Progress in Empirical Plasma Reconstruction of the NSTX Divertor

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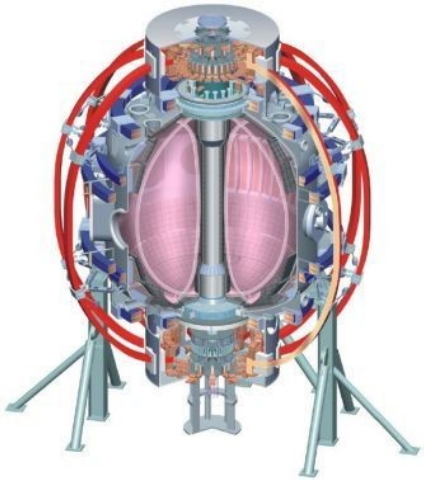


Outline of material

- Description of empirical plasma reconstruction
- Langmuir probe overview and interpretation in NSTX
  - Classical method
  - Non-local method
- OEDGE modeling results and comparison with other diagnostics
- Discussion and next-steps

What is empirical plasma reconstruction?

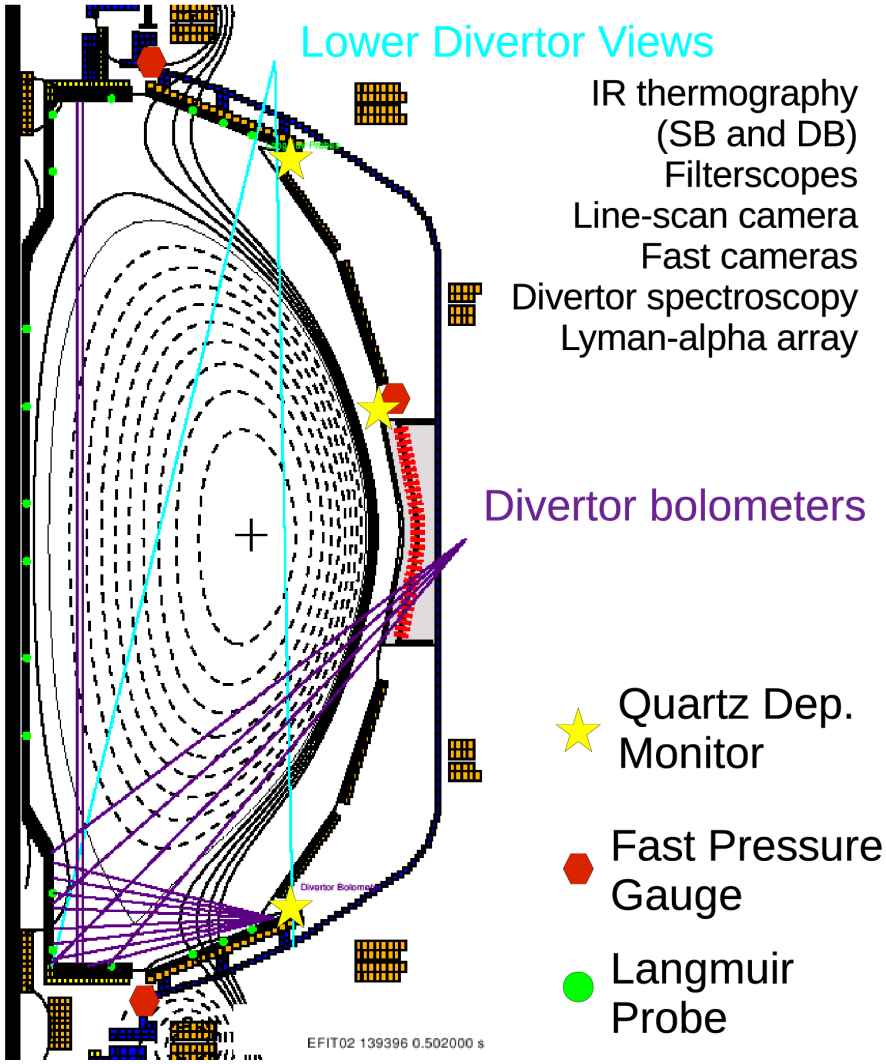
- Measurements in the SOL and divertor often widely spaced spatially – how does one relate measurements in different areas of the machine?
- Plasma model is utilized to produce single, self-consistent (if possible) background plasma for comparison to measurements at different locations
- Empirical plasma reconstruction utilizes a “bottom-up” approach
  - Take target data and integrate up along field lines – generalized two-point method
  - Can extract transport coefficients from resulting plasma
  - Can prescribe plasmas otherwise difficult to model (e.g. detached operation)
- Fluid code methods typically utilize “top-down” approach
  - Define power input at core boundary, solve 2D fluid equations
  - Specify transport coefficients
- Both methods produce overall picture of the plasma that can be compared to experimental measurements

OEDGE interpretative modeling code

- OEDGE: OSM (Onion-skin Method) + EIRENE + DIVIMP
  - Developed by U. Toronto Group (PC Stangeby and JD Elder)
  - Previously used on JET, C-MOD, DIII-D, MAST
- Onion-skin method
  - 1D integration of fluid equations along field-lines
  - Simultaneous solution of particle, momentum and energy equations for ions and electrons
  - **Relies on target data as input**, coupled to EIRENE
- EIRENE
  - Hydrogenic neutral transport code (developed by D Reiter)
  - Uses Monte Carlo methods to calculate transport
- DIVIMP
  - Impurity neutral and ion transport code (U Toronto)
  - Uses Monte Carlo methods – specified cross-field coefficients, classical parallel transport

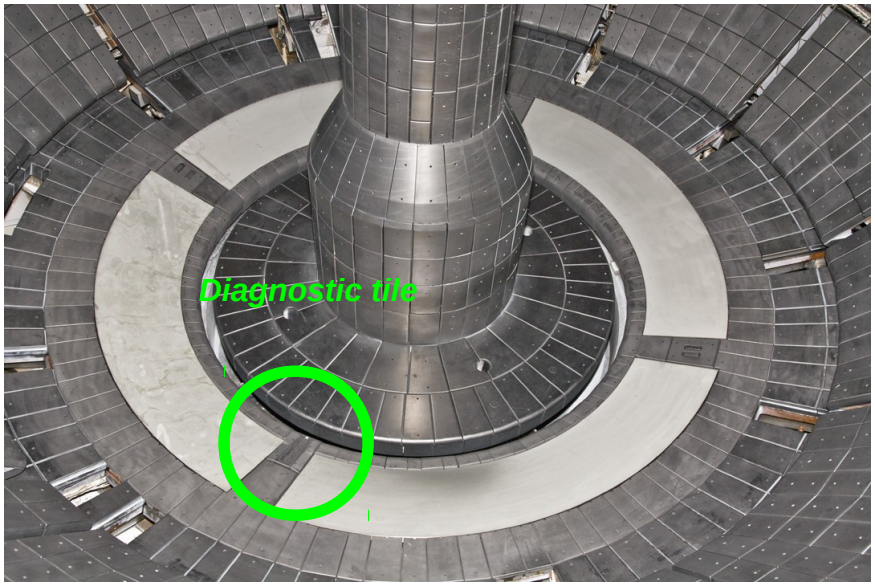
Empirical reconstruction applied to NSTX

