NSTX

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Effect of non-Maxwellian Electron Energy Distributions on Langmuir Probe Measurements and Heat Transmission in Tokamak Divertor Sheaths

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and the NSTX Research Team

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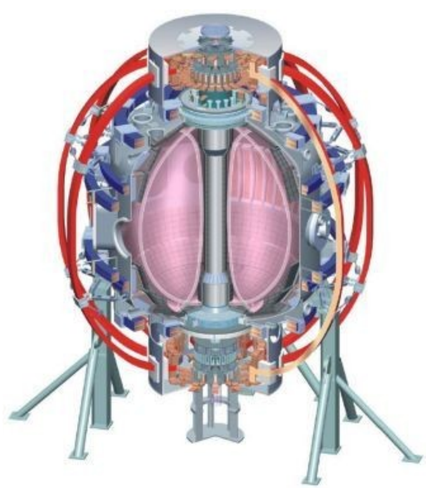

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Overview

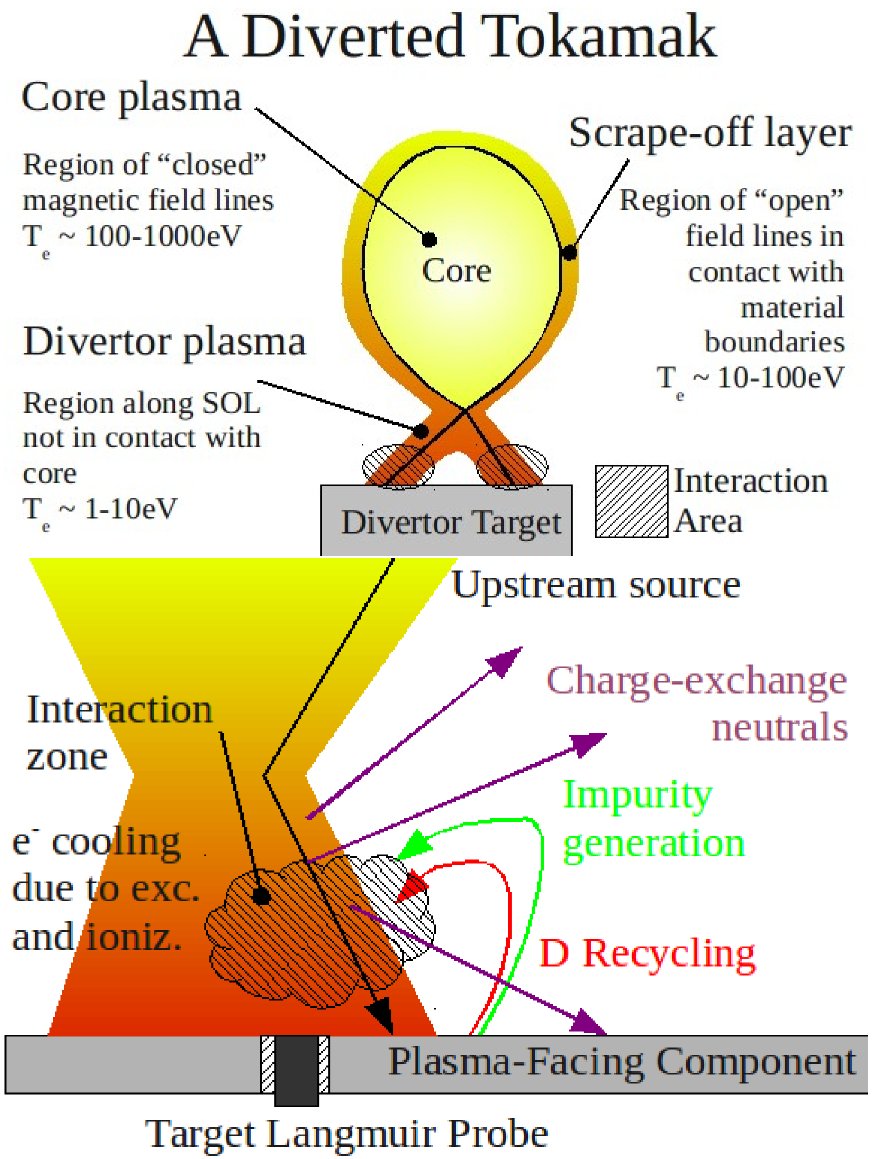
- Tokamak divertor and scrape-off layer orientation
- Overview of Langmuir probe interpretation methods in tokamak devices
  - Classical method
  - Non-local method
- Observation of non-Maxwellian distributions in the NSTX divertor
  - Bi-modal distributions in Langmuir probe results
  - Comparison with spectroscopic measurements
- Empirical plasma reconstruction results
  - Comparison of theoretical sheath heat transmission with IR thermography
- Discussion of non-Maxwellian formation mechanisms
  - Non-local electron transport calculations in the tokamak divertor
- Summary

Divertor plasmas often characterized by low temperatures and steep gradients

- Scrape-off layer (SOL) transmits power from core to target
  - Divertor config. moves material interactions away from core
  - Plasma thermal conduction results in large gradients in low temperature regions

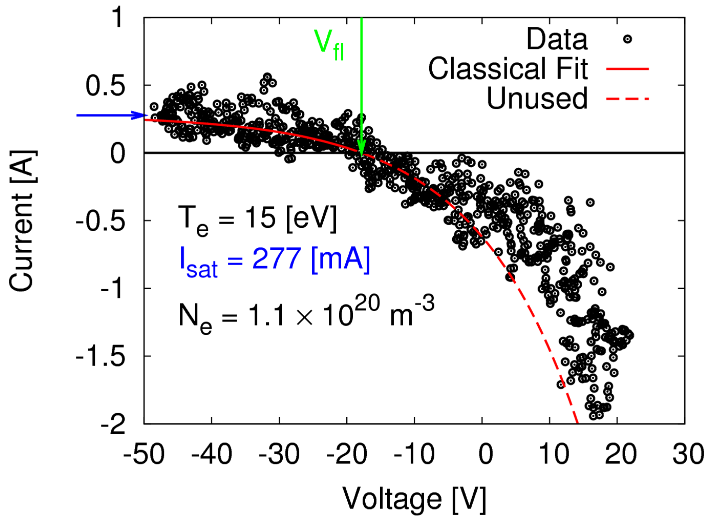
$$T' \propto q_{||} T^{-5/2}$$

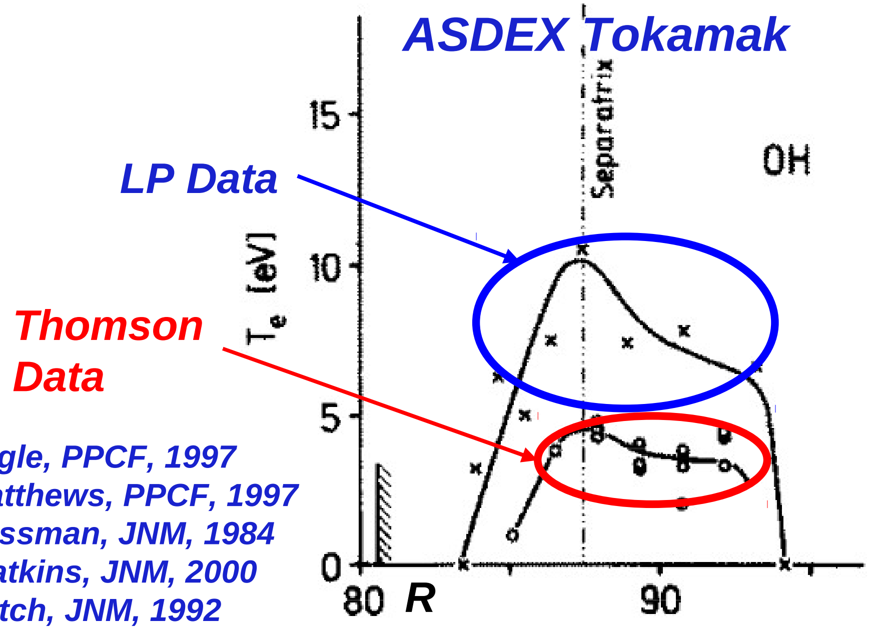
- Multiple processes affect energy transport from upstream source to divertor target
  - Hydrogenic and impurity interactions and radiation
  - Localized sources at the divertor target can further steepen local gradients
- Process rates are highly dependent on local plasma conditions (N_e, T_e)



