Sheath structure in negative ion sources for fusion (invited)

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Sheath structure in negative ion sources for fusion (invited)[a]

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In fusion negative ion sources, the negative ions are formed on the caesiated plasma grid predominantly by hydrogen atoms from the plasma. The space charge of the negative ions leaving the wall is not fully compensated by incoming positive ions and at high enough emission a virtual cathode is formed. This virtual cathode limits the flux of negative ions transported across the sheath to the plasma. A 1D collisionless model of the sheath is presented taking into account the virtual cathode. The model will be applied to examples of the ion source operation. Extension of the model to the bulk plasma shows good agreement with experimental data. A possible role for fast ions is discussed. [doi:10.1063/1.3670339]

I. INTRODUCTION

Future fusion applications, such as ITER, will use negative ion sources[1] in order to generate the neutral beams for heating, current drive, and diagnostics. Negative ion sources are required as the neutralization efficiency in a gas cell is much higher than for positive ion beams operating at the required energy for plasma penetration for heating and current drive (1 MeV for the ITER heating beams). Conventional volume-type sources cannot produce the required extracted current densities[2–6] of 300 $\mathrm{Am^{-2}}$ of D^- and 350 $\mathrm{Am^{-2}}$ of H^- and negative ion production is enhanced by the addition of caesium into the plasma discharge. The caesium forms a low work function surface on the plasma grid and negative ions are formed by positive ions and atoms striking the wall.

In order to be extracted, the negative ions formed at the plasma grid must be transported across the sheath between the grid and the plasma. This transport of negative ions depends on the conditions within the sheath as determined by the density of not only the emitted particles but also the densities of the plasma particles that are entering the sheath. Under the plasma conditions in these ion sources it is clear that for thermal positive ions, the negative ions are formed predominantly by atoms striking the wall and the space charge of the emitted negative ions is then not fully compensated by the incoming positive ions. When the emission of negative ions from the plasma grid is relatively low and the electric field at the cathode is positive. Increasing the emission of negative ions from the grid increases the negative space charge at the cathode decreasing the electric field. When the field at the cathode reaches zero this is the familiar space charge limit. As the emission increases further the field at the cathode becomes negative and, since the potential must return to zero at the plasma, a minimum or virtual cathode is formed in the sheath. Negative ions from the cathode are now retarded by the virtual cathode. This limits the negative ion flux which can be transported across the sheath and thus the current which can be extracted.

The presence of virtual cathodes has been predicted by 1D (Ref. 7) and 2D Particle in Cell (PIC) (Refs. 8 and 9) codes. In this paper, a 1D model of the sheath including the formation of a virtual cathode will be described based on Poisson's equation. This has the advantages of giving physical insight into the sheath dynamics and its solutions are computed very quickly. The model will be applied to examples of ion source operation. Furthermore, it can be simply extended to allow comparison with measured data. The effect of fast positive ions is also discussed.

II. THE SHEATH MODEL

The model is based on the work of Amemiya *et al.*[10] who analyzed electron emission into a sheath of a plasma containing positive ions, electrons, and negative ions up to the space charge limit. This model was trivially modified[11] to consider negative ion emission into the sheath. It has been extended to include virtual cathode formation.[12] Only the outline of the model and the main results will be given here.

The general situation in the sheath and the plasma is shown in Figure 1 where the sheath has been split into a number of regions. In the virtual cathode region, the potential falls from the cathode potential ($-V_c$) to the minimum of the virtual cathode – a potential difference V_k. From the virtual cathode to the edge of the pre-sheath where the field is zero at both positions, the potential increases by an amount $V_m = V_c + V_k$. This is termed the standard sheath region since at low emission where there is no virtual cathode then $V_m = V_c$ ($V_k = 0$). The pre-sheath region connects the sheath edge to the plasma region by a potential difference U_0 which is the energy gained by positive ions on reaching the sheath edge to satisfy the Bohm (or modified Bohm) criterion. The model is collisionless and does not take into account the effects of magnetic fields in the source. The positive ions have been assumed to be protons only. Secondary electrons from particle impact or photo-emission will increase negative space

