Parallel and Perpendicular Plasma Flows in the Edge of Alcator C-Mod

N. Smick, B. LaBombard, MIT PSFC*

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Background / Motivation

Tokamak plasmas show a reduced power threshold for L-H transition depending whether BxB points towards or away from the active x-point.

Recent measurements from the high field side (HFS) SOL on C-Mod show a reversal in parallel flow velocity depending on whether the plasma is in the 'favorable' or 'unfavorable' magnetic topology.

These may be the first indications of a connection between SOL flows and edge tranpsort barriers through flow-shear turbulence supression.

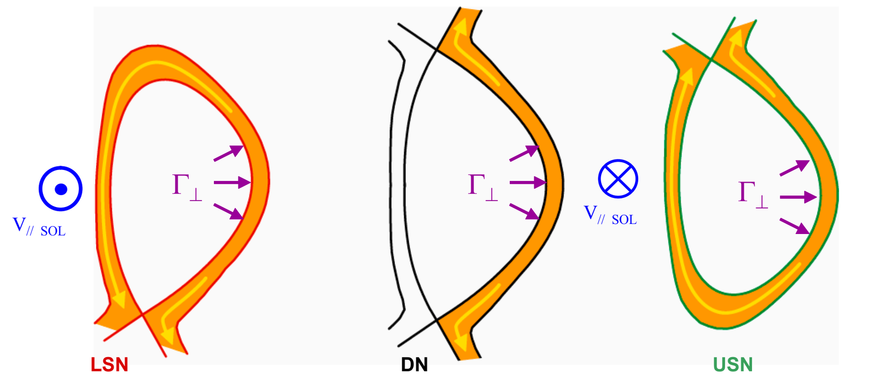
Results point to a ballooning-like transport asymmetry as a driver for these flows.

The transport picture could also be affected by ExB shear, that is: flows in a flux surface perpendicular to the magnetic field.

Attempts at using measurements of floating potential to deduce cross field flow component have met with difficulties.

We need diagnostics capable of measuring the parallel and perpendicular flow components at a variety of poloidal locations in the SOL.

The transport-driven flow picture:



Balooning-like cross-field transport pattern for all topologies

Resulting flow pattern drains SOL plasma along field lines to divertors

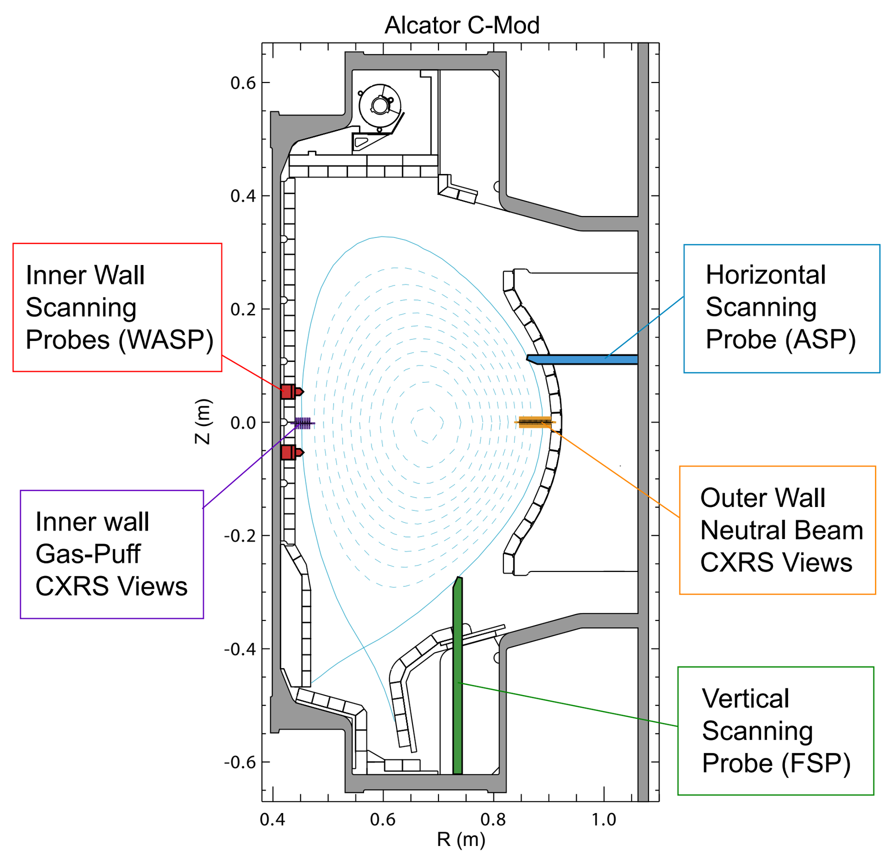
Dominant toroidal SOL flow direction is co-current in LSN, counter-current in USN