Classical interpretation often yields higher temperatures relative to other diagnostics

- Classical interpretation makes use of data up to floating potential
  - Assumes single Maxwellian distribution
  - Only uses ~5% of distribution
  - T_e calculated found to rise as data past floating potential included
- Independent measurements often indicate lower temperatures
  - Thomson scattering on ASDEX had some indications of non-Maxwellian populations
  - Thomson scattering on DIII-D consistently lower T_e than probes
  - Anomalously low sheath heat transmission coeff. On numerous machines (Kallman PP9.00038)





Tagle, PPCF, 1997
Matthews, PPCF, 1997
Fussman, JNM, 1984
Watkins, JNM, 2000
Futch, JNM, 1992

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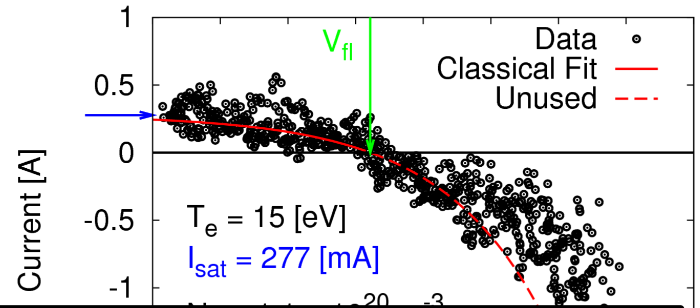
  - Only uses ~5% of distribution



"Don't trust the probes."

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  - Thomson scattering on ASDEX had some indications of non-Maxwellian populations
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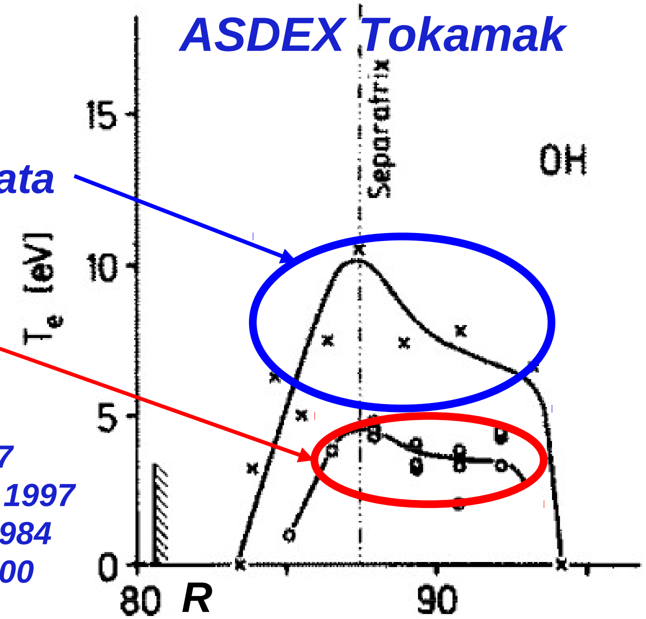
LP Data

Thomson Data



Tagle, PPCF, 1997
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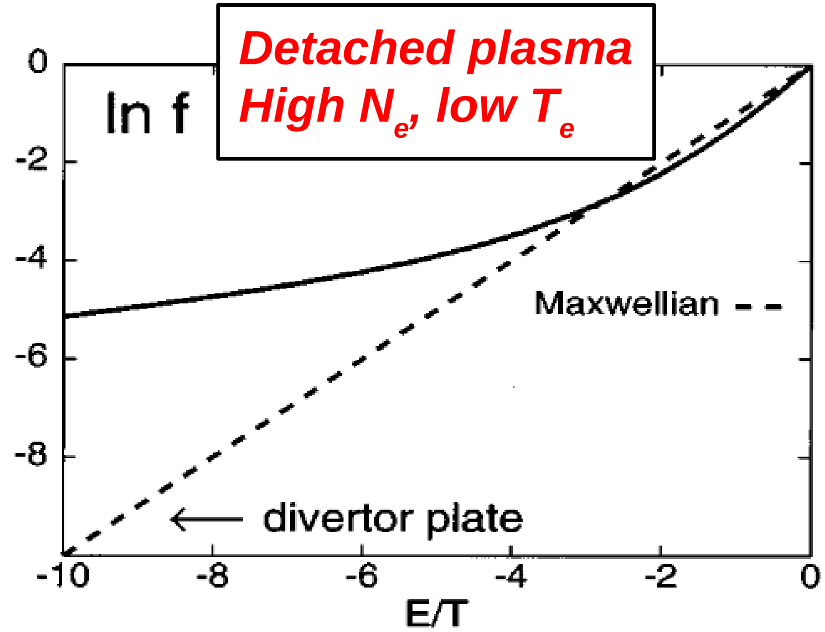
Watkins, JNM, 2000
Futch, JNM, 1992

Why expect a Maxwellian distribution?

- Maxwellian plasmas assumed on the basis of plasma collisionality
  - Collisionality often calculated based on system length[1]
  - Is this reasonable?
- Numerous modeling and theoretical works indicate that non-Maxwellian distributions will arise in tokamak divertors
  - Target plasmas result in low T_e and high N_e – yield large collisionalities in the divertor
  - Non-Maxwellian distributions still obtained
- Modeling indicates that in addition to field-line connection length, temperature scale length requires consideration as well

$$\lambda_{ee} \approx 1 \times 10^{16} \frac{T_e^2}{N_e} \qquad \nu_{ee}^* = \frac{L}{\lambda_{ee}}$$

$$L_{\|} \text{ vs. } \lambda_{Te}$$



Batischev, PoP, 1997

Other exmples:
Fokker-Planck: Chodura, CPP, 1992
PIC modeling: Tskhakaya, JNM, 2011

[1] *PC Stangeby, "The Plasma Boundary of Magnetic Fusion Devices", IoP, 2000.*

Non-local probe interpretation provides more complete analysis of IV characteristics

- When electron energy scale length much longer than probe perturbation scale, velocity "diffusion" term negligible
  - f(r,v) → f(x,W)
  - W is total energy
  - f_0 is distribution far from probe
- Solution for probe characteristic determined by geometry and diffusivity
  - In magnetized plasma, cross-field diffusivity scales with Larmor radius
  - Diffusivity parameter takes form $\psi(W)=\psi_0 W^{-1/2}$ in this case
- When ψ_0 >> 1, first derivative becomes proportional to distribution function (a.k.a. first derivative method)
- Demonstrated on CASTOR tokamak

$$x = r \qquad W = \frac{1}{2}mv^2 + e\phi(x)$$

$$\lambda_\epsilon \gg r_s$$

$$\nabla_x D_x(W)\nabla_x f_0 = 0$$

$$j_e(V) = \frac{8\pi e}{3m^2\gamma}\int_{eV}^{\infty}\frac{(W-eV)f_0(W)\mathrm{dW}}{1+\frac{W-eV}{W}\psi(W)}$$