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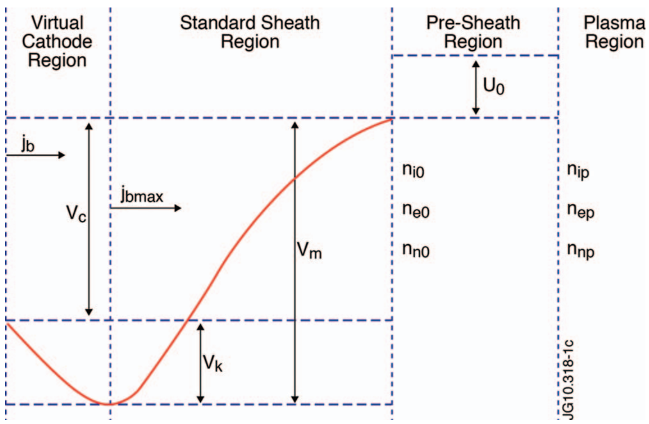

FIG. 1. (Color online) The virtual cathode, standard sheath, presheath, and plasma regions.

charge in the sheath and reduce transport of negative ions if significant. At the same energy the electron flux must be ∼43 times that of the negative ion flux to have the same charge density and so in this model they have not been accounted for.

The densities of the electrons, positive ions, and negative ions $n_{e0,p}$, $n_{i0,p}$, and $n_{n0,p}$, respectively, represent the values at the sheath edge (subscript 0) or in the plasma (subscript p). The emitted current density is j_b and the maximum transported current density is j_{bmax}. The method of solution[10–12] of Poisson's equation is to initially solve the equation up to the space charge limit. This allows the maximum transported current density j_{bmax} before the formation of a virtual cathode to be calculated. The virtual cathode is formed, if $j_b > j_{bmax}$. Since at the space charge limit, the field is zero at the cathode, this solution can also be applied to the region between the virtual cathode and the sheath edge with V_c replaced by V_m. The region between the cathode and the minimum of the virtual cathode can also be solved and the solutions on either side of the virtual cathode are matched since both the potentials and the fields have the same value at the virtual cathode.

Analysis of the Poisson equation and the appropriate boundary condition gives the following results. At the sheath edge, plasma neutrality holds and so

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

where U_b is the initial energy of the emitted negative ions. The derivative of the space charge density with respect to potential must be zero at the sheath edge and this gives the total energy of the positive ions as

$$V_0 = \frac{n_{i0}}{2\left(\frac{n_{e0}}{T_e} + \frac{n_{n0}}{T_n} - \frac{j_{bmax}}{e}\left(\frac{M_b}{e}\right)^{1/2}(2V_m + 2U_b)^{-3/2}\right)}, \qquad (2)$$

where M_b is the mass of the beam ions, $V_0 = U_0 + T_i/2$, T_i is the positive ion thermal energy, and T_e and T_n are the electron and negative ion temperatures in the plasma. This is the modified Bohm criterion and for no negative ions $V_0 = T_e/2$. From the requirement of zero field at the cathode for the space charge limit or at the virtual cathode, one obtains

$$j_{bmax} = \frac{e n_{i0} V_0 \left(\frac{2e}{M_b}\right)^{1/2}}{(V_m + U_b)^{1/2} - U_b^{1/2}} \left(\begin{array}{l} \left(\left(1 + \frac{V_m}{V_0}\right)^{1/2} - 1\right) \\ + n_{e0} T_e \left(\exp\left(\frac{-V_m}{T_e}\right) - 1\right) \\ + n_{n0} T_n \left(\exp\left(\frac{-V_m}{T_n}\right) - 1\right) \end{array}\right). \qquad (3)$$

