Chapter 2

Electron Guns for Electron Beam Machines

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Electron Gun is a device which generates, accelerates and directs a stream of electrons (called as electron beam) in an empty space (vacuum). The very first question strikes a curious mind is "What is the use of an electron gun, after all? The answer can be very lengthy. But to satisfy his or her inquisitiveness, the shortest answer would be "it is used to generate **intense source of energy**". Following are some of classical applications of electron beams.

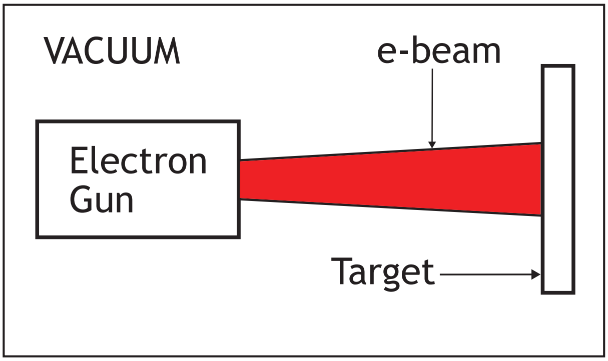

Figure 2.1: Electron Gun – A first Look.

It is up to one's ingenuity to use it for any of them or invent something new to suit his or her specific requirement.

Material Processing - Welding, Melting, Evaporation, Lithography etc
Irradiation – Sterilization or Initiation of chemical reactions
Electromagnetic wave generation - X-ray or Microwave
Imaging – Scanning or Transmission electron microscopes

The first three applications are based on the particle nature of electrons and the last one with its wave nature. Electrons are ubiquitous in nature (it is a part of all four states of matter), have tiny mass (so it travels freely in empty space) and an electric charge (two electrons always repel when brought nearby). No one has seen an electron till today. But the ways and means of their generation and control have been mastered over hundreds of years. The applications of electron beams are ever growing since its discovery in 1897. In this short treatise, the nuances of electron guns in EB machines used for thermal applications are brushed upon. The reader will get a fair idea of the physical principles involved with the electron guns and also get some design tips and tricks. The components of a typical electron gun (Fig. 2.1) and its functions are explained in the next section.

2.1 Functionalities of Electron Gun Components

The major functions of an electron gun are generation and acceleration of electrons. The basic physics behind acceleration and generation are explained in this section.

2.1.1 Electron Acceleration

An electron is pushed forward when subjected to a time independent electric field in vacuum. An electron can also be accelerated under time varying field which is beyond the scope of our current interest. An interested reader can refer to the literature on RF electron accelerators. The force on an electron ($\overrightarrow{F}$) is the product of the electric field ($\overrightarrow{E}$) and its charge (e).

It should be noted that the electron, owing to its negative charge, travels in the opposite direction of the electric field. A uniform electric field can be produced in the gap between two parallel plates separated by a distance x, having a potential difference (V). The plate with negative charge is called cathode and the one with positive charge is called anode. Due to the electric field ($|\overrightarrow{E}| = V/x$) between the electrodes, an electron appearing with negligible initial velocity near the cathode surface is accelerated towards the anode (Fig. 2.2a). This electron hits the anode with a velocity ($\overrightarrow{v}$) determined by the energy balance Eq. (2.1).

$$\begin{gathered}\frac{1}{2}mv^2 = Ve \\ (Kinetic\ Energy) \quad (Potential\ Energy)\end{gathered} \tag{2.1}$$

Where m, e are mass (kg) and charge (C) of an electron respectively;
v is the velocity of the electron (m/s);
V is the accelerating potential difference (Volts).

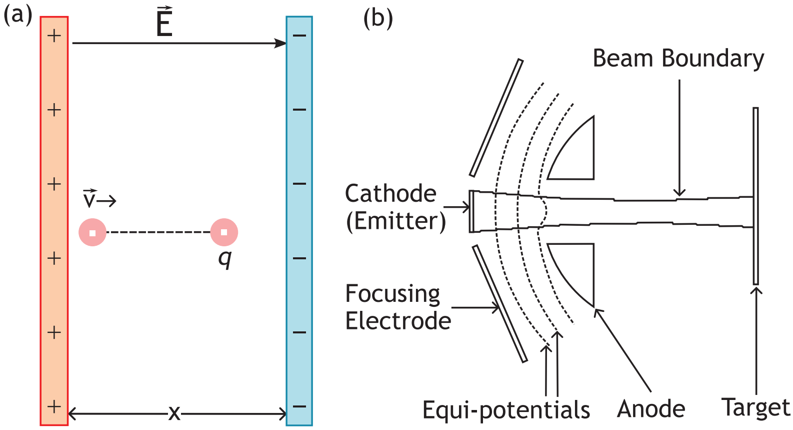

Figure 2.2: (a) A charged particle in an Electrostatic field produced by a parallel plate geometry, and (b) Electron beam formation in an electron gun.

Relativistic correction of mass starts becoming significant for $V \geq 30$ kV, for accurate calculations and is given by,

$$m = \frac{m_0}{\sqrt{(1 - \frac{v^2}{c^2})}} \tag{2.2}$$

Where m and m_0 are relativistic and rest mass of the electron in kg and c is the velocity of light in vacuum in m/s. An interesting treatment on relativistic issues can be referred from [1]. When a fairly large number of electrons ($\sim 10^{18}$ for example) are accelerated, the resultant swarm is called as an electron beam. For extracting the energetic electron beam out of the electron gun, the anode is provided with a properly shaped aperture. This ensures maximum transmission (in other words, minimum electrons hitting the anode). The size of the anode aperture, mutual repulsion of the electrons and small random initial velocities at the source determine the shape of the beam emerging from the anode aperture. The electrodes are suitably shaped to produce a convergent beam which is a general requirement for all EB guns. The modified electrode shapes are shown in the Fig. 2.2(b).

The technique for contouring the electrodes is fairly complex. Conventionally this problem is solved using the analogy of electron motion in electric (and magnetic) fields with the light rays in a refracting media. This analogy is fully explored in the subject called electron optics.

