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

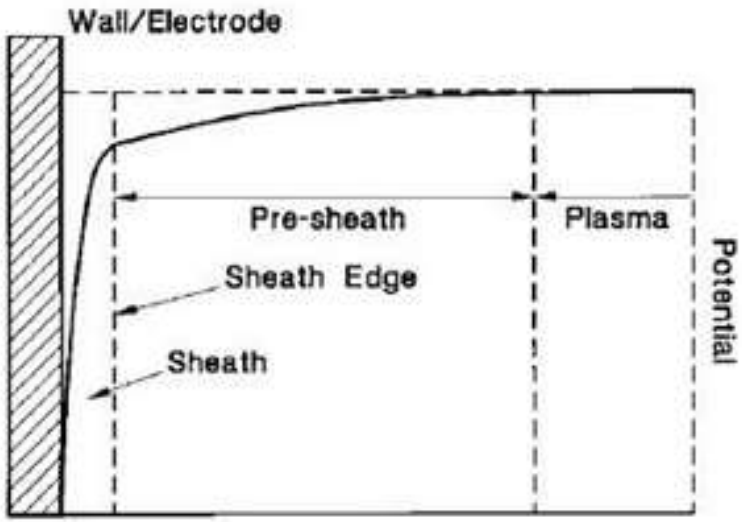
Noah Hershkowitz
University of Wisconsin – Madison
Greg Severn
University of San Diego, San Diego

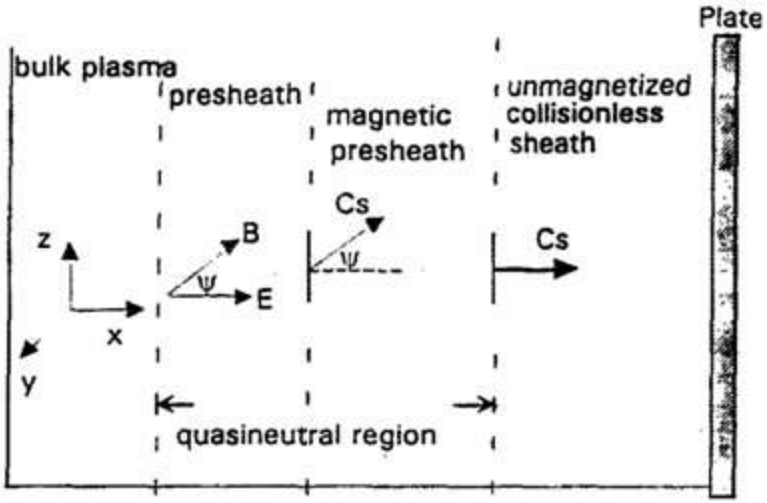
WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

University of San Diego

We present 2 new frontiers to explore for low temperature, plasma wall interactions

First, the canonical picture of presheaths and sheaths in both unmagnetized … … and magnetized plasmas





Presheaths length ≈ ion-neutral charge exchange length (λ_{in})

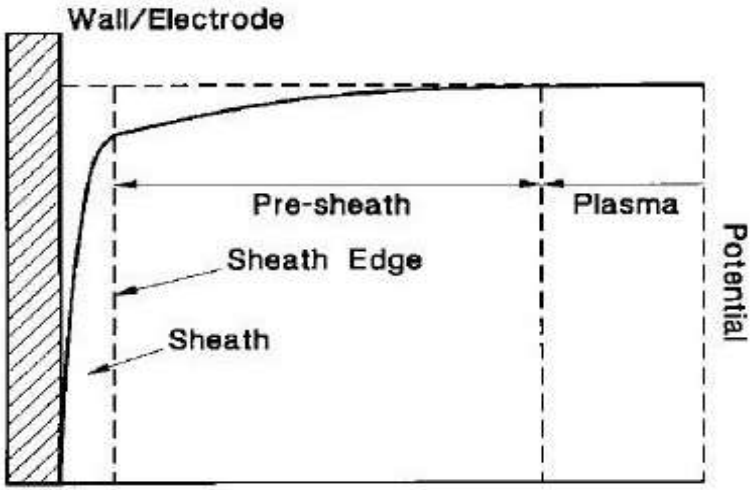
Chodura (Chodura 1982):

$$\lambda_{MPS} = 2.5\frac{c_s}{\omega_{ci}}\sin\Psi \quad , \lambda_{in} \approx \infty$$

