Critical next-step experiments regarding instability enhanced friction and sheath formation in both unmagnetized and magnetized systems

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One of the most important, essential, and characteristic collective effects of the plasma state of matter, is Debye shielding. Sheath formation is Debye shielding about plasma-surface interfaces, and is no less fundamental.[1–5] It is known that sheath formation entails presheath formation.[6–8] Recently it has been shown both in experiment[9–12] and theory[13–16] (the work of Baalrud et al., which for brevity will be called the BCH theory) that sheath formation at plasma-surface interfaces also depends on instability enhanced collisional friction (IEF). These ideas are depicted in the laser-induced fluorescence (LIF) measurements found in figures 1 and 2. Most recently it has also been shown that the Chodura model[17] in magnetized plasma-wall interfaces is not in agreement with some recent experimental works.[18–20] This model, still widely accepted in the community, has accumulated theoretical detractors[21, 22], and has not been benchmarked from an experimental point of view, as evidenced by the paucity of citations in experimental works. All of these findings suggest that the usual assumptions with regard to sheath and presheath formation in low temperature plasmas, for both unmagnetized and magnetized plasma-surface interactions, be questioned aggressively, and in the context of a wide variety of plasma confinement devices.

1) In single ion species plasmas, the BCH theory conjectured that the ion acoustic instability led to IEF at the plasma boundary and was offered, among other things, as a theoretical resolution of Langmuir's Paradox.[23] The Langmuir Paradox is the observation, made first by Langmuir in 1925,[24] that in the vicinity of the plasma boundary where the high energy tail of the electron energy distribution is unconfined by the sheath potential, the tail rethermalizes. And it does so remarkably close to the boundary, over a distance short compared with the e-n collision mean free path. Since theory held that the instability was in the ion acoustic range of frequencies, it was thought that IEF could thermalize the ions at the sheath edge as well. Results consistent with this contention about ion thermalisation at the sheath edge have recently been published.[11] No experiment yet, however, has been done to see what is happening with the electrons directly, and it is important to do so.

The BCH theory predicts that the wavelength of the ion-acoustic instability increases with T_e, and that as the instability's wavelength lengthens compared to the presheath length, the instability should fail to grow. It is important to investigate these predicted effects by measuring EEDFs in a in a wide variety of plasma-wall systems. Using the Maxwell Demon,[25, 26] for example, one may raise T_e and attempt to observe deviation of the electron velocity distribution from a Maxwellian due to failure of the instability to grow.

2) To return to the effect of the ion acoustic instability on the ion velocity distribution function (IVDF) in the vicinity of the sheath, it also important to extend what has already been observed in the ion response to the instability by looking for a spatially resolved signature of the perturbed IVDF or first order IVDF, using LIF techniques to unfold $\tilde{f}_i(v)$ from $f_i(v)$ where the latter is usually measured using phase-sensitive detection. This would require an advance in the state of the art in photon counting techniques, quite likely. But if this could be done, a much more direct measurement of ion response to the instability would then be possible, along with a closer comparison with the BCH theory.

3) It is also critical that the effects of these instabilities on transverse ion velocity distribution functions (tIVDFs) should also be examined. This work has begun for single ion species plasmas,[27] but we be generalized to multiple ion species plasmas. A critical requirement of plasma etching employed in semiconductor processing is that the IVDFs be highly anisotropic in order to achieve the creation of high aspect ratio submicron features characteristic of ultra-large scale integration. Ion acceleration at the plasma boundary is established by a weak electric field in the presheath, which accelerates ions in single ion species plasmas to the Bohm speed at the sheath edge. But it was found that in plasmas with multiple positive ion species, each ion species did not in general reach the sheath edge at their individual Bohm speeds. In experiments, in the BCH theory, and now in PIC simulations,[28] it has been shown that for comparable ion densities, the ions are lost at the sheath edge with a common velocity equal to the ion sound velocity of the system. For very different relative ion concentrations, the ions are lost at their individual Bohm velocities. The parallel IVDF is also broadened by charge-exchange collisions in the presheath[29] but the BCH theory and experiments show that the IVDF can be thermalized at the sheath edge. In many cases, sheaths are collisionless, so ion anisotropy at the surface being processed is limited by the transverse IVDF (tIVDF) at the sheath-presheath boundary. It has been demonstrated with LIF that the tIVDF in the presheath region of a low temperature, pure Ar plasma broadens by a factor of two[27]. Benchmark experiments are needed to provide data for simulations[30] and to establish the extent to which in-

