Dispersion relation measurements of plasma modes in the near-field plume of a 9-kW magnetically shielded thruster

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The ion density perturbations in the near-field plume of a 9kW magnetically shielded Hall thruster are experimentally characterized. A translating array of ion saturation probes is employed to measure local fluctuations in the cross-correlation and power spectra of the plasma density oscillations. It is found that an ion acoustic-like wave propagating primarily in the azimuthal direction is the dominant mode in this region. Depending on the position in the plume, the mode exhibits a peak in power at a frequency 50-250 kHz and with wavenumbers 50-200 m^{-1}. Applying weak-turbulent theory, an effective collision frequency is estimated based on the power of the acoustic-like fluctuations. It is shown that the effective collision frequency from the acoustic-oscillations is several orders of magnitude higher than the classical collision frequency. Furthermore, the Hall parameter in this region is on the order of unity. Together these results imply the measured acoustic-like mode can be a dominant contributor to electron transport in the near-field region.

Nomenclature

c_s	= ion sound speed
γ	= growth rate
k	= wavenumber
M_s	= mass of particle s
ϕ	= plasma potential
T_s	= temperature of species s
v_s	= themal speed of species s
V_s	= drift velocity of species s
ν_{AN}	= anomalous electron collision frequency
ω	= wave frequency
ω_s	= cyclotron frequency of species s
ω_{pe}	= electron plasma frequency
ω_{pi}	= ion plasma frequency
Ω_e	= Hall parameter

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I. Introduction

The Hall thruster is a form of crossed-field plasma device commonly employed for in-space electric propulsion. In the standard coaxial configuration, a strong radial magnetic field confines the lighter species of the plasma, electrons, which collide with and ionize the injected propellant, while an applied axial electric field accelerates the heavier species, the ions, downstream. Ideally, the electrons would be confined by the magnetic field in an azimuthal E×B drift current, serving as an efficient ionization source. However, it has been found experimentally that electrons can cross field lines in these devices at rates orders of magnitude higher than can be explained by classical effects. This is the so-called problem of anomalous electron transport, and to date, there is no first-principles explanation for what causes this enhanced transport. While a lack of understanding about this process has not precluded the successful implementation of Hall thrusters on orbit, or their expanding use for both commercial and government applications, our uncertainty about this underlying physical process has precluded the development of self-consistent models for thruster performance. Such self-consistent models are increasingly important for both life-validation of these devices[1] as well as for the coveted goal of having a predictive design capability.

The need to understand this anomalous mechanism has given rise to a large body of work—both experimental and numerical.[3−16,18,19,22,30] While several different mechanisms have been proposed to explain this anomalous transport, an emerging consensus in the field[2] points to the onset of azimuthal plasma oscillations in the channel as the most likely candidate. Indeed, recent simulations have indicated that one mode in particular may be a dominant contributor to the transport, the so-called electron cyclotron drift instability (ECDI).[9,10] To support this idea, collective scattering experiments have detected megahertz modes in the near field of a Hall thruster discharge which show there is a turbulence spectrum of ECDI-like oscillations[11,12] at high frequency ($\omega > 5$ MHz) and wavenumber ($k >4000$ m^{-1}) .

Despite the mounting evidence suggesting that the ECDI may play a dominant role in driving the cross-field transport in these devices, there are still a number of questions about the nature of this instability. From the perspective of simulations, the effects of ECDI turbulence have yet to be incorporated self-consistently into full-scale models of the thrusters. And despite on-going efforts to accomplish this aim,[13,14] it is still not clear how to model effectively the propagation of the ECDI in the thruster or its impact on the background plasma parameters. From an experimental perspective, despite the extremely insightful previous work with collective light scattering on detecting the ECDI, there were inherent limitations on this technique that have left open questions about the nature of ECDI. Due to geometric constraints, the scattering experiments were only capable of resolving large wavenumbers ($k > 4000$ m^{-1}), i.e. small wavelengths. Although these measurements were sufficient to show the dispersion of the mode, and thereby identify them as ECDI, there are key properties of the ECDI spectrum in the thruster plasma that experimentally remain unresolved.

These key properties are both related to the shape and magnitude of the turbulent spectrum of ECDI in the thruster plume. For example, simulations that predict the onset of ECDI in thruster-like configuraitons almost unambiguously show that the spectrum of waves should be dominated by a single mode located at the wavenumber and frequency of maximum growth.[9,10,15,16] This maximum is predicted to be at either the Debye length or a multiple of the cyclotron Larmor radius. Due to the limited wavenumber resolution of the experimental techniques to date to assess this mode, however, measurements have only been able to show a monotonic decrease of the power spectrum of the waves with increasing wavenumber. In other words, it is not clear if there is in fact a dominant mode in the spectrum. It is critical from a need to reconcile experimental results with the leading theories for the growth of the ECDI to establish if there is in fact a dominant mode.

