Effective Sheath Heat Transmission Coefficient in NSTX Discharges with Applied Lithium Coatings

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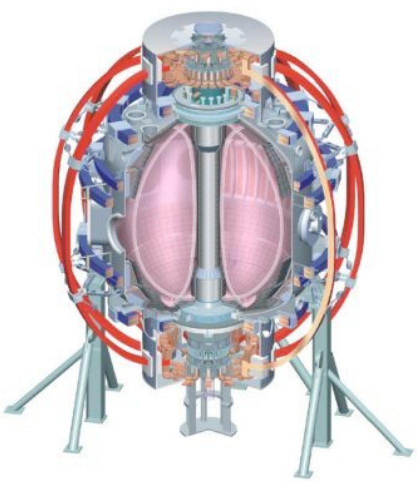

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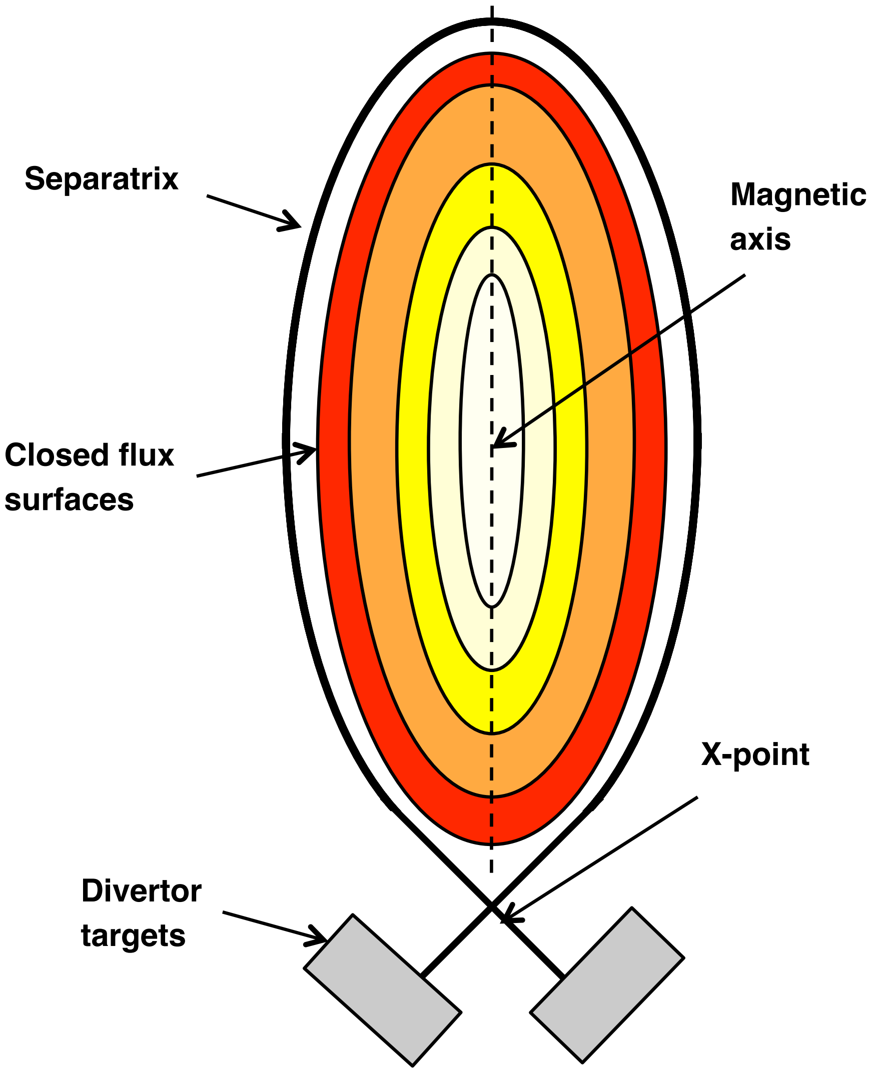
Outline

- The magnetic fusion plasma edge
  - Diverted tokamaks, heat and particle flux
  - Sheath heat transmission
- NSTX and edge measurement capabilities
  - NSTX overview
  - The Liquid Lithium Divertor and associated diagnostics
- Diagnostics for heat flux analysis
  - Dense Langmuir probe array
  - Dual-band IR camera
- Heat flux data and analysis
  - Data acquistion
  - Analysis methods
  - Measurements of sheath heat transmission
- Conclusions and Discussion
- Future work

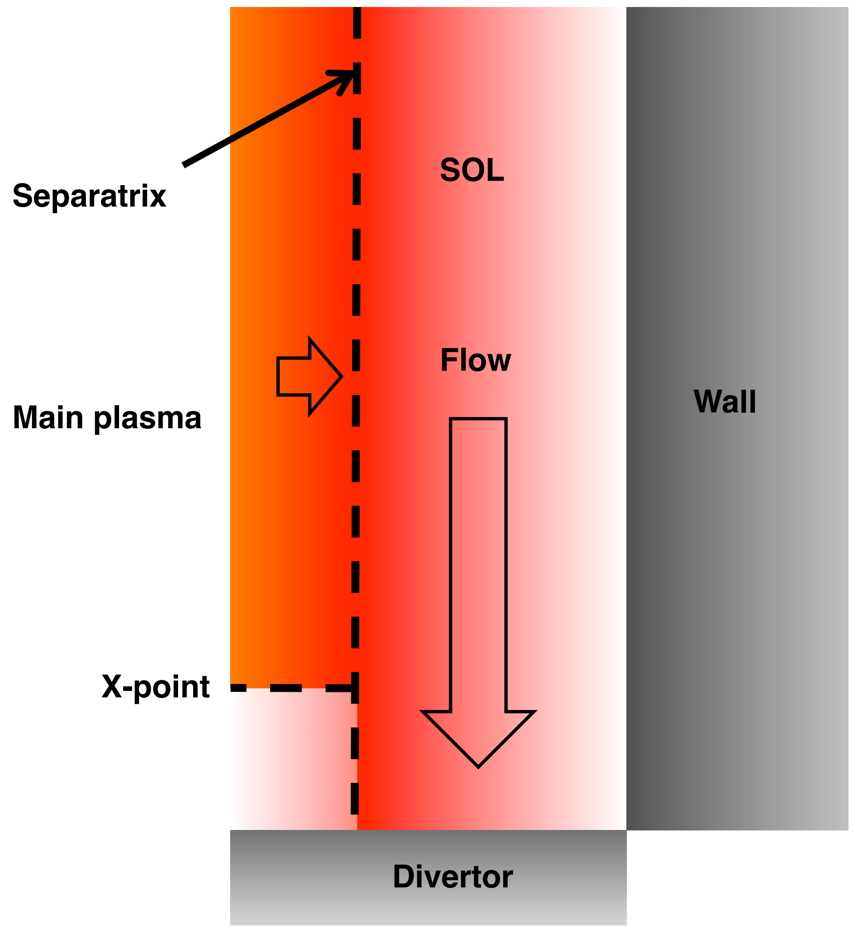
The diverted tokamak



- The divertor is a magnetic field geometry that directs particle flux to target plates rather than using device walls as limiting structures
- Allows for control of location of particle interaction: isolates from main plasma and can be located near pump ducts for ease of exhaust
- Drawbacks: high localized heat flux magnitudes; in ITER, where average heat flux magnitudes can be expected to be >10 MW/m^2, with peak values from 20-50

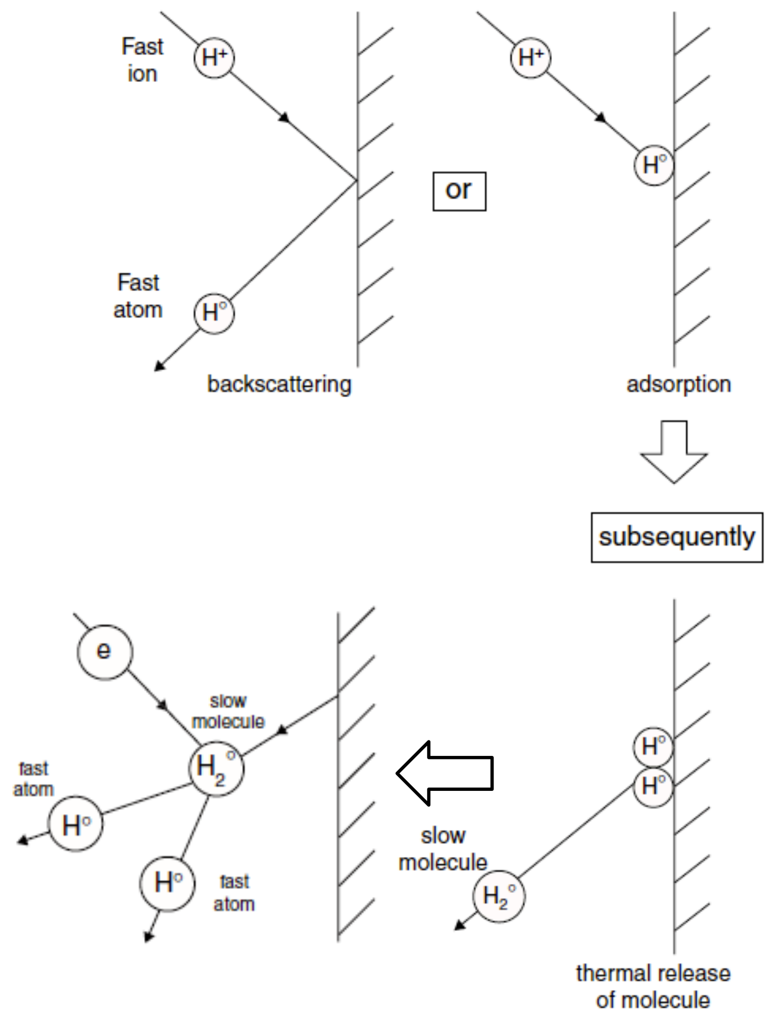
Heat and particle flux at the divertor

- All power input into plasma (ohmic, NB, RF) must be exhausted by particles or radiation
- Particles escaping core confinement enter the scrape-off layer (SOL), and are transported to divertor surfaces
- Wall-interactions are localized, but can have far-reaching consequences for the plasma



Recycling – not the good kind

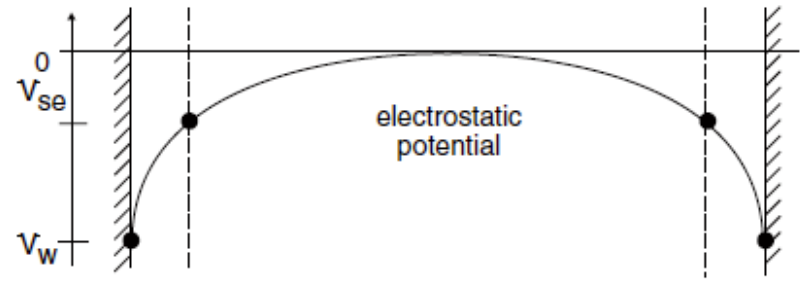
- Graphite, a traditional tokamak wall material, is an excellent heat handler, but a poor particle sink
- Incoming particles will saturate the wall tiles, and subsequent incoming ions will lead to ejection of cold neutrals
- Recycling coefficients for graphite can exceed 98% when saturated
- Recycled neutrals re-enter the SOL, and consume energy as the are re-ionized, increasing edge density and lowering edge temperature