Experimental Outline

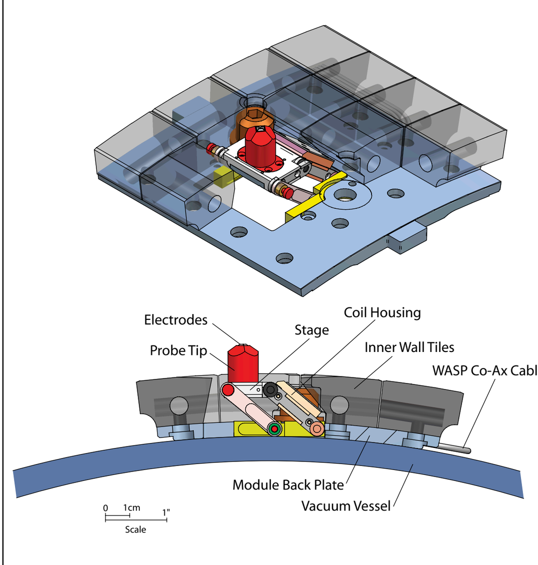
In principle, a 'Gundestrup Probe' has the ability to measure parallel and perpendicular flow components. Therefore, we proceeded to:

- Design and build a new probe diagnostic: *The High-Heat Flux Gundestrup Probe* which will be capable of operating in the C-Mod Environment
- Devise a method of placing such a probe on the HFS of the torus in addition to the normal LFS probes
- Assess the performance of the high-heat flux Gundestrup probe
- Revisit the parallel flow measurements made previously with Mach probes
- Measure the perpendicular flows and identify regions of high shear
- Explore the available parameter space and determine which variables influence the shear layer

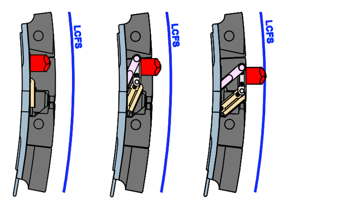
C-Mod Diagnostic Layout



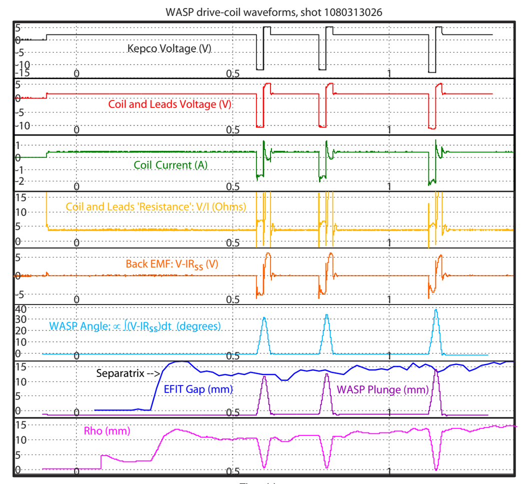
The WASP Probe (High Field Side)



- Linear plunge, four-electrode probe
- EM drive allows flexible targetting
- Position determined by back-EMF integration
- Outfitted with new high-heat flux Gundestrup probe-tip geometry
- Routinely plunges ~few mm inside LCFS



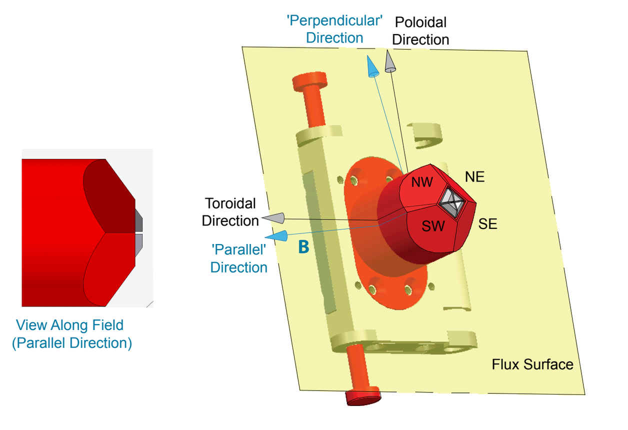
- The WASP is driven electromagnetically via an embedded coil
- The probe position is calculated using the back-EMF measured on the drive coil
- With repeatable discharges, the location of the last closed flux surface can be targetted individually for each probe plunge



