RADIAL CURRENT DISTRIBUTION AT A PLANAR MAGNETRON CATHODE

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Radial Current Distribution at a Planar Magnetron Cathode

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Abstract

Experiments and theory are used to investigate the radial distribution of current at the cathode of a cylindrically symmetric planar magnetron discharge. We have developed a simple model of the distribution of incident ions at the cathode, in the form of an integral equation. Energetic electrons, produced by secondary electron emission when ions strike the cathode, are accelerated into the discharge through a thin sheath. The Hamiltonian motion of the energetic electrons in the magnetic field determines the birthplace of discharge ions, and thus, the distribution of ion current density at the cathode. The radial current distribution has been measured for various magnetic fields using a radially staggered array of sixteen 1 mm diameter current probes imbedded in a 9" diameter cathode. In agreement with the model, the current distribution is peaked at the radius at which the magnetic field is tangent to the cathode plate, and the width of the distribution scales as the square root of the energetic electron larmor radius.

Introduction

Planar magnetron sputtering is a plasma assisted process used in the deposition of thin films.[1] This method of thin film deposition is used widely in the production of integrated circuits for deposition of metallic films that interconnect circuit elements. A planar magnetron is a DC glow discharge in which the anode is grounded and a negative voltage of 200 volts or more is applied at the cathode, or target. The plasma shields the electric field through most of the chamber, and a cathode sheath of the order of 1 mm develops, which sustains most of the externally applied voltage. A magnetic field is applied such that field lines enter and leave through the cathode plate. Argon ions in the plasma, unconfined by the magnetic field, are accelerated toward the cathode and strike it at high energy. In addition to sputtering target material, the impact of the ions produces secondary electron emission. These electrons are accelerated back into the plasma and are confined near the cathode by the magnetic field. The electrons undergo a sufficient number of ionizing collisions to maintain the discharge before being lost to a grounded surface.

Investigation of the spatial structure of the plasma discharge is one route to understanding discharge dynamics and has important implications for understanding and controlling nonuniformity of target sputtering. One aspect of the spatial structure that can be measured noninvasively is the distribution of current density at the cathode surface. Using current probes imbedded in the surface of the cathode plate, local measurements of current density have been made. By observing the dependence of this structure on external parameters and combining the observations with a model of the discharge, insight into the dynamics of the discharge is gained.

Ion Current Distribution

A model of the radial ion current distribution at the cathode of a cylindrically symmetric planar magnetron is developed to investigate the spatial structure of the discharge and its dependence on the magnetic field. We summarize the procedure to determine the radial distribution of ion current density, $j_i(r)$, at the cathode. We will not obtain an absolute current density, but will give a relative measure of the radial dependence of ion current. At the cathode, the discharge current is carried primarily by ions. Secondary electrons are produced only for a small fraction of the incident ions (γ is typically about 0.05), and thus make only a small contribution to the total discharge current. The local current density of electrons leaving the cathode is $j_e(r) = \gamma j_i(r)$. Assuming these electrons are not collisional, they will undergo Hamiltonian motion in the magnetic field. Since the magnetic field configuration in the system is known, the motion of an electron in the field can be determined. The density of occupation of one of these high energy electrons is uniform over its range of motion in the r-z plane. This range of motion is dependent on the structure of the magnetic field and is different for electrons emitted at different radial locations on the cathode. In the simplest scenario, the ions created in the plasma are accelerated toward the sheath by a weak axial electric field (the Bohm presheath), moving in a straight line perpendicular to the sheath surface from their point of origin until they strike the cathode. This closes the cycle of discharge maintenance.

This model of discharge maintenance imposes a constraint on the discharge in order for it to remain in the steady state. The electrons entering the discharge from the sheath must carry just enough energy to maintain a constant flux of ions back to the cathode. This sequence of events is expressed mathematically in the form of an integral equation for the ion current density, $j_i(r)$.