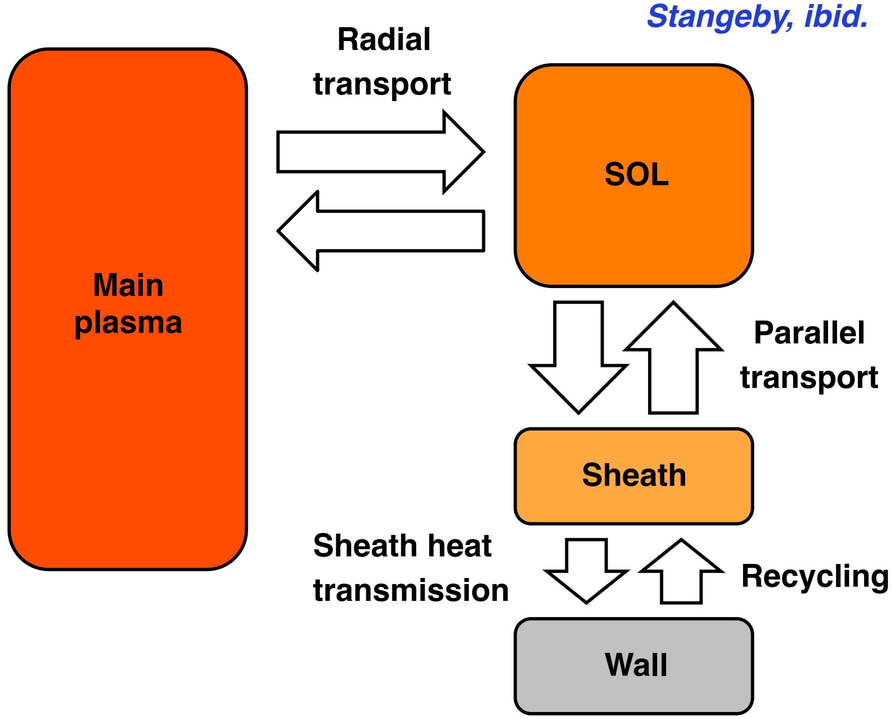
Stangeby, The Plasma Boundary of Magnetic Fusion Devices

The plasma sheath links the wall to the main plasma

- An electrostatic sheath forms around all plasma-facing surfaces
- All particles impacting the divertor surface must pass through the sheath
- The surface is linked to the SOL through the sheath, and the SOL parameters set the boundary conditions for the bulk plasma
- Modeling efforts can quantitatively establish this relationship, but require knowledge of how power is transmitted through the sheath



Stangeby, ibid.



Classical picture of sheath heat transmission relies on several key assumptions

- The sheath heat transmission coefficient, γ, links the material walls with the plasma
- SOL electrons are modeled as a Maxwellian distribution, while the ions are treated as a drifting Maxwellian moving at the sound speed
- The net heat flux to the sheath is the contribution from these populations and is given by: $q = \gamma k_B T_e \Gamma$

$$\gamma = 2.5\frac{T_i}{T_e} + \frac{2}{1-\delta_e} - 0.5\ln\left[\left(2\pi\frac{m_e}{m_i}\right)\left(1+\frac{T_i}{T_e}\right)\frac{2}{\left(1-\delta_e\right)^2}\right]$$

- The classical value of γ is ~ 6.9 if $T_e = T_i$, and $\delta_e = 0$
- Does the experimental sheath heat transmission match the classical value, or does an ‘effective’ value need to be used?
- Requires multiple diagnostics for measurement, good cross-calibration abilities

Measurements necessary for determining sheath heat transmission

- Heat flux is given by: $q = \gamma k_B T_e \Gamma$
- The necessary quantities are therefore:
  - a direct measurement of the heat flux to the surface, q
  - the electron temperature, T_e
  - the particle flux to the surface, Γ
- The heat flux measured via IR camera readings
- Electron temperature and particle flux determined from Langmuir probe measurements
- Empirical value of γ given by ratio of IR and Langmuir probe measurements

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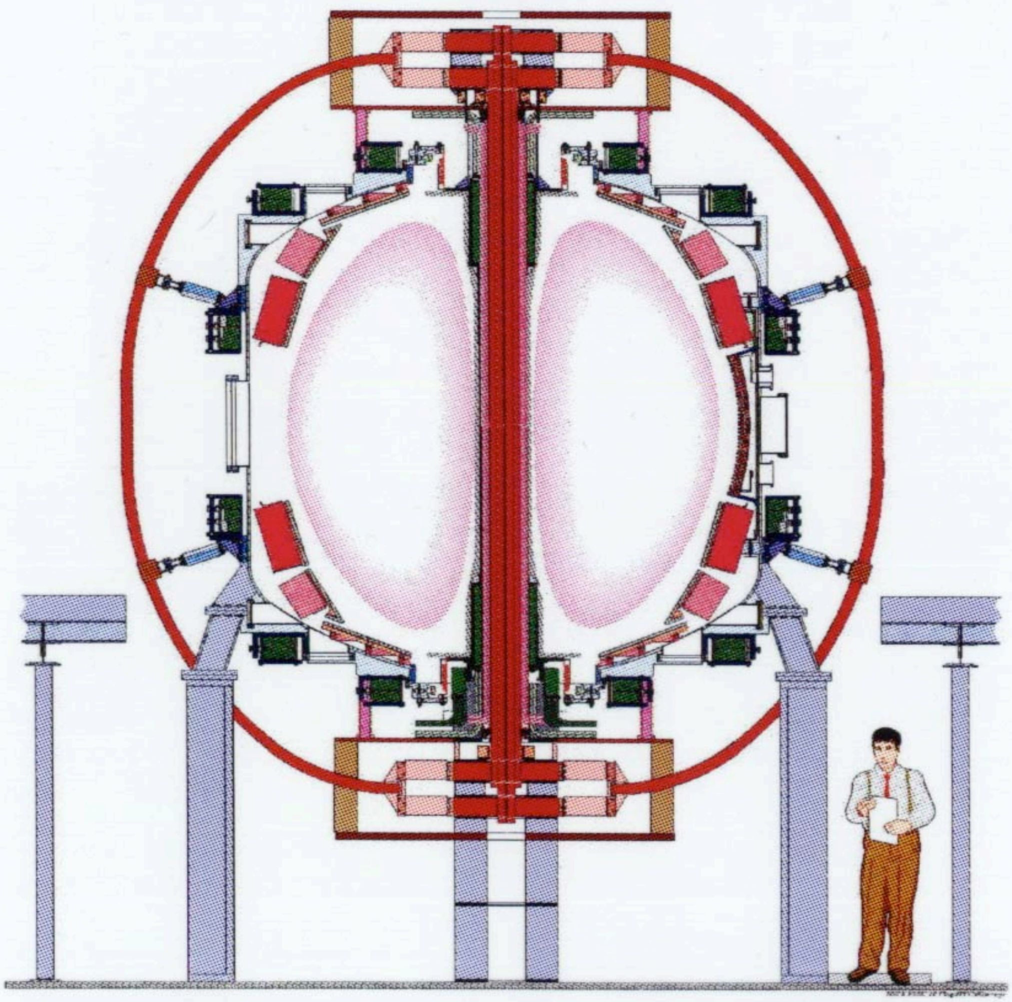
NSTX

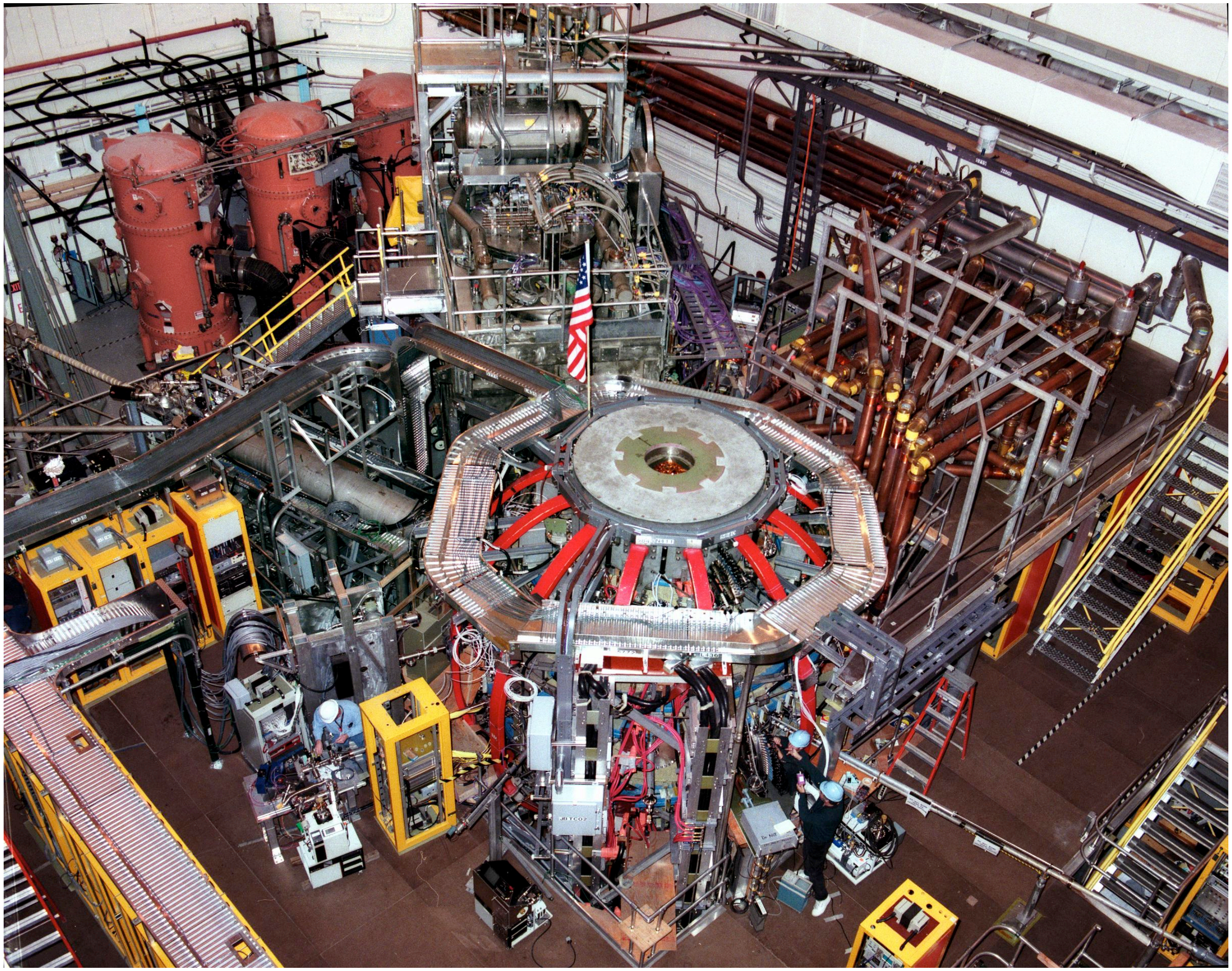


Baseline Parameters

- Major radius
  $\leq$ **85 cm**
- Minor radius
  $\leq$ **68 cm**
- Plasma current
  1 MA
- Toroidal field
  0.3–0.6 T
- Heating and current drive
  6–11 MW
- Flat-top time
  .5–1.6 s

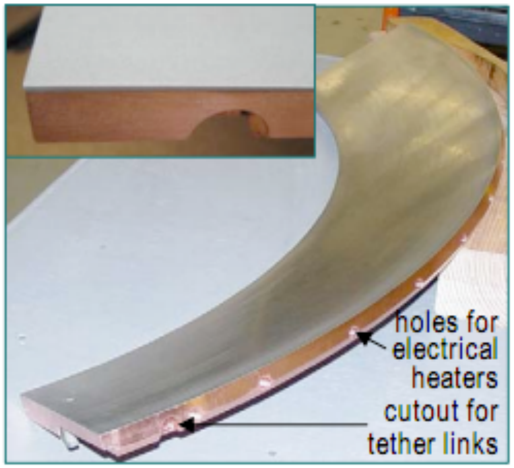
Joint Project of: Columbia University ornl PPPL UW

