First results from Electron Energy Distribution Function (EEDF) Analysis of Langmuir Probe Signals

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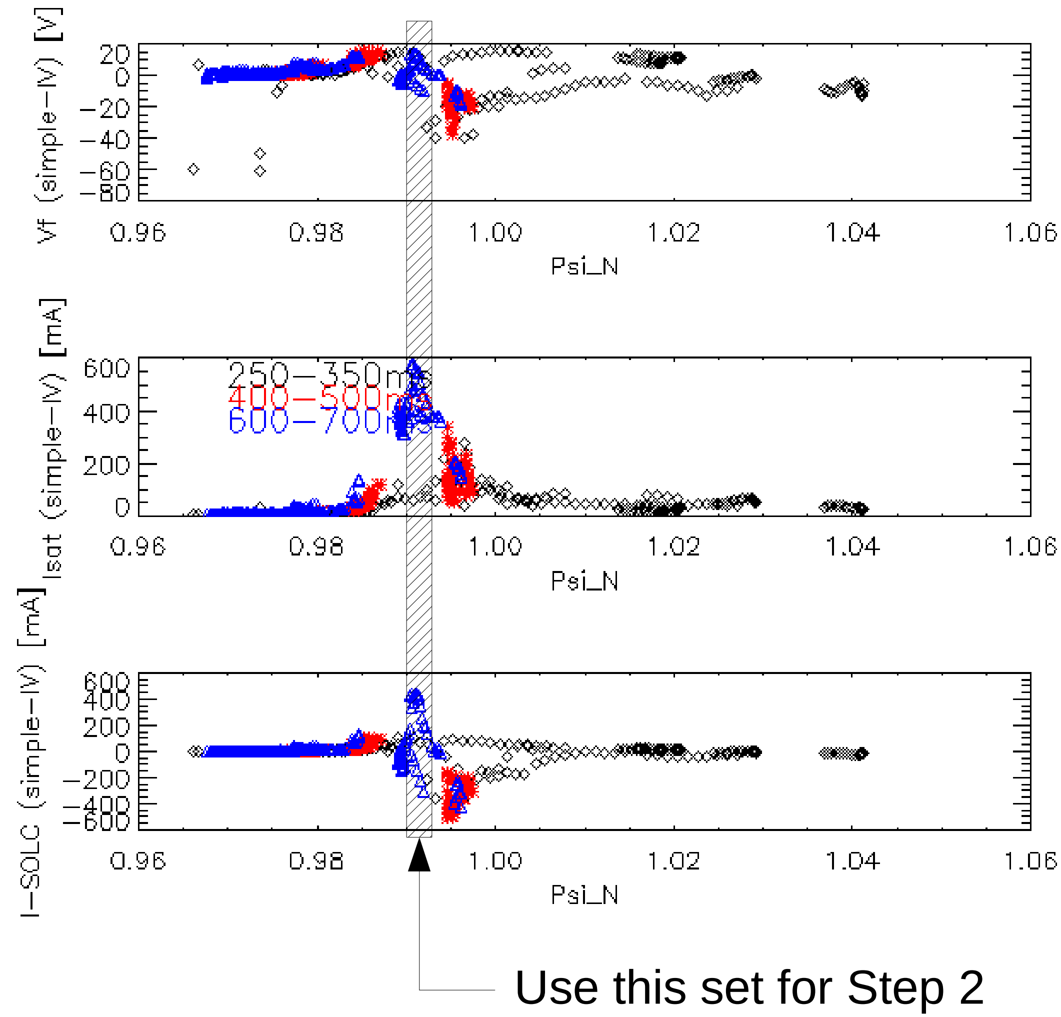
Motivation

- LLD discharge observations of reduced Vf (coming up)
- Recent research trends suggesting single Maxwellian fluid approach posing difficulties (e.g. Chankin, 2007, “Discrepancy between modelled and measured radial electric fields in the scrape-off layer of divertor tokamaks: a challenge for 2D fluid codes?” **NF** 47)
- Previous work indicating kinetic effects in the SOL should be expected (Chodura 1992 and Batischev 1997)

Discharge comparison process

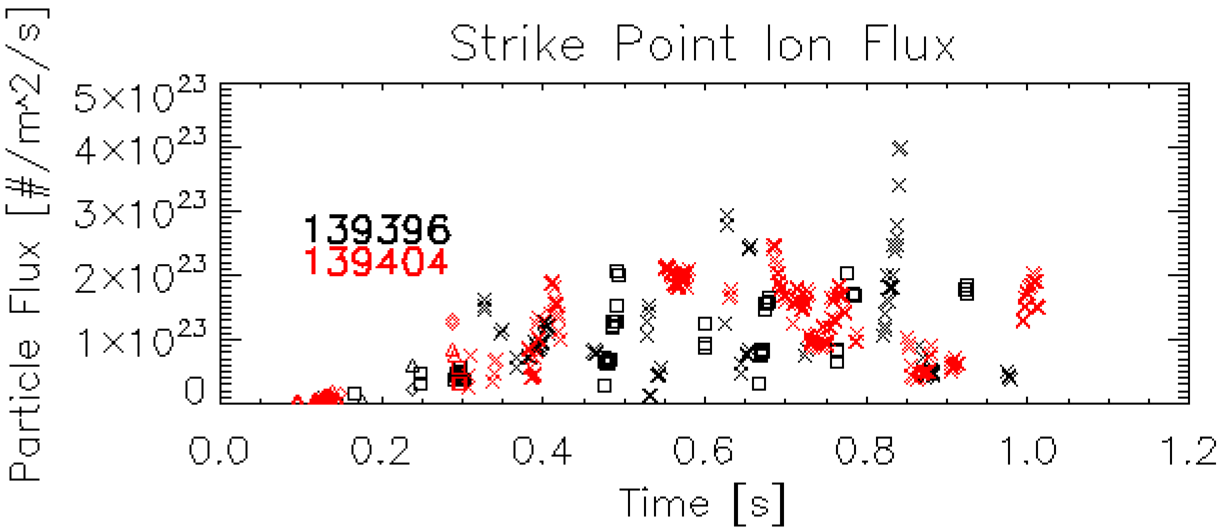
- General problem of high-gradient region moving about over spatially localized measurement points
- Step 1 makes use of EFIT to generate a psi value for each probe in time and then construct strike-point sweeps (but indicates time evolution)
- Step 2 Filter resulting data set along specific psi value to generate a time-base plot of the value of a quantity on a specific magnetic surface