Rectangular Geometry

Before attempting to solve the problem in the cylindrical geometry, a simplified version in a rectangular geometry is constructed (see figure 1). In this model, the cathode is an infinite strip of width $2R$. The magnetic field is generated by a single current-carrying wire running parallel to the plate under the midpoint at a distance a below the surface. In this formulation of the problem, all lengths will be normalized to units of a. The problem is posed as a two-dimensional problem in the plane of the cross-section of the system across the short dimension of the cathode. The x-coordinate runs parallel to the cathode surface, with the origin at the center and the y-coordinate is the perpendicular distance from the cathode surface. The z-coordinate runs along the length of the cathode, and, because of the symmetry in this problem, is an ignorable coordinate.

For this model, we assume that the sheath thickness is small compared to the range of electron motion, so that we may start the calculation above the sheath. The electric field in the sheath is treated as an impulse, giving an initial velocity to electrons emitted at the plate. There are no important electron dynamics in the sheath, and the only role of the sheath is to provide initial energy to the electrons coming from the cathode.

The problem is formulated in terms of $j_i(x_0)$, the current density of ions incident on the cathode plate at $x = x_0$. The total current of ions incident at x_0 in a strip of width dx_0 and length L in the z direction is $j_i(x_0)L\,dx_0 = e\Gamma_i(x_0)L\,dx_0$. Thus the current of secondary electrons emitted from that strip is $j_e(x_0)L\,dx_0 = \gamma j_i(x_0)L\,dx_0$. The area in the x-y plane accessible to electrons emitted at x_0 is called $\tau(x_0)$. Assuming that the density of occupation of the energetic electrons is evenly distributed over this area, ionization will also be distributed uniformly over the same area. The rate of change of density within τ of fast electrons emitted between x_0 and $x_0 + dx_0$ is

$$\frac{dn(x_0, x, y)}{dt} = \frac{\gamma}{e\tau(x_0)} j_i(x_0)L\,dx_0. \tag{1}$$

Inside the region τ, within a volume $L\,dx\,dy$, there are $L\,dn\,dx\,dy$ fast electrons that were emitted between x_0 and $x_0 + dx_0$ in a time dt. We let H be the number of ion-electron pairs created in the plasma by each energetic electron. The total number of ions created in a time dt in the volume $L\,dx\,dy$ is $HL\,dn\,dx\,dy$. To find the number of ions incident in a time dt between x and $x + dx$ from this pool, $HL\,dn\,dx\,dy$ must be integrated over y for a fixed value of x, since the ions move parallel to the y direction. Because the integrand is zero outside the electron range of motion and constant within it, the integral can be performed by multiplying the integrand by the distance between the two y values that bound the motion for a given x. Calling this distance $h(x, x_0)$, the flux of ions incident at x due to electrons emitted at x_0 is

$$H h(x, x_0)\frac{\gamma L j_i(x_0)}{e\tau(x_0)} L\,dx\,dx_0. \tag{2}$$

In order to find the total ion flux at x, the contribution from electrons emitted at all values of x_0 must be included. This is achieved by integrating (2) over x_0. Thus the current of ions falling on $L\,dx$ is

$$j_i(x)L\,dx = \int_{x_0} Hh(x,x_0)\frac{\gamma L j_i(x_0)\,dx_0}{\tau(x_0)}L\,dx \tag{3}$$

or

$$j_i(x) = \gamma H \int_{x_0} dx_0 \frac{Lh(x,x_0)}{\tau(x_0)} j_i(x_0). \tag{4}$$

This is a Fredholm equation of the second kind. The values of $\tau(x_0)$ and $h(x,x_0)$ can be expressed analytically for the case at hand.

To obtain expressions for $\tau(x_0)$ and $h(x,x_0)$, we introduce the radial coordinate r, measured from the location of the magnetic field-producing wire. If ϕ is the corresponding azimuthal coordinate, the magnetic field is

$$\mathbf{B} = \hat{\phi}\frac{B_0}{r}, \tag{5}$$

where B_0 is the field at $r = 1$, the radius at which the field line is tangent to the cathode surface at $x = 0$. The corresponding vector potential is

$$\mathbf{A} = -\hat{z}B_0 \ln r = -\hat{z}B_0 \ln\left[x^2 + (y+1)^2\right]^{\frac{1}{2}} \tag{6}$$