The NSTX Facility

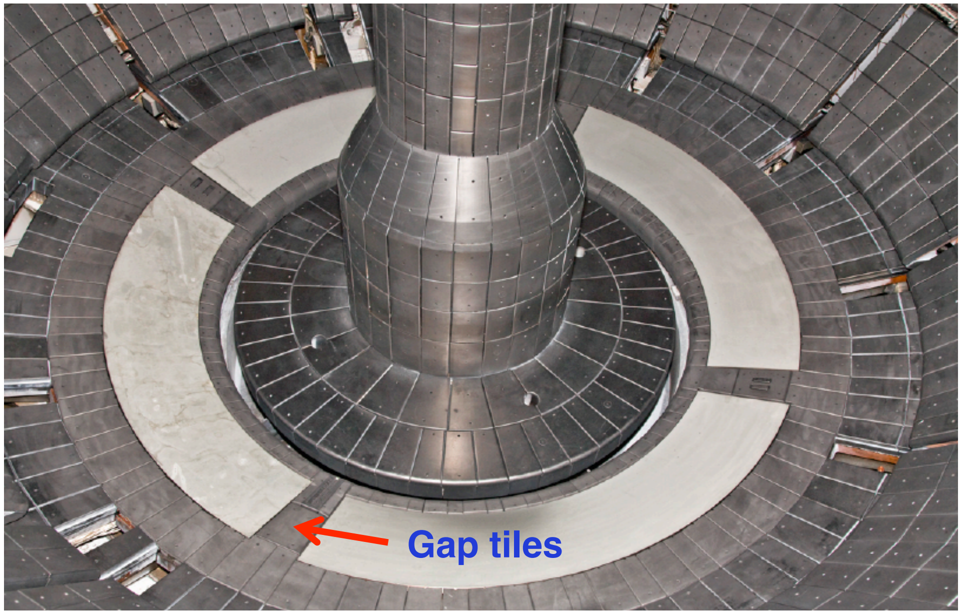


The Liquid Lithium Divertor (LLD)

- Lithium research in NSTX has produced many favorable results linked to reductions in recycling[1]
- This motivated the installation of a substrate specifically designed for liquid lithium surfaces
- A suite of diagnostics was installed to support this research, making possible the measurements necessary to determine sheath heat transmission



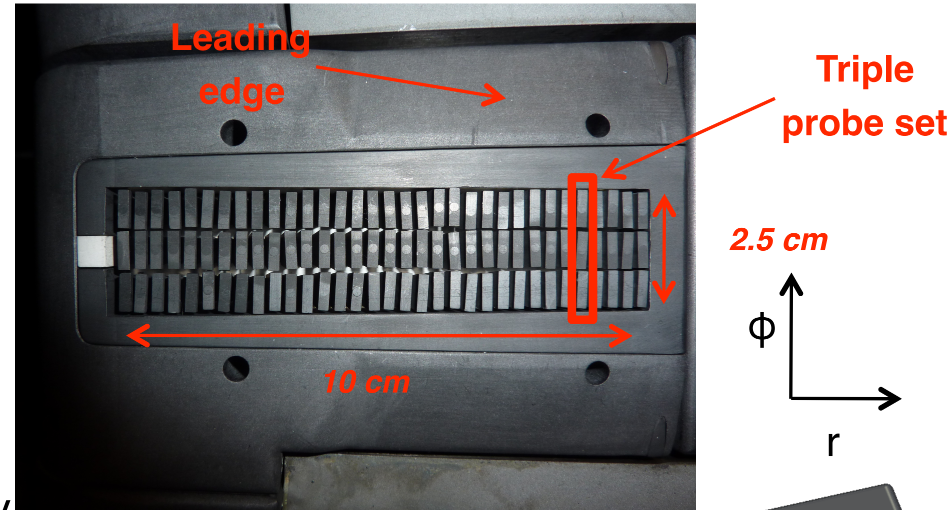
R. Nygren. Journal Nucl. Mat. (2011)



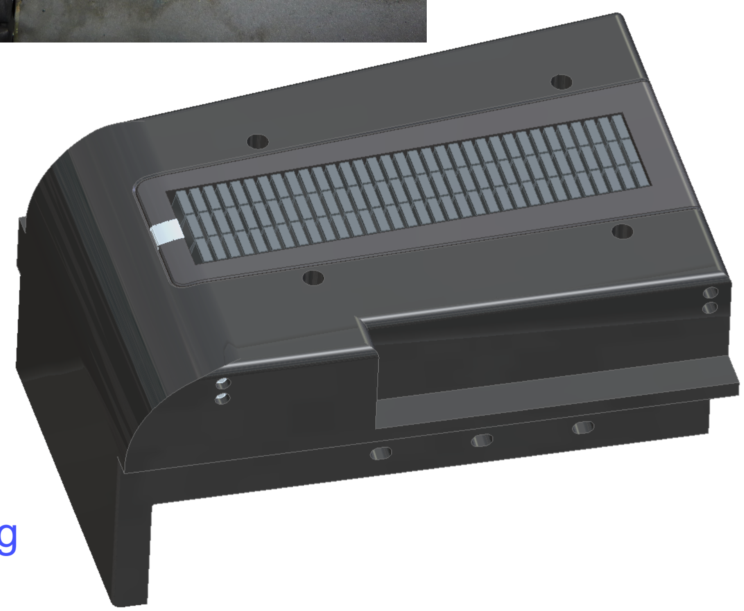
[1]M. Ono. Fus. Eng. and Design. 85:6 (2010)

Triple Langmuir probe array addresses edge diagnostic needs

- 99 individual electrodes arrayed as 33 rows of triple probes, providing density and temperature on a continuous basis
  - can also be operated as swept or SOL current probes
  - triple probes acquire at 250 kHz, swept at 500 Hz
- Probes based on MAST design utilizing a Macor cassette of closely spaced probes embedded in a carbon tile
  - tile mount with radial coverage of divertor
  - electronics provided by UIUC
  - described in RSI papers[1]



- Close spacing of probes provides better resolution in high-gradient (strike point) regions
  - each probe covers 3 mm radially, including spacing
  - probe heads are 2mm radial x 7mm toroidal rectangles

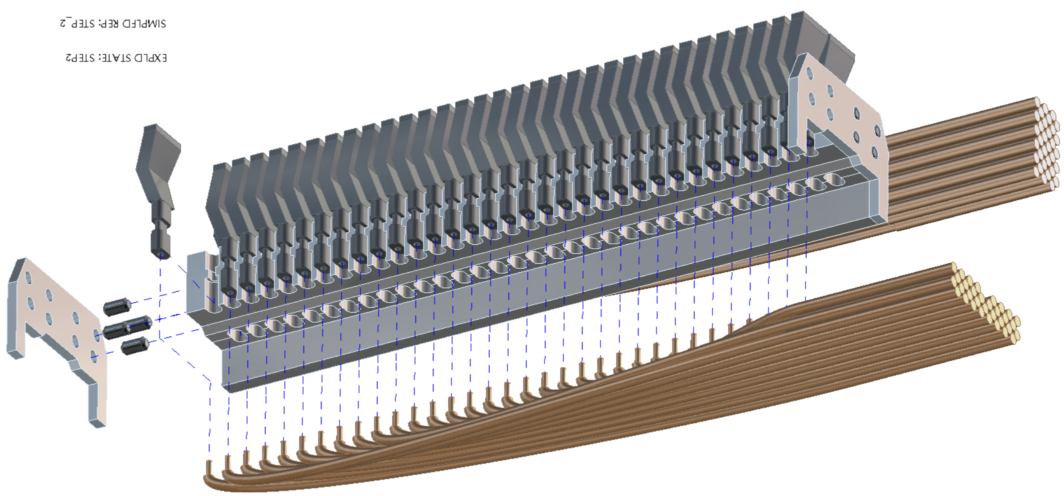


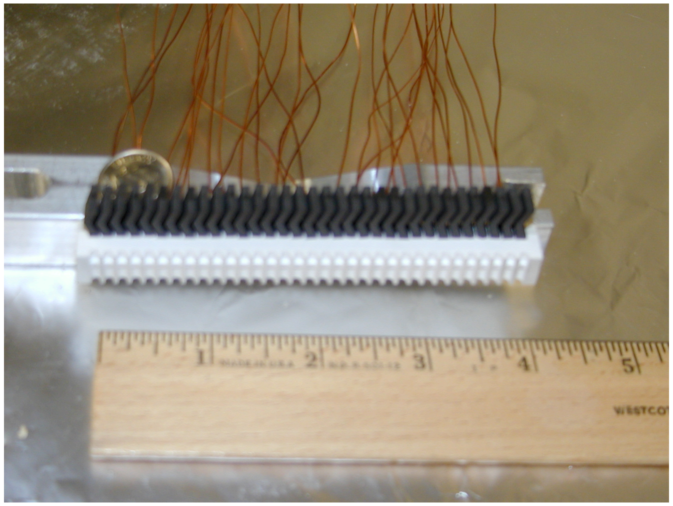
[1]Kallman; Jaworski, RSI (2010); **81**:10

Heavy lithium depositions on divertor surfaces present materials challenge

- Graphite chosen as probe material due to ease of machineability and previous experience
  - previously installed (graphite) Langmuir probes showed no appreciable loss of signal with heavy lithium loading – but LLD operations necessitated large lithium depositions
- Elemental lithium is conductive, providing a possible path for shorting electrodes to each other or ground
- Lithium also reacts with carbon in the presence of oxygen (residually present in NSTX) to form lithium carbonate, or reacts with water to form LiOH, both insulators
  - beneficial in avoiding grounding and direct conduction, but can provide barrier for incident electrons and ions
- Strike point ablation can remove evaporated lithium, but large integral effect of continuous loading depositions was unknown
  - comparison of signal strength throughout run year showed that signal magnitude did not decrease appreciably

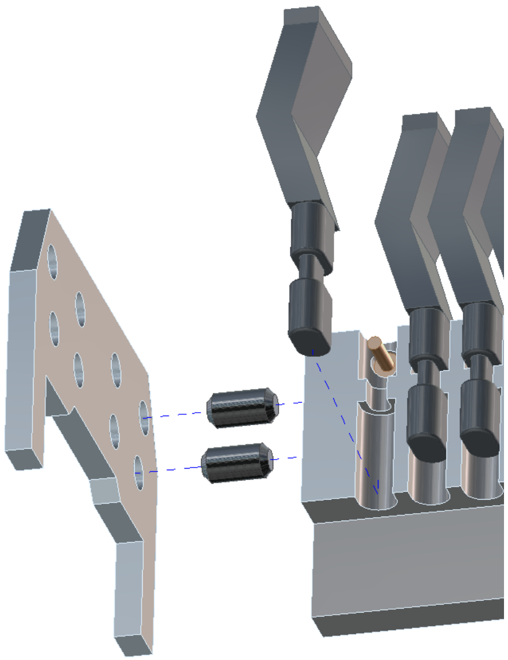
Cassette design allows for ease of probe mounting and includes channels for wire transport

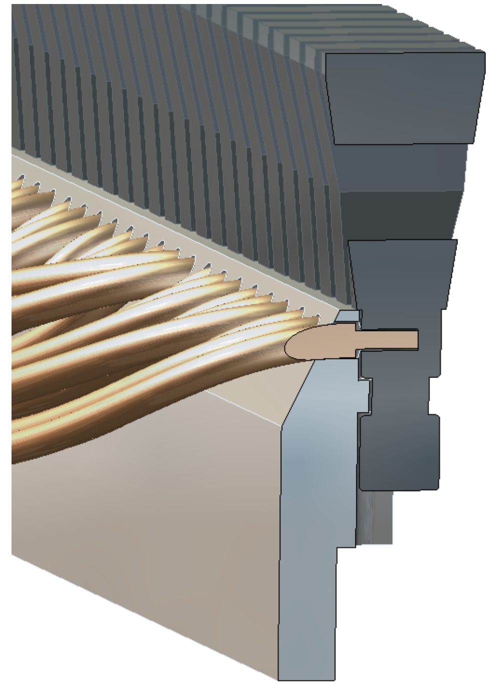




- Boron nitride cassette features interlocking segments that allow for individual probe seating and securement
  - screwless design reduces mechanical stresses on the probes
- Wiring channels allow for the wires from each group of probes to exit independently
  - wires exit on sides of edge probes and through base of central probes
  - graphite cement used to attach wires to probes; near-identical thermal properties reduce risk of loss of contact due to material expansion
  - Fortafix adhesive used to provide strain relief for wires exiting cassette