C-Mod Pyramidal Gundestrup Probes

Installed on all three C-Mod scanning probes throughout 2007 and 2008 campaigns

C-Mod High Heat Flux Pyramidal Gundestrup Probe



- 4-electrode Gundestrup arrangement allows the measurement of parallel and perpendicular plasma flows.
- Pyramid-shaped probe tip allows probe to spread heat flux over larger surface area.
- Close spacing of electrodes produces measurement with high spatial resolution and can measure the phase velocity of plasma structures.
- New electrode geometry provides well-defined collection area.
- Tungsten Electrodes placed at the very tip of the probe allow maximum operational depth and survivability.

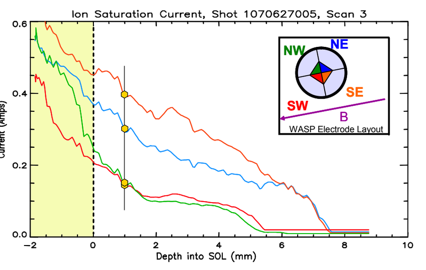
Probe electrodes are aligned with the field direction.

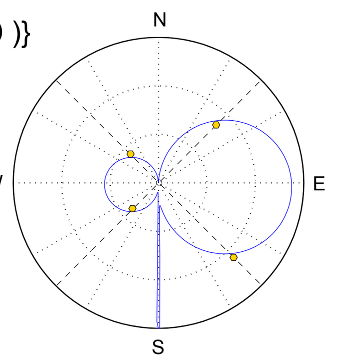
Electrodes are labeled by compass points when viewed from the plasma

Example of Gundestrup Fit for Shot 1070627005, Scan 3, Rho = 1mm

Gundestrup Model: Ion Saturation Current as a function of facet angle. Ref [4,8]

$$I_{sat}=A_p n_\infty c_s \exp\{-1-1.1(M_{||}-M_\perp \cot\theta)\}$$





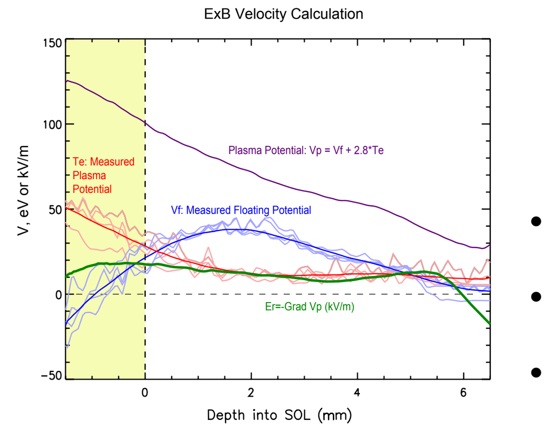
Data Point
Gundestrup Fluid Model Fit

In this example,
Mpar = 0.37
Mperp = 0.05

Other Diagnostic Techniques

Other methods of measuring Vperp can be useful for benchmarking Gundestrup results and can provide additional information

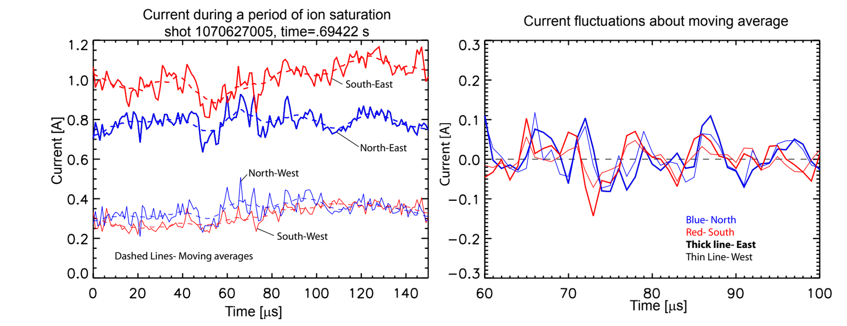
1. Computation of Vperp through Floating Potential Measurement



