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The Response of Surface Negative Ion Yield and Virtual Cathode Formation to the Effective Work Function of Caesium.

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Abstract. A one dimensional model of the sheath between the plasma and the wall in a negative ion source has been expanded to include the effects of a variable wall surface work function and fast positive ion species. The plasma consists of positive ions, electrons and negative ions. The model also includes the emission of negative ions from the wall into the sheath and thus represents the conditions in a caesiated ion source with surface production of negative ions. At high current densities of the emitted negative ions, the sheath is unable to support the transport of all the negative ions to the plasma and a virtual cathode is formed. This model takes this into account and allows the calculation of the transported negative ions across the sheath with the virtual cathode. It has been suggested that the work function of caesium can be higher than 1.5eV in certain plasma conditions relevant to H⁻ production. As the negative ion yield has a dependence on the work function there will be an effect on the negative ion current density from the surface and hence the virtual cathode behaviour. Including this effect has shown that in changing the work function from 1.5eV to 2.2eV reduces the maximum transported H⁻ current density by a third.

Keywords: negative ion source, plasma sheath, virtual cathode

PACS: 41.75.Cn, 52.50.Dg, 52.40.Kh

INTRODUCTION

Large magnetic confinement fusion devices regularly use neutral beam heating and current drive to meet the requirements of steady state plasma burn and plasma stability. For a fusion power plant these neutral beams will need to be of energies in excess of 1MeV and hence require negative ion precursors [1]. Volume production of negative ions cannot produce the required current densities and enhancement due to the addition of caesium in the source is required [2,3,4,5]. Surface production of negative ions by atomic and ionic bombardment is generally considered to be the cause of this enhancement. Before they can be extracted as a beam these surface produced ions must make their way across the sheath and into the plasma.

A variety of models have shown that under certain circumstances this transport can be inhibited by the surface produced negative ions modifying the potential in the sheath to form a double sheath system known as a virtual cathode. The virtual cathode

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forms when the negative ion production at the wall is high enough that the associated space charge cannot be supported by the sheath. This has been seen in PIC simulations by Wunderlich et al. [6], Hatayama [7] and Taccogna et al. [8], it was also observed by Fukano and Hatayama in analytical solutions to Poisson's equation [9]. Amemiya et al [10] produced an analytical model of electron injection into a plasma containing negative ions. This model was adapted to the case of negative ions emitted from the source wall by McAdams and Bacal [11] and allowed the calculation of the maximum current density before the formation of a virtual cathode. This adaptation gave good agreement with a PIC code simulation [6].

This model was extended to take into account the formation of a virtual cathode [12] and also the finite energy of the negative ions created at the surface. The model was then adapted further to include the effects of a pre-sheath region [13]. This gave a relationship between the particle density at the sheath edge and the bulk plasma, which allowed for a comparison between the model and experiment. This comparison showed that the model could accurately predict the formation and depth of a virtual cathode given appropriate inputs.

In the applications of this model so far the production of negative ions by positive ions on the surface has been ignored because the production by hydrogen atoms on the surface is dominant. However, if the energy of the initial positive ions is higher than a few electron volts then the yield will increase significantly and the energy of the emitted negative ions will be higher, allowing more penetration through the virtual cathode. The work of McNeely [14] et al shows that differences in the plasma potential of $\sim 40\text{V}$ can be established across the magnetic filter field from the driver to the extraction region at a pressure of 0.3Pa and an RF power of 80kW . Although it is unclear whether such potentials are generally present in neutral beam plasma sources and there would be a slowing down of these ions by collisions and charge exchange process, this would be a source of fast positive ions at the surface. An initial attempt to include fast positive ions was made in [15]. However, this only included the effects of the production of negative ions, not the effect on the sheath model as a whole. Hence faster positive ions have been included in the model fully and their effect studied.

The previous results from the model have assumed a surface work function of 1.5eV , however Gutser [16] suggests that the effective work function of a caesiated surface can be increased in the presence of a plasma to as much as 2.4eV . A variable work function has been included in the model to account for this in both positive ion and atomic yield.