Probe design includes features to protect underlying surfaces and uses novel materials to facilitate assembly

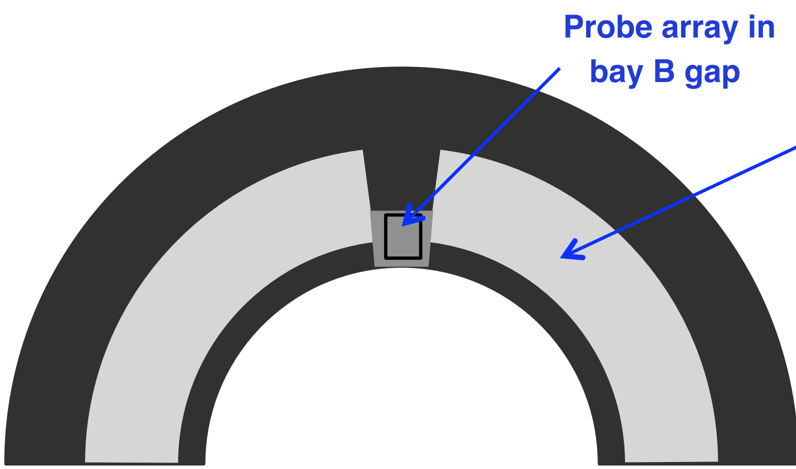




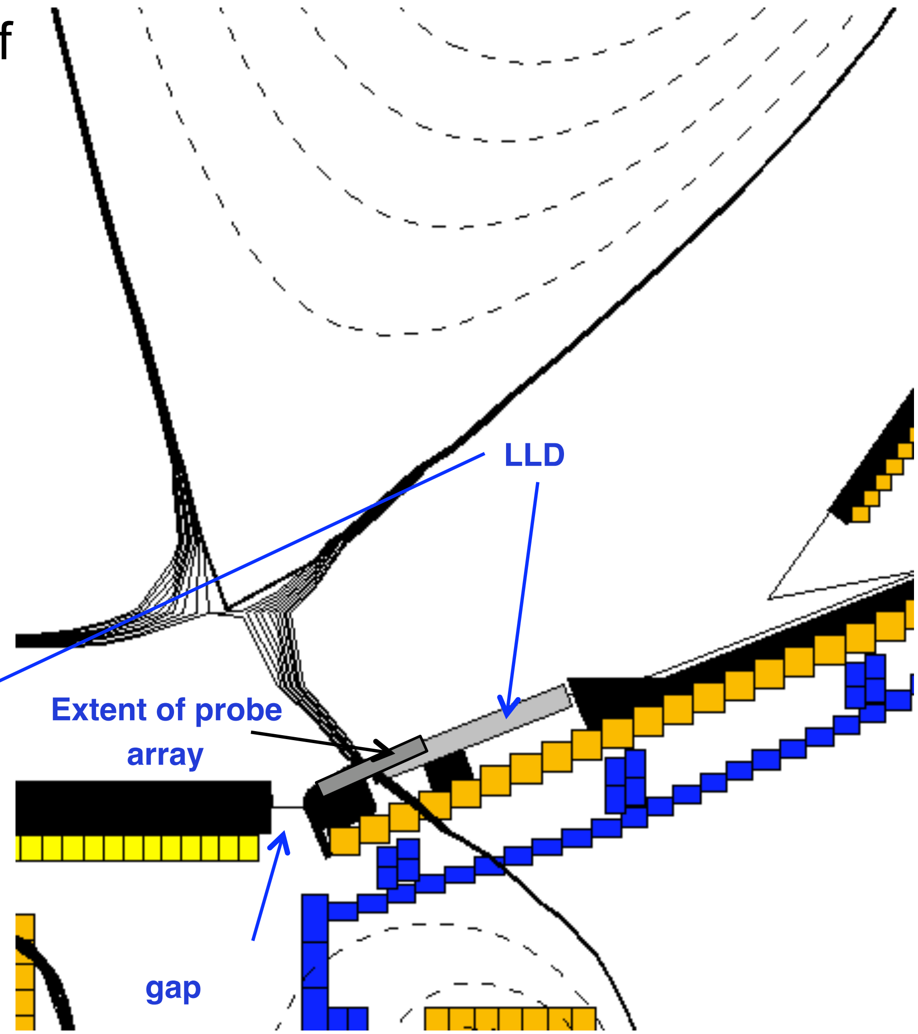
- Boron nitride offers greater lithium compatibility than original macor design
- Probes are shaped so as to minimize direct exposure of BN to plasma or lithium
  - probe bend prevents direct line of sight for lithium or plasma down to cassette
  - probe widening at top allows for smaller gaps and greater shielding of surfaces below
  - electrode material is vacuum compatible HK-6 Tokai graphite

Probe array is located near LLD to provide local measurements

- Probe array begins just outboard of lower divertor gap and extends over roughly 1/3 of LLD radially
- Provides local measurements for plasma incident on both carbon and lithium PFCs
- Probe array engineering requirements lead to surface geometry different from surrounding structures

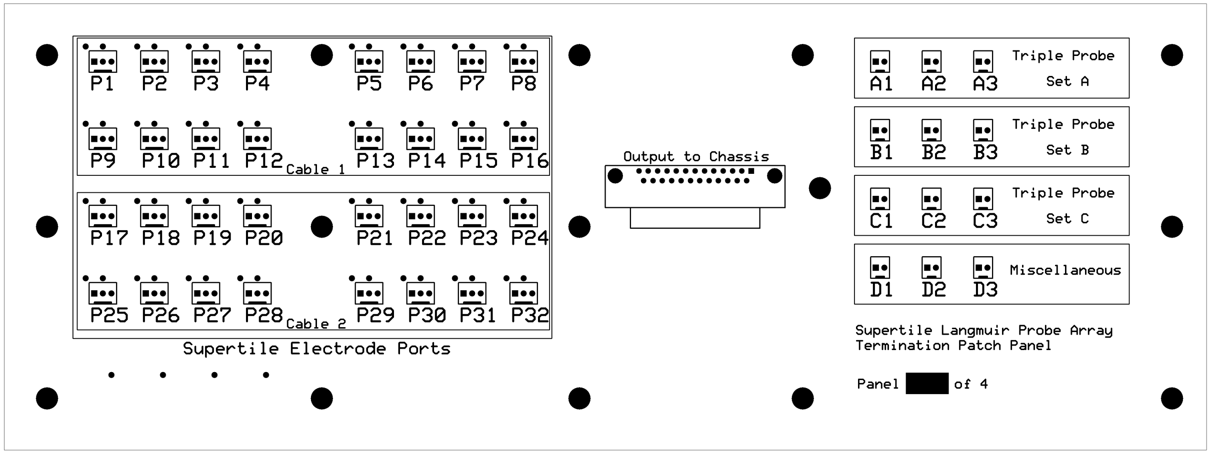


Downward view



Langmuir probe data acquisition

- Each electrode is attached to a single insulated copper conductor by means of graphite cement
- Wires run to a vertical 'organ pipe' where they exit the vessel through a vacuum-feedthru
- Wire bundles run to a diagnostic rack where they enter a patch panel, allowing for fast reassignment of electrodes to sensor sets
- Initial package from UIUC provides for 8 triple-probe sets and 4 swept probes
- Triple probes biased through isolated 48V DC power supply
  - acquire floating potential, as well as current and voltage on one of the electrodes
- Single probes swept to -40/+28V using a 200 W Kepco BOP with a sinusoidal waveform
  - acquire current and voltage on electrode only

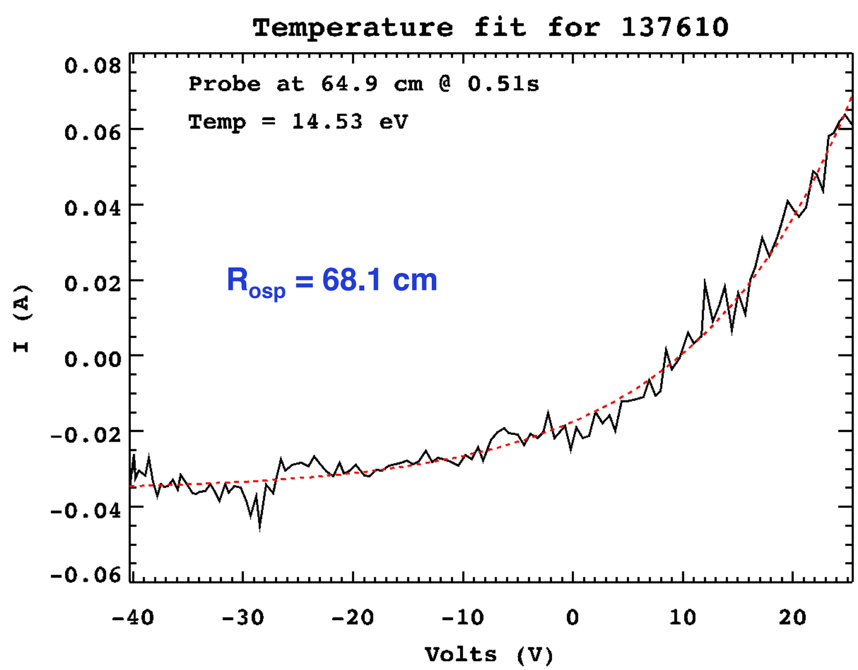


Swept probe signal interpretation

- Electron current flow to probe tip is given as a Boltzmann distribution dependent on bias voltage, while ions are free-streaming at the sound speed
- Four traces (two periods) are averaged to account for fluctuations (250 Hz effective)
- A 3-parameter least-squares fit is performed to determine I_{sat}, T_e, and V_f
- Several fits are performed on each trace, varying the cutoff voltage to stay in the exponential region
  - resulting temperature is normalized by the chi-square of each fit range to produce error bars
- Once a temperature is fit, density can be obtained from the saturation current equation

$$I_{probe} = I_{sat}\left[1 - \exp\left[\frac{e\left(V_{bias} - V_f\right)}{kT_e}\right]\right]$$

$$I_{sat} = \frac{1}{2} e n_0 c_s A_{probe} \qquad c_s = \sqrt{\frac{k\left(T_e + T_i\right)}{m_i}}$$

