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by

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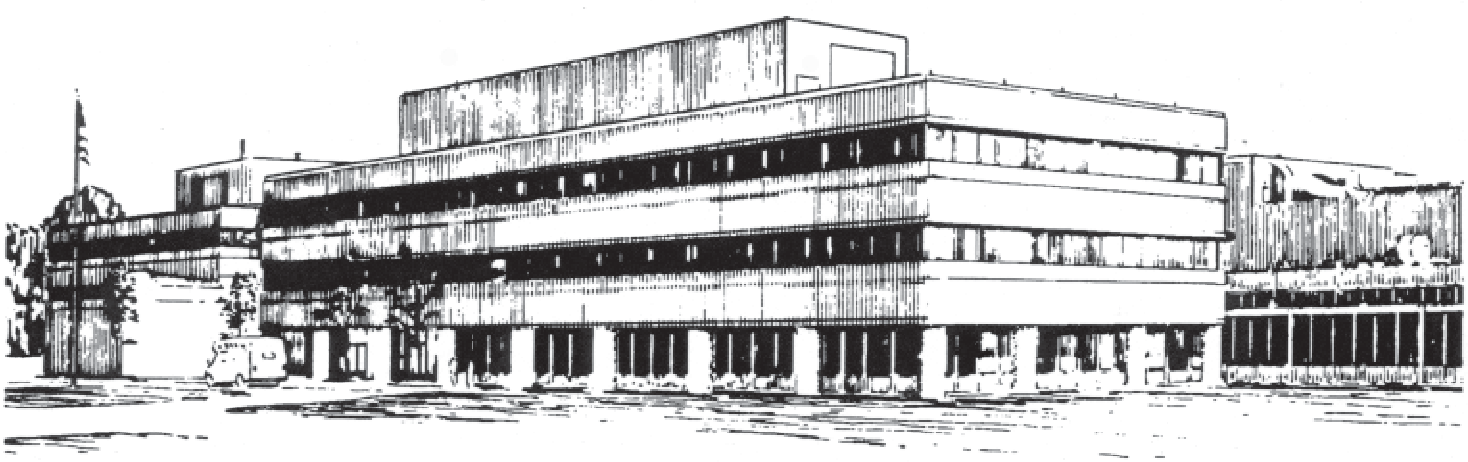

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Temperature gradient in Hall Thrusters

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Plasma potentials and electron temperatures were deduced from emissive and cold floating probe measurements in a 2kW Hall thruster, operated in the discharge voltage range of 200-400 V. An almost linear dependence of the electron temperature on the plasma potential was observed in the acceleration region of the thruster both inside and outside the thruster. This result calls into question whether secondary electron emission from the ceramic channel walls plays a significant role in electron energy balance. The proportionality factor between the axial electron temperature gradient and the electric field is significantly smaller than might be expected by models employing Ohmic heating of electrons.

A conventional magnetic layer Hall thruster is a crossed field electric discharge device with a radial magnetic field and axial electric field applied in a coaxial channel.[1] The ions are electrostatically accelerated through the azimuthally rotating cloud of magnetized electrons. Secondary electron emission (SEE) from the ceramic channel walls is considered to be a major effect limiting the electron temperature in the thruster. Current analytical models[2,3] rely on SEE effects to produce operational characteristics similar to experiments. The use of such theoretical models has not, however, been justified in detail.

In recent experiments, emissive and cold floating probe floating potential profiles were used to estimate the plasma potential and electron temperature in the PPPL 2kW laboratory Hall Thruster for discharge voltages in a range of 200V to 400V. These measurements indicate no limitation by SEE of the walls on the electron temperature below 40 eV, which tends not to support existing theoretical models. They also exhibit a yet unexplained mechanism of electron energy loss proportional to the electric field.

The 2kW PPPL laboratory Hall thruster and test facility have been described in detail elsewhere.[4] The vacuum facility is a 28m^3 vessel with two CVI cryogenic pumps providing ~10-5 torr background pressure when operating the thruster. The thruster has inner and outer diameters of 73 and 123mm respectively. The channel was made entirely of boron nitride HP grade.

