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A DIRECTLY HEATED ELECTRON BEAM LINE SOURCE

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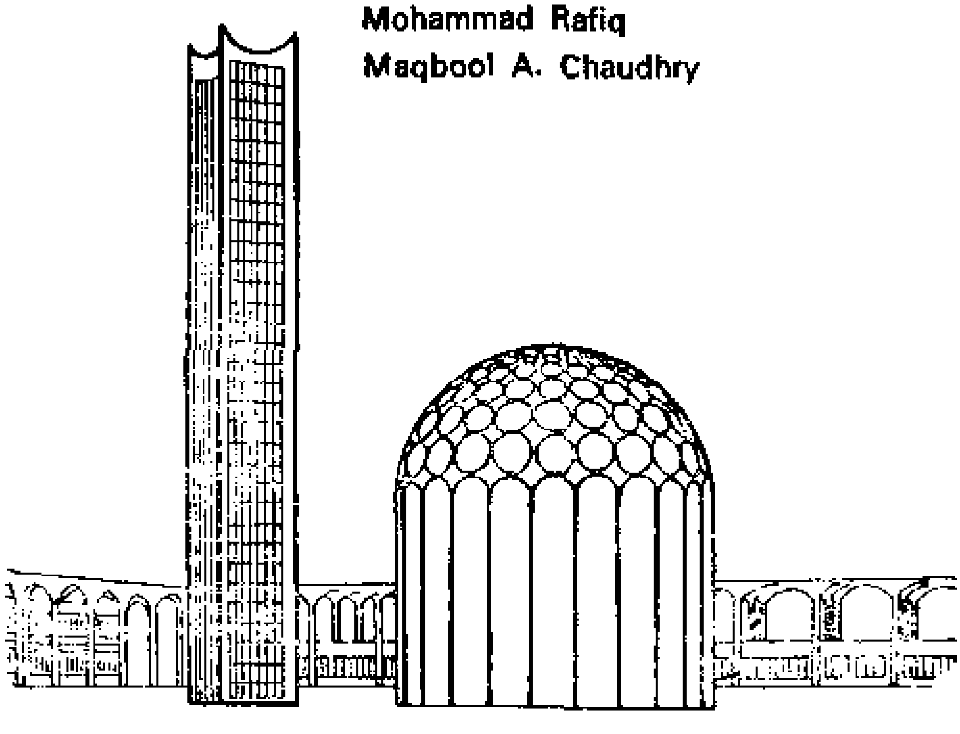

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ABSTRACT

A 140-mm cathode length, Electron Beam Line Source with a high degree of focusing of the beam is constructed. The design principles and basic characteristic considerations for electron beam line source consists of parallel plate electrode geometric array as well as a beam power of 35kW are worked out. The dimensions of the beam at the work site are 1.25x100mm. The gun is designed basically for the study of evaporation and deposition characteristic of refractory metals for laboratory use. However, it may be equally used for melting and casting of these metals.

I. INTRODUCTION

In this report, we have described the development of electron beam emitter assembly and its beam deflection in the external uniform magnetic field. The gun is constructed for the evaporation and deposition of refractory materials in the laboratory.

Our gun design is similar to that of [1] with some additions. The deformation of the cathode because of its strong and long heating is avoided with the help of a suitable spring action in the elastic range of the cathode material. The attentive emphasis has been given on the focusing properties of maximum emission current passing through the anode aperture and on the narrowest final beam crossover, by launching a series of experiments for different beam parameters.

We used 0.9mm wire type tungsten cathode as a filament and placed the whole emitter assembly in a square pipe of stainless steel (SS) that delivers the electron line beam with 180^0 deflection under the action of uniform field. Means are suggested for the partial compensation of the 180^0 deflection line source beam to avoid gun contamination due to evaporant material with the help of proper shielding. The design and performance of the line source is suitable for generation of beam up to the power of 35kW and beam current density at work site of the order of 10 amp/cm^2.

In the first part of the report, we have discussed the generation of uniform magnetic field. In the following section the design specification, beam considerations and gun characteristics of the whole system are discussed. Finally, the measured characteristics, results and performance of gun are presented.

II. GENERATION OF UNIFORM MAGNETIC FIELD

1). General considerations:

Fabrication of the line electron beam source required the application of external uniform magnetic field over the region of interest. It is frequently desirable to use a twin, parallel conducting circular and co-axial air core coil arranged for the production of uniform magnetic field over a specific volume. Large the radius of the coil the larger the region of uniform magnetic field available.

In an arrangement due to Helmholtz, the region of uniform magnetic field was obtained in the center between two coaxial circular conducting coils set parallel to one an other with their centers at a distance apart equal to $\sqrt{2.2}$ times the radius of either coil. The two coils were connected in series so that the same current passes through each coil and their magnetic field are in the same direction. The axial magnetic field at the point are additive and the rate of variation of strength is zero[2] and magnetic field is uniform on the common axis of the two coils and field at off axis position is not uniform.

Thus two coils at a separation equal to radius of either coils [3] are known as Helmholtz coils. The magnetic field at the mid point is therefore,

$$B = \frac{\mu N a^2 I}{(a^2 + a^2/4)^{3/2}} \text{..} (1)$$

where "N" is the number of turns of each coil carrying current "I" at a coils separation equal to radius a of each coil.

The electromagnetic equivalence is,

$$B = \frac{2.86 \mu_{cm} N I}{a} \, gauss \text{..........................} (2)$$

Since Helmholtz coils have advantage of much excess to free experimental space from all directions, they are particularly suited to our experiment for the deflection of line source electron beam in uniform magnetic field. We were restricted at the coils separation equal to $\sqrt{2.2}$ times the radius of coils at the separation greater than Helmholtz arrangement because of the available design facility.

In precise, positioning and orientation for the absolute measurements of the field set out graphically which shows the uniformity of the magnetic field. Linearity and field characteristics for a set of values are described in **Fig.1.** which gives information about current field relationship.

2). Thickness to width ratio of winding:

The Garrett had investigated the general theory of the geometrical configuration of circular coils for generating uniform field. Franzen[4] has discussed the effect of rectangular limit winding cross section on field uniformity and optimum conditions for Helmholtz coils by choosing an appropriate thickness to width ratio of winding without changing the coils arrangement given by Garrett with properly adjusted coils position.

The optimum dimensions of coils configuration can be determined with the practical condition that the ratio of thickness to width of winding cross section should be the ratio of relatively small integers[5]. However, an optimum coil design is always possible when the ratios of thickness and width of actual winding are ratios of integers and the resultant design can have same degree of uniformity.

It was a matter of great importance and it is found convenient to compensate the effect of coils separation restriction by means of selection of proper thickness to width cross section of winding so that the magnetic field due to each coil exactly overlaps in the uniform region of interest at a coils separation of $\sqrt{2.2}$ times the coils radius. The appropriate choice of rectangular cross section was (6.5 X 15) cm ... thickness to width ratio of winding is 0.46. That is employed by relatively thick coils in order to achieve optimum field configuration in our design of twin parallel circular and coaxial coils. The ratio of 0.46 correctly depicted the additive effect of field configuration in an appreciable region around the center point where magnetic field is essentially uniform with very close approximation with the designed consideration.

3). *Coils Separation:*

The investigated field characteristics include the region of remarkably constant magnetic field in the region of interest. Of course, the utilization of twin parallel coils converges in uniformity attainable and in position upon those of the ideal Helmholtz pair as the axial length of the coil decreases as discussed by Carig. The coil separation less than the Helmholtz[6] is advantageous when the problem is that of obtaining optimum uniformity of field over a definite volume of specific shape. The coil separation greater than Helmholtz is comparatively inferior and ... will be deteriorated on departing from the optimum position.

The uniform magnetic field is necessary for the precise deflection of charged particles especially when the particles paths are long. Each coil ... has of course its own particular field form. For our predetermined ... dependence the way in which the field between the coil varies with "Z" and "r" are best seemed by plotting ... contours of ... field through points which have same magnitude as described in Fig.2

Because of the variation of the field with "Z" and "r" from the central region of the uniform field, it is ... convenient and useful to take the differences and deviations ... point in terms of central field of uniform region. It is observed that at the central region, 24 units along and 32 units across the coil axis, the field is uniform at a distance of separation equal to $\sqrt{7}$ times the radius of the coils. This permissible coil spacing produces equally uniform field, as the field at any point is the algebraic sum of those due to each of the two coils at that point. Although, the overall uniform region was decreased to some extent but it was uniform in the region of interest. But the non standard configuration of coils separation of √3 times the coils radius [7] as discussed by Murgatroyd had been able to achieve fair uniformity over wider region than in the standard case. This is more than the coil separation employed in our case.

4). Coils Dimension

We have constructed a pair of coils, 112 cm in diameter capable on a 100 volts and 60 amperes power supply at coil separation of 85 cm. The coils are made of 5mm thick SS sheet. These are specially designed to attain massive windings. Each coil has weight of 141.93 Kg with a facility of water-cooling channel inside. The 16 S.W.G. copper wire is used with maximum current capacity of 5 amperes and total resistance of each coil is 35.4 ohms.

The thickness to width cross section of winding is (16.5 X 15) cm with total 19 layers and each layer contains an average of 56 turns. There are total 1068 turns on each coil and thick insulation paper is used between each layers. Maximum magnetic field that it can generate is 80 Gauss. A uniform field of 46 gauss at 69.5 volts and 13.75 amperes give rise to coil temperature of 37°C.

Coils dimensions are given in **Fig. 3.** and winding **specifications are presented in Table a.**

Copper Wire Gauge	= 16SWG
Average Turns on Each Coil	= 56
Total number of Layers on Each Coil	= 19
Length of Wire on Each Coil	= 4361.6m
Total Number of Turns on Each Coil	= 1068
Total Resistance of Each Coil	= 35.4 Ohm
Maximum Current	= 5A
Radius of Each Coil	= 59.5cm
Maximum Value of Magnetic Field	= 80G
Weight of Copper Wire on Each Coil	= 141.93Kg
Total Weight of Each Coil	= 221.93Kg

Table a. Coils Winding Specifications

III. BEAM CHARACTERISTICS

1. Electron Beam in Uniform Magnetic Field

Once the emitted electrons are shaped in to a beam with the help of control electrodes, they are accelerated by electrostatic field and focused by the gun. The external magnetic field is used to further deflect and control the trajectories of the beam.

Under the action of the electrostatic field, the emergence of the electron beam from the anode slit takes place. These high-energy charge particles are projected and then deflected perpendicular to the plane of the field at every point as they enter in the uniform magnetic field. These charge particles will describe a circular motion whose radius corresponds to the kinetic energy associated with each particle.

If all the particles enter perpendicular to the edge of the field and leave the magnetic field after 180° of motion, we will find that they spread out in the plane of motion. This is because different particles have different velocities and angle of emergence thus, will have different radii of curvature. These different velocities and angle of emergencies are used to get beam of electron having equal velocities provided they have the same charges. In such an arrangement, even if the electron having the same momentum, enter the uniform magnetic field at different angles, will be focused at one point [8].