139404, Outboard Swept Probes



Can Now Compare Apples-to-Apples

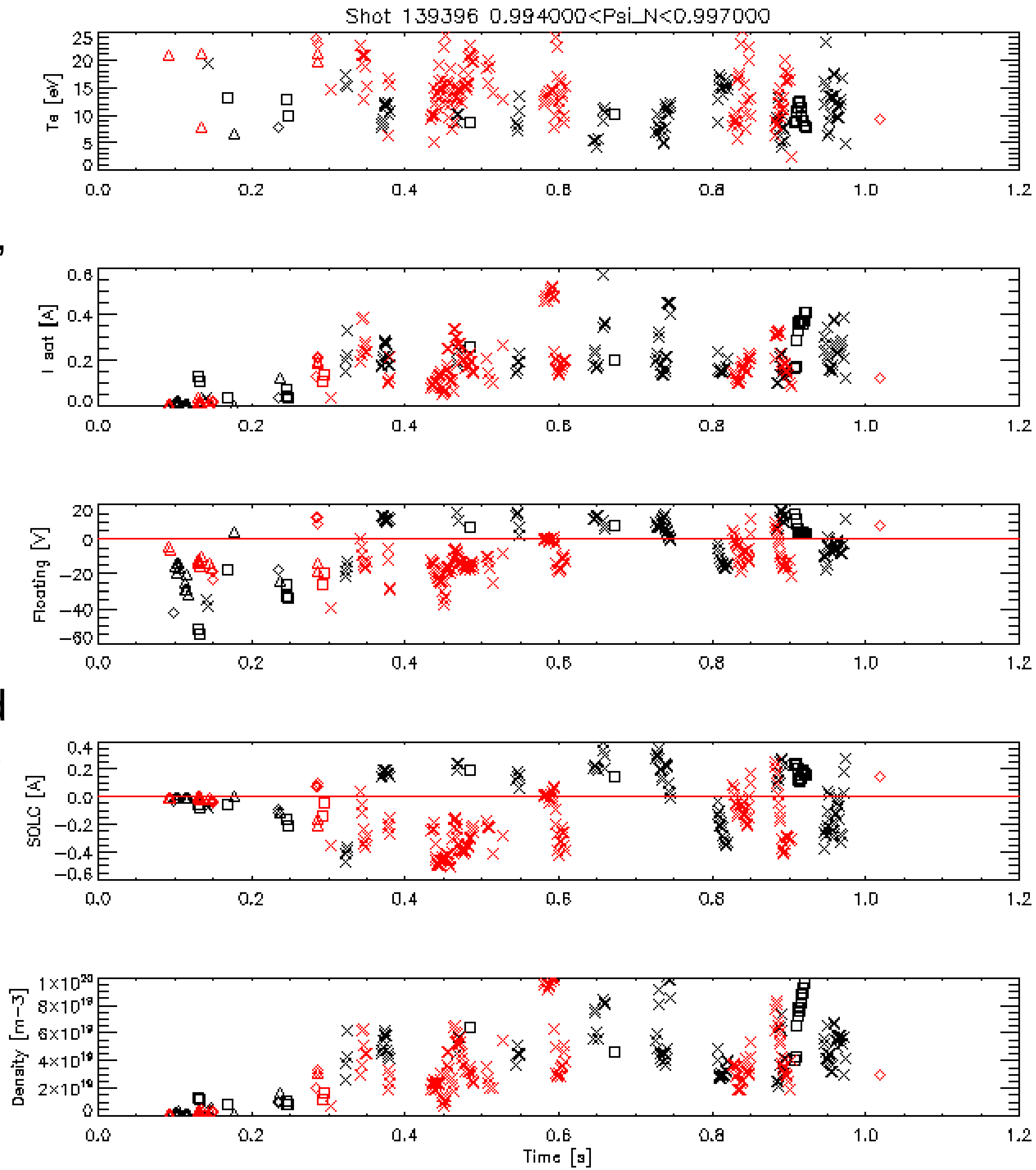
- Use same psi-surfaces where peak ion current occurs to provide strike-point flux values
- Colors denote shot
- Symbols indicate different probes falling within desired psi range



