magnet installed in the beam line of the horizontal Linac. Table 34.1 shows the value of NI and corresponding field with achieved steering with the same.

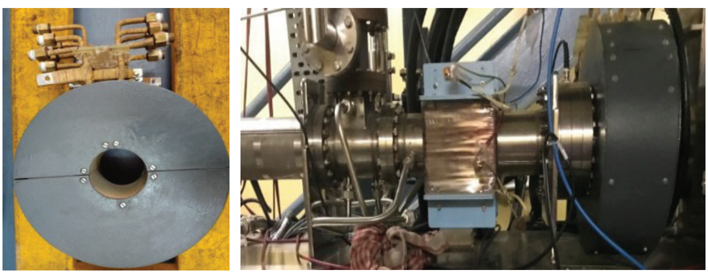

Figure 34.11: Fabricated solenoid and steerer magnet in the beam line of horizontal linac.

34.3.2 Practical Considerations for Magnet Design

MS1010 or MS1020 are low carbon steel material with carbon content of less than 0.25% and is used in the fabrication of the magnet. The total cross section area of the magnetic material for the flux return path is such that desired magnetic field is achieved. The heat generated in the coil due to I^2R losses when added with number of turns gives total heat flow through the coil which contributes to temperature rise of the coil and is desired to be in the range of ±5 °C [163]. This helps in calculations of flow rate required to pass through the coils. Coil thickness is decided by AWG wire gauge standard so as to ensure desired I (current) though

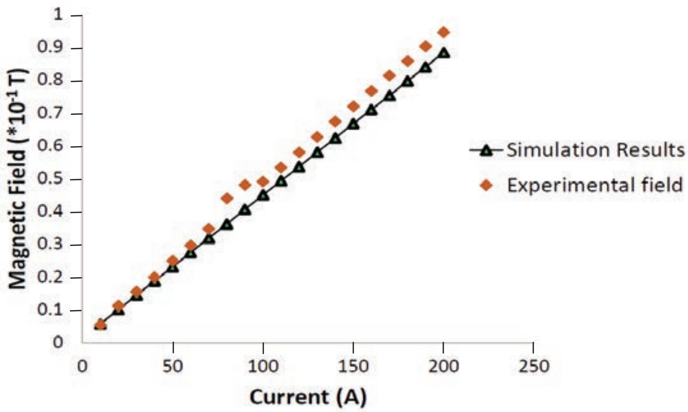

Figure 34.12: Experimental and theoretical field of the magnet made with thk. of 135 mm.

the coil. The fabricated focussing magnet specification is given in Table 34.2. Due to the

Table 34.2: Focusing magnet specifications as placed in magnet assembly.

Parameter	**Specification**
Length of flux return bar	135 mm
circular end plates thickness	3 mm
Height of the magnet	390 mm
Thickness of end plates	10 mm
Pole piece	
Thickness of rectangular section	30 mm
Magnet Coil	
Wire	7 mm × 7 mm with 4.5 × 4.5 mm^2 hole
Inner dia	170 mm
Outer dia	360 mm
No of turns	120
Pancake coils number	6
Current	200 A
Coil resistance	0.06 Ω
Power dispersed in coil	2.4 kW

space constrain the magnet length is squeezed to 135 mm, while the actual design thickness of the magnet was 200 mm. The field of the new magnet is measured using a Gauss meter and the experimental and simulated magnet field is shown in Fig. 34.12

34.4 Summary

In this chapter, we discussed the design of focusing and steering magnet for a horizontal 10 MeV, 5 kW Linac assembly. The theoretical analysis conducted using the transfer matrix method. It shows that magnetic field of 0.21 T is required to get a parallel beam. The simulation studies done in CST particle studio, show that about 0.35 T field is required to get a parallel beam. Steerer magnet analysis done in CST shows beam skewness correction can be done for approximately 21 mm from the centre of magnet corresponding to a magnetic field of 100 Gauss. A prototype focusing magnet was designed, fabricated and tested and is placed in Linac assembly for future experiments.