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stability enhanced ion-ion collisions plays a role in determining ion flow anisotropy at the sheath edge. Emissive probe measurements should be carried out to determine details of the plasma potential near the sheath edge, something typically missing from previous IVDF measurements in rf discharges, where LIF is most often used for spatially resolved measurements of atomic or molecular species concentrations.

4) Recently, Baalrud et al. [28] developed a PIC-MCC (particle-in-cell/Monte-Carlo collision, noted above) simulation which also showed good agreement with experiment. A principle result of this work was illustrating the critical role played by the ratio T_e/T_i, which must exceed 20 (depending on the mass ratio and relative concentration) in order for the ion-ion streaming instability to appear in the simulation. Interestingly, as similar inequality is important in for the ion acoustic instability. It is important to perform an experiment that controls T_e relative to T_i so as to turn the instability on and off for the case that the relative concentrations of the ion species is the same. This would be a further critical test of the theory.

5) It is critical also to explore three-species plasmas. LIF measurements should be carried out on three-species plasmas consisting of Ar+, Xe+, and Kr+, utilizing a KrII LIF scheme excited near 729nm.[12, 31]LIF has been applied to presheath measurements in two ion combinations of Ar, Xe, and He plasmas[9, 10, 32, 33] but as yet no visible wavelength LIF scheme exists for He. With the KrII LIF, the Bohm Criterion may be tested experimentally by directly measuring the IVDFs of all three ion species. As described above, evidence that Ar ions reach the sheath edge in three-ion species plasmas (Ar, Kr, Xe, in ascending order of masses) traveling more slowly than their individual Bohm speed was found, just as was found in two ion species plasmas (Ar, Xe).[9, 10, 32, 33] These results were explained as a consequence of instability enhanced ion-ion friction in the BCH theory. These contributions to the understanding of sheath formation in complex plasmas were unanticipated. Diode laser systems exist to diagnose this set of ions, although a dye laser system would be advantageous for this work.

6) Beyond these experiments, finally, it is urgent to generalize results for multiple electropositive ion species plasmas to electronegative plasmas, due to the paucity of experimental work that test theoretical predictions with respect to sheath formation in electronegative discharges.[34]

7)Recent work with a linear magnetized device with a helicon source (see fig. 3) involved an experimental comparison between Chodura's model,[17] depicted in figure 4, and ion flow measurements to an orientable plasma-surface boundary, [18–20] by direct measurements of IVDFs in the vicinity of the boundary plate. The plasmas diagnosed were Ar plasmas, ($P_{rf} \approx 450 \rightarrow 750W$, $T_e = 2.5 \rightarrow 5eV$, $T_i = 0.1 \rightarrow 0.6eV$, $n_0 \approx 1 \times 10^{12} cm^{-3}$, $p_n = 1 \rightarrow 6.5mTorr$, $\lambda_{mfp} = 0.3 \rightarrow 2cm$, $\rho_i \approx 0.5cm$) with the usual LIF scheme suitable for diode lasers excited at 668nm. It was found that Chodura's picture of two separate consecutive presheath structures (a normal presheath parallel to the magnetic field followed by a magnetic presheath parallel to the boundary's surface) was conceptually incorrect for even weakly collisional, magnetized plasmas. Measurements of IVDFs were the first comparisons of Chodura's predictions of ion flows (see fig. 5). It was found that for all orientations tested, a) Chodura's model incorrectly predicted the spatial location of the sonic points, and incorrectly located the regions in which the ions acquired significant $v_\perp$ (where $\perp$ and $\|$ in this section refer to the local direction of the magnetic field lines.) It turns out that for even weakly collisional plasma, where $\lambda_{in} >> \rho_i$, and $f_{ci} >> \nu_{i-n}$, one finds the ions acquiring significant $v_\perp$ before the $v_\|$ sonic point, which is far closer to the wall than Chodura's model indicates. For the parameter regime $0.5 \leq \lambda/\rho_i \leq 4$, The magnetic presheath and the usual presheath are interpenetrating, and therefore are not separately useful concepts. Moreover, the presence of double layers were discovered that were important in establishing the presheath length at plasma boundaries. The major issues are the interdependence of presheath structure on the angle of the B field with respect to the boundary, the strength of the magnetic field, the ion mass, collisionality and ionization rate. It is critical that Measurements such as these should be pursued at higher and lower magnetic field strengths than those of these initial measurements (which was nominally 1 kG for the experiments cited).