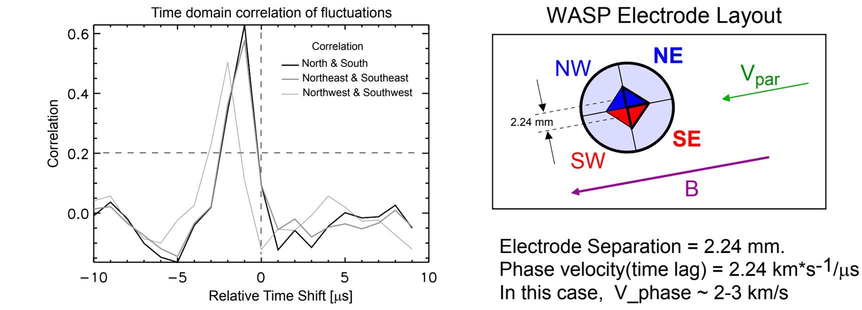
ExB Method: Here, we assume that ExB flows are the primary constituent of cross field flow that is measured by the probes. We then use a sheath model to derive the plasma potential from the electron temperature and floating potential and take its gradient to determine Er. There are many uncertainties associated with this process:

- Sheath prefactor 2.8 uncertain and changing with plasma and surface conditions
- Gradient of uncertain quantities results in large uncertainty
- Required smoothing makes it difficult to resolve fine features

2. Measuring the Perpendicular Phase velocity of fluctuations



WASP Electrode Layout

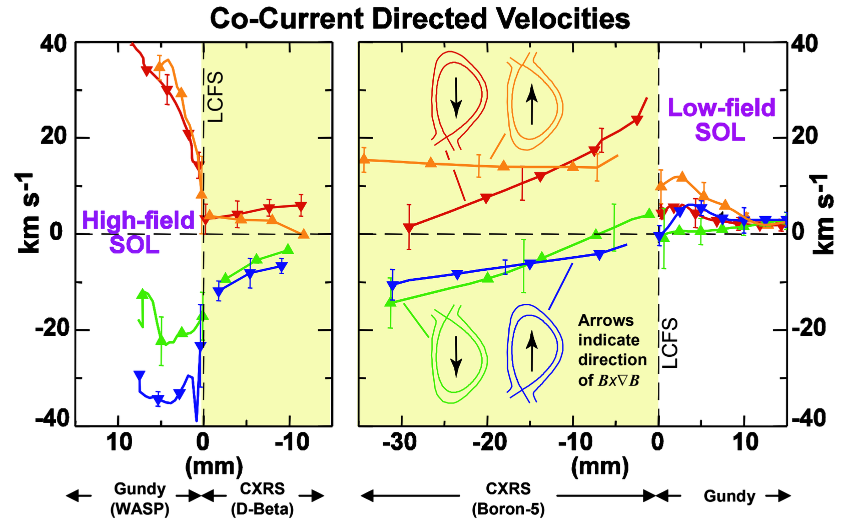


Electrode Separation = 2.24 mm.
Phase velocity(time lag) = 2.24 km*s^{-1}/μs
In this case, V_phase ~ 2-3 km/s

- Phase velocity is not a flow velocity but is often observed to correlate. There is some evidence that the phase velocity shear may be just as important as the fluid velocity shear.
- Phase velocity measurements are less reliable on the High Field Side due to the reduced magnitude of fluctuations there. In general, the measurement is best in the far SOL where the variations are the largest.

Parallel Flows: The Transport Drive

New Gundestrup Parallel Flow Data Support Transport-Driven SOL Flow Picture and Toroidal Rotation Boundary Condition



The parallel flow measurements support our previous understanding of the flow pattern:

- Strong, x-point dependent parallel flows on the HFS appear to be driven by balooning transport
- Weaker, LFS flows are persistently co-current and are modulated by x-point location