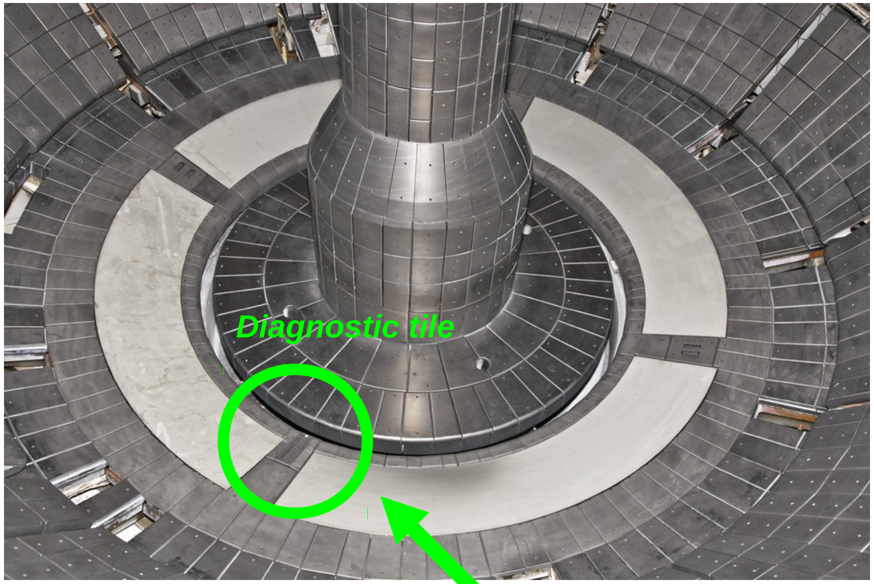
$$\psi(W) = \frac{1}{\gamma\lambda(W)}\int_a^{\infty}\frac{D(W)\mathrm{dr}}{\left(\frac{r}{a}\right)D(W-e\phi)}$$

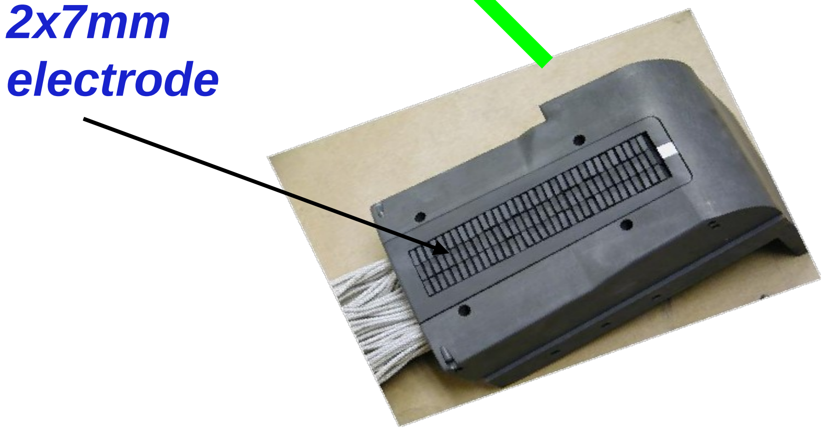
$$\boxed{\frac{\mathrm{d}j_e(V)}{\mathrm{d}V} \propto \frac{(eV)^{3/2}}{\psi_0}f_0(eV)}$$

Bernstein, Phys.Rev., 1954
Golubovskii, Sov.J.Plasma Phys, 1981
Arslanbekov, PSST, 1994
Demidov, PoP, 1999
Popov, PPCF, 2009
Godyak, Demidov, J.Phys:D, 2011

High-density Langmuir probe array installed for divertor plasma characterization

- Liquid Lithium Divertor (LLD) installed to study lithium plasma-material interactions
  - See also: R. Kaita PP9.00024, H. Kugel B04.00009
- Probe array characterizes local plasma properties in a range of experiments
  - See also: R. Perkins B04.00008, V. Surla PP9.00043
- Provides high spatial density of measurements
  - 3x33 array of electrodes
  - Swept probe and triple probe configurations used
- Oblique incidence yields smaller effective probe size
  - Probe scale-length less than energy scale length
  - Large inter-probe gap results in thin-sheath regime



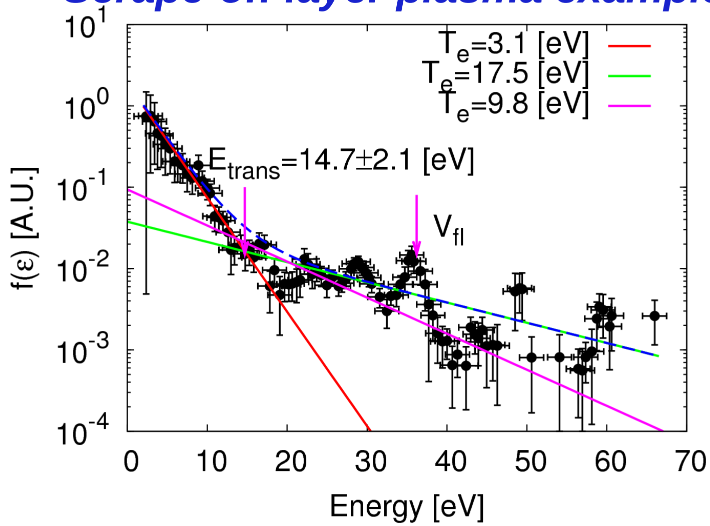


J Kallman, RSI 2010
MA Jaworski, RSI 2010

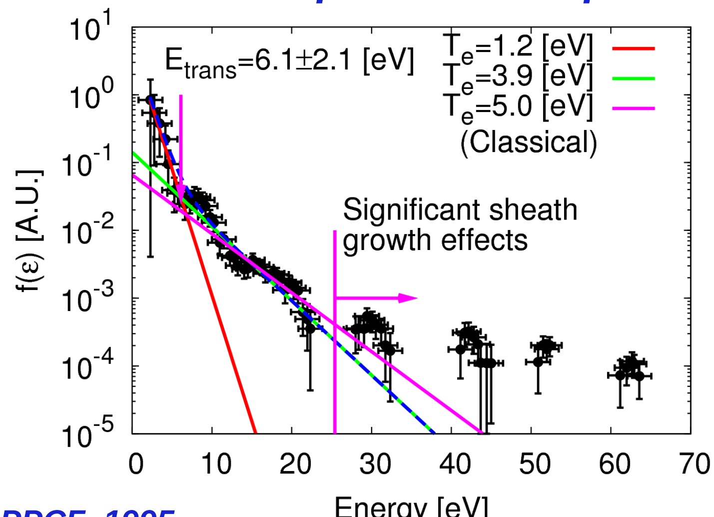
Bi-modal distributions observed in NSTX divertor

- Typical distributions shown
  - Scrape-off layer plasma where classical T_e~15eV
  - Private plasma example demonstrating T_e~1eV
- Ion current effects due to sheath growth estimated to avoid including in fits[1,2]
- Some robust features observed in data
  - Bi-modal distribution often "best" model
  - Cooler bulk population often observed
- Total density calculated from I_{sat}
  - Sound speed calculated using mixture of both plasma populations[3]
  - Dominated by bulk (cool) population
- Can now make comparisons to other diagnostics