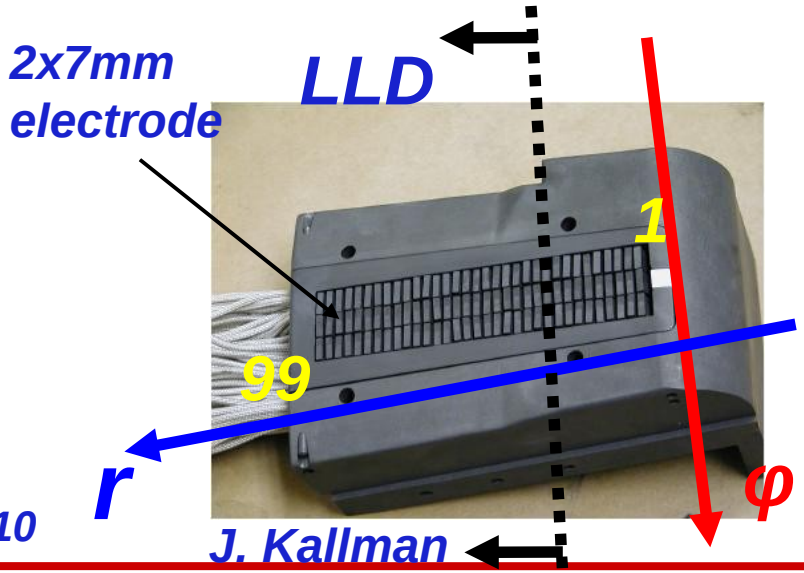
- Empirical reconstruction improves as the background is constrained with more and more data
- **Provides framework for combining measurements and checking consistency between diagnostics**
- Have begun comparing and constraining with: magnetics, Langmuir probes (target T_e, N_e), IR thermography (target q), midplane Thomson (T_e, N_e), midplane CHERS (T_i)
- Still to be included: pressure gauges, spectroscopy, bolometers, QDMs...
- First use: validate probe interpretation methods



High-density Langmuir probe array in NSTX

- Situated between liquid lithium divertor plate segments
- Provides coverage over graphite and LLD PFCs
- Electronics developed for flexibility, speed and accuracy (U-Illinois collaboration)
- Provides high spatial density measurements of local plasma conditions
- Interpretation of Langmuir probes common issue

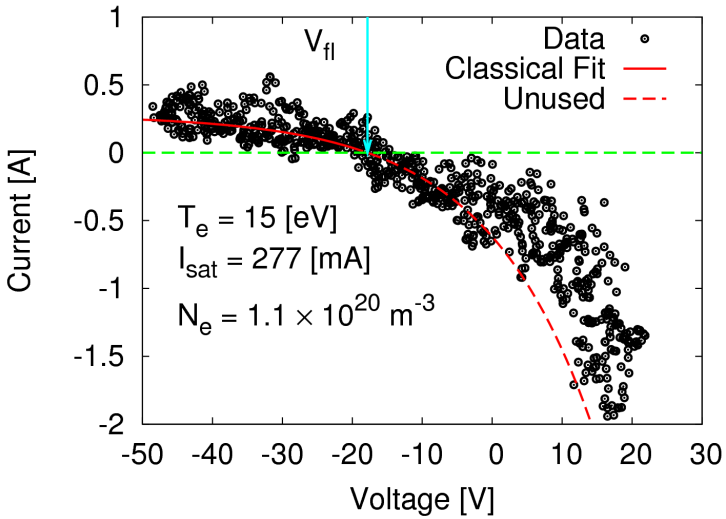


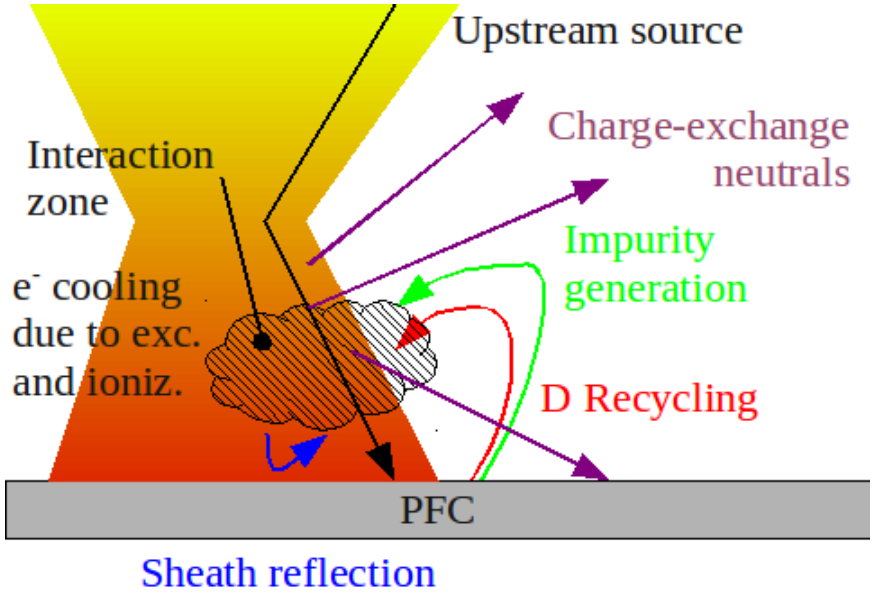


J. Kallman, RSI 2010
M.A. Jaworski, RSI 2010

The "classical" method of interpreting a probe

- Classical interpretation makes use of data up to floating potential (Tagle, **PPCF**, 1997; Matthews, **PPCF**, 1994)
- Historically, Langmuir probes yield high temperatures relative to other diagnostics
  - G. Fussman, **JNM**, 1984 – Asdex Thomson system (indications of non-Maxwellian distr.)
  - J. Watkins, **JNM**, 2000 – DIII-D comparison with DTS (LP consistently low)
  - A. Futch, **JNM**, 1992 – anomalously low sheath heat transmission coeff.
  - PC Stangeby, **PPCF**, 1995 – proposed SHTC calculations resulting from non-Maxwellian EEDFs
- Significant payoff if properly assessed as T_e indicative of myriad processes in SOL





Physics available from probe measurements

- Local plasma conditions determine most of the processes impacting the PFC
  - Surface heat flux determined by local plasma
  - Sputtering determined by incident flux and impact energy
  - Ionization rates of hydrogen and impurities determined by local plasma
- Langmuir probes can provide some of these parameters
  - I_{sat}, V_f directly measured
  - T_e, N_e interpreted from I-V characteristic
  - More advanced probe interpretations can yield more information

