CROSS-FIELD MOBILITY IN A PURE ELECTRON PLASMA

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An electron trapping apparatus was constructed in order to study electron dynamics in the defining electric and magnetic fields of a Hall-effect thruster. The approach presented here decouples the cross-field mobility from plasma effects by conducting measurements on a pure electron plasma in a highly controlled environment. Dielectric walls are removed completely eliminating all wall effects; thus, electrons are confined solely by a radial magnetic field and a crossed, independently-controlled, axial electric field that induces the closed-drift azimuthal Hall current. Electron trajectories and cross-field mobility were examined in response to electric and magnetic field strength and background neutral density.

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1. INTRODUCTION

The defining characteristic of Hall thrusters is the crossed axial electric and radial magnetic fields. The criteria of the E- and B-fields are such that the electron gyro radius is small compared with apparatus dimensions while the gyro radius and mean free path for ions are larger than apparatus dimensions; these criteria are necessary so that ions are only affected by the electric field, whereas the electron trajectories are controlled by both electric and magnetic fields. The crossed E and B fields induce the confining ExB electron drift, which holds electrons in azimuthal orbits around the discharge channel annulus. Cross-field electron transport is necessary to sustain thruster discharge; however, mobility takes energy away from the accelerating region, which, in excess, has negative effect on thruster efficiency.

In past experiments the cross-field electron mobility has been found to be much larger than the classical collisional diffusion model [1,2]. Several hypotheses exist for the discrepancy including plasma fluctuations, turbulence and wall interactions [3-6]. The approach used in this investigation removes such plasma fluctuations and wall interactions by examining the electron dynamics of a pure electron plasma in a Hall thruster's defining fields with an independently-controlled electric field in vacuum. While such an approach has not been documented in Hall thruster studies, an examination of non-neutral plasma has proven to be useful for numerous types of charged particle transport studies [7-13].

2. MOBILITY CONCEPTS

In a Hall thruster, the predominant electron motion is the azimuthal ExB drift. Classical cross-field mobility states that collisions with neutrals or walls provide the only mechanism responsible for motion across B-field lines, which allow an electron to "jump" to a new field line with a step length on the order of the Larmor radius. A detailed description of cross-field mobility can be found in Chen [14].

Cross-field mobility is defined as the constant of proportionality between the cross-field velocity of electrons, u_{ez}, and the axial electric field, E_z:

$$\mu_{ez} \equiv \frac{u_{ez}}{E_z} \tag{1}$$

Given the case of a large Hall parameter, the cross-field electron velocity in radial magnetic and axial electric fields is given by classical model as:

$$u_{ez} = \frac{E_z}{B_r}\frac{\nu_{ne}}{\omega_{ce}}, \tag{2}$$

and thus mobility becomes:

$$\mu_{ez} = \frac{\nu_{ne}}{B_r \omega_{ce}} . \tag{3}$$

Classical mobility can be determined at any point in the discharge channel where the magnetic field is known and an effective collision frequency can be estimated accurately.

In these experiments, where a one-component plasma is examined, there exists a space charge due to the absence of shielding ions. The magnitude of the induced negative space charge is found from a solution of the Poisson equation $\nabla^2\Phi = qn_e/\varepsilon_0$, where Φ is the electric potential. If the experimental geometry is approximated as a cylindrical annulus infinite in the z-dimension, then the solution to the Poisson equation for n_e=constant, becomes:

$$\frac{\Phi(r)}{n_e} = \frac{e}{4\varepsilon_0}\left[r_{out}^2 - r^2 + \left(r_{out}^2 - r_{in}^2\right)\frac{\ln(r_{out}/r)}{\ln(r_{in}/r_{out})}\right] . \tag{4}$$

For the physical scale of the apparatus used in the present investigation, Φ_{max}/n_e~1×10^{-11} Vm^3, so if the electron density were limited to $n_e<5\times10^{10}$ m^{-3} (very typical for electron non-neutral particle traps [9]), then the space-charge potential at channel mid-radius would be on the order of 1 V below unperturbed local trap potential, which will not significantly alter the electron trajectories.

3. ELECTRON TRAPPING APPARATUS

An electron trapping apparatus shown in Fig.1 was constructed to reproduce the defining characteristics of a Hall thruster's accelerating region.