8) Finally, these results also suggest that the mutual interaction of the ion and neutral flows be studied. The experimental work described immediately above was done in with a Helicon source which launches whistler waves in a bounded system. While the first order dispersion relation of bounded whistler waves gives a linear relationship between density and magnetic field, it has been found empirically that there is a saturation effect. It currently is not possible to increase the density much past $10^{20} m^3$. Fast ionization of neutrals and rapid ion losses lead to strong neutral depletion on the axis, which prevents further plasma build up. It is necessary to explore the neutral particle dynamics responsible for this result and to overcome it, for example, by selective local fueling with gas puffing. It is of particular importance to establish the relationship between the upstream ionization processes with the downstream plasma boundary layer physics. It is critical to understand the sheath aspects of neutral depletion including the effects of the IVDFs of both the neutrals and the ions. It has been found possible to measure ground state neutral IVDFs in hydrogen and Krypton with two-photon LIF or TALIF systems, which will be of great help with these experiments. Further, simulations exist which supply predictions for the relationships between ion and neutral flows, that is, models that predict neutral transport and ionization (EIRENE).[35–37]

I. FIGURES

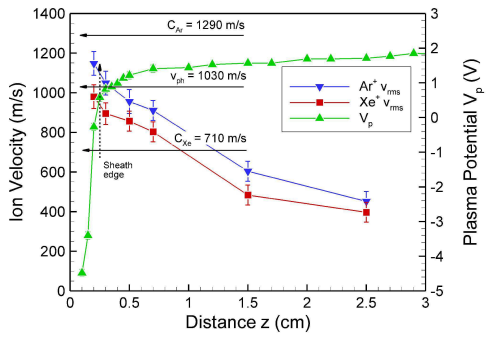

FIG. 1. Spatial profiles of the plasma potential and Ar^+ and Xe^+ flow velocities in the case of plasma with partial neutral pressures, Ar 0.5, and Xe 0.2 mTorr.

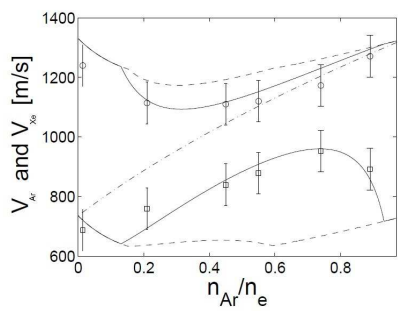

FIG. 2. Comparison of data and the prediction of the kinetic theory of instability enhanced collisional friction. The circles are the measured argon drift velocity and the squares are the measured xenon drift velocity. The dashed line uses the fluid plasma dispersion relation for the two stream instability, while the solid line is the new prediction which incorporates finite ion thermal corrections to the dispersion relation. The system ion acoustic velocity is represented by the dashed dotted line.

