

April 30, 1968

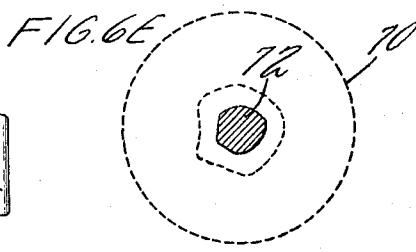
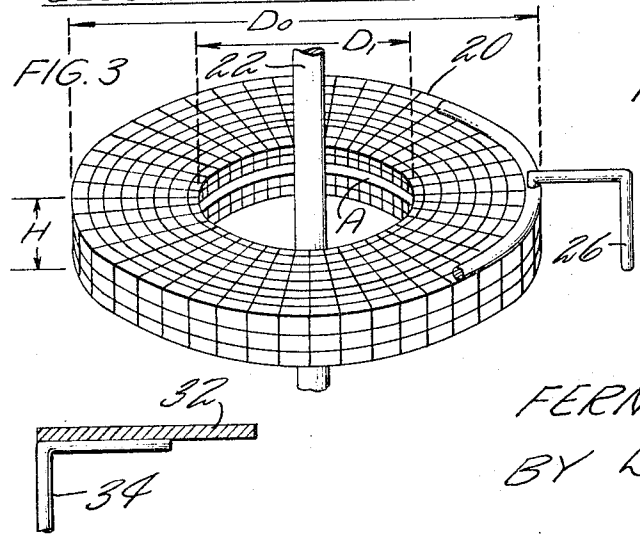
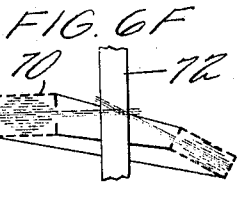
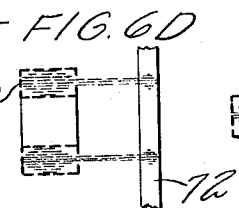
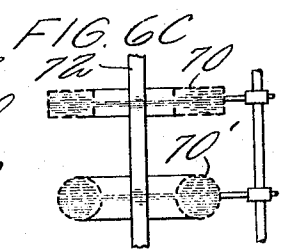
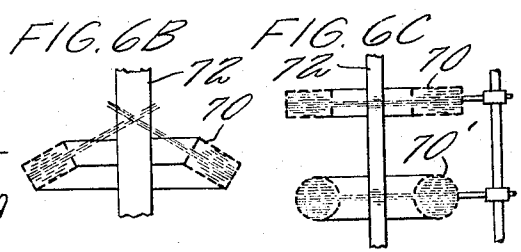
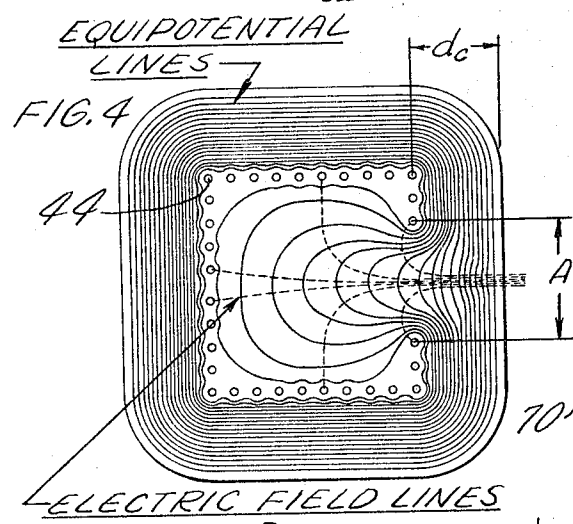
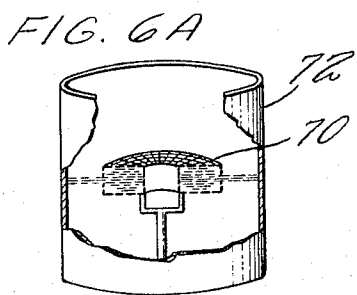
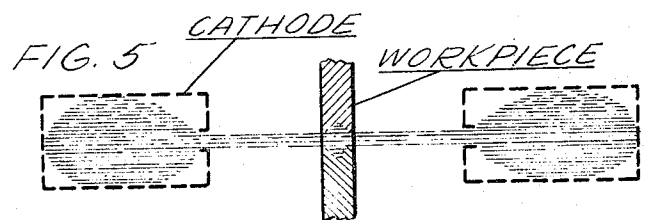
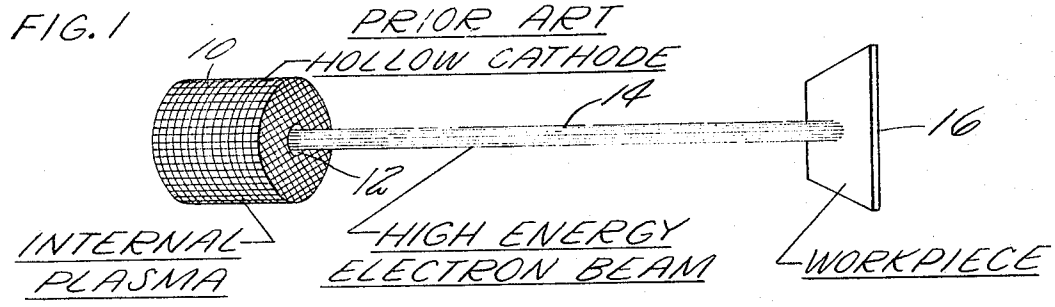
F. J. FERREIRA