THE MODEL

The problem is subdivided according to Fig. 1 into a virtual cathode region, a standard sheath region, a pre-sheath region and the plasma. The model is detailed fully in [12] but the basic parts of the process are presented here. The plasma is not modeled itself in this system, but provides values for the different particle densities. Figure 1 also shows the different parameters involved in the model; j_b is the current density emitted by the surface, V_c is the cathode potential with respect to the potential at the sheath edge, V_k is the depth of the virtual cathode, V_m is the potential between the virtual cathode and the sheath edge, j_{bmax} is the current density that is transported

across the virtual cathode, U_0 is the potential between the sheath edge and the plasma (assumed to be the classical $T_e/2$), U_i is the energy of incoming positive ions from the plasma and the densities n_{i0} , n_{e0} and n_{n0} represent the ion, electron and negative ion densities at the sheath edge (0 subscript). At low production levels of negative ions at the wall there is no virtual cathode and the emitted current can be supported by the sheath and so $V_c = V_m$ ($V_k=0$) and $j_{bmax} = j_b$. The Poisson equations for the situations where the virtual cathode does not exist and when it does exist can be set up. Analysis of those equations [10,12] yields results for the transmitted current across the sheath. This analysis also allows the potentials themselves to be calculated but these are not reported here.

The maximum transmitted current across the sheath in the presence of a virtual cathode is given by

$$j_{bmax} = \frac{2n_{i0}V_0 \left(\left(1 + \frac{V_m}{V_0} \right)^{1/2} - 1 \right) + n_{e0}T_e \left(\exp\left(\frac{-V_m}{T_e} \right) - 1 \right) + n_{n0}T_n \left(\exp\left(\frac{-V_m}{T_n} \right) - 1 \right)}{\frac{2}{e} \left(\frac{M_b}{2e} \right)^{1/2} \left[(V_m + U_b)^{1/2} - U_b^{1/2} \right]} \quad (1)$$

where $T_{i,e,n}$ are the electron and negative ion temperatures, V_0 is the initial energy of the positive ions crossing into the sheath ($V_0 = U_i + U_0 + T_i/2$) and U_b is the initial energy of the emitted negative ions. The emitted negative ions are treated as one species and their energy is given by a weighted average of the energy of the atom and positive ion produced negative ions. Equation 1 arises due to the condition that the electric field at the potential minimum in the virtual cathode is zero. If in this equation we set $V_m = V_c$ i.e. no virtual cathode this represents the point at which the electric field at the cathode is zero i.e. the space charge limit and j_{bmax} is the maximum transported current density before the virtual cathode is formed.

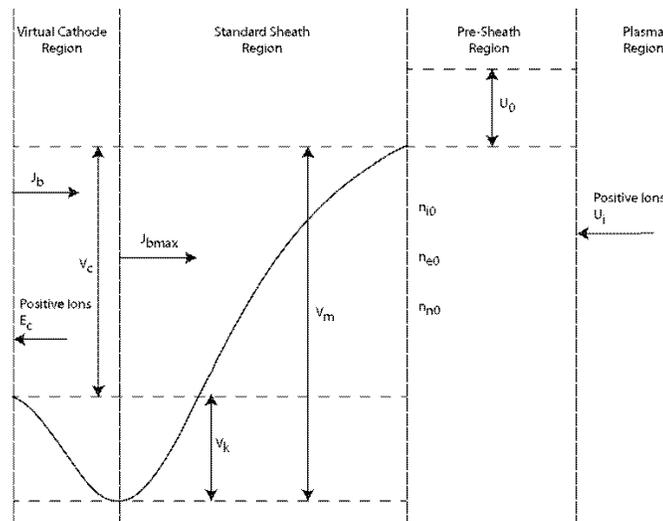


FIGURE 1. The virtual cathode, standard sheath, pre-sheath and plasma regions.

The densities and the maximum transported current density are related by the quasi-neutrality condition at the sheath edge

$$n_{e0} = n_{i0} - n_{n0} - \frac{j_{b\max}}{e} \left(\frac{M_b}{2e} \right)^{1/2} (V_m + U_b)^{-1/2} \quad (2)$$

When a virtual cathode exists the negative ions emitted from the cathode are retarded by the virtual cathode potential V_k . It is assumed that the emitted current density, j_b , and the current density at the minimum of the virtual cathode, $j_{b\max}$, are related by a simple exponential barrier i.e.

$$V_k = T_b \ln \left(\frac{j_b}{j_{b\max}} \right) \quad (3)$$

where T_b is the emitted negative ion temperature, $U_b = T_b/2$.