In the above equations if $j_b < j_{bmax}$, then no virtual cathode is formed and $V_m = V_c$. Finally, in the case of a virtual cathode being formed it remains to relate the emitted negative ion flux to that reaching the virtual cathode minimum across the potential barrier. A simple Boltzmann distribution is assumed

$$j_{bmax} = j_b \exp\left(-\frac{V_k}{T_b}\right), \qquad (4)$$

where T_b is the temperature of the emitted negative ions and is related to the initial energy by $U_b = T_b/2$. These equations can be solved given the initial densities at the sheath edge of positive and negative ions, temperatures, and emitted current density to provide V_0, V_k, and j_{bmax}. These can then be used to integrate Poisson's equation for the potential across the sheath. Estimates can be obtained for the negative ion emission from the cathode and the average energy of the negative ions. The flux of negative ions is given by

$$j_b = eY(T_H)\Gamma(T_H), \qquad (5)$$

where $Y(T_H)$ is the yield of negative ions from a caesiated surface from incident atoms with temperature T_H and $\Gamma(T_H)$ is the thermal flux of atoms. For an atomic density of 10^{19} m^{-3} and a temperature of 0.8 eV and a yield of ∼0.12 (Ref. 13) this flux is ∼670 Am^{-2}. The initial energy of the negative ions can also be estimated.[12] The threshold for negative ion production is $E_{thr} = \phi - E_A$, where ϕ is the work function and E_A is the electron affinity. For $\phi = 1.5$ eV and $E_A = 0.75$ eV, then $E_{thr} = 1.5$ eV. This can be used to estimate the average energy of emitted negative ions taking into account an energy reflection coefficient. For $T_H = 0.8$ eV, a value of $U_b = T_b/2 \sim 0.7$ eV is obtained.

III. APPLICATIONS OF THE SHEATH MODEL

The sheath model has been shown to be in very good agreement with the 1D PIC code result.[12] Consider the case where the potential applied to the grid V_c is constant and the emission of negative ions from atoms striking the grid is increased. Figure 2 shows the calculated potentials for three values of the H^- emission current density of 175, 200, and 250 Am^{-2} for the conditions where the plasma parameters were $n_{i0} = 3.5 \times 10^{17}$ m^{-3}, $T_i = 0.8$ eV, $T_e = 2$ eV, $U_b = 0.7$ eV, and $V_c = -1$ V. This low value of cathode potential is consistent with the operating conditions required to reduce co-extracted electrons to minimum levels. It is assumed that there are no volume produced negative ions.

As the emission current is increased then the formation of the virtual cathode can be observed. The virtual cathode is formed at an emitted current density of just less than 200 Am^{-2}. The transported current density and the depth

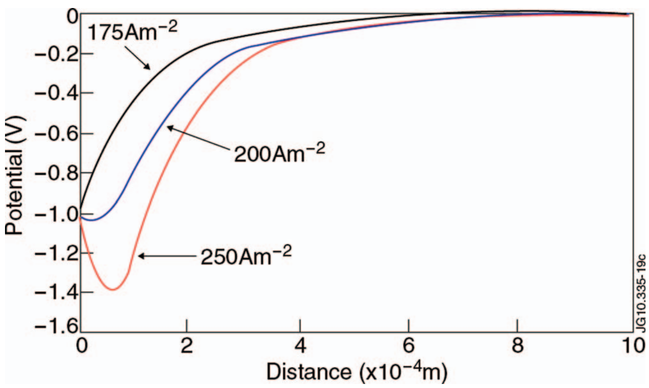

FIG. 2. (Color online) Sheath potentials for H^- emission current density of 175, 200, and 250 Am^{-2}.

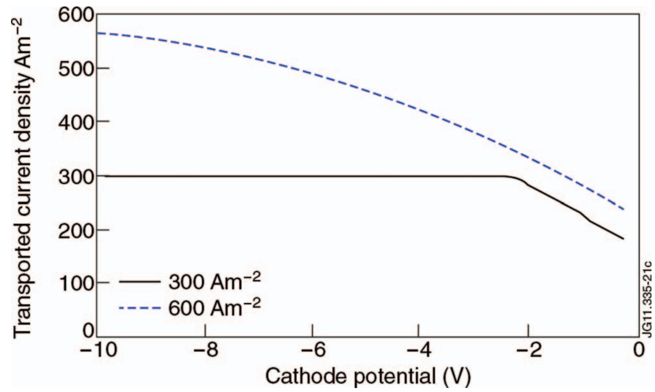

FIG. 4. (Color online) The transported current density as the cathode potential changes for emission current densities of 300 and 600 Am^{-2}.