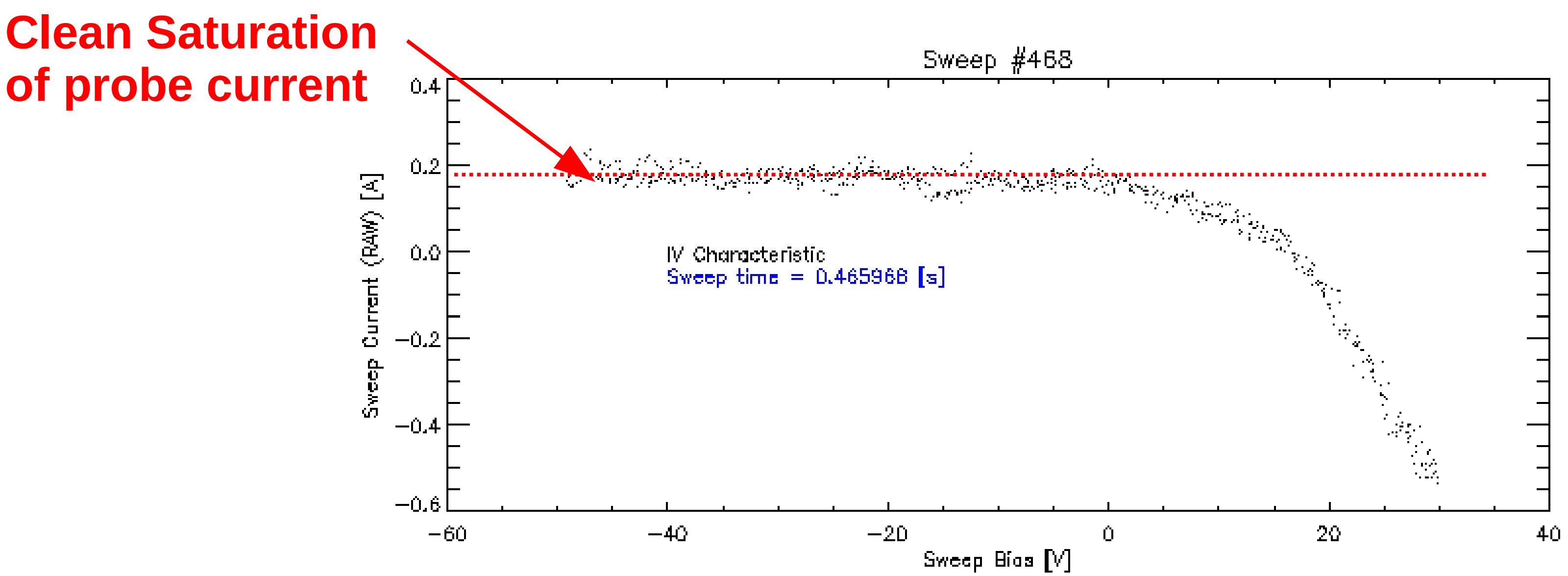
$$\Gamma = \frac{I_{sat}}{e\, A_{probe}}$$

Discharge comparison during XP1041A

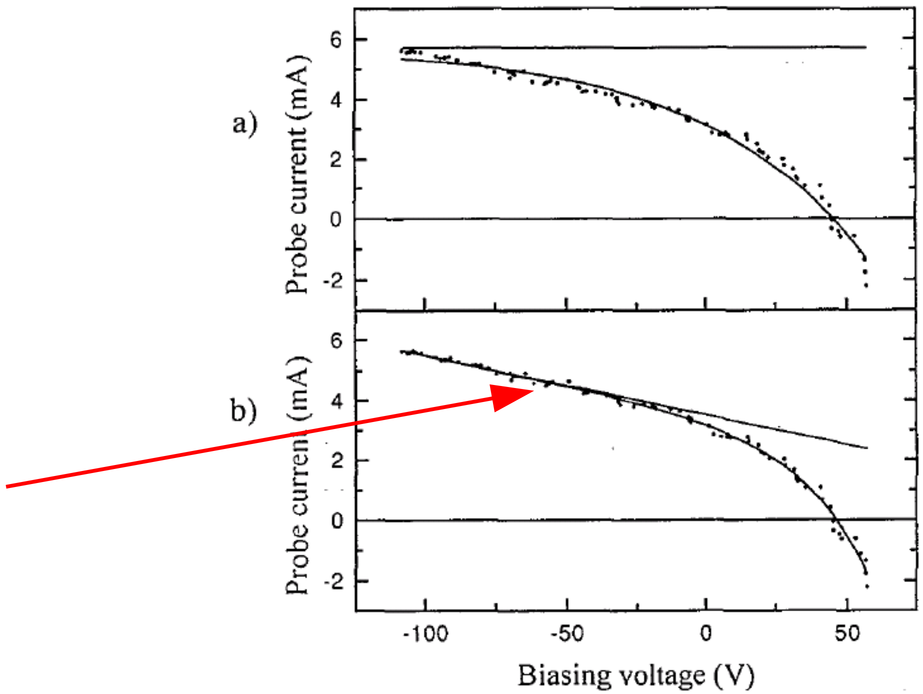
- 139396 compared with 139404
  - More gas, but not much change in electron density, nor in deuteron content **(where did it go?)**
  - Type V ELMs return by end of sequence – not present in 139404
- Tantalizingly higher electron temperatures in 139404
- Reduced floating potential and corresponding negative SOLC
- **But can I trust Te and classical interpretation method?**
- **Motivation for EEDF**



Probe Regime Enables EEDF Analysis



- Outboard probes typically in "thin-sheath" regime (due to probe geometry)
- Simplifies analysis by removing sheath growth effects (Gunn probes, NSTX inboard probes)