The desired electrode shapes are arrived by using the principle of ray tracing (a classical method in light optics) either by analytical or numerical methods. The exquisite properties of electrons like relativistic effects, mutual coulomb repulsion, self-generated magnetic fields and random velocities at the emission point are included for more accurate calculations. The aberrations in the light optics are equally valid for electron optics as well [2, 3]. The beam energy, beam current, beam shape and size are decided by the application at hand. The following discussion is devoted to the generation of electrons (electron source).

2.1.2 Electron Generation

An electron source is capable of supplying copious amount of free electrons continuously with time. This component is also called as "cathode" (means electrode having excess electrons). Emission of electrons from incandescent bodies (Thermionic emission) is the most preferred method of electron generation for many applications. Emission from a sharp metal whisker with the application of electric field (field emission) or bombarding with another electron beam (secondary emission) or a combination of any two are less common. The reason behind thermionic emission is a stable source of high electron current continuously for a longer time. In this method, electrons are emitted from a material heated to incandescence in vacuum. Tantalum and tungsten are widely used as emitters in such electron guns. Platinum, Molybdenum, Thorium, Thoriated tungsten, Tungsten-Rhenium and Lanthanum hexaboride are also reported as emitters [4]. Conventionally, a high electric current is passed through the emitting material to raise its temperature due to ohmic losses. Other methods like bombarding the emitter with low velocity electrons or laser beams have also been reported. In this method the emission current density is an increasing function of the absolute emitter temperature of emitter. This is given by Richardson's equation

$$J = AT^2 e^{-\frac{11600\phi}{T}} \tag{2.3}$$

where, J - Current density emitted from the emitter surface,
A - Constant (120.4 A/cm^2-K^2),
T - Absolute temperature of the emitter (K),
ϕ - Work function of the emitter (4.52 eV for tungsten and 4.1 eV for tantalum).

The graphical representation of Eq. (2.3) is shown in Fig. 2.3 for various emitters. Tungsten and Tantalum are the widely used emitters in EBW machines as mentioned earlier. The following table 2.1 can be treated as a guideline in selecting the emitter material. A wide variety of emitter shapes are used in electron guns, such as simple hairpin type, helical, spiral or strip type. The choice of emitter shape is constrained by the beam shape at the target (eg a rectangular emitter is chosen for a strip beam). The power required for raising the temperature of a given emitter to a specified value can be calculated from,

$$\underset{(I^2R)}{Power\ required} = \underset{(\sigma AkT^4)}{Power\ radiated} + Conduction\ losses + \underset{(Case\ specific)}{Lead\ losses} \tag{2.4}$$

where, I - Heating current,
R - Resistance of filament at temperature T,
σ - Stefan–Boltzmann's constant,
A - Area of radiating surface,
k - Radiation efficiency at temperature T, and
T - Absolute temperature of the cathode (k for some common emitters is given in the Fig. 2.3).

The practical constraints are

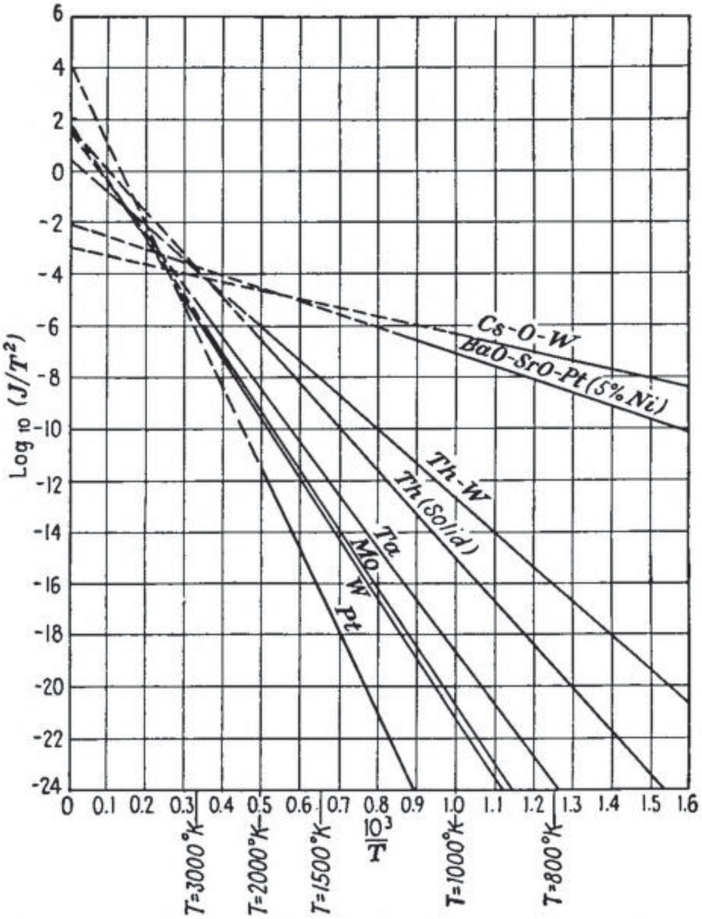

Figure 2.3: Emission characteristics of some common emitters [4] (Pt - Platinum, W - Tungsten, Mo - Molybdenum, Ta - Tantalum, Th - Thorium, Th-W - Thoriated Tungsten).

a. Shape stability at high (more than 2000 °C) temperatures
b. Ratio of Extraction to radiation area (emitter efficiency)
c. Low lead losses
d. Emitter life and
e. Dimensional tolerances

A good filament design should have high shape stability, emitter efficiency and life. The lead losses and the emitter dimensional tolerances should be kept low. We shall now look at the various electron gun configurations (ways of electrode connections) and their characteristics. The electron guns are modified versions of vacuum tube devices. The gun characteristics are similar to that of vacuum devices. This is explained in the following section.

2.1.3 Electron Gun Configurations and I-V Characteristics

This section deals with the basics of most commonly used gun configurations (electrode arrangements) and their electrical characteristics. The electron gun configuration varies

Table 2.1: Properties of some pure metallic electron emitters.

