Abstract

Recycled particle flux can be a significant contributor to tokamak edge plasma density, and lead to reductions in edge temperature. Previous measurements have shown that lithium PFC coatings can lead to lowered edge recycling, corresponding decreases in edge plasma density, and a radial broadening of the electron temperature profile. During the 2010 run campaign, The National Spherical Torus Experiment operated with both solid and liquid lithium coatings on its plasma-facing components.

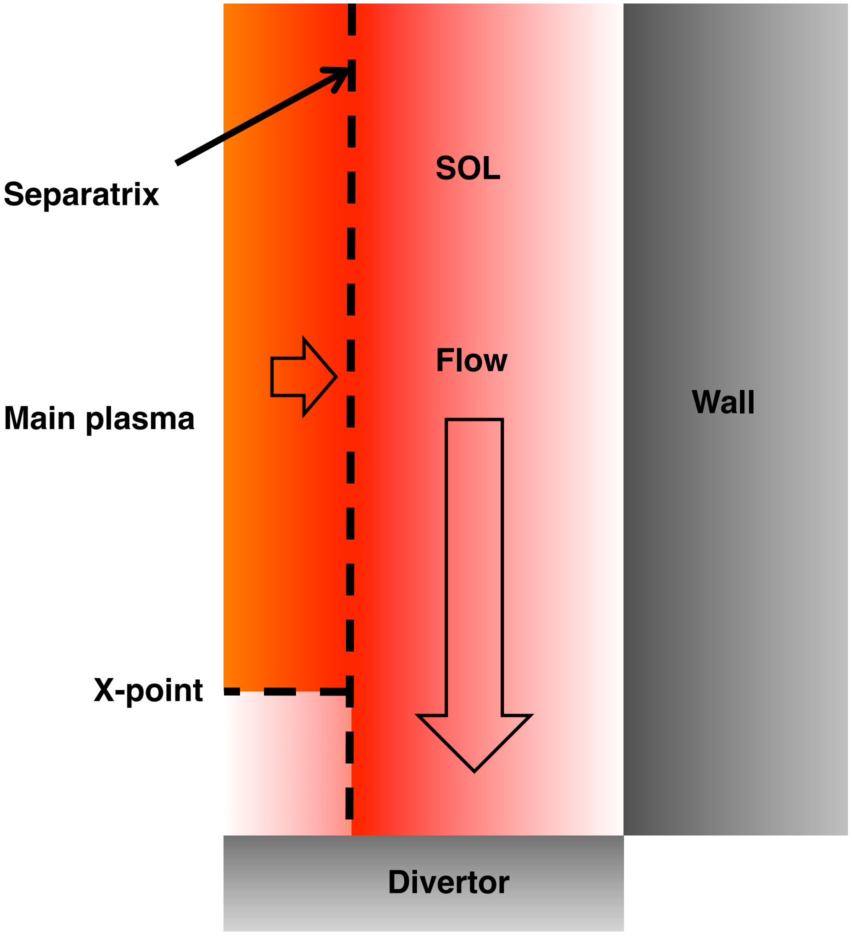
A 99-tip dense Langmuir probe array was installed in the NSTX outboard divertor to measure scrape-off layer density and temperature. A dual-band fast IR camera was also installed to provide surface temperature and heat flux measurements.

The present study compares the derived heat fluxes from these diagnostics to determine the sheath heat transmission coefficient γ. The value of γ was measured to be 2.49, smaller than the expected classical result of ~7. Implications and possible mechanisms will be discussed.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344, and in part under Contracts DE-AC02-09CH11466 and DE-AC05-00OR22725.

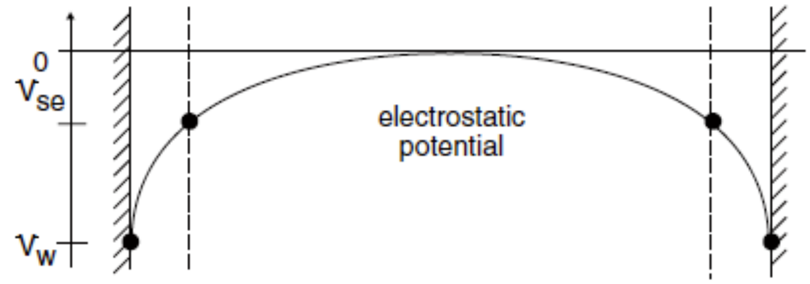
Heat and particle flux at the divertor

- 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

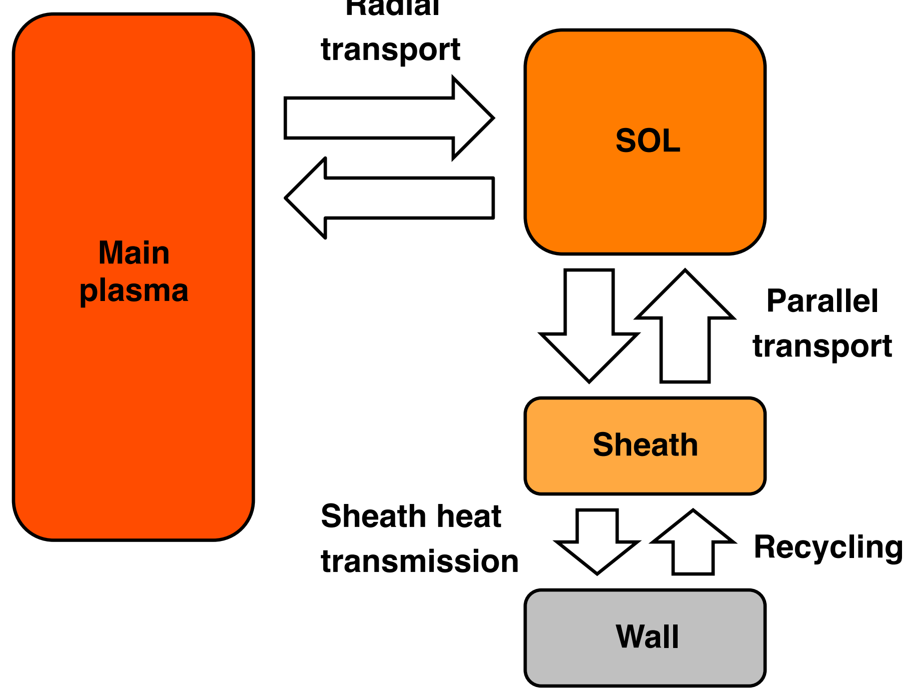


The plasma sheath links the wall to the main plasma

- 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: $q = \gamma k_B T_e \Gamma$