By measuring the distance from the anode slit to the point at which the beam of electron strikes the target area, we can experimentally measure the beam diameter. Since the radius of curvature of the electron beam is directly proportional to the square root of acceleration voltage and inversely proportional to the value of uniform magnetic field. Therefore, the radius 'r' is,

$$r = \sqrt{2/\eta}\ V^{1/2}/B \quad \text{weber/m}$$

where $\eta = e/m$

Therefore,

$$r = 3.37\ V^{1/2}/B \text{ cm (B in gauss)}$$

There is a close relevance between the experimental and calculated values of the electron beam radius. Our measured beam diameter is 1.5mm.

2. *Beam Profile:*

The emergence of the extracted stream of beam through the anode aperture into the post anode region in the deflection field causes it to diverge from its parallel form. Those electrons, which are emitted normally from the cathode, appear to amanate. Electrons emitted with low and high angular velocity distribution form parallel streams inclined at small angles with respect to the beam axis forming a common cross over in the post anode region. These electron trajectories strongly depends on the electrodes geometric configuration, accelerating space and field.

The space charge effects, thermal directional orientation and velocity distribution of the electrons rapidly become significant in the post anode region in the presence of magnetic field. The image formed is that of the cathode surface and emission at all angles contributes to each trace of the image trajectories. With different beam velocities at the cross over some spatial separation occur between beam lines emitted at different angles with different energies and have the size at the cross over is attractively small. If the geometric configuration of the electrodes is most appropriate and magnetic field is uniform, these beam line trajectories again spread in to the uniform space and then ultimately combine at a common place at work site.

The characteristics beam profile for a given set of parameters was measured directly by placing a thin metallic SS sheet in the passage of the line beam for the tracing of electron beam trajectories. These traces of trajectories produces image on the metallic plate. The central trace of the image was illustrated by electrons emitting normally, while those emitted at short and increasing angles found separate circular traces of different radii. The computer printout of the beam trajectories is shown in the **Fig.4.**

The metallic plate will cause the each beam line to melt the plate in the same position of beam line cross section where as the respective electron emission from cathode edges with increasing divergence having low energy density will form only their image on the plate and will not contribute in melting. If a suitable sized metallic aperture plate with exit slit cross section sufficient for providing a passage for electrons is placed at center perpendicular to the plane of the lines, only those electrons line beams with emission velocity above some minimum value will be transmitted and the necessary sorting can thus be accomplished. Such filter aperture subsequently is placed inside the hearth cap in order to avoid gun contamination due to evaporent material.

3. *Electron Beam at Work Site*

As indicated in the design section of the report that, while using a wire cathode, we were able to reduce the width of the parallel line sheet beam. At the work site the beam dimensions are ~ 1.25x100mm at low emission current under the best focusing condition. The line source electron gun was designed to deliver the emission current density from the cathode surface as high as $10A/cm^2$ with the maximum peak of beam power ~20kW with the available power supply. Typically, the system has been operated at beam current ~20A and the acceleration voltage of 10 kV.

The beam spot size parameter and current density profile across the narrow dimension of the line were checked directly by using SS and Mo. sheets and plates as work piece material. The minimum spot size on Mo sheet is taken at 10 kV and at emission current of 600mA. The size of the beam line is observed to be 2x85mm while using the thick SS plates at 10 kW the measured size of beam line is 8x140mm.

The molten spot size and shape of the line source electron beam indicate the central uniform longitudinal strong current density region and the associated regions with drop in current density due to heat transfer at work site. The **Fig.5.** respectively shows typical examples of lateral and longitudinal current density profiles of the line shape beam.

Fig.5a. shows lateral beam profile across its narrow dimensions, which is of Gaussian pattern. Any deviation can be attributed to mechanical misalignment or due to change in position of the parallel electrode geometry. The uniformity along the length of the beam is also quite good as shown by the measured profile of the longitudinal beam in **Fig.5b**.

The photographic pictures of the beam lines at work site on Mo sheets are presented in **Fig. 5c** The result is not surprising, since space charge effects smooth out irregularities along the beam axis. The beam is operated in working pressure of 10^{-5}mbar, which compensates the space charge effect around the beam cross section and helps in containing the beam.

On increasing cathode to anode spacing, the total beam current decreases and the corresponding beam line size increases at the work site. The final beam spot geometry depends upon not only the deflection field and work site material but also on the space charge. Similarly, the deflection aberration is caused due to the fluctuation or decrease in the deflection field. The resultant increase in the radius of the deflected beam can cause not only the focus spot parameters to change but also make it possible for the beam to pass through slightly non-uniform field region.

4). Cross Over

The paths of electrons starting at axis with angles of 45° and even at slight variations from this angle will make the cross over after 180°. A uniform magnetic field has focusing properties and electrons with the same energy which pass through the anode aperture in slight different directions will nearly converge at a point diametrically opposite. In our electron gun line source, it was found out experimentally that the low, intermediate and high curvatures of trajectories follow a particular track in uniform magnetic field, which has a common cross over after 180° of deflection.

A series of experiments is performed to locate the precise position of cross over. It is found that the evaluation of cross over in the vertical plan lies approximately 37mm below the anode surface. A cross sectional view of the electron beam trajectories transmitted from anode aperture is very well described already in **Fig. 3**. That provide information about the elevation of the cross over below the anode level at work site. The point of cross over is estimated to be in exact experimental relevance with that of the Avida's design of line source. Any deperture from the most approperiate architecture, the beam trajectories and hence the degree of expected cross over specification of low intermediate and high electron trajectories will shift the cross over at a different point.

5). Best Focus Position

The best focus position with adequate and precise adjustment of parallel plate electrodes can be obtained by observing the image quality of the line source beam. The best focus position can then be found out at the point where the highest quality image is produced. The best focus position is an essential and vital consideration whenever we calculate the properties of the electron beam melting and evaporation. In order to obtain good focusing accuracy, especially at the desired work site level, the variation in the uniform magnetic field must be avoided.

After a series of experiments, the optimum focus position at a horizontal distance of 14cm away from the cathode at 10kV is obtained. At this distance under the specified gun parameters, the best focusing position at work site lies approximately 37mm below the elevation of the anode. At this distance, the trajectories of the beam line make a sharp cross over and the highest quality image of beam line is obtained. This best focus position determined at a uniform value of magnetic field of 50 gauss. The contrast performance of the beam line focusing is checked by using different work piece material.

This focus position is influenced by several factors, including geometric layout of electrodes, mechanical alignment, extraction voltage, working pressure and stability of uniform magnetic field. The field uniformity in the whole volume of experimentation is estimated to be fairly good. The effects of any change in electrodes as the high field strength exists between them and will exhibit a change in the beam spot parameters in the post anode region. This change after transformation due to deflection field completely changes the beam parameters at work site.

6). Focusing Consideration

The outer electrons in the beam trajectories are principally associated with appreciable transverse velocity resulting from their emission from the cathode due to thermal directional and velocity distribution of the beam electrons. In our case of a low perveance gun with uniform emission current density and relatively small spherical aberration, the transverse velocity distribution is found to be Maxwellian. Further, as the transverse area of the beam is changed either due to change in geometric configuration on deflection field, the random transverse electron energy will also change, so that as the beam is caused to converge, the effective electron beam temperature will be expected to increase inversely as the beam size decreases.

Since the focusing is principally by means of electric field and the focused electron flow is initiated in a magnetic field. It is also interesting to note and measure the ability of the gun and the focusing field system combined to produce a well-focused beam. One method of observing the focusing action is the observation made visually by means of inspection of the beam line at the work site. In this way, we can see the effects of change in electrodes geometry and magnetic field strength with different work piece materials and the electron beam configuration and the focusing of the beam envelope as well as the beam spot size and thus the exact radius of the beam may also be physically measured and recorded.

The focusing characteristics of the beam from the line source gun are observed by introducing metallic plates as SS and Mo. at work site. A series of results regarding precise and accurate values of focused beam parameters such as cross over, beam shape, size, length and current density distribution is reproduced. This illustrates qualitatively the defects, which are arisen while studying the focusing of the line source beam.

One defect of the beam is seen to form two similar shaped beam lines, one dense beam covering 75% to 80% of the total beam current. The other associated beam line of lower density representing the two cross over due to emergence of electron beam trajectories in to the magnetic velocity appreciable random transverse velocity due to mis-alignment of electrodes geometry. This defect is redressed by adequate adjustment of electrodes geometric parameters.

Even more detailed picture of the magnetically focused beam is obtained by using an aperture placed in the middle of the beam path and normal at hearth surface which gives information about the each beam trajectory orientation.

Beam spread is also observed while varying the magnetic field. Similar effects are observed by the changes in the extraction field. A unique best focusing location is a result of overall compatibility and harmony in the factors responsible for adequate beam focusing.

IV. GUN DESIGN

In this report, a magnetically focused line source electron gun is described which is fabricated, tested and its characteristics are measured. The requirements for production of 20 kW beam power obtained in an electron gun using 180° deflection in uniform magnetic field demands for further taking in to account the gun spot parameters described by Avida. We have made certain changes in design regarding electrodes dimensions, design and introduction of sporting mechanisms to avoid cathode deformation. The beam profile configuration that produces satisfactory focusing is given in **Fig.4**. These electron trajectories emerge from the upper surface of cathode where the electric field is strong enough to prevent accumulation of space charge. The heating damage due to electrons striking the anodes lower surface is also avoided by using an optimum slit.

The gun design discussed in [9] are somewhat different because the first design is based on a point source electron gun where as the second design consists of a low power gun which requires electrodes spacing greater than our designed gun. The design specifications and experimental considerations of our design as well as our experimental results matches in good approximation with the design discussed by Avida.

Similarly, it is clear that spacing between cathode and the focus electrodes causes variation of potentials and this spacing is necessary for thermal and electrical insulation of focusing electrodes from cathode. In the gun design discussed by Avida, this spacing is taken as 3mm and overall spacing between the central electrodes is 6mm same as employed by us. In an actual gun, it is hardly possible to keep this spacing under 2mm due to deformation and melting of electrodes material for the gun with beam power of 20 kW. At such close spacing the potential deviation near the cathode edges due to divergence force on electrons is also unavoidable. From this, conclusion can be drawn that line shaped beam can not be produced with non-biased control electrodes. That is why, we have provided the potentials to the control electrodes same as that of cathodes.

Similarly, in the line source gun design [10], this spacing is same as 3mm with semicircular and rectangular cross-section cathodes. In both theses designs, the performance of later cathode design proved to be more practical. As for as, the cathode to anode spacing is concerned in these two designs, they are 8mm and 16.5mm respectively. In design [I] the performance of gun with cathode to anode spacing of 8mm proved to be efficient and the current efficiency will biased control electrode all through structurally complex is more than un-biased electrodes. Similarly in design [10] the control electrode is at cathode potential using the same acceleration voltage of 10kV.

While taking in to consideration the different line source guns design's it seems reasonable to take the spacing of 6mm between the control electrode and the little wider spacing of 7.5mm between the cathode and anode. Similarly, using the anode aperture slit width of 7.5 slightly different from Avida's design provide to be most appropreate low emerging beam and has a suitable converging effect.

