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Coaxial Cathode Design for Plasma Sources

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An electron bombardment heated cathode structure is described which is capable of producing an electron emitting surface 5.7 cm in diameter at 2700 K, with ±5 K azimuthal temperature uniformity. The coaxial structure allows access along the axis, is assembled from modular components machinable on a lathe, and requires no water cooling internal to the vacuum system. The "cathode" is particularly suitable as an emitting end plate for a thermionic plasma (Q machine).

I. DESIGN CONSIDERATIONS

IN this article we describe an electron emitting hot plate structure designed for use as an end plate in an alkali-metal contact-ionized plasma (Q machine[1]). The hot plate is also suitable for use as a cathode in any gas discharge or plasma source. The particular advantages of this design are (1) the high degree of temperature uniformity achievable, (2) the possibility of introducing particle or photon beams or current carrying wires into the plasma along the axis, and (3) the ease and accuracy of assembly due to the coaxial, modular construction.

The necessity for extreme care in eliminating temperature gradients in Q machines has been pointed out previously.[2] In such plasmas the electric potential on each magnetic line of force is determined by the sheath drop at the hot plate, and this, in turn, is determined by the balance between the random electron flux arriving at the plate and the thermionically emitted flux. Since thermionic emission varies exponentially with temperature, a small temperature gradient on the plate will cause a large potential gradient in the plasma. The resulting $\mathbf{E}\times\mathbf{B}$ drift in the plasma will seriously affect experimental measurements unless the plate temperature is uniform to much better than 1%.[2] Particularly harmful are azimuthal gradients, which lead to radial drifts, asymmetry of the plasma column, and loss of plasma via steady state convection.

Heating of the plate by electron bombardment from a filament was chosen because a high impedance power supply could be used. An alternative would be to heat the tungsten plate directly by passing current through it. However, the large currents required would distort the magnetic field near the plate, and ripple in the power supply would excite oscillations in the plasma. Another alternative is to heat the plate by radiation, but it is not easy to achieve high temperatures by this method. For instance, to supply the random electron flux of 1.2 A/cm^2 at a density of 10^{12} cm^{-3}, a temperature of 2660 K is required for tungsten. Operation at such densities under electron rich conditions[3] thus requires temperatures of the order of 2700 K.

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[2] F. F. Chen, Phys. Fluids **9**, 2534 (1966).
[3] F. F. Chen, Phys. Fluids **8**, 752 (1965).

In designing an electron bombardment system,[4] the problem is the insulation of the filaments for high voltage. On the one hand, if the insulators are placed close to the filaments, high temperature operation is limited by the melting point of available ceramics. On the other hand, if the insulating supports are placed far from the source of heat, the accurate alignment of parts necessary for uniform temperature distribution is difficult. In the present design, we make use of thin insulators placed near the filaments and depend on the heat conductivity of the ceramics to keep them cool.

To achieve temperature uniformity we used the following tricks: (1) a plate thickness (1.3 cm) comparable to the filament spacing to smear out the discrete filament structure; (2) preferential input of heat near the plate edge, where there are additional conduction and radiation losses, together with an aperture limiter which masks off the outer 6 mm of the plate; (3) the use of the $\mathbf{j}\times\mathbf{B}$ force on the filaments to keep them in the same plane; and (4) space charge limited operation to avoid thermal runaway,[5] together with accurate alignment of the filament plane with the hot plate. In regard to the last point, note that *local* thermal runaway would lead to temperature gradients even if the plate as a whole operated stably. Space charge limited operation avoids this problem but requires extreme accuracy in alignment. The bombardment current density is given by the Child–Langmuir formula

$$j=(2e/m)^{\frac{1}{2}}V^{\frac{3}{2}}/9\pi d^2, \tag{1}$$

where V is the bombardment voltage and d the filament–plate spacing. The heating power $P=jV$, then, varies as $V^{\frac{5}{2}}$ and is radiated away according to the Stefan–Boltzmann law,

$$P\propto V^{\frac{5}{2}}d^{-2}\propto\sigma T^4. \tag{2}$$

Thus

$$\Delta T/T=-\tfrac{1}{2}\Delta d/d,$$

and $\Delta T/T<0.2\%$ (5° out of 2500°) would require a spacing error less than 0.04 mm when $d=1$ cm. We do attempt to align the filament plane to this order of accuracy. Fortunately, individual filaments can deviate from the plane by considerably more than this if the deviations are random. Equation (2) shows that T is proportional to $V^{5/8}$. If the series–parallel arrangement of filaments (see Sec. II.D) is used, and $V=2000$ V, then the voltage drop of 6 V along the filaments would be sufficient to cause a $\Delta T/T$ of 0.2%.