of the virtual cathode are shown in Figure 3 as the emitted current density is changed. It is clear that once the virtual cathode has been formed, then increasing the emitted current density produces a relatively smaller further increase in the transported current density as the depth of the virtual cathode increases. At typical emission current densities of ~650 Am^{-2} then the virtual cathode depth is larger than the bias potential. In the case of deuterium negative ions Wünderlich *et al.*[7] showed that the transported current density was less than for hydrogen by a factor of $\sqrt{2}$. This result follows from the model.[11]

Control of the co-extracted electron flux in negative ion sources for fusion is achieved by biasing the plasma grid at a potential near the plasma potential. This allows the electrons to be collected on the plasma grid. This situation can be simulated using the sheath model. Figure 4 shows the effect of changing the plasma grid potential for the plasma conditions given above for two emission current densities of 300 Am^{-2} and 600 Am^{-2}.

For the lower emitted current density of 300 Am^{-2} at high cathode voltages all the emitted current is transported across the sheath. As the voltage becomes more positive then the sheath cannot support the current density and the virtual cathode is formed and the transported current density is decreased. The virtual cathode depth is shown in Figure 5. At the higher emitted current density of 600 Am^{-2}, the virtual cathode is sustained even to voltages of −10 V. This persistence of the virtual cathode arises from the requirement that at very high V_c, if the current density of positive ions at the sheath edge is lower than the emitted current density, then a virtual cathode will be formed to make the current densities equal independent of the value of V_c. If, in Eq. (3) the limit of high V_c is taken, the penetration of electrons or negative ions from the plasma into the sheath can be neglected and then

$$j_{bmax} = en_{i0}\sqrt{\frac{2eV_0}{M_b}}. \tag{6}$$

This is simply the positive ion current density at the sheath edge. Thus, if the emitted negative ion current density is greater than this positive ion current density, the virtual cathode will always form and increasing the cathode voltage will not allow all the negative ions to be transported across the sheath.

IV. EXTENSION TO THE BULK PLASMA

The sheath model outlined above deals only with plasma parameters defined at the sheath edge. Unfortunately, measurements are not made here but somewhere in the bulk plasma. As Figure 1 shows, between the sheath edge and the plasma is the pre-sheath region separating the sheath edge and the plasma thorough the potential difference U_0. Thus in or-

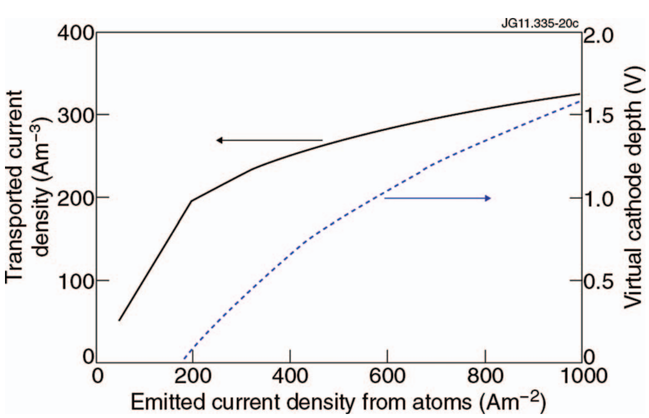

FIG. 3. (Color online) The transported current density and virtual cathode depth.

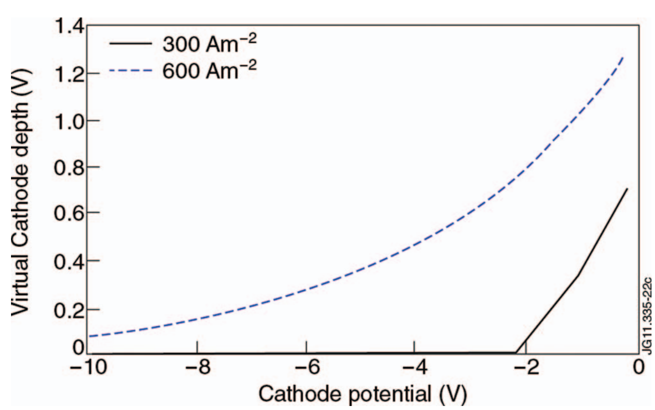

FIG. 5. (Color online) The virtual cathode depth as the cathode potential changes for emission current densities of 300 and 600 Am^{-2}.