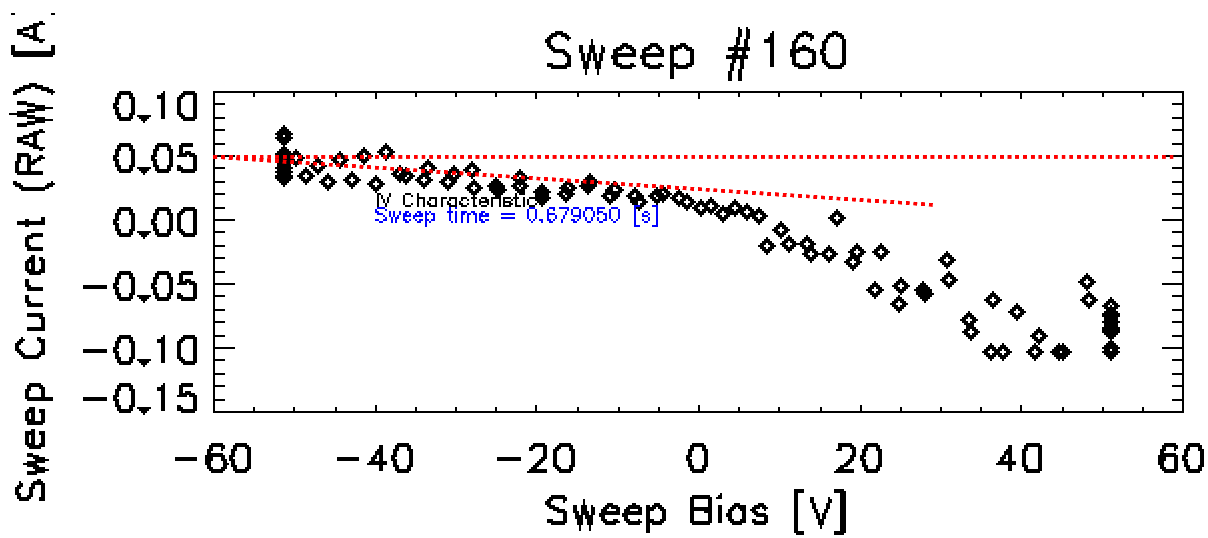


Gunn, **RSI**, 1995

Probe Regime Enables EEDF Analysis

Inboard probes do not always saturate due to sheath growth (probe 3, 139396) (else Te~28eV!)

Shift from Isat is function of angle of incidence, density and temperature [Gunn, 1997, RSI]



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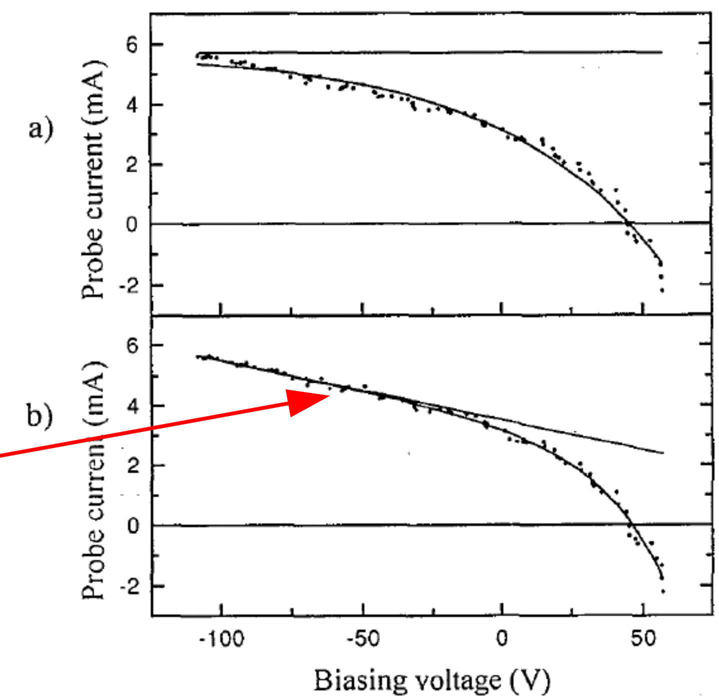


Gunn, **RSI**, 1995

Recent Work Demonstrates EEDF Extraction in Magnetized Plasmas

- Requires energy scale length to be long compared to probe perturbation scale length
- Magnetic field makes distribution function f(e) proportional to first derivative in some cases, avoiding noise-prone second derivatives

$$\tau_{\varepsilon}^{-1} \approx \nu_{ee} + \delta \nu_{e-n} + \nu_{e-i}$$

$$\lambda_{\varepsilon} = \sqrt{4 D_e \tau_{\varepsilon}}$$

~6cm vs. 1-2 mm

Arslanbekov, **PSST**, 1995
-High pressure and magnetic fields

Demidov, **PoP**, 1999
-Magnetic fields

Popov, **PPCF**, 2009
-CASTOR Tokamak, cylindrical probes

This will be the first usage of this EEDF method in a high-power tokamak and with divertor probes

Non-Local Probe Theory

- When energy scale-length is much larger than probe scale, then leading terms in kinetic equation is diffusion in spatial coordinates [Arslanbekov, 1994, Golubovskii, 1981]
- Solution to current drawn by probe given as:
-
-

$$j(V)=\frac{8\pi e}{3m^2\gamma_0}\int_{eV}^{\infty}\frac{(\varepsilon-eV)f_{\infty}(\varepsilon)d\varepsilon}{1+\frac{\varepsilon-eV}{\varepsilon}\psi(\varepsilon,V)}$$

- Where psi is a diffusion parameter depending on probe geometry and system type (i.e. e-n collisions, classical (Demidov) or Bohm (Popov) cross-field diffusion)