Heat flux to a biased PFC

$$V_f \neq 0$$

$$q_{surface}(V) \equiv \gamma(V) k T_e \Gamma$$

$$\gamma(V) = -\frac{eV}{T_e} + 2.5\frac{T_i}{T_e} + \cdots$$

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

See also: D. Donovan – this session

Physical sputtering Yield

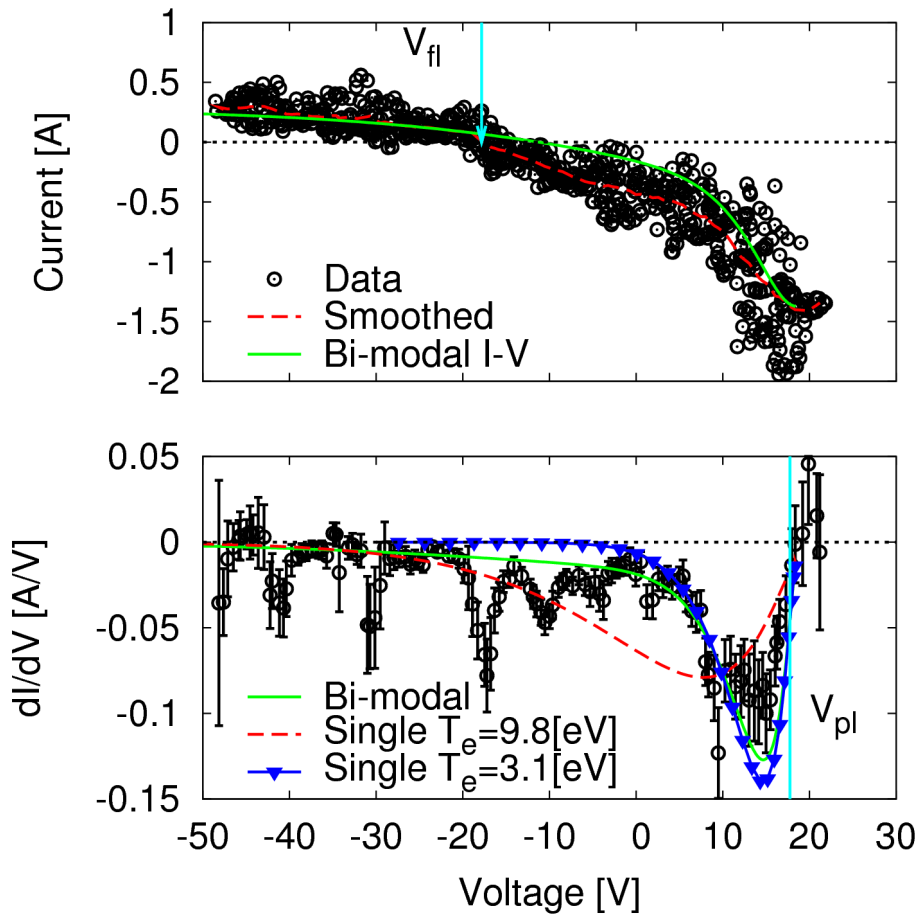
$$Y_{sputt.} = Y(M_{tar.}, M_{inc.}, E_0, \text{matl.prop.})$$

$$E_0 = V_p + E_i \approx \underbrace{3kT_e + 2kT_i}_{?} \approx \underbrace{5kT_e}_{???}$$

Novel probe interpretation enables calculations of EEDF

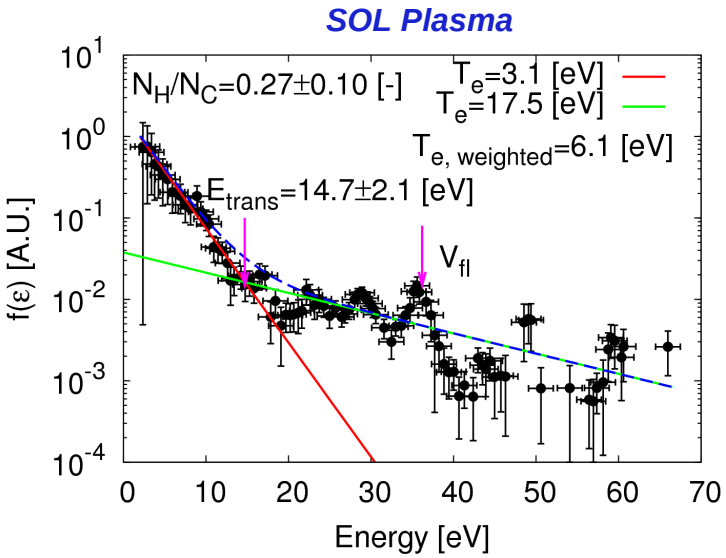
- Recent developments open a means to interpret the entire transition region of electron current
- So-called, first derivative method relies on “non-local” probe regime
- Approximate form for integral equation developed by Popov and demonstrated on CASTOR (Popov, **PPCF**, 2009)
- At right illustrates the determination of plasma potential from the I-V characteristic and derivative

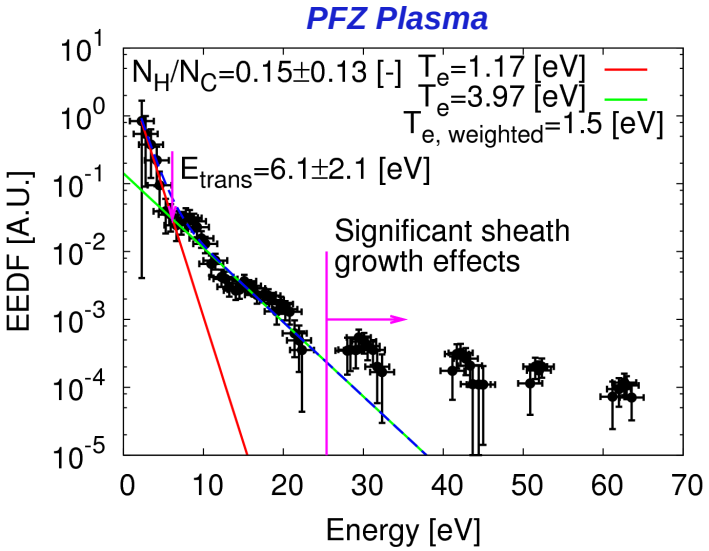
$$I_e(U) = -\frac{8\pi e S}{3m^2}\int \frac{(W-eU)f(W)\,dW}{\gamma(W)\left[1+\frac{(W-eU)}{W}\psi(W)\right]}$$



Bi-modal plasmas observed in divertor

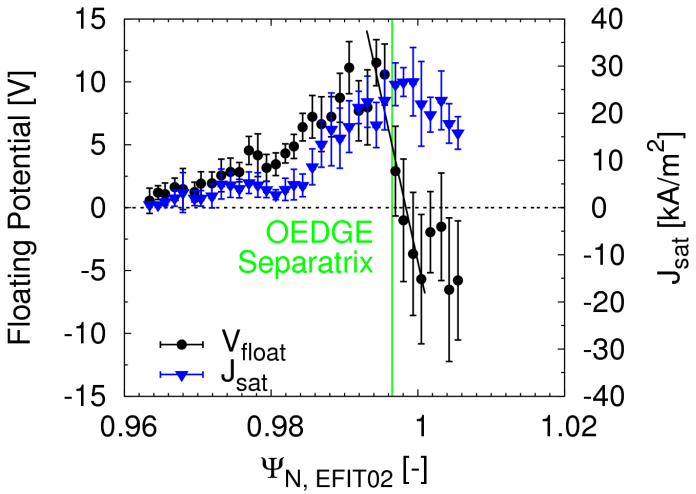
- Two cases shown here: SOL and PFZ plasmas
  - Tail temperature close to calculated value with classical method
  - PFZ plasma just inside the separatrix is dense and cool and may show evidence of recombination
- General features of the plasmas examined so far
  - Bi-modal character common feature
  - Bulk population with lower temperature
- Beginning studies to model the distribution function for comparison with measurements
  - Non-Maxwellian EEDFs predicted by Chodura, **CPP,** 1992 and Batischev, **PoP,** 1997, Tskhakaya, **JNM**, 2010 with kinetic codes
- **...but can we provide independent evidence that this interpretation method is valid?**