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

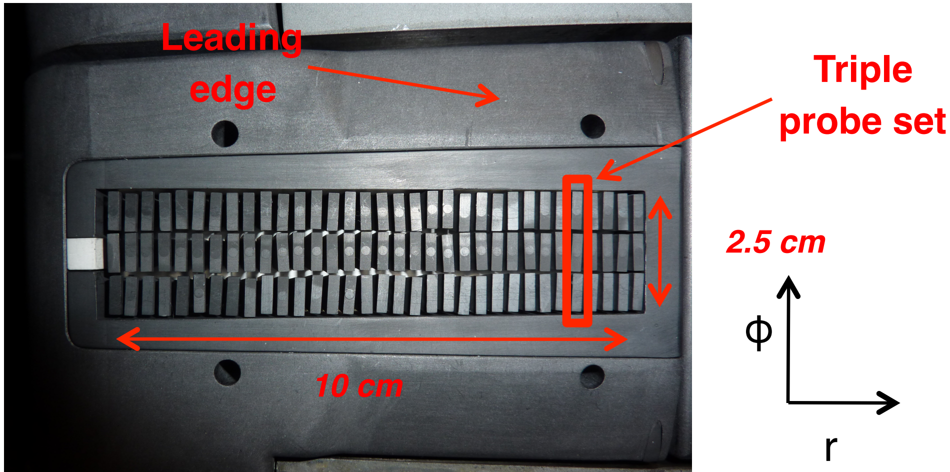
- The classical value of γ is ~ 6.9 if $T_e = T_i$, and $\delta_e = 0$
- Does the experimental sheath heat transmission match the classical value, or does an 'effective' value need to be used?
- Requires multiple diagnostics for measurement, good cross-calibration abilities

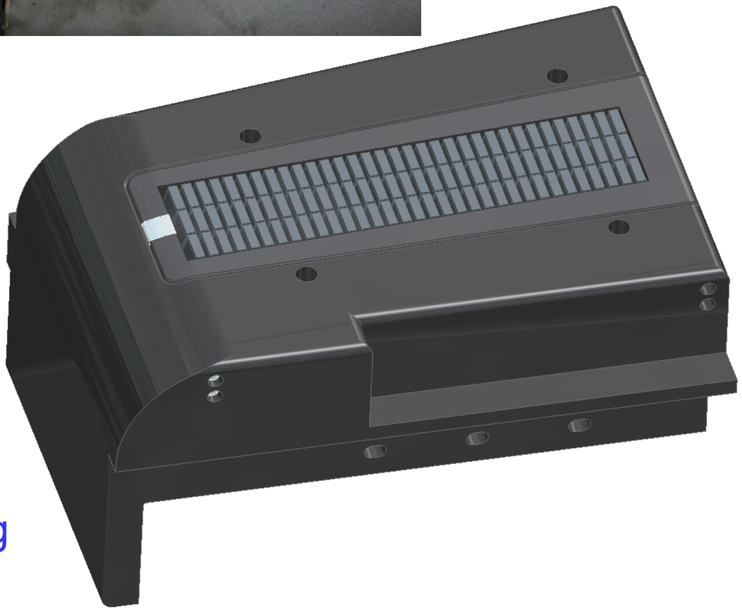
Measurements necessary for determining sheath heat transmission

- 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

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





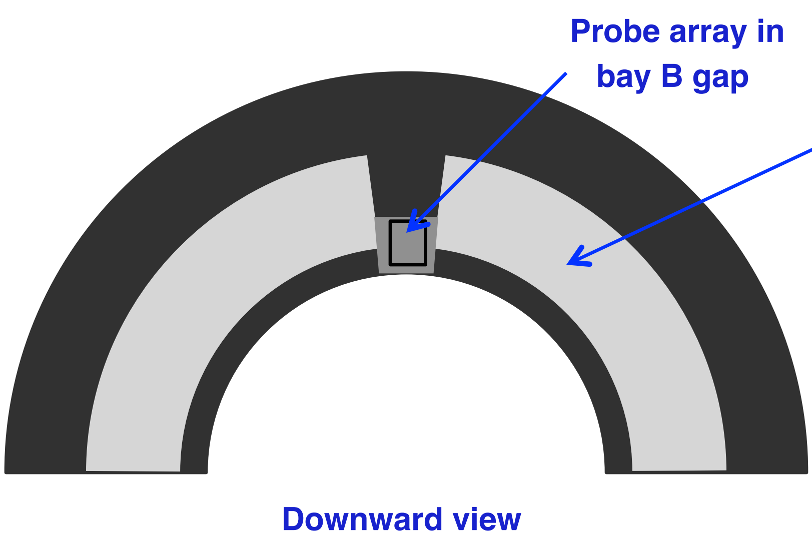
[1]Kallman; Jaworski, RSI (2010); **81**:10