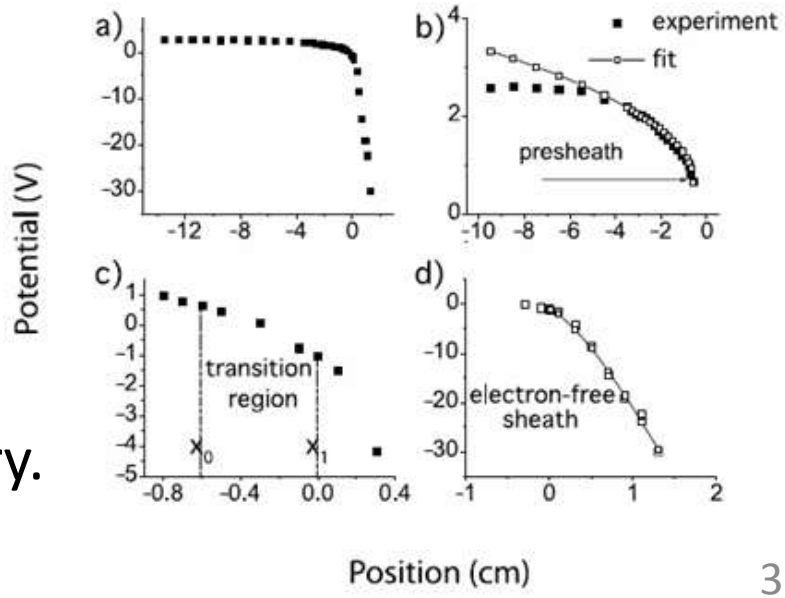
Including results that challenged accepted pictures, leading to experiments that now need to be done

There are presheaths in single ion species, unmagnetized plasmas

Debye shielding and sheath formation are important, essential, and characteristic collective effects of the plasma state of matter.



In collisionless and weakly collisional plasmas, sheath formation requires a presheath. This picture (1950s) was confirmed by experimentalists.



In single ion species plasmas, presheaths accelerate ions to the Bohm velocity $\sqrt{T_e/m_i}$ at the sheath/presheath boundary. This is also the ion sound velocity.

IECF adds a complication

In single ion species plasmas, the BCH theory (Baalrud, Callen, Hegna, 2009) argued that the ion acoustic instability led to instability enhanced collisional friction (IECF) at the plasma boundary and provided a theoretical resolution of Langmuir's Paradox.

Langmuir's Paradox is the observation (Langmuir 1925) 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 re-thermalizes over a distance short compared with the e-n collision mean free path near the boundary. No experiment has been done to directly see this phenomena, and it is important to do so.

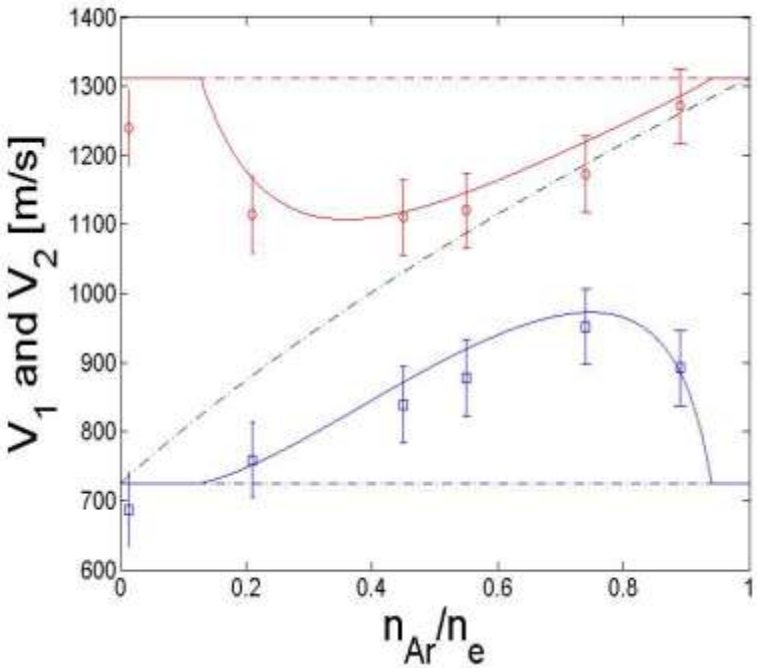
The instability is in the ion acoustic range of frequencies so IECF could thermalize ions at the sheath edge as well. This was proven to be true.

We now know that Presheaths in two-ion species, unmagnetized plasmas require IECF

With two ion species, both experiment and theory (BCH theory) now show that sheath formation depends on IECF.

