Chapter 3

Electron Gun Design for Electron Beam Melting

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The industrial revolution has emphasized on costly methods to convert the rare and exotic materials into structural and engineering components had been increased. This encouragement leads to the development of Electron Beam Technology for producing the superior quality materials. Industrial size electron beam devices and technology utilizes the basic research in many fields which is accumulated in more than 350 years. The developments in various fields such as high vacuum, control system, electrical discharge studies etc. accelerated the growth of advancements in the field of electron beam technology.

The electron beam machines (EBM) are device for producing the electrons and accelerating them towards the work piece with the control of direction and focusing of the beam on a work piece. These machines utilize the kinetic energy of electron for thermal applications such as melting, welding, evaporation etc.

3.1 Introduction

Electron beam melting is a process wherein a focused beam of high energy electrons is directed to the target material (charge). The kinetic energy of the electrons is transformed into heat upon striking the target material. Due to the control of electron beams EB melting process can produce homogeneous melt pools. The vacuum environment in the EBM machine maintains the chemical composition of the material and provides an excellent environment for building parts with reactive materials such as titanium alloys. High power electron beam ensures an even large throughput within the target, which gives a fully melted metal with homogeneous mechanical and physical properties. Due to these capabilities of electron beams, high power melting machines are more in demand for the industrial processes. The average electron beam (EB) power density (defined as the ratio of beam power falling on the melt target to the area of circular beam spot) for melting application lies within the range 10^3 W/cm^2 to 10^5 W/cm^2 [10, 11]. This range ensures melting of refractory metals kept in a water cooled crucible.

The subsystem of electron gun can be divided into five parts which are,

1) A primary electron gun (for 40 kV, 150 kW beam power generation)
2) A secondary electron gun (used for heating the primary cathode by electron bombardment)
3) Two Electromagnetic focusing lenses (for beam focusing)
4) Intermediate beam aperture (for vacuum decoupling between the gun region and the melt zone)
5) Deflection and Oscillation lens (for beam maneuvering on the melt charge).

3.2 Primary Electron Gun

The primary electron gun consists of solid cathode, grid and anode. The emission current density of these cathodes is given by the Richardson-Dushman equation which is

$$J_{eT} = AT^2 e^{\frac{-11600\phi}{T}} \tag{3.1}$$

Where J_{eT} is emission current density in A/cm^2; A is Richardson Constant in A/K^{2}cm^2; T is temperature in K; ϕ is work function of the emitter (eV).

The primary electron gun design is derived with the classical pierce geometry for producing the axi-symmetric parallel beams (zero beam divergence). The anode cathode gap (18 mm) is calculated from the analytical expression { Eq. (3.2)} for the space charge limited current of 3.75 A at 40 kV acceleration voltage [12].

$$J = 3.33 \times 10^{-6} \frac{V^{\frac{3}{2}}}{d^2} \tag{3.2}$$

The anode shape is generated by solving the analytical equation [12] for Pierce gun. The geometry is used as a baseline for the design problem. This beam simulation for this electrode geometry was carried out using commercial 3D beam simulation software CST studio suite. The beam divergence angle and the space charge beam current were found to agree with the analytical results to a fair accuracy ($< 5\%$). This model is taken as the starting point and further synthesized in steps to achieve the designed beam current. The position of cathode with respect to the focusing electrode and the bias voltage were optimized to extract the desired beam current with zero anode collection. Electrostatic analysis of the primary electron gun was carried out to calculate electric field at all the electrodes. The maximum electric field at anode is 64 kV/cm. The electric field at anode is within the permissible limit of 100 kV/cm.