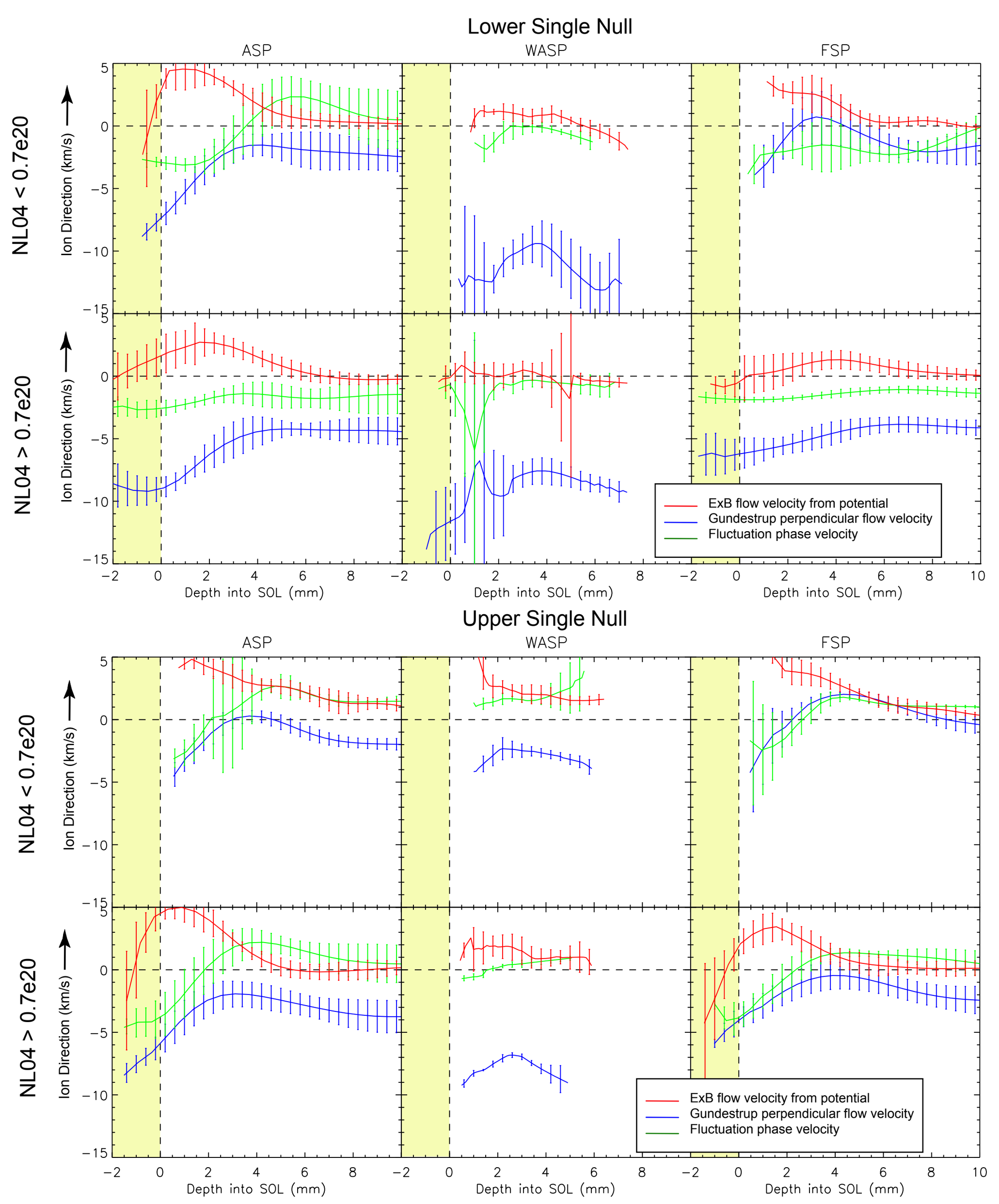
New data show:

- Gross features of the flows are invariant to a symmetric reversal of field, current and x-point location
- The flows appear to be well coupled across the separatrix to flows measured by charge exchange on the outside edge of the confined plasma - See K. Marr: P37, R. McDermott: Edge II
- New Gundestrup geometry indicates slightly lower parallel velocities than previous probes, perhaps due to closer spacing and reduced isolation of the electrodes