Each species is lost at close to the system sound velocity when densities are comparable.

Laser Induced Fluorescence (LIF) and Emissive Probes are the diagnostics of choice for determining ion velocity distribution functions (IVDF) and Plasma Potential.



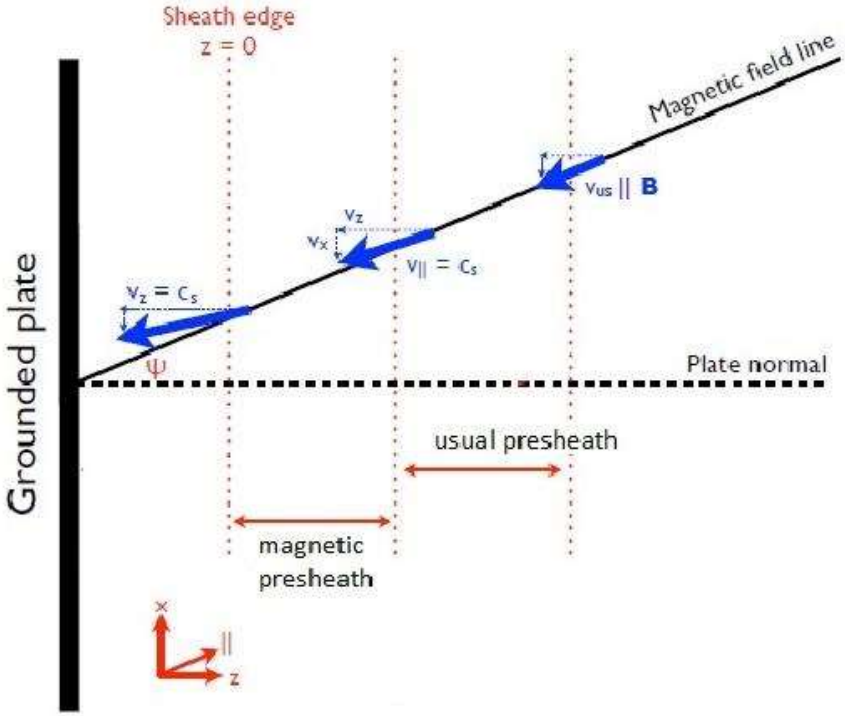
Circles: argon drift velocity
Squares: xenon drift velocity.
Solid line: predicted drift velocities.
Dashed dotted line: the system ion acoustic velocity.

Chodura has modeled presheaths in single ion species, magnetized plasmas.

The "magnetic sheath" associated with plasma flowing into a boundary at an angle to the B field has been modeled Chodura.

This model, still widely accepted in the community, has not been benchmarked from an experimental point of view.

The problem of two species in magnetic field has not yet been considered, but it should be.



Is Chodura's model correct?

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, should be questioned aggressively, and in the context of a wide variety of plasma confinement devices.

Recently it has also been shown that the Chodura model in magnetized plasma-wall interfaces is not in agreement with experiments.

Getting the story right matters! Some examples include plasma etching of semi-conductors, re-deposition of material at boundaries in fusion plasmas, wall erosion of Hall thrusters, and overall confinement in all plasma devices.

BCH Theory is new and needs further checking.

The BCH theory predicts that the wavelength λ of the ion-acoustic instability increases with T_e. As λ increases, the instability should fail to grow. This should be verified by electron energy distribution functions (EEDF) control and measurements in a variety of plasma-wall systems.