Scrape-off layer plasma example



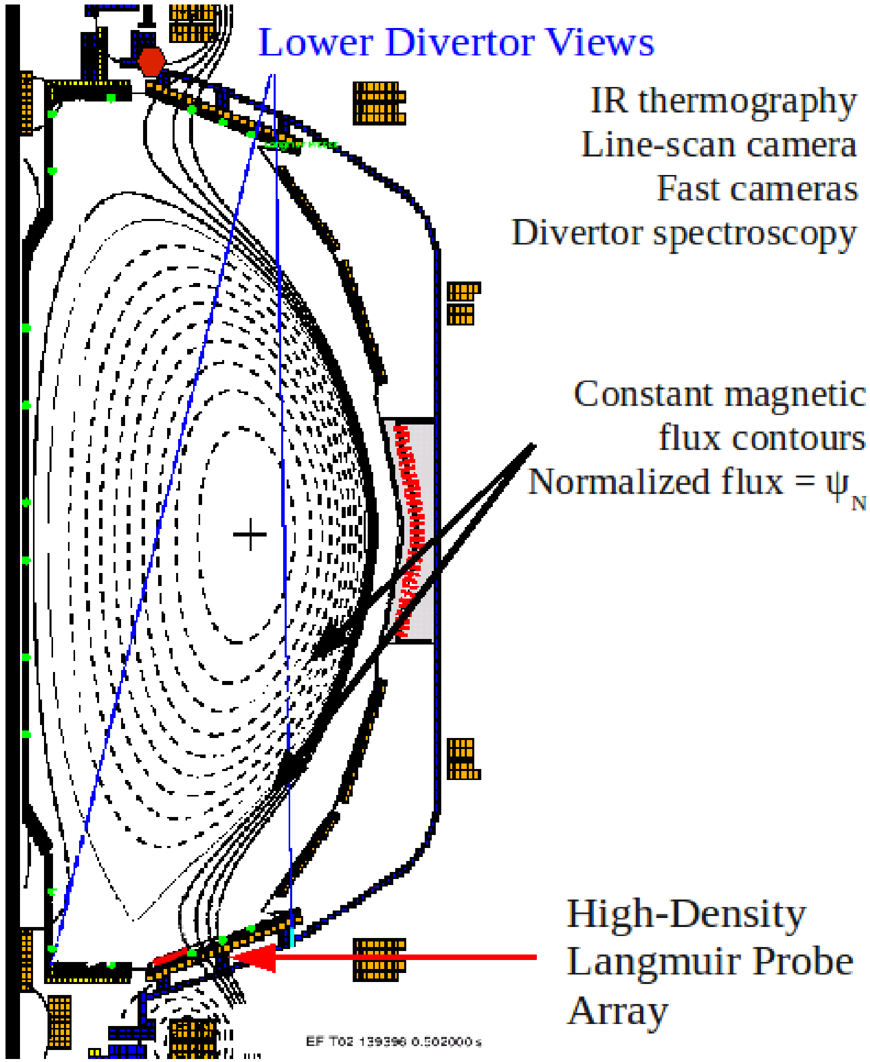
Private plasma example



[1] Gunn, RSI, 1997; [2] Godyak, Demidov, J.Appl.Phys.D, 2011; [3] PC Stangeby, PPCF, 1995

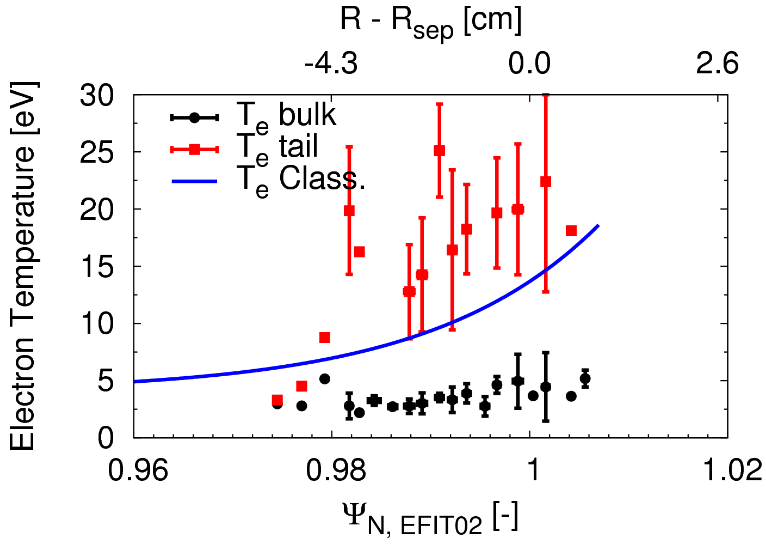
Empirical plasma reconstruction provides framework for checking consistency between diagnostics

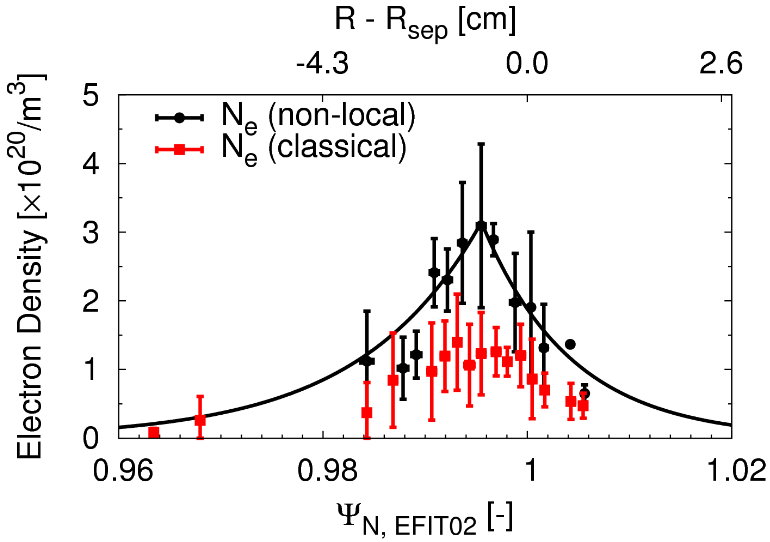
- Utilizes measured data points as starting point in constraining plasma models to fill the gaps between diagnostics
- Solution improves as more and more data constrains background
- OEDGE code suite used here: Onion-Skin Method (OSM2)+EIRENE+DIVIMP
  - OSM2 solves plasma fluid equations (mass, momentum, ion and electron energy)
  - EIRENE performs Monte Carlo neutral hydrogen transport, iteratively coupled to OSM2
  - DIVIMP performs Monte Carlo impurity transport (neutral and ion)
- Utilized here to compare probe interpretation methods against other diagnostics



Interpretation methods result in significant variance in density and temperature

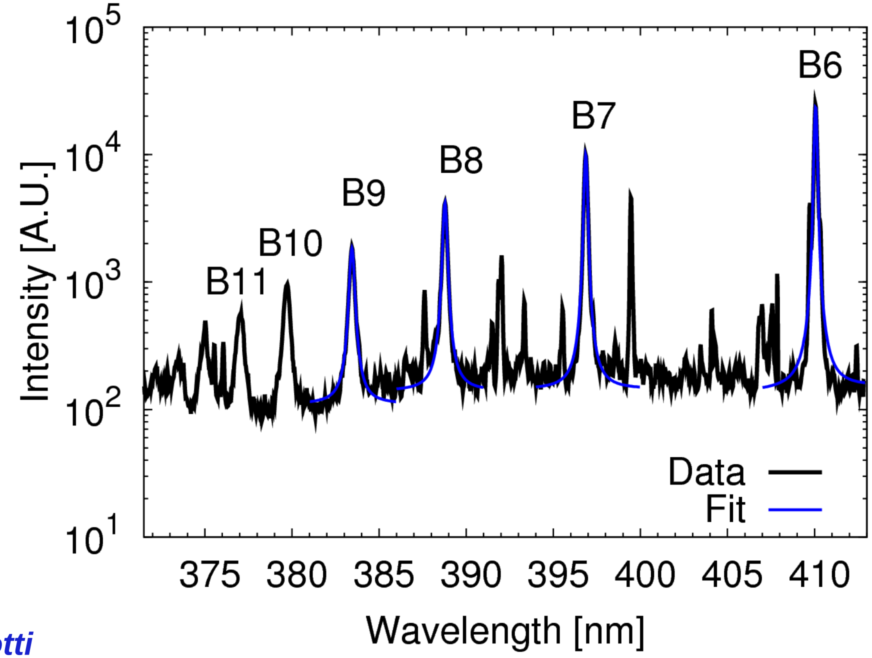
- Plasma motion sweeps out profile during discharge, data aggregated and averaged
  - Nominal equilibrium separatrix location at $\psi_N = 1.0$
  - I_{sat} peak (N_e equiv.) provides indicator of LP-based separatrix location
- Significant temperature variance between interpretation methods
  - 10-20eV temperatures with classical method (fit only shown for clarity)
  - 2-5eV temperatures with non-local interpretation
- Lower temperatures result in higher densities with non-local interpretation