Since p_z is a constant, the Hamiltonian for an electron in this field is

$$\mathcal{H} = \frac{p_x^2}{2m} + \frac{p_y^2}{2m} + \frac{(p_z - eA_z)^2}{2m} + qV. \tag{7}$$

In the region of interest, there is no electric field, so V can be set to zero. In this geometry, z is an ignorable coordinate, so that the corresponding conjugate momentum, p_z, is a constant of the motion. From Hamilton's equations,

$$\dot{z} = \frac{\partial\mathcal{H}}{\partial p_z} = \frac{p_z - eA_z}{m}, \tag{8}$$

so

$$p_z = m\dot{z} + eA_z(x,y). \tag{9}$$

The value of p_z for an electron is equal to its value at the point of origin of the electron at the cathode plate, corresponding to $x = x_0$, $y = 0$, and $\dot{z} = 0$. Thus,

$$p_z = p_{z0} = eA_z(x_0, 0) \tag{10}$$

The Hamiltonian can be written in terms of an effective potential, Ψ:

$$\begin{aligned}\mathcal{H} &= \frac{p_x^2}{2m} + \frac{p_y^2}{2m} + \frac{(p_z - eA_z)^2}{2m} \\ &= \frac{p_x^2}{2m} + \frac{p_y^2}{2m} + \Psi,\end{aligned} \tag{11}$$

where

$$\begin{aligned}\Psi &= \frac{(p_{z0} - eA_z)^2}{2m} \\ &= \frac{e^2}{2m}\left[A_z(x,y) - A_z(x_0,0)\right]^2\end{aligned} \tag{12}$$

Using (6) for the vector potential in (12), we obtain

$$\Psi = \frac{e^2 B_0^2}{8m}\left[\ln\left(\frac{x^2+(y+1)^2}{x_0^2+1}\right)\right]^2. \tag{13}$$

For a newly generated electron, $\Psi = 0$, and the electron energy consists only of its initial kinetic energy, $e\Phi_0$, gained in acceleration through the sheath potential. The boundaries of the electron motion are located where the initial electron kinetic energy has been converted to potential energy. These boundaries are found by equating the potential energy, Ψ, equal to the initial kinetic energy, $e\Phi_0$. This entails finding the values of x and y for which

$$e\Phi_0 = \frac{e^2 B_0^2}{8m}\left[\ln\left(\frac{x^2+(y+1)^2}{x_0^2+1}\right)\right]^2. \tag{14}$$

Writing $e\Phi_0 = \frac{1}{2}mv_0^2$ and introducing the electron gyroradius $\lambda = v_0/\omega_c$, the condition satisfied at the boundary can be written

$$x^2 + (y+1)^2 = \left(x_0^2+1\right)e^{\pm 2\lambda}. \tag{15}$$

Thus, electron motion is bounded by a pair of concentric circles. The radii of the inner and outer potential boundaries will be referred to as r_- and r_+ respectively, where

$$r_\pm = r_0 e^{\pm\lambda}, \tag{16}$$

and r_0 is the value of r corresponding to the location of x_0 on the plate. The cathode plate serves as a third boundary. Since there is a sharp potential fall at the cathode plate, corresponding to the sheath, it is treated as an infinite potential step, reflecting incident electrons. For electrons emitted near $x = 0$, the electron never reaches its inner circular boundary because of the presence of the cathode, and is bounded only by the cathode plate and the outer boundary. The value of x_0 below which an energetic electron is confined by the outer potential boundary and the cathode and above which an electron is confined by both circular potential boundaries and the plate is x_1, the value of x_0 for which the inner potential boundary is tangent to the cathode plate. On using (15),

$$x_1 = \left(e^{2\lambda} - 1\right)^{\frac{1}{2}}. \tag{17}$$

For some initial conditions, x_0, the outer boundary is at a radius so large that it does not intersect the cathode. These electrons are lost from the system before producing appreciable ionization and thus are ignored in the calculation. This upper limit for x_0 is computed by finding the x_0 for which the outer boundary intersects the plate right at the edge $x = R$. The corresponding boundary will have radius $r_R = \sqrt{1+R^2}$. Then x_m, the maximum allowable value of x_0, is given by