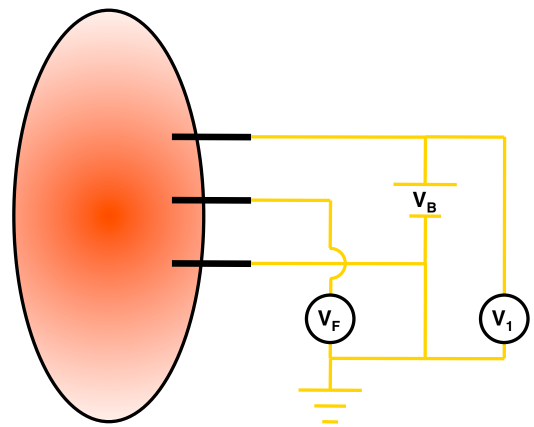


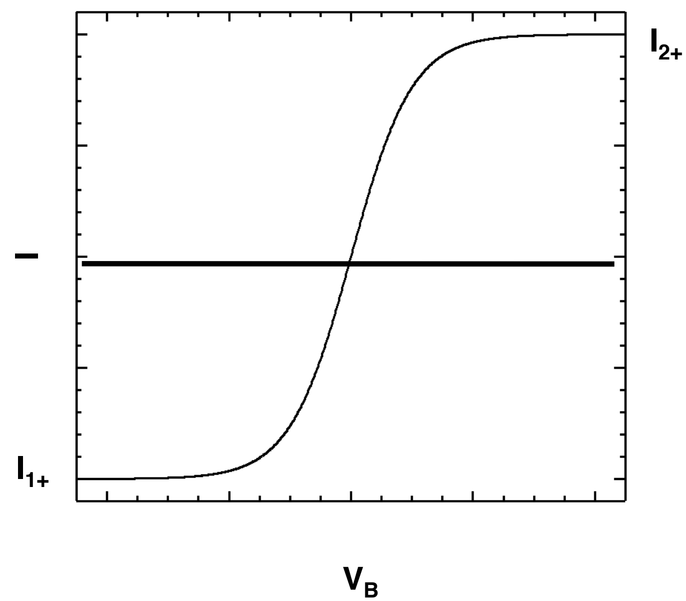
Triple probe interpretation

- Three individual electrodes can be utilized to give instantaneous temperature readings
  - two probe tips offset by a DC voltage (48 V) referenced to a third tip operating at floating potential
  - the two biased tips are offset around the floating potential so that there is no net current flowing (i.e. electron current = ion current)
- Using the same assumptions about the electron distribution as the swept probes, setting $I_1 = -I_2$ yields an equation for the electron temperature

$$T_e \cong \left(\frac{e}{k}\right)\frac{\left(V_1 - V_f\right)}{\ln 2}$$

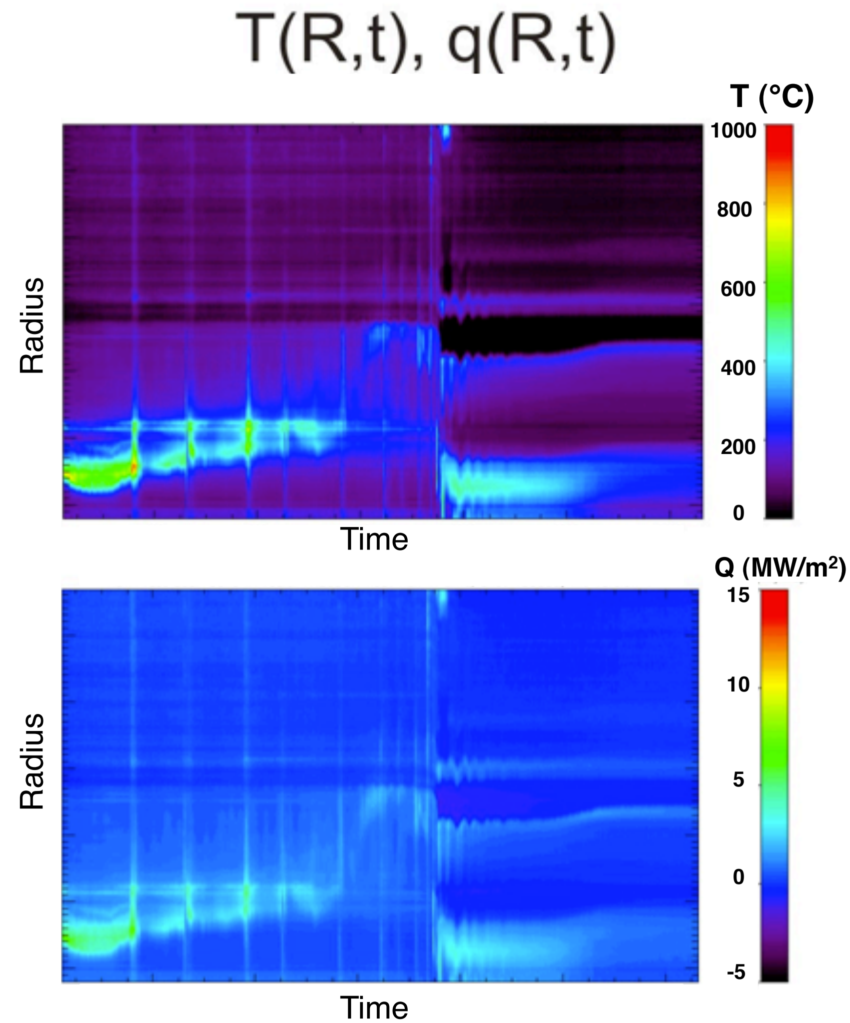
- If bias voltage is sufficiently above electron temperature, measured current is generally ion saturation
- Density can be obtained in the same manner as swept probes
- Provides temperature and density measurements at 250 kHz, but median filtering smoothes noise and reduces effective frequency to ~400 Hz





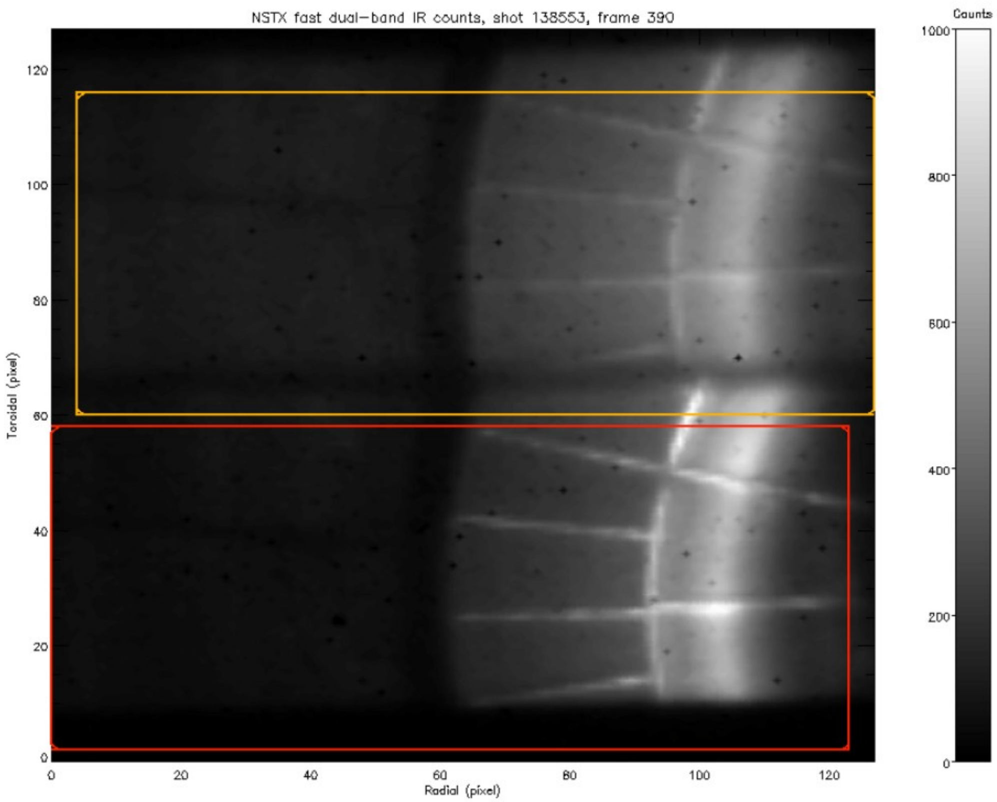
Dual-band IR camera compensates for emissivity changes in the lithium surface

- ORNL collaboration to take fast camera IR measurements at 2 wavelengths at 1.6 kHz
  - 4-6 μm and 7-10 μm
  - ratio of signals cancels out emissivity-dependence in radiated power
- In-situ calibration using heated LLD allows for precise temperature measurements
- 2D heat-conduction code THEODOR determines incident heat flux necessary for observed temperature change

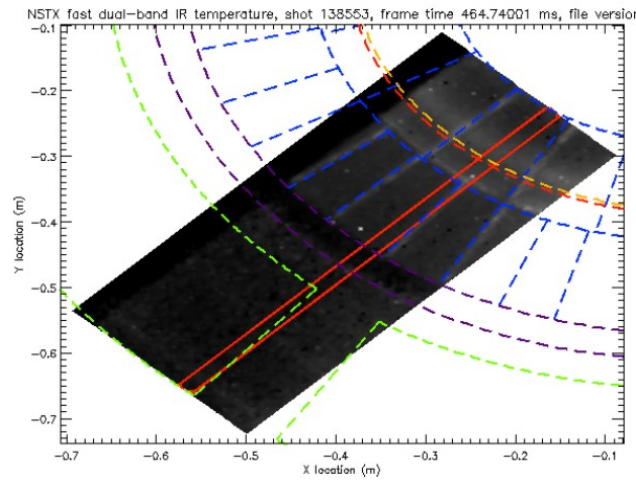


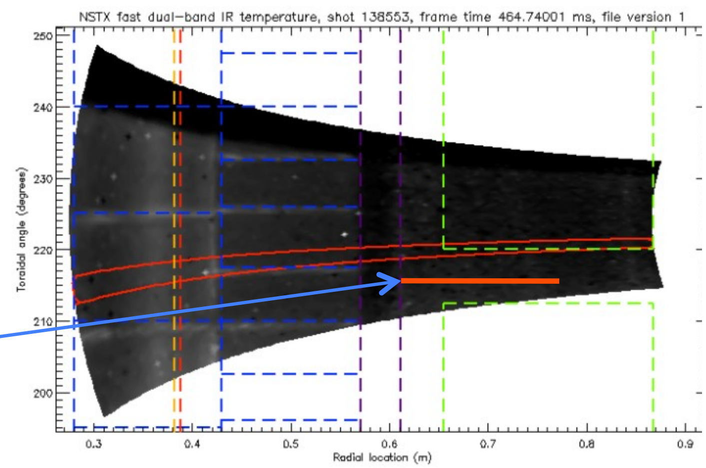
Raw pixel data is mapped to NSTX geometry