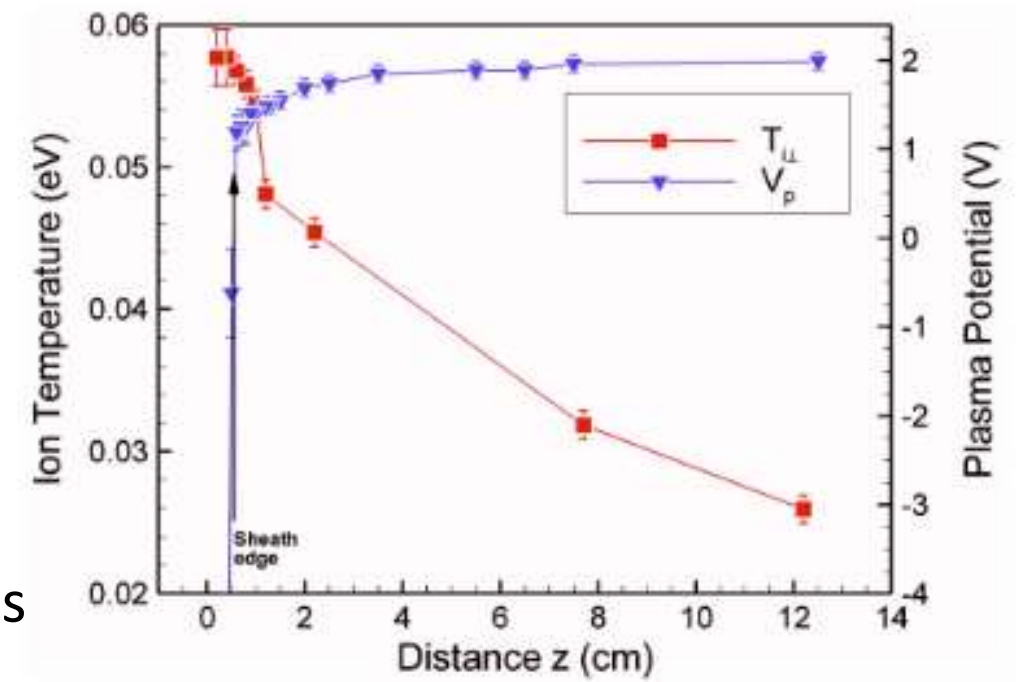
It is also important to extend what has already been observed in the ion response to the instability by looking for a spatially resolved signature of the perturbed IVDF or first order IVDF, using LIF techniques to unfold perturbations of $f_i(v)$ from $f_i(v)$ where the latter is usually measured using phase-sensitive detection.

This requires an advance in the state of the art in photon counting techniques. A direct measurement of ion response to the instability would then be possible, allowing a closer comparison with BCH theory.

Effects of IECF on the transverse IVDF should also be examined

A critical requirement of plasma etching of semiconductors 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.

Measurements of transverse IVDFs (tIVDFs) has begun for single ion species plasmas, but should be generalized to multiple ion species plasmas.

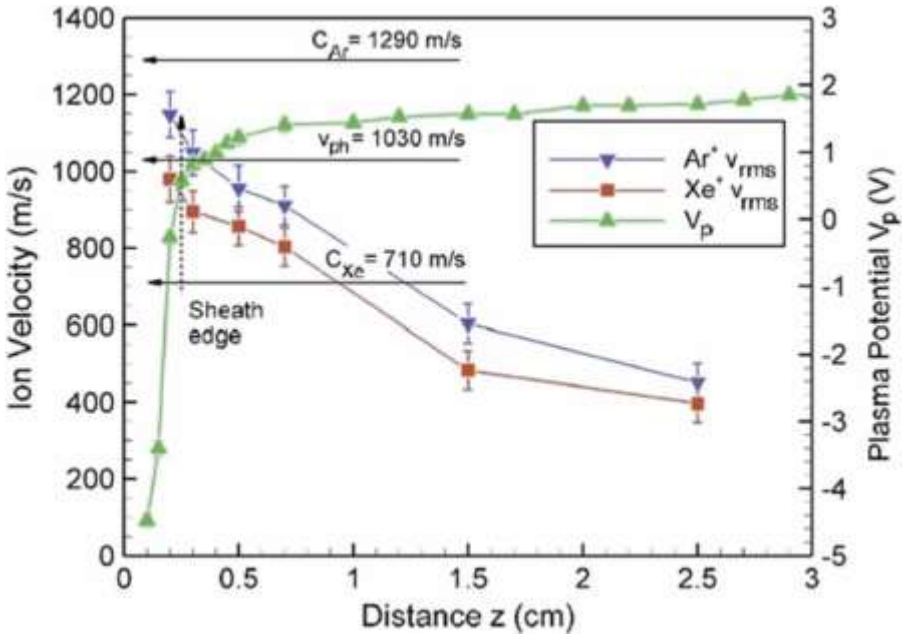


Spatial profiles of the transverse ion temperature $T_{i\perp}$ and the plasma potential V_p. The sheath/presheath boundary is z=0.45cm.

Ions try to reach the system sound velocity at the sheath/presheath boundary

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.

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.