3,381,157

ANNULAR HOLLOW CATHODE DISCHARGE APPARATUS

Filed Dec. 10, 1964

2 Sheets-Sheet 1



INVENTOR
FERNAND J. FERREIRA
BY Donald J. Bradley
ATTORNEY

April 30, 1968

F. J. FERREIRA

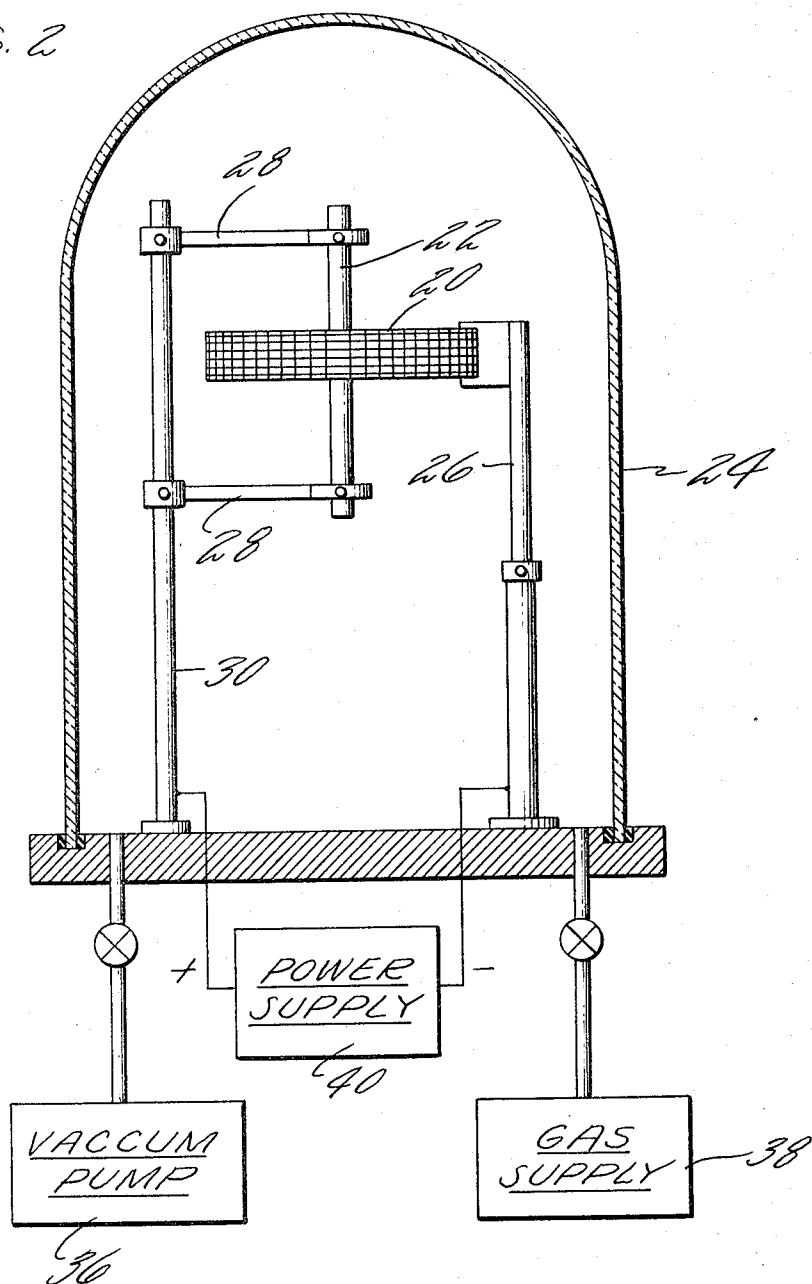
3,381,157

ANNULAR HOLLOW CATHODE DISCHARGE APPARATUS

Filed Dec. 10, 1964

2 Sheets-Sheet 2

FIG. 2



INVENTOR
FERNAND J. FERREIRA
BY Donald & Bradley
ATTORNEY

1

3,381,157

ANNULAR HOLLOW CATHODE DISCHARGE APPARATUS

Fernand J. Ferreira, Hazardville, Conn., assignor to United Aircraft Corporation, East Hartford, Conn., a corporation of Delaware

Filed Dec. 10, 1964, Ser. No. 417,399

16 Claims. (Cl. 313-348)

This invention relates to a novel annular hollow cathode and particularly to a perforated cathode which emits a disc-like beam of electrons radially inward from a slit aperture around its entire inner periphery.

Conventional methods of producing electron beams liberate electrons from the surface of a heated cathode by thermionic emission. Electron beams are produced in a hollow cathode by the release of electrons as a result of the impact of high energy electrons with background gas molecules within the hollow cathode itself.

Previous conventional hollow cathodes comprise closed hollow cylinders fabricated from wire mesh or perforated metal with a circular aperture in one end. When the cathode is biased to a high negative potential with respect to its surroundings which act as the anode, a glow discharge is initiated. Under certain combinations of cathode geometry and pressure level, a well-collimated pencil beam of high current density, high-energy electrons emanates from the hollow cathode aperture. The beam can be focused by conventional electromagnetic lenses to power densities comparable with those of conventional electron beam welders.