Raw dual-band data



Aligned, calibrated



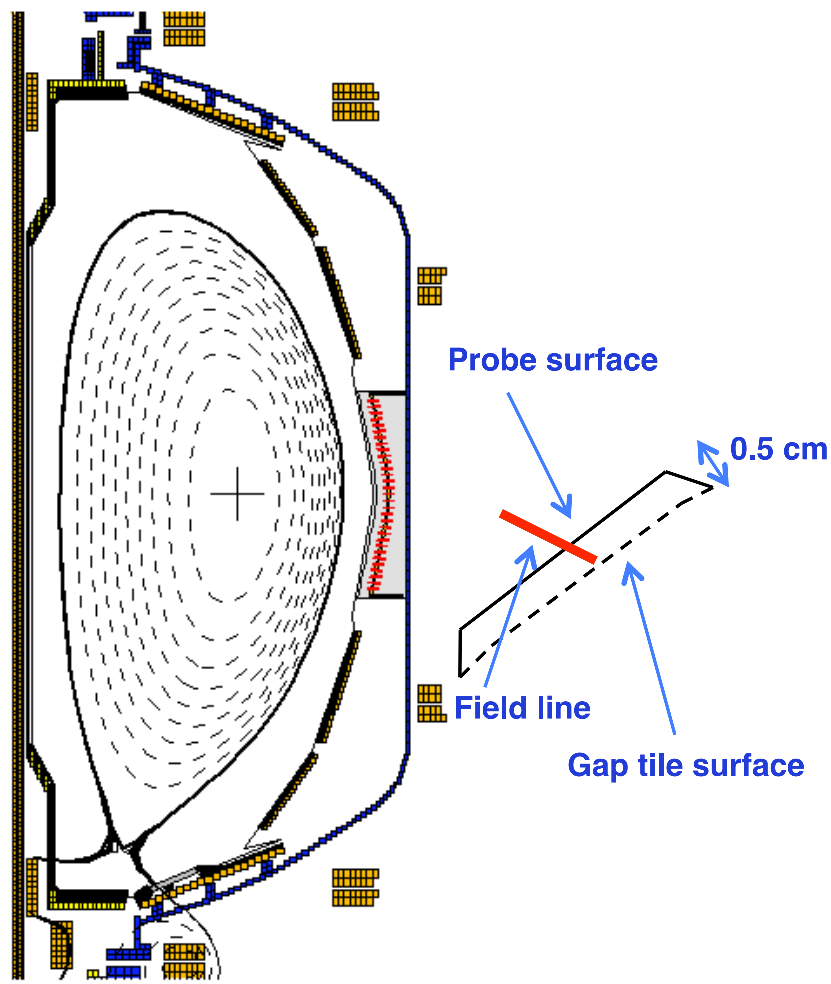


Chord used for present study

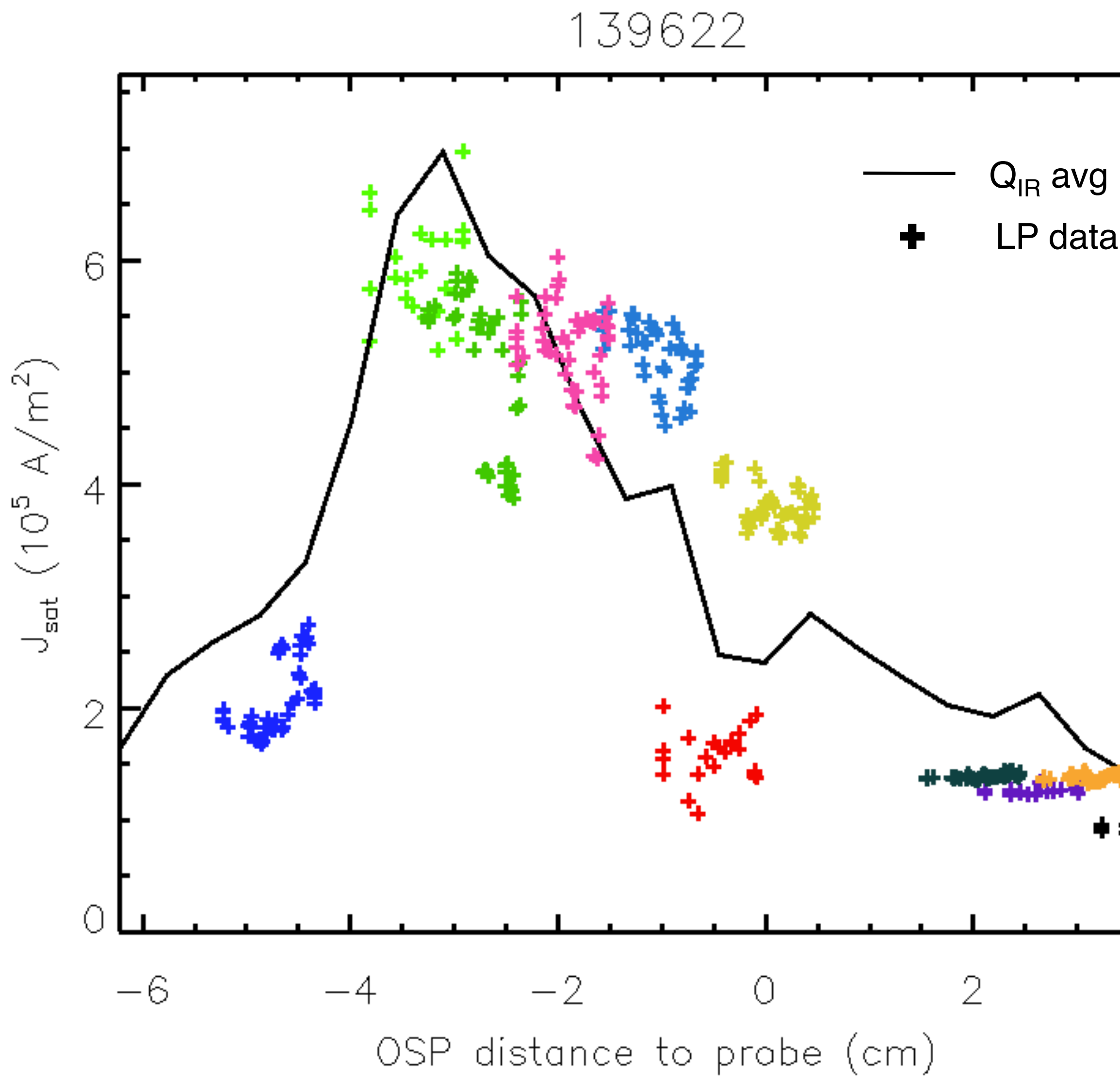
Different toroidal locations, surface geometries necessitate mapping of flux coordinates

- The probes are approximately 180° away from the IR viewing region and have a unique surface geometry
- FARO arm measurements are utilized to provide an accurate topographical map of the surface at both toroidal positions
- The use of magnetic equilibrium reconstructions in the EFIT code (Grad-Shafranov solver) allows for the determination of polodial flux at any point in the device
- Using the assumption of toroidal axisymmetry, two positions on the same flux surface experience identical plasma conditions
- Using a fixed probe radius, the flux at each camera point is compared to that at the probe at each time point and the closest match is obtained
  - generally changes effective radius by 2-3 cm, which is significant in high-gradient regions

139625 @ 700 ms



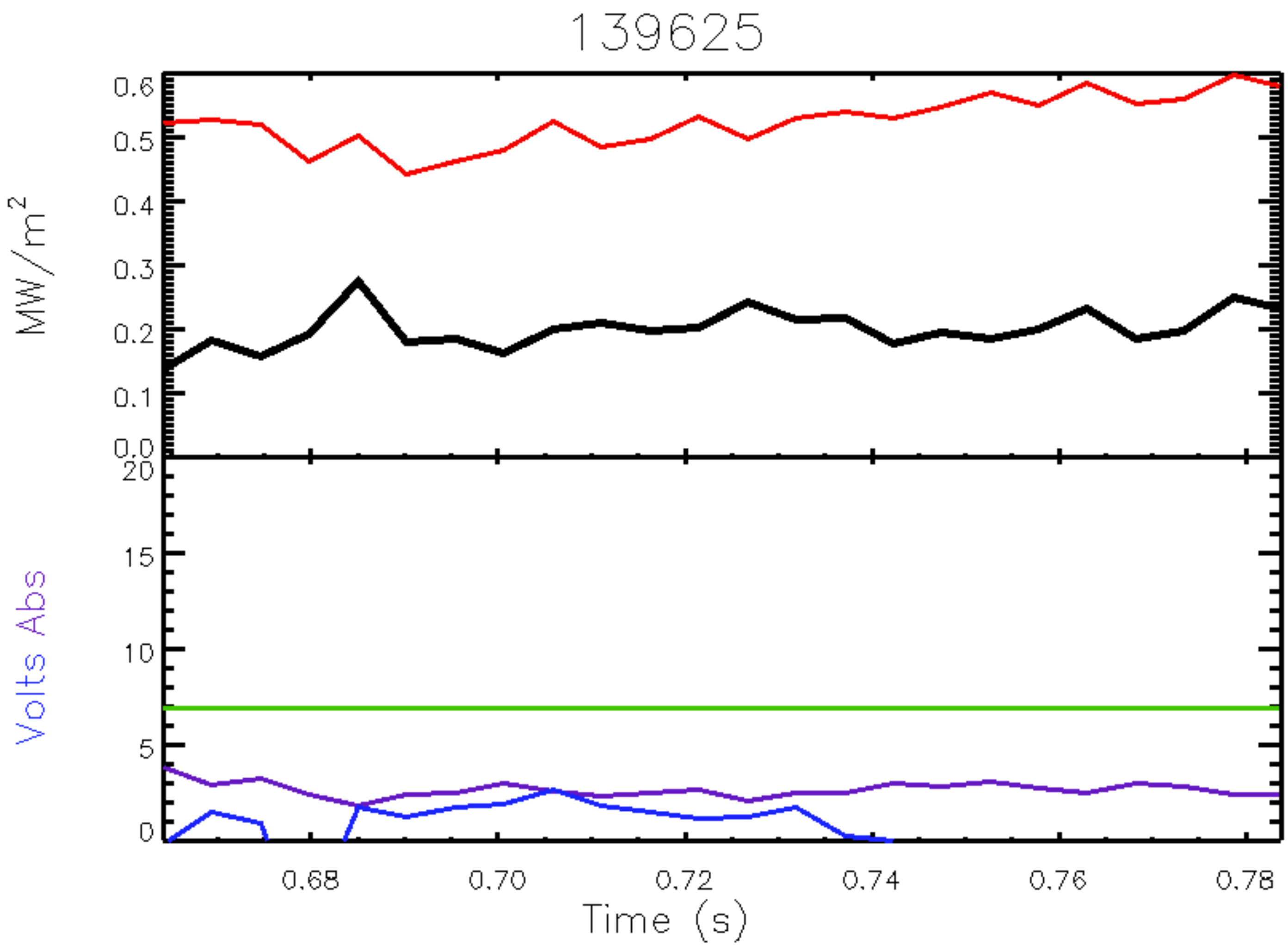
Heat flux and Langmuir probe radial profiles show good qualitative agreement