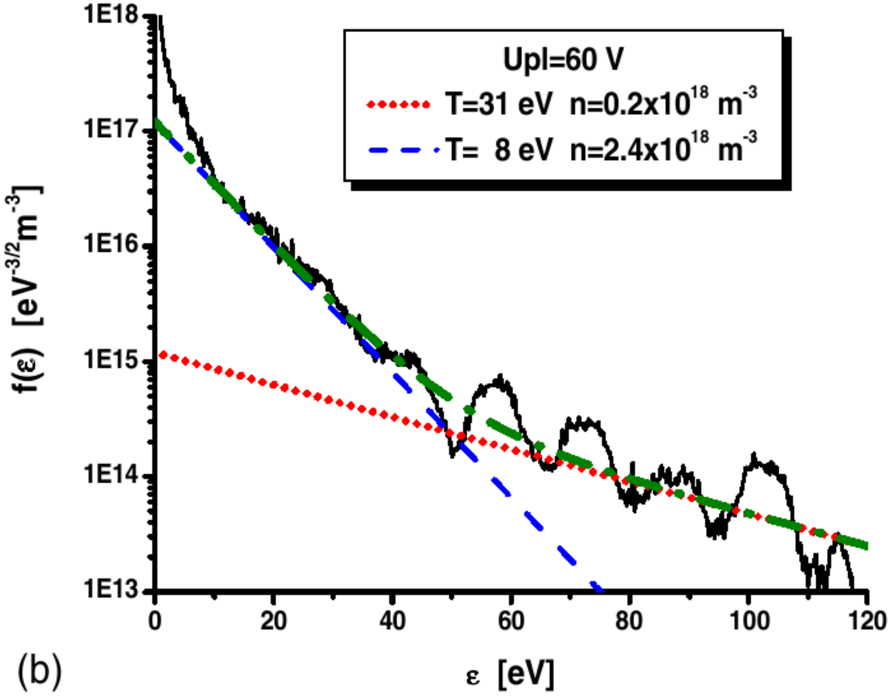
$$\psi(\varepsilon,V)=\frac{1}{\gamma_0\lambda(\varepsilon)}\int_a^{\infty}\frac{D(\varepsilon)dr}{(r/a)^n D(\varepsilon-eV(r))}$$

Limit cases for Non-Local Theory

- In the limit of very small psi parameter (i.e. collisionless or non-magnetized) resulting form is identical to Langmuir formula:
- $$j(V) \propto \int_{eV}^{\infty} (\varepsilon - eV) f(\varepsilon) d\varepsilon$$
- Which results in the usage of second derivative for EEDF
- In the limit of very large psi parameter (i.e. high neutral pressure, high magnetic field), results in first-derivative method:
- $$j'(V) \propto -\frac{eV\sqrt{eV}}{\psi_0} f(eV)$$
- Popov, 2009, categorized according to psi_0 value, which is value of psi parameter for a 1eV electron
- For intermediate values, mixture of methods.

CASTOR Usage of EEDF Method

- Found that for values of psi_0>100, little error (2-5%) in using first derivative method alone
- For values less than 100, recommended using iterative method due to integral equation for first derivative
- Found bi-modal distribution in edge of their plasmas
- **Initial estimate of NSTX outboard probe diffusion parameter was Psi_0~75**

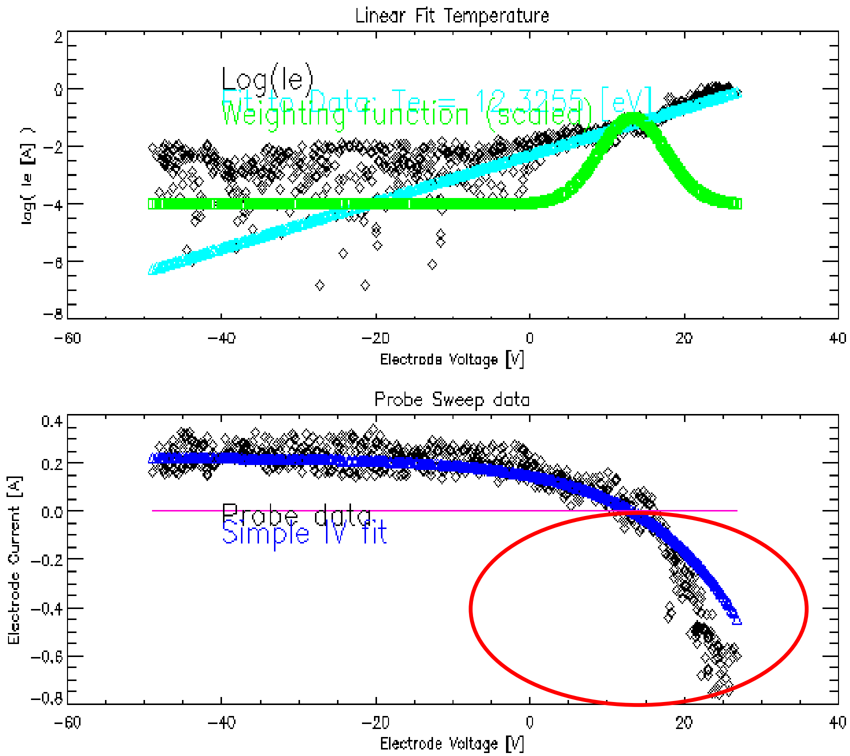


CASTOR tokamak EEDF obtained via first-derivative method (Popov, 2009, **PPCF**)

NSTX Data Example

- Simple IV method (“Classical”) measures sub-section of data
  - Initial analyses used Gaussian weighting around floating potential (Jaworski, **RSI**, 2010)
  - Typical usage is for $V<V_f$ (Stangeby, **PPCF**, 1995; Matthews, **PPCF**, 1994)
- Discards most of the electron current, samples only the tail (or less)