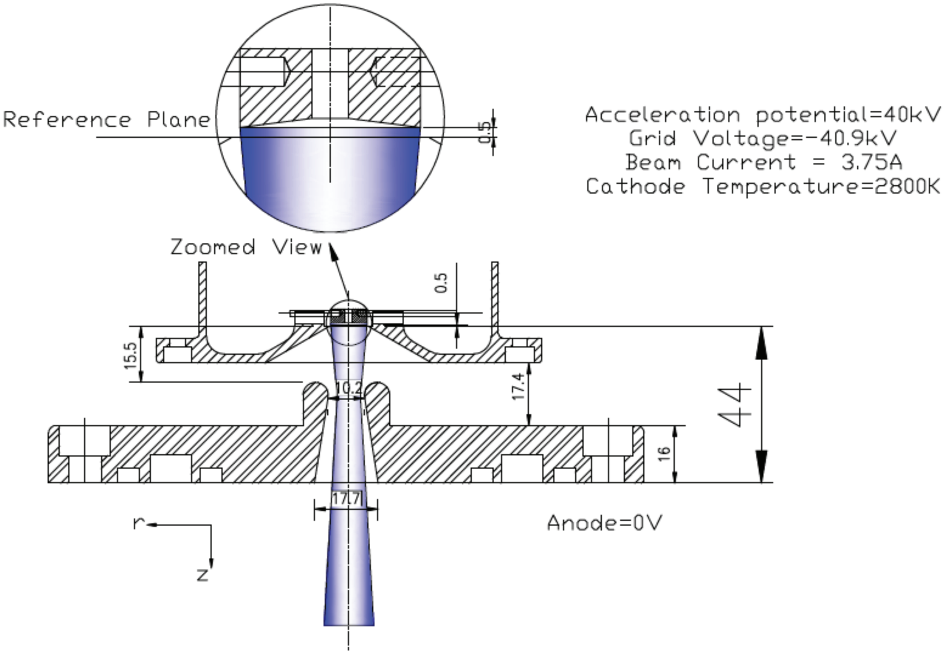

Figure 3.1: The electron beam envelope of primary gun.

The beam envelope and trajectories for different grid voltages are shown Figs. 3.1 and 3.2 respectively. For obtaining 3.75 A at 40 kV solid cathode should be 0.5 mm inside and grid voltage is 900 V w.r.t. cathode which is shown Fig. 3.3.

3.3 Electromagnetic Lenses for Beam Focusing

Electromagnetic lens is an indispensable component in any electron optical column. This device brings back a diverging electron beam emerging out of an electron gun on to a target

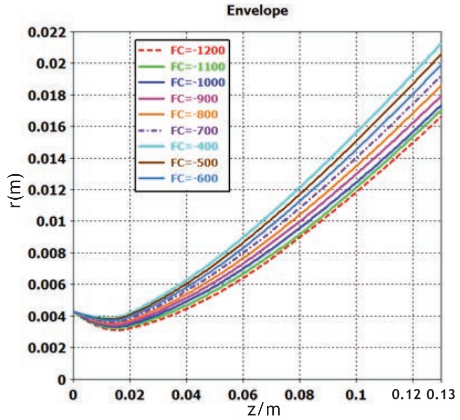

Figure 3.2: The beam trajectories for various grid voltages.

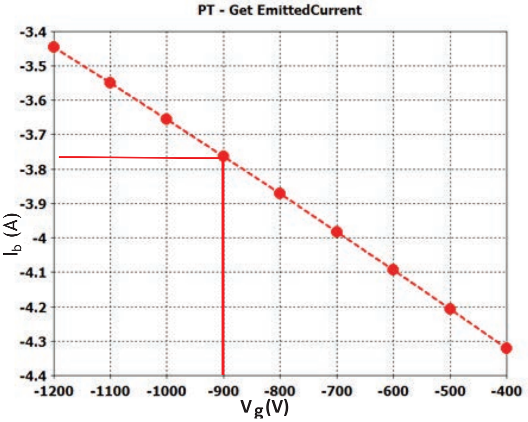

Figure 3.3: Beam current for various grid voltages.

(usually placed a few hundreds of mm away). A diverging beam from an electron gun, is caused by

1. Diverging lens effect of the anode aperture
2. Coulomb repulsion between electrons
3. Thermal velocity distribution of electrons at cathode

An electron optical column without a focusing lens will merely produce an electron spray on the target. The focusing lens in an EB welding machine is analogous to a condenser lens in electron microscopes. This concept of an EM lens is explained below. It has been proved [2] that an axi-symmetric electromagnetic field generated by a finite solenoid has imaging property for electron beams passing around its axis of symmetry, as a spherical convex lens does with light rays. The coordinate system used for explaining the principle of magnetic focusing of electrons is shown in Fig. 3.4. The magnetic field vector B produced by a finite solenoid can be represented in cylindrical coordinates system (Fig. 3.4). The magnetic field vector $\overrightarrow{B}$ has only two components B_z and B_r. If an electron having two velocity components v_r and v_z , enters this magnetic field, it sees a force in the direction of φ,