Sample dataset from probe shows heat flux evolution agreement with IR

LP Q

IR Q



γ

V_f

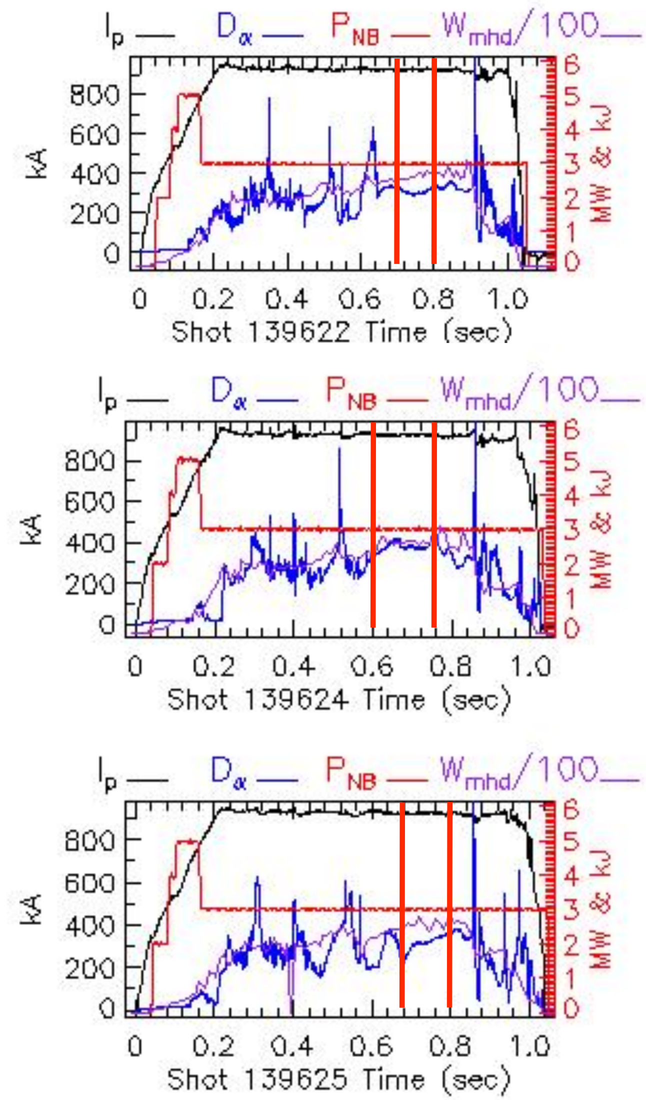
$\gamma_{theory} = 6.9$

Data selection criteria

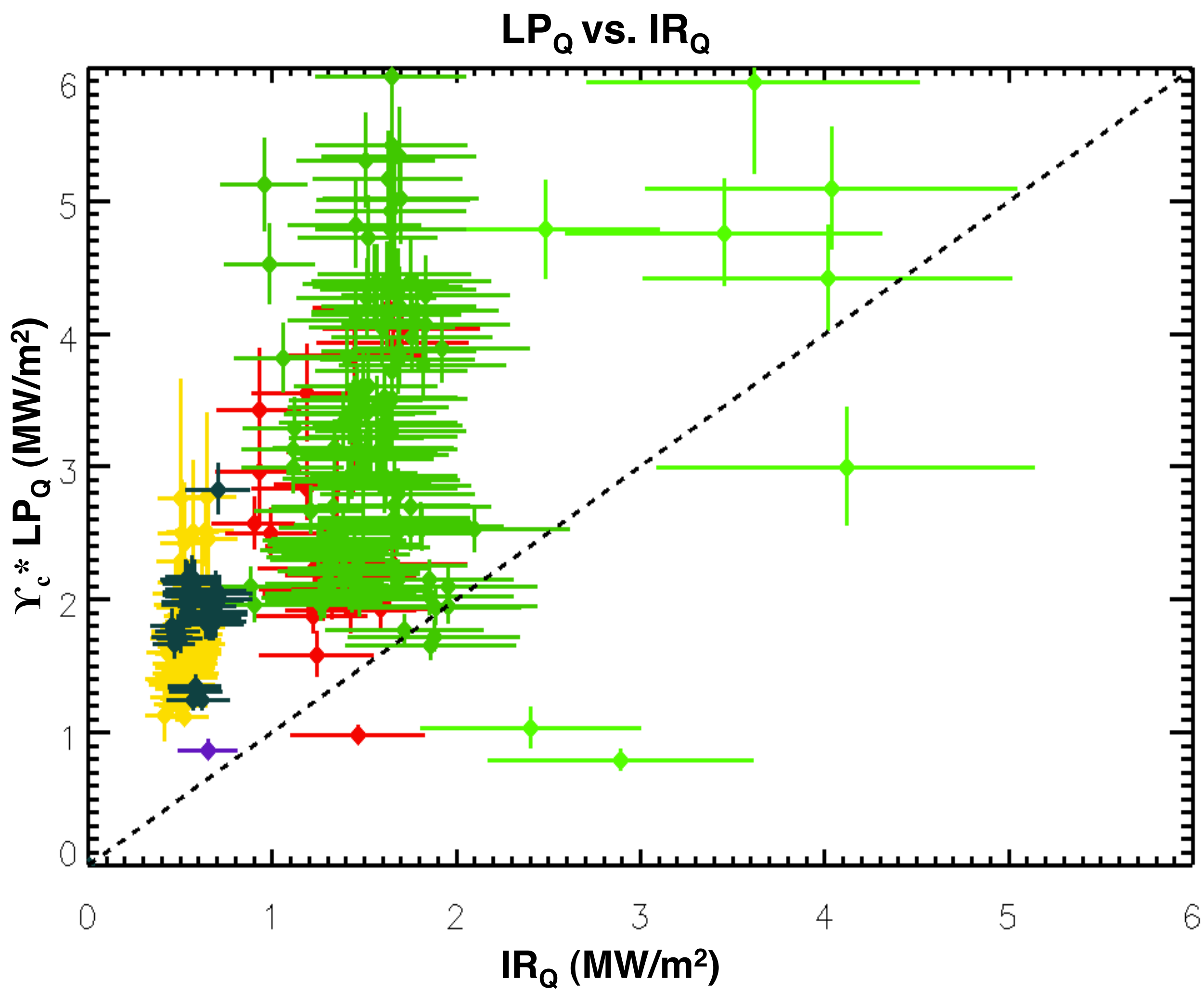
- Discharges must have the strike point position on the probe array to ensure sufficient signal
- Quiescent periods chosen to minimize high transient fluxes due to ELMs
  - generally restricted time windows to 100-200 ms
- IR camera data not available for all shots; sufficient signal desired for optimal comparison
- 2D heat flux model for IR data uses thin lithium film on bulk thermal conductor
  - works better for carbon tiles, motivates chord selection discussed above
- Only looked at signals where floating potential was close to ground
  - floating potential crosses zero at strike point, so this ensures high signal in the relevant region
  - mitigates effects of non-zero floating potential on γ

Case study: combine 3 similar discharges for good statistics

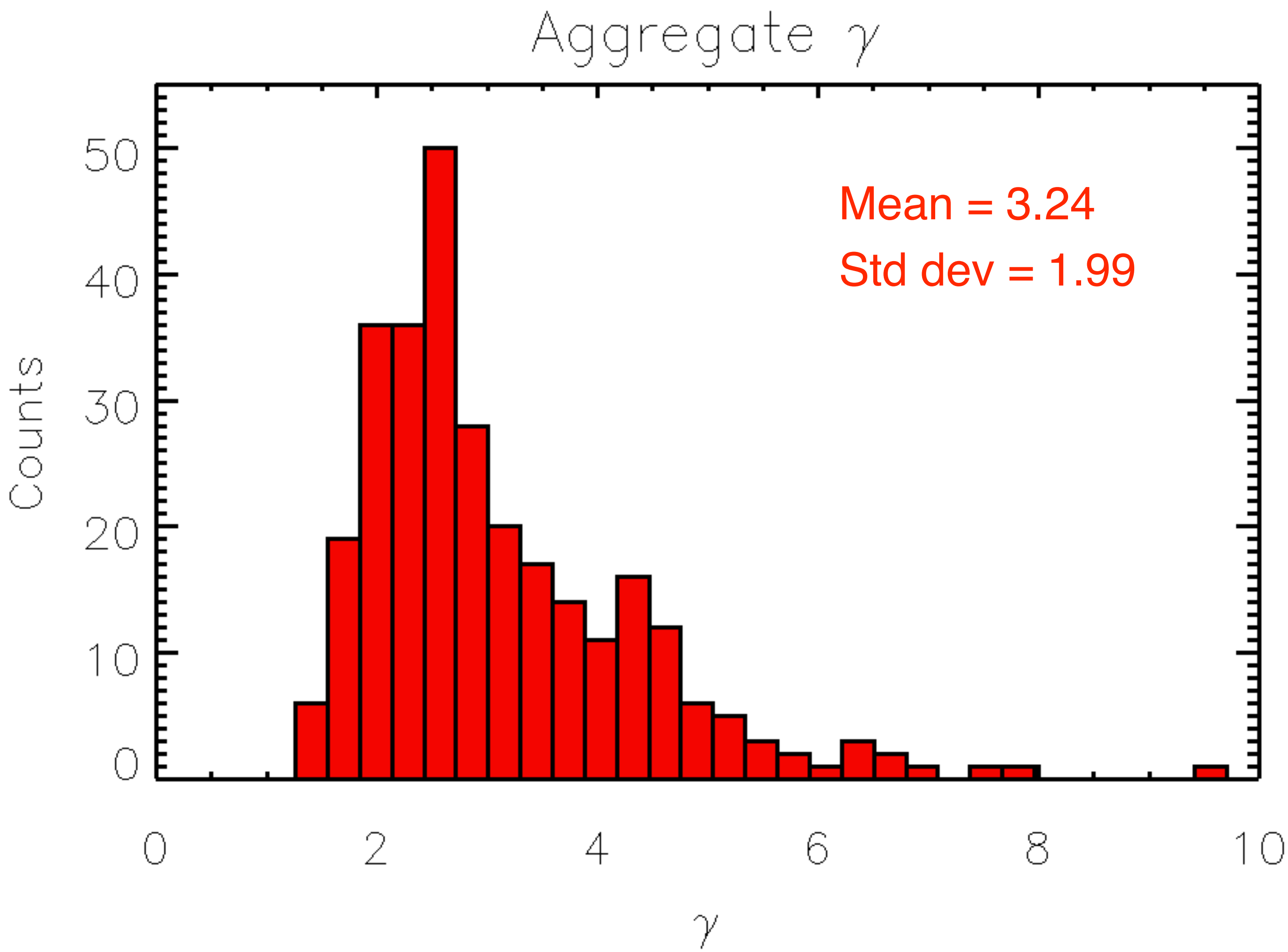
- Selection criteria above limit the number of useable data points for each discharge
- 100-150ms time window limits to approximately 25 points per single probe and 50 points per triple probe
- Floating potential criteria further eliminates data points, sometimes excluding probes altogether
- Signals excluded if low strength or if probes exhibited intermittency/ shorting issues
- All 4 single probes kept, but only 4 of 7 triple probe signals included
- Results from three discharges combined to give best possible statistics with remaining data with good confidence interval



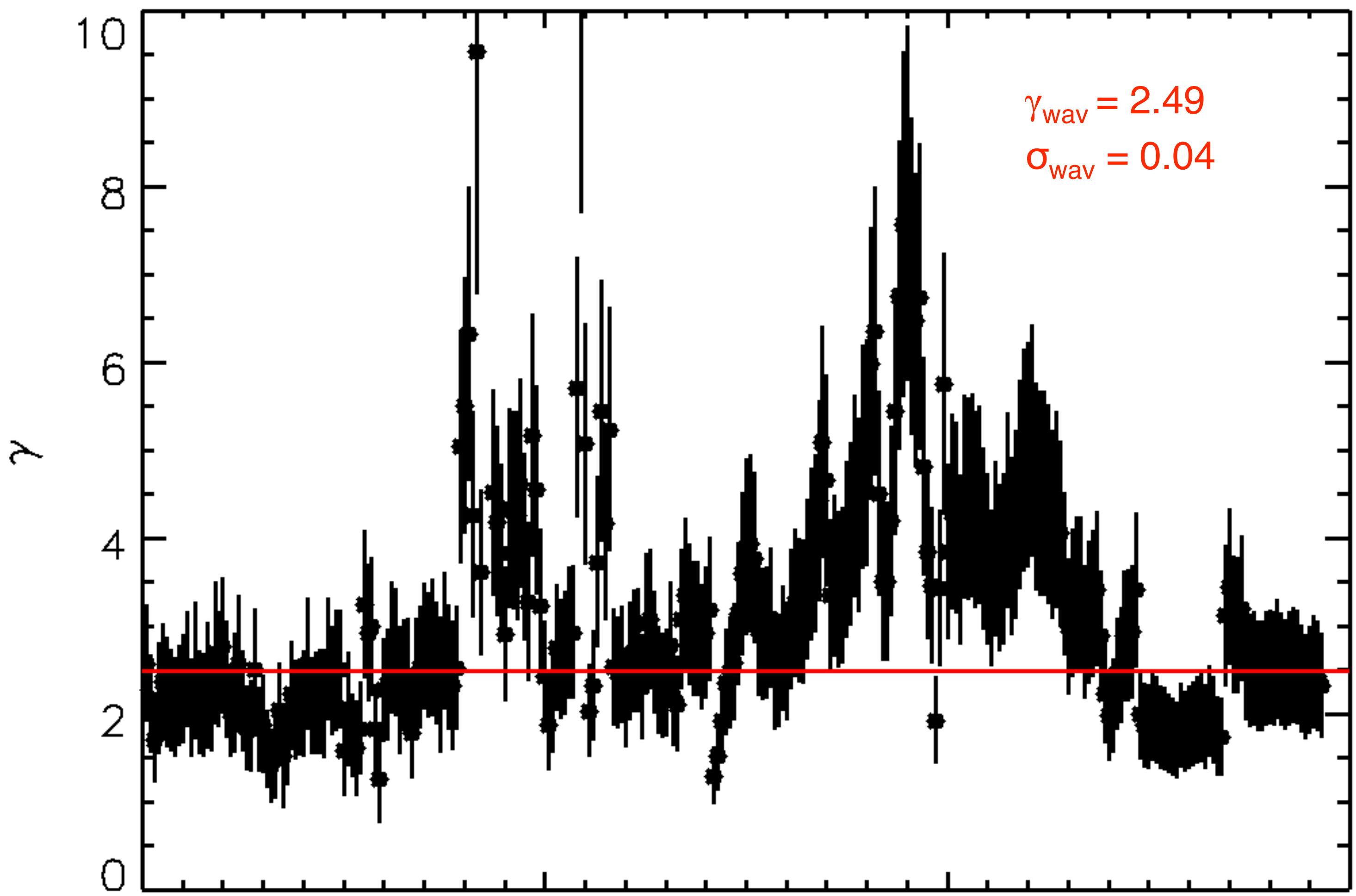
Aggregate data from several shots show deviation from classical predictions