II. DESCRIPTION

A diagram of the hot plate assembly is shown in Figs. 1 and 2. This design incorporates improvements made in the course of three years of operation.

A. Cooling

The assembly is encased in the copper cylinder (1) and the clamping lid (2). The cylinder (1) is machined to slide snugly into a copper vacuum chamber which is water cooled from the outside. When the assembly is heated, the cylinder (1) expands until it makes good thermal

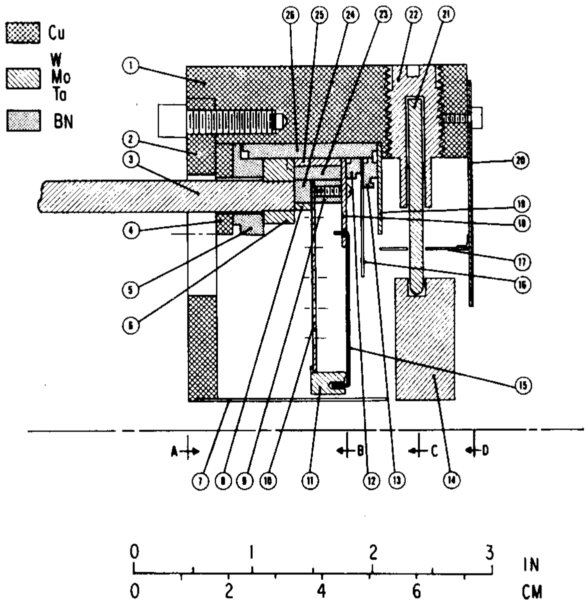

FIG. 1. Diagram of one-half of the cross section of the hot plate assembly.

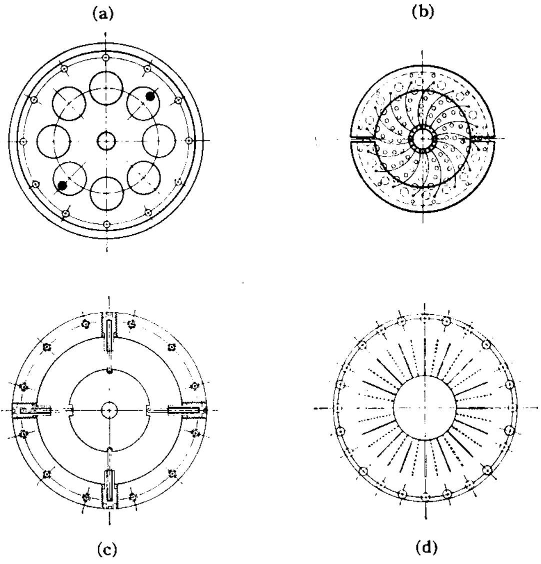

FIG. 2. Axial views of the hot plate assembly in the planes A, B, C, and D shown in Fig. 1.

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[4] The hot plate is the *anode* of the electron bombardment system and the *cathode* of the gas discharge or the zero potential ionizer of a Q machine.

[5] Thermal runaway can occur if the filament emission is temperature limited; then an increase in emission makes the hot plate hotter, and the increased back radiation heats the filament, leading to a further increase in emission.

contact with the vacuum chamber. No internal water cooling lines are needed.

B. Ceramics

The insulators, parts (5), (9), (12), (13), (23), (24), and (26), are all in the shape of circular rings. The material must be chosen to have relatively high heat conductivity and high electrical resistivity at elevated temperatures. Particularly critical is (13), which must support a large thermal gradient as well as the full bombardment voltage. Note that the parts subjected to high voltage have grooves machined in them to prevent surface conduction along evaporated metallic layers; part (13) has a particularly complicated groove. After experimenting with various grades of alumina, we have found that boron nitride (BN) works better than alumina in all respects. It is less brittle than alumina, and, if care is taken to keep moisture out of the BN, the outgassing time and ultimate pressure are no worse than for alumina. The high material cost of BN is more than compensated for by the ease of machining.