$$F_\varphi = ev_r B_z + ev_z B_r \tag{3.3}$$

This force introduces the third velocity component v_φ. In other words the electron tends to rotate around the axis. This velocity component, combining with the axial field B_z gives rise to a radial force F_r,

$$F_r = \frac{e^2}{2m} B_z^2 r \tag{3.4}$$

This force is always positive irrespective of the direction of B_z i.e. towards the axis of symmetry and is proportional to r which are the essential conditions for focusing a beam. All electrons emerging from a point A which is on one side of the lens will meet at a point B on the other side of the lens as shown in the Fig. 3.5. This figure shows the magnetic field lines of a short air core coil. The dashed line shows the trajectory of an electron ejected from a point source. The distances a and b are the object and the image distances respectively measured from the centre of the lens. It should be noted that the fringing field B_r has a

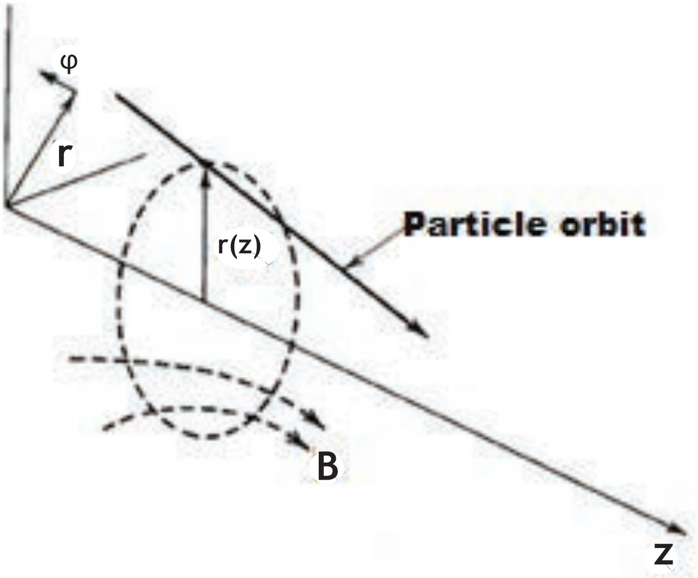

Figure 3.4: Coordinate system used for explaining the principle of magnetic focusing of electrons [Ref: Stanley Humphries].

decisive role in initiating the lens action. The focal length arrived from the paraxial equation [2, 12] is

$$\frac{1}{f} = \frac{e}{8mV_r} \int_{-\infty}^{\infty} B_z^2 dz \tag{3.5}$$

Since the magnetic field is proportional to the coil current, the focal distance can be varied by changing the coil current. The image obtained by an electromagnetic lens will be a rotated image rather than an upright one. A three dimensional electron trajectory in an axisymmetric magnetic field is given in Fig. 3.5 for a better understanding.

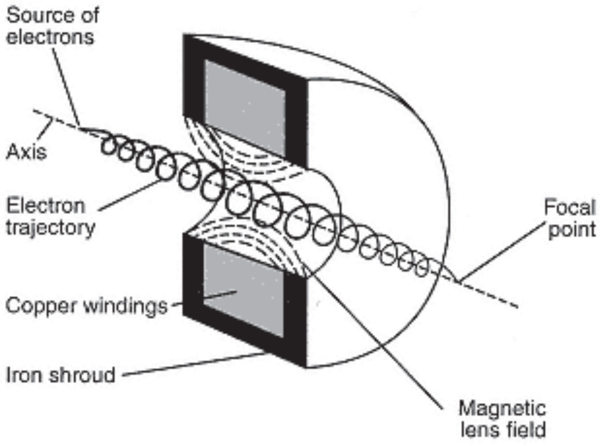

Figure 3.5: A three dimensional view of a magnetic lens.

3.3.1 Design

In low power electron beam melting gun single focusing configuration is used but in the case of high power electron beam melting gun double focusing configuration is used to neutralize the space present in the electron beam (Fig. 3.6). For simplicity, geometry of electromagnetic lenses are identical as the functionality of both the electromagnetic lenses is common. The lenses are of short solenoid type shrouded by a magnetic material.
The focal length can be calculated by Eq. (3.6),

$$\text{Focal Length (f)} = \frac{1}{(\frac{1}{u} + \frac{1}{v})} \tag{3.6}$$

where u and v are object and image distance in mm respectively.

Table 3.1: UFL and LFL lens excitation calculations.