Distribution of measured values of γ inadequately described by Gaussian statistics



Weighted average method shows that γ ~ one third of classical value



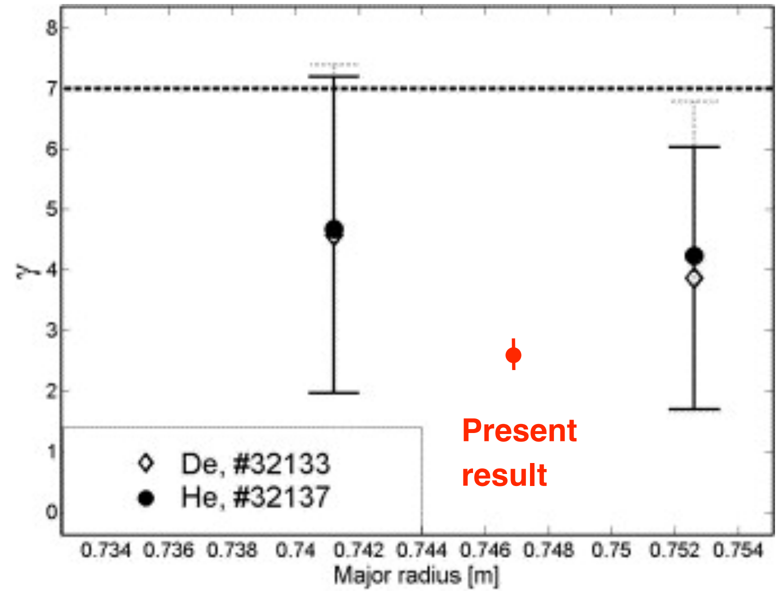
Measured values of γ

Conclusions and discussion (I)

- New diagnostic capabilities allow for precision edge measurements – an area traditionally neglected
- High density Langmuir probe array used in conjunction with IR camera data to successfully calculate sheath heat transmission for the first time in NSTX
- Good statistics obtained by overlaying multiple shots with similar profiles
- Sheath heat transmission coefficient is measured to be 2.49 +/- 0.04
- This value is about one third of the classical value, so what accounts for the discrepancy?

Discussion (II)

- Previous measurements of γ have trended lower as well
- Lithium can alter basic picture
  - changes to temperature ratio
  - impurity accumulation/suppression
  - collisionality
- Conception of γ comes from fluid picture of plasma edge in thermodynamic equilibrium
  - does lithium alter the fundamental physics by changing collisionality?



J. Marki et al. Journal Nuc. Mat. 363-365 (2007)

$$\gamma = 2.5\frac{T_i}{T_e} + \frac{2}{1-\delta_e} - 0.5\ln\left[\left(2\pi\frac{m_e}{m_i}\right)\left(1+\frac{T_i}{T_e}\right)\frac{2}{(1-\delta_e)^2}\right]$$

Future research ideas

- Link edge heat transport regimes to lithium loading; explicit study with different amounts/quality of lithium surfaces
- Build/install diagnostics to measure edge ion temperature and impurity levels directly
- Test fluid picture with edge modeling; match conditions at probes to mid-plane diagnostics
- Develop and employ kinetic modeling tools with empirical input if fluid picture proves inaccurate

Acknowledgements

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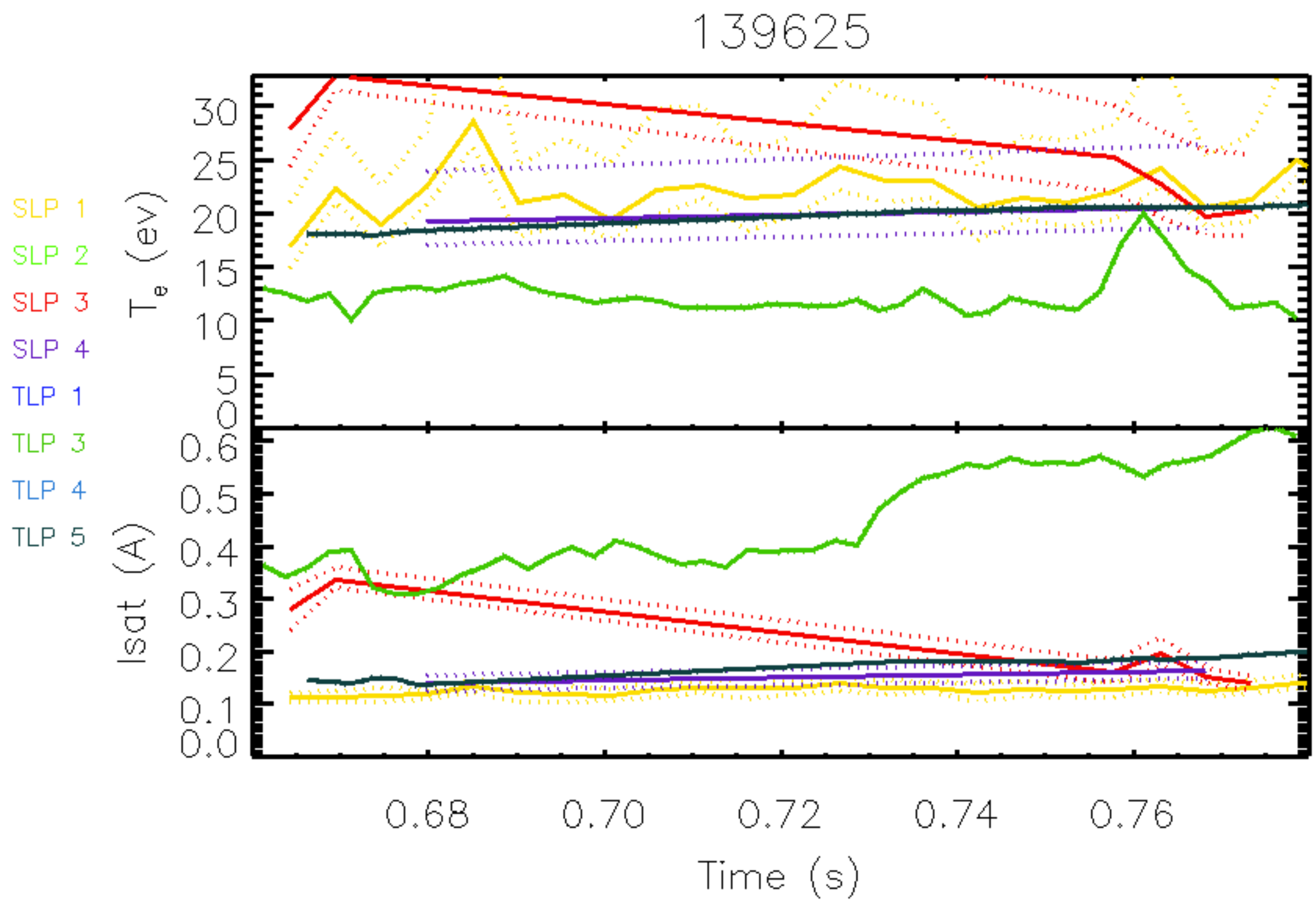
- Jess Baumgaertel, Craig Jacobson, and Luc Peterson for discussions regarding the data and for moral support
- Viewers like you

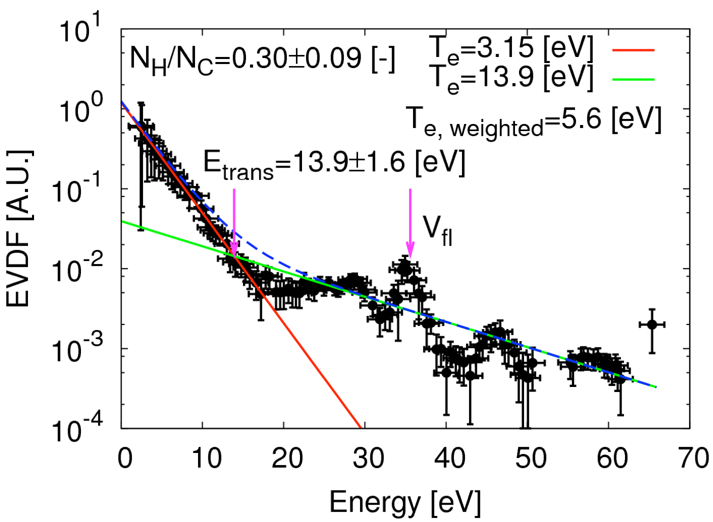
Raw temperature and saturation currents used

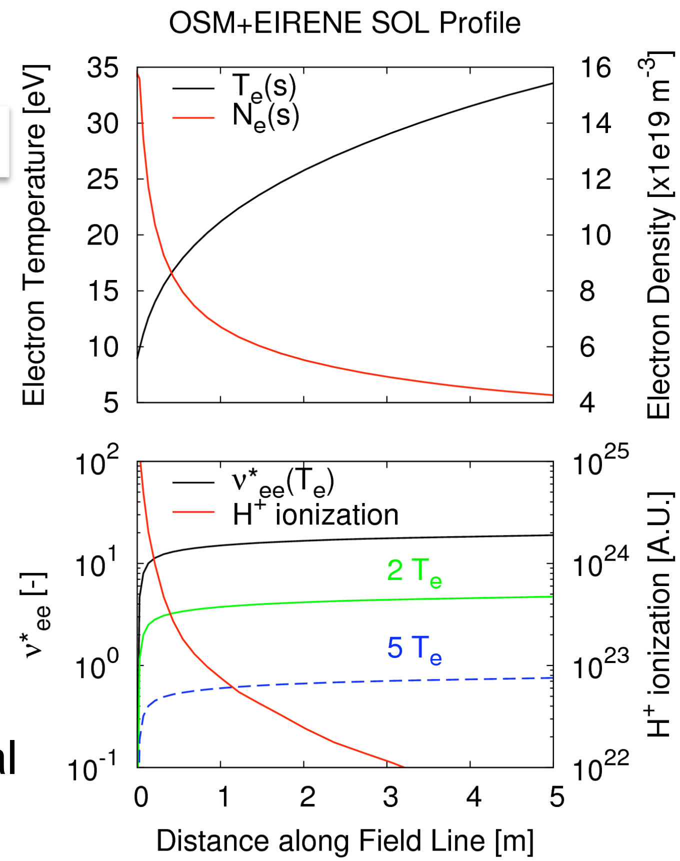


Mike Jaworski's measurements of kinetic effects in NSTX SOL

- Langmuir probes with non-local interpretation infer non-Maxwellian features in EVDF

•Courtesy of M. Jaworski





- Preliminary fluid code run indicates SOL is at marginal
- collisionality even for ***High-recycling PFC***
- OEDGE = Onion-Skin-Method(OSM) + EIRENE + DIVIMP Edge code
- OSM assumes single fluid equations
- Collisionality calculated based on distance, s, from PFC along field-line

$$\nu^*_{ee} = \frac{s}{\lambda_{ee}} \approx 10^{-16}\frac{n_e \cdot s}{T_e^2}$$