Gundestrup probes appear to be successful at measuring parallel flow dynamics

Perpendicular Flows: The Shear Layer

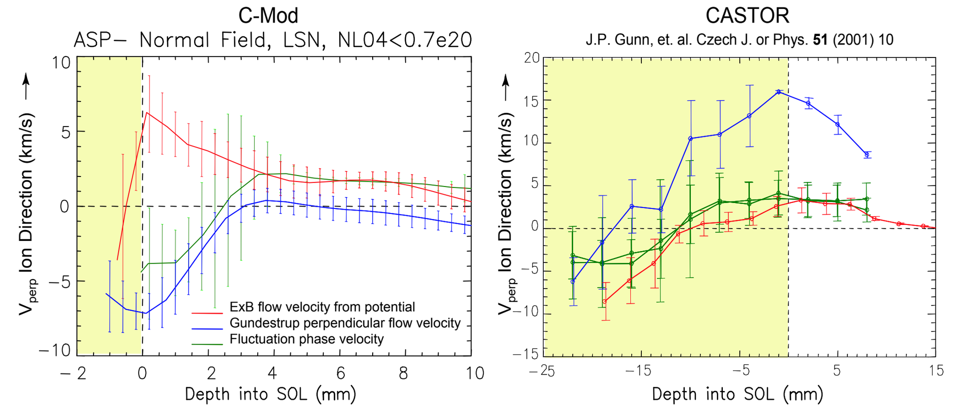
Results for a variety of machine configurations, holding field and current constant:



- There is a gradient towards the electron diamagnetic direction in the vicinity of the separatrix on the LFS probes. This shear layer is regularly observed in both the Gundestrup and phase velocity measurements
- The best agreement in the near SOL is between the Gundestrup and the phase velocity measurements. However, in the Far SOL the best agreement is usually between Vphase and ExB velocities.
- The Gundestrup measurement from the WASP shows large velocities in the electron diamagnetic direction which persist throughout the SOL.

=> These results cast doubt on the Gundestrup measurement, particularly in the far SOL

Simlar Measurements have been made on the CASTOR Tokamak



Data from an "ideal Gundestrup Probe" (IGP) in the CASTOR Tokamak have some similarities:

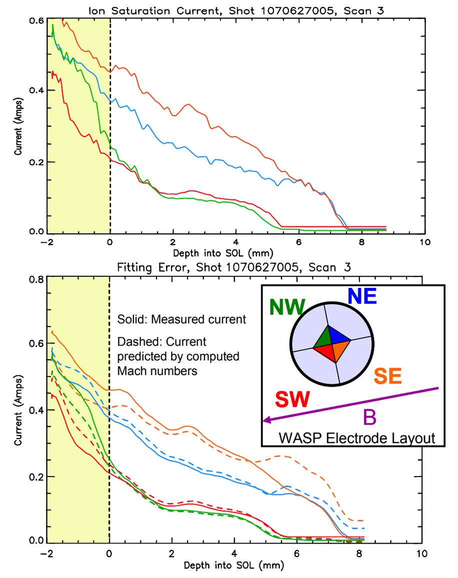
- Similar trend towards electron-diamagnetic directed flows seen inside LCFS
- Agreement between ExB flow and phase velocities comparable to C-Mod far SOL
- *However,* CASTOR Gundestrup measurement is offset in opposite direction

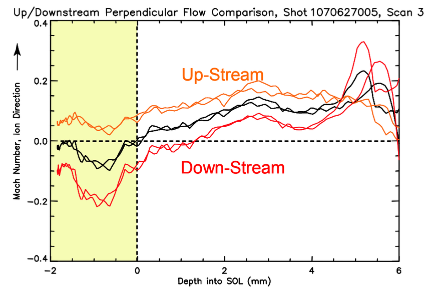
Note CASTOR characteristics: low density, low temperature, M_{par} ~0

Assessing Gundestrup Performance

Over-Constrained Gundstrup Data can Present Non-Physical Picture

Problem tends to be most pronounced for WASP data



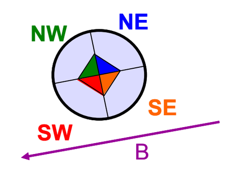


Based on this WASP example we can see:

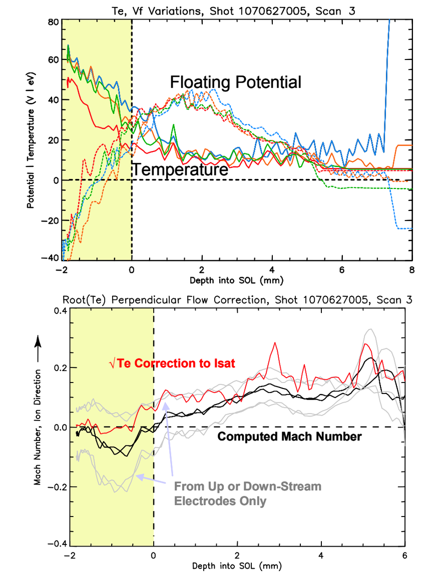
- Ordering at rho<1mm is incorrect!
- Can down-stream electrodes be trusted? Is the current too low? Could the probe wake be connected to cold divertor plasma?
- Using up or down-stream electrodes only to calculate M_{perp} causes offset and re-scaling, but no change in shape of profiles
- M_{perp} from up-stream electrodes only does not show flow reversal
- For USN, ordering is often incorrect in *far* SOL!