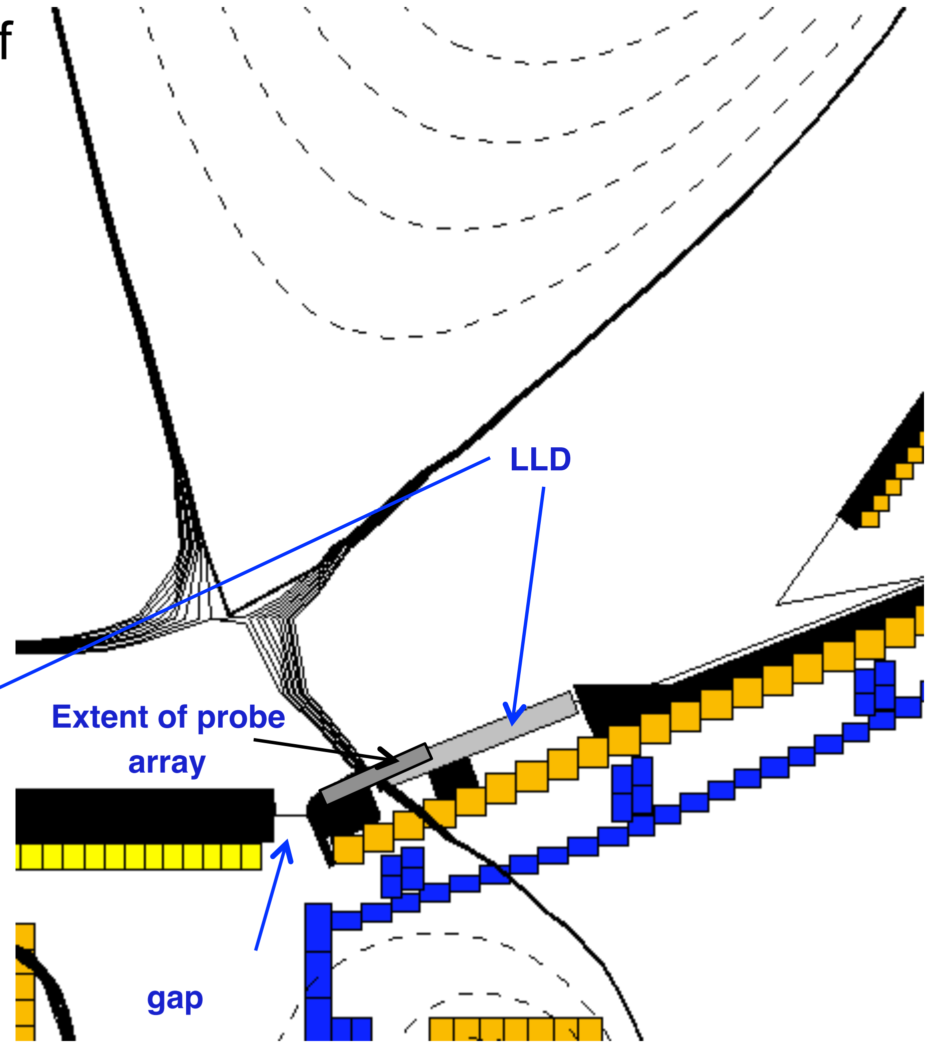
Heavy lithium depositions on divertor surfaces present materials challenge

- 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

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

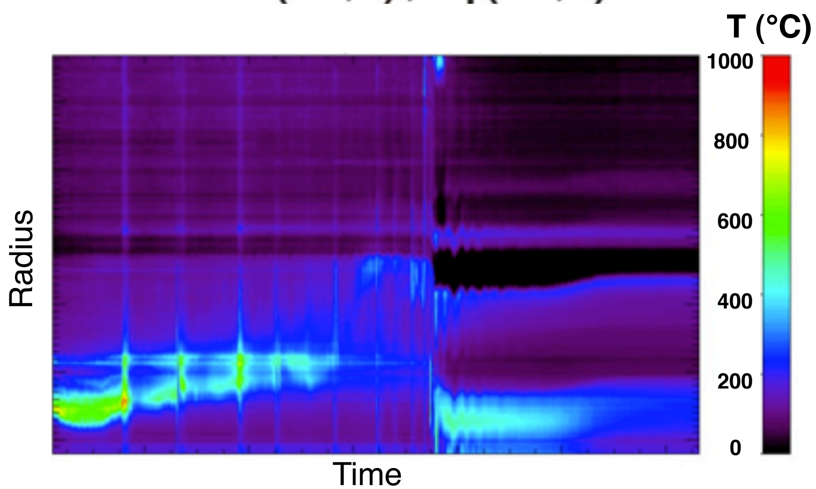


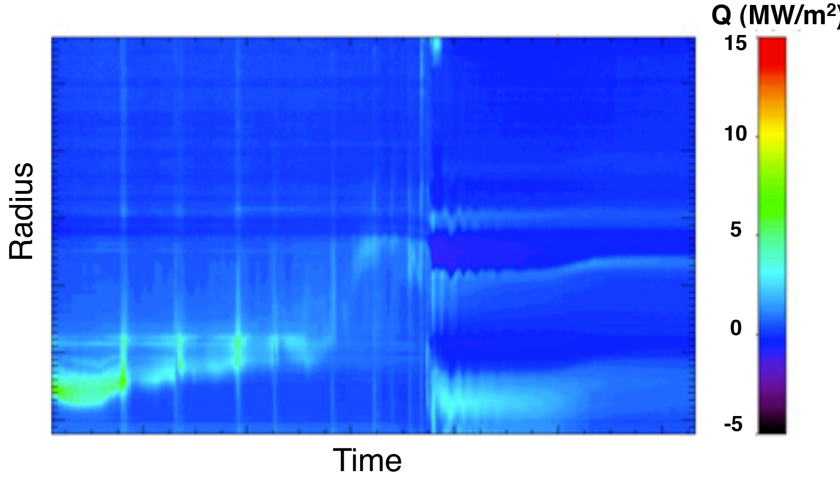


Dual-band IR camera compensates for emissivity changes in the lithium surface

- ORNL collaboration to take fast camera IR measurements at 2 wavelengths at 1.6 kHz
  - 4-6 μm and 7-10μm
  - 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