S. No.	Property	Tantalum	Tungsten	Remarks
1	Nominal Current density (A/cm^2)	2	5	Tungsten is the obvious choice for high currents for a given emitter area
2	Operating temperature (K)	2500	2700	The life of the emitter is limited by the temperature
3	Property after heating	Remains soft	Becomes brittle	Tungsten filaments can't be practically reused
4	Resistance to positive ion bombardment	Poor	Extremely good	Tungsten is ideal for working under residual gases.
5	Workability	Good	Poor	Manufacturing of filament is easy with tantalum

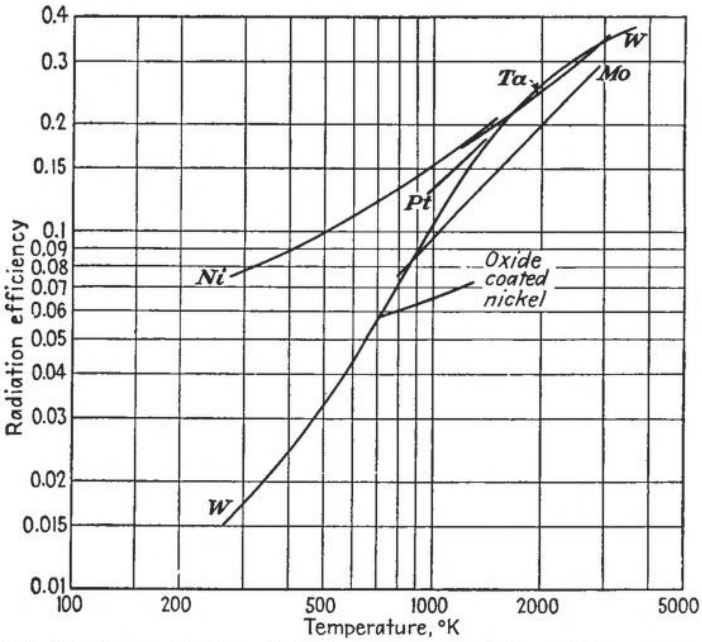

Figure 2.4: Radiation efficiency as a function of Temperature [4].

widely depending on the end applications. The configurations used in most EBW machines are explained in this section. The electron gun shown in Fig. 2.2(b) has two electrodes, viz. a cathode and an anode. This is the most fundamental configuration and is called as DIODE. A simple electrical circuit diagram of a diode electron gun is given in Fig. 2.5. The power sources are replaced with batteries in the figure. The vacuum vessel of the EB machine (not shown in the figure), the target and the anode of the electron gun are connected to earth for safety reasons.

I_f - Filament current,
I_b - Beam current,
I_a - Anode current, and
I_t - Target current and

$$I_b = I_t + I_a \tag{2.5}$$

If the acceleration voltage is varied with the filament heating current as a parameter, the beam current varies as shown in Fig. 2.6. This graph is known as the I-V characteristics of the diode gun. This graph gives a better understanding of the physical processes happening in the gun and is explained below.

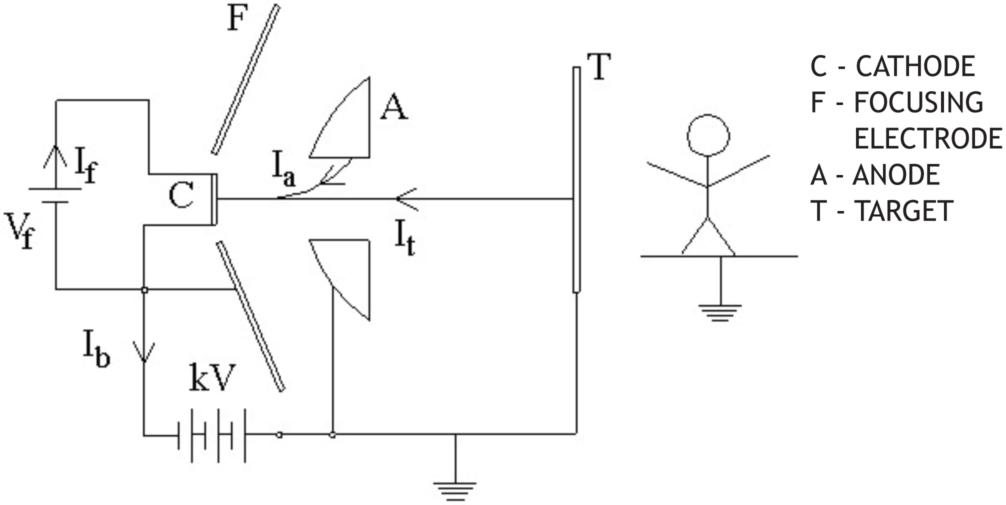

Figure 2.5: Electrical circuit diagram of a diode gun.

Where V - Accelerating Voltage
I - Beam Current
I_{f1} and I_{f2} - Filament currents.

This graph has three zones.
ZONE-I: In this zone the beam current can be varied by varying the accelerating voltage (i.e. not all electrons emitted from the emitter are extracted). This region is called "space charge limited" zone. This means a space charge cloud is formed in front of the emitter. The beam current density (J) is proportional to $V^{3/2}$ (Child's Law) and is independent of emitter temperature. The term perveance (analogous to the term admittance) is defined as the ratio $I_s/V^{3/2}$, where I_s is the saturation beam current. The perveance is a geometrical factor of the gun. For a simple parallel plate configuration with a plate separation 'd' {Fig. 2.2(a)}, the perveance G [5] is

$$G = \frac{3.3 \times 10^{-6}}{d^2} \tag{2.6}$$

The perveance of other gun configurations are more complicated to be calculated analytically. The perveance of welding guns usually lie within 0.01 μP. Zone-I is recommended for EBW