This invention comprises an improved hollow cathode in which the cathode is substantially annular and which produces a thin, disc-shaped beam. Electrons are emitted from a circular aperture in the cathode and are accelerated radially inward toward a workpiece with energies corresponding approximately to the full voltage applied across the discharge, usually in the kilovolt range. If the workpiece is a metal, it may act as the anode. If the workpiece is an insulator, the electrical circuit is completed for example by secondary electron emission from the workpiece surface and conduction through the residual ambient plasma to a remotely located anode. The annular cathode may be used for applications such as welding, brazing, zone melting, fibre drawing and vapor deposition.

The annular hollow cathode is preferably a hollow toroid or similar shape fabricated from wire mesh, usually a refractory metal. The cathode is maintained at a negative potential with respect to the anode, which is either the workpiece or a metallic portion of the apparatus such as the supporting structure. Electrons are emitted from the slot or annular gap which is provided on the inside of the toroid. To operate the cathode, the surrounding pressure is lowered to the range of generally 0.1 micron of mercury. The substantially evacuated chamber is then back filled with an inert gas such as helium or argon, or any gas compatible with the workpiece at the temperatures employed. With the appropriate pressure, usually in the range of 1 to 1000 microns, a hollow cathode discharge can then be initiated and maintained with a potential difference of several thousand volts between the cathode and anode or workpiece. Under these conditions a well-focused beam of electrons is emitted from the annular slot and bombards the workpiece uniformly around its circumference.

Modified cathode shapes and arrangements may be used, for example, inverted cathodes with beams directed radially outward, cathodes with axially directed beams, multiple or stacked cathodes, and cathodes with irregular

2

cross-sectional areas, geometries or shapes to weld irregularly shaped pieces.