Lens	**Design criteria**	**Focal Length (mm)**	**Lens excitation (AT)**	**Coil Current (A)**
UFL (Lens centre is 120 mm from the cathode)	Focus the electron beam from the gun to the flow resistor inlet located at 160 mm away from UFL centre.	70	1900	1.5
LFL (Lens centre is 422 mm from the cathode)	Produce a parallel electron beam on the melt target located at 1000 mm from the LFL centre.	231	990	0.7

It can be seen from Table 3.1, the target distance is 1000 mm. To transport the focused beam to such a large distance is not possible due to space charge repulsion effect. This effect gets nullified by the plasma formation due to the collision of electron with the gas molecules in the environment during melting. This effect is observed experimentally also. There is no software till date to model such a situation. Hence, in simulation it is assumed that after LFL lens space charge is completely neutralized and parallel electron beam can be transported to the target for melting.
Calculation of NI can be done using Eq. (3.7),

$$NI = \frac{30 \times 1000 \times V_r \times (S + D)}{f} \tag{3.7}$$

Where N = No. of turns
V_r = Relativistic Acceleration Voltage
D = Bore Diameter
f = focal length of lens
S = Pole Distance.

3.4 Electron Optics Design of Secondary Gun

The objective of the secondary gun design is to deliver the required heating power to the block cathode to raise it to 2800 K. The electron beam is generated by using the wire filament as source. The filament is placed 2 mm behind the block cathode. This small distance ensures most of the electrons emitted from the filament are accelerated towards the block cathode

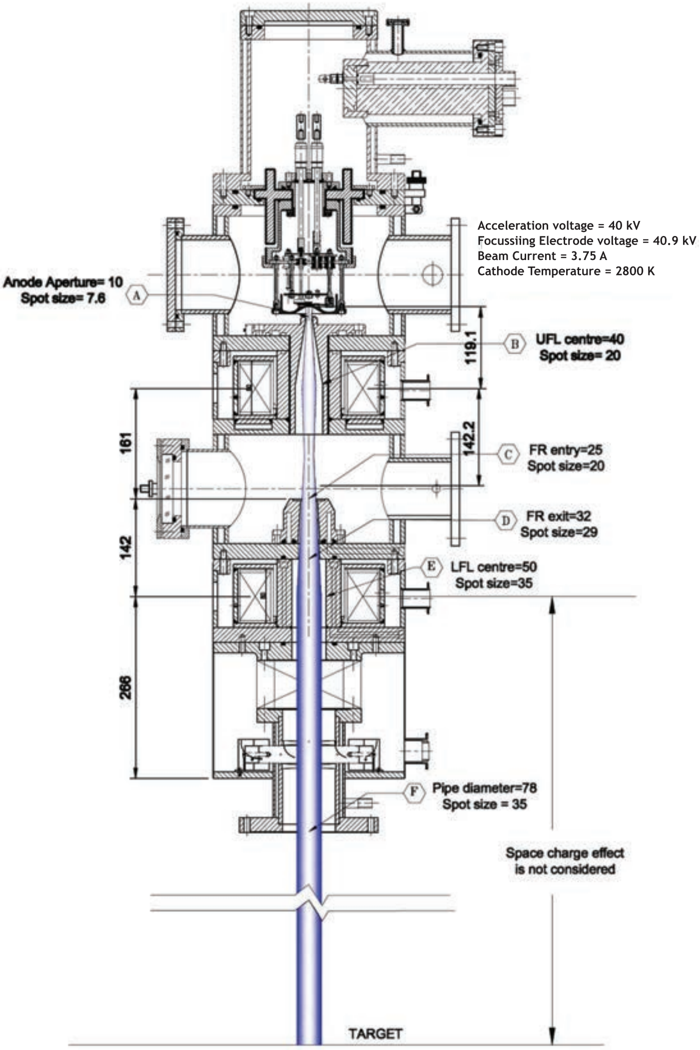

Figure 3.6: 40 kV, 150 kW gun column with the beam envelope (all dimensions are in mm).

without the use of an additional focusing electrode. An acceleration voltage of 900 V is applied between the filament and block cathode. The same voltage is applied for the primary gun. The electrical circuit of the primary and the secondary electron guns are shown in Fig. 3.7. It was experimentally found that the power required for solid cathode heating is 530 W. The block cathode voltage and current required to achieve this power at 900 V is 550 mA. The maximum current extracted from this secondary gun is 1.1 A (as shown in Fig. 3.8). Hence maximum power extracted from this secondary gun is 1 kW.