V. GUN DESCRIPTION

1. Gun Construction

The line source electron gun consist of a directly heated tungsten wire cathode having 0.9mm diameter with an emission surface length of 140mm. The cathode clamps and blocks made up of molybdenum having dimensions (3x10x20)mm and (3x20x40)mm are used to hold the cathode supported on the stain less steel base bar with which the control electrodes are vertically connected with a spacing of 6mm between them. In this spacing, the cathode is positioned and aligned at the center exactly 3mm below from the top surface of control electrode. The metallic plates made up of tantalum of 1mm thickness are used for the fabrication of control electrodes and anode plates of the shape and geometry of parallel plates electrodes configuration. The whole emitter assembly is situated at the base of square SS pipe. This square pipe is specially designed for not only to accommodate and align the emitter assembly but also to elevate the anode plates *having dimensions (1x20x140)mm. The anode plates as well as the* square pipe are at ground potential by introducing the high voltage locating insulators in between the emitter assembly and the square SS pipe. The control electrodes are at cathode potential. A precise positioning and accurate alignment of the gun components is the vital aspect as far as the required beam parameters at work site are concerned. The formation of anode slit is accomplished with proper holes for connecting them at the top edges of the square pipe as well as to facilitate alignment exactly above the properly adjusted emitter assembly.

The acceleration voltage required for the extraction of the *electrons emitted from line cathode is 10 kV. The tantalum* extraction anode slit is positioned at 7.5mm above the cathode level with a slit width of 7.5mm. It is aligned 1mm away from the control cathode central plane towards the direction of beam deflection in order to facilitate the emergence of the beam line from anode slit without melting it. The control electrodes provide the preliminary beam formation and initial beam shaping under the action of potential distribution created by the electrostatic field in the region of its rectangular shaped cavity.

In the extraction stage, the electron beam passes through the 7.5mm wide anode slit across the main accelerating *gap of 7.5mm between cathode and anode, which can be, set at any* potential difference in the range from 2.5 - 10 kV. The anode is set at ground potential and the velocity of beam electrons emerging from the anode slit is associated with the acceleration voltage applied. The beam is focused electrostatically by making a cross over in the post anode region. After this, it is deflected and guided towards work site under the action of external magnetic field. The spring mechanism is used to apply a suitable spring compression in order to avoid cathode deformation. For this purpose a slot is fabricated in the right-hand side cathode block for the easy movement of block in compression mode of cathode. This mechanism solved the problem of cathode deformation. The basic pressure required for the operation of electron gun assembly is ~ 10^{-6}mbar but during operation, the pressure of the system drops in the range of 10^{-5}mbar. The gun operation in the better pressure regime provides stability and improvement in beam focusing. A detailed sketch of the electron gun line source assembly and a list of detail of its components are briefly given in **Fig.6**.

2. *Cathode Consideration*

A line source electron beam has advantages over a spot focused beam in material melting. In particular, the line shaped beam can process wide areas of material in shorter time than a spot beam. Beam density provided with a line source has as uniform configuration as possible along the length of the line. It is very difficult to obtain a long line beam with a resplendent uniformity along the length from usual emission sources. The beam density profile along the line beam relates strongly to the temperature distribution along the line cathode. The larger the length of the line source the more difficult to keep the temperature constant along the line.

The present report contains the development of such a line source electron gun in which the cathode is of the same size and length as the electron beam profile required at work site. The diameter of cathode wire made of Tungsten is 0.9mm with the effective length of 14cm. The use of such a thin cathode wire has permitted us to adopt direct heating of the cathode and enable us to make our gun structure much simpler than that of a gun with an indirectly heated cathode. In this simple configuration, there is no technological limit regarding the formation of quite a long line. The gun produces beam with a line profile measuring (1.5x90)mm beam dimensions at work site with Molly as target material.

One side of the cathode is electrically connected to the beam former and the other is insulated by the Alumna spacers. The cathode is clamped with Molly pieces resting on Molly cathode blocks. The cathode is kept in place in the confined fashion between the control electrodes and the expansion and compression compensation is provided along the whole line with the help of spring action on one side. For this purpose, a slot is fabricated in the concerned cathode block. The desired beam shaping is accomplished with parallel plates beam former structure which serves also as a radiation shield. The whole cathode assembly is connected on a SS base bar which is fixed with the grounded SS square pipe base with the help of high voltage insulators which provides necessary electrical insulation. The possible accurate positioning and aligned spring compression of the line cathode between the line cathode plates has a symmetry plane in shape is examined within a mechanical accuracy.

The trajectories begin at the cathode surface which are initially subdivided into segments on each side and center due to thermal angular orientation and velocity distribution of electrons also incorporating the space charge in the region associated with the beam generation. The wide angle cathode segments of beam follows the paths which are represented by the broad based electron beam trajectories are stopped by anode plates leaving their traces on it.

A series of experiments has showed that the position of the cathode is exactly 3mm below the top level of control electrodes is the best. It has been evaluated that the location of the cathode further upwards or downwards than the said position causes in a decrease in the beam power and disturb the overall beam parameters. The central red-hot cathode region describes the strong emission region due to the higher temperature. The associated edges have pronounced drop in emission current density due to heat transfer towards the cathode clamps. This effect is more important in producing non-uniformity in the beam edges emission current density. The gun cathode blocks and spring assembly

Design has been revised to minimize much heat transfer by reducing the size of a cathode blocks. The spring compressing assembly has been also reduced in size in order to make the spring action more soft.

3. *Cathode Life*

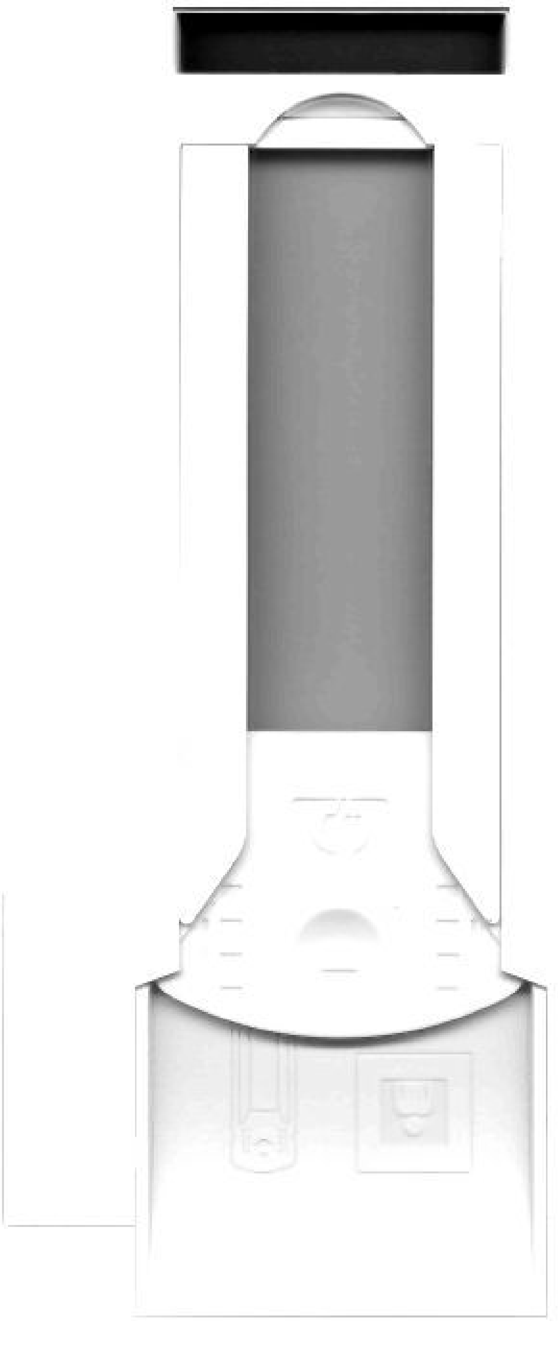
The performance of a cathode is directly related with the long term stability of gun operation. The main factors that *influences the life of the cathode are sputtering, mechanical* stress and evaporation. The mechanical stresses were over come through adequate design, proper support, care in handling and accurate alignment. The impingement of beam produced ions upon cathode results in sputtering of cathode material. This diminishes its useful emission surface [11]. This effect is minimized by providing an appropriate aperture in the passage of beam and by properly protecting the gun components from contamination. The both its high operating temperature and its vacuum environment are the required operating parameters, little can be done to eliminate it. However, a useful cathode life for 100 hours of continue operation is experimentally checked and no physical change in shape is found.

4. *Electrodes Configuration*

In an axially symmetrical electron gun system, the field strength between the parallel plate electrodes geometric layout *specifies the electrostatic field in the region bounded* the edges of the field in the form of equipotential surfaces. In our gun design, the control electrodes are at the same potential i.e. 10 kV as that of cathode whereas the anode is at ground potential. Since the condition of the electron beam focusing is independent of the charge to mass ratio of electrons and depends only on voltage, electrodes shapes and the associated distances between the electrodes.

In our gun design, the control electrodes are placed 6mm , apart, whose position lies 3mm below the top level of control electrodes. These electrodes are connected normally with the base bar. These electrodes are made of Tantalum and they are in the form of parallel plates. Similarly, the parallel plates for anode slit are placed 7.5mm above the cathode level with a slit width of 7.5mm. This anode aperture slit is displaced 1mm towards the direction of beam deflection. Apparently, majority of emitted electrons passes through the anode slit and is focused in to a beam in post anode region. We find striking of beam electrons in small proportion with the lower surface of anode slit due to thermal directional orientation and velocity distribution of electrons. The focusing electrodes gap of 6mm has been found necessary for proper beam formation although slight deformation at center is observed. The electron gap less than 6mm further causes deformation of parallel electrodes and it may also cause the electrodes to melt. Whereas, the accelerating gap of 7.5mm is suitable for line source gun to operate at 20 kW beam powers. Similarly, the slit gap of 7.5mm is accurate for the beam passage at the designed acceleration voltage under the action of uniform magnetic field. In this gun design, the overall dimensions of the electrodes depends upon the length of the cathode.

The small errors in mechanical construction of electrodes and their alignment in the emitter assembly were seriously taken in to account. It is desired to design the shape of electrodes in such a way that the electric field results in a uniform emission. Consequently, a well-collimated line beam resulting in uniform emission current density over a greater correction of the beam is obtained. It is observed that the configuration of the fields in the flow region is affected by both the control electrodes, which define the entire beam formation, shape of the beam line and the anode. In the anode aperture slit, the field strength causes an outwards push to the beam electrons. This effect is frequently treated by



considering the anode aperture slit as an electric lens. This thin lens concept is useful for gun of low perveance ($\sim 10^{-6}$), it breaks down rapidly as the gun perveance value is increased. This effect is important because the width of the aperture slit must be selected to be compatible with the configuration of control electrodes and their dimensions. From the above mentioned facts, it is clear that the electrodes material selection, their design shape and required distances between them are vital for the determination and precise implementation of focal spot parameters to attain maximum emission current density.