It is therefore an object of this invention to provide a novel substantially annular hollow cathode.

Another object of this invention is a novel annular hollow cathode having solid or perforated walls which may be used with nonconductor as well as with metallic workpieces.

A further object of this invention is a novel annular hollow cathode which may be used for welding, brazing, zone melting, fibre drawing and vapor deposition.

Another object of this invention is a novel annular hollow cathode having an irregular shape for operating upon irregular workpieces.

A still further object of this invention is a novel inverted annular cathode for performing welding or other operations from inside a pipe or workpiece.

These and other objects and a better understanding of the invention may be had by referring to the following description and claims, read in conjunction with the accompanying drawings, in which:

FIGURE 1 shows a perforated wall hollow cathode of the prior art;

FIGURE 2 is a schematic of a typical annular hollow cathode system;

FIGURE 3 shows the detail of the preferred annular hollow cathode;

FIGURE 4 shows schematically the operation of the annular cathode;

FIGURE 5 shows a detailed cross section of the cathode structure and the beam generated therein; and

FIGURE 6 shows additional geometries and configurations of the hollow cathode of this invention.

Referring now particularly to FIGURE 1, there is shown the prior art hollow cathode comprising a closed hollow cylinder 10, the cylinder being fabricated from the wire mesh. A circular aperture 12 is cut in one end of the cylindrical cathode 10. When the cathode is biased negatively with respect to the anode, which may be the surroundings or the workpiece, a glow discharge is initiated and a high energy electron beam 14 is generated. Because of the special geometry of the cathode 10, most of the electrons in the portion of the plasma within the cylinder emerge from the aperture as beam 14. Furthermore, these electrons are accelerated through approximately the full potential drop across the discharge in a region very close to the aperture 12. Hence, any small electric fields which exist in the ambient plasma filling the enclosure have a negligible effect on the energy or direction of the beam 14. A workpiece 16 positioned in the path of the beam 14 may be heated, welded or otherwise acted upon by the electron beam 14. While not shown, the beam 14 can be focused by electromagnetic lenses. Likewise, discharge will generally only take place at a pressure level below 1000 microns.

FIGURE 2 shows schematically an annular hollow cathode beam discharge system of this invention, and FIGURE 3 shows the structure of the novel hollow cathode. The annular hollow cathode 20 may be fabricated from stainless steel from a 10 mil, 40 mesh wire cloth or similar substance. Cathodes thus far fabricated have had an outer diameter, D_o , typically from 1.3 to 4 times the inner diameter D_i , but are obviously not limited thereto. The height H of the cathode assembly does not appear to be a critical factor; however, the size of the aperture A may well be critical as will be explained subsequently. Nor does it appear that the wall thickness or the mesh size have an appreciable effect upon the electron beam output.

The cathode 20, workpiece 22 and associated supports are enclosed in an air-tight enclosure 24 which may be

of glass or other suitable material. The cathode is supported by arm 26 which may also be the negative potential lead to the cathode. Workpiece 22 may be held in place by a metallic arm 30 on which are positioned two adjustable clamping structures 28 and 28'. If the workpiece 22 is metallic, it may be grounded to act as the anode. If the workpiece 22 is a nonconductor, the workpiece support structures 28 and 30 may act as the anode. If desired, a separate anode 32, as shown in FIGURE 3, may be provided at any location within the enclosure 24 with a positive potential lead and anode support 34. FIGURE 5 shows in cross section the beam as generated by cathode 20 and focused upon workpiece 22.

The enclosure 24 may be initially evacuated by means of vacuum pump 36. After evacuation to the proper pressure level, a supply of gas 38 may be used to produce a gas atmosphere within the enclosure. The gas may be helium, hydrogen, nitrogen or argon, or any gas suitable for the workpiece.

The theory of operation of the hollow cathode, as presently known, may be explained by reference to FIGURE 4. Several different modes of operation exist. The desirable mode of operation, that is the electron beam mode, is similar to abnormal glow discharge in that it has a positive voltage-current characteristic and undergoes a transition into an arc-like mode of operation, sometimes called the "fountain" mode, as the power level is increased. The voltage or current at which this transition occurs depends upon the cathode geometry, gas type and gas pressure.