Outboard probe

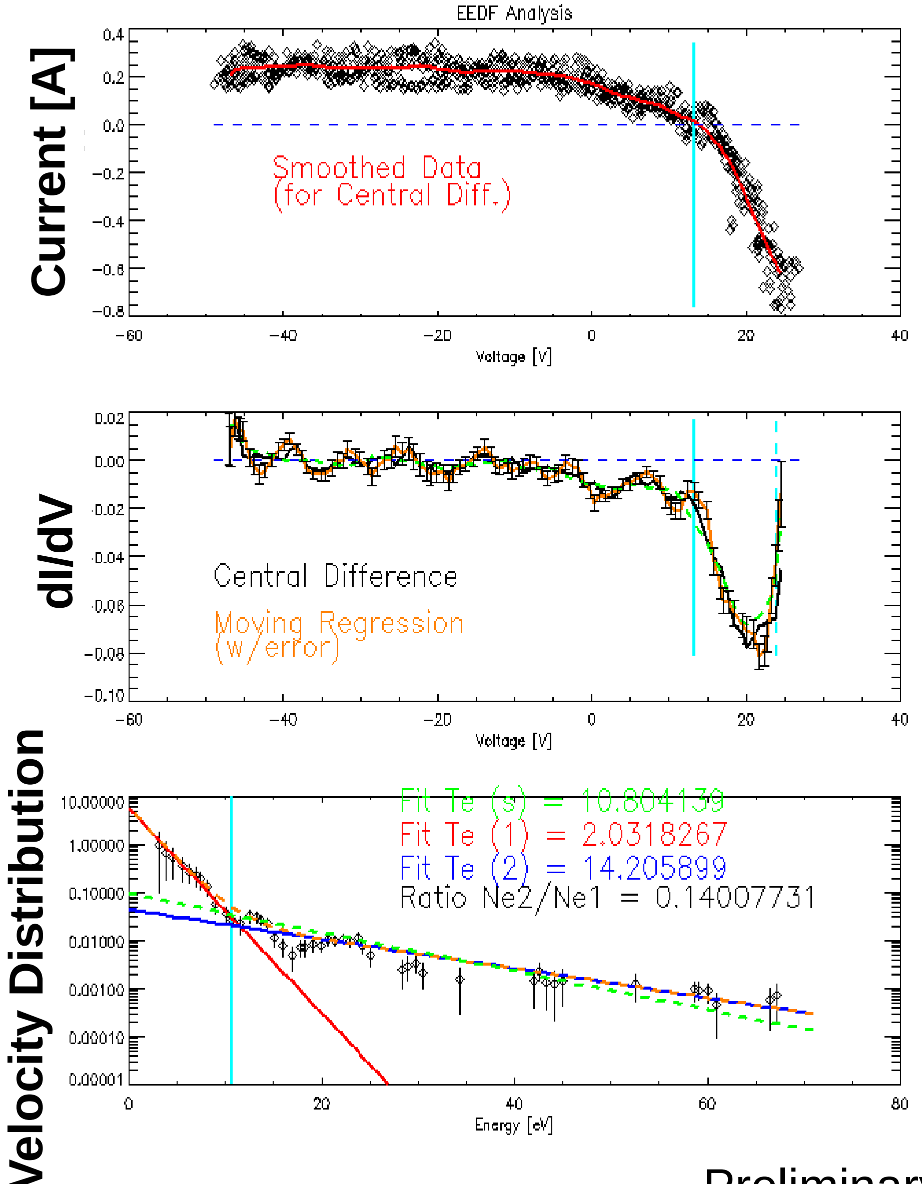


Dark blue is the resulting fit – Classical method assumes single Maxwellian and only measures the tail of the distribution (below Vf).
Red ellipse indicates unused data in the classical method.

Bi-modal EEDF in Divertor

- First derivative method requires some processing (two methods shown for calculating, non-iterative method used initially, hence “preliminary”)
- Reveals bi-modal distribution (also seen in CASTOR) and relative fractions of hot and cool populations
  - Will attempt to get absolute densities from EEDF
  - Chi^2-minimization algorithm developed to determine best fit (less subjective input from user)

Same data set shown previously

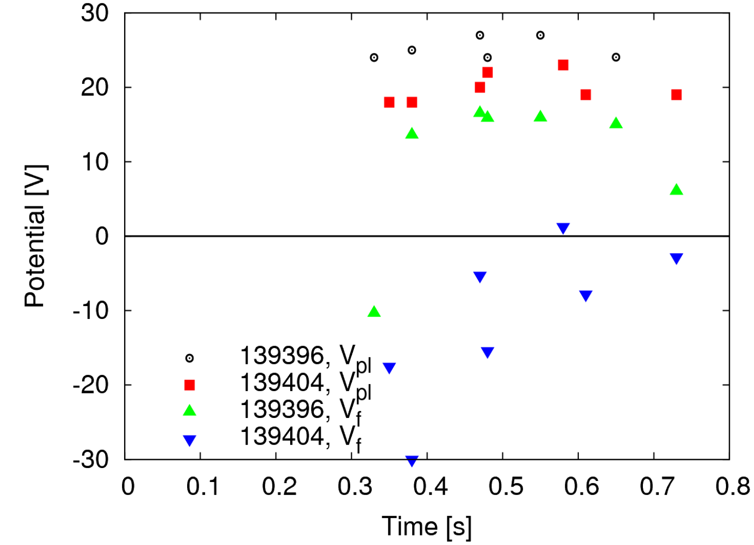


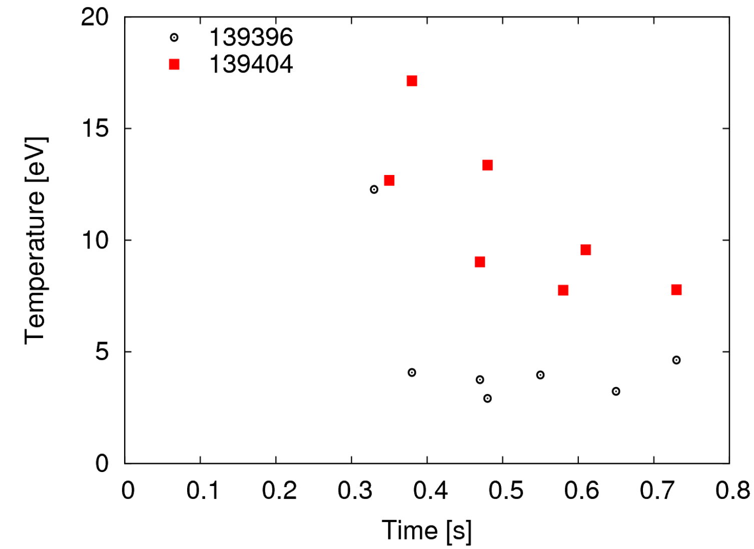
Preliminary

Application of Analysis to LLD

- Return to XP1041A discharges
- Can the floating potential reduction be attributed to plasma biasing of plasma potential downward?
    - Floating potential difference is about 20V
    - Plasma potential difference is only about 6V
    - Cannot remove with only Vp reduction (although there is a reduction in this quantity)
- Increase in Vp-Vf is often attributed to an increase in Te ~ (Vp-Vf)/2.8 (for pure D plasma)

NB: Sparse data set because EEDF still a "by-hand" process. Time points correspond to points in shot shown earlier.