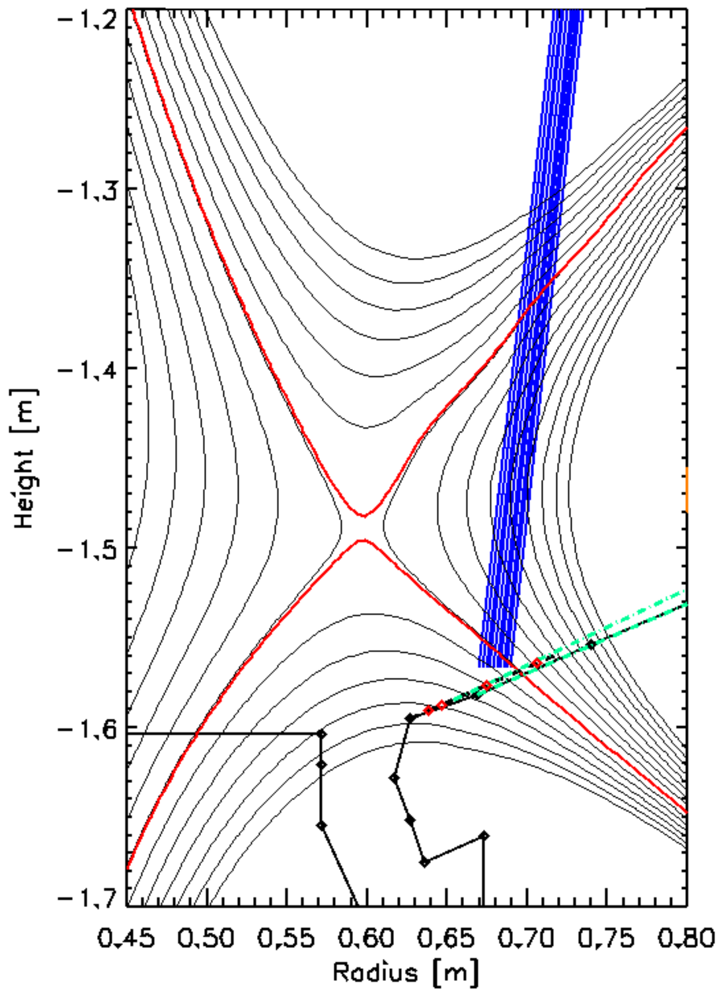


Spectroscopy consistent with non-local probe interpretation

- Divertor spectrometer viewing strike-point region during discharge
- Deuterium Balmer lines shown in this spectra
- Pressure broadening analysis indicates density of **3.6×10^{20} m^{-3}** (mean, $2.1\text{-}5.5\times10^{20}$m^{-3} min/max)
  - Consistent with non-local calculation for N_e



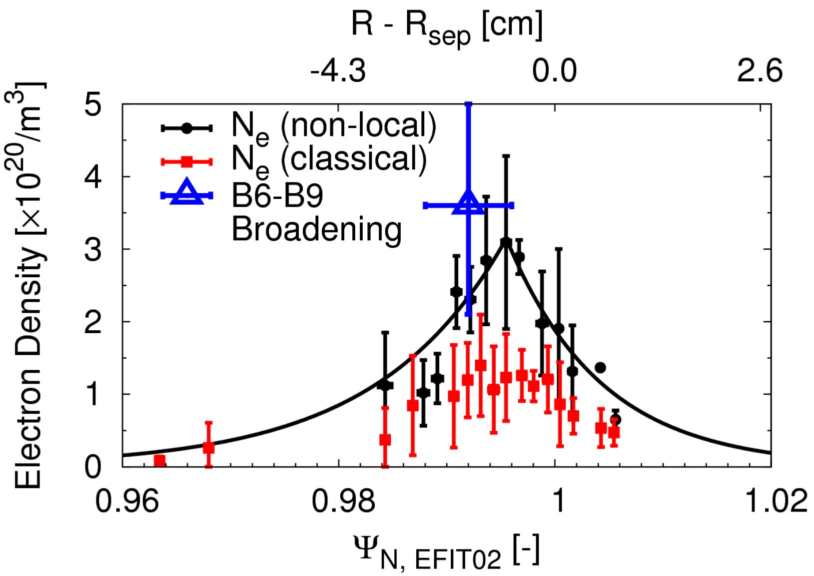
Divertor spectrometer view



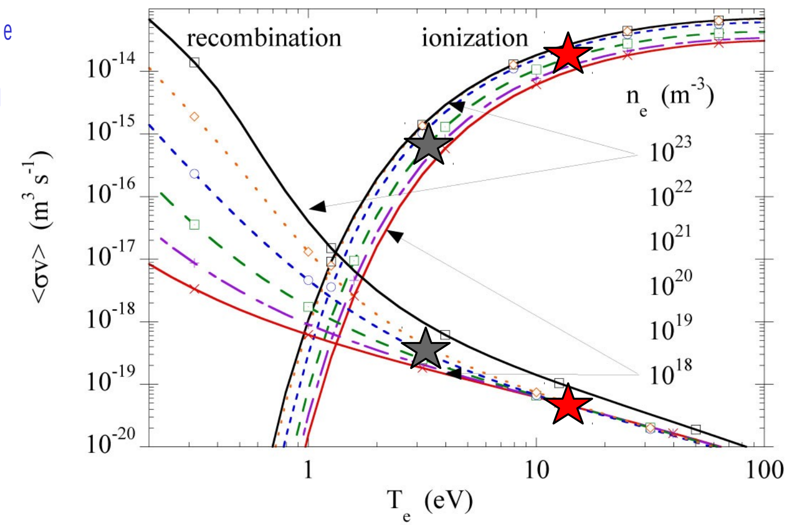
F. Scotti

Spectroscopy consistent with non-local probe interpretation

- Divertor spectrometer viewing strike-point region during discharge
- Deuterium Balmer lines shown in this spectra
- Pressure broadening analysis indicates density of **3.6×10^{20} m^{-3}** (mean, 2.1-5.5x10^{20}m^{-3} min/max)
  - Consistent with non-local calculation for N_e
  - Not consistent with classical interpretation



How significant a difference?
Consider hydrogen rate coefficients determined with collisional-radiative modeling[1]



Probe Method	N_e m^{-3}	T_e eV	S_{eff} m^{3}s^{-1}	R_{eff} m^{3}s^{-1}
Classical	1×10^{20}	15	1.8×10^{-14}	4.2×10^{-20}
Non-local	2×10^{20}	3.2	6.9×10^{-16}	3.0×10^{-19}

[1] DP Stotler, DEGAS 2 User's Manual, 2009

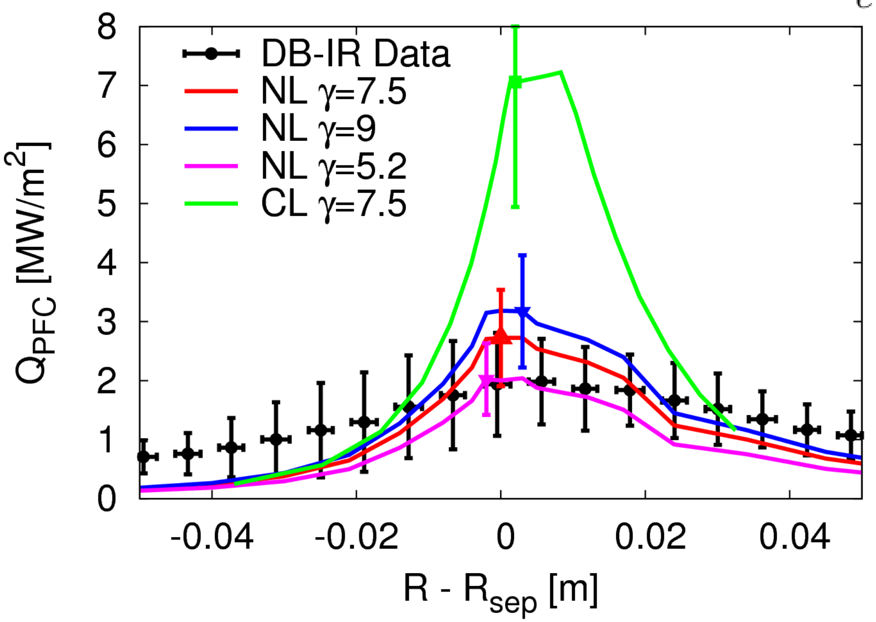
Empirical reconstruction indicates classical values for the sheath heat transmission coeff. obtained with non-local T_e