5. *Cathode to Anode Spacing*

The cathode to anode spacing is a very important gun parameter. It contributes in the field strength distribution but also the beam formation, its focal spot parameter and saturation current density is also influenced by this spacing. The emission current density for space charge limited system is related[12] to the extraction voltage v_A and the cathode to anode spacing by an equation of the form,

$$Je = 2.3 \times 10^{-6} KV_A^{3/2} \qquad (1)$$

where Je is measured in amperes per square centimeter, V_B is the acceleration voltage in volts, and K is the quantity, given in cm^{-2}, that depends on the geometric configuration of the electrodes. In our simplest case of parallel plates electrodes $K = 1/Z^2_{KA}$, where Z_{KA} is the distance between cathode and anode. In our gun design Z_{KA} = 7.5mm and if the line source is to work over a wide range of energies, it is of course necessary to select Z_{KA} in the most appropriate manner. The relation between current density and cathode to anode spacing is best described in Fig.7.

The divergence of the beam emerging from the anode is mainly determined by the cathode to anode spacing and by the anode aperture slit width. To keep the divergence of the beam within manageable limits, the cathode to anode spacing must not be too small. A large spacing cause a decrease in current density as well as greater acceleration voltage is therefore necessary to provide a sufficient extraction field. We have selected an appropriate value of spacing so that the saturation value of the emission current density lies exactly below our described limit of emission current for 20 kW beam power. It is also experimentally inferred that higher emission current can also be obtained by decreasing the cathode to anode distance.

6. *Anode Aperture*

The slit of the anode aperture allows the beam to pass through with the velocity of electrons equal to the field strength between the control electrodes and the anode. While considering the perveance, the anode aperture must be made large for appropriate beam emergence. When the width of the anode slit is considerably larger than the cathode to anode spacing, the beam emerging from the slit will be divergent. This is because of the divergent lens action of the anode slit. On the other hand, the smaller slit width configuration can cause the anode to melt. The large anode slit causes a serious distortion of potential distribution in the flow region as the equipotential lines bend up in to the aperture. The parallel plate electrode geometry takes up the potential distribution along the entire beam line space charge limited emission provided the anode slit is accurately and precisely aligned and positioned with the rest of the assembly. Under these conditions, the field configuration will result in a uniform emission current density over the cathode. The tracks of the beam trajectories even at the edges are such that they do not strike with the anode plates and from a well-collimated beam passing through the anode slit.

With the optimum gun design for a cathode to anode distance of 7.5mm the most suitable value of anode aperture slit width is formed to be 7.5mm. The overall electrode layout is such that it is possible to cause the outer few equipotential lines to be necessarily parallel with respect to control electrodes. It is also determined experimentally that with continuos operation, the focusing electrodes from center are slightly bent outwards. It is therefore, clearly impossible to achieve the optimum beam parameters all along the beam line without taking in to account each parameter of gun design. We must content to force the matching of all the factors responsible for adequate beam line formation at work site. In such a design procedure the emission current can further be enhanced by decreasing the cathode to anode distance, changing the shape of control electrodes and by increasing the potential difference between the electrodes.

VI. OPERATING PARAMETERS

1. *Electrical Power*

The power level is selected according to the required working conditions. In the beginning the line source power supply that provides the constant emission current in the range of 1mA - 1A is used having the acceleration voltage ~ 1 to 10 kV. Later, it is extended to 5A and 10 kV power supply to achieve the higher degree of power depending upon the requirement of the operation.

The stability of applied voltage is quite necessary for the correct implementation of the beam phenomenon with desired beam parameters at work site. Similarly, the correct stability of the Helmholtz coils power supply is vital to produce excellent processing. For characterization of beam, several parameters can be monitored from power supply including acceleration voltage, filament current and emission current. The maximum beam power used in the evaporation process until now is between 2.5-20 kW.

The beam power used in any such operation is a function of several variables including the evaporent geometry of hearth, melting mode and the ability of the vacuum system to remove evolved gases. Similarly, more beam power is required to melt refractory metals and the specific energy expenditure required to melt various metals is given below in the **Table b**.

Cu	Fe	Ni	Zr	Mo	Ta	W
1 - 2	1 - 2	1 - 2	2 - 5	5 - 15	10 - 18	20 – 40

Table b: Energy expenditure required to melt various metals kWh/Kg

2. *Vacuum Atmosphere*

The maintenance of a vacuum environment in the melting chamber is also required to prevent excessive scattering of the beam. Typically, the vacuum required for our line source in the chamber is in the range of 10^{-5} - 10^{-6}mbar, below which the space charge and scattering effects in the beam are dominant.

The necessary pump down of beam generation, guidance and its unrestricted propagation depends upon pressure, gas type, acceleration voltage and beam current which are the principal parameters mainly determine the desired pumping speed. In our line source gas chamber, this is accomplished by using the oil vacuum pump capable of removing gases volumes of the order of 1900 l/sec. To maintain such vacuum levels while pumping the evolved gases and compensating for the extremely small leaks in the system required to be removed for efficient pumping.

3. Process Control

A major advantage of the electron beam line source is the possibility of controlling the dimensions and shape of the beam pattern, which impinges on the target. The beam size and shape is controlled by external magnetic field, and the beam power. This is controlled by both the accelerating voltage between the gun electrodes and by cathode temperature, i.e. by changing the beam current. The desired value of saturation current density can be selected by altering the electrodes configuration. It is possible to further change the beam cross-section and line of the beam line as well. It is also common for the beam to be changed within seconds in both shape and location by using the uniform deflection field.

4. Water Cooled Hearth

The water-cooled hearth is a block made of copper, with a hearth boat for evaporent material as well as the platform for installation of the line source gun assembly. The platform is designed so that the anode plates are fixed at the top surface of hearth with taps. The assembly is screwed with the taps below one side in the slot at center of the platform base for accommodating the screw heads. The dimensions of the hearth are (32.5 x 17.5 x 7.5)cm, The dimensions of the hearth boat top are (21.5 x 7.5)cm where as the depth of hearth boat is 6.2cm with the sides tapered at 9^{o}. The platform level and the depth of hearth evaporent boat are so designed that the emerging beam after deflection when enter in the hearth boat, the half depth of the hearth boat in the central plane exactly coincide with cross over level of the beam line.

In the plane at center of hearth surface between cathode and center of hearth boat, their are taps for screwing the beam aperture slit. Around the hearth boat, there is a well of 1 x 1-cm at the top surface for adjustment of hearth cap which also covers the gun assembly. The complete design picture of the water-cooled hearth is shown in Fig.8.

The water-cooled jacket 9mm in diameter around the hearth boat in the central horizontal plane provides sufficient cooling with water at a flow rate of 30 L/min.

5. *Design Specifications*

In this report, we are led to a line source gun design which has the desired beam characteristics. In this section, we will now out line the design specifications followed in the procedure in designing the gun for final beam line required. Our principle parameters are,

Beam current = 2A
Acceleration voltage = 10kV
Uniform magnetic field = 50G
Beam power = 10 – 20kW

Where as, following are our design parameters,

Control electrodes width = 6mm
Elevation of cathode below top level of control electrodes = 3mm
Cathode to anode distance = 7.5mm
Final energy of beam = 10keV
Cathode diameter = 0.9mm
Cathode length = 14cm
Elevation of beam cross-over below anode slit = 3.7cm
Beam width at work site with Moly as work piece material = 2mm
Beam length = 9.5cm
Diameter of beam from cathode plane to plane of cross-over = 14cm

VII. RESULTS AND DISCUSSIONS

1. Evaporation and Deposition Rates

Evaporation in vacuum is a significant process for production of desired deposition. The use of line source beam for evaporation is due to the energy flow in evaporant with direct heating by impinging electrons. The vapor-emitting surface has higher temperature of evaporation that allows the evaporation of material from water-cooled hearth with high purity deposition because reactions with hearth walls are avoided. By using insulating inserts, the heat losses at the hearth walls can be reduced to obtain higher evaporation rates as the energy utilization is enhanced. By this process, the greatest portion of kinetic energy of the line source beam is converted into heat. The surface is brought to such high temperature that it becomes the source of vapor stream. The deposition is obtained by arranging the metallic plates in the passage of vapor stream and a part of vapors condenses on it in the form of thick film.

Beam control further enhances the energy flow to evaporant. Evaporation in turns directs vapor stream propagation from hearth to the deposition level. Since, generation and guidance of beam take place in a high vacuum, evaporation generally requires no additional expenditure. To ensure both beam generation and vapor stream unimpeded so that particle density of gas is kept low and the effects of collision are minimized.

In the hearth region, higher vapor density produces interactions between electron flow and vapor stream. This causes the vapor particles and electrons to depart from their initial trajectories. The evaporation takes place from the molten state in order to obtain the required rates.

The constant hearth surface temperature, is a necessary condition to obtain uniform adequate deposition. The evaporant surface becomes deformed due to beam line melting and concave vapor emitting surface results with drop in vapor density. The cold walls of hearth also effect the vapor stream distribution and tend to change the evaporation rates and consequently the deposition rates. Higher evaporation rates results in the creation of vapor cloud above avaporant surface. The vapor cloud does not contribute in deposition due to the formation of virtual source some where in cloud because of vapor particle inter-collision. With growing evaporation rates, the deformation of melting surface as well as the deviation of surface from designed cross over position is observed. Therefore, more increase in beam power is required, since the directional dependence is important as for as deposition rates are concerned.

Vapor interaction with the gas molecules causes the vapor scattering and consequently, the deposition rates drops to some extent. The advantage of reducing the effects of surface irregularities is observed when deposits are produced from vapor cloud, under the action of scattering, the deposition takes place without preferred orientation and energy of vapor particles is lowed. Uniform deposition on the copper plates was obtained over the entire surface along the beam line. The evaporation and deposition rates of SS. were taken for different beam powers and the rates were measured by taking the differences of the weights of evaporant blocks and deposition plates.

The evaporation rate is strongly dependent upon the installed beam power, evaporent geometry, evaporation material and the pumping capacity of vacuum system. A metallic hearth cap with a slit of 1 x 21.5cm in dimension at a height of 15cm in the central plane of hearth boat associated with a beam aperture plate for the exit of beam is introduced. This arrangement is advantageous for not only to confine the vapor stream but also to avoid the gun assembly from contamination as well. Separation of beam generation and the evaporation from hearth boat, is due to the magnetic deflection of the beam prior to impingement on evaporant. Thus, the use of line cathode implemented by using beam deflection at an angle of not less than 180° produces fair values of evaporation and deposition rates. The evaporation rates in the beam power range of 5 - 12 kW can, therefore, range from 20g/h to 140g/h. Where as the deposition rates in this power range are1g/h to 4g/h as shown in Fig 9a and 9b.

2. *Emission Current Vs Acceleration Voltage*

Emission of the electron or the beam current mainly depends on two parameters. Firstly, inter-spacing between the cathode and anode (Ha,f). Secondly, the potential difference (kV) applied between these electrodes.