By that same token, if both the dispersion of the modes as well as the power spectral content of these oscillations are known, it is in principle possible to estimate the effective transport driven by these waves[13,17] (as represented by an enhanced anomalous collision frequency). However, although previous measurements of the ECDI were able to measure the dispersion, due again to the limitations of the technique, they could only resolve a small fraction of the power spectrum of the oscillations. Thus, it is not possible to directly infer the effective cross-field transport from these oscillations. As a consequence, although the ECDI is a leading candidate to explain the cross-field transport, there is to our knowledge no direct experimental calculation of the effective collision frequency that can be attributed to it. This leaves the possibility that, although this mode exists in the thruster, it may not be a dominant contributor to transport.

With these unresolved questions, the need is apparent for a diagnostic technique that is capable of addressing these outstanding questions about the nature of the ECDI spectrum and its role in the plume of these devices. The natural candidate to survey the lower wavenumbers not accessible with the coherent scattering technique is the use of physical probes. It is worth noting that previous experiments, such as those by Gascon et al[18] and Lazurenko et al,[19] have employed similar probing techniques for wave detection in Hall thrusters, but to our knowledge this is the first time these techniques have detected ECDI like waves at low wavenumber. In principle, the probing technique described in Sec. III. can measure arbitrarily small wavenumbers, but have some effective limit on the maximum measureable wavenumber due to physical constraints and probe shealth effects. Unfortunately, as compared with collective scattering techniques, studies have shown that direct probing can be perturbative in the thruster channel,[20,21] and distort the measurements. On the other hand, these same studies on probe perturbations demonstrated that if the probes are sufficiently far downstream of the thruster, then they do not perturb the thruster operation. Furthermore, most thruster simulations seem to suggest that the anomalous transport is actually highest in the thruster plume i.e. downstream of the accleration zone.[22] This suggests that we may be able to address some of the questions about the ECDI in the region where it is likely the greatest contributor to anamolous transport while using more traditional probing techniques.

In light of this possibility, the goal of this investigation is to use physical probes to explore the properties of the ECDI in the near-field of a Hall-effect thruster. This paper is organized in the following way. In the first section, we briefly review the linear theory for the onset of the ECDI and how its properties can be related to an effective anomalous collision frequency. In the second section, we describe the experimental setup including the probing techniques for measuring the wave properties as well as the local plasma parameters. In the third section, we present results from our wave measurements as well as estimates for the effective cross-field transport. In the fourth and final section, we discuss the implications of our results in terms of the role of ECDI in driving the plume physics of these devices.

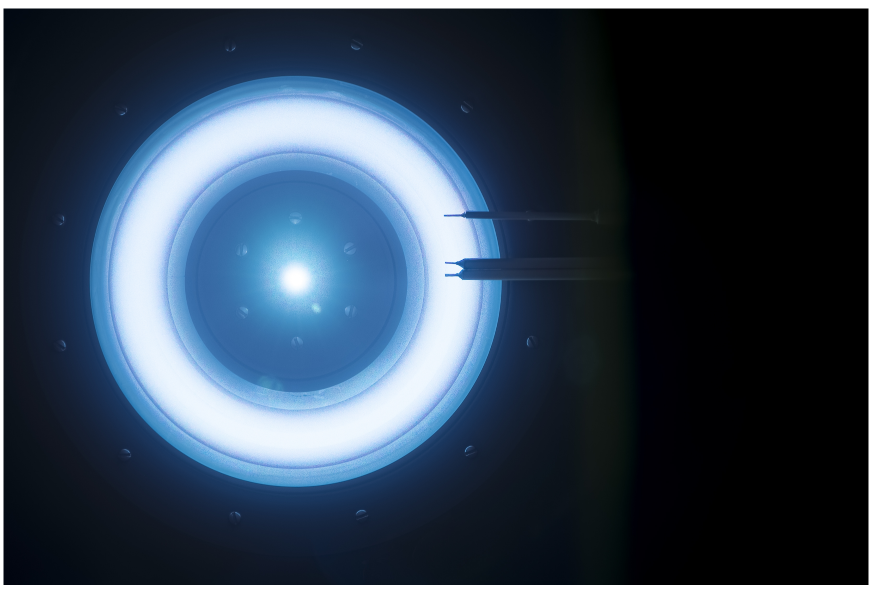


Figure 1: H9 during axial and azimuthal dispersion measurements

II. Theory

In this section, we briefly review the properties of the ECDI in the form they are believed to exist in Hall effect thrusters and in turn how these modes can be related to an effective electron collision frequency driving cross-field transport.