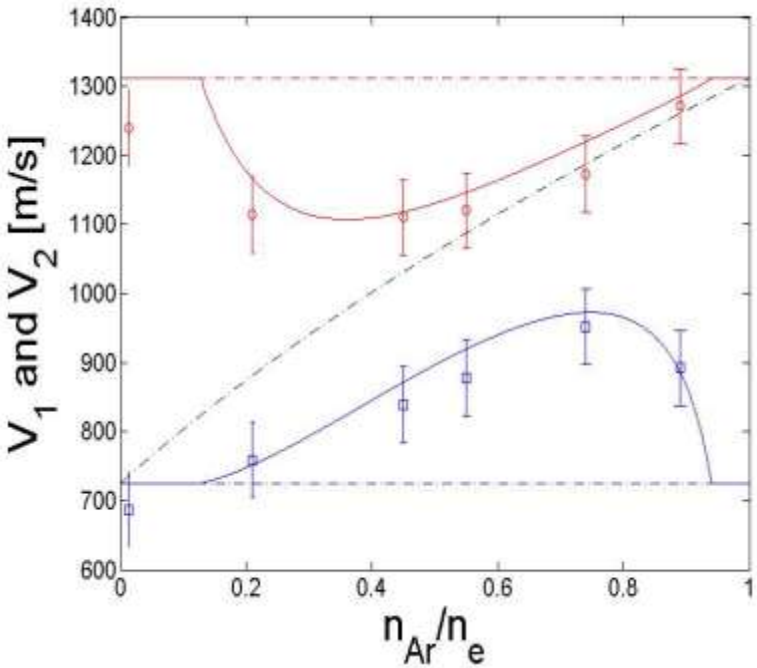


Ar and Xe ion speeds with respect to position relative to the plasma boundary in Ar – Xe plasma.

BCH Theory solved the problem

Experiments, BCH theory, and PIC simulations have shown that for comparable ion densities, the ions are lost at the sheath edge with velocities approaching a common velocity equal to the ion sound velocity of the system.

But for very different relative ion concentrations, the ions are lost at their individual Bohm velocities.



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Benchmark experiments are needed to provide data for simulations

Benchmark experiments are needed to provide data for simulations and to establish the extent to which IECF 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.

Today, IVDF measurements in rf discharges are most often used for spatially resolved measurements of atomic or molecular species concentrations, and plasma potential measurements are often missing.

It is important to carry out measurements on three ion-species plasmas.

It is critical also to explore three-species plasmas. There are many applications in basic plasma, industrial plasmas, and fusion plasmas.

LIF measurements can be carried out with diode lasers on three-species plasmas consisting of Ar+, Xe+, and Kr+, utilizing a KrII LIF scheme excited near 729nm. With the KrII LIF, the appropriate Bohm Criterion may be tested experimentally by directly measuring the IVDFs of all three ion species.

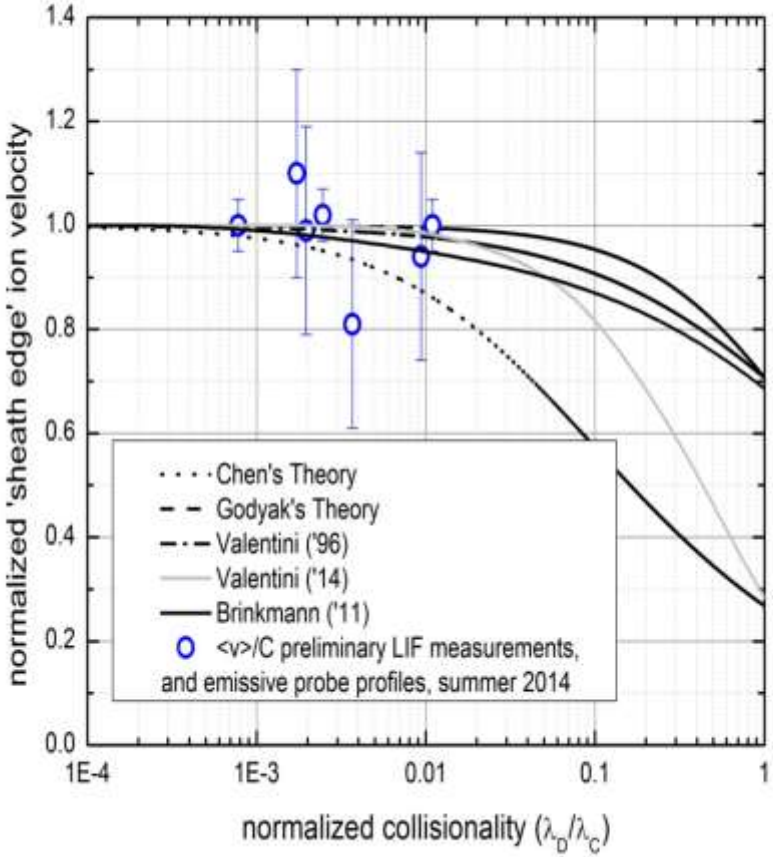
LIF with dye lasers can greatly expand the choice of ions.