The emission current is noted for various values of Ha,f spacing, for different cathode to anode voltages. For a fix value of Ha,f it is observed that cathode to anode voltage is used to increase the emission current [13]. At higher distances Ha,f emission is limited at low values while at lower distances it shoots abruptly as it is clear from Fig. 10. This figure indicates that at Ha,f = 11.5mm the maximum emission obtained is 1000 mA at 10 kV acceleration voltage. At Ha,f =8mm it is 2000mA at 8kV acceleration voltage. While at Ha,f= 6mm it is 2000mA at an acceleration voltage of 4kV only. It is therefore, observed that by increasing the Ha,f the emission current is increased even at very low values of acceleration voltage. Although it is very clear from the above results that the lower distance is the most favorable to in crase the power of the line source. But we have here the limitations for our power supply. The maximum current and voltage that it can deliver is 2000mA and 10kV respectively. We can not exceed this limit, consequently, we get lower power as prescribed.

Rather lower gap can enhance the emission current even more in a highly efficient vacuum environment of the order of < 10^{-6} mbar. This is essential so that any deformity of the beam and the evaporation of the gun components along with the gun components can be compensated.

3. *Voltage Current Characteristics*

The voltage current characteristic of the filament determines its heating capacity. Temperature of the filament is increased be the voltage applied to it that enhances the current drawn by it. Due to this current filament is heated and its temperature is raised. At the same time by increasing the diameter of the filament, we can also increase its heating power. The comparative study of voltage current characteristics for different electron guns has been investigated.

In the point focussed (original) electron gun, the filament draws the lesser current at the applied input voltage. At 40V, the current drawn by it is 22.4A. In case of LS electron gun having 4.2 cm filament length, the current drawn by it is 73 A at an input voltage of 40V. While for the 14cm LS electron gun the current drawn by filament is 46A at 40V as an input voltage. Therefore it draws lesser current and glow at lower voltages as compared to the 4.2cm filament LS electron gun. This also depends on the diameter of the filament. The diameter used for calculation is 1.5mm and the material is Tungsten. The voltage current characteristics are described in Fig.11.

4. *Filament Current Vs Variac Voltage*

The heating power of a indirectly heated filament depends upon its size, shape [14] and temperature as well as loses due to heat radiation and conduction. The heating power (watts) for tungsten filaments of different diameters is measured. The larger the diameter of the filament the greater will be the current drawn by it to heat it up. Hence, for a diameter of 1.5mm the heating power ranges from 500 to 1000 watts. While for a diameter of 0.9mm it is ranging 3.80 to 322 watts for the input voltage of 10 to 180 volts. The maximum output voltage for the above said range is 10V. Also, *the length of the filaments is fixed and is 14cm. It is* noted from the measured data that the 1.5mm diameter draws almost three times more current than of 0.9mm diameter. Due to this the temperature of filament goes to its melting point. For our gun design, it is suggested to use 0.9mm-diameter filament because of its heating power as described in Fig.12.

5. Emission Characteristics of LS Emitter Assembly

The filament heating power is responsible for the increase in the emission current. that ultimately enhances the power of the line source electron gun. Keeping the acceleration voltages fix, the output power of the gun initially increases abruptly and then slowly. Finally this value saturates as shown in the Fig. 13. In the above said, the LS electron gun, the output power, at 6kV and almost 500W as a filament power having an emission of 1250mA. corresponds to a power of 7.5kW as an output of the gun. For 7kV at 500W, with an emission current of 1570mA the measured power generated is 11kW. Similarly, for 8kV and 500W, with an emission current of 1875mA the output power is 15kW.

The limitations are made in calculating the above data i.e. Ha,f (height of the anode from the filament) because of range of the power supply. In our case this height is 7.5mm.

VIII. CONCLUSIONS

For AVLIS program there is a need to have a uranium vapor source. The electron gun (point source) has proved to be an efficient source of evaporation. It has been studied that a point source electron gun has a very limited charge for long term evaporation for refractory metals. In literature, a magnetically focussed line electron gun design was discussed. However, no information about its evaporation characteristics was reported.

Keeping in view the requirements, we design line source capable of operating at 35kW power range is fabricated. Although we have reported the power 15 kW only as we have mentioned previously in the design section, we are restricted by the limitations of the available power supply.

Deformation of the cathode at this power level was a serious problem, which had been solved successfully giving a uniform stretch of nearly 2Kg with the help of a spring mechanism. The evaporation characteristics studied indicate that at low power level, the gun is not an efficient one but it starts improving efficiency as the power rises. The gun has a good application for melting and evaporation of the refractory materials.

ACKNOWLEDGMENTS

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Figures and Graphs

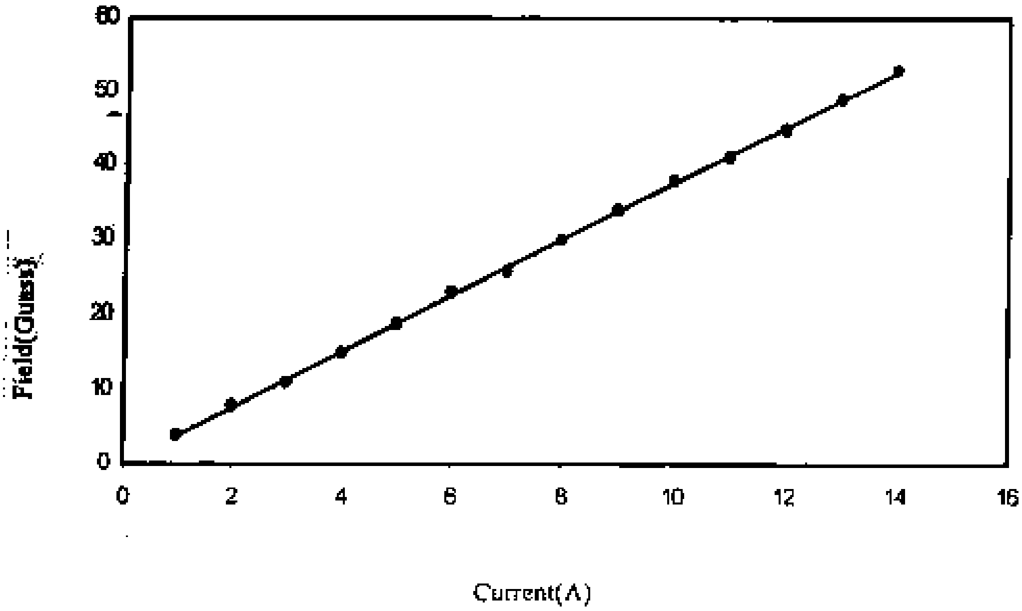


Fig.1: Magnetic Field at the Centre of the Coil

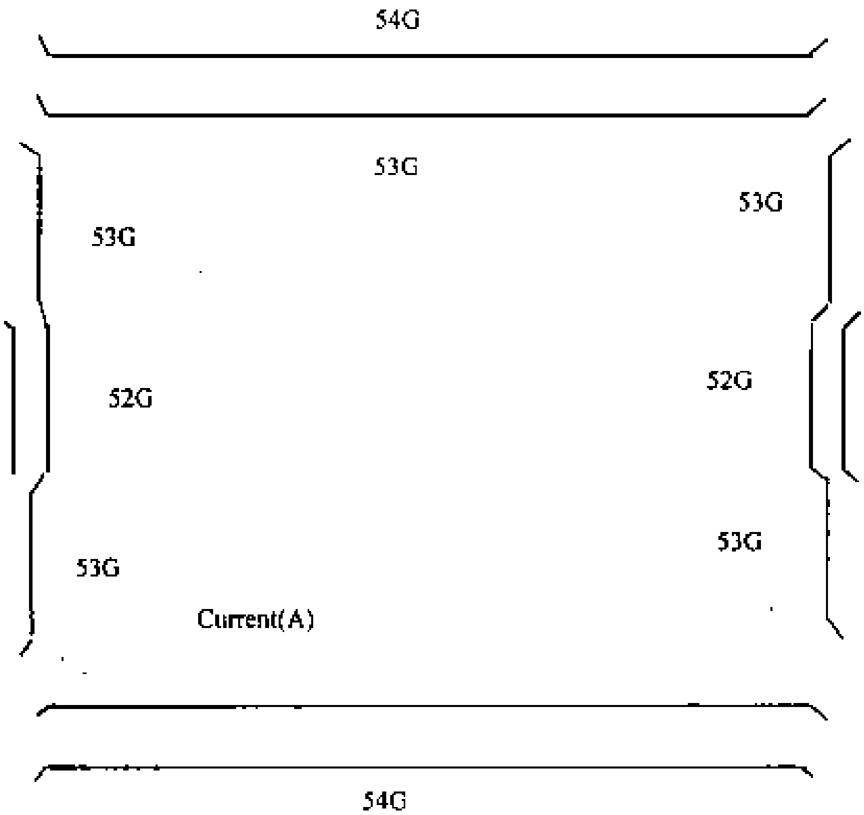


Fig.2: Uniform magnetic field configuration 2cm below the plateform level. The field is uniform 24 *units along and 32 units across the coils axis*