1. *Electron Cyclotron Drift Instability in the Acoustic limit*

The electron cyclotron drift instability (ECDI) is an electrostatic mode in E×B discharges that is driven unstable by the relative azimuthal drift of the electrons, $V_e = E/B$, with respect to the much heavier, unmagnetized ions. Both the dispersion and growth rate of this mode in principle rely on the wave properties satisfying the so-called cyclotron resonance criteria, i.e. $k_z V_e \approx n\omega_e$, where k_z is the component of the wave vector along the magnetic field, n is an integer multiple, and ω_e is the electron cyclotron frequency. In practice, for either large amplitude waves[23] or if the wave component along the magnetic field is sufficiently large,[12] then the cyclotron resonances for the mode disappear, leaving a dispersion relation that is identical to that of ion-acoustic waves:

$$\omega_r \approx kc_s \tag{1}$$

$$\gamma = 2\omega_i = kc_s \left[\left(\frac{\pi}{2}\right)^{1/2} \left(\frac{V_e}{v_e}\right) - \frac{v_i}{kc_s} \right], \tag{2}$$

where ω_r is the real frequency part, k is the wavenumber, $c_s = \sqrt{eT_e/M_i}$ is the ion sound speed, γ is the growth rate, and $v_s = \sqrt{eT_s/M_s}$ is the thermal speed of plasma species s. Physically, these modes represent acoustic-like perturbations propagating with the ion sound speed in the ion frame of reference. The source for the instability of this mode is the electron drift V_e in the E x B (i.e. azimuthal) direction for Hall thrusters. This dispersion relation has been observed experimentally by Tsikata et al. in the near field plume of the Hall effect thruster with coherent-Thomson scattering techniques.[11]

2. Collision Frequency

The growth of the ECDI comes at the expense of energy in the relative electron drift with respect to the ions. The electron drift therefore experiences an effective drag, which in turn can be modeled as an effective collision frequency, ν_{AN}. Indeed, it can be shown[13] that for acoustic-modes with propagation primarily in the azimuthal direction that

$$\nu_{AN} = \frac{\omega_{pe} e^2}{T_e^2} \sum_{\omega}^{\omega_{pi}} [\phi(\omega)]^2, \tag{3}$$

where $\phi(w)$ is amplitude of plasma potential flucuations at frequency ω, ω_{ps} is the plasma frequency of species s, and T_e is the electron temperature. The physical interpretation of this result is that the larger the instability grows in the spectrum $\phi(\omega)^2$, the higher the effective collision frequency it drives. Armed with these relations, in the following sections, we outline an experiment to search for modes with the properties of Eq. 1 in the near field of a Hall thruster and then use Eq. 3, to evaluate the effective collision frequency driven by these modes.

III. Experimental Setup

The experimental testbed we employed for this setup was the H9, a new laboratory model 9-kW magnetically shielded thruster.[24,25] This thruster was developed by the Jet Propulsion Laboratory in conjunction with the Air Force Research Laboratory and the University of Michigan to serve as a standardized test-article for investigating state-of-the art, high-power, magnetically-shielded thruster technology. For this campaign, we operated the thruster at the Air Force Research Laboratory in the SPace Environmental Facility(SPEF), a 9 meter diameter spherical vacuum chamber. Inside this chamber the thruster was mounted in a large Faraday cage, approximately 4 by 2 meters, isolated from the chamber and thruster body. This configuration is a carry-over from the Electric Propulsion Test & Evaluation Methodologies for Plasma in the Environments of Space and Testing (EP TEMPEST) campaign, but was only incidental to our study. We operated the H9 for this experimental test at 300V discharge voltage and 4.4A discharge current with a background pressure of 40 μTorr Xe. The anode flow was 45 sccm Xe and the cathode flow fraction was 10%. We operated below the H9's standard discharge current, 15-20A, as we found that during operation, the thruster would enter into an unstable global mode oscillation at high current, ultimately leading to shut downs. The thruster has not exhibited this behavior at other facilities[24,25], so we believe it may in part be correlated with the unusual boundary conditions presented by the TEMPEST cage. A full discussion of these effects are beyond the focus of this investigation, but we do note that even at this abnormal operating condition, the thruster still exhibited visual features implying that it was operating in a magnetically-shielded configuration. For example, there was carbon buildup in the discharge channel and reduced luminosity near the channel walls.

A. Probes

We used two sets of translating probes to characterize the plasma parameters and wave properties in the thruster plume. For the plasma parameters, we employed a single langmuir probe to generate I-V traces.