$$r_R^2 = \left(x_m^2 + 1\right) e^{2\lambda}, \tag{18}$$

or

$$x_m^2 = r_R^2 e^{-2\lambda} - 1. \tag{19}$$

The area of the arc region, $\tau(x_0)$, can be computed explicitly by combining the areas of simple geometric shapes. This area can be expressed simply in terms of x_- and x_+, the points on the cathode surface that are intersected by the potential boundaries, and the angles ϕ_- and ϕ_+, defined as

$$\phi_\pm = \operatorname{arcsec}(r_\pm). \tag{20}$$

Thus, the area of the region of access for an electron emitted at x_0 is

$$\tau(x_0) = \begin{cases} \left(r_+^2\phi_+ - x_+\right) L & x_0 < x_1 \\ \left(r_+^2\phi_+ - r_-^2\phi_- - x_+ + x_-\right) L & x_1 < x_0 < x_m. \end{cases} \tag{21}$$

For $x_0 > x_m$, the energetic electrons are lost from the system and we set $\tau(x_0) = \infty$. The height of the strip of width dx within $\tau(x_0)$ containing electrons emitted at x_0 that contribute to the production of ions striking the cathode at x, is

$$h(x, x_0) = \begin{cases} \sqrt{r_+^2 - x_+^2} - \sqrt{r_-^2 - x^2} & x < x_- \\ \sqrt{r_+^2 - x^2} - 1 & x_- < x. \end{cases} \tag{22}$$

Now the integral equation may be written out analytically. The equation cannot be solved analytically, but it can be discretized and solved numerically as an eigenvalue problem. Defining the kernel, $k(x, x_0)$, in (4) such that

$$j_i(x) = \gamma H \int_{x_0} dx_0 k(x, x_0) j_i(x, x_0), \tag{23}$$

the integral is converted to a sum:

$$j_{i_m} = H \sum_n k_{nm} j_{i_n}, \tag{24}$$

where n and m are indices corresponding to the discretized values of x_0 and x, respectively. Writing this in vector notation, we obtain a standard eigenvalue equation:

$$\mathrm{J}_{\mathrm{i}}(\underline{\mathrm{K}} - \lambda_i \underline{1}) = 0. \tag{25}$$

where J_{i} is the vector of values of j_i at the discrete locations along the cathode surface, and $\underline{\mathrm{K}}$ is the matrix containing the kernel elements. This is solved numerically for the eigenvalues, $\lambda_i = 1/\gamma H$ and the eigenvectors J_{i}. We are interested only in the lowest eigenmode of the system, since the flux must be positive everywhere on the plate. Thus we determine numerically the eigenvalue with the smallest magnitude and its corresponding eigenvector.

Results and Discussion

Results are shown in figure 2 for two different magnetic field strengths. The ion current distribution is peaked at the center of the plate and falls to zero near the edge. The units of the ion current are arbitrary, since this is a model of *relative* ion current density. Thus, the eigenvectors are normalized to be 1 at their peak. The distribution becomes more sharply peaked as the magnetic field strength is increased. The value of a, the distance of the magnet current wire below the surface of the plate, was chosen so that the curvature at the cathode surface corresponds approximately to the curvature of the magnetic field lines at the cathode plate in the experimental system. The width of the plate is chosen to correspond to the radius of the electrode in the experiment.

The presence of the magnetic field has a focusing effect on the plasma discharge. Electrons emitted at the cathode plate far from $x_0 = 0$ travel along magnetic field lines to produce ionization in the region of accessibility for that electron. The range of motion perpendicular to the magnetic field is inversely proportional to the strength of the magnetic field. On any magnetic field line, an energetic electron generated far from the center of the plate can produce ionization near the center of the plate since it passes above the center as it travels parallel to the field line. However, it can only produce ionization further away from the center than its origination point by its cross field travel, which depends sensitively on the size of λ, the larmor radius of the energetic electrons.