The electron temperature and plasma potential measurements were made using emissive and cold probes[5] which were rapidly inserted and removed from the thruster while the floating potential of the filament tip was measured. These potentials are related to the electron temperature and plasma potential[6]. For xenon we have $T_e=(\phi_e-\phi_c)/4.27$ and $\phi=\phi_e+1.5T_e$ were T_e is the electron temperature, ϕ is the plasma potential, and ϕ_c and ϕ_e are the cold and emissive probe floating potentials. Although the electron energy distribution may depart from an isotropic Maxwellian, which was used in derivation of these equations, the results presented below still reflect an averaged electron energy, and hence qualitatively reflect the actual physical processes. The probe design and thruster operating regimes were chosen to minimize probe-induced perturbations[7]. The results are only shown for regions where the probe induced changes in thruster discharge current were less than 15%, and the changes in the floating potential of a fixed Langmuir probe mounted 2 mm inside the thruster exit plane were less than 25V.

Figure 1 shows the electron temperature and plasma potential profiles calculated from the emissive and floating probe potential profiles when the thruster was operated at a discharge voltage of 300V and an anode gas flow rate of 5.0 mg/s. Outside the thruster the temperature is greater than 14 eV beginning about 20 mm from the exit plane. The temperature peaks at a value of about 37 eV, 4 mm inside the thruster. For this measurement the change in discharge current during probe insertion was less than 5% and the changes in stationary probe voltage were less than 8 volts. The standard deviations of the averaged probe measurements were at most 12 volts. Based upon the perturbations and the standard deviations for this measurement the error in plasma potential is less than 20 V and the error in electron temperature is less than 4 eV.

Figure 2 is a plot of the electron temperature as a function of the plasma potential. This T_e-ϕ plot is a very useful indication of the electron energy gain. Three distinct regions are noted a cathode/plume region, the acceleration region, and the ionization region. The electron temperature varies nearly linearly with the plasma potential in the acceleration region. A linear fit to this region is accurate within +/- 2 eV and yields the equation: $T_e = 0.10\phi + 5.2$. This linearity is also visible between the independently measured cold and emissive floating potentials.

The linear dependence of the electron temperature on the plasma potential can be simply put as an energy relationship in the form $dT_e/dz = -\beta E$ with $\beta = 0.10$, where the electric field $E = -d\phi/dz$. A simplified electron energy equation of the form $T_e = \beta\phi$ has been suggested in the past for Hall thrusters[8]. This relation considers only ohmic heating of the electrons in which case we would find $\beta = 0.4$. As can be seen from Fig. 3 the measured value of β is significantly smaller. This indicates an energy loss mechanism nearly proportional to the electric field. The linear relationship holds both inside and outside the thruster for electron temperatures up to 40 eV.

Theoretical models of Hall thrusters generally use a Mawellian or bi-Maxwellian electron distribution function. The presence of high SEE from ceramic channel walls then limits the electron temperature in the plasma. This electron cooling mechanism is most effective for SEE of about 100% when the sheath becomes space charge limited.[9] For boron nitride ceramic walls and a Maxwellian electron distribution, the critical electron temperature is about 17eV.[10] The precise temperature depends on the experimental data used for SEE properties of the material. In contrary to these theoretical predictions, our measurements show that the linear relationship holds both inside and outside the thruster channel for electron temperatures up to 40eV.

T_e-ϕ diagrams, for comparison, were deduced from published data. High spatial resolution experimental data on different hall thrusters[11, 12, 13] is available and refs 11 and 12 show the same linear trend in the T_e-ϕ diagram over the acceleration region, and ionization region, though the cathode/plume region is not as distinct. Reference 12 uses a similar method as here to determine the electron temperature, and shows a definite linear relationship at 100V, 160V, and 200V in the acceleration region both inside and outside the thruster with $\beta = 0.09$, 0.13, and 0.14 respectively. Reference 11, which is the 90mm outer diameter PPPL Hall thruster, has a β of 0.15 for 250V operation. The T_e-ϕ diagram of reference 13, which uses double probe characteristics to determine the electron temperature, has a different structure and no linear region is observable.