T(R,t), q(R,t)

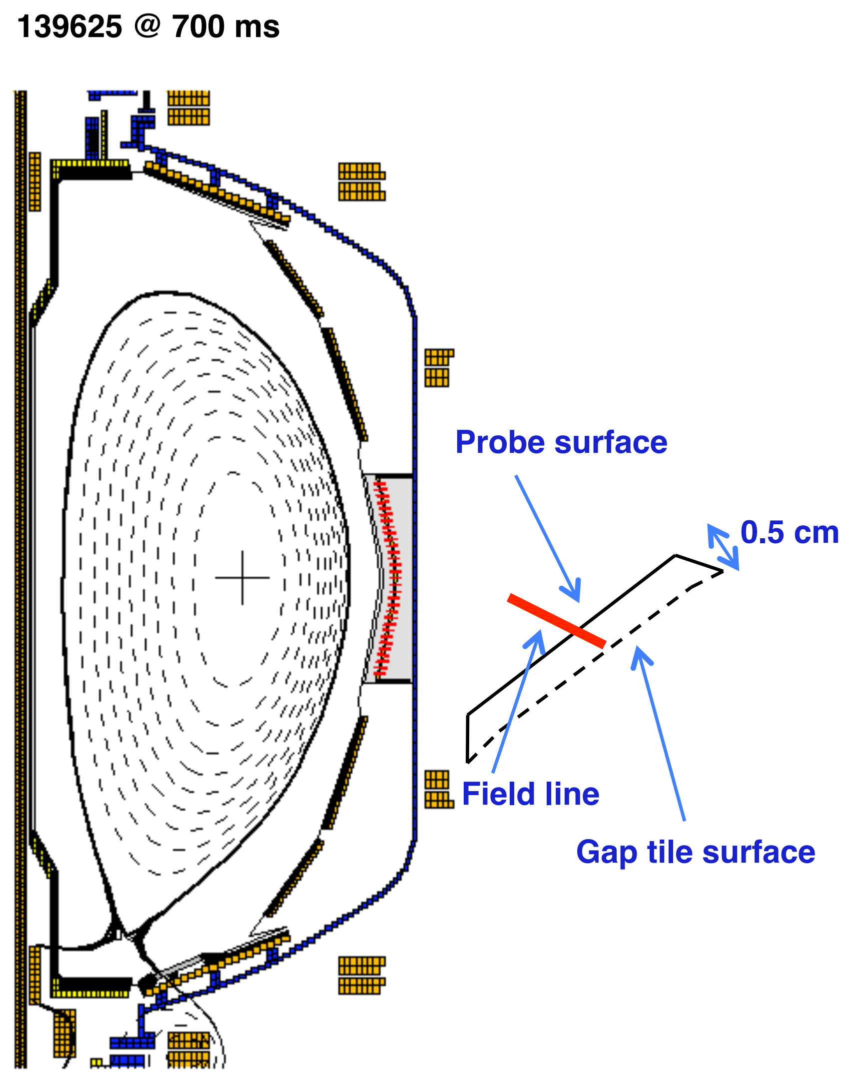




See PP9.00069 by A.G McLean

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

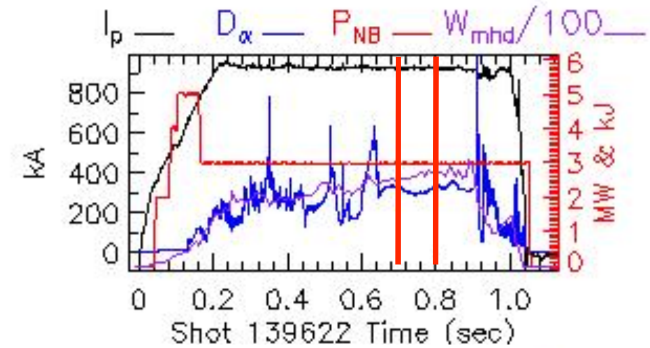


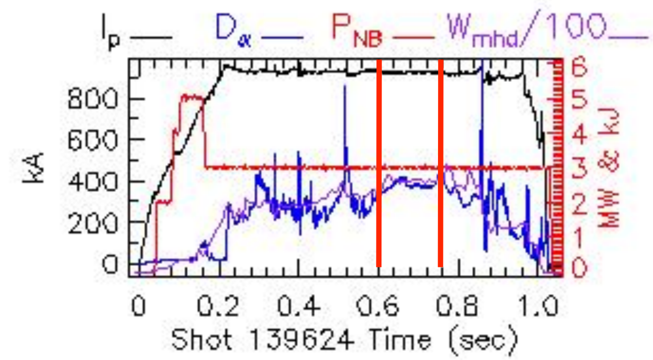
Data selection criteria

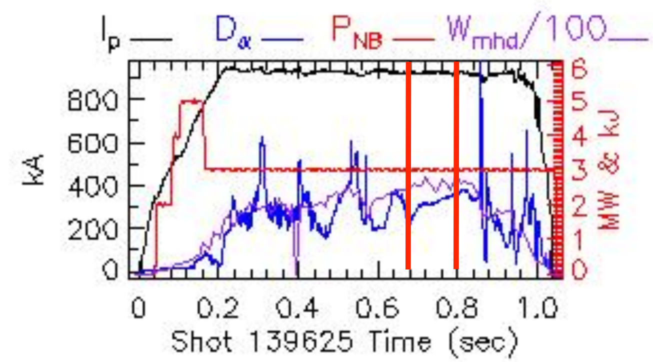
- Discharges must have the strike point position on the probe array to ensure sufficient signal
- Quiescent periods chosen to minimize high transient fluxes due to ELMs
  - generally restricted time windows to 100-200 ms
- IR camera data not available for all shots; sufficient signal desired for optimal 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