Electrostatic analysis of the secondary electron gun was done for ensuring electric field at all the critical points should be under the permissible limits. The Fig. 3.9(a) shows that electric field is maximum at grid (24 kV/cm). Figure 3.9(b) shows equipotential lines on the secondary electron gun components. The electric field at filament and solid cathode is less than 20 kV/cm. Hence electric field in this assembly is under the permissible limits.

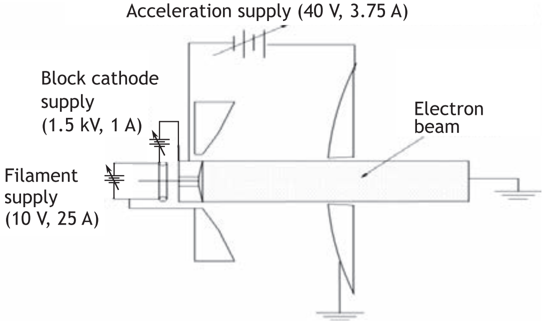

Figure 3.7: Electrical circuit of the primary and the secondary guns.

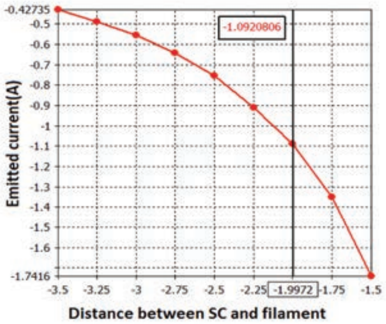

Figure 3.8: Space charge limited current for various SC and filament distance.

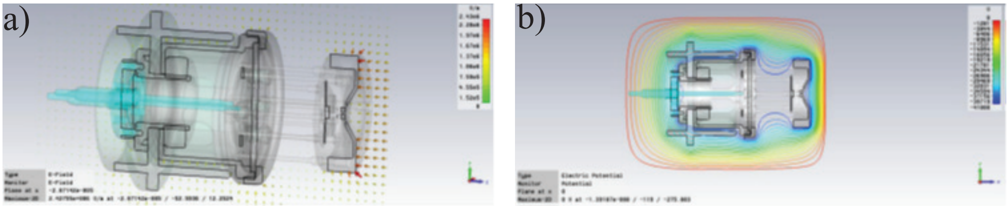

Figure 3.9: (a) Electric field in the secondary electron gun with its holding arrangement, and (b) Equipotential in the secondary electron gun with its holding arrangement.

3.5 Deflection and Oscillation Lens

3.5.1 Magnetic Field Requirements

Beam deflection is used to maneuver the beam on the 260 mm diameter target. This target is at 700 mm from deflection lens. Considering beam diameter of 40 mm. Hence deflection required on one side is 110 mm. Beam oscillation is required (30 mm) super imposed on the beam deflection for obtaining a homogeneous melt pool. A uniform time invariant magnetic field perpendicular to the beam direction is used for beam deflection. Time varying phase phase shifted magnetic field of 300 Hz frequency perpendicular to the beam flow is used for X & Y beam oscillation.

The electromagnetic lens are of two types viz air core or iron core lens. For the same deflection of 110 mm at 700 mm beam throw distance the air core deflection lens requires 1.87 A while Iron core deflection lens requires 220 mA. Hence, iron core lens is preferred for large deflections.

The deflected spot size for air core deflection lens {Fig. 3.10(a)} is distorted while that of iron core deflection lens is relatively undistorted {Fig. 3.10(b)}. Hence iron core lens is preferred for large deflections to preserve the beam shape after deflection.

Design of coil is done in the similar manner as of UFL and LFL lens and the electrical parameters and output of coil design is shown in Table 3.1. A low frequency beam oscillation on the melt pool produces stirring action forming a homogeneous ingot. The maximum oscillation required is 15 mm with frequency of 300 Hz to 1 kHz. Oscillation lens is designed with the same procedure as the deflection lens. The oscillation coil is of 300 turns wound above the deflection coil. The Fig. 3.11(a) and (b) describes the deflection vs deflection current and oscillation vs oscillation current respectively.