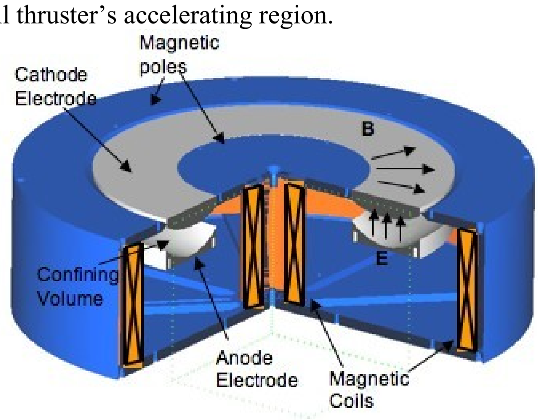
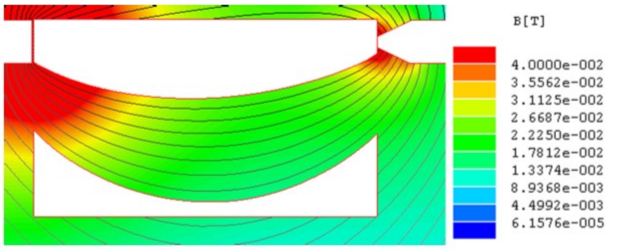


Fig. 1. Electron Trapping Apparatus

The magnetic field was applied through inner and outer magnetic coils shown, much like a typical Hall thruster. However, the electric field in the region of interest was formed through electrodes in vacuum, rather than via a self- consistent plasma. (Field maps are shown in Fig. 2)

Because of the curved electrodes, the B-field and equipotential lines coincide over a large fraction of the trapping width. This coincidence allows electrons to be thermally mobile along field lines within the trap, with the effective trap potential only varying by a few eV over the confining width [15], much like that of a Hall thruster [16]. Equipotential lines depart from the magnetic field lines at the inner and outer radii of the trap creating a confining electric force at the trap edges, $F_{E||}$.



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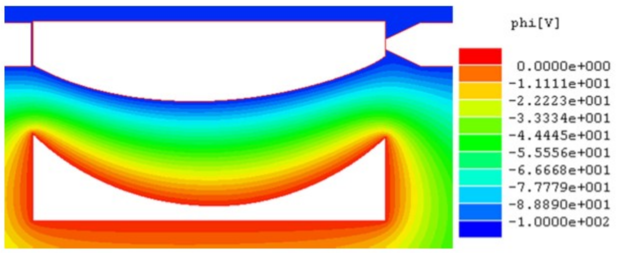

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Fig. 2. Magnetic Field (a) and Electric Equipotentials (b)

The trap was loaded with electrons by passing a radial ~75 eV ionizing electron beam from a thermionic emitting filament through the trap from the outer pole. Electron-ion pairs are created within the trap by collisions with background krypton neutrals. The unmagnetized krypton ions are immediately neutralized through collisions with the cathode, while the low-energy ejected electrons are trapped in azimuthal orbits via the applied fields.

4. TECHNIQUE TO MEASURE MOBILITY

The cross-field mobility was evaluated experimentally by combining a measurement of the azimuthal Hall current with the axial (anode) current. The mobility can be expressed as:

$$\mu_{ez} = \frac{J_a}{q n_e E_z} \quad , \qquad (5)$$

where J_a is the anode current density. A measure of electron density is obtained by measuring the azimuthal Hall current with an in-situ probe. The current density incident on the probe is J_p, where $J_p = q n_e u_{e\theta}$, and thus electron density can be determined, since $u_e = E_z/B_r$, where both E_z and B_r are known from applied field conditions. By substitution, equation (5) simply becomes:

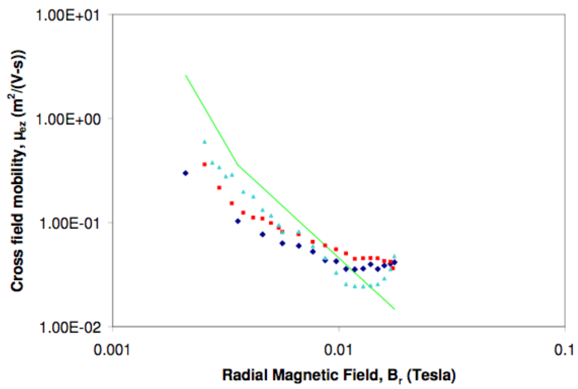
$$\mu_{ez} = \frac{J_a}{B_r J_p} \quad . \qquad (6)$$

This experimentally determined mobility can then be compared quantitatively with the classical model.