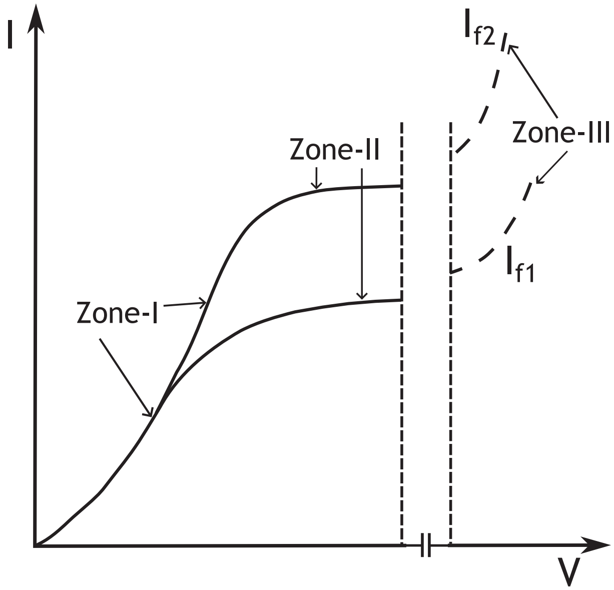

Figure 2.6: V-I Characteristics of a diode gun (ref. [5]).

guns, the reason being small variation in the filament temperature does not affect the beam current.

ZONE-II: In this zone the beam current is almost constant for any change in acceleration voltage, i.e. all electrons emitted from cathode are extracted. This indicates that, for a given filament current, an increase in acceleration voltage does not increase the beam current. This is called "temperature limited" zone. This zone follows Richardson's Equation [Eq. (2.3)].

ZONE-III: This zone is called the "field emission" zone, wherein the operating regime shifts from thermionic emission to field emission. Here, the beam current rises rapidly with the voltage. (The beam current is a function of Electric field at cathode given by Fowler-Nordheim equation). This zone is not used in EBW guns (thermionic cathode guns) as this adversely affects the beam stability and filament life. In the above discussion, it was mentioned that the beam current is a function of emitter heating current (and hence the emitter temperature) as well as acceleration voltage depending on the operating zone. In electron beams for welding applications, variation of acceleration voltage during the process is not recommended as it adversely affects the beam shape at target. The variation of filament current, on the other hand, is sluggish due to the thermal inertia. Therefore, it is convenient to operate the gun in space charge limited region and control the beam current by introducing a third electrode called "gate" (also called as control grid or Wehnelt or bias) , between the anode and the cathode. The potential of the gate electrode is kept negative with respect to cathode. This gate can be thought as analogous to a 'gate valve' used to control the water flow in a dam. By adjusting the control grid potential which is lesser than the acceleration potential, the beam current can be varied precisely and quickly from zero to the nominal value. The electrical circuit diagram of this three electrode gun (called as TRIODE) is given in Fig. 2.7. The triode electron gun has two characteristics:

A. Grid characteristics, and

B. Anode characteristics

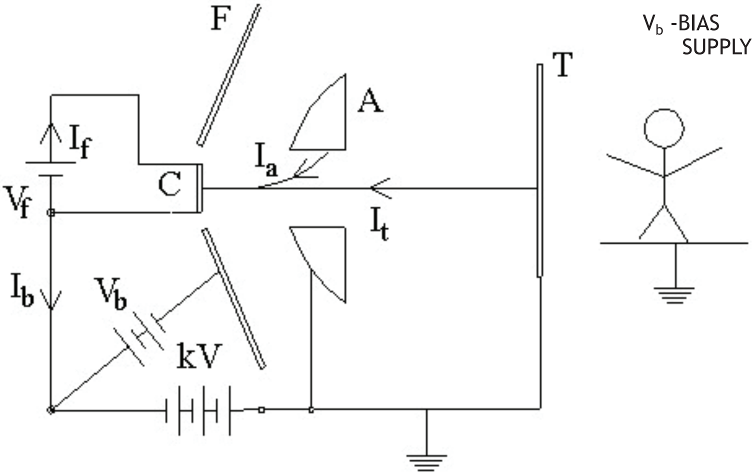

Figure 2.7: Electrical circuit diagram of a triode gun.

A. Grid characteristics

This is the relation between the beam current (I_b) and the Grid (or bias) Voltage (V_b) for constant acceleration voltage (kV). The graph is given in Fig. 2.8(a). It can be seen from the figure that the beam current reduces with increasing negative Grid voltage. The beam current reaches zero at a minimum grid voltage (called as cut-off voltage) for a given acceleration voltage. The family of curves shows increasing accelerating voltage (V_a) from left to right. The analytical equation of the family of curves is given by

$$I_b = G\left(V_g + \frac{V_a}{\mu}\right)^{\frac{3}{2}} \tag{2.7}$$

Where, I_b – beam current,
G – Perveance given in Eq. (2.6),
V_g - Grid Voltage,
V_a - Acceleration Voltage, and
μ - Amplification Factor.

B. Anode characteristics

This is the relation between the beam current (I_b) and the Acceleration Voltage (kV) for constant Grid voltage (V_g). The graph is shown in Fig. 2.8(b). The Filament voltage is kept constant.The electron paths for various grid voltages from no bias to cut-off bias are shown in Fig. 2.8(c). The exact calculation of grid cut-off voltage for a given electrode shape is explained later in this chapter. The electron beam formed by the electron gun is transported to the target with the help of electromagnetic lenses. In olden days electrostatic lenses were used in the place of electromagnetic lenses. The electrostatic lenses suffer from the very fact that they need high voltages for their operation. Hence electromagnetic lenses are more preferred than electrostatic lenses for focusing the electron beam.