- Sheath heat transmission coefficient, γ, determines the amount of power transferred to a material surface
  - Fluid theory provides theoretical minimum of 5.2 for D plasma[1]
  - Previous experiments often indicate lower γ (e.g. γ~2)[2,3]
- Calculated γ depends sensitively on T_e
- OEDGE (OSM2 + EIRENE) background plasma created from LP data
  - Total heat flux to PFCs calculated using plasma, neutrals and rad.
  - Bi-modal distribution γ~9 estimated from multi-component plasma
- Dual-band IR heat flux[4] indicates non-local interpretation in better agreement

$$q_{classical} = \gamma \Gamma k T_e = \gamma \frac{j^+_{sat}}{e}(kT_e)$$

$$\gamma(V) = -\frac{eV}{kT_e} + 2.5\frac{T_i}{T_e} + \cdots$$
$$2\left[\left(1+\frac{T_i}{T_e}\right)\left(\frac{2\pi m_e}{m_i}\right)\right]^{-1/2} e^{\frac{eV}{kT_e}}$$

$$\gamma_{min,D} \approx 5.2 \qquad \gamma = \frac{q_{tot}}{\Gamma k T_e}$$

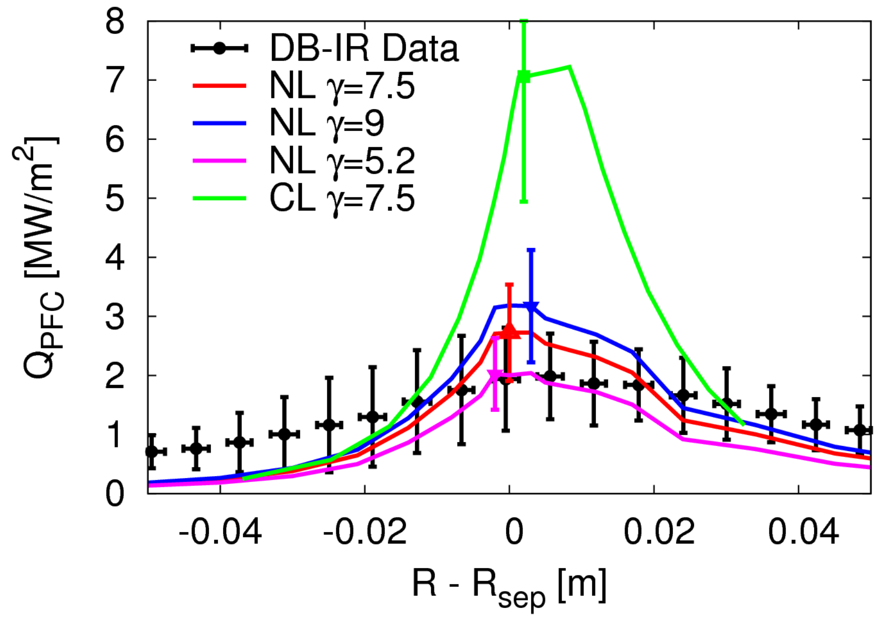


[1] PC Stangeby, 2000, ibid.; [2] D Buchenauer, JNM, 1992;
[3] J Kallman, PP9.00043; [4] AG McLean, PP9.00069

Non-Maxwellian distribution strongly alters T_e calculated and resulting values of sheath heat transmission coeff.

- I-V interpretation below V_f only captures high-energy population of distribution
  - Tail population determines classical result for T_e
  - Assumption of single Maxwellian over-estimates plasma temperature
- Indicates that an underlying issue in anomalously low sheath heat transmission coefficients is likely the interpretation of the probe characteristic
  - Originally proposed by PC Stangeby in 1995
- Uncertainty in analysis is unable to determine γ definitively, but values above theoretical minimum are obtained
  - Classical T_e yields γ~2 here

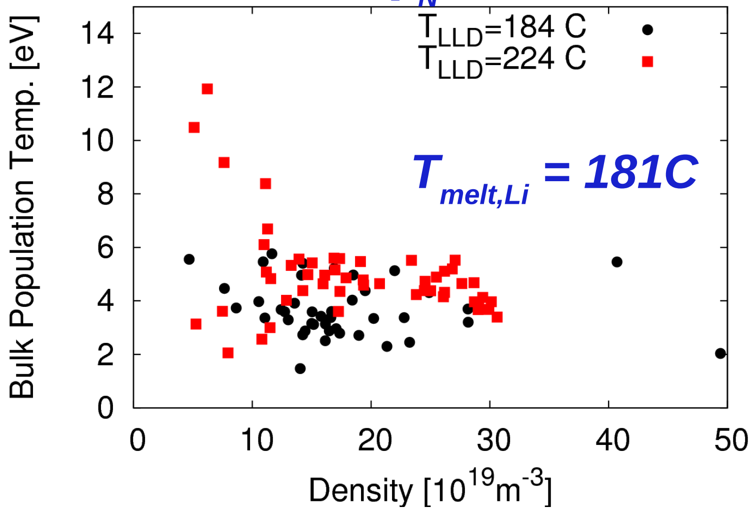
$$\gamma = \frac{q_{tot}}{\Gamma k T_e}$$

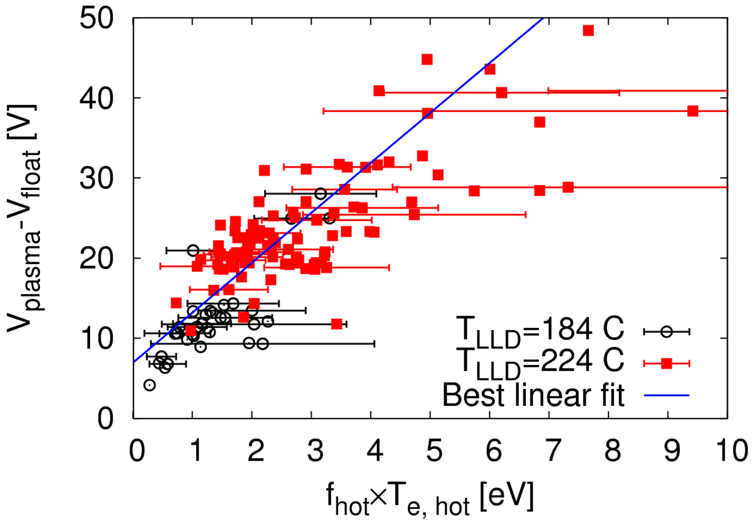


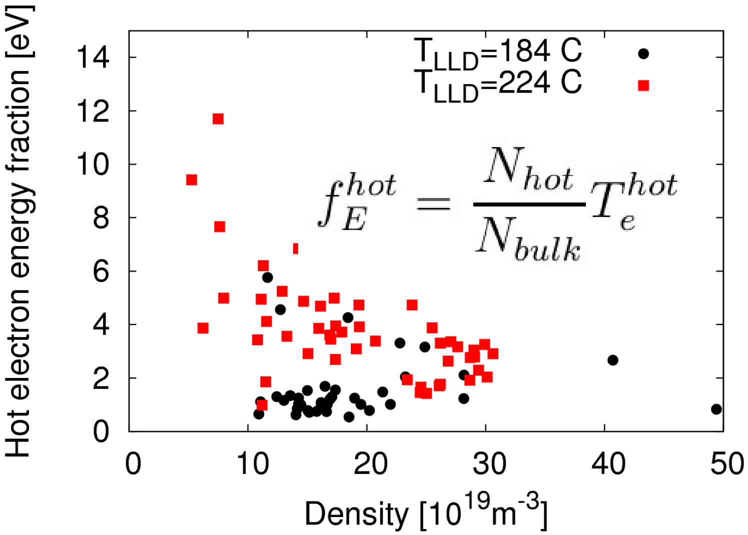
Distribution function analysis indicates increased electron temperatures during operation on plasma-heated LLD

- Discharge sequence repeatedly heated and plasma-conditioned the LLD surface
- Local plasma temperatures elevated with hotter LLD surface temperature ($T_{LLD} > T_{melt,Li}$)
- Increase in plasma temperatures correlated with increase in V_p-V_f potential difference[1]
- Understanding the changes during lithium experiments requires us to first find some model for the non-Maxwellian distributions...