This set of equations can be solved iteratively. To reach a solution for the system the values of n_{i0} , V_c , U_i , the temperature of each species and the effective work function of the surface, ϕ , are required. It has been assumed throughout that there are no negative ions present in the plasma as their effect is negligible. The emitted current density must be calculated for both the atom production, j_{ba} , and the positive ion production, j_{bi} using the expression:

$$j = Y\Gamma e \quad (4)$$

where Y is the yield and Γ is the flux. For atoms a flux of $6.61 \times 10^{22} \text{ m}^{-2}\text{s}^{-1}$ has been used throughout, based on $T_H = 0.8$ and $n_H = 10^{19} \text{ m}^{-3}$ as in [12], while the positive ion flux is calculated from the positive ion density and energy at the surface, $E_c = V_0 + V_c$:

$$\Gamma_i = 0.4 \times n_i \left(\frac{2eV_0}{m} \right)^{1/2} \quad (5)$$

the factor of 0.4 comes from the consideration of how many positive ions reach the surface according to probe theory [17].

The yield for the atom-produced negative ions is taken from data in Seidl et al [18] and is given by:

$$Y_a = R_n \eta_0 \exp \left(\frac{-E_{thr}}{R_e T_H} \right) \quad (6)$$

where $E_{thr} = \phi - E_{aff}$, $E_{aff} = 0.75 \text{ eV}$, $R_n \eta_0 = 0.42$ and $R_e = 0.7$.

The yield for the positive ion produced surface ions is taken from a fit to data from Seidl et al [18] and Isenberg et al. [19]:

$$Y_i = A \exp\left(\frac{-BE_{thr}}{\sqrt{E_c}}\right) \quad (7)$$

where $A = 0.385$ and $B = 3.3837$.

The current densities calculated for a given yield are then combined to give a total j_b , while the energy of the emitted negative ions is calculated as a weighted average of the two species, U_{ba} and U_{bi} . The energy of the atom-produced ions, U_{ba} , can be calculated from the kinetics of the conversion process [12], while the energy of the ion-produced ions is simply the energy of the incoming positive ions at the surface, E_c . The first part of the process is to guess a value of V_m , which is then used to find the electron density at the sheath edge using the plasma neutrality condition. On the first iteration the value of j_b is used for j_{bmax} but on subsequent steps the calculated value is used. Following this, the value of j_{bmax} and subsequently a value for V_k from Eq.1 and Eq.4 are calculated. The process is completed by the recalculation of V_m through Eq. 8 and a mixing of V_m with the previous version.

$$V_m = V_c + V_k \quad (8)$$

The entire model is coded as an IDL program that runs on a standard UNIX workstation and solves in less than a second.

RESULTS

In order to demonstrate the effects of both fast positive ion surface production of negative ions and the variation of the effective work function a number of parametric studies have been performed. Throughout these studies the input values from [12] have been used, i.e.: $n_i = 3.5 \times 10^{17} \text{ m}^{-3}$, $T_e = 2 \text{ eV}$, $T_i = 0.8 \text{ eV}$, and $U_{ba} = 1.2 \text{ eV}$.

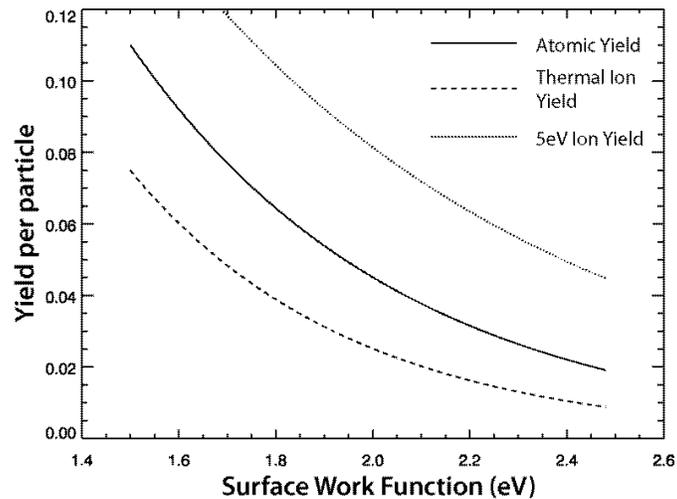


FIGURE 2. Variation of negative ion yield with effective work function for incident atoms and positive ions of varying energy.