This suggests a natural scaling for the width of the distribution. Call $\tau'(x_0)$ the volume of the portion of τ that corresponds to $|x| > x_0$. Little current will fall at the cathode for the value of x above which the region $\tau'(x_0)$ does not contribute significantly to $\tau(x_0)$. Thus we approximate the width of the current distribution by the width of $\tau(x_1)$ at the cathode, where x_1 is the value of x_0 (defined in (17)) for which the inner potential boundary is tangent to the cathode surface. The result is that the mean width of the region of ion flux, $\overline{w}$, scales as the square root of the unnormalized electron larmor radius, and as the square root of the magnetic field line radius of curvature:

$$\overline{w} \propto (a\lambda)^{\frac{1}{2}}. \tag{26}$$

This scaling is observed in the results of the model, as long as $\overline{w}$ is small compared to $2R$, the width of the plate.

Cylindrical Geometry

In order to make a more direct comparison between the modelling and experimental results, the model was extended to a cylindrical geometry. Instead of approximating the magnetic field by that produced by a single straight wire, it was determined by POISSON, a computer code that computes magnetic field strengths and field lines for a given configuration of iron and current-carrying elements and was used in designing the magnet for the experimental system. A comparison was made between the output of POISSON and the actual magnetic field produced by the magnet in order to verify the reliability of the POISSON output. Measurements were made of both the axial and radial magnetic field strengths using a Hall effect gaussmeter. The variation in field strength as a function of radius was found to be consistent for both the radial and axial fields. The magnitude of the field calculated by POISSON was found to be within 10 percent of the measured field, giving confidence to the use of the POISSON output in calculating the range of electron motion. POISSON was used to determine both the magnetic field and the vector potential on the gridpoints of a mesh covering the r-z plane. The dimensions of the magnet used in the experiment, including both the current carrying element and the iron core were fed into the program, along with the magnet current for the case of interest. The vector potential thus produced, $\mathbf{A}(r,z) = \hat{\phi} A_\phi(r,z)$, is then used to determine the effective potential well. The vector potential for each starting position r_0 in the discretized problem is determined by linear interpolation between the grid points on the mesh. This is then used in the cylindrically symmetric Hamiltonian,

$$\mathcal{H} = \frac{p_r^2}{2m} + \frac{p_z^2}{2m} + \frac{\left(p_\phi^2 - eA_\phi r\right)}{2mr^2} + eV(r,z), \tag{27}$$

along with the initial kinetic energy to determine the value of A_ϕ at the boundaries of the electron motion in the potential well. The values of vector potential on the grid are again interpolated, this time to find the values of r and z at which the particle is reflected. Once the region of access for an electron is determined, the values of $r(r_0)$ and $h(r,r_0)$ can be calculated directly, and the kernel constructed and the eigenvalue problem solved.

Preliminary results are consistent with those for the rectangular geometry, and further studies are underway.

Ion Current Distribution Experiments

In conjunction with the modelling described above, we are conducting experiments to measure the ion current distribution. We have designed and constructed an experimental system for the purpose of studying the planar magnetron . The system consists of a 12" diameter cylindrical aluminum vacuum system. Two parallel 9" diameter copper electrode plates, mounted on axis, are water cooled and insulated from the vacuum vessel. The electrodes can be moved independently along the axis, allowing variation of electrode separation and permitting the axial movement of the discharge past fixed diagnostics for spatially resolved measurements.

A variable magnetic field for the planar magnetron is provided by a DC electromagnet mounted behind the cathode plate. The design of the iron core electromagnet was optimized for our system using POISSON. The presence of the magnetic field results in the reflection of electrons moving back and forth along the field lines, so that they are confined near the cathode. The output of POISSON suggests that magnetic mirroring is important at the inner radius, but is unimportant at the outer radius of the electron's motion. This is presumably the case in other planar magnetrons. Thus, electrostatic reflection at the cathode sheath plays an important role in electron confinement in the planar magnetron.

Cathode Current Probes

Sixteen current probes have been installed in a radial array in the cathode plate. Each probe is a 1 mm diameter pin, whose surface is flush with the cathode surface and is electrically isolated from the cathode. The current collected by the probes is determined by measuring the voltage across a small resistor connected between each pin and the cathode. The presence of the pins does not appear to disturb the discharge or affect the operation of the magnetron. There is a voltage difference between the pins and the cathode plate, but that difference is small ($\sim$ 1V) compared to the cathode voltage ($\sim$ 400V) and causes only a minor perturbation on the local electric field. In addition, since the pin size is small, the perturbation is localized.