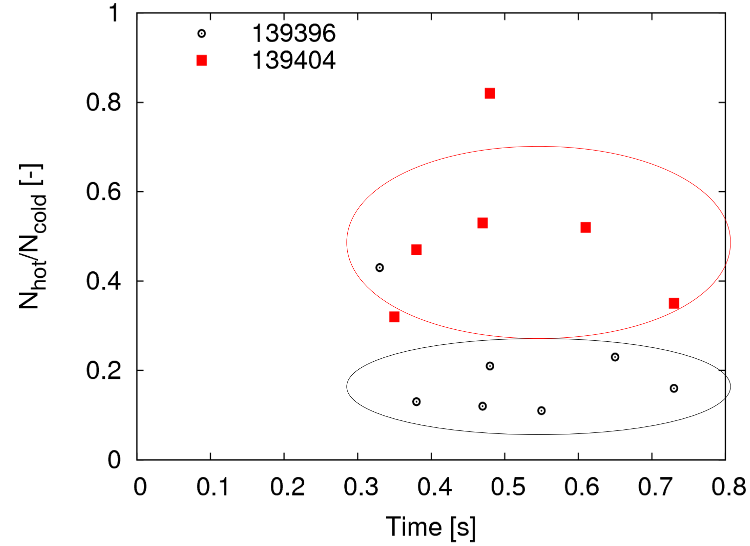




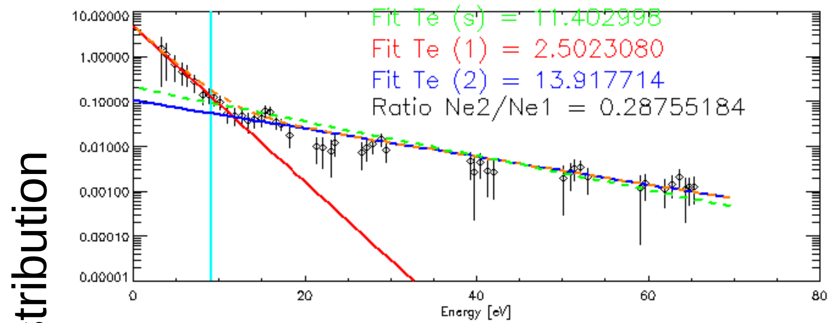
Preliminary

Hot Electron Fraction Larger in 139404

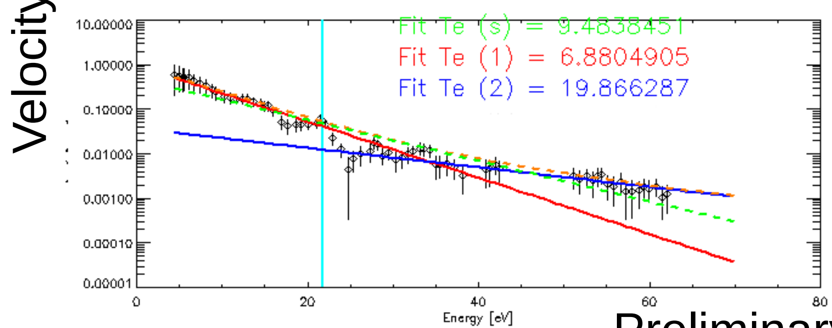
- Bi-modal temperatures compared
  - Still determining reliability of low-temperature solution, but similar Te's within scatter but...
  - Fraction of higher temperature population larger in 139404 discharge
- Hot fraction typically less than 20% in 139396 vs. >40% in 139404
- Have since added functionality to determine when single Maxwellian better than bi-modal via Goodness-of-Fit statistic