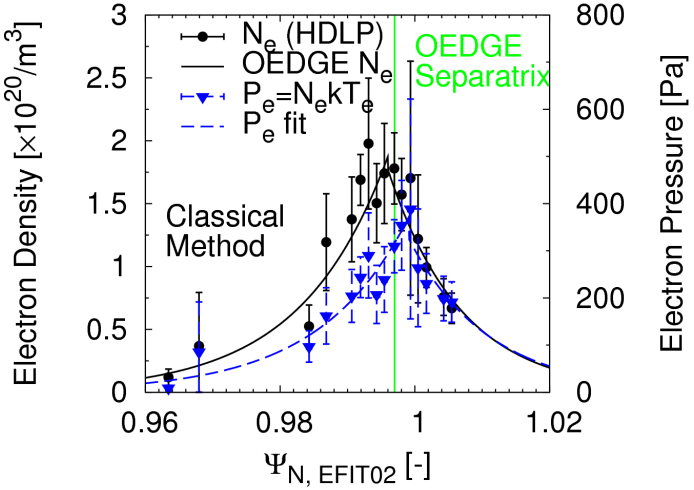


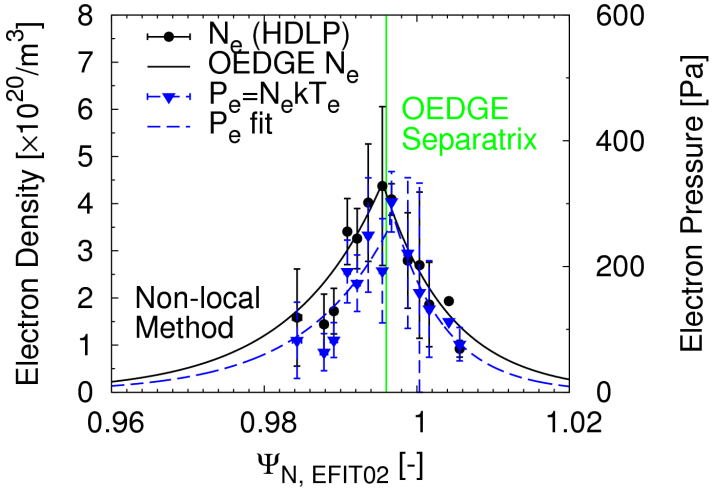


Langmuir probe input data: Classical vs. Non-local 1

- V_f and J_{sat} are fundamental data
- Steep descent in V_f used to identify separatrix location (*c.f.* Watkins, **JNM**, 1997) – corresponds to peak in pressure profile
- Error bars indicate variability during period of data acquisition – natural strike-point motion produces smooth profile

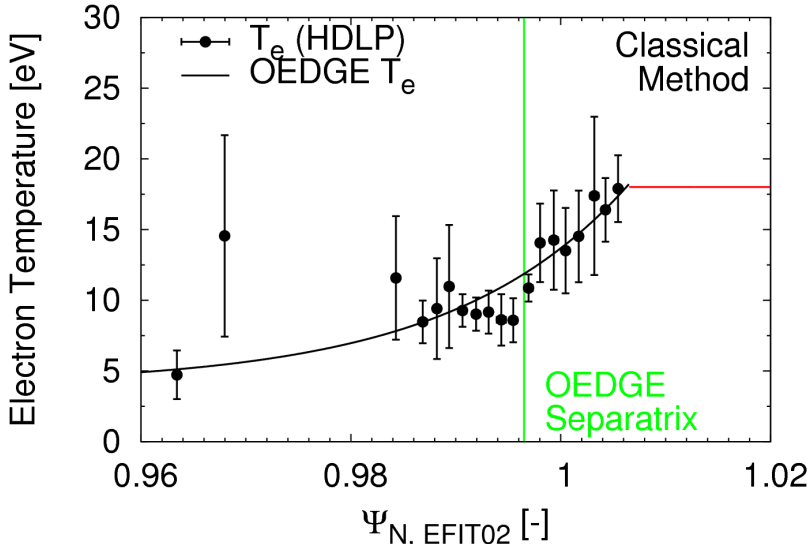


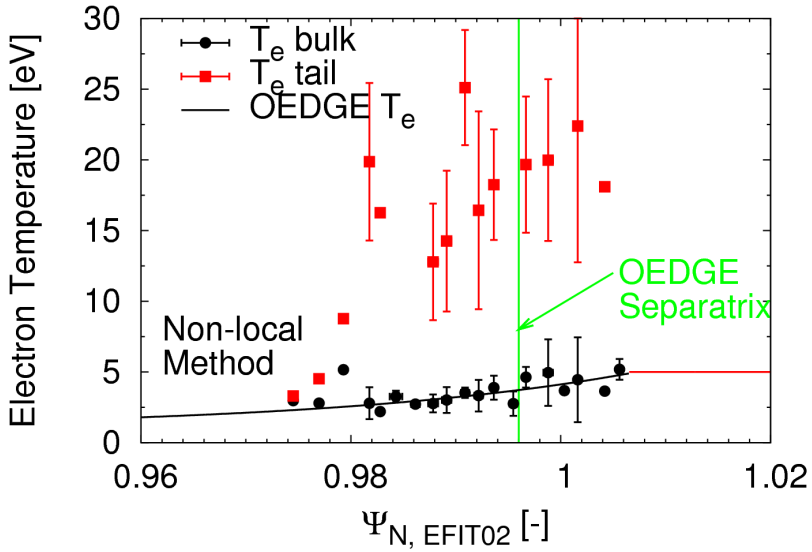




Langmuir probe input data: Classical vs. Non-local 2

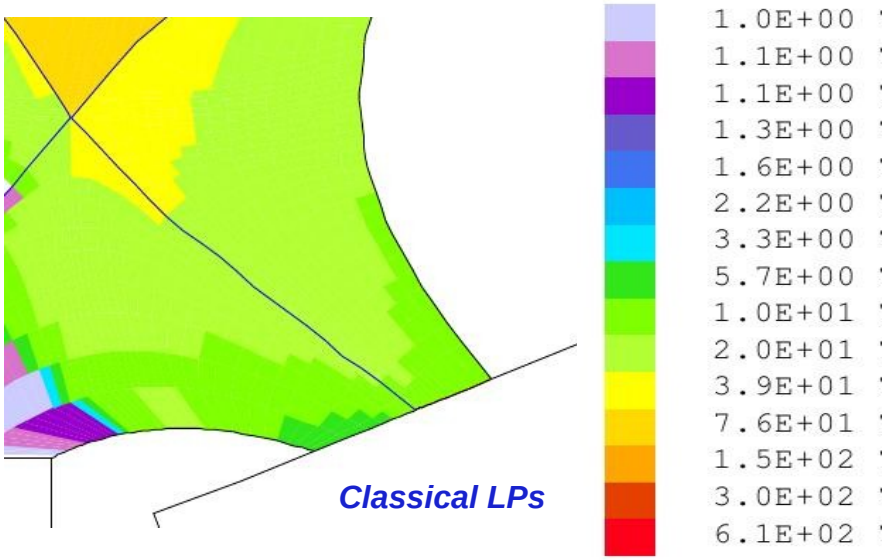
- Density and pressure dependent on T_e calculated from the two methods
- Hot electron population has temperature similar to those obtained by classical method (i.e. about 15-20eV SOL)
- Non-local interpretation indicates bulk plasma is much cooler than classical method would yield (2-5eV vs. 5-15eV)
- Variation in density due to T_e used, also modifies pressure profile slightly
- Both interpretations indicate significant density at target (>1e20)