Firstly, to demonstrate how both the positive ion energy and the work function of the surface affect production of negative ions the atomic and ion yields are shown in Figure 1. The ion yield is shown for both thermal ions, i.e. $U_{bi}=0\text{eV}$, and $U_{bi}=5\text{eV}$. This is obviously a much lower energy than the 40eV referred to in Section 1, but as there is doubt over the existence of such high energies in fusion plasma sources and negative ions of such high energy would escape across the filter field and be destroyed it is of more practical interest to observe the effects of lower energy positive ions on the model. These yields are used to calculate the current density of negative ions according to Equations 4 & 5. The current density of the negative ions produced by positive ions is shown in Figure 3 for a bias voltage of 1V .

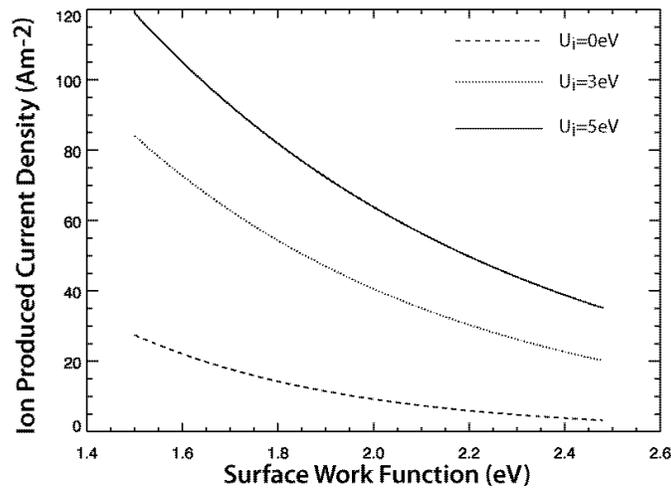


FIGURE 3. Variation of negative ion current density produced by incident positive ions with effective work function for varying incident energy.

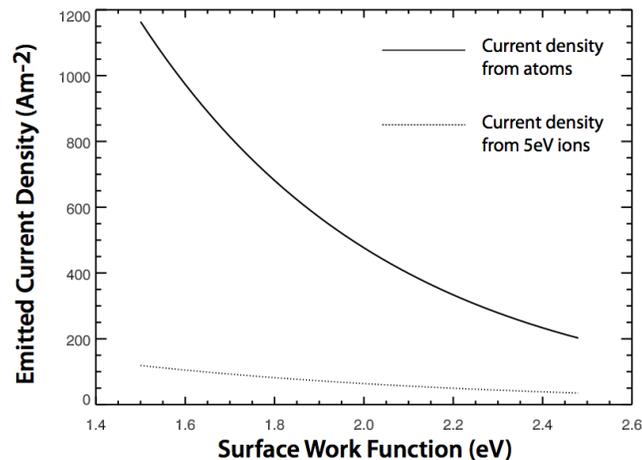


FIGURE 4. Variation of negative ion current density from atoms and 5eV positive ions with effective work function.

It is clear that higher energy positive ions produce higher current densities of negative ions, but even for an incident energy of 5eV the current density produced is below 200Am^{-2} , which is much lower than the current density produced by atoms

incident on the surface. To demonstrate this the variation of current density with work function for atoms and 5eV positive ions is shown in Figure 4.

A scan of the bias voltage was performed with positive ion energies of 0, 3 and 5eV while keeping the work function constant at 1.5eV. The effect on total transported current density can be seen in Figure 5.