139396, 0.65s Bimodal is better



139404, 0.58s Single is better



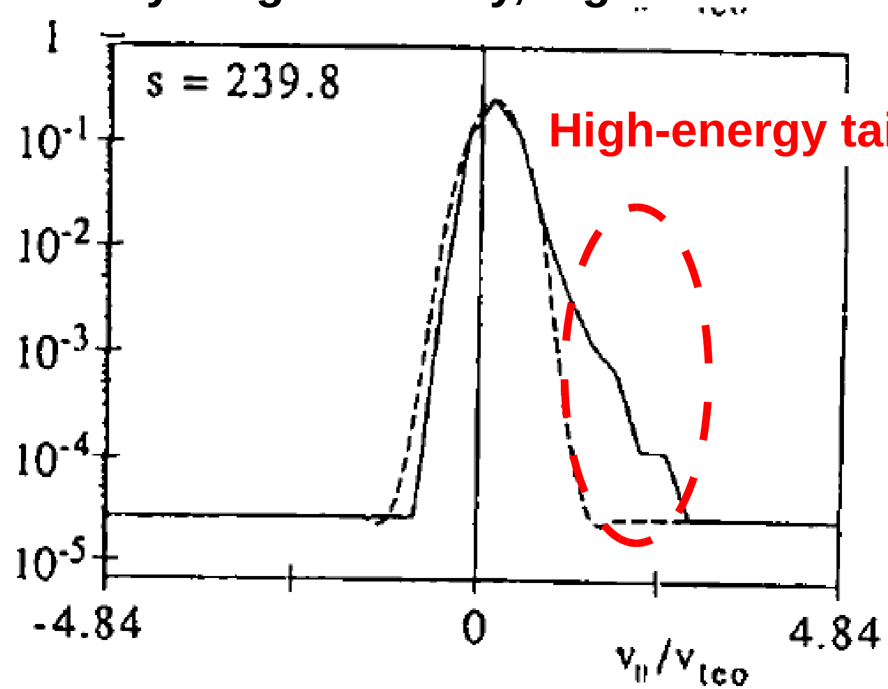
Preliminary

Larger hot fraction consistent with lower R

- Chodura kinetic effects in the SOL paper from 1992 simulated low/high recycling with Fokker-Planck code (Chodura, **Contrib. Plasma Phys.** 1992)
  - Demonstrated high-energy tail effects (Also seen in Batischev paper of 1997)
  - High energy tail predicted to be in recycling plasmas
  - Low recycling looks more like “mid-plane” distribution (i.e. single, hot Maxwellian)
- **The increase in hot fraction during the LLD experiment toward a value of 1 is consistent with reduced recycling (i.e. evolving toward single Maxwellian with higher temperature)**

Chodura states in body of paper that: “[in the case of no recycling] the velocity distribution stays nearly Maxwellian if the source is Maxwellian.” I.e. electrons free-stream from midplane to target. On the other hand, recycling plasma is cool, but tail can penetrate to PFC.

Recycling boundary, high collisionality



Improvements in the current method

- Add in iterative solution methods for the full integral equation to handle arbitrary psi values
- More rigorous calculation of a divertor probe diffusion parameter
- Careful examination needed to determine if Plasma-Electron Spectroscopy (PLES) is possible for impurity identification/tracking (Demidov, 2010, **CPP**)
- Analyze more shots and start determining relevant quantities for comparison with other diagnostics (e.g. energy flux from EEDF for comparison with IR)

Summary

- Outboard probe geometry seems compatible with EEDF analysis
  - First usage of this method in a high-power tokamak and with divertor mounted probes – encouraging results so far
  - Still some theory development required for more confidence
- EEDF method reveals far more information about the plasma than classical interpretation
  - Plasma potential, actual distribution function
  - Initial survey indicates it may be possible to perform PLES with the Langmuir probes (impurity diagnostic)
- Comparison of LLD discharges with EEDF method reveals:
  - Depression in floating potential (direct measure/observation) in discharge with suspected “actively pumping” LLD
  - Larger fraction of hot electrons in the suspected “actively pumping” discharge – would explain floating potential depression, increase in temperature
  - Increase in hot fraction consistent with kinetic modeling of the SOL comparing non-recycling/recycling boundary condition

BACKUP

Other Kinetic Modeling

- Batishchev also predicted high-energy tail at divertor plate
- Utilized ALLA Fokker-Planck code to simulate attached and detached divertors
- High-gradient regions do not have enough interactions to slow high-energy electrons
- Consistent with Chodura modeling

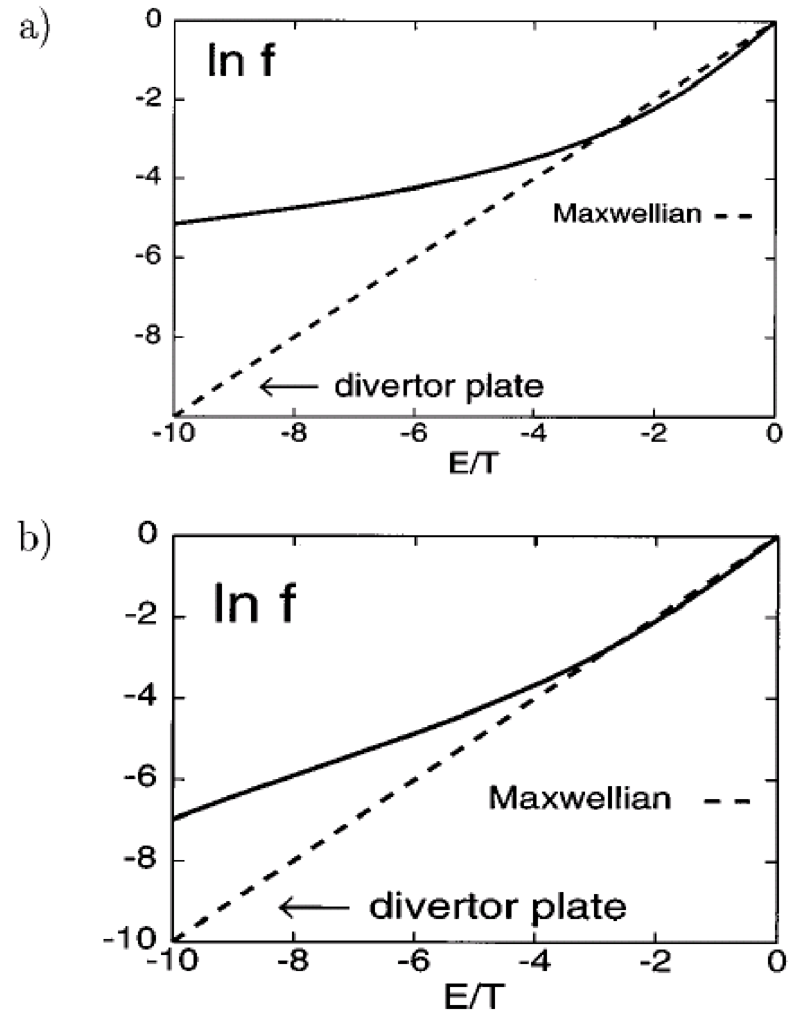


FIG. 12. Normalized distribution function at the plate for detached (a) and attached (b) cases compared to a Maxwellian.

Batischev, 1997, **PoP**

Shots:
139396
139404