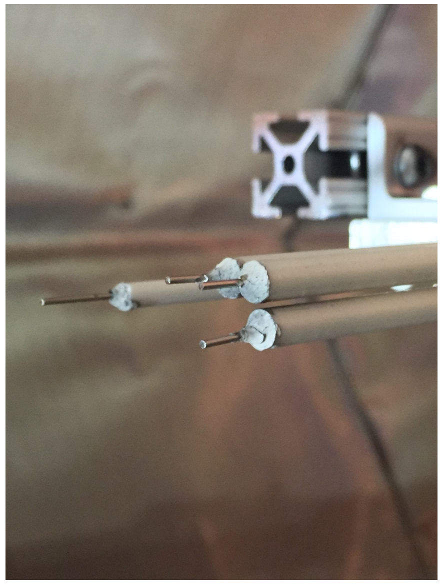


Figure 2: Array of langmuir probes mounted on translation stage

Traces were generated using a source-measurement unit, and we determined the electron temperature and plasma density employing the log-slope technique coupled with the thin-sheath approximation.[26] To detect fluctuations in the thruster plume, we followed the methods of Jorns et al[17] by employing a cluster of three ion saturation probes to measure high frequency variations in ion density that can be related to waves propagating in two orthogonal directions (Fig. 2). Each probe consists of a tungsten tip, 1 mm diameter and 9 mm in length, connected to coaxial wiring inside an alumina tube. The probes in the array were spaced by ≈7 mm, which allows for wavenumber detection up to ~ 400 m^{-1}.We biased the ion-saturation probes to -38V using batteries, to minimize noise, and measured ion saturation current as the voltage across a 100Ω bulk metal foil resistor using a 1GHz bandwidth Lecroy oscilloscope at a 20 MHz sampling rate.

Both the swept-Langmuir probe and ion saturation probe array were mounted on a stage capable of translating in the axial direction. In all cases, this stage was aligned so that the probes moved from the far-field toward the thruster along the channel centerline. The stages swept the probes between 50 cm and 3 cm from the thruster exit plane. It was noted that the thruster operation, as reprsented by the DC discharge current, remained constant as the probe was inserted to its most upstream locaiton. In order to generate wave measurements for all three orthagonal directions, we inserted the probes at the 3 o'clock position to measure azimuthal and axial waves and the 6 o'clock position to measure azimuthal and radial waves. Adjusting the probe configuration required us to vent between trials.

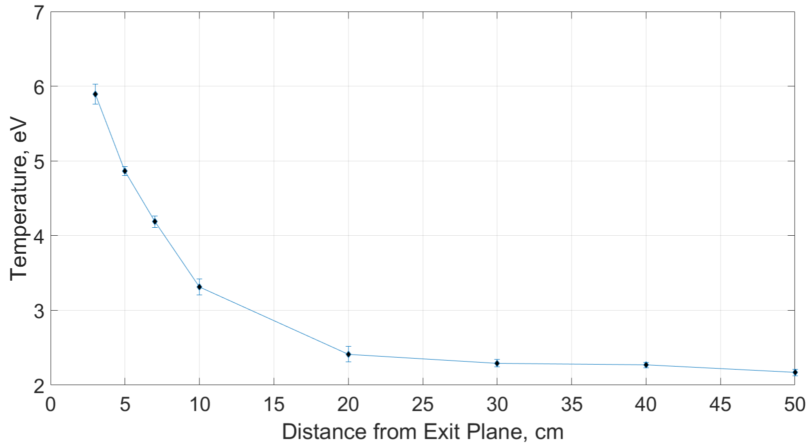
B. Results

1. *Background Measurements*

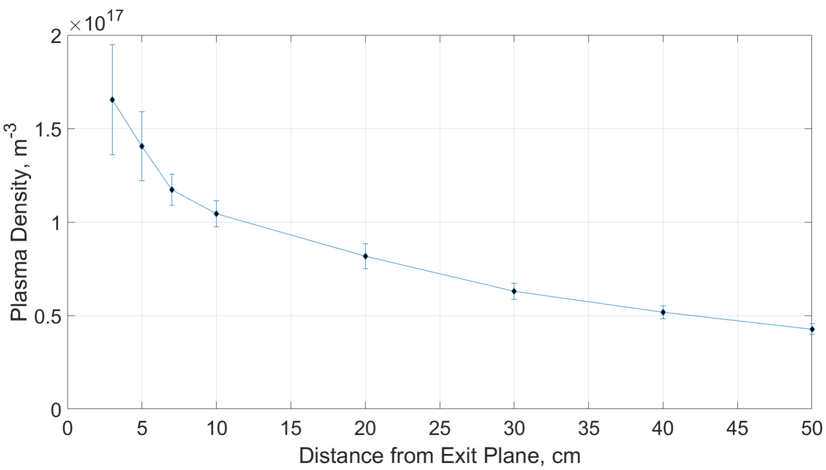
We show in Fig. 3 measurements of the background electron temperature and plasma density in the near field of the thruster. The error bars for T_e were calculated using by the 95% confidence interval in the determined slope of $ln(I_e)$ and the error bars in density represent different samplings of $I_{probe}(V_{bias})$ in the ion saturation region. As can be seen, the electron temperature only decreases slightly—indicating we are downstream of the acceleration region in the thruster. The density falls off nearly exponentially, as is consistent with an expanding plume in the near field.