C. Filament Subassembly

The filaments (15) are preassembled in a jig consisting of parts (9), (10), (11), and (18). The filament support ring (18) and the back plate (10), which is drilled with pumping holes, are molybdenum plates 0.76 and 2 mm thick, respectively, screwed into threaded holes in the ceramic ring (9) with molybdenum screws. The screws holding the back plate are removed prior to assembly. The inner support ring (11) is press fit into (10). The filaments (15) are 0.5 mm diam tungsten wires with 3% rhenium additive and are preformed to a 19 mm radius of curvature before being inserted into positioning holes in the support rings. The filament curvature serves two purposes: (1) It allows the filaments to expand and contract without breaking and (2) when all the filaments are electrically in parallel, the $\mathbf{j}\times\mathbf{B}$ force on them can be used to keep them in the same plane. The spotwelding onto the relatively cool outer ring (18) poses no problems; the weld onto the hot inner ring (11), however, must be carefully done. The support (11) is machined from a 90% Ta–10% W rod, and the weld is made onto a raised lip with the help of 0.025 or 0.05 mm thick Ta flux. After spotwelding, the filament ends are covered with a 0.05 mm sheet of Ta, which is tacked down between filaments with spotwelds.

D. Electrical Path

For best temperature distribution, all 16 filaments are connected in parallel. About 290 A at 5 V are required, including losses in the leads, when the plate is at full temperature. The filament current enters along the tungsten rod (3) which is press fit into a semicircular molybdenum ring (6). The latter is pressed against the molybdenum ring (25) which, in turn, contacts the outer filament support ring (18). The latter is made in one piece and conducts current to all the filaments. Part (8) is omitted in this half of the assembly. In the other azimuthal half of the assembly, current leaves via the back plate (10), which contacts the semicircular ring (8) and the other tungsten rod (3). In this half, the semicircular ring (6) is grooved, as shown by the dashed line, so as not to contact ring (25). The clearances are designed so that when the clamp plate (2) is screwed down the full pressure is applied to these electrical contacts. For convenience it is sometimes desirable to achieve a higher impedance by putting eight filaments in series with the other eight. In this case, the ring (25) and the outer support ring (18) can be split, as shown in Fig. 2(b), and the current enters on one split ring and leaves on the other. The back plate (10) is then floating, and ring (18) is omitted.

E. Shielding

The back plate (10) serves both as a heat shield and as an electrical shield preventing electrons from bombarding the copper lid (2). The pumping holes in (10) fall between the filaments, as shown in Fig. 2(b). The floating shield (16) prevents electrons from bombarding the aperture limiter (20). Both (16) and (20) are double-slotted shields Fig. 2(d)] of 0.25 and 0.5 mm molybdenum sheet, respectively, with the slots staggered. The slots are necessary to minimize warping. Part (17) is a heat shield with U-shaped slots to accommodate the plate support legs. Part (19) is a heat shield to protect ceramic ring (13). Molybdenum tube (7) shields the high voltage from the central hole. With this arrangement of shields, no high energy electrons can enter the region of the plasma when the magnetic field is more than a few hundred gauss; this has been verified experimentally. The aperture limiter can be insulated from ground, if desired, by use of a thin piece of mica against the water cooled surface and ceramic screws. Note that no more than 2 cm separates the high potential points from the farthest ground point; this allows operation at fairly high pressures without gas breakdown (as long as one stays on the low pressure side of the Paschen curve).

F. Hot Plate Support

The W or Ta hot plate (14) is supported by four 6.35 mm diam tungsten legs (21), which are accurately held in molybdenum sockets (22) screwed into the copper block (1). The holes in the hot plate are drilled to an accuracy of 0.025 mm by electrical-discharge cutting under oil. The support legs are rounded to reduce thermal contact. The hot plate is centered, with the sockets (22) tight; then each socket is loosened by about 0.38 mm to allow