It is important to generalize these results to electro-negative plasmas.

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.

The transition from presheath to sheath is not well understood in collisional plasmas.

Experiments are also needed to understand sheaths in collisional plasmas where a variety of predictions now exist.

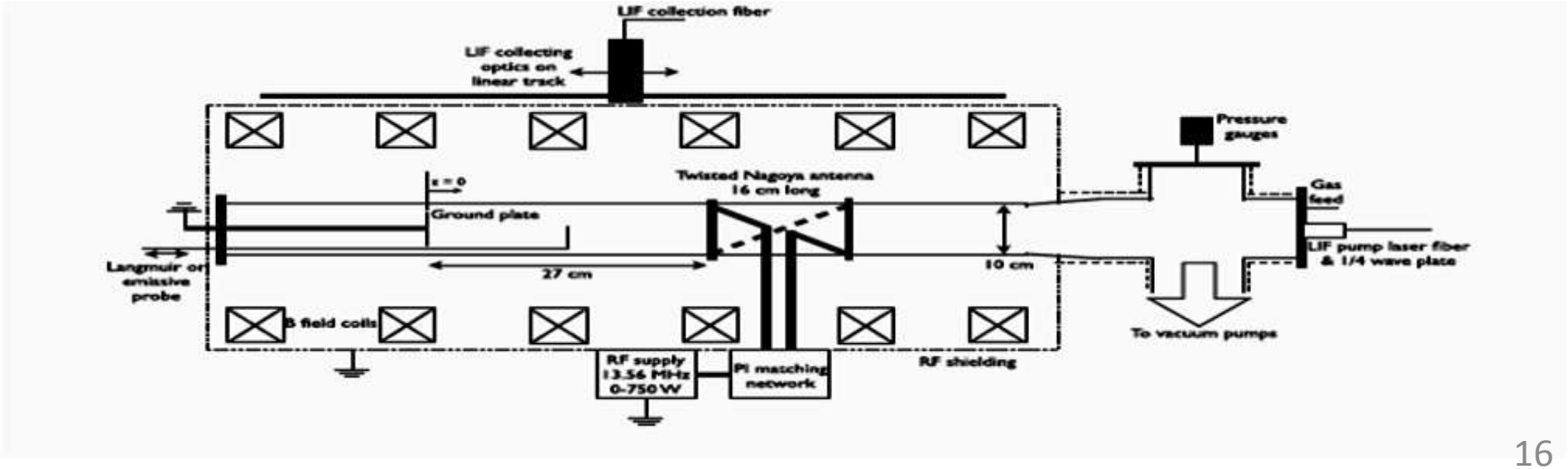


Comparison of preliminary measurements of ion drift velocities at the sheath-edge of argon plasmas at varying collisionality to the different theoretical predictions.

We have carried out a test of Chodura's model.

Recent work with a uniform linear magnetized device with a helicon source made an experimental comparison between Chodura's model, and ion flow measurements to an orientable plasma-surface boundary, by direct measurements of IVDFs in the vicinity of the boundary plate.