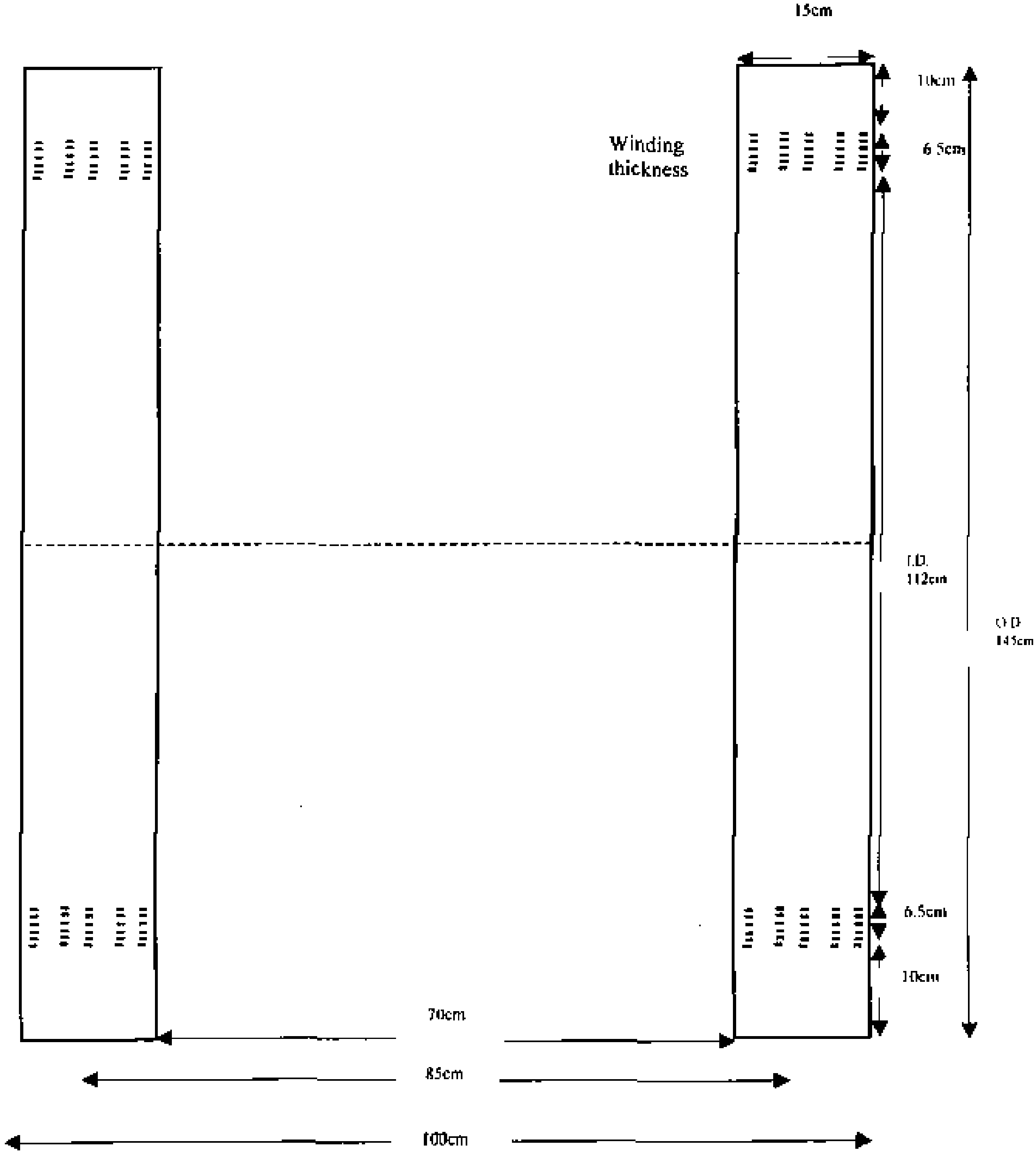


Fig.3: Large Diameter Helmholtz Coil

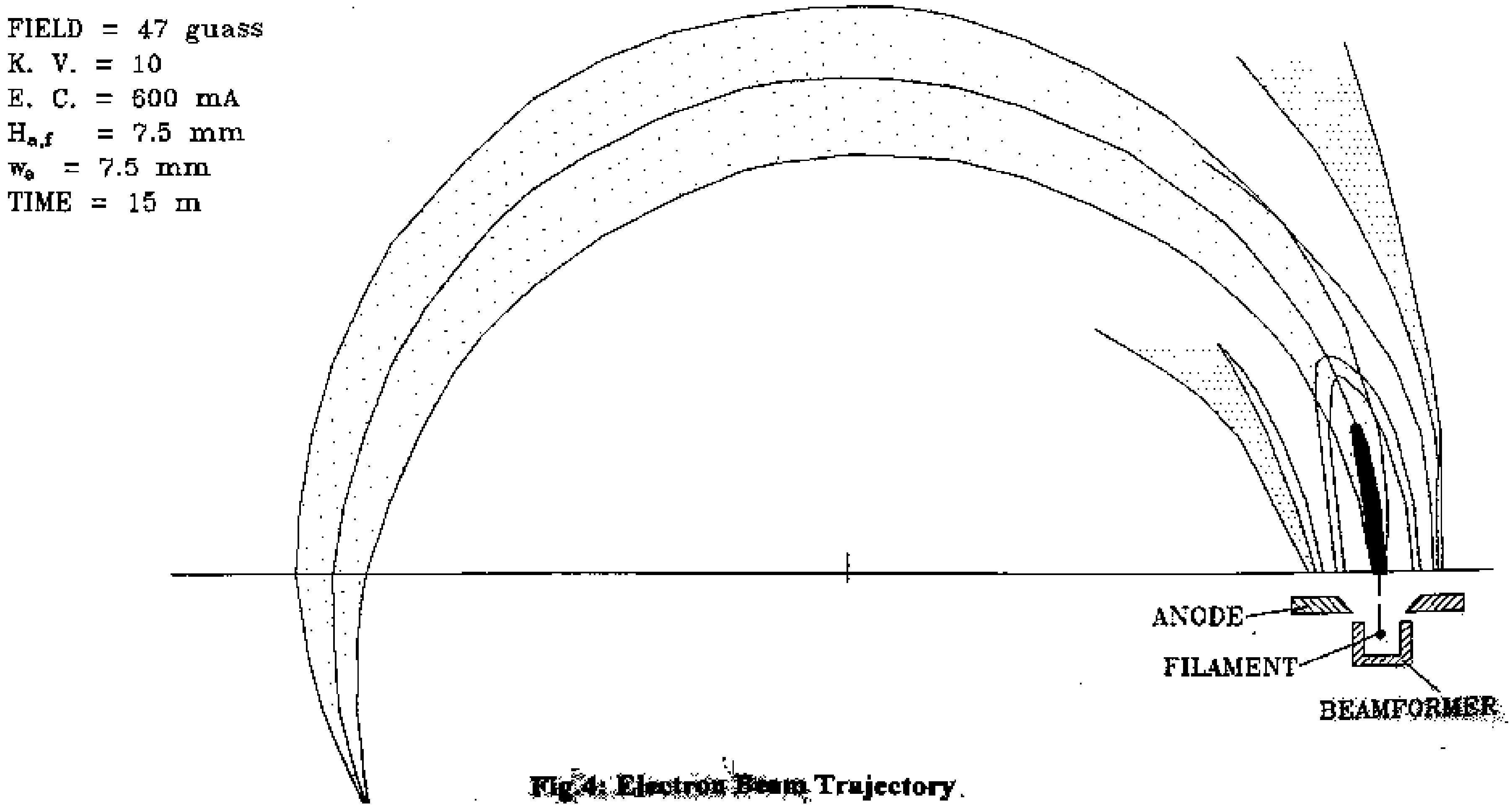


Fig.4: Electron Beam Trajectory

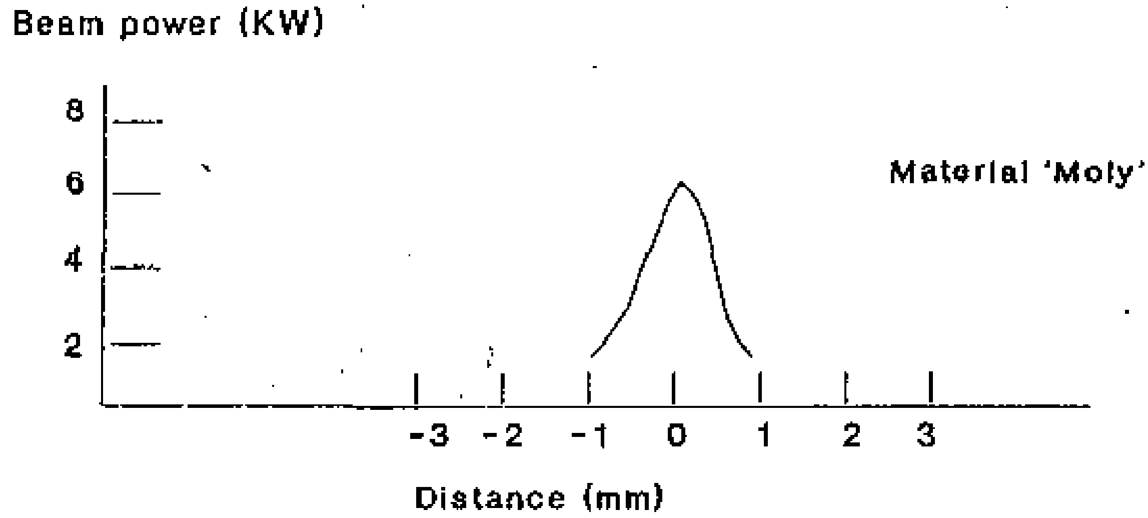


Fig.5(a): Profile of a Typical Beam Shape Across the Beam Dimension

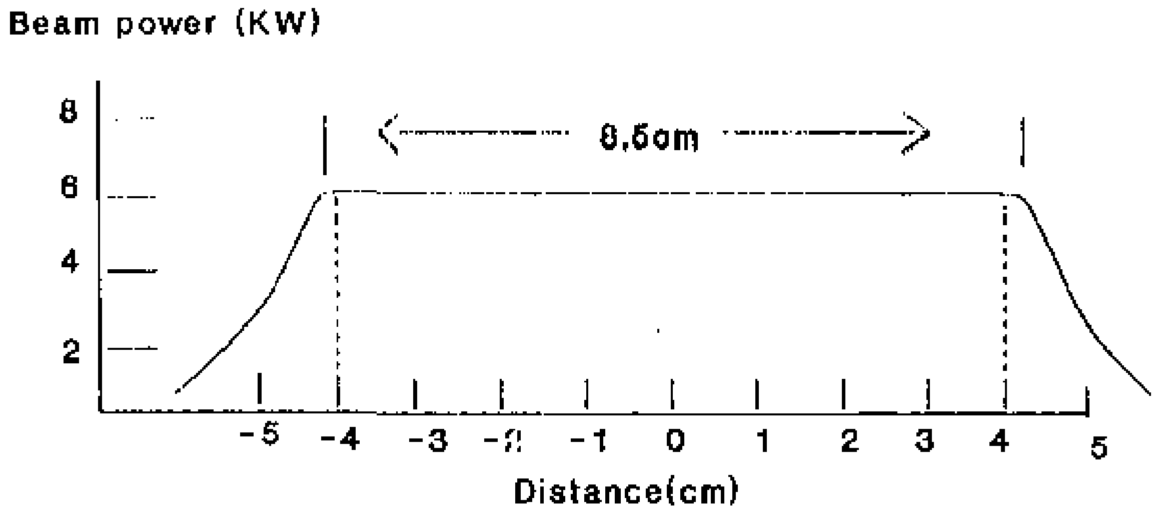
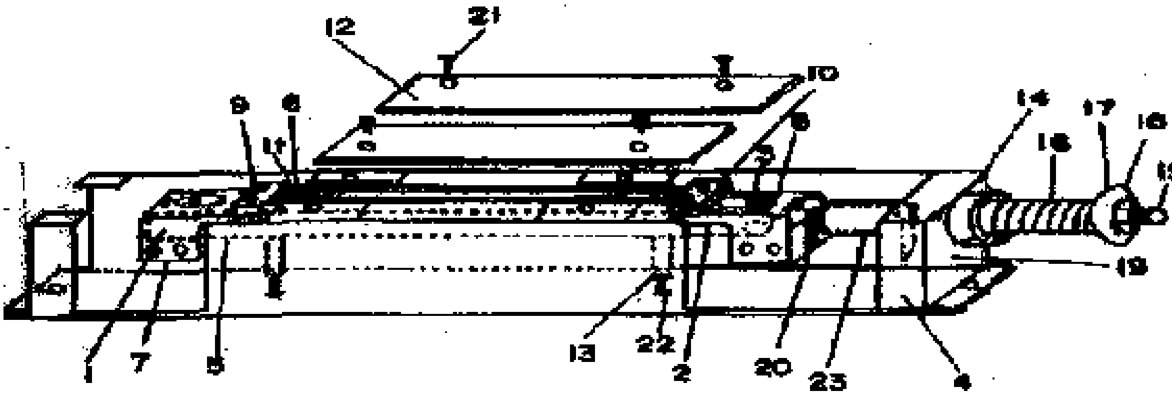