T_e–ϕ diagrams from analytical models[2,3] do not show a linear relationship over the majority of the acceleration region. Only a short region near the cathode plane is linear with a slope near 0.4, that for ohmic heating. The T_e-ϕ diagram of a fully kinetic 2D PIC code[14,15] shows a linear relationships similar to as observed experimentally. For 300V and 400V simulations the linear fit slopes are 0.1 and 0.13, in the range of those measured experimentally. In the PIC code the linear relationship ends at the thruster exit plane where the temperature is a maximum. This indicates that in the PIC model as in references[2,3,10] energy loses to the wall are more significant than deduced from experiment.

In conclusion, by plotting the electron temperature as a function of the plasma potential we found a linear dependence of the electron temperature gradient on the electric field for several Hall Thrusters and for a variety of operating regimes. The constant of proportionality, β, ranges between 0.08 and 0.14 depending on the thruster and operating conditions. The value of β is significantly smaller than can be expected from ohmic heating and this indicates a yet unexplained energy loss term proportional to the electric field. Fluid models do not capture this relationship. Furthermore the linear relationship holds both inside and outside the thruster for electron temperature up to 40eV, indicating that the walls and SEE do not have a significant effect on the electron temperature.

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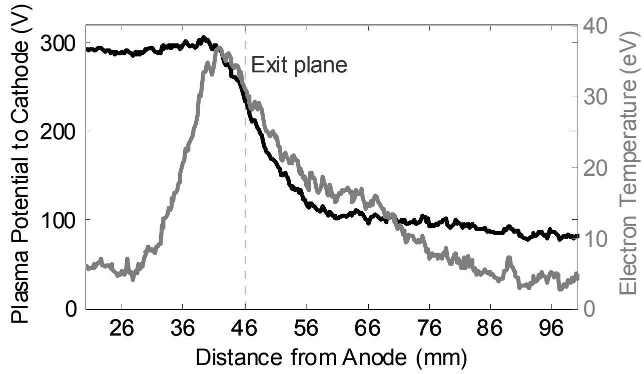
FIGURE CAPTIONS

Fig 1: Plasma potential and electron temperature profiles for 300V discharge voltage, 5.0 mg/s xenon flow rate, and 4.56 A discharge current.

Fig 2: Electron temperature vs. plasma potential for 300V discharge voltage, 5.0 mg/s xenon flow rate, and 4.56 A discharge current. Z indicates the distance from the anode.

Figure 3: Linear fit parameter β for several discharge voltages, mass flow rates (M), inner to outer magnetic coils current ratios (I_r), and probe design (AP = unshielded alumina probe holder, SP = segmented graphite shielded probe holder[7]).



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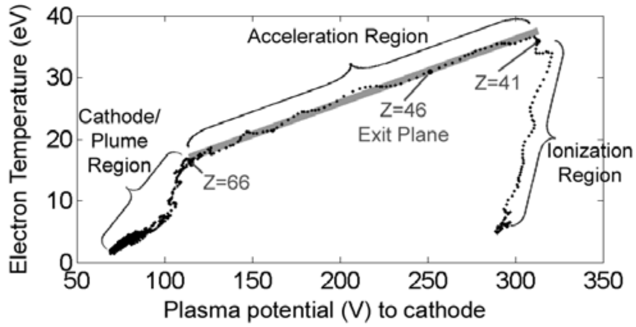

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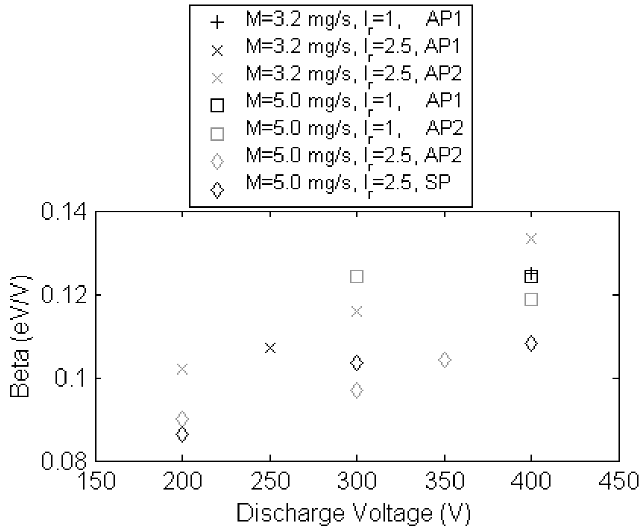

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