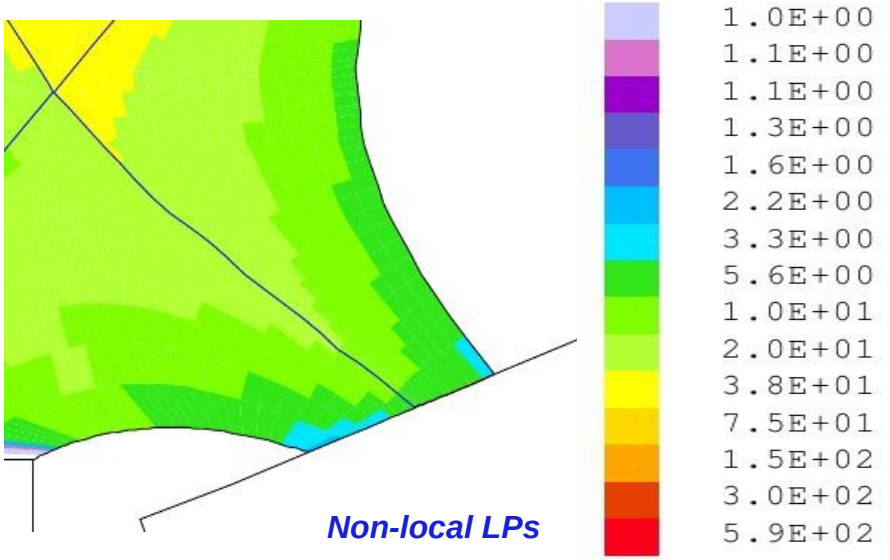




OEDGE Solutions at target

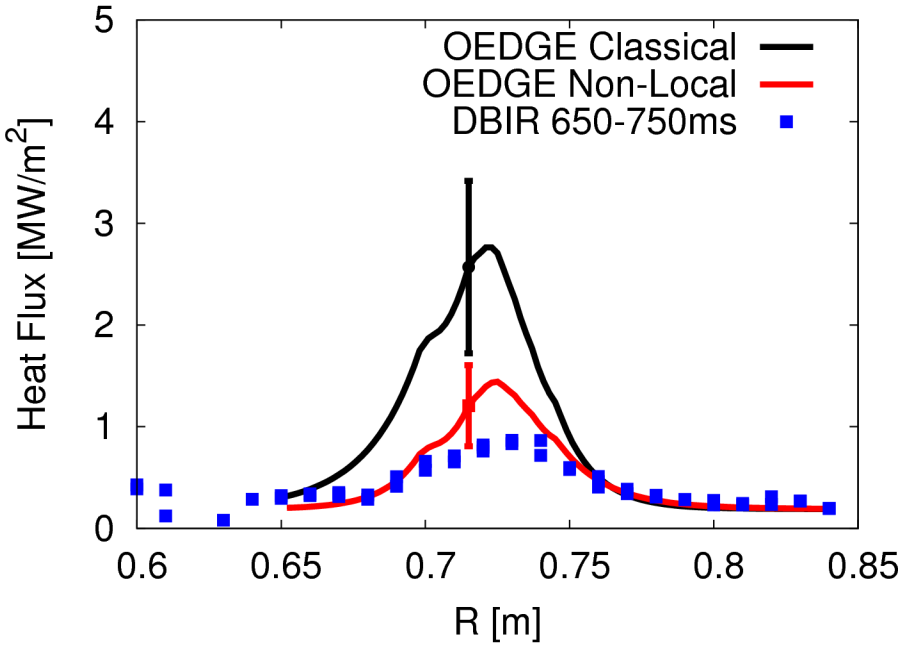
- Solutions shown from OSM+EIRENE
- Based on LP target data only
- Assumes high recycling wall for the time being (will constrain with spectroscopy when available)
- Attached plasma modeled for outer SOL and outer PFZ
  - Focus of this talk is near target and SOL
  - Detachment modeling ongoing on the inboard divertor leg





Non-local interpretation compares better with IR thermography

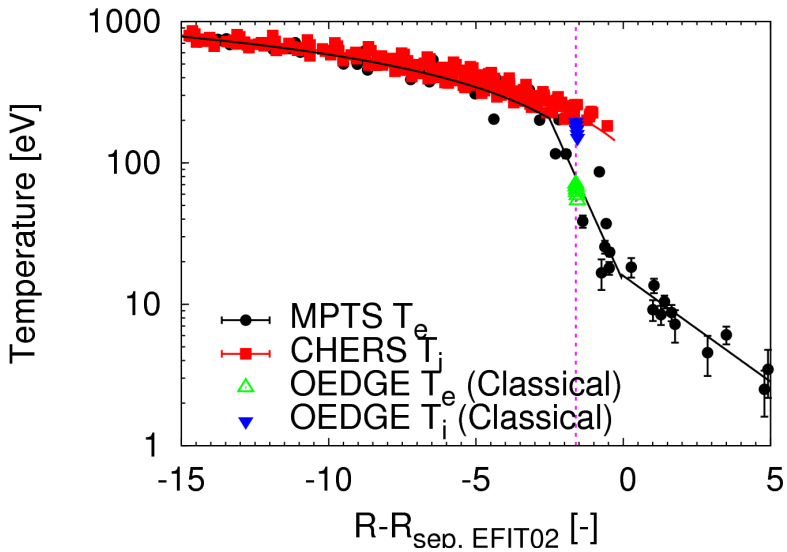
- Applied classical sheath heat transmission coefficient (γ=7.5)
  - I_{sat} common to both cases
  - T_e is the main difference
- Neutral atom heating of the PFC included as well as radiation heating
- Mean target IR profile (on ATJ) over quiescent period shown at right (TK Gray, A McLean, ORNL)
- Non-local interpretation in better agreement with IR thermography
  - Error estimated from LP density variance at present, sensitivity study planned

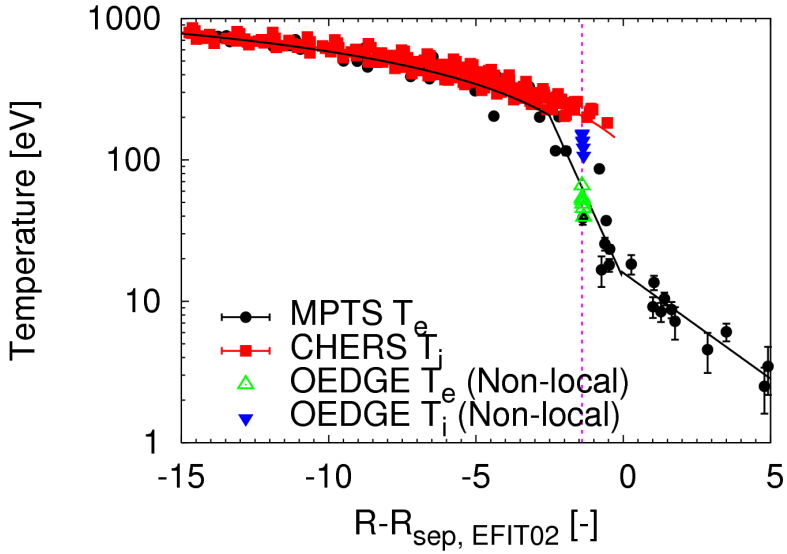


- Neutrals contribute about 30% of the strike-point heating
- Radiation contributes about 20%
- Neither well constrained in the model yet