The operation of the discharge modes may be compared with the operation of conventional glow discharges. In a conventional glow discharge, practically all the potential drop across the discharge occurs in a region quite close to the cathode, this drop being known as the cathode fall. The characteristic thickness, d_c , of the cathode fall depends on the gas pressure, gas type, cathode material and applied voltage. The high potential end of this region can be identified visually by a sharp demarcation between a dark portion of a discharge near the cathode, called the cathode dark space, and a bright region called the negative glow. Equipotential lines for this distribution are parallel with the cathode.

When the annular hollow cathode aperture A is less than the cathode fall thickness d_c by a factor of ten, the aperture does not perturb the potential distribution significantly. This occurs at low pressure and/or at low voltages. At these operating conditions the cathode operates like a solid cathode without any aperture, and practically none of the discharge occurs inside the cathode because the interior region is at a cathode potential. Consequently no electron beam forms. Likewise very little glow occurs inside the cathode under these conditions.

When the annular hollow cathode aperture dimension A is approximately equal to d_c , the aperture perturbs the potential distribution and a portion of the cathode fall occurs inside the cathode. FIGURE 4 shows these conditions. The potential drop inside the cathode usually comprises a small fraction of the total cathode fall. Furthermore, the special shape of the cathode makes it highly improbable for electrons formed by ionization in the cavity to escape from the cathode cavity through any of the holes except the aperture. Electrons emitted from the inside of the wire screen 44 by secondary emission processes also have a high probability of being trapped in the internal potential well. Even with a discharge of thousands of volts, the maximum potential inside the cathode is probably less than 100 volts. Electrons trapped in this potential well form a secondary discharge which results in volume production of ion-electron pairs due to electron bombardment. Secondary electrons emitted from the cathode are the primary source of electrons for sustaining the discharge within the cathode. Bombardment from ions formed exterior to the cathode is another major source of secondary electrons.

As shown in FIGURE 4, the perturbed potential distribution in the vicinity of the aperture A resembles a

concave lens. The electric field lines normal to the equipotential lines converge in the vicinity of the aperture. Electrons inside the cavity drift toward the aperture in the relatively weak electric field within. In the aperture region they are accelerated through the full cathode fall and thus acquire a highly directed velocity approximately along the fluid lines. In this manner the perforated wall hollow cathode forms a highly collimated energetic electron beam. Therefore, it is quite desirable to keep the potential drop which occurs inside the cathode to a small fraction of the total cathode fall. For this reason it appears that the aperture A should be held somewhat less than d_c . However, A cannot be made too small or no electron beam will form as explained previously.

When the aperture A is substantially larger than the cathode fall thickness d_c , the entire cathode fall occurs inside the cathode. Electrons emitted from the inside surface of the cathode are accelerated through nearly the full discharge voltage in a rather short distance from the wall. Relatively few electron trajectories pass through the aperture. Most of the electrons are trapped in the deep potential well inside the cathode, and these electrons can escape only by making collisions and/or repeated reflections from the walls of the potential well. Most electrons will lose energy in collisions with neutral ions and in elastic collision with low energy electrons and then drift toward the aperture in the relative weak electric field in this region. Therefore, a rather intense plasma forms within the cathode and many ion electron pairs are created in the volume by electron bombardment. The ions so produced are accelerated directly into the cathode wall. When operating in this mode, known as the arc mode, the cathode often heats up to incandescence, indicating a significant dissipation of power at the cathode, and such operation is generally undesirable.

Tests of solid wall cathode in the annular configuration have shown that at the same gas pressures and applied voltages, the solid wall cathode has a lower discharge current and a lower beam power efficiency than that of a perforated cathode of the same geometry. The contribution of the perforations is usually attributed to a pressure gas flow phenomenon. Operation of the solid wall annular cathode can be improved by providing a direct gas feed to the cathode. However, the wall perforations have other important effects on the operation of the cathode.