2. *Dispersion Relation Measurements*

We present here fluctuations in the local plasma potential as inferred by the ion saturation fluctuation measurements from each probe in the cluster. To make this transformation, we employed the relation valid for low-amplitude electrostatic modes:



(a) Electron temperature in near field



(b) Plasma density in near field

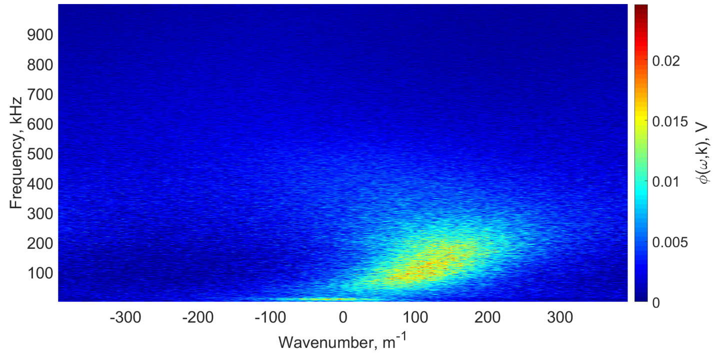
Figure 3: Measured plasma parameters in near plume along the channel center line from 3 to 50cm from the thruster exit plane

$$\tilde{\phi} \approx \frac{T_e}{q} \frac{\tilde{i}_{sat}}{\bar{i}_{sat}}. \tag{4}$$

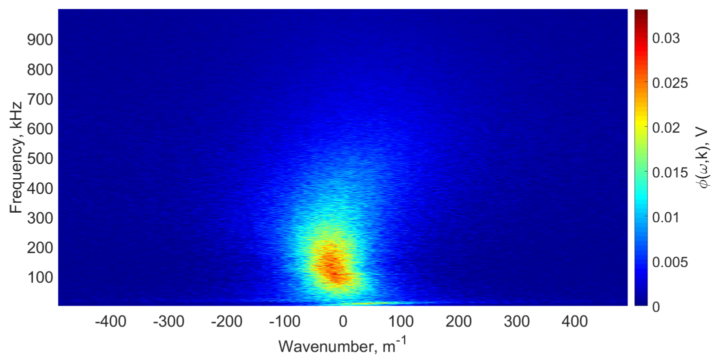
In order to correlate the dispersion relation between modes, we adopted the Beall technique[27] as was recently employed by Jorns et al[17] to infer wave dispersion in the plume of a hollow cathode. This technique effectively creates probability plots of the frequency and wavenumber in the direction defined by the chord connecting two adjacent probes in the probe array.

Characteristic Beall intensity plots are shown in Fig. 4 for data collected 5 cm downstream from the exit plane of the H9. The structures seen here appear strongly for distances 3 cm to 10 cm after which the structures start gradually diminishing and disappear by 30 cm. In the azimuthal direction a distinct linear dispersion is seen in the frequency range of 50-250 kHz and corresponding to wavenumbers of 50-200 m^{-1}. For the radial and axial dispersions there is a roughly constant wavenumber in the frequency range where we observe the azimuthal mode from the Beall plots.

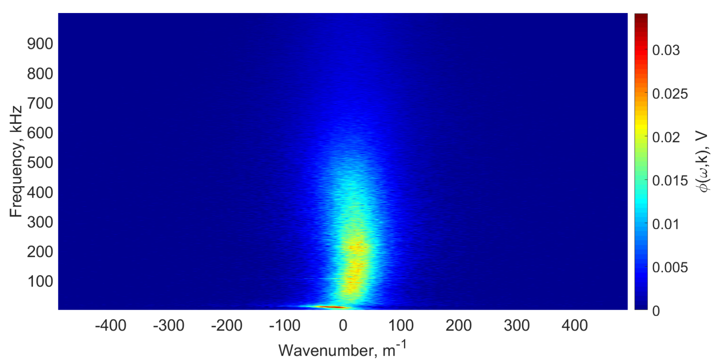
For the azimuthal dispersion a group velocity is fitted to the linear region and compared with the calculated ion sound speed (Fig. 5) that was inferred from the electron temperature measurements. There is decent agreement between the two values which is characteristic of ion acoustic waves. Taken together with the small wave components in the azimuthal and radial directions, the results confirm that we are seeing in



(a) Azimuthal dispersion, positi ve wavenumbers correspond to waves propagating in the E×B direction



(b) Axial dispersion, positive wavenumbers correspond to waves propagating downstream



(c) Radial dispersion, positive wavenumbers correspond to waves propagating outward

Figure 4: Beall Intensity Plots when probes are 5cm downstream of exit plane

the low-frequency regime, acoustic-like modes with small but finite components in the radial (along magnetic field lines) and axial directions (opposite direction of acceleration for thruster). We thus conclude that these modes are similar at least in dispersion to the instabilities observed by Tsikata et al. However, we note that the wavenumber range we measure is signficnatly lower ($k < 400$ m^{-1}) as compared to 4000 m^{-1}.