5. RESULTS AND DISCUSSION

Cross-field mobility as a function of magnetic field was determined by varying the radial magnetic field from 0.003 to 0.018T (30…180 G) under constant facility vacuum pressure. The results are shown in Fig.3 with a solid line representing classical mobility. Colors indicate several sweeps done with all conditions held constant, with the possibility of slight variations between sweeps in base pressure due to time lapse between data acquisition. Experimental and classical mobility were found to agree both in trends and absolute magnitude. The determination of classical mobility is described in more detail in [15].

Mobility was measured in response to collision frequency by bleeding krypton gas into the vacuum chamber to raise the pressure from 9×10^{-7} to 1×10^{-4}. The observed cross-field mobility for three magnetic field strengths is shown in Fig. 3. Classical mobility is shown as solid lines in corresponding colors. The trends exhibited by the observed mobility are reasonable; mobility scales with increasing neutral density and decreases with increasing magnetic field. However, the observed cross-field mobility was found to scale with $\nu_{ne}^{1/2}$ through a power-law fit, rather than scaling linearly with ν_{ne} as would be expected by the classical model. An explanation for this odd departure is still absent.



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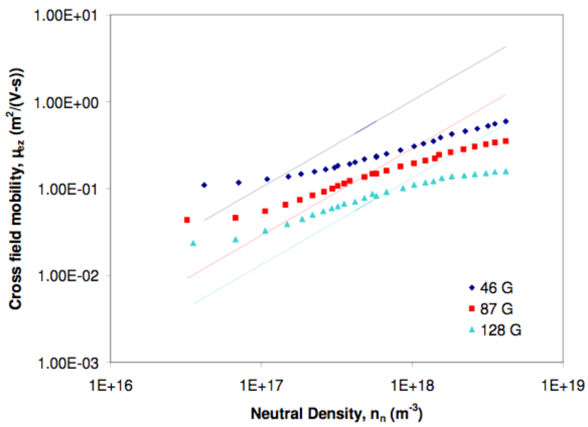

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Fig. 3. Mobility vs. Magnetic Field (a) and neutral density (b). Classical mobility is shown as a solid line

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ПОПЕРЕЧНАЯ ПОДВИЖНОСТЬ В ЧИСТО ЭЛЕКТРОННОЙ ПЛАЗМЕ

Эмили С. Фоссум, Лайон Б. Кинг

Для исследования динамики электронов в ведущих электрическом и магнитном полях ускорителя с эффектом Холла было разработано устройство для запирания электронов. Представленный здесь подход подразумевает разделение поперечной подвижности и плазменных эффектов за счёт измерений проводимости в чисто электронной плазме в строго контролируемых внешних условиях. Влияние стенки полностью исключается путём удаления диэлектрических стенок; таким образом электроны удерживаются только радиальным магнитным полем и независимо изменяемым скрещенным аксиальным электрическим полем, которое индуцирует азимутальный ток Холла с замкнутым дрейфом. Выяснялись зависимости траекторий электронов и поперечной подвижности от напряжённости электрического и магнитного полей и фоновой плотности нейтралов.

ПОПЕРЕЧНА РУХОМІСТЬ В ЧИСТО ЕЛЕКТРОННІЙ ПЛАЗМІ

Емілі С. Фосум, Лайон Б. Кінг

Для дослідження динаміки електронів в ведучих електричному і магнітному полях прискорювача з ефектом Хола був розроблений пристрій для запирання електронів. Підхід, що подається, припускає розділення поперечної рухомості і плазмових ефектів за рахунок вимірювань провідності в чисто електронній плазмі зі строгим контролем зовнішніх умов. Вплив стінки виключається повністю завдяки віддаленню діелектричних стінок; тим самим електрони утримуються тільки радіальним магнітним полем і схрещеним аксіальним електричним полем, яке змінюється незалежно і збуджує азимутальний струм Хола із замкненим дрейфом. З’ясовувалися залежності траєкторій електронів і поперечної рухомості від напруженості електричного і магнітного полів та фонової густини нейтралів.