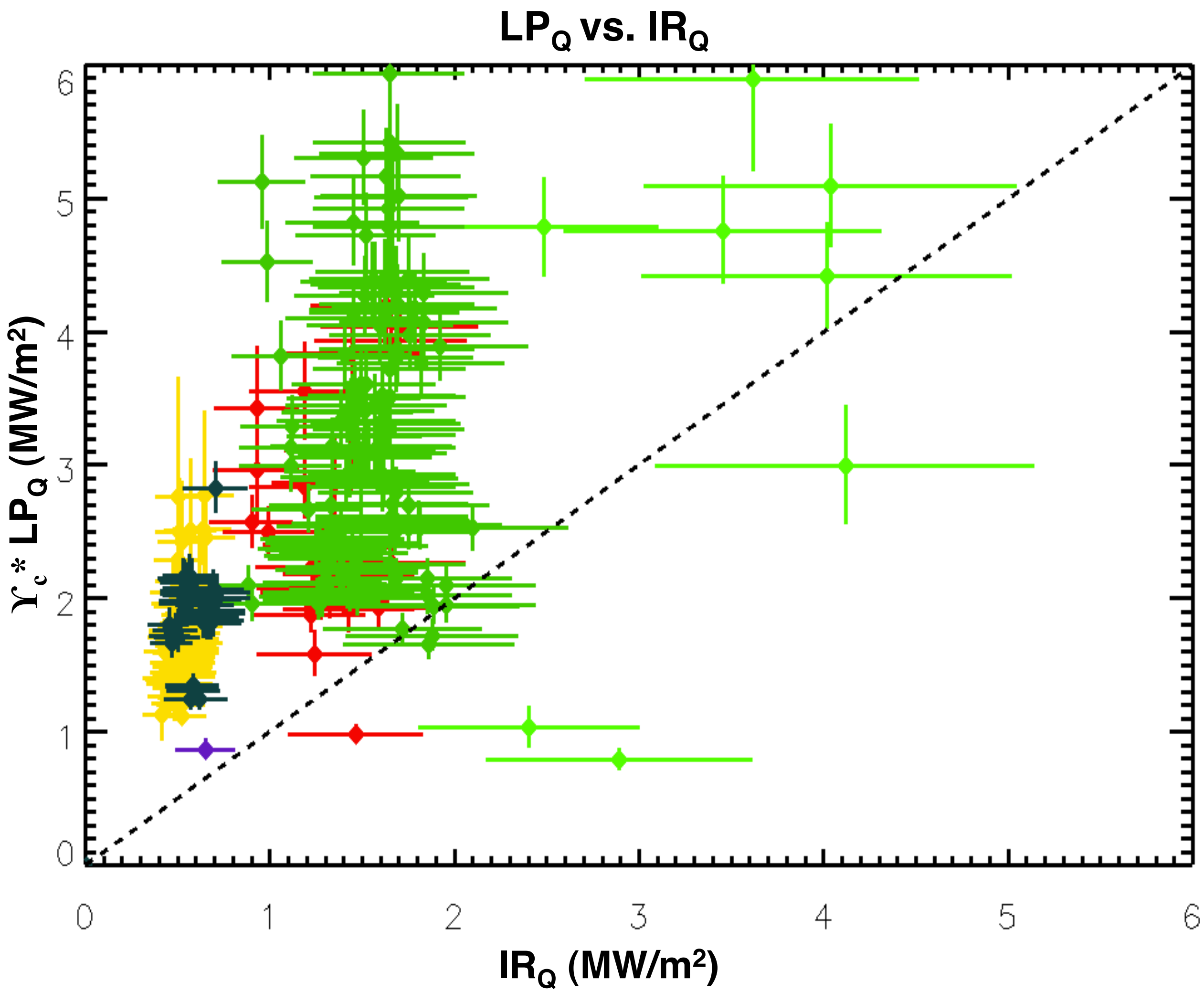
- Selection criteria above limit the number of useable data points for each discharge
- 100-150ms time window limits to approximately 25 points per single probe and 50 points per triple probe
- Floating potential criteria further eliminates data points, sometimes excluding probes altogether
- Signals 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