Comparisons made on identical ψ_N locations



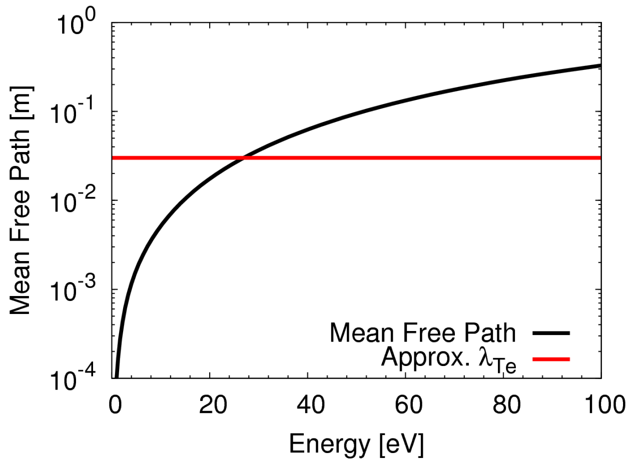




[1]*Jaworski, 2nd Int. Lithium Symp. on Fusion Appl., 2011.*

Non-local electron transport models developed for high gradient regions can be applied to tokamak SOL

- "Non-local" transport occurs when collisional scale lengths become long compared to gradient scale lengths
  - Electrons from high temperature regions reach low temperature regions with few collisions
- Simple Krook model developed for laser-produced plasmas[1]
  - Dist. function split into isotropic and anisotropic portions (f_0, f_1)
  - Coordinate transform allows reduction to single ODE in f_1
- Solution depends on scale parameter *k*
- Can be solved with Green's functions



$$\frac{1}{3}v\frac{\partial f_1}{\partial x} - \frac{1}{3}\frac{eE}{m}\frac{\partial f_1}{\partial v} = -\nu_e(f_0 - f_m)$$

$$y = x \qquad W = 1/2mv^2 - e\phi$$

$$\frac{\sqrt{2(W+e\phi)/m}}{(\nu_e+\nu_i)}\frac{\partial}{\partial y}\left[\frac{1}{3\nu_e}\sqrt{2(W+e\phi)/m}\right]\frac{\partial f_1}{\partial y} - f_1 = \frac{\sqrt{2(W+e\phi)/m}}{(\nu_e+\nu_i)}\frac{\partial f_m}{\partial y}$$

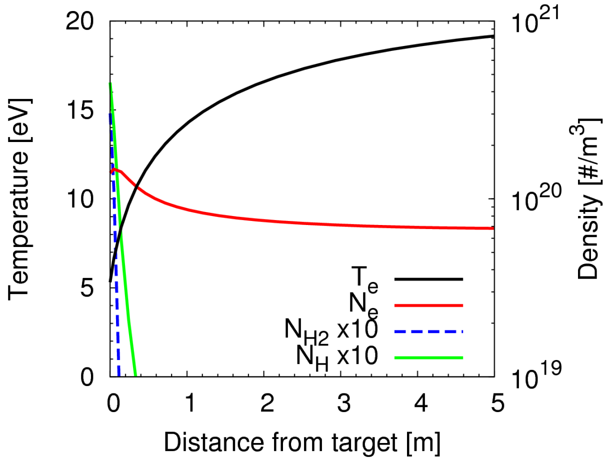
$$k^{-1}\frac{\partial}{\partial y}k^{-1}\frac{\partial}{\partial y}f_1 - f_1 = S$$

$$k(x,v) = \frac{\sqrt{3\nu_{ee}(x,v)[\nu_{ee}(x,v)+\nu_{ei}(x,v)]}}{v}$$

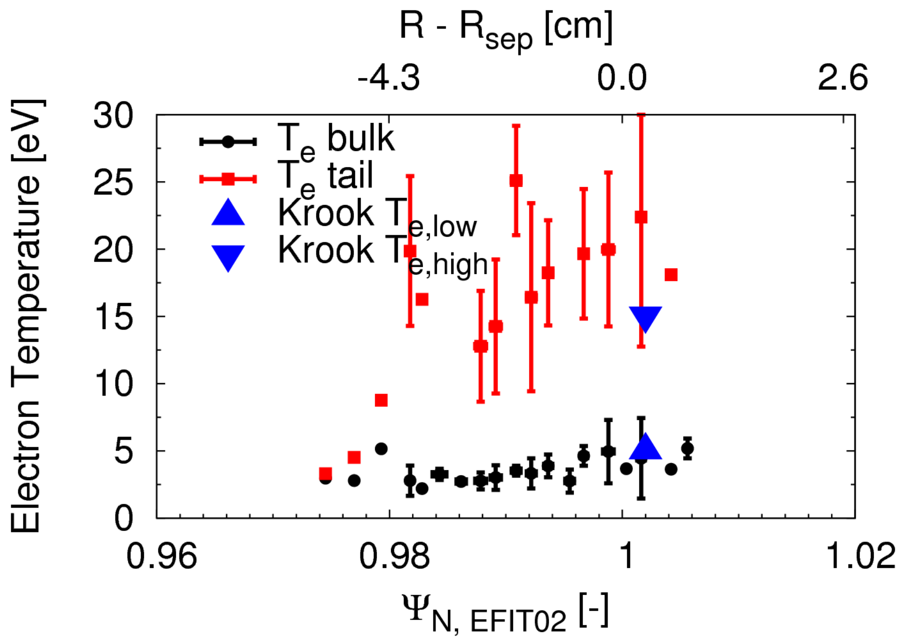
[1] Mannheimer, PoP, 2008; See also YI3:00003 Friday

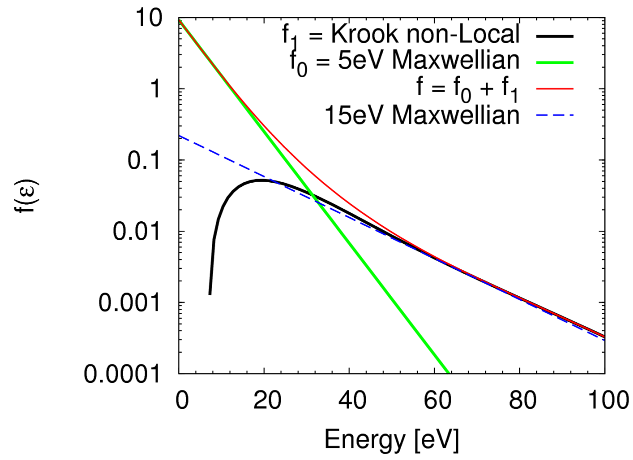
Krook non-local transport model reproduces bi-modal distribution temperatures

- Fluid plasma profile used as background
  - Fluid solution obtained with OEDGE
  - Convolution over space determines resulting distribution
- Mannheimer Krook model reproduces the bi-modal structure and temperatures observed with the Langmuir probe



$$f_1(x,v) = -\xi \int_{-\infty}^{\infty} dx' \frac{1}{2} k(x',v) \times \exp\left[-\left| \int_{-x'}^{x} k(x'',v)dx'' \right| f_{1L}(x',v) \right]$$





Summary and Conclusions

- "Classical" interpretation of Langmuir probes prone to inconsistencies with other diagnostics
- Non-local probe interpretation is applied to these discharges
  - Non-Maxwellian distributions have been inferred
  - Bi-modal structure with a cooler bulk plasma often the best model for the data
- Comparison with other diagnostics indicates better agreement with non-local interpretation than with classical interpretation
  - Spectroscopic line broadening, high-N lines
  - Resulting heat fluxes indicate classical SHTC in reasonable agreement with data
- Distribution function found to vary during lithium experiments
  - Increase in plasma temperature found in both the cool, bulk plasma as well as the tail population
- Krook model for non-local transport applied using background fluid solution obtained using empirical plasma reconstruction
  - Krook model reproduces observed bi-modal distribution temperatures
- Application of PIC simulations underway...

