Chapter 33

Development of Scan Magnet for Industrial Accelerator

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Over a span of two decades, Accelerator and Pulse Power Division has been engaged in development of DC and RF electron accelerators that are useful in various sectors of society from basic research, medical to food processing. A 10 MeV, RF electron linear accelerator (linac) is commissioned in Electron Beam Center, Kharghar that is routinely used for various applications. RF linac consists of an electron gun that generates electrons. These electrons are injected in accelerator cavity that consists of several cavity resonators, each operating in a TM_{010} mode. Electrons are accelerated by the axial electric field of the order of ≈15 MV/m. Klystron power source is used to provide RF power to the linac. RF power is fed to the cavity using WR284 waveguide that is pressurized with SF_6 gas to avoid arching due to high power. Beam current is measured by Fast Current Transformer that is connected at the exit of the accelerator cavity. A solenoid focusing magnet is used to minimize beam spread. Accelerator assembly is evacuated using turbo-molecular pump and ion pump that are connected in the beam line.
A magnetic sweep scanner is used to deflect an electron beam through an angle of 30°. Sweep scanner consists of a dipole magnet that is energized by alternating current. Due to the time varying field, electron beam is continuously deflected through an angle of -30° to +30° about the axis. Figure 33.1 shows the linac assembly in horizontal configuration.
The product to be irradiated is placed on a conveyer belt that moves in horizontal direction. In order to ensure uniform irradiation of the product, the beam is scanned over a length of 1 meter in vertical direction using a scan magnet that sweeps the beam at a frequency of 1 Hz.

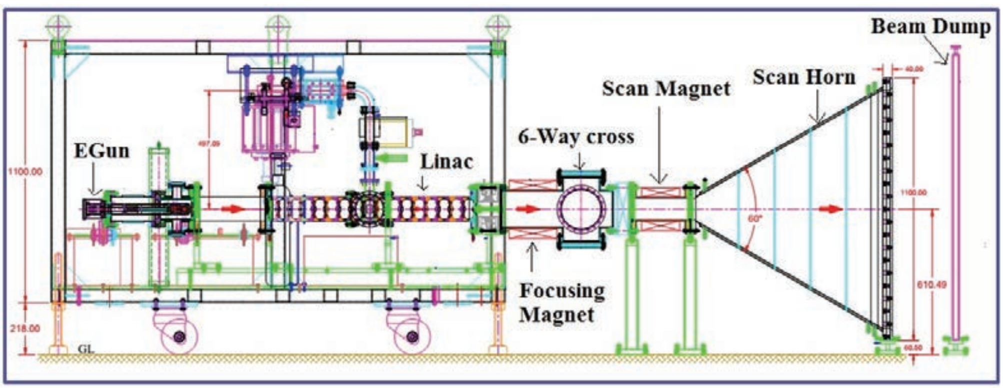

Figure 33.1: Schematic of the linac in horizontal configuration.

33.1 Design of Scan Magnet

An electron moving with velocity $\vec{v}$ (in z-direction), when acted upon by a magnetic field $\vec{B}$ in perpendicular direction (y-direction), gets deflected in a direction that is perpendicular to both $\vec{v}$ and $\vec{B}$ (x-direction) due to the Lorentz force (see Fig. 33.2). The angle of deflection θ depends on the magnitude of the force. In case of relativistic electron, it is directly proportional to B. Equation (33.1) shows the relation between the physical quantities.

$$Sin\theta = \frac{L}{R} = \frac{300\ B\ L}{E} \tag{33.1}$$

In Eq. (33.1), L is the magnet length including fringe field, E is electron energy in MeV, R radius of curvature in meter and B is the magnetic field in tesla. Using this equation, we

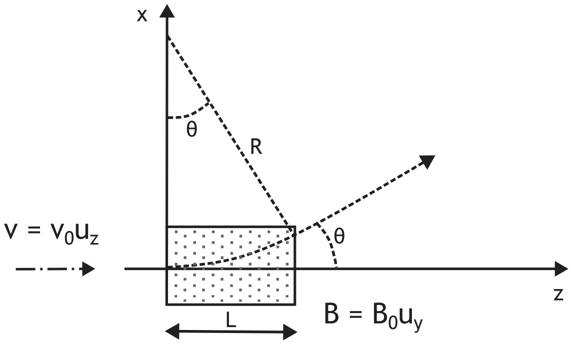

Figure 33.2: Deflection of an electron in a magnetic field.

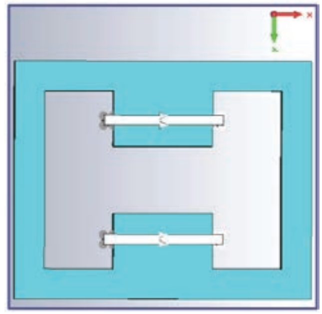

Figure 33.3: H-type dipole magnet.

can calculate the magnetic field required to deflect an electron of energy 10 MeV through an angle of 30° to be 1.7 kG. H-type dipole magnet is preferred due to symmetry of magnetic flux lines for beam scanning. Beam passes through the centre of magnet. Coil is wound on the central arm of the magnet as shown in Fig. 33.3. Magnetic field in a dipole magnet having pole gap d, coil current I and number of turns N is given by Eq. (33.2) [156],

$$B = \frac{\mu_0 NI}{d} \tag{33.2}$$

Design of scan magnet is optimized using different simulation software like POISSON, PANDIRA, CST Particle Studio [147, 157]. Figure 33.4 shows magnetic flux lines for one quarter of the magnet simulated by using the POISSON code. Figure 33.5 shows the path of a 10 MeV electron beam due to the scan magnet; about 1.78 kG magnetic field is required to deflect the beam through 30° [158].