3. Power spectrum measurements

While our results from the previous section show that these modes are acoustic-like in nature, as is consistent with previous work, the advantage of our probing technique allows us to take a more detailed look at the properties of the spectra of the oscillations at low wavenumbers in order to address outstanding questions

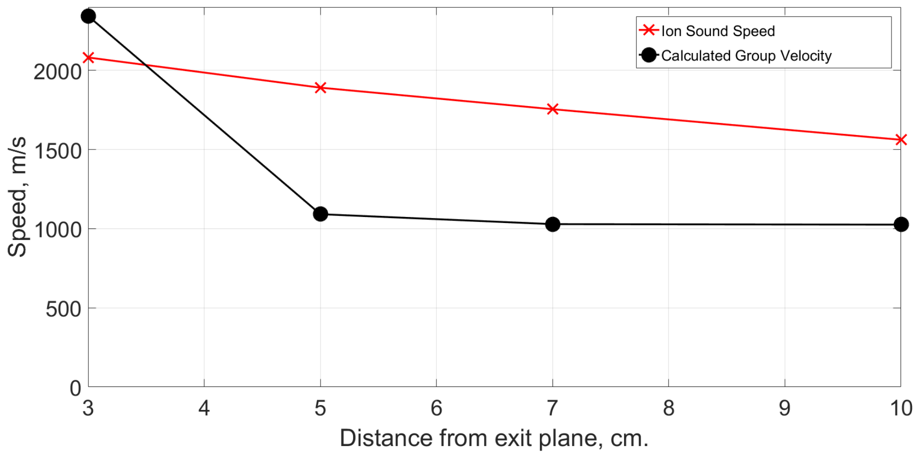


Figure 5: Group velocity vs ion sound speed

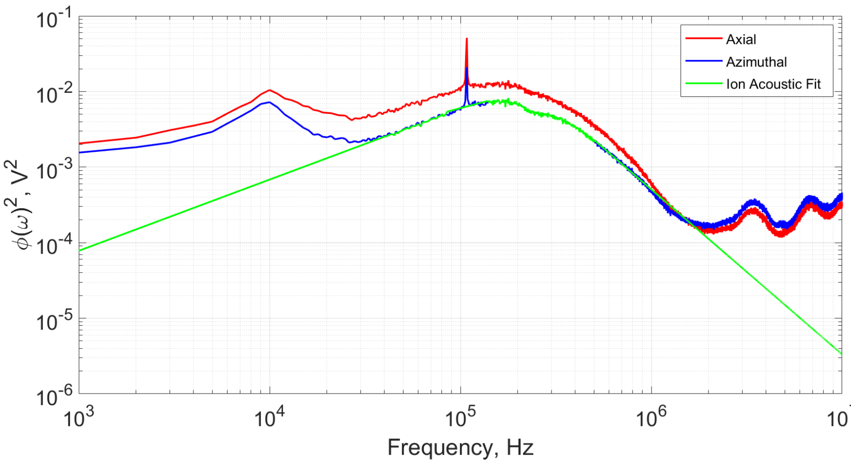


Figure 6: Characteristic power spectrum and power spectrum fitting of ion acoustic wave for collision frequency calculations

about these modes. To this end, we show in Fig. 6 the power spectrum as a function of frequency, where the wave power specturm is the average of the power spectrums from the two probe signals associated with that wave direction. There are a number of features we can point to with these graphs. The first observation is that there are two peaks which are consistent with known fluctuations in Hall thrusters, one at ≈10 kHz which is representative of the breathing mode, and another, highly coherent peak at ≈110 kHz, which is a feature of cathode-related oscillations in magnetically shield hall thrusters.[28] Backset against this there is a gradual peak (labeled as "ion acoustic fit" in the plot) which is where the Beall plots (Fig. 4a) show the acoustic-like dispersion. This peak is reminiscent of the oscillation power spectra that were reported by Jorns et al[17] for acoustic-like turbulent spectra in the plume of a cathode, and indeed, as discussed in this reference, is typical for acoustic like spectra in these types of low-temperature plasmas. At even higher frequencies, there appears to be some spectral content, but as our dispersion relation did not reveal an acoustic-like dispersion for these modes and the power in this frequency range is two orders of magnitude lower than the low frequency content, we neglect their contribution.

For direct comparison with the work by Tsikata et al,[11] we show in Fig. 7 the power spectrum as a function of azimuthal wavenumber, accounting only for contributions over the range where the Beall plots show that the dispersion relation is acoustic in nature. While we can see that at high wavenumber ($k > 130$ m^{-1}), there is a characteristic decay in power, at low wavenumber, there is in fact a peak in the spectrum. In direct contrast to the work by Tsikata et al, who could only resolve a monotonic spectra at high wavenumbers, we provide evidence that there is in fact some wavenumber with the most amount of power in the spectrum. We discuss the implications of this in Sec. IV.