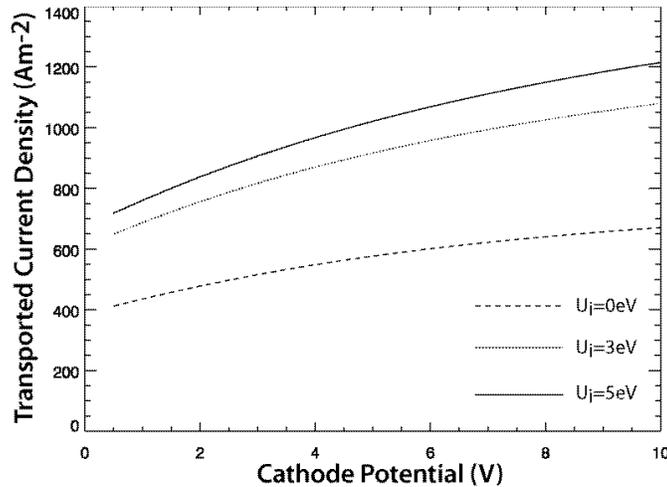


FIGURE 5. Variation of transported current density with cathode potential for varying incident positive ion energy.

At first this plot appears to contradict the results shown in Figure 3 as the transported current has increased by approximately 400Am^{-2} , while Figure 3 showed that increasing the positive ion energy to 5eV only produced an extra current density of $\sim 100\text{Am}^{-2}$. This can easily be attributed to the effect of the virtual cathode, which is shown in Figure 6.

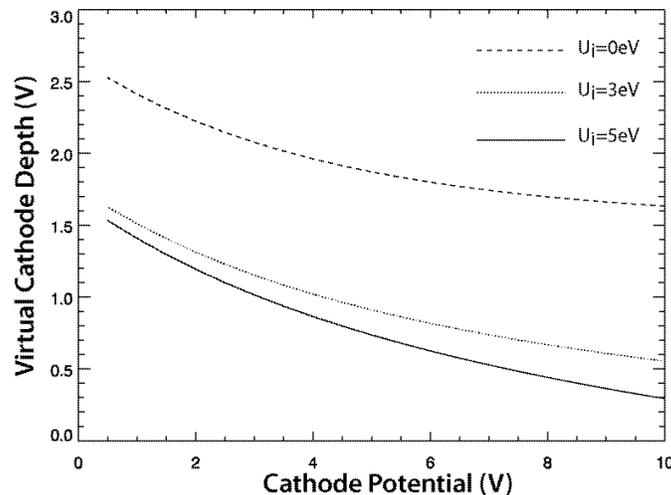


FIGURE 6. Variation of virtual cathode depth with cathode potential for varying incident positive ion energy.

As the virtual cathode is not as deep for higher incident positive ion energies more of the negative ions become available for extraction. Also, according to Equation 3 there is an exponential relationship between the transported current and the ratio of V_k and T_b .

Bias scans were also performed for varying work function with a positive ion energy of 3eV. The transported current density is shown in Figure 7 while the virtual cathode depth is shown in Figure 8. For the higher work function values there are not enough negative ions to produce a virtual cathode and that even taking the virtual cathode into account a work function of 1.5eV provides a factor of 3-5 more negative ions than 2.5eV.

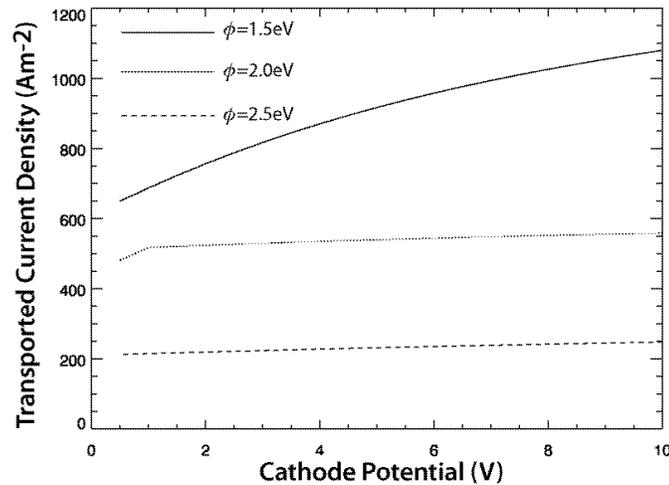


FIGURE 7. Variation of transported current density with cathode potential for varying effective work function.