As previously described, the operation of the perforated wall hollow cathode in the electron beam mode is analogous to an abnormal glow discharge. However, the secondary discharge that occurs inside the hollow cathode and the associated production of ion electron pairs provides it with an additional source of electrons and a higher current capability than a glow discharge. Most efficient operation is achieved when the current from the aperture greatly exceeds the outward current emanating from the exterior surface of the cathode. The outward current represents losses since it does not contribute in any way to the electron beam current. However, some ions outside of the cathode are accelerated through the cathode perforations and through the aperture, and strike the inner wall of the cathode thereby resulting in the release of secondary electrons inside the cathode. For a cathode of given total porosity or open area, the ion current penetrating to the interior cathode region is essentially independent of the characteristic pore size. This is because the ions are accelerated uniformly through the cathode fall, and thereby acquire a sufficiently high velocity so that their trajectories are not perturbed significantly by the detailed structure of the electric field at close proximity to the cathode pores. However, effective trapping of electrons in the discharge within the cathode requires that a significant portion of the internal potential drop should occur close to the inner cathode wall. Thus, more effective electron trapping is achieved when the characteristic pore size is reduced while maintaining

a constant open area and increased beam power efficiency occurs as characteristic pore size is reduced.

In the electron beam mode of operation, a perforated wall annular hollow cathode has a positive-voltage current characteristic. For a given cathode the voltage-current operating regime is strongly dependent on the gas pressure, or more technically the gas density. Experiments show that transition into a high current arc mode occurs at higher pressures as the discharge power level is increased. Observations have been made that the maximum voltage which can be sustained across the discharge in the electron beam mode of operation decreases with increasing pressure. Further, for a given pressure, lower current levels are obtained with a solid wall configuration than with a perforated wall. However, the solid wall cathode is capable of operation at higher pressure levels before transition into the arc mode, and this feature may provide some advantages for certain applications.

At the same pressure and voltage, the measured beam power as well as the input power of the perforated wall cathodes is slightly higher for the larger cathodes. The solid wall cathode operates at significantly lower power than any of the perforated wall cathodes regardless of size. Beam power efficiency is comparable for all perforated wall cathodes. Efficiencies of the annular cathode of 75% have been achieved. Shielding around the solid wall annular hollow cathode is an effective means for increasing the efficiency of this cathode to this level.

FIGURE 6 shows additional modifications of the cathode assembly. In FIGURE 6A, the cathode assembly 70 is inverted so that the beam is directed radially outward to thereby weld from the inside of the pipe or other workpiece 72. The ends of the pipe 72 will require sealing. In FIGURE 6B the cathode 70 is not plane, but at an angle so that the beam focuses on the workpiece 72 at a point other than the plane of the cathode. The beam would therefore be conical in shape.

FIGURE 6C illustrates the use of multiple or stacked cathodes 70 and 70' which may operate upon a workpiece 72 simultaneously. One of the cathodes is shown to be circular in cross section. The cathodes may be movable relative to the cathode support. FIGURE 6D shows the use of a cathode 70 having an axially directed beam which forms a circular pattern upon workpiece 72.

For irregularly shaped workpieces, numerous modifications of the cathode may be used. In FIGURE 6E an irregularly shaped cathode 70 is shown operating upon an irregularly shaped workpiece 72. Or the cathode may be irregular in cross section, as shown in FIGURE 6F. Other modifications are obvious to those skilled in the art, such as cathodes of various geometries such as triangular or trapezoidal, cathodes with varying width apertures or with irregularly shaped apertures, or with a portion of the aperture blocked.

An obvious application of the annular hollow cathode is that of butt welding tubes of similar or different materials such as aluminum, stainless steel, Kovar, titanium and columbium. Welds of high strength may be produced. If the workpiece is misaligned from the centerline of a symmetrical cathode, that portion of the workpiece farthest from the cathode may be overheated, so that alignment should be precise.

Other applications of the annular hollow cathode are brazing, sputtering, and zone heating. For example, the feature of the annular hollow cathode which allows it to heat insulators as well as conductors produces a high potential for such applications as zone refining of ceramics and growing crystals of materials such as alumina. The use of the annular hollow cathode in a cusped magnetic field provides a mechanism for spreading the heated zone.