Fig.5(b): Profile Along the Length of the Beam at Work Site

Fig.5(c): Electron Beam Lines at Work Site Recorded on Molybdenum Sheets



1. Filament Buss Bar (LH) Ta
2. Filament Buss Bar (RH) Ta
3. Flanged Insulator (Alumina)
4. Emitter Frame (SS)
5. Support Bar (SS)
6. Filament (W)
7. Cathode Block (LH) Mo
8. Cathode Block (RH) Mo
9. Filament Clamp (LH) Mo
10. Filamp Clamp (RH) Mo
11. Beam Former (Ta)
12. Anode (Ta)
13. High Voltage Insulator (Alumina)
14. Spring Holding Cap (SS)
15. Rod Copper
16. Spring Carbon Steel
17. Washer (SS)
18. Nut (SS)
19. Spring Support (Ta)
20. Insulator Bar (Alumina)
21. Screw (SS)
22. Washer (SS)
23. Insulator Cover (SS)

Fig. 6: Line Source Electron Gun

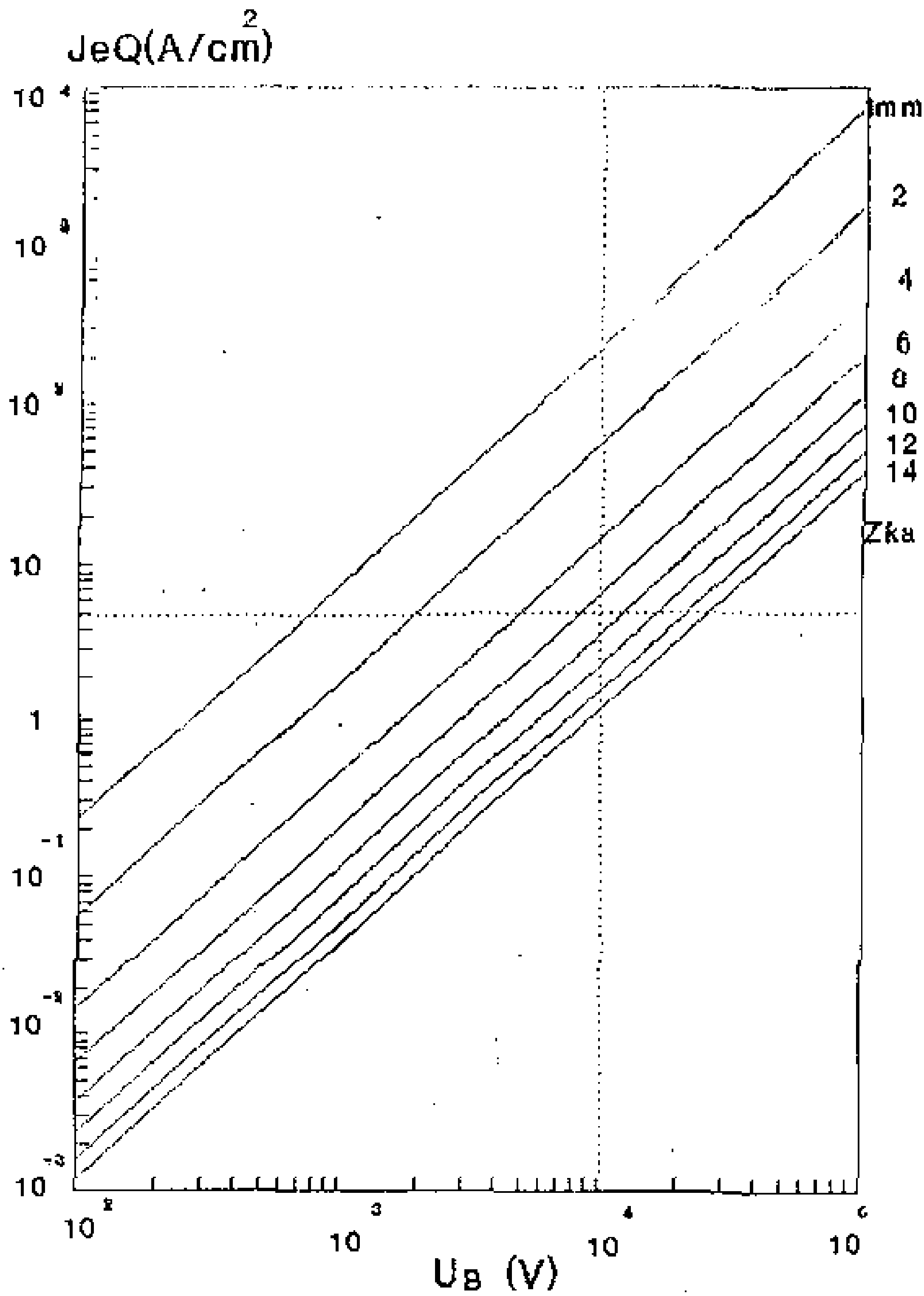