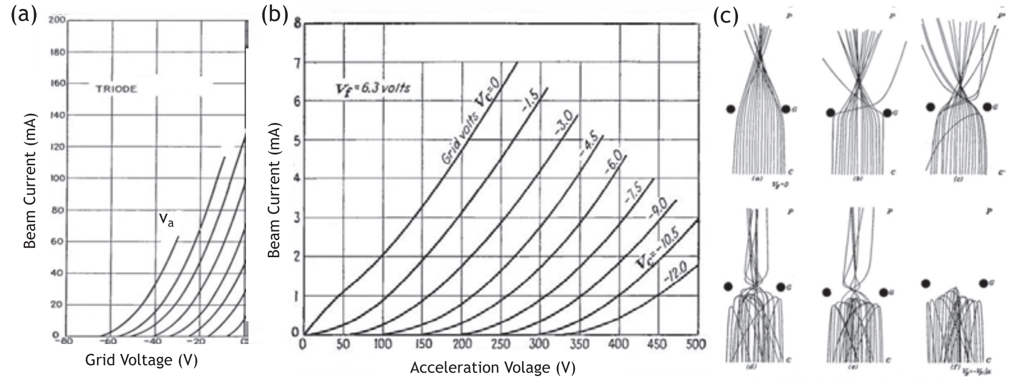

Figure 2.8: (a) Grid Characteristics of the triode, (b) Anode Characteristics of the triode (Note: The numbers are notional), and (c) Electron paths as a function of bias {Zero bias (a) through cut-off bias (f). The trajectories are obtained from an elastic membrane model (C - cathode, G - grid, P - anode)} [4].

2.2 Electron Gun Design

Electron gun design is carried out using analytical methods and simulations. E-gun software and CST particle studio.

2.2.1 A Primer to Gun Designers

The electron gun design by analysis is generally started with known electrode geometry. Hence the designer is expected to be aware of as many electrode geometries as possible and their characteristics. This section deals with some electron gun geometries available in literature.

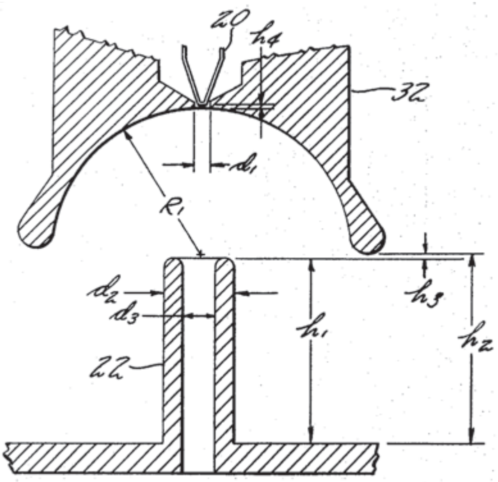

Figure 2.9: A 150 kV, 6 kW EB Welding gun with Rogowski electrode profile (Ref: Google patent US3835327A [6]).

The above gun geometry is just for an example and there exist many more. An expert gun designer is expected to study all the above gun models thoroughly in his leisure time, with the help of a suitable electron trajectory solver and invent his own geometry to suit his specific requirements.

2.2.2 Electron Gun Design Approach

An electron gun design means design of electrostatic (or electromagnetic) fields in space which will accelerate and shape the electrons emitted from a cathode into a beam of desired characteristics (Beam spot size, emittance, perveance etc.). Design of electrostatic fields in turn means the design of electrodes (in other words electrostatic boundaries). The electrostatic design should also take into account the beam effects like relativistic, space charge, thermal velocity distribution and self-generated magnetic fields. **A good electrostatic field alone is necessary but not the sufficient condition for practically realizing an electron gun.** There are essential engineering constraints like the High voltage, high temperature and high vacuum which are to be satisfied. This makes the gun design more challenging and motivating. An electron gun design starts with known accelerating voltage and beam current. One or more additional parameters like beam aperture angle, beam emittance, beam minima location and spot size at beam minima are specified, depending on the application. The design can be approached in two ways.

A. Gun Design by Analysis

This approach is a classical one. The design problem is stated as follows. “Given is the shape of the electrodes, compute and determine the beam parameters”. This approach starts with known electrode geometry. The electrode shapes are either perturbed or scaled to get the desired beam properties. This is a tedious process and depends greatly on the experience of the designer. Sometimes it is impossible to obtain a beam of desired properties. In that case the beam parameters are modified slightly to match the output of best possible solution obtained.

B. Gun Design by Synthesis

The problem is stated as follows. "Given the beam shape (envelope) along its direction of travel, determine the electrode shapes and distances”. This is a straight forward approach and requires little designer’s experience. However, there is a very little contribution in this area and hence hardly any literature or knowledgebase. A classic example for this approach is Pierce gun for producing parallel or convergent axi-symmetric / planar electron beams [7]. The electron guns designed by either of the approach may fail to work in the actual system due to many reasons. It is important to note that, unless these causes are carefully taken in to consideration, the man-hours spent in the gun design would be wasted.

2.2.3 Design Constraints

Electron gun design is done by optimizing various parameters like gun perveance, anode loss, beam aperture and laminarity, electric field stress and vacuum constraints. These points are mentioned below,

A. Gun Perveance

This term is a measure of maximum beam current that can be extracted from the gun at a given acceleration voltage. Usually a margin of +50% is kept for all simulations while designing the electron gun. A common mistake made in the gun simulations is neglecting the edge emission. The edge emission could be as significant as 50% of the total beam current in high power guns. It is hence important to consider the edge emissions.

B. Anode loss

This is defined as the fraction of the electrons hitting the anode. It is important to design the gun with minimum anode loss. This anode loss will raise the anode temperature and cause further complications like anode degassing, damage of ‘O’ rings, contamination of gun electrodes high voltage discharges and ultimately anode melting. The design thumb rule is to keep anode losses less than 0.5% of the total beam power. It is valid at all operating beam powers. However at special cases where the anode losses could not be reduced, the anode should be provided with sufficient water cooling. It is important to note that the emitter deformations (due to thermal expansion of the leads or thermal cycling or ion bombardment) increase the anode loss. A provision of anode collection measurement interlocked with power source will save the gun from permanent damage.

C. Beam aperture angle at gun exit

This is defined as the angle measured between the gun axis and the edge of the beam envelope. This value is normally taken as a design parameter in the EB welding guns. This value must be measured at beam cross -section plane where the beam enters the field free zone (drift region).

D. Beam laminarity (Emittance)

This parameter is derived from the phase plot of beam at a given beam cross section. A linear phase plot implies that the beam is laminar. This parameter is conserved in any aberration free beam transformation. A laminar beam can be safely transferred over a long distance.