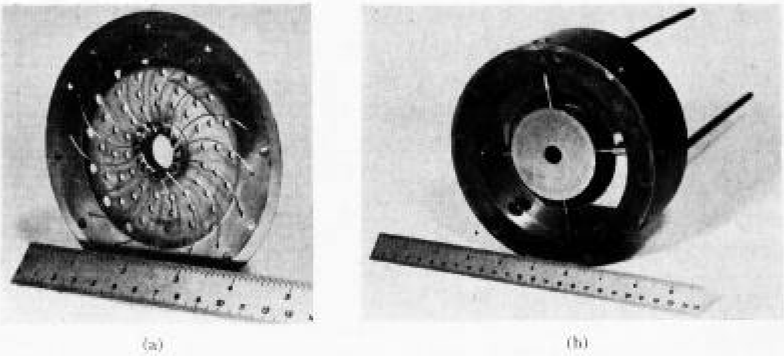
(a) (b)

FIG. 3. Photographs of the filament subassembly (a) and of the completed assembly (b) with the aperture limiter shield removed.

for thermal expansion. Note that the side holes in the hot plate [Fig. 2(c)] are elongated to allow for this expansion. We depend on small machining tolerances to hold the filament supports parallel to the hot plate to 0.05 mm. Before the installation of the aperture limiter (20), the parallelness of the front face of the hot plate with the face of the copper block (1) is checked with a depth micrometer. Small errors can usually be corrected by rotating a slightly bent support leg. We have had no success with spring loading the support legs; tungsten springs lose their flexibility under the 700 g weight of the tungsten hot plate. The sockets (22) can be made of BN if the hot plates are to be externally grounded.

G. Assembly and Operation

Assembly is particularly simple because of the modular construction. Starting with shield (19), the various circular pieces and the filament subassembly are slipped into the copper block (1), and the clamp lid (2) is screwed down tight. The hot plate is then mounted concentrically with shields (7) and (16). The alignment of the hot plate is checked and the limiter–shield assembly (20 and 17) is mounted. Photographs of the filament subassembly and of the complete assembly are shown in Fig. 3.

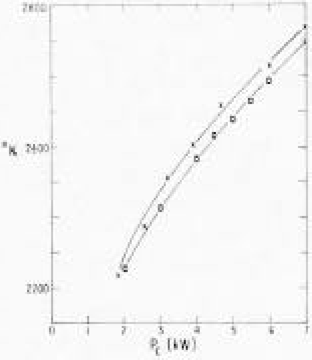

FIG. 4. Temperature of hot plate vs bombardment power P_e. The two sets of points were taken a year apart with different optical pyrometers and with a slightly different arrangement of shields and supports around the hot plate. The temperatures are corrected for the emissivity of tungsten. The errors are due to reading errors and the nonuniformity of plate temperature; in addition, there is a ±10 K error in the 40 K window loss correction which has been assumed. The magnetic field was 2 kG.

To outgas the ceramics, the filament current is brought up to 300 A (all filaments in parallel), and the bombardment power P_e slowly brought up to 6 kW (about 3 A at 2 kV), keeping the vacuum better than 5×10^{-5} Torr. The filament current may be reduced as the hot plate heats up. The outgassing procedure usually requires 2–4 h. We have operated the hot plate continuously up to $P_e=6$ kW and for short periods at 7 or 8 kW. Below 6 kW, evaporation of the filaments is not a limiting factor in the operating lifetime of the assembly; it is usually one of the ceramics that fails first. Breakage of filaments or spotwelds occurs seldom with this design, and the probability of breakage can be further reduced by keeping the filaments at red heat when the hot plate is not being used. Figure 4 shows a plot of plate temperature vs P_e.

H. Modifications

The spacing between the filament and the hot plate can be decreased by reversing the hot plate. The spacing can be increased by replacing shield (19) with a thicker copper ring, with a corresponding change in the thickness of copper spacer (4). These are simple machining operations.

Since the temperature of each filament varies along the filament, one can operate with space charge limited emission at the center of the filament and temperature limited emission near the ends. By varying the transition point, one can, in principle, make small changes in the radial temperature profile. To make larger changes, one can modify the filament structure. If the hole in the hot plate is eliminated, the present filament structure produces a small temperature depression (~5 K) at the center. By eliminating the tube (7) and adding an auxiliary, independently controlled filament near the axis, we have been able to reverse the direction of the radial temperature gradient. Alternatively, we have produced a temperature peak of 30–40 K at the center of a solid hot plate by shrinking the ring (11) to the axis and using longer filaments.