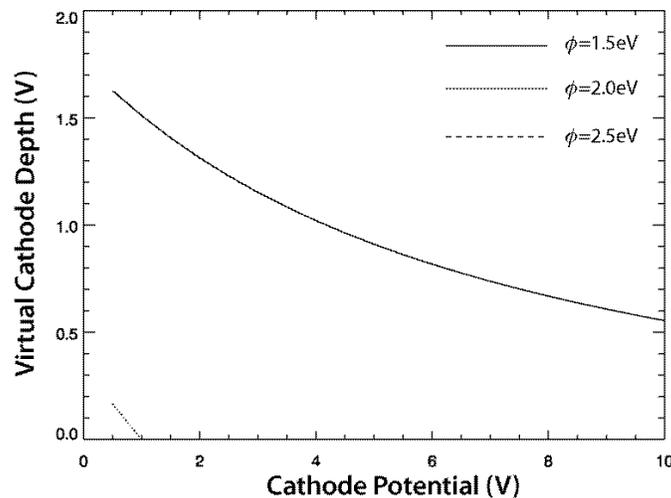


FIGURE 8. Variation of virtual cathode depth with cathode potential for varying effective work function.

Finally scans of varying effective work function for incident positive ion energies of 0, 3 and 5eV were performed. The transported current density is shown in Figure 9 and the virtual cathode depth in Figure 10. It is clear from these plots that the incident positive ion energy only has a significant effect on the transported current density in the presence of a virtual cathode. Below an effective work function of around 2eV the transported current density for 3 and 5eV ions differs by $\sim 30\%$, whereas above 2eV the difference is only $\sim 5\%$. Once the effective work function reaches 2.4eV there is little difference between thermal ions and 5eV ions.

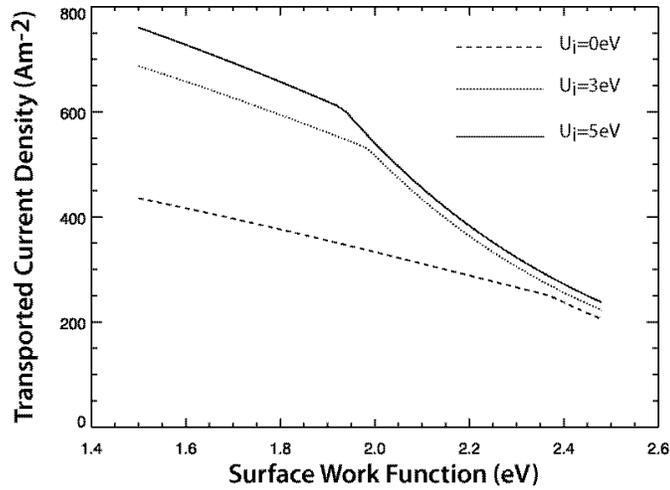


FIGURE 9. Variation of transported current density with effective work function for varying incident positive ion energy.

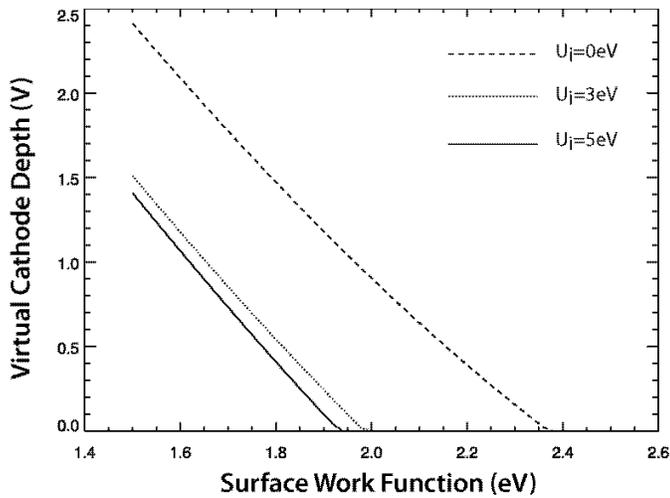


FIGURE 10. Variation of virtual cathode depth with effective work function for varying incident positive ion energy.

CONCLUSIONS

A model of virtual cathode formation in the presence of surface negative ions has been further developed and the results presented. It has been demonstrated that surface negative ions produced by incident positive ions can produce a significant enhancement of the transported current density even though they are an order of magnitude fewer than negative ions produced by incident atoms. This enhancement has been shown to be caused by the virtual cathode, as it is not present in conditions without a virtual cathode, i.e. high effective work functions on the surface. This is easily explained by the exponential dependence of the maximum transported current density on the emitted ion temperature in the presence of a virtual cathode.

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