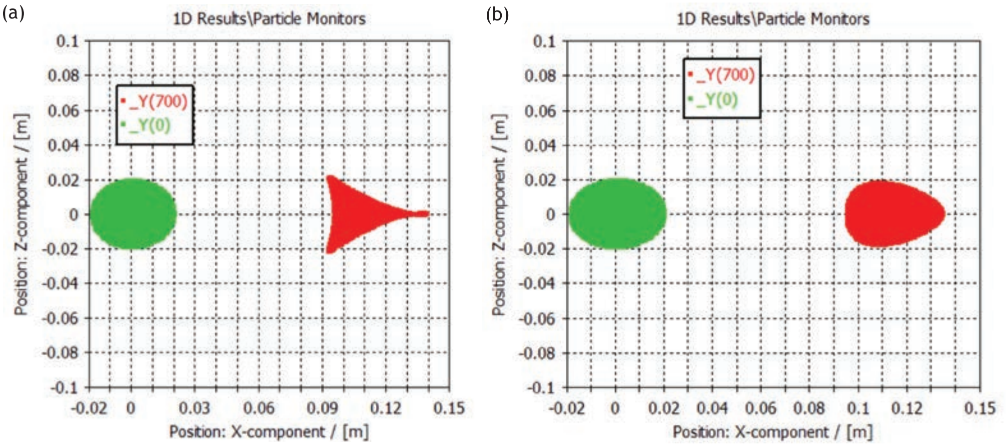

Figure 3.10: (a) Source (S) and deflected beams (D) by air core deflection lens, and (b) Source (S) and deflected (D) beams by iron core deflection lens.

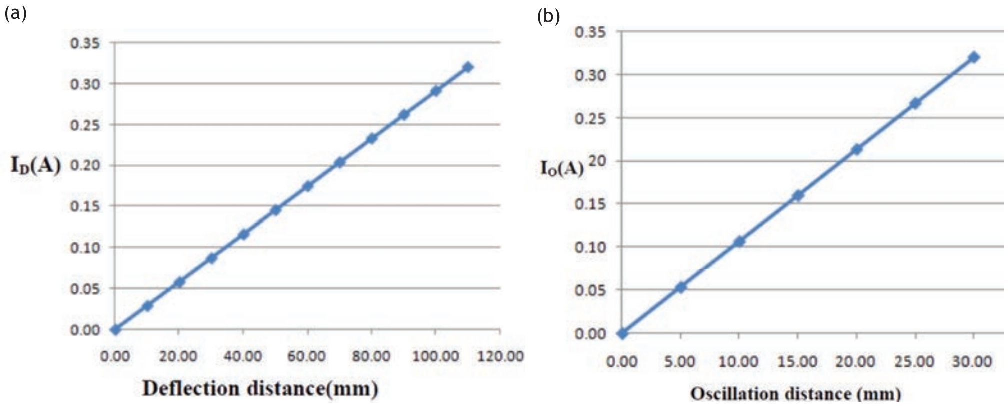

Figure 3.11: (a) Deflection vs deflection current, and (b) Oscillation vs oscillation current.

3.6 Conclusion

In this chapter, a basic of electron beam gun column and its importance is explained in detail. Step by step design of all the electron beam gun components was described from the electron optics point of view with critical parameters taken into account. On the basis of this design, electron gun column was fabricated. The fabricated components QA is also of prime importance and should be done with utmost care. This gun was fabricated along with other subsystems under EBMF melting furnace project for NFC, Hyderabad. 10 nos. of melting operations were carried out using two guns (150 kW each) simultaneously in the various sizes of crucibles starting from 60 mm to 280 mm diameters to establish the performance of EBMF. Melting trials were carried out with Zr4 and Zr-Nb alloy material. Both the guns have been tested for 150 kW each to its rated capacity. Process operations were smooth with no abnormality whatsoever. All the commissioning activities were successfully conducted by NFC, BARC and suppliers jointly. This project was inaugurated by **honourable President** of India under the **Make in India** initiative.

Questions

1) What is the average power density required on target for EB melting process?
2) Why intermediate beam aperture is used?
3) What is the use of secondary electron gun?
4) What is the use of deflection lens?

Answers

1) The average electron beam power density for melting application lies within the range 10^3 W/cm^2 to 10^5 W/cm^2.
2) Intermediate beam aperture is used for vacuum decoupling between the gun region and the melt zone.
3) The secondary gun design is used to deliver the required heating power to the block cathode to raise it to 2800 K.
4) Beam deflection lens is used to maneuver the beam on the target.