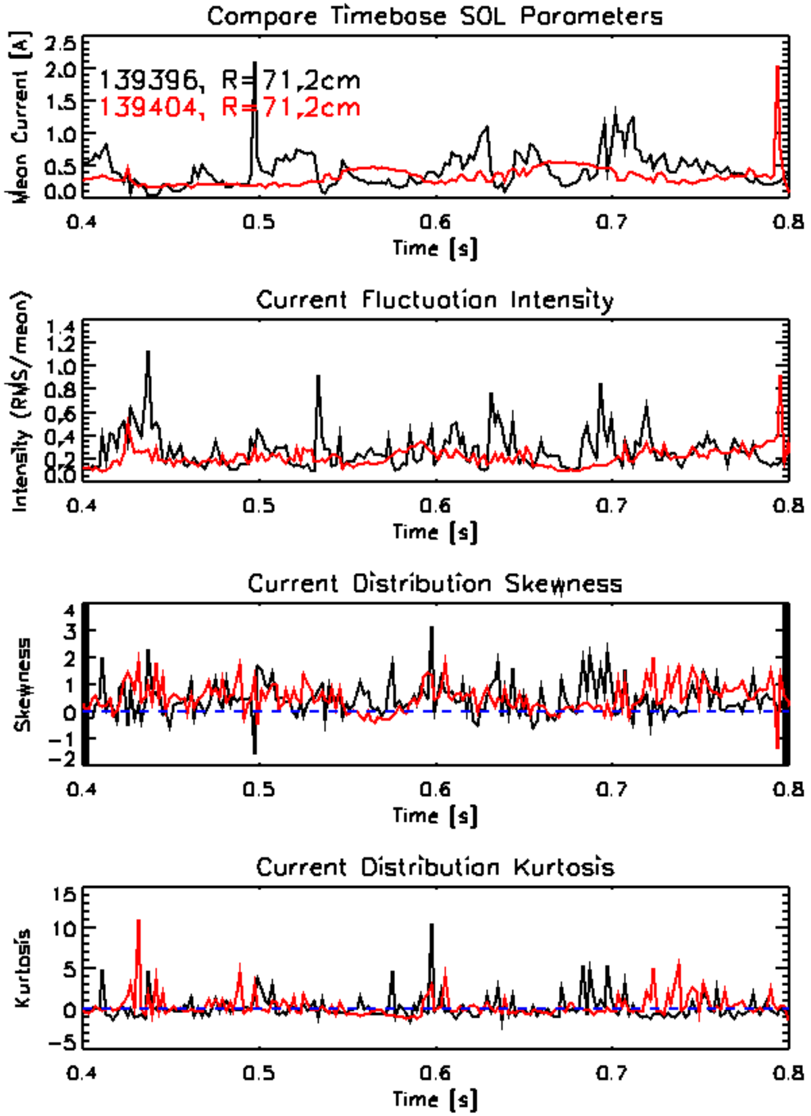
Thank you

This work supported on Department of Energy contract:
DE-AC02-09CH11466

Backups

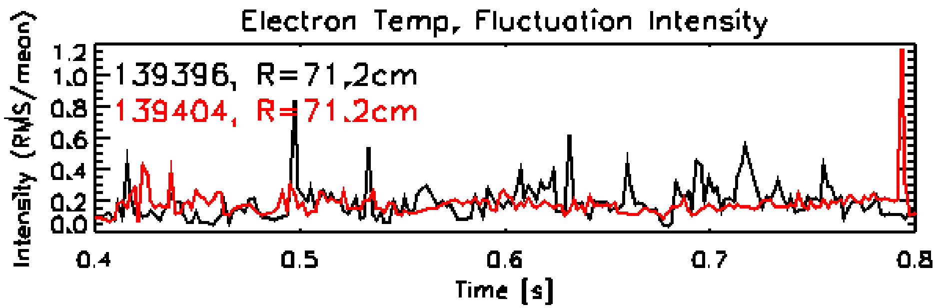
Fluctuations remain at similar levels in the two discharges

- Fluctuations are present in both discharges
  - Measured with Triple Langmuir probes within 1cm of swept probe
  - Non-local analysis limited to Gaussian PDFs
  - This is most easily obtained near strike-point as turbulence increases in the far-SOL
- However, fluctuation characteristics are nearly identical in the two discharges (RMS, skewness, kurtosis) yet the hot electron energy fraction increased
  - While fluctuations may be responsible for some of the EEDF shape, they cannot be the only component

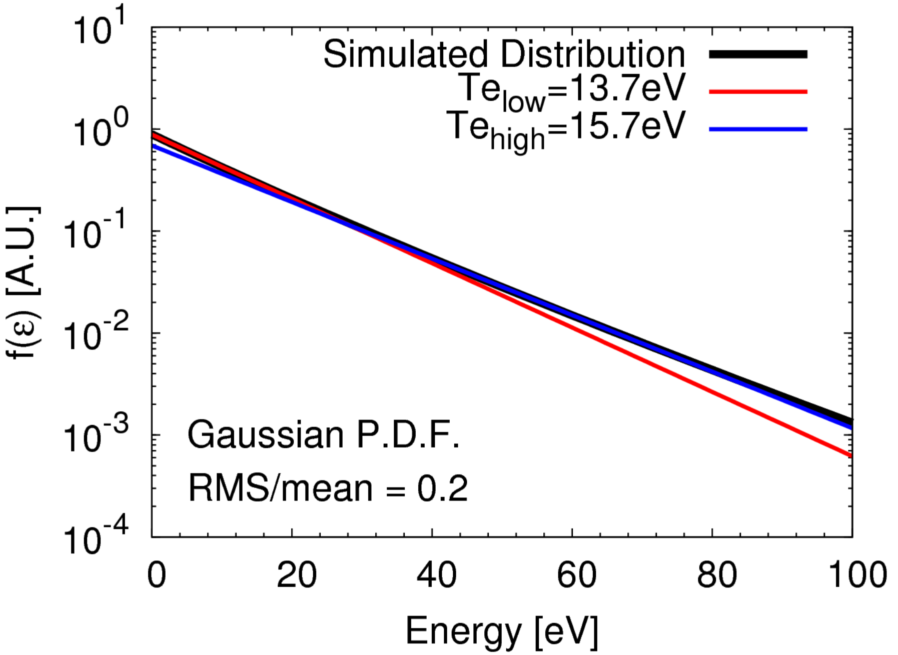


Simulated distribution via summation of Maxwellians does not reproduce observations as well as Krook model

- Consider a fluctuating plasma that is made of fully Maxwellianized portions
  - Triple Langmuir probes provide measure of T_e equivalent to classical interpretation[1]
  - Probability distribution function, φ, best modeled as Gaussian distribution of temperatures
- Using the measured fluctuation RMS, very little range in fitted T_e is found
  - Can only reproduce observed bi-modal structure if bi-modal temperature distribution used for PDF
  - However, near-SOL plasma does not have RMS/mean ~4 needed to match EEDF observations



$$f_{fluct.} = \sum_{i}^{N} \phi_i(\mu_T, \sigma_T) f_m(T_i)$$



[1]Jaworski, RSI, 2010.

CR-model and OEDGE solution indicate spectroscopic lines consistent with non-local bulk temperature

- Collisional-radiative model by DP Stotler provides excited states up to n=9
  - Local contribution estimated from plasma background density of 3e20m^{-3}
  - Contribution from neutrals obtained from EIRENE peak density at target plate
  - CR model assumes Maxwellian elec.
  - A_{ij} values obtained from NIST
- Line strengths normalized to B6 line intensity from spectrometer
- Preliminary comparison with data is encouraging
  - Re-calculation with measured distribution function will provide more consistent model