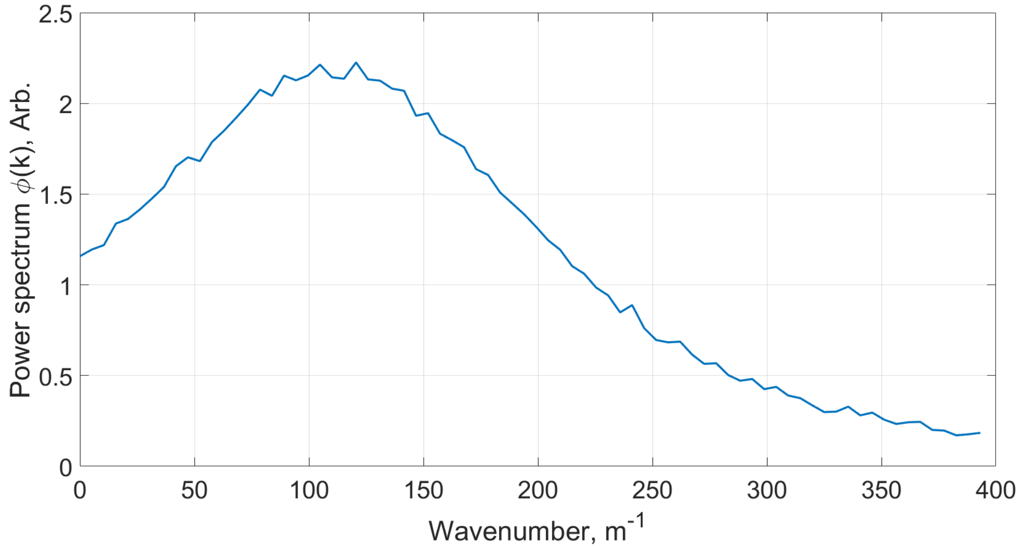


Figure 7: Azimuthal power spectrum in wavenumber space 5cm from exit plane

4. Calculation of anomalous collision frequency

Armed with the results from the previous section, we now are in a position that we can evaluate the effective anomalous collision frequency for these modes. We note here that in contrast to previous work performed with coherent spectrum, we have a clear measure of where most of the power in the mode is concentrated (i.e. near the maximum peak exhibited in Fig. 6). At higher frequencies, the ion acoustic-like spectrum disappears as this region is dominated by some other distinct low power spectra, but if we accept the results from Tsikata et al[11] that the spectrum monotonicaly decreases with increasing wavenumber and frequency, we can approximate this higher wavenumber content by applying a fit to the observed decay; shown in Fig. 6 as the "ion acoustic fit." This fit similarly excludes the non-acoustic like power content at lower frequencies. With this result, we can use Eq. 3 to calculate the effective collision frequency, which we show in Fig. 8 as a function of axial position. For comparison, we also show the classical collision frequency on the same plot.

What is immediately evident from this plot is that the anomalous collision frequency is orders of magnitude higher than the classical, ion-electron collision frequency. This suggests that the anomalous effects from the ion acoustic turbulence(IAT) can in fact be dominant. As the most conclusive evidence of this, we show in Fig. 9 the Hall parameter ($\Omega_e = \omega_e/\nu_{AN}$) as a function of position in the plume. This result shows that the Hall parameter approaches order unity when taking into account the anomalous mobility. Moreover, this Hall parameter remains this value in moving downstream. This serves as additional proof that the IAT spectra in this location can be a dominant contributor to transport.

IV. Discussion

Given the results from the previous sections, we briefly discuss here some of the features we have observed in the context of outstanding questions about the nature and role of the ECDI in the near-field plume of Hall thrusters. To this end, we first note that while the work of Tsikata et al[11] showed that these oscillations exist in the plume of these devices, there was an open question as to whether or not there was a dominant mode in the spectra. Different theories have suggested that this dominant wavelength should be on the order of the Larmor radius or the Debye length. While we did observe a peak in the spectra at a wavenumber of 120 m^{-1}(and corresponding wavelength of 5 cm), both the Debye length and Larmor radius in this location are several orders of magnitude smaller than this observed wavelength. The fact that the peak in