Experimental Results

Preliminary results have been obtained with the cathode current probes. A series of current profiles have been measured in a planar magnetron discharge in 5 mtorr argon, with a fixed total discharge current of 0.5 A. The magnetic field was varied between 140 G and 570 G. Because of the variation in the magnetic field, the discharge voltage was also varied in order to keep the total current fixed. The current distribution is found to be peaked at $r = 5.0$ cm, the radius at which the magnetic field lines are tangent to the cathode surface, as predicted by the model. In addition, the width of the distribution becomes narrower as the strength of the magnetic field is increased. These results are illustrated in figure 3. We see a scaling of the width of the distribution:

$$\overline{w} \propto \lambda^{\frac{1}{2}}, \tag{28}$$

as predicted by (26). However, this scaling is observed for a restricted range of magnetic field strengths. Once B is raised beyond a certain level (in this case it seems to be about 430 G, but it depends on the discharge current), no further decrease in $\overline{w}$ is observed. This suggests that there is another mechanism that is producing cross field particle transport, which may be insignificant at lower field strengths, but which controls the value of $\overline{w}$ at higher magnetic fields.

Acknowledgements

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References

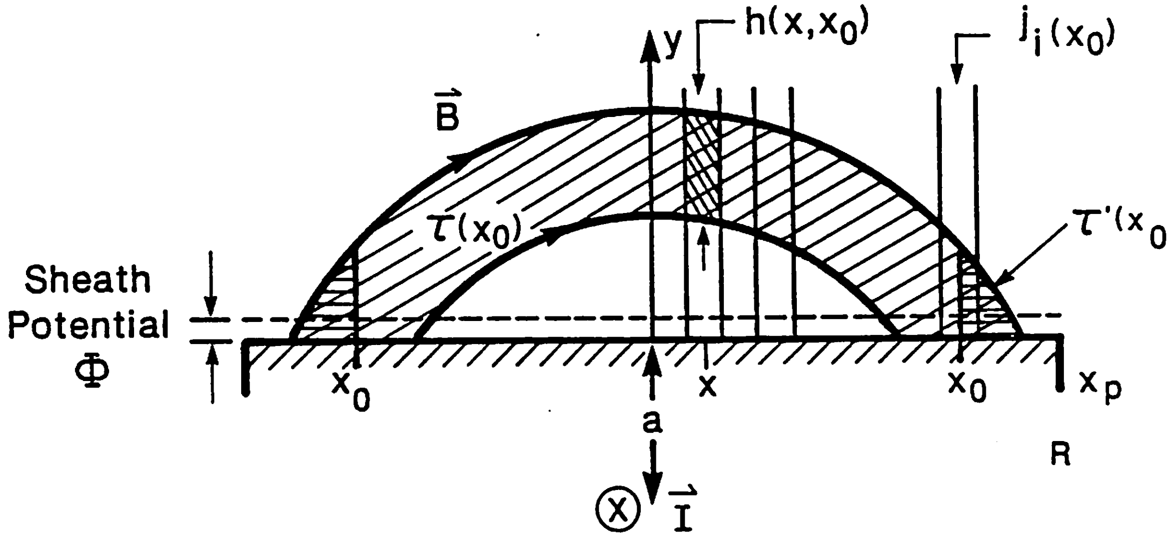
1. J. A. Thornton, in Thin Film Processes ed. by J. L. Vossen and W. Kern, (Academic, New York 1978), p.76.