Fig. 7: Emission Current (Space Charge Limited) Vs Acceleration Voltage

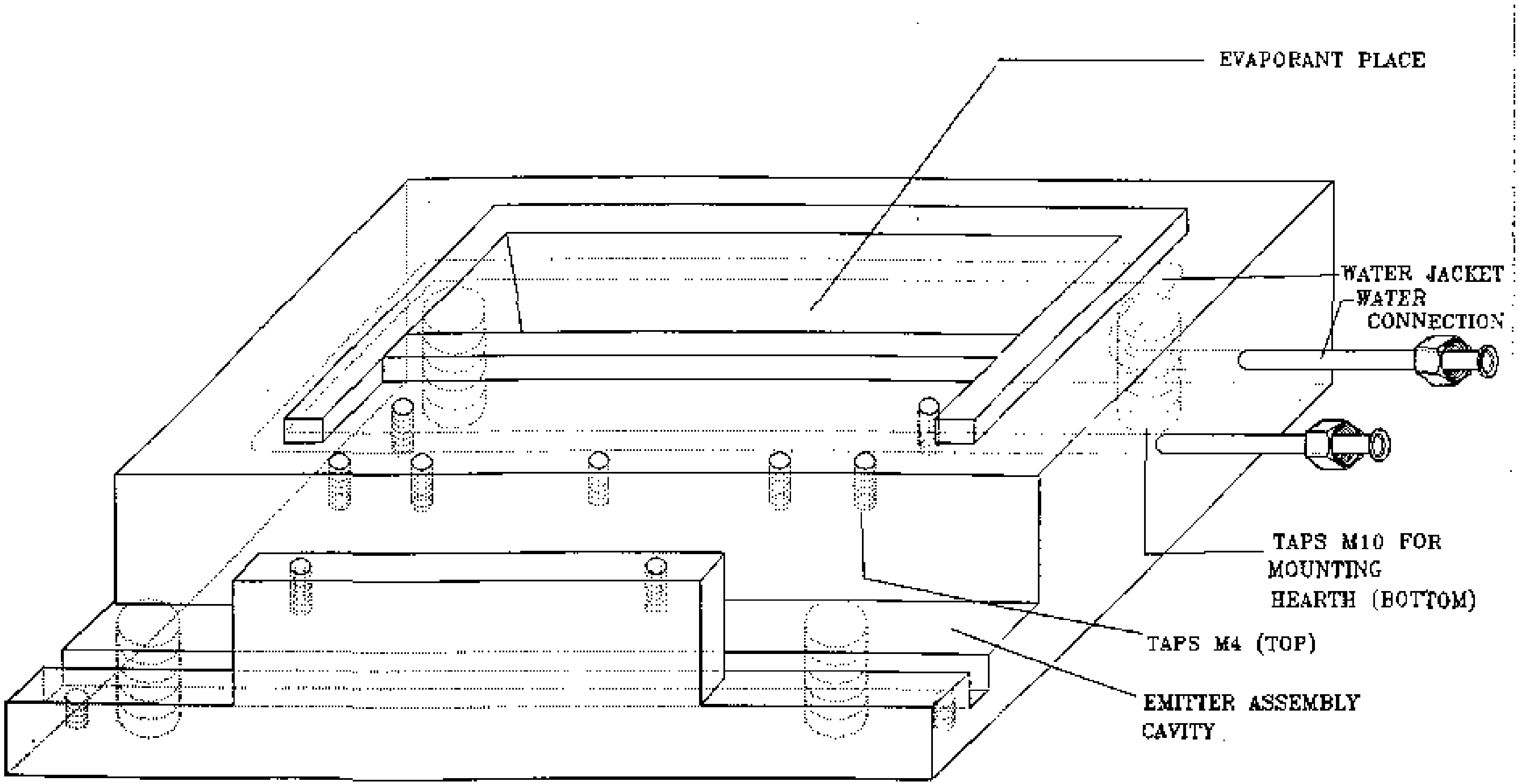


Fig.8: Water Cooled Copper Hearth

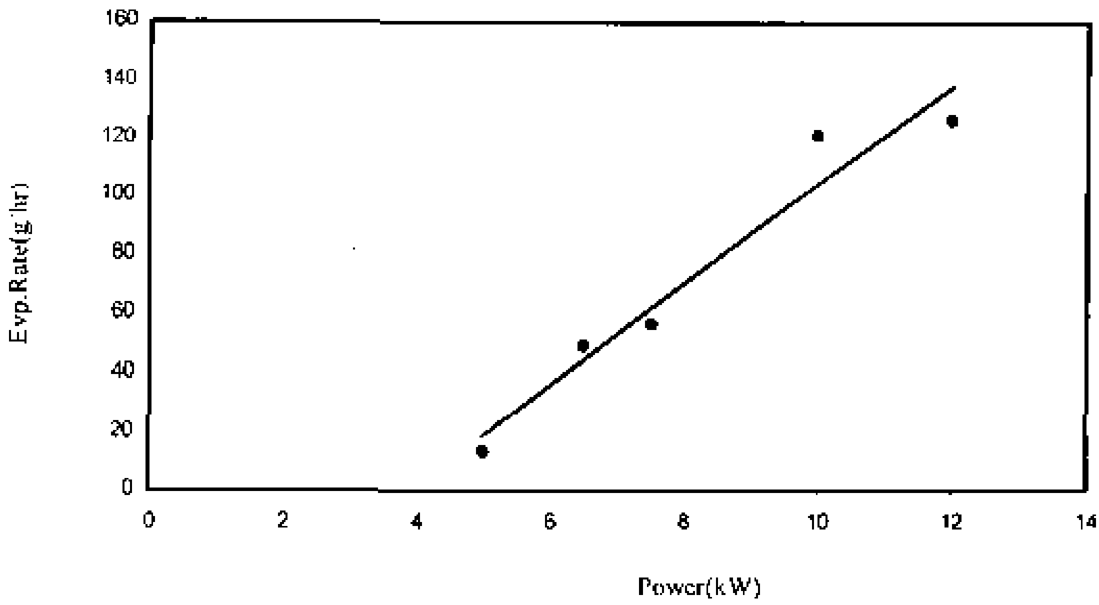


Fig. 9(a): Evaporation Rate Vs Power at $H_{a,f}$ = 7.5mm

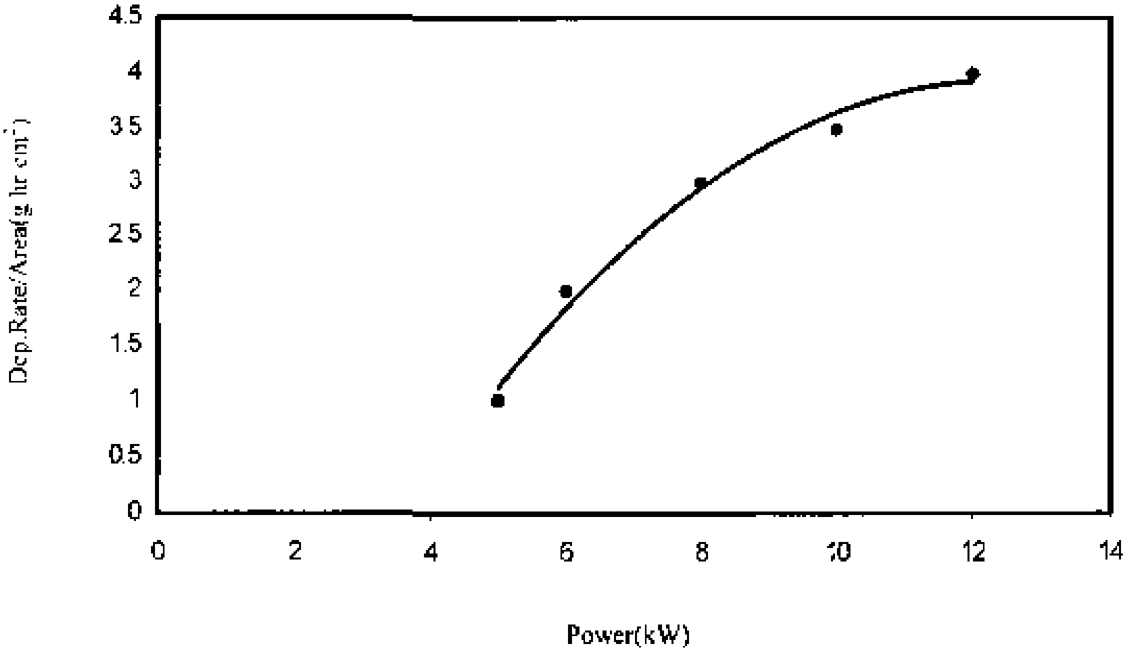


Fig.9(b): Deposition Rate Vs Power at $H_{a,f}$=7.5mm

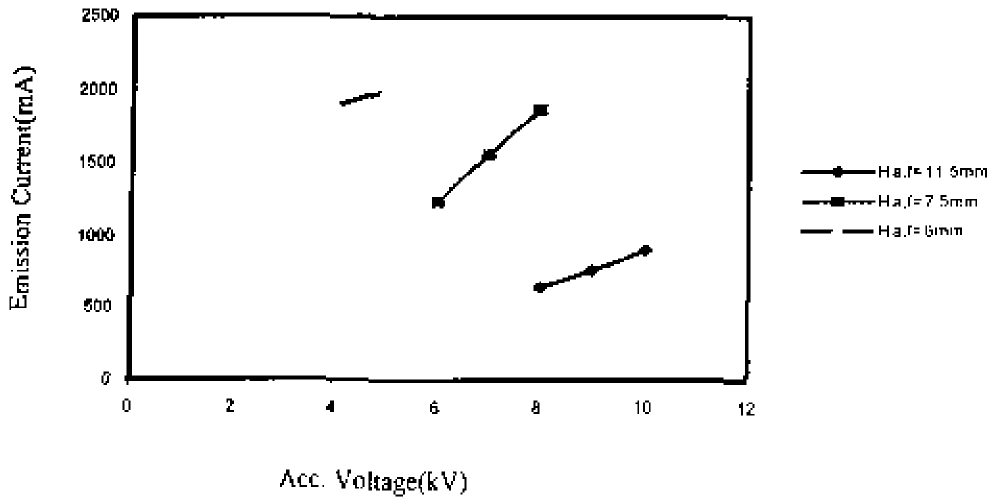


Fig.10: Emission Current Vs Acceleration Voltage

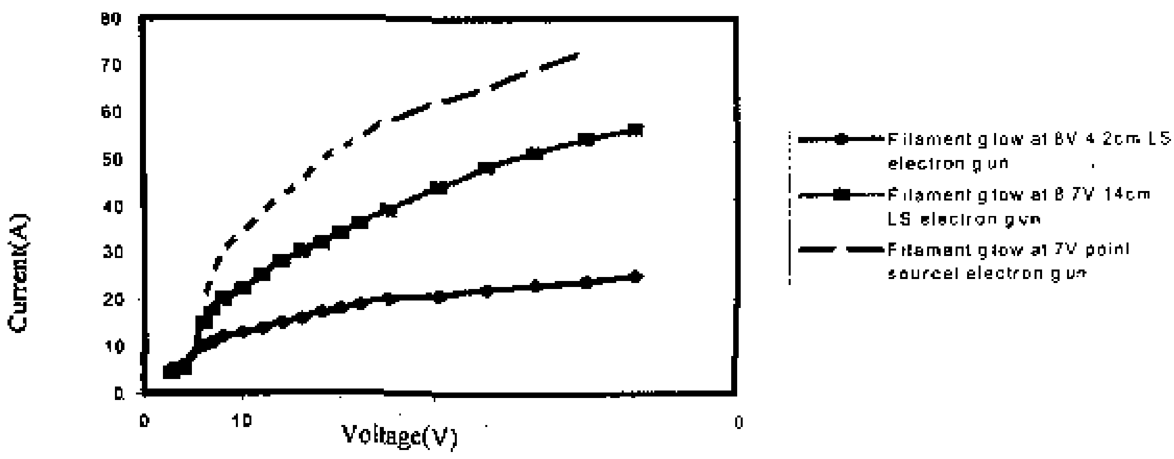


Fig.11: Voltage Current Characteristics

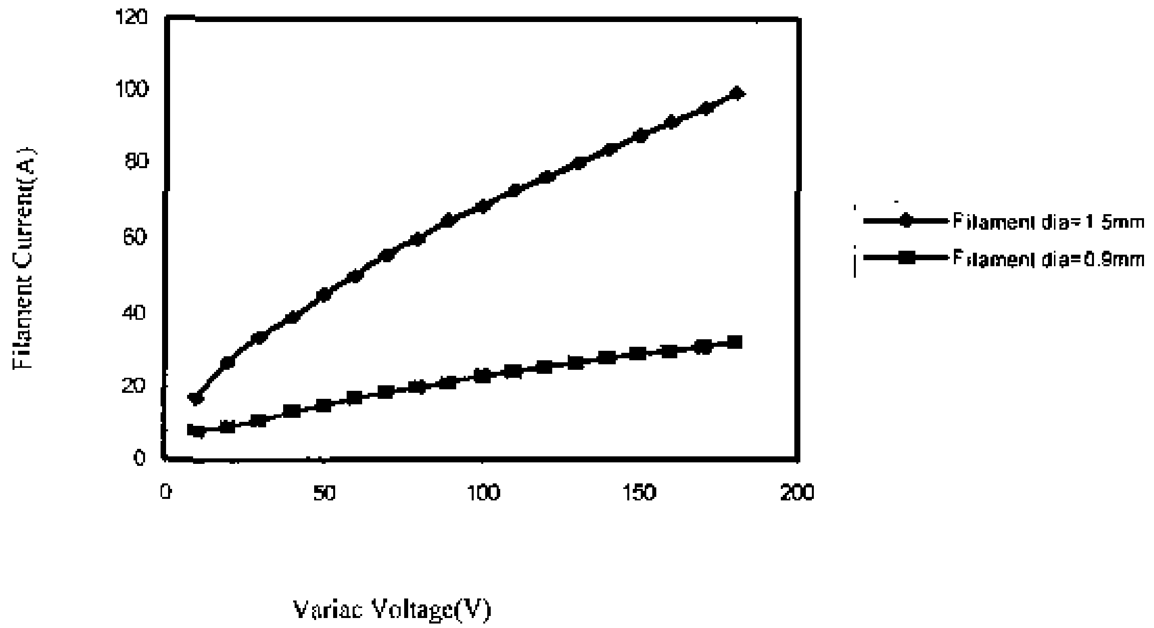


Fig. 12: Filament Current Vs Variac Voltage

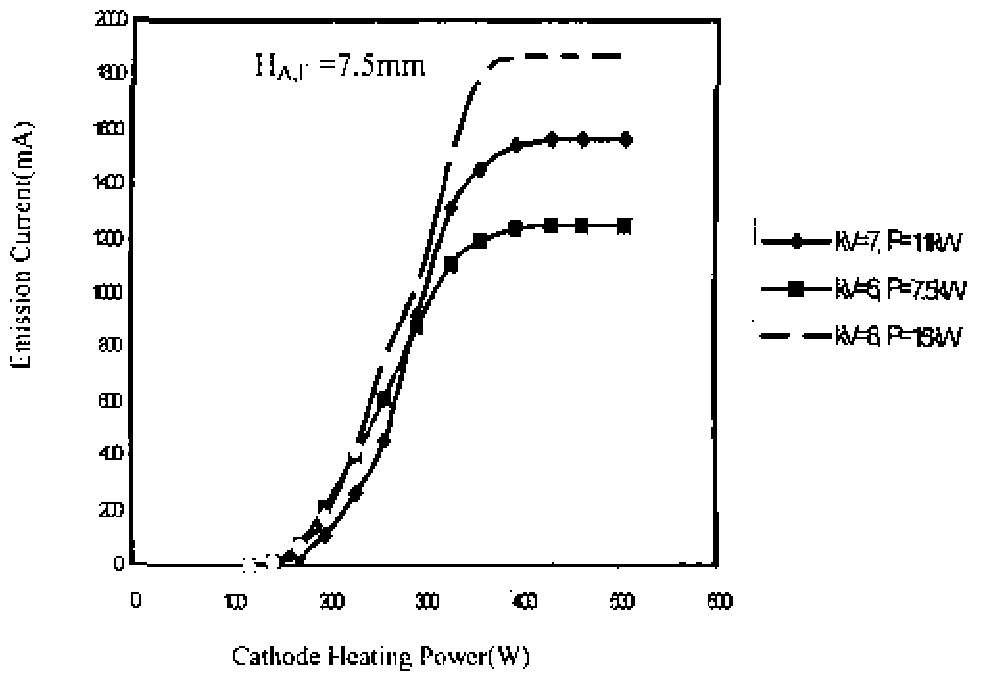


Fig.13: Emission Characteristics of LS Emitter Assembly