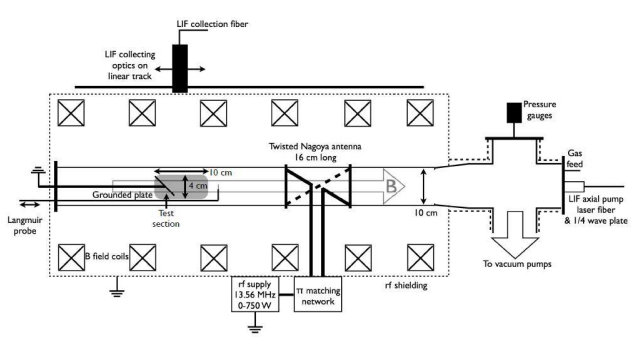

FIG. 3. Diagram of the experimental apparatus for the $\Psi = 16^o \rightarrow 60^o$ experiment. The shaded region shows approximately where measurements were made for this experiment. The grounded plate is 'tiltable'.

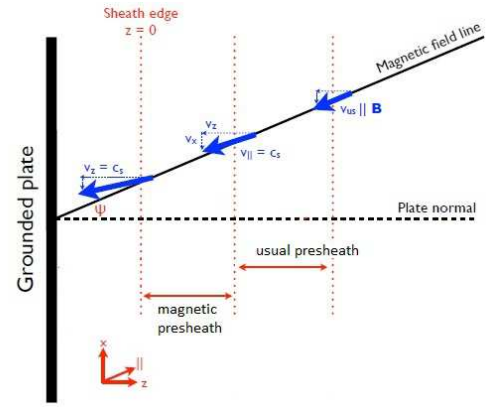

FIG. 4. Diagram of the simulation space for the ion fluid model as understood in Chodura's model. Ions drifting in from rest along magnetic fields lines reach at length a sonic point where the parallel speed reach C_s along $\vec{B}$; this is the beginning of the Chodura's magnetic presheath, still quasineutral, in which the ions begin to turn off magnetic field lines and, in the presheath electric field normal to the plate, acquire a C_s in the direction normal to the plate at the sheath edge. The thick blue arrows represent velocity vectors and red arrows and dotted lines represent spatial positions and axes.

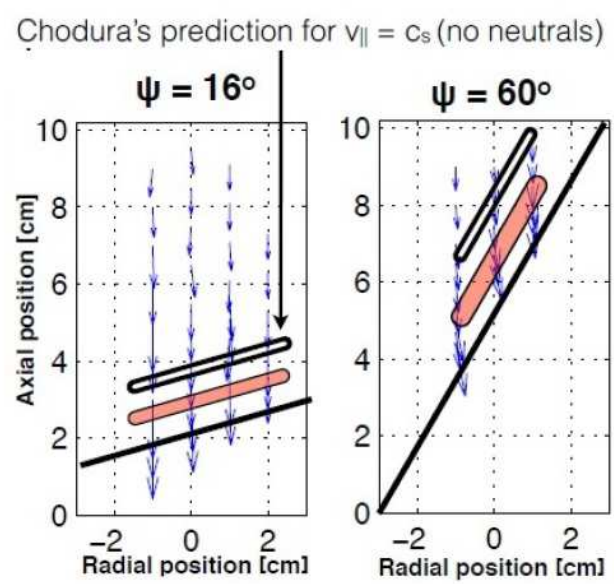

FIG. 5. Representative velocity field from LIF measurements for a 1 mTorr plasma with $\Psi = 16^o$ and 60° . For this particular case, $f_{ci}/\nu_{in} \sim 10$, that is, the ion gyrofrequency is much larger than the ion-neutral collision frequency. The solid black line indicates the location of the grounded plate. Velocity vectors are in blue, he thick black lines indicate the location of the grounded plate, the grey rod indicate the region in which $v_{||}$ was measured to reach c_s, the black rod, the region calculated by Chodura's simulation to be the same thing.

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