Comparison to midplane values

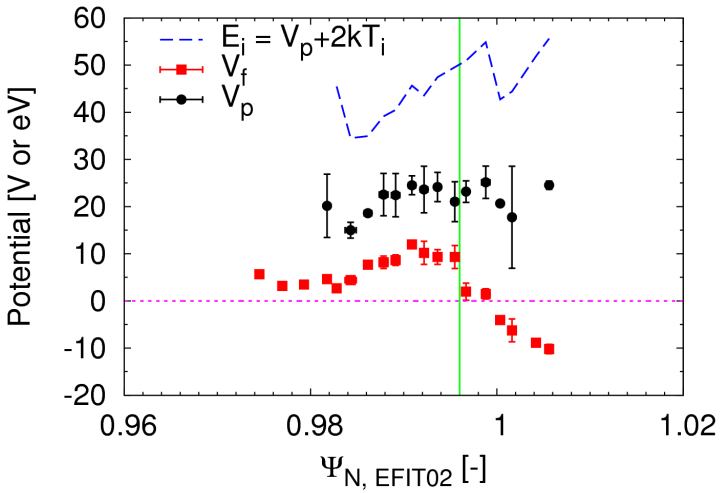
- MPTS and CHERS data provide midplane profiles but only provide "weak" constraints
  - Spatial resolution is low relative to OEDGE mesh
  - OEDGE typically compared to high-spatial resolution diagnostics such as reciprocating probes
- Plasma solution from target yields possible method for improving equilibrium reconstruction
  - Provides means for specifying separatrix temperature with T_e leading to new R_{sep}
- Midplane data indicates T_i/T_e~3
  - These simulations utilize $T_i=T_e$ at the target
  - Implies that $T_{i,targ}>T_{e,targ}$ (Non-local sim.)
  - Classical simulation implies $T_{i,targ}$~10-15eV at the target plate
  - More work needed to further clarify

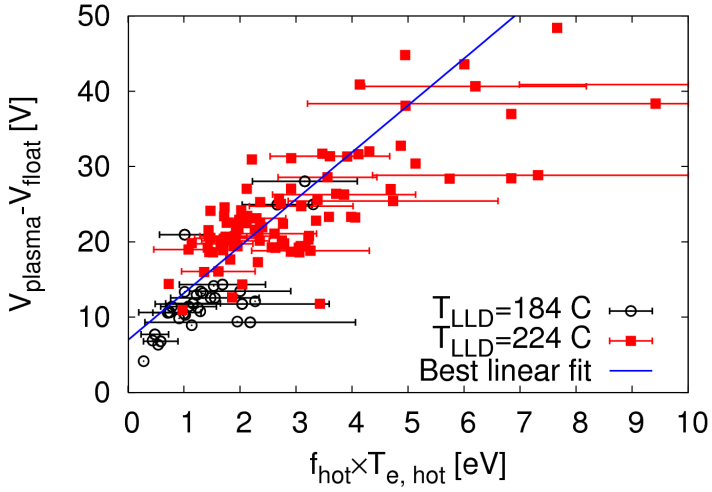




Impact energy estimate and further aspects of EEDFs

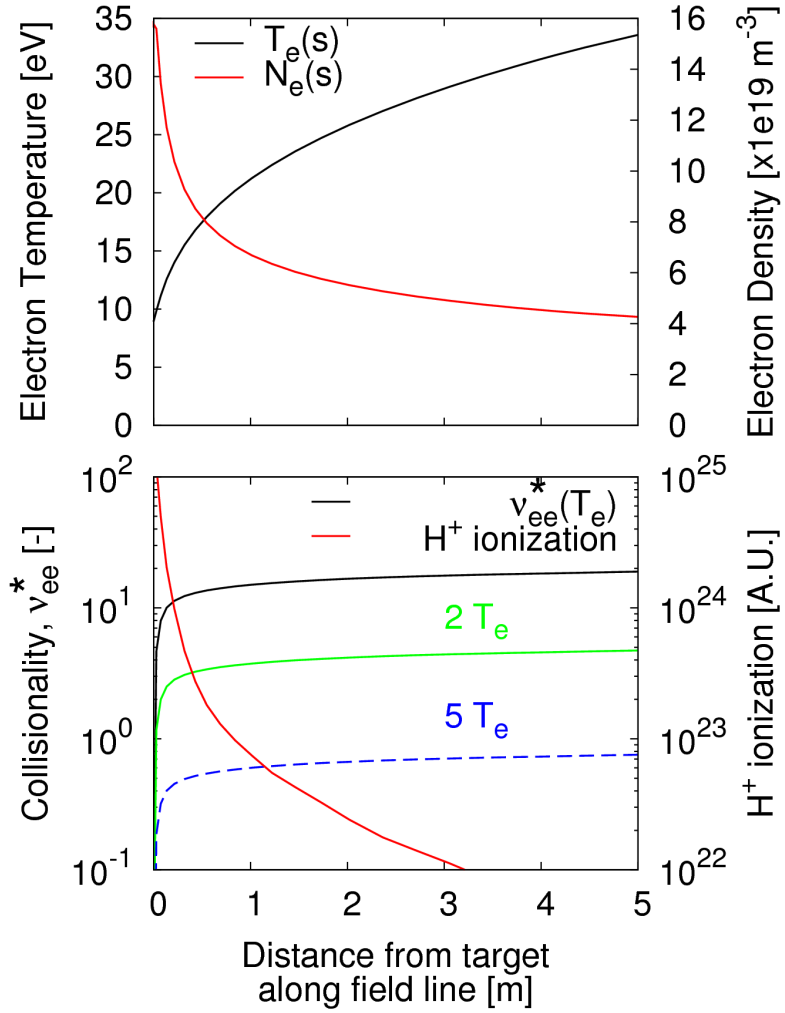
- Ion impact energy can be estimated from the Langmuir probe data and simulations
  - $T_{i,targ}/T_{e,targ}$~3 based on OEDGE simulations
  - V_p obtained from non-local interpretation method
  - E_i ~ 40-50eV (vs. ~25eV for $5T_{e,class}$)
  - Erosion measurements may provide some indication of validity of impact energy estimate
- Inferred EEDF modified during LLD experiments exhibiting reduced fueling efficiency
- Plasma-to-floating potential difference correlated with hot electron energy





Next-steps and further modeling

- More experimental constraints of the divertor plasma will be applied
  - Further refinements will be applied to better evaluate target T_i
  - Sensitivity studies
  - Further experimental tests of non-Maxwellian obs. (e.g. identification of $\lambda_{ioniz.}$)
- OEDGE fluid background will form the starting point for further kinetic modeling
  - Kinetic modeling planned to compare observed EEDFs
  - Non-local gradient effects (Chodura, Batishchev)
  - Atomic physics (Tskhakaya)
  - Fluctuation effects