The annular hollow cathode may also be used to provide the heat for drawing fibres of Pyrex, Vycor, fused silica and other similar materials. In addition, the cathode may be used to heat both tungsten and fused silica or other substrates in chemical vapor deposition.

The annular hollow cathode thus produces a well-focused electron beam of high power density utilizing a mechanically simple electron accelerating system requiring no critical alignment. There is no need to electrically heat a cathode, thereby producing improved cathode lifetime. Nor is there a need for a high vacuum system, thereby eliminating the need for a diffusion pump as in electron beam systems. Of particular advantage is the fact that the annular hollow cathode may be used on non-conductors as well as on metals without any special accessories.

It is apparent to those skilled in the art that the cathode configurations shown are not the only possible configurations, and that a wide range of regular and irregular cathode geometries may be derived from this teaching. It is also obvious that various modifications and substitutions may be made without departing from the scope of the invention as hereinafter claimed.

In the following claims, the words "substantially annular" mean having a substantially closed perimeter and include irregular shapes such as C, U, polygonal, elliptical, or circular.

I claim:

1. In a hollow cathode device for producing an electron beam,
 - a cathode structure comprising a hollow metallic element containing a continuous elongated aperture along at least a portion of the surface thereof, and means for causing said cathode structure to emit from the said aperture a plane-collimated uninterrupted sheet of electrons by nonthermionic discharge, said aperture being curved in the plane containing said sheet of electrons.
2. A hollow cathode device as in claim 1 in which said cathode structure is substantially annular, said aperture extending about the center of said element.
3. A hollow cathode device as in claim 1 in which said cathode structure is at least partially perforated.
4. A hollow cathode device as in claim 1 in which said hollow metallic element is ring-shaped, said aperture extending continuously about the inside surface of said element whereby said sheet of electrons converges at the center of said element.
5. A hollow cathode device as in claim 1 in which the electron beam is produced by means of an abnormal glow discharge having a cathode fall region adjacent the cathode, the said aperture being approximately as wide as the cathode fall region.
6. A hollow cathode device as in claim 1 and including an enclosure surrounding said element, means to produce a low atmospheric pressure within said enclosure, electrode means within said enclosure, and power supply means for applying a voltage between said element and said electrode means.
7. A hollow cathode device as in claim 6 in which said enclosure is filled with a gas at a pressure of about a fraction to several mm. Hg.
8. A hollow cathode device as in claim 7 and including a workpiece, and means for supporting said workpiece within said enclosure in the path of said electron beam.
9. A hollow cathode device as in claim 8 in which said workpiece is the electrode means.
10. A hollow cathode device as in claim 8 in which said workpiece is an insulator.
11. A hollow cathode device as in claim 1 in which said aperture is continuous about the surface of said element.
12. In a hollow cathode device for producing an electron beam,
 - a cathode structure comprising a hollow metallic element containing a continuous elongated aperture along the surface thereof, said hollow metallic element being ring shaped and having a cross-section in the form of a substantially

7

closed planar figure interrupted by a narrow peripheral slot, said slot forming a portion of said continuous aperture,

and means for causing said cathode structure to emit from the said aperture a plane-collimated uninterrupted sheet of electrons by nonthermionic discharge.

13. A hollow cathode device as in claim 12 in which the cross section of said hollow metallic element varies on area with azimuthal locations about the center of said element.

14. A hollow cathode device as in claim 12 in which the cross section of said hollow metallic element varies in geometric shape with azimuthal locations about the center of said element.

15. A hollow cathode device as in claim 12 in which said slot varies in orientation with azimuthal locations about the center of said element.

8

16. A hollow cathode device as in claim 12 in which said slot varies in width with azimuthal locations about the center of said element.

References Cited

UNITED STATES PATENTS

2,084,172	6/1937	Weiller	313—339 X
3,210,518	10/1965	Morley	313—339 X
3,218,431	11/1965	Stauffer	219—121
3,262,013	7/1966	Allen	313—339

FOREIGN PATENTS

888,609	1/1962	Great Britain.
---------	--------	----------------

JAMES W. LAWRENCE, *Primary Examiner*.
STANLEY D. SCHLOSSER, *Examiner*.