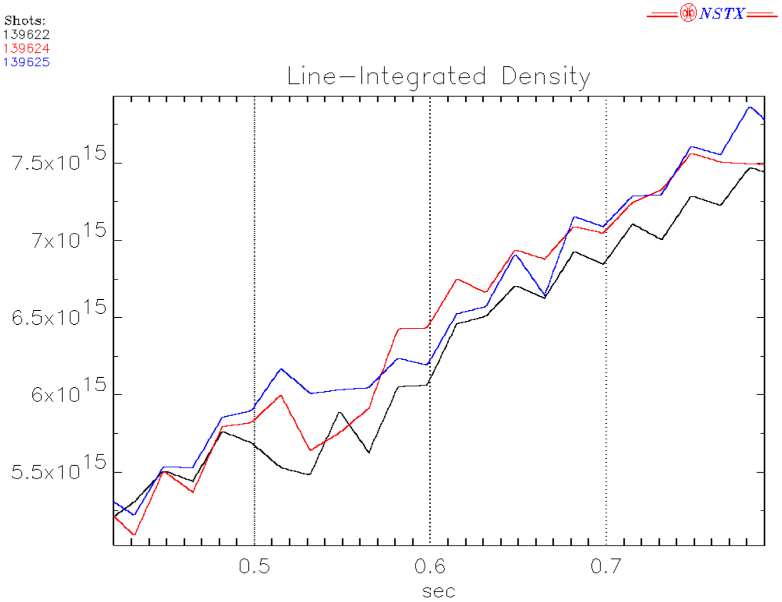


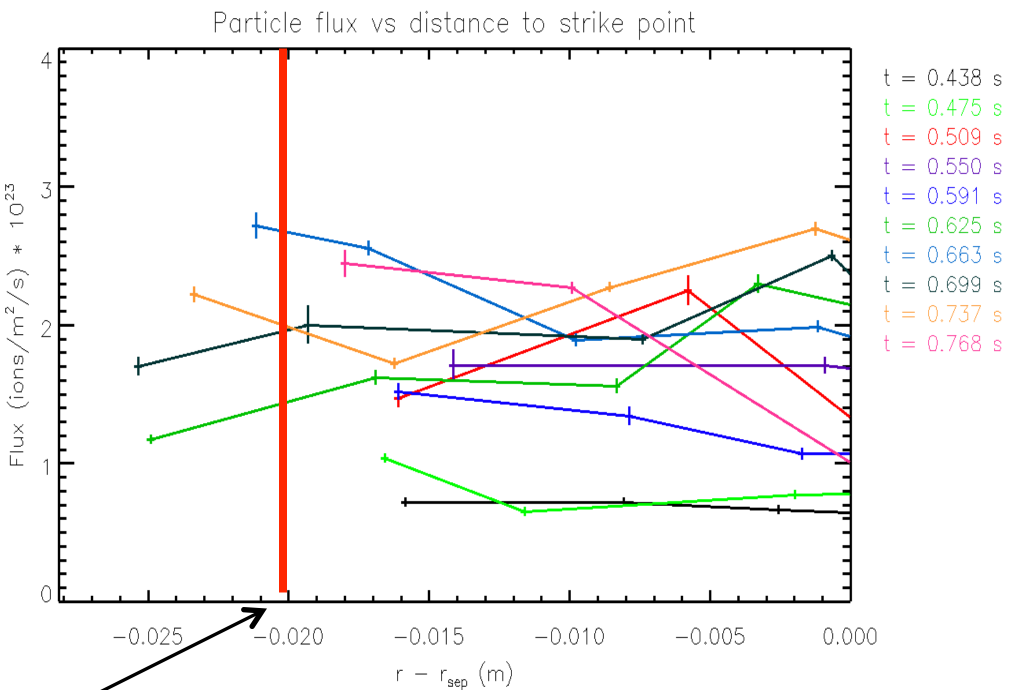
Aggregate data from several shots show deviation from classical predictions



- Weighted average is 2.49, nearly a factor of 3 below classical result
- Lithium can alter basic picture
  - changes to temperature ratio
  - impurity accumulation/ suppression
  - altering collisionality of plasma over time and vs. radius
- How does the time history of plasma parameters contribute to profiles for γ?
  - broaden shot time window to include earlier periods

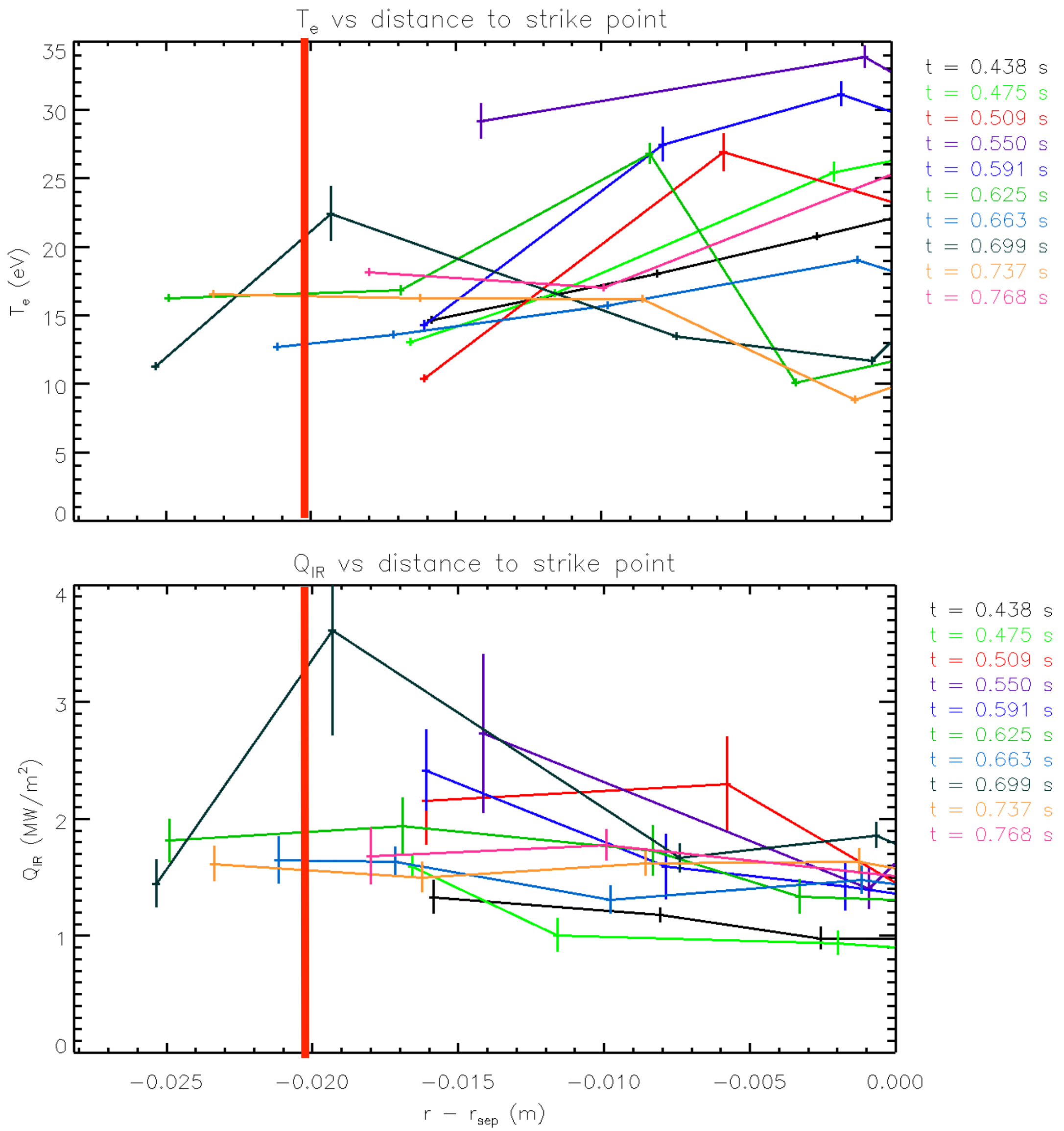
Time evolution of particle flux to probes near strike point follows line-integrated plasma density