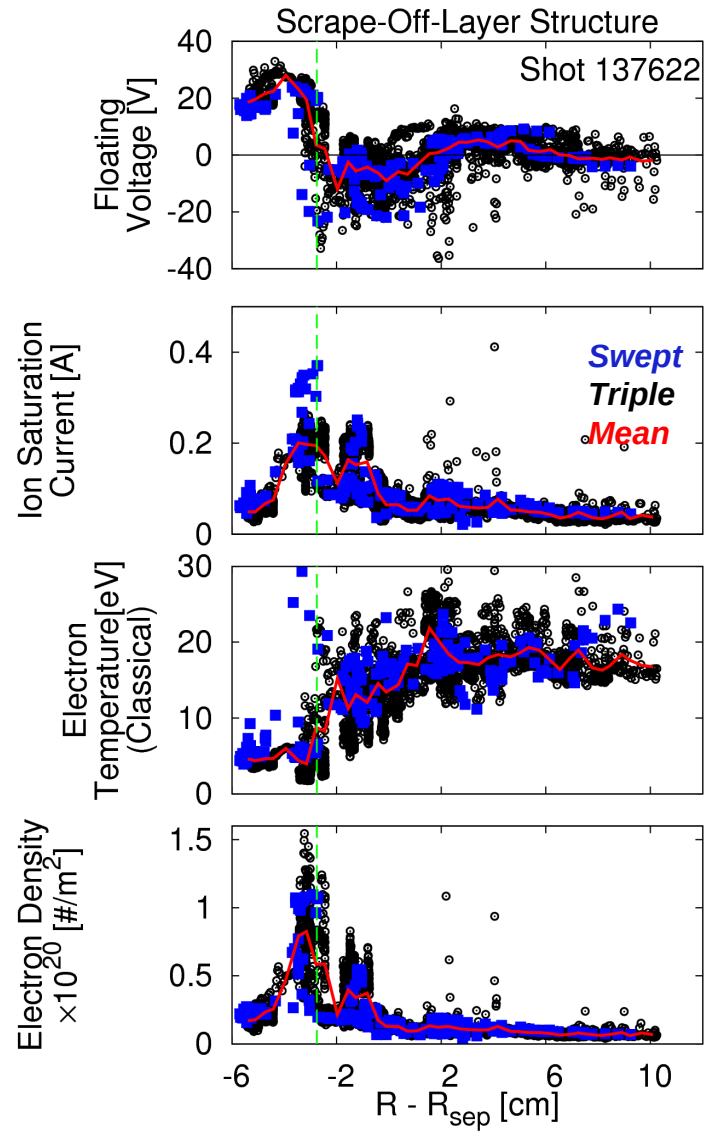
Summary

- Empirical plasma reconstruction described and contrasted with fluid modeling
- Importance of Langmuir probes to OEDGE methodology and implementation on NSTX described
- Non-local interpretation method briefly described and typical analysis result shown (*i.e.* bi-modal distributions)
- OEDGE framework used to compare classical and non-local probe interpretation methods
- **Comparison of IR thermography with OEDGE heat fluxes indicates non-local interpretation method in better agreement**
- Comparison with midplane data imply target ion temperatures ~1-3T_e and D ion impact energy estimated to be about 50eV at target
- Further refinement and modeling is planned to examine the formation of non-Maxwellian EEDFs in the NSTX divertor

Thank you!

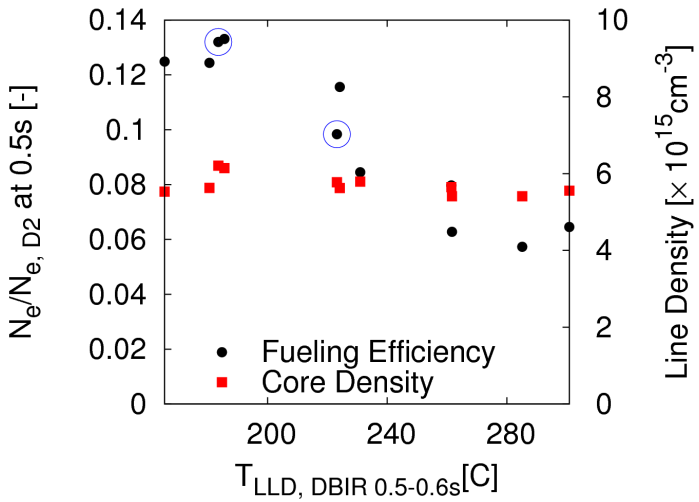
Backup: Classical method can be fast and reveals structure

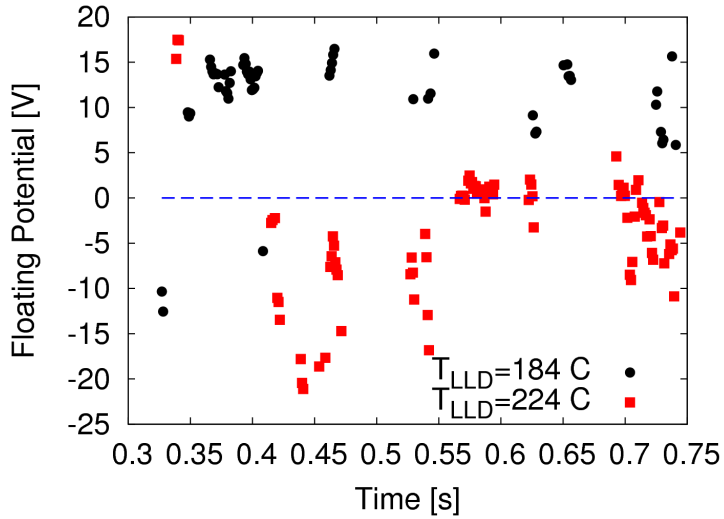
- Simple comparisons from shot to shot often difficult
  - Strong spatial gradients in the SOL result in sensitivity to position
  - Constant plasma motion results in temporal variation
- Methods developed to utilize magnetic equilibrium reconstruction as position reference for probe array
- Provides the means of making comparisons between discharges on magnetic flux surfaces



Backup: Trends in the classical method and machine

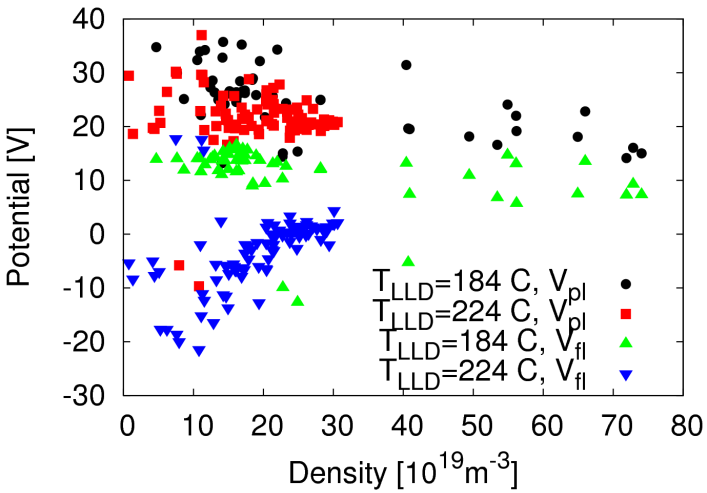
- Experiments in mid-run indicated possible changes in LLD performance
  - Fueling increased will negligible impact on the core
  - LLD heated by the plasma during this sequence
- Two shots in sequence used for comparison avoiding discharges with significant ELM activity
- Observe a significant shift in floating potential with the later and hotter LLD discharges