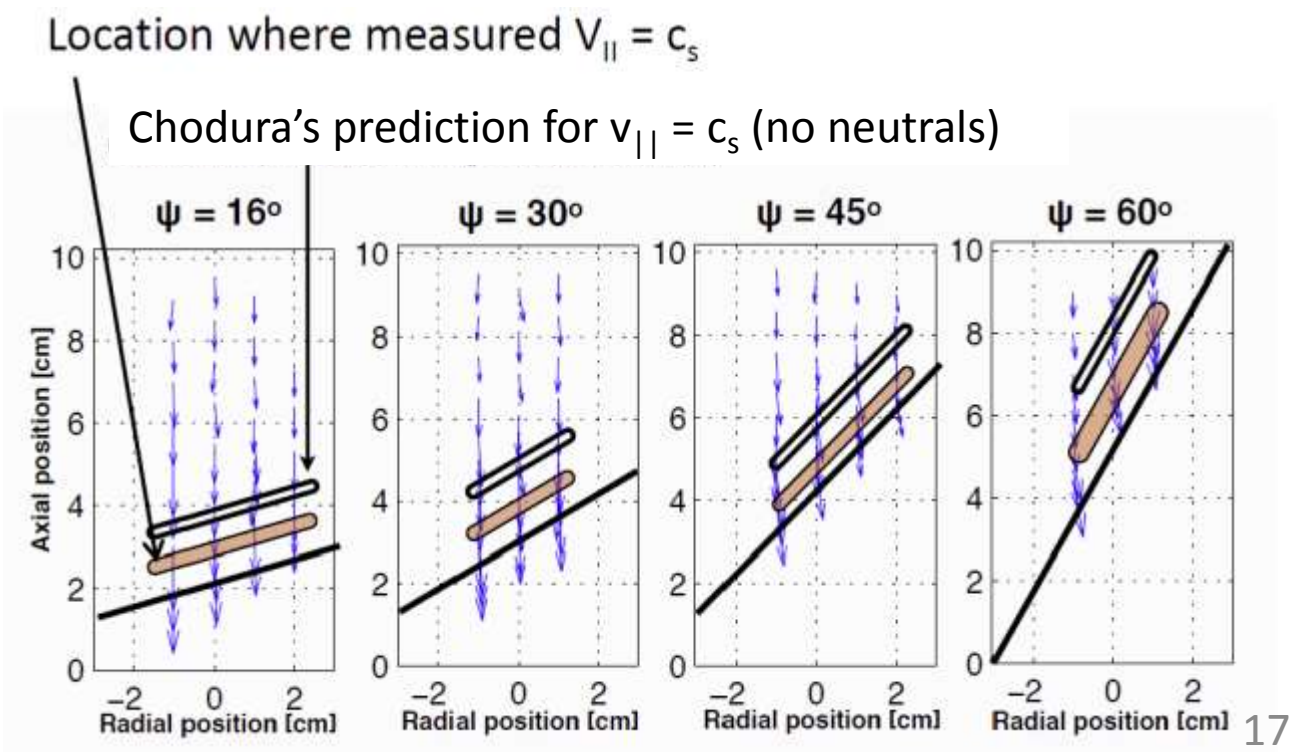
Argon plasmas were diagnosed with the usual LIF scheme suitable for diode lasers excited at 668nm.



It failed (but neutral pressure was finite).

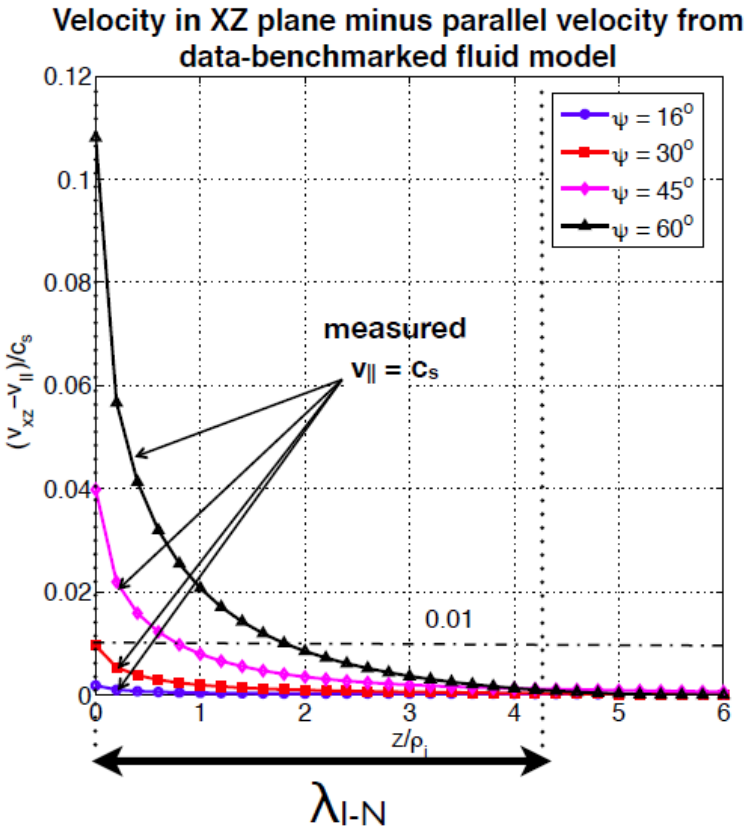
It was found that Chodura's picture of two separate consecutive presheath structures (a normal presheath parallel to the magnetic field followed by a magnetic presheath parallel to the boundary's surface) was conceptually incorrect for even weakly collisional, magnetized plasmas.