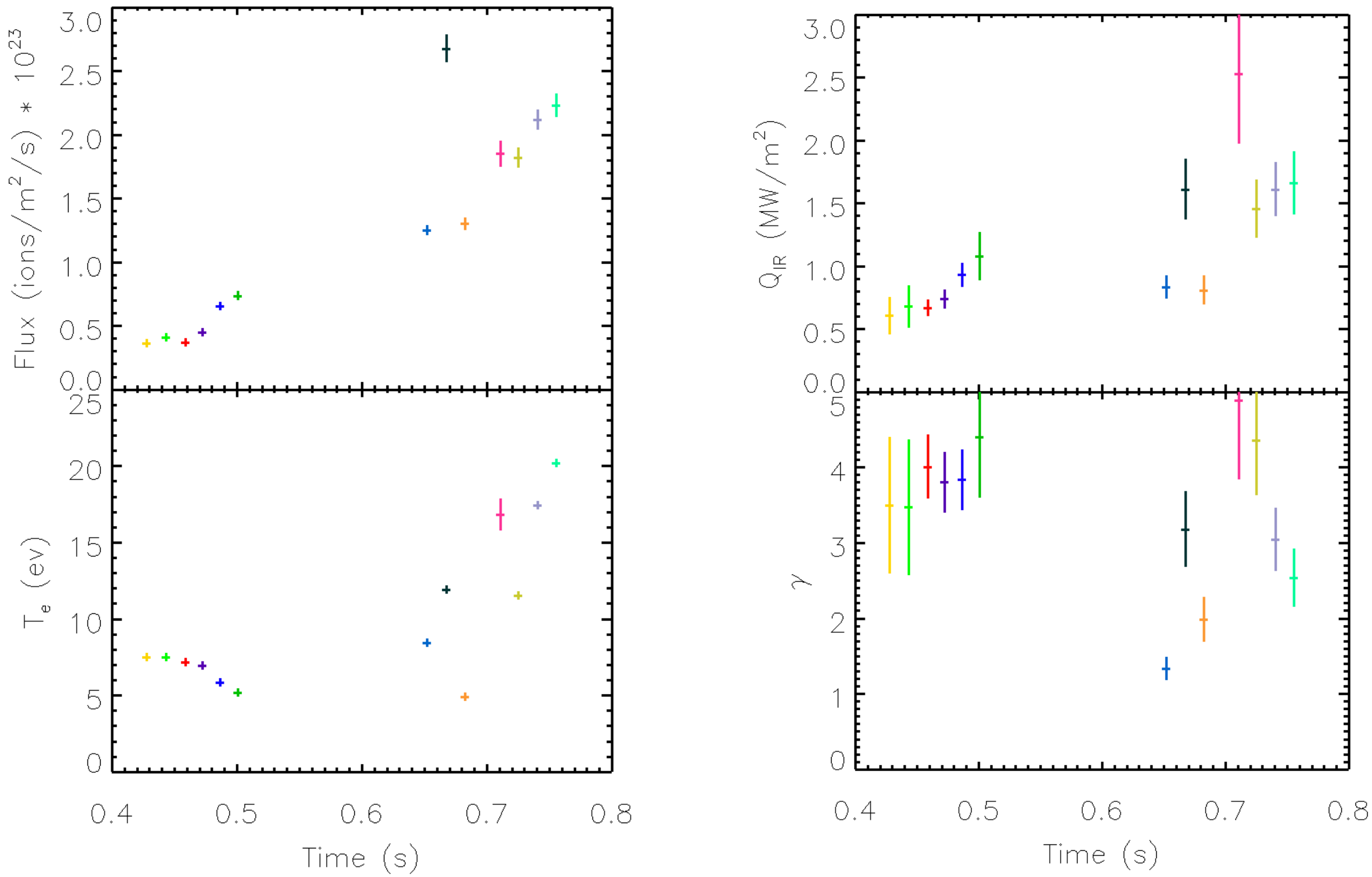
Strike point location

Over same interval, IR flux and electron temperature show no clear trending

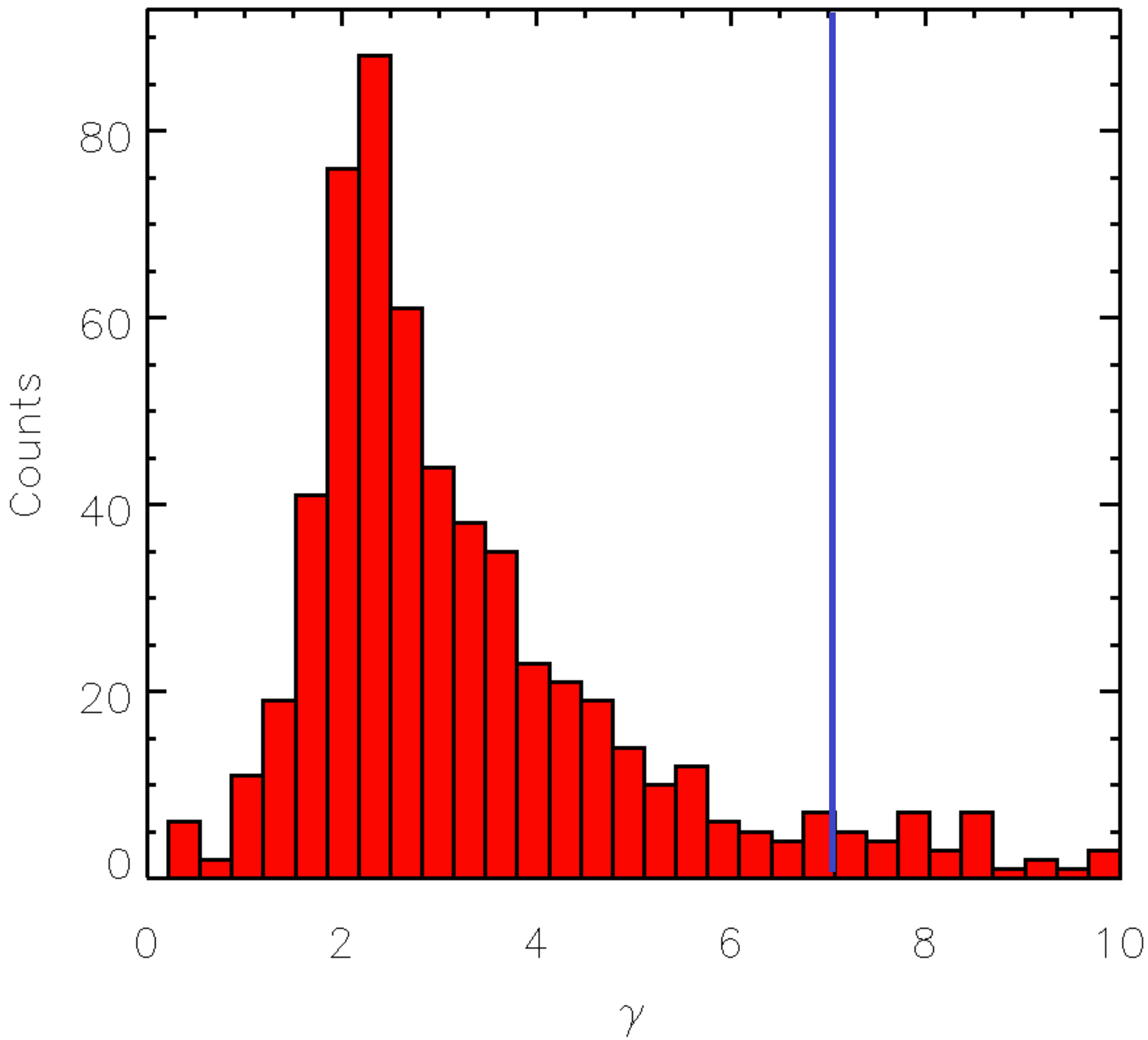


Closer examination of strike point region shows later time evolution of γ

- **Early time shows steady γ, while value is increasing at later times**



Aggregate values of γ are still well below classical prediction of ~7

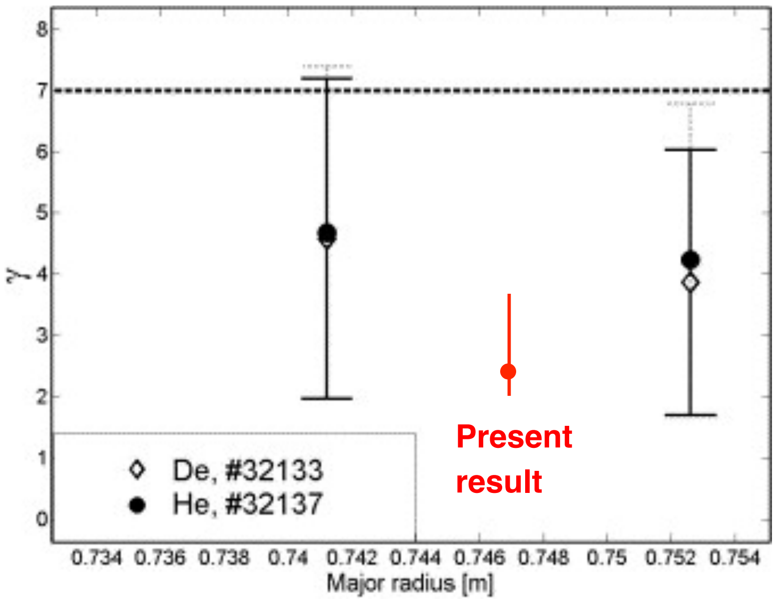


Conclusions and discussion (I)

- 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 for quiescent periods, though temporal evolution is observed in strike point region
- 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
- Modifications of terms in classical equation lead to *higher*, rather than lower values for γ
- Conception of γ comes from fluid picture of plasma edge in thermodynamic equilibrium
  - values in strike point region seem to evolve during quiescent period (though plasma density is still evolving as well)
- Plasma parameters at divertor target (probe measurements) are indicative of high collisionality



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

- Work is in progress to determine role of other factors (such as importance of local temperature scale lengths) that can lower γ below theoretical minimum

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