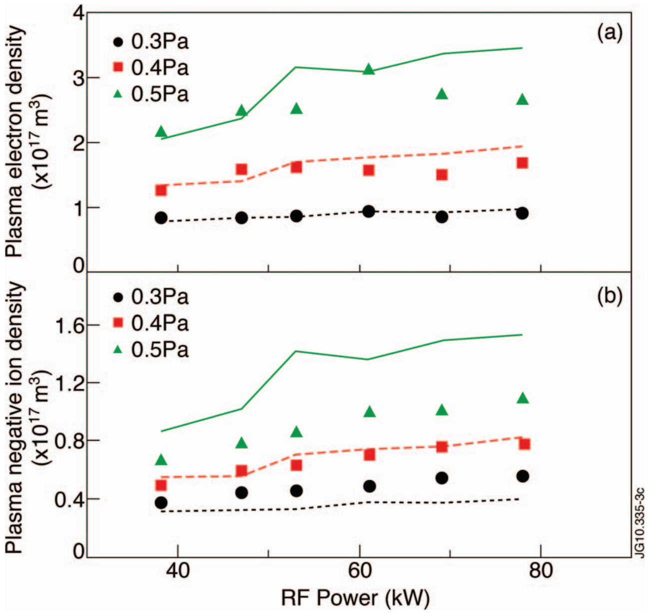

FIG. 6. (Color online) Comparison between measurements of the (a) electron density and (b) the negative ion density and the sheath model.

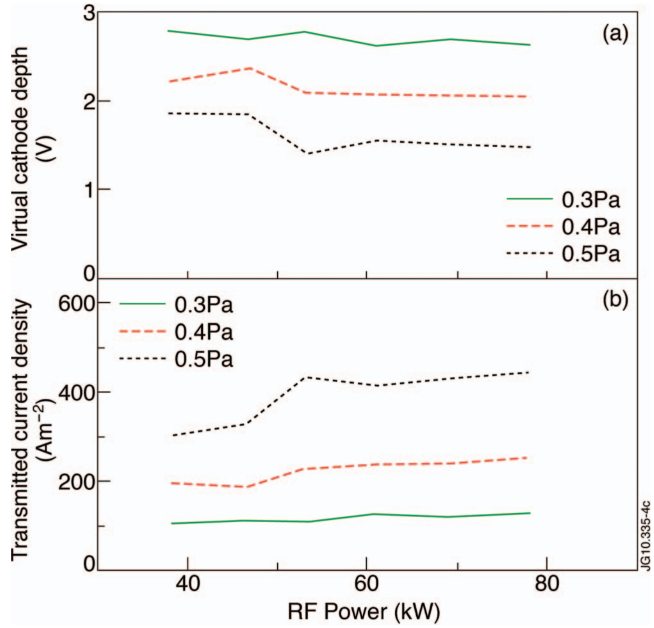

FIG. 7. (Color online) The calculated (a) virtual cathode depth and (b) transmitted negative ion flux across the sheath.

der to compare the model with measurement, the sheath edge and the plasma must be connected in some way. To do this in a way that preserves plasma neutrality, the simple assumption is made that densities at the edge and in the plasma are related by expressions such as $n_{e0} = n_{ep}\exp(-U_0/T_e)$.

In order to compare the model with measurements as complete a dataset as possible was compiled from the literature for the Institute of Plasma Physics (IPP) BATMAN source.[14–17] Measurements of positive ion density, electron temperature, and an average measured value of hydrogen atom dissociation of 17% were used. It was assumed that $T_i \sim T_H = 0.8$ eV (with an associated yield of 0.12). This allowed the emitted current density to be estimated at each data point. The data also give the negative ion density arising in the plasma volume as $n_{np} \sim 0.02n_{ip}$. The cathode potential was assumed as $V_c = -1$V. Using these parameters, the plasma electron and negative ion densities can be calculated allowing comparison with experiment. The virtual cathode depth and negative ion flux transported across the sheath could also be calculated.[18] Figure 6 shows the comparison between the measured electron and total negative ion densities for a range of RF powers and operating pressures and the calculation using the sheath model. Generally, good agreement is found between measurement and calculation except at the lowest pressure. Figure 7 shows the calculated depth of the virtual cathode and the transported current density across the sheath. Even at low powers, the depth of the virtual cathode is relatively high although this is due in part to the low cathode potential. Using an extraction probability of ~26% (Ref. 7), this gives the extracted current densities as being in the range 30–120 Am^{-2} which are probably low compared with experiment.