E. Maximum Electric Field

The maximum electric field is an important parameter for a reliable gun operation. Keeping the electric field within limits reduces the gun discharges even under moderate electrode contamination conditions. However electrical discharges are unavoidable under heavy contaminations. The safe electric field limit on negative electrodes with temperatures more than about 300 ℃ is 60 kV/cm and near cold electrodes is 100 kV/cm. The electric field limit near positive electrodes should be limited to 150 kV/cm [8]. The reason for a higher field at positive electrode is that field emission does not occur at these electrodes.

F. External magnetic / Electric fields

The external magnetic fields include magnetic fields produced by filament heating currents and residual magnetism in gun components. The gun should be effectively shielded against these stray fields. The Grid electrode manufactured with a magnetic material (e.g. Mild Steel) offers an effective solution provided the operating temperature is below its curie temperature (i.e. 770 ℃).

G. Electrode Tolerances

The electrode machining and alignment tolerances is a unique feature in electron guns. Tolerances of less than a micron are common in electron microscopes. Analytical (and numerical) techniques are established for evaluating the beam under various tolerances and misalignments in axi-symmetric guns [3]. However no known techniques are established for non-axisymmetric guns.

H. Vacuum constraints

The anode aperture size is major parameter in maintaining the vacuum decoupling between the work chamber and gun chamber. Optimum cathode diameter and beam convergence angle (beam minima occurring near anode aperture) ideally provides small anode aperture and hence good vacuum decoupling. Additional apertures at suitable places add more efficient decoupling. However sufficient care should be taken as not to increase the aperture losses while operating the gun at various power and voltage levels.

I. High temperature constraints

The thermionic emitter is an intense heat source in an electron gun. The heat radiation and conduction are to be properly addressed. Otherwise the heat losses will lead to

1. Melting of leads and filament holders
2. Damage of ‘O’ rings
3. Mechanical distortion of electrodes
4. Degassing of electrodes which receive heat radiation
5. Expansion of leads leading to dislodging the emitter position.

All the above points are taken in to account with extra care to engineer an electron gun. The next section describes the numerical calculation of Grid cut-off voltage in axi-symmetric electron guns.

2.2.4 Calculation of Grid Cut-Off Voltage

Triode electron guns are conventionally being used in electron beam welding guns due to ease of beam control. The operating principle explained earlier is elaborated here. The triode guns essentially consist of three electrodes. The cathode (emitter), anode and a control electrode (also called as Grid or Wehnelt electrode or bias or shield). The Wehnelt electrode is connected to a variable voltage source which is more negative with respect to cathode. When the Wehnelt voltage is equal to that of cathode, the electron gun behaves like a diode gun. Hence the Wehnelt voltage serves like a gate to control the beam current. Let us call Wehnelt as bias henceforth. It is important to know the bias characteristics of any electron gun {Fig. 2.10(a)} for the reasons given below. The electron gun in an EB system produces a focused high velocity electron stream. The parameters like filament current, acceleration voltage or beam current are varied individually or together. The most precisely controllable parameter among the three is the beam current and hence preferred by the designer. It is also true that the beam quality can be maintained for a wide range of beam current than with other two parameters. It has to be borne in mind that the triode electron gun operates in the space charge region **(Zone-I)** for effective beam control. The conventional operating procedure of a triode gun is quite different from that of a diode gun. The operator’s desk contains the set points for acceleration voltage and the beam current. The bias voltage setting is achieved through an automatic feedback control. The beam current is measured at the return path through a non-inductive resistor and fed back to the bias controller. Hence, the operator sets the beam current at his desk. This in turn adjusts the bias potential till the set value of the beam current is achieved. This process stabilizes in few microseconds. Thus a quick and precise control of beam current is achieved. The basics of the grid cut off voltage for triode gun is explained with electrostatic analysis of Pierce electron gun [5]. In this example, the cathode is considered to be at zero potential. The anode is considered to be at +V. The Grid is varied from 0 V and the cut-off voltage. It can be seen that as grid voltage moves towards cut off, two phenomena occurs.

1. The effective cathode emission moves towards center of cathode. That means the electric field in front of cathode periphery changes its sign. In other words, electrons are repelled back from the cathode periphery.
2. The beam aperture angle at the anode exit varies with the grid voltage.

The key factors at the grid cut-off are

1. The electric field direction in front of the cathode surface is negative as compared to zero grid bias (diode configuration)
2. The electric field just in front of the cathode centre is zero.
3. The net charge of the cathode is zero. (i.e. the cathode is electro-statically shielded by the grid electrode)

The Grid cut-off voltage calculation is carried out in the following steps.

1. The electron gun profile is modeled with FEMM as an axi-symmetric electrostatic problem.
2. A code is written with Lua script (a programming language compatible with FEMM) for sweeping the grid voltage from -V_{acc} to $-V_{acc} - \Delta V$ (ΔV is an initial guess of grid voltage which is beyond cut-off) and solving the problem for every ΔV. The electrostatic field at the center of cathode is recorded at every step.
3. The Grid bias voltage at which the electric field is null at the cathode is computed using linear interpolation. This value is the Grid cut-off for the electrode configuration.The Electric field at the cathode Vs. Bias Voltage is shown in the following Fig. 2.10(a).