III. MEASUREMENTS

Measurements of the temperature distribution in a 6.35 cm diam hot plate with a 1.27 cm diam central hole are shown in Figs. 5–7, together with the isothermal contours. A Leeds and Northrup model 8641 Mark I automatic pyrometer was used, which photoelectrically compares the object with a standard filament and adjusts the filament for a null. The effective spot size was 0.5 cm and the relative accuracy was better than 1 K. From such measurements it was found that the discrete filament structure and support legs did not produce noticeable variations in temperature. The primary nonuniformity was an $m=1$ azimuthal asymmetry caused by a slight misalignment of the plane of the filaments, as explained in Sec. I. Because of the warping of materials at high temperatures, it was not possible to reduce the azimuthal nonuniformity to less than ±4 K. A deviation of ±6 K could be routinely achieved.

When operating with a solid hot plate with no central hole, we have varied the temperature gradient by means of an auxiliary set of eight filaments spotwelded to the inner support ring (11) and brought out through the back plate in a bundle. Figure 8 shows the changes in temperature profile as the current in the auxiliary filament is varied.

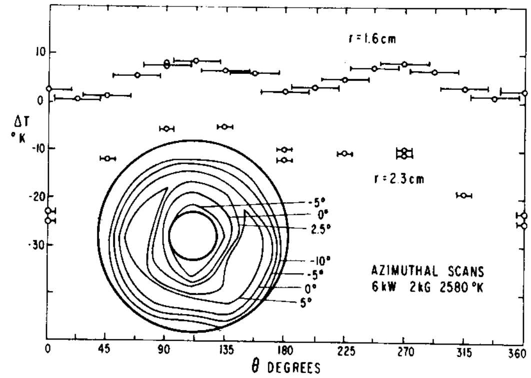

FIG. 5. Azimuthal scan of plate temperature at two radii for $P_e=6$ kW. The error bars indicate the spatial resolution of the pyrometer. The inset shows the isothermal contours.

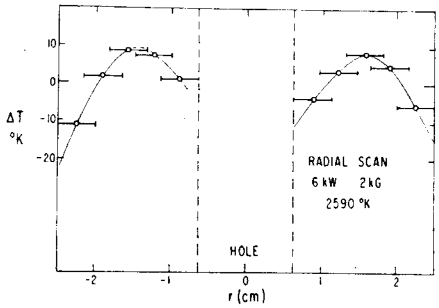

FIG. 6. Radial scan of the plate temperature under the conditions of Fig. 5.

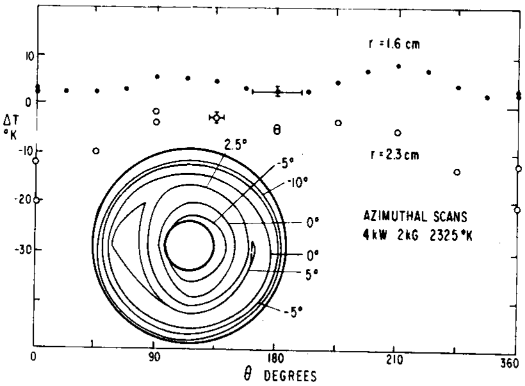

FIG. 7. Azimuthal scan of plate temperature for $P_e=4$ kW.

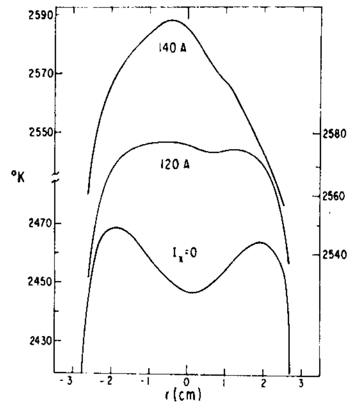

FIG. 8. Radial temperature profiles on a plate with no central hole as the current I_x in the central auxiliary filament is varied. The curves were taken directly on an X–Y recorder. The bombardment power was adjusted slightly between curves.

The magnitude of the temperature gradients shown in Figs. 5–8 is an order of magnitude smaller than previously achieved in Q machines. Subsequently, several other experiments have achieved comparable degrees of uniformity.[6,7] In addition, significantly smaller gradients, but at lower temperatures, have been achieved by rotating the filament structure.[8]

ACKNOWLEDGMENTS

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