V. A ROLE FOR FAST IONS?

The work of McNeely *et al.*[15] shows that differences in the plasma potential of ~40 V can be established across the magnetic filter field from the driver to the extraction region at a pressure of 0.3 Pa and a RF power of 80 kW. This potential difference will accelerate positive ions and these may have an effect on the negative ion production and the sheath thus changing the negative ion flux transported across the sheath. The sheath model can also be used to estimate the effect of such positive ions. These fast positive ions can be simply incorporated into the model by setting the energy V_0 of the positive ions at the sheath edge. The emitted negative ion flux is increased according to the yield from the positive ions. The initial energy of the negative ions is set to be a weighted average of that arising from atoms and that from positive ions taking into account an energy reflection coefficient. The results are shown in Figure 8 for the conditions given in Figure 2 with the energy of the positive ions at the sheath edge set at that for thermal plasma ions and at 3 and 5 eV. Figure 9 shows how the onset and depth of the virtual cathode depends on the positive ion energy. It is clear that ions with

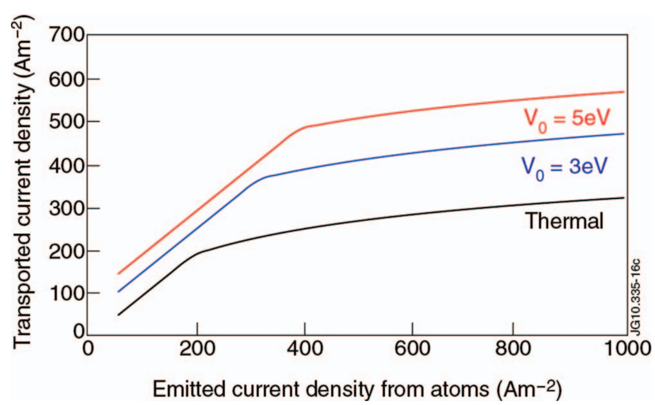

FIG. 8. (Color online) The effect of fast positive ions on the transported negative ion flux.

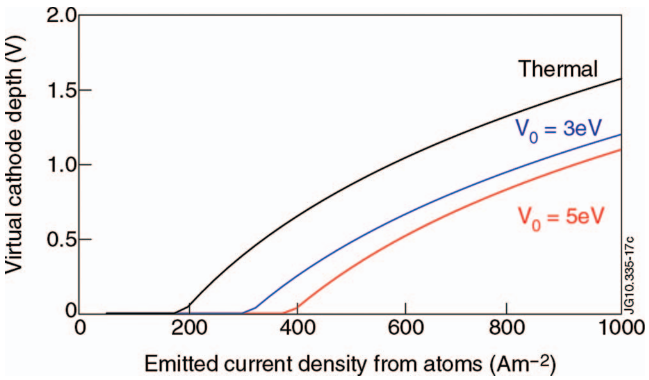

FIG. 9. (Color online) The effect of fast positive ions on the depth and onset of the virtual cathode.

a relatively low energy have a significant effect in increasing both the production and transport of negative ions across the sheath.

VI. CONCLUSIONS

Formation of a virtual cathode will limit transport of negative ions across the sheath and thus limit the performance of the ion source. The presence of a virtual cathode could hamper the search for replacement materials providing higher current densities than caesium since the transported current density would be limited and no measurable increase in performance would be observed. A relatively simple model for the sheath in a negative ion source has been modified to take into account the formation of a virtual cathode. It gives insight into the physics of the sheath and is in very good agreement with a 1D PIC code. A simple extension of the model to the bulk plasma has produced reasonable agreement with experimental data. The model has also shown that relatively low energy positive ions can improve the yield of negative ions and their transport across the sheath. It is clear that in order to improve the performance of these negative ion sources that higher densities of positive ions in the source and fluxes of positive ions reaching the plasma grid are required.

ACKNOWLEDGMENTS

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