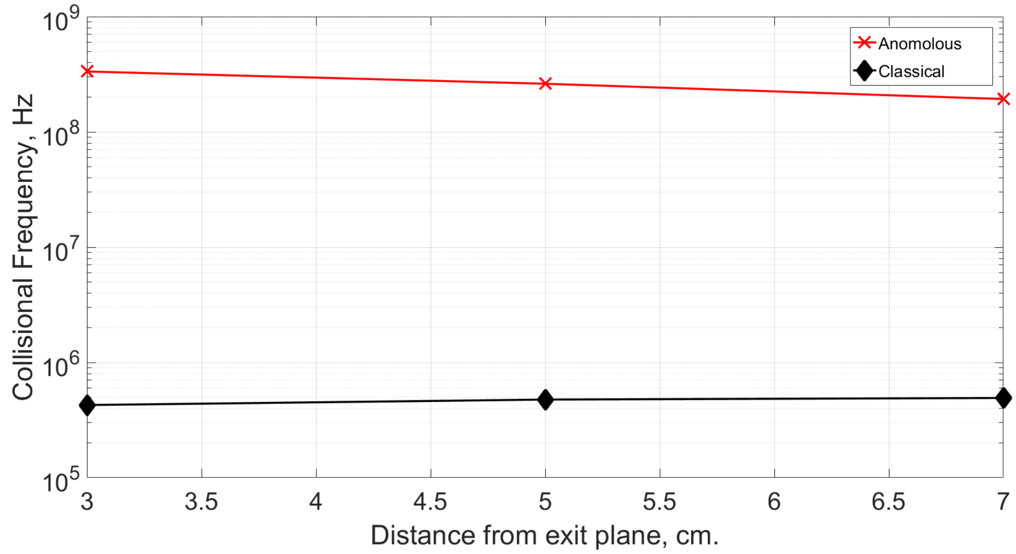


Figure 8: Calculated collision frequencies versus axial position

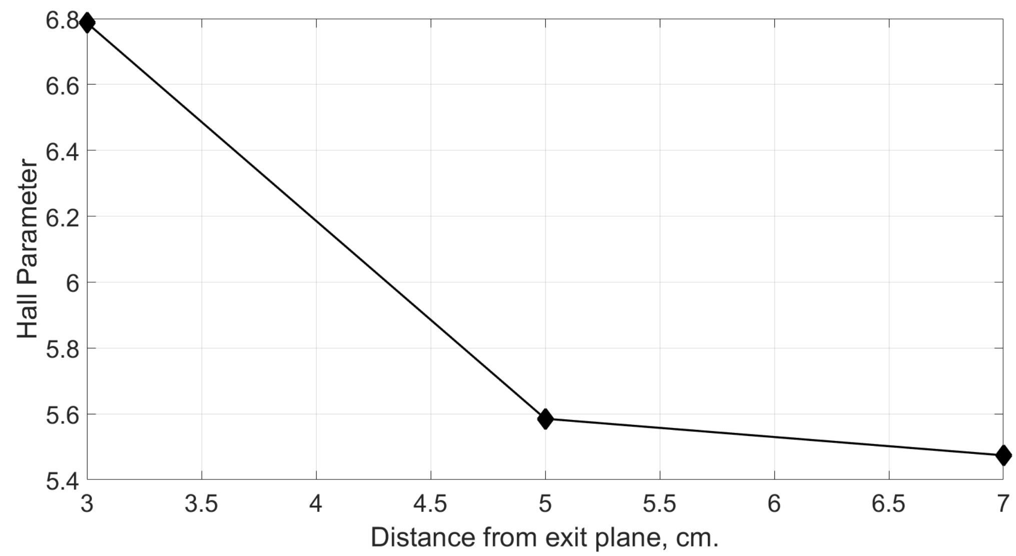


Figure 9: Calculated Hall parameter versus axial position

the spectrum appears at such a wavelength is not necessarily expected given that our analysis is inherently Cartesian. This long wavelength is almost on the order of the circumference of the thruster, which suggests that a full treatment of the modes may require a consideration of a cylindrical, rather than a cartesian geometry.

With that being said, the dominance of the peak at lower frequency is consistent with some of the saturation mechanisms discussed by Jorns et al in Ref. 17. In this reference, it was noted (drawing on other works therein), that the shape of the turbulent spectrum of acoustic mode oscillations can be the result of an inverse energy cascade where by shorter wavelength modes conduct energy to longer wavelength. This process is inherently cut off by ion-neutral collisions or length scale effects.[29]

The other outstanding question about the nature of the ECDI in the thruster plume has centered around its contribution to the cross-field turbulence. While efforts to calculate this have been curtailed in previous investigations due to the inabiltity to resolve where most of the power was concentrated in the spectrum, we have here resolved a sufficient degree of the spectrum to make this calculation. Our results suggest that the acoustic-like mode can in fact contribute, at least in the near-field of the plasma, dominantly to an enhanced electron collisionality in the plume. We have found that it can yield Hall parameters on the order of unity, which is a key assumption currently employed in Hall thruster models.[13,30]

We note these trends with the caveat that the range of wavenumbers over which we observed the oscillations was also limited and there is still the oustanding possibility that the probes we employed perturbed the plasma in a local way that we could not observed by monitoring the local plasma parameters. Moreover, we emphasize that we operated this thruster in an off-nominal condition dictated by facility constraints. The fact that we observe strong properties of the ECDI in this condition does not necessarily translate to thrusters operating at higher performance conditions.

V. Conclusion

Using direct probe measurements we were able to observe ion acoustic like oscillations in the plume of a magnetically shielded Hall thruster. While this technique was perturbative, it allowed for direct calculation of an anomalous electron collision frequency that previous non-perturbative measurements could not perform. The ion acoustic oscillations unexpectedly appear in a mid-frequency range (50-250 kHz) and show a peak power around a wavenumber of 120 m^{-1}. The calculated anomalous collision fequency was orders of magnitude above the ion-electron collision frequency in this region and yielded Hall parameters on the order of unity. The results imply that, subject to many assumptions, ion acoustic turbulence can play a dominant role in electron transport in the near-field plume of Hall thrusters. Hopefully, future work can confirm these results using non-invasive techinques and explore the wavenumbers currently unaccessible by direct probe or light scattering measurements.

Acknowledgments

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