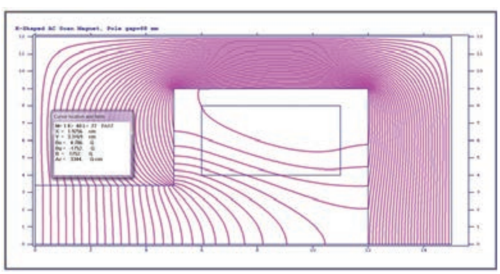

Figure 33.4: Magnetic flux lines for a quarter of the Scan Magnet [158].

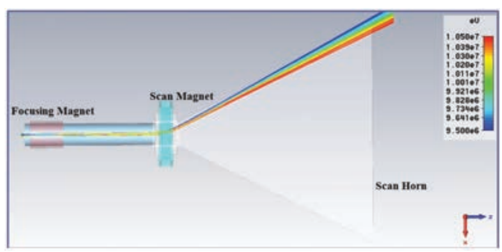

Figure 33.5: Deflection of a 10 MeV electron beam by the Scan Magnet [158].

33.2 Development of Scan Magnet

Si Steel laminations of standard thickness 0.27 mm are used for the magnet fabrication. Figure 33.6 shows the photograph of the scan magnet. As it is required to sweep electron beam in vertical direction, scan magnet is energized using alternating current having triangular waveform. Frequency of scanning depends on the pulse repetition rate, which is 1 Hz in our case.

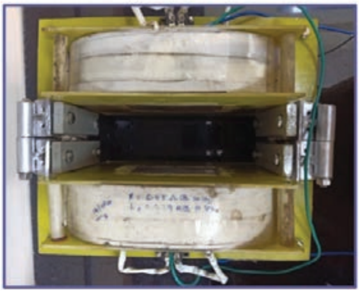

Figure 33.6: Scan Magnet made up of *Si steel* [158].

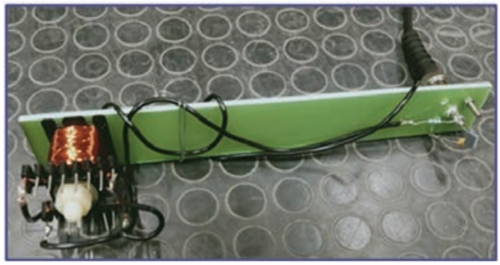

Figure 33.7: Search coil [158].

33.3 Field Measurement

To energize the magnet, a close loop controlled Scan Magnet supply is developed that generates triangular current waveform at 1 Hz frequency. A time-varying magnetic field gives rise to an emf given by [158, 159]:

$$emf = n\frac{d\phi}{dt} = -n\frac{d(BA)}{dt} = -nA\frac{dB}{dt} \tag{33.3}$$

where A is cross-sectional area of coil. When a 'search coil' is placed in between the pole gap, a voltage is produced at the output of coil. Output voltage V_0 of the search coil is the integration of the input voltage, V_i given by Eq. (33.4).

$$V_0 = \frac{1}{RC}\int V_i dt; \quad V_i = emf \tag{33.4}$$

In practice, cross-section, number of turns and 'RC' time constant of search coil are chosen depending on the operation frequency of the power supply. Output voltage of search coil is measured by oscilloscope. Figure 33.7 shows the photograph of the search coil. Figures 33.8 and 33.9 show the triangular output current waveform of the power supply used to drive the magnet, and the output of search coil [158], respectively.

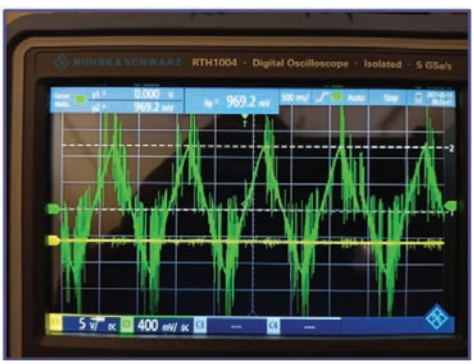

Figure 33.8: Output waveform of the scan supply [158].

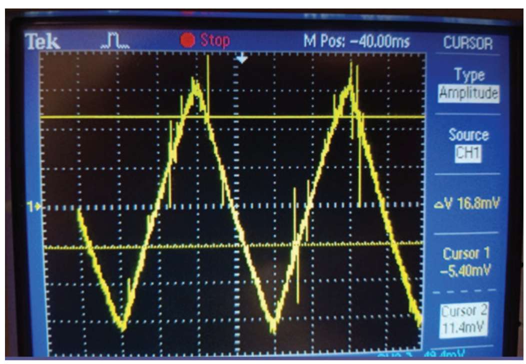

Figure 33.9: Output waveform of the search coil [158].

33.4 Conclusions

This chapter gives a brief description of the scan magnet design. It shows some of the simulation results to make readers familiar with the design concept. A short description of experimental procedure is added.

Exercises

1. How much magnetic field is required to deflect 6 MeV electron beam through angle of 0°, 10° and 30°? (Assume magnet length = 100 mm)

2. A dipole magnet having pole gap 5 cm produces 0.1 T magnetic field at NI = 10,000 A-turns. If gap is doubled how many Ampere-turns are required to produce same field?

3. How much e.m.f. is generated in a coil having cross-sectional area of 4 cm^2, no. of turns 750 if magnetic field is changing from zero to 2 kG in 0.5 sec?

4. What is the output voltage of Search Coil if input voltage has a time dependence given by

$$V_i(t) = V_0 sin(\omega t + \phi)$$