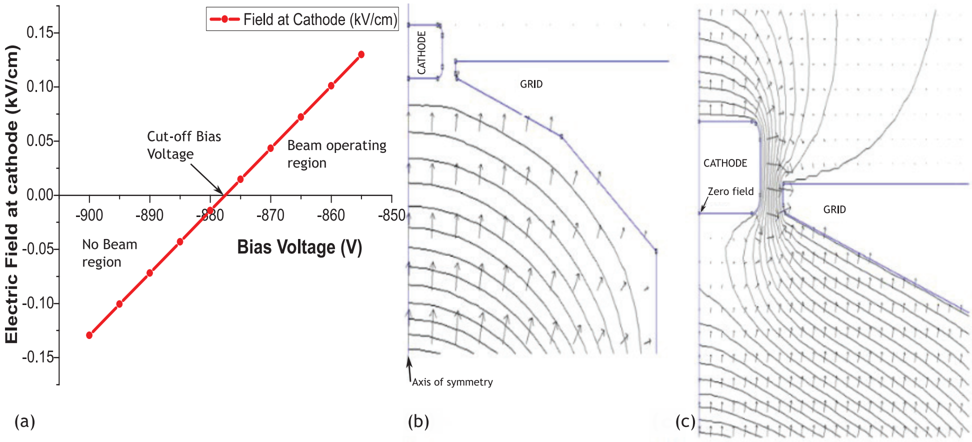

Figure 2.10: (a) Bias Voltage Vs Electric field at cathode centre, (b) equipotential lines at zero bias voltage, and (c) equipotential lines near bias cut-off voltage.

It can be seen that the electric field at the center of cathode varies from negative to positive. Negative field implies that the electrons are repelled back to cathode and positive field represents electrons are extracted from cathode. A zero electric field represents that the electrons just produce a cloud in front of cathode stopping further emission. This represents grid cut-off voltage. The equipotential plots near the cathode at zero bias and at bias close to grid cut-off is shown in Fig. 2.10(b) and Fig. 2.10(c) respectively. The electric field (arrow plot) is superimposed on the equipotential plot. The anode is not shown in the figure for better clarity.

2.3 Engineering an Electron Gun – A Short Guide

Needless to say, this is totally left to the creativity of the engineer how he applies the fundamental principles of the electron gun explained in this chapter. The gun designer is encouraged to have multiple rounds of brainstorming sessions with the user until he gets a clear understanding of the end application. This is followed by the hand calculations (an Excel sheet will be great) to choose the parameters of the gun. The exact numerical design is done with the help of a commercial or self-written charged particle tracking code. The engineering design begins after finalizing the geometry. The designer would kick his imagination, creativity, technical knowledge and experience to come up with multiple design concepts. A detailed engineering drawing is made after choosing the most suitable one considering the functional requirement, ease of fabrication, availability of standard components and cost. This detailed drawing along with a clear quality assurance procedure is mandatory for fabrication of an electron gun.Last but not the least, synergy with other subsystem designers, fabricators and the end user makes the success best assured.

2.4 A Case Study in Electron Gun Design

In this section electron gun design required for specific applications is presented.

2.4.1 Design of 80 kV, 12 kW Electron Gun for EB Welding

The initial electron gun geometry consists of a cascaded spherical-cylindrical grid, a circular emission surface and a hollow cylindrical anode. It is important to at least qualitatively understand the significance of all the geometrical numbers before attempting to quantify the gun parameters. This gives a confidence to the designer to estimate the results at every stage of design iteration. Each parameter has got a specific function and affects the beam depending on its influence on the beam quality. The parameters are either strongly or weakly coupled with one another. The parameters and their functionality are listed below. The following table 2.2 qualitatively explains the functionalities of the geometric parameters given in Fig. 2.11. The geometrical parameters of the electron gun were modified iteratively to meet the high voltage and beam spot requirements using FEMM (explained earlier) and CST particle studio respectively. CST particle studio solves the electromagnetic field in 3D using Finite integration Technique followed by particle trajectory iteratively until a self-consistent solution is obtained [8]. The designed values of the electron gun are shown in the following table 2.2. The space charge limited beam current, the beam spot diameter at gun exit and the beam aperture angle at the gun exit are monitored. The beam trajectories of the gun are shown in Fig. 2.12. The values of rs and r1 are tuned to meet the perveance, object distance (200 mm) and the image distance (700 mm) of this gun.

2.4.2 High Voltage Design

High voltage design is an important design step in the gun design (table 2.3). A good electron optics design can be practically useless if it has frequent high voltage discharges. High voltage discharges in the gun cannot be eliminated but can be minimized by

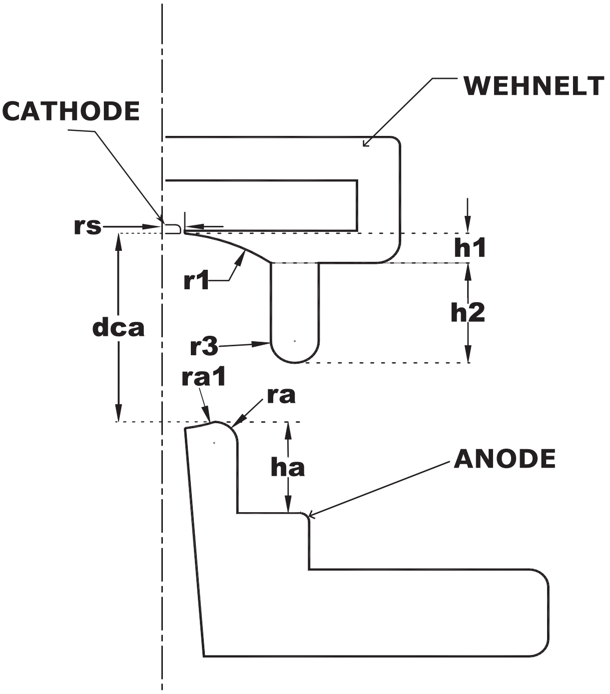

Figure 2.11: Parameters of the selected EB Welding Gun Geometry.

Table 2.2: Functionalities of Geometric parameters.

Parameter	**Functionality**
rs	Controls the edge emission. Controls the Grid cut off voltage
r1	Controls the Perveance and plays a vital role in initial beam divergence
h1	Controls the spot size at beam minima
h2	Controls the location of beam minima and slightly affects the beam perveance
r3	Controls the electric field at bias electrode
dca	Controls the Perveance
ra1	controls the anode diverging lens effect
ra	Controls the Electric field at anode
ha	Controls electric field between bias electode and anode

a) Minimizing the macroscopic and microscopic electric fields on the electrodes and insulators below recommended values.

b) Reducing electrode contamination

c) Reducing the energy fed into a discharge

d) Maintaining a clean vacuum in the gun region

e) Maintaining the electrode temperatures as low as possible and

f) Controlling the stray beam hitting unwanted portions of the chamber

The following section deals with the macroscopic high voltage design. The design problem is stated as follows. “The maximum electric field is an important parameter for a reliable gun

Table 2.3: Geometric parameters of the 80 kV, 12 kW gun (refer Fig. 2.11).