Figure Captions

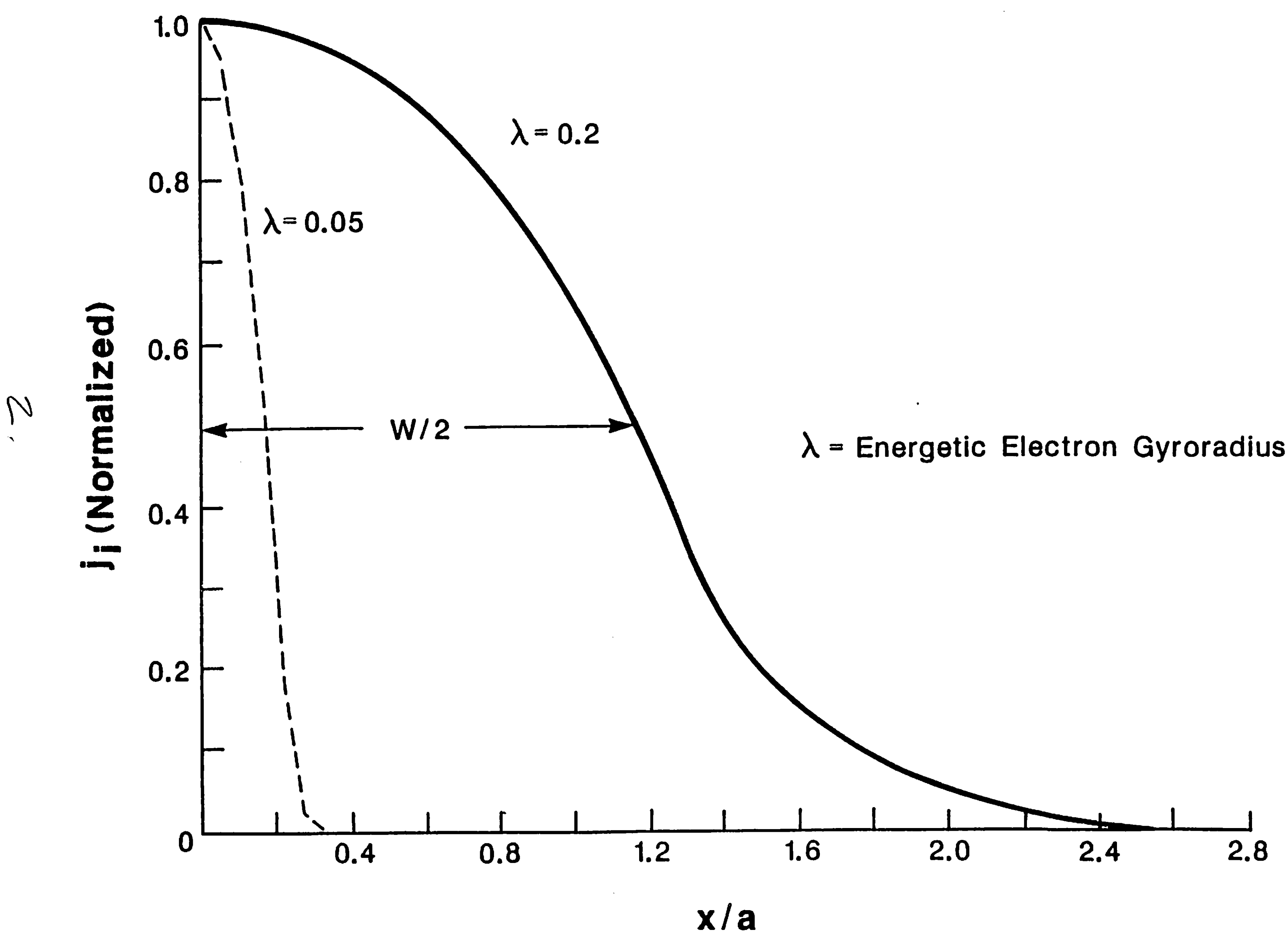
1. Two dimensional, rectangular geometry model for current distribution at the cathode.