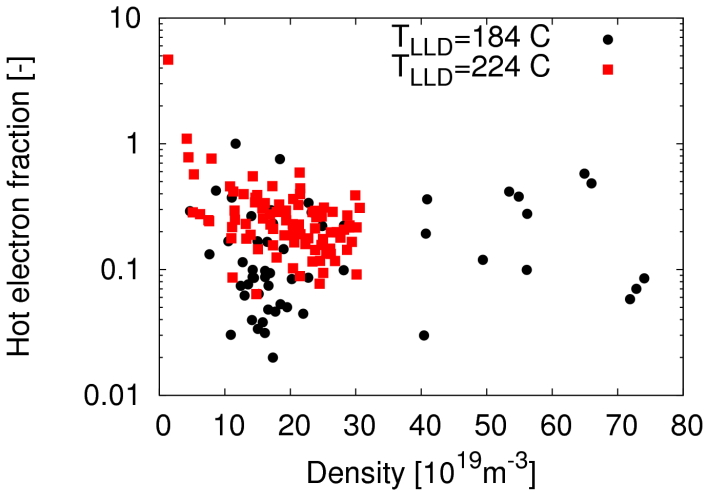




Backup: Increase in temperature due to increase in hot population fraction

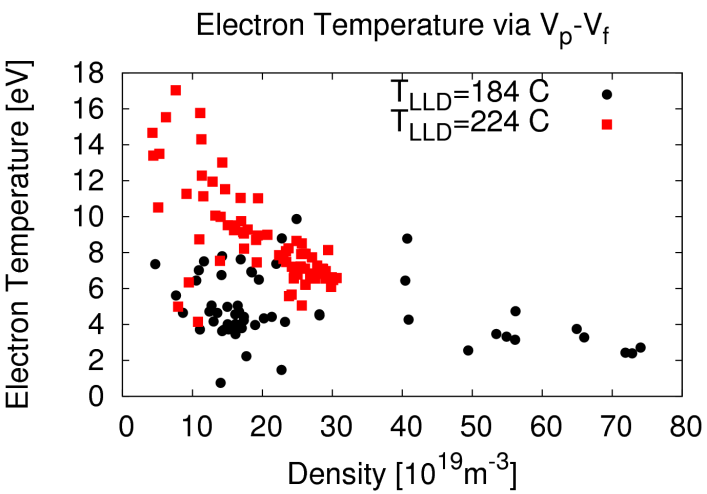
- Increase in the amount of the hot electron population observed in the hotter LLD discharge
  - Could point to reduction in inelastic energy sinks
  - Reduction in gradient effects
  - Both effects suggested in the literature via kinetic codes (Chodura, **CPP**, 1992; Batischev, **PoP**, 1997)
- Plasma potential reduced but not enough to explain the full decrease in floating potential

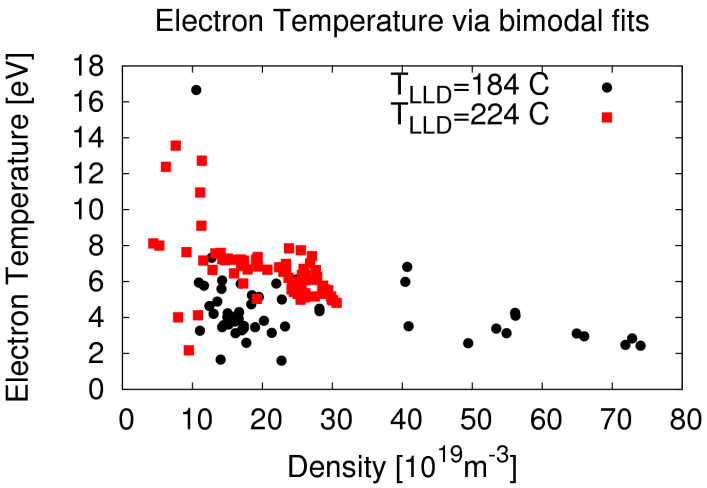


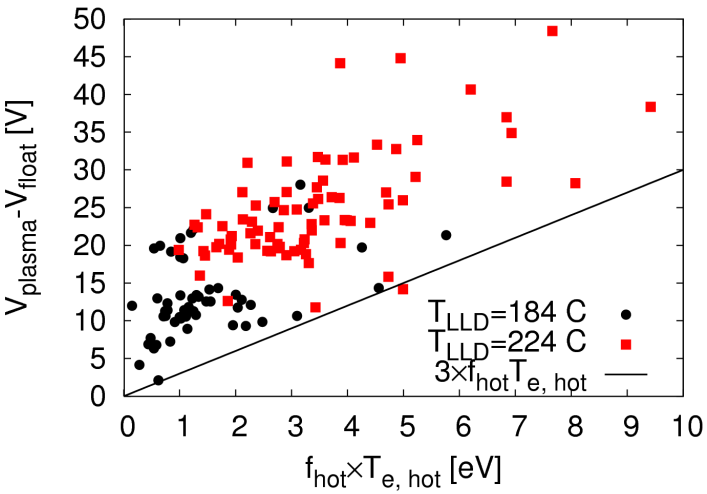
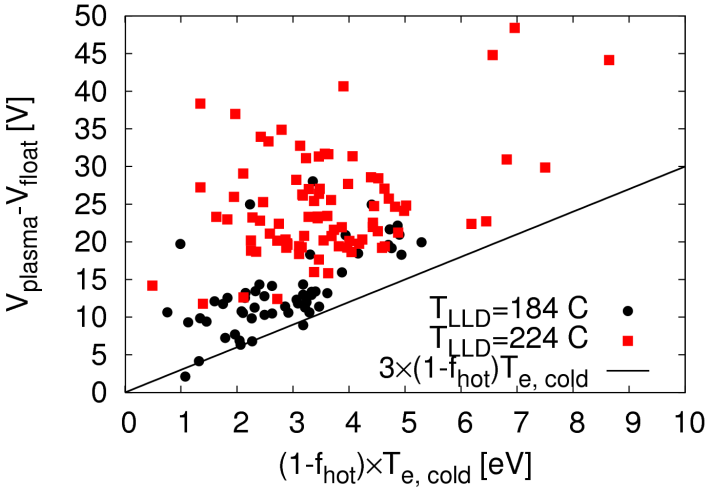
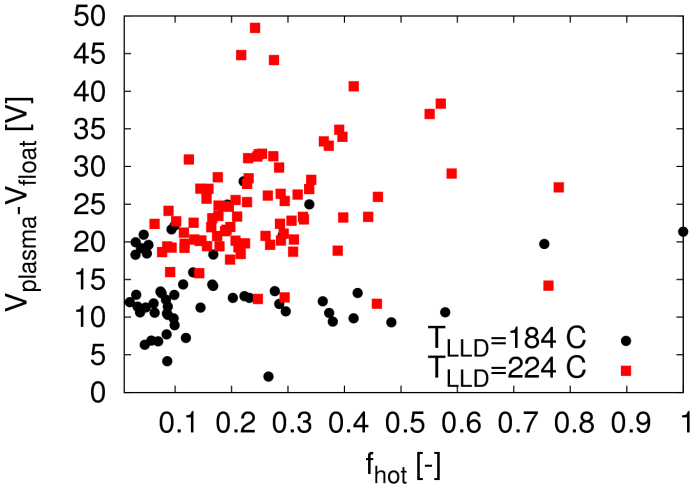


Backup: This comparison of LLD discharges shows an increase in temperature at the divertor target

- Separation observed between two discharges
  - Identical psi surfaces compared here (situated in SOL, outboard of I_{sat} peak)
- Most noticeable change is in the electron temperature channel
- Showing electron temperature calculated from V_p-V_f and calculated from density-weighted bimodal temperatures
  - V_p-V_f method may be susceptible to "beams"
  - Both show increase in T_e with the hotter LLD





Backup: what population determines (V_p-V_f)?

- Both populations play role in determining (V_p-V_f)
- f_{hot}*$T_{e,hot}$ has best correlation to (V_p-V_f)