Models assume uniform temperature and floating potential on a flux surface. Could asymmetries in these quantities be to blame?

- The four electrodes see similar values of temperature and floating potential.
- Outliers sometimes exist (SW in this case) and tend to show lower temperatures in the down-stream direction.
- Could there be a √Te modification to the expected ion saturation current? This can make a significant difference in M_{perp} in some cases.



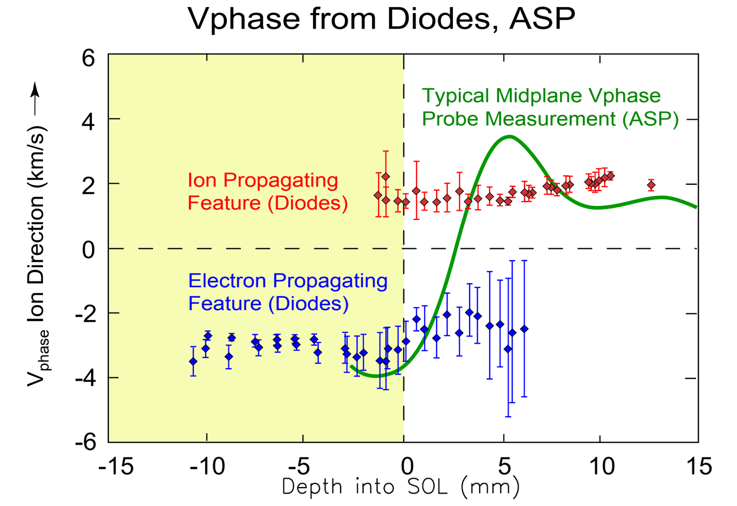
WASP Electrode Layout



Vphase Shear Layer Analysis

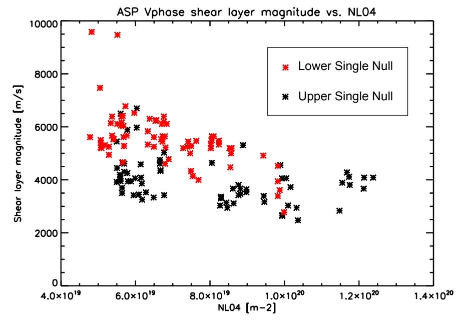
While there may be problems with the Gundestrup measurement, the phase velocity measurement is corroborated by other diagnostics. An array of fast diodes viewing the LFS edge also sees a strong perpendicular phase velocity shear layer in the vicinity of the separatrix.
(See I. Cziegler, Momentum III this afternoon)

Vphase from Diodes, ASP



V-Phase Shear Layer Trend: Magnetic Topology and Density Sensitivity

Armed with confidence in the phase velocity measurement, we began to look for correlations between the phase velocity shear layer and plasma parameters. One quantity we believe we can measure with high confidence is the jump in poloidal velocity across the shear layer from the far SOL to near the separatrix; the *shear layer magnitude.*



- The velocity jump is sensitive both to density and magnetic topology
- The velocity jump tends to decrease at higher density
- The LSN plasmas have higher velocity jump than the USN plasmas

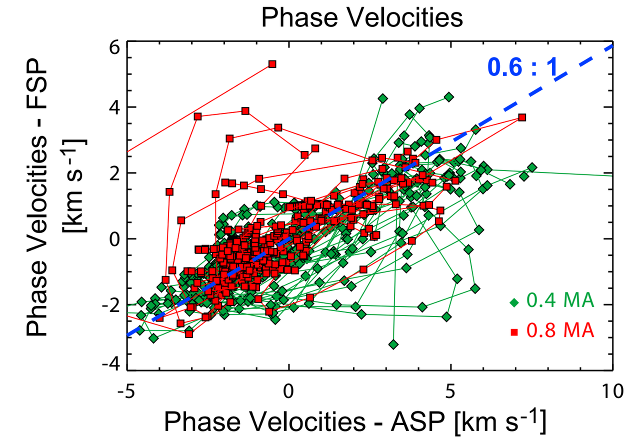
Could this be connected to the reduced L-H power transition threshold in LSN?