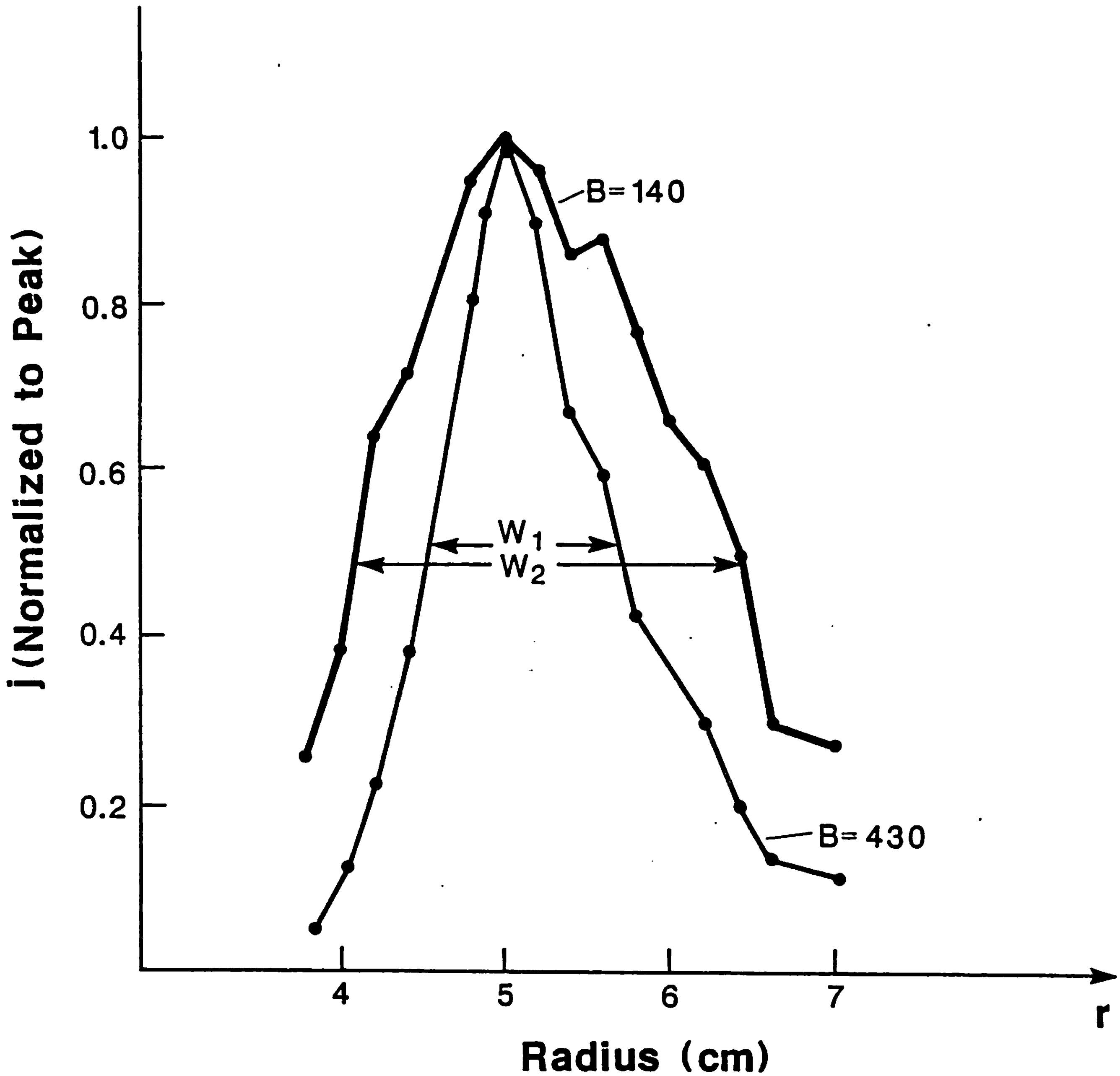
2. Theoretical current distribution at the cathode for the rectangular model at two different values of the energetic electron gyroradius λ(cm). For both cases, $a = 2.$ cm.

3. Experimental current distribution at the cathode for two magnetic fields strengths of 140 and 430 gauss at the cathode. The corresponding electron larmor radii for the two cases are $\lambda = 0.68$ cm and 0.14 cm, respectively.



y
h(x,x0)
j_i(x0)
B
τ(x0)
τ'(x0)
Sheath
Potential
Φ
x0
x
x0
xp
a
R
I


1.0
0.8
0.6
0.4
0.2
0
j_i (Normalized)
λ = 0.2
λ = 0.05
W/2
λ = Energetic Electron Gyroradius
0.4
0.8
1.2
1.6
2.0
2.4
2.8
x/a



1.0
0.8
0.6
0.4
0.2
j (Normalized to Peak)
B= 140
B= 430
W1
W2
4
5
6
7
r
Radius (cm)

3.