Ion drift velocity along the perpendicular direction of the plate is never found to reach c_s, as opposed to the predictions.



It failed (but neutral pressure was finite).

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 ⊥ and ∥ in this section refer to the local direction of the magnetic field lines.)



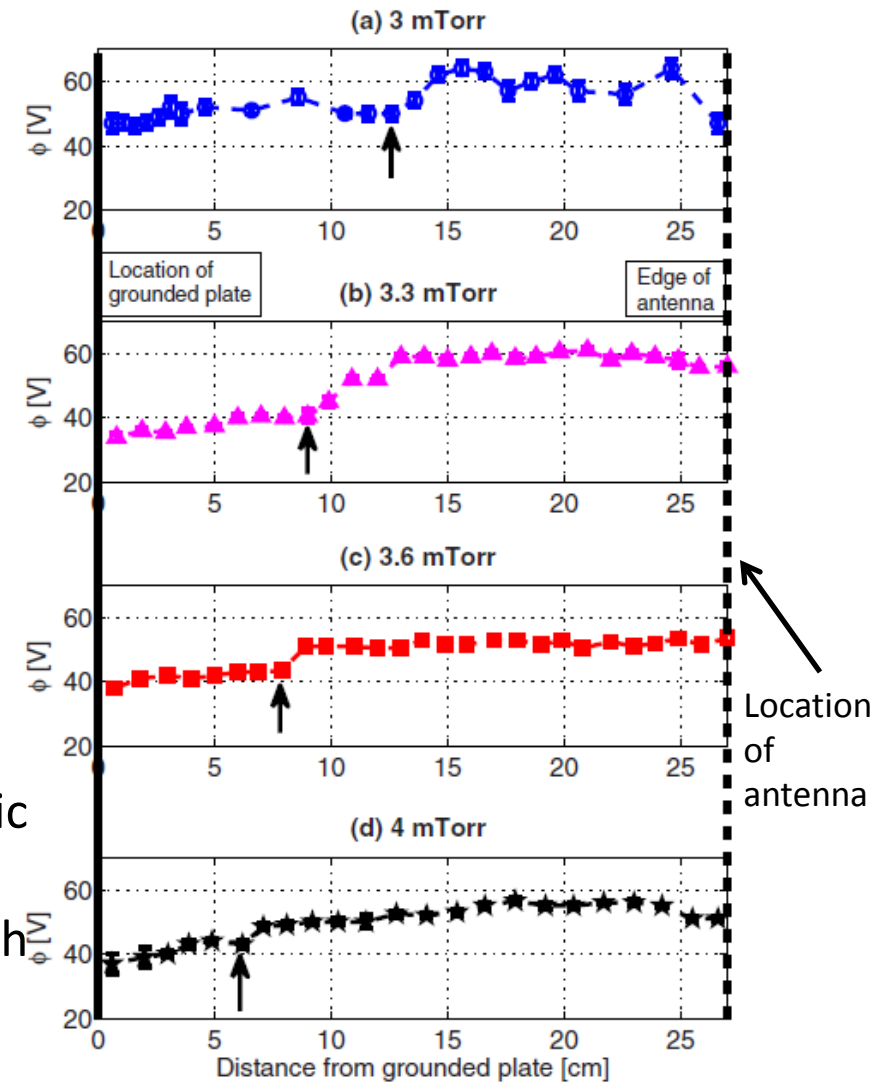
Measured $v_{||}$ significantly deviates from Chodura's predictions.

Double Layers were found in a Helicon plasma.

Most recently, the presence of double layers were discovered that were important in establishing the presheath length at plasma boundaries in magnetized plasmas.

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 and different neutral pressures than those of these initial measurements (which was nominally 1 kG magnetic field and 3mTorr neutral pressure for the experiments cited).



Summary: More sheath-presheath studies are needed. The answers matter!

After 80 years, presheath and sheath characteristics are only well understood in single ion species, weakly collisional, unmagnetized plasmas.

In two ion species, unmagnetized plasmas, the picture changes due to IECF. Only the tip of the iceberg has been investigated suggesting that sheaths and presheaths in multi-ion-species plasmas are inadequately understood. This means that applications associated with such understandings are in turn poorly developed.

Understanding of collisional, electronegative, and magnetized presheaths and sheaths is even less well understood in both single ion species and multi ion species plasmas. Preliminary experiments disagree with the generally accepted Chodura magnetic presheath model.