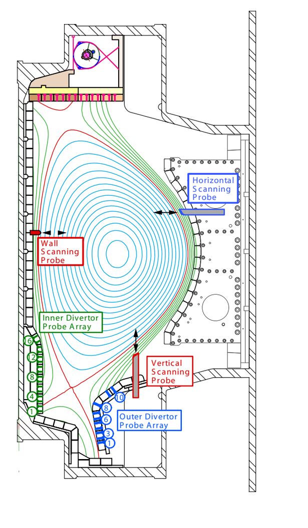
Vphase Shear Layer- Field and Current Scan

Variations observed in the phase velocity shear layer when varying field and current

Low Field Side Scanning Probes: Phase velocity scales with field and flux expansion, suggests flows are tied to the gradient of a flux function.

Phase Velocities





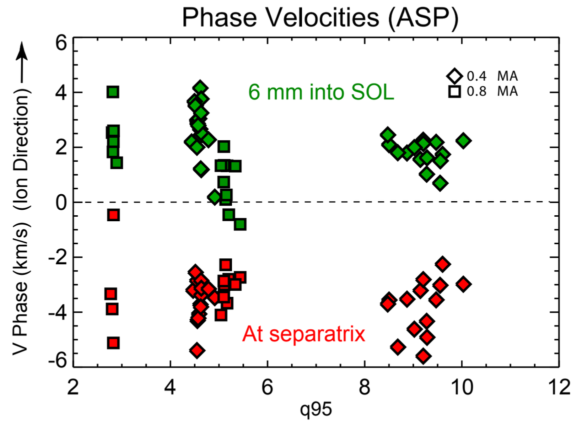
This is consistent with flows being proportional to ExB/B^2 or $\nabla P x B/B^2$ with Φ, P being flux functions.

Flux surface spacing: $\Delta_F/\Delta_A = R_A B_{pA}/ R_F B_{pF}$ ~ 1.4

Magnetic field variation: $B_F/B_A = R_A/ R_F$ ~ 1.2

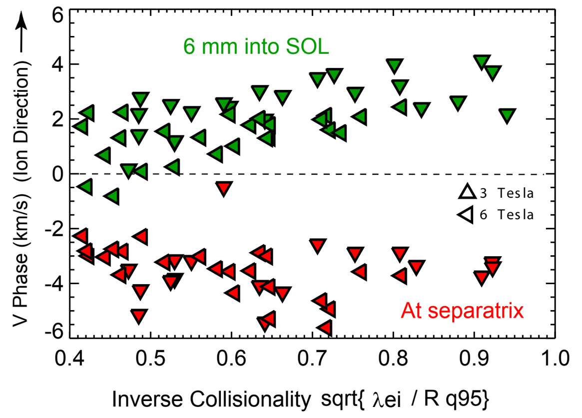
We expect: $(-\nabla\Phi/B|_F \sim 0.6\,(-\nabla\Phi/B|_A$, which fits the data well.

Phase Velocities (ASP)



Vphase q Scaling:

- The q-scan showed no dependence of the velocities on q ∴ the perpendicular velocity is not set by the poloidal sound speed.



Vphase Collisionality Scaling:

- We again see the trend towards higher ΔVphase at low collisionality.
- It appears that this trend is caused primarily by a change in the velocity in the far SOL rather than at the separatrix.

Conclusions / Future Work

- Parallel flow measurements from the Gundestrup Probes agree with past measurements and support the transport-driven flow picture.
- Perpendicular flow measurements from the Gundestrup probe can disagree with other velocity measurements. Several possible explanations for the disagreements require further investigation.
- Perpendicular flows from both Gundestrup and phase velocity measurements often show strong shear layers, with the flow tending in the electron diamagnetic direction near the separatrix.
- Investigations of the phase velocity shear layer at a variety of fields and currents have shown:
  - Decreasing velocity jump across the shear layer at higher density
  - Velocity jump scales as the gradient of a flux function over the magnetic field. on the low field side.
  - Velocity jump is independent of q-95.
  - Changes in the velocity jump across the shear layer appear to result from changes in the magnitude of the ion-diamagnetic directed flows in the far SOL.

References

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