S. No.	Parameter	Value (mm)
1	rs	2
2	r1	18
3	h1	3.5
4	h2	12
5	r3	4
6	dca	22
7	ra1	15.9
8	ra	2.5
9	ha	11.5

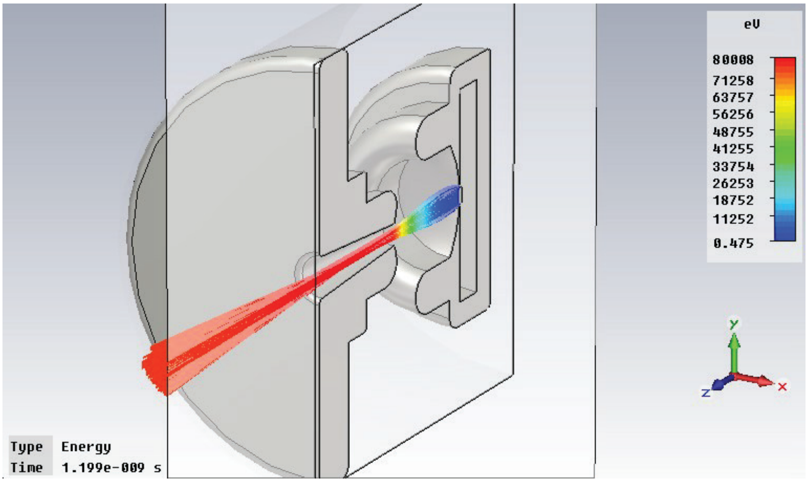

Figure 2.12: Trajectories in 80 kV, 12 kW EB Welding Gun.

operation. The safe electric field limit on negative electrodes with temperatures more than about 300 °C is 60 kV/cm and near cold electrodes is 100 kV/cm. The electric field limit near positive electrodes should be limited to 150 kV/cm [9]. The reason for a higher field at positive electrode is that field emission does not occur at these electrodes.” The microscopic fields are due to electrode surface conditions and triple junctions (metal-vacuum-insulator junctions) and are not dealt in this chapter The following methodology is used for the HV design of the electron gun.

1. The electron gun profile under investigation is modeled with FEMM [9] as an axi-symmetric electrostatics problem. The assumed voltage for the computation is -90 kV. This voltage corresponds to the conditioning voltage of the gun.
2. The electric fields along the electrode and insulator boundaries are evaluated. The conductor radii or the insulator lengths are modified until the safe electric fields are obtained.

The FEMM Model for the calculation is shown below (Fig. 2.13 (a)). The axi-symmetric model includes

1) The anode of the gun
2) The Grid of the gun

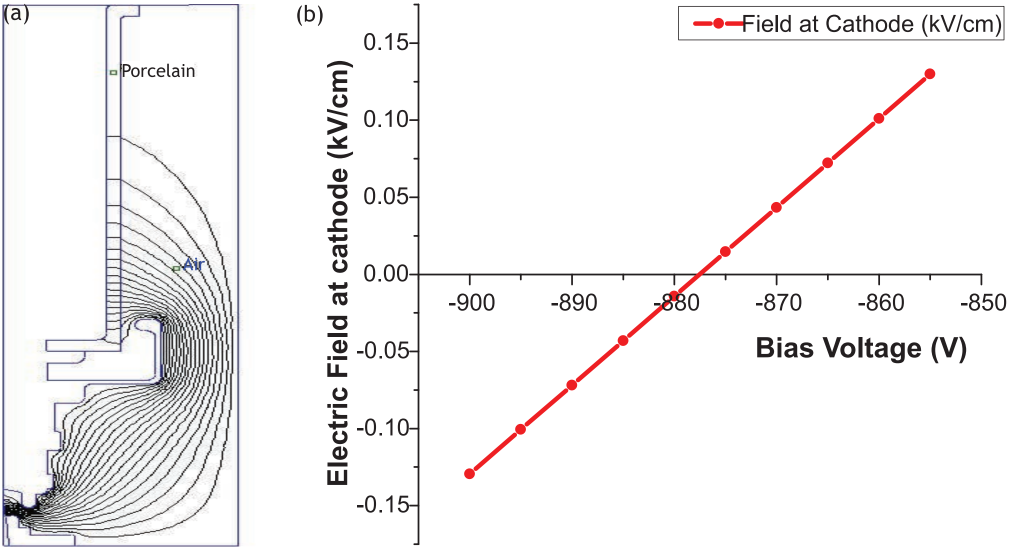

Figure 2.13: (a) FEMM Model for electrostatic design of the electron gun and equi-potential lines, and (b) Electric field at cathode vs Bias voltage.

3) The Alumina stand-off insulator
4) The Triple junction shield to reduce the electric stress in the metal-alumina-vacuum interface,
5) The vacuum chamber (this is chosen as the problem boundary)

The region enclosed in a conductor is not meshed to reduce the computation time. The electric fields obtained on various electrodes and insulator surface are given below (table 2.4). This value is taken as acceptable for this gun configuration .

Table 2.4: Electric fields at Gun parts.

Electric field at	**kV/cm**
Grid	110.3
Anode	149.6
Alumina surface	9.5

2.4.3 Grid Cut-off Voltage Computation

The procedure for the calculation of Grid cut-off Voltage is explained earlier in section 2.2.4. The grid cut off voltage calculated from Fig. 2.13(b) using linear interpolation is -877.5 V. This completes the electron optics and high voltage design of the 80 kV, 12 kW EB gun for welding applications. The author will feel satisfied if the reader could learn the rudiments of electron guns from this chapter and apply them practically for his/her applications.