Measurements of impurity concentrations and transport in the Lithium Tokamak Experiment (LTX)

D.P. Boyle, R. E. Bell, R. Kaita, M. Lucia, R. Majeski, J. C. Schmitt, PPPL

F. Scotti, LLNL

S. Kubota, UCLA

C. Hansen, University of Washington

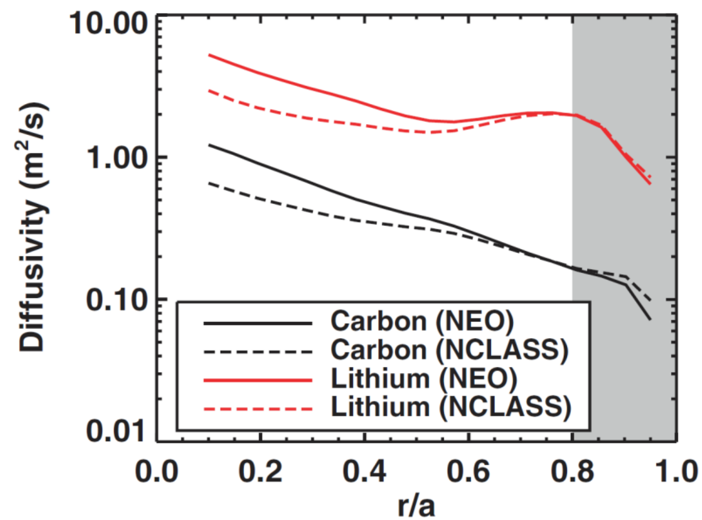
T.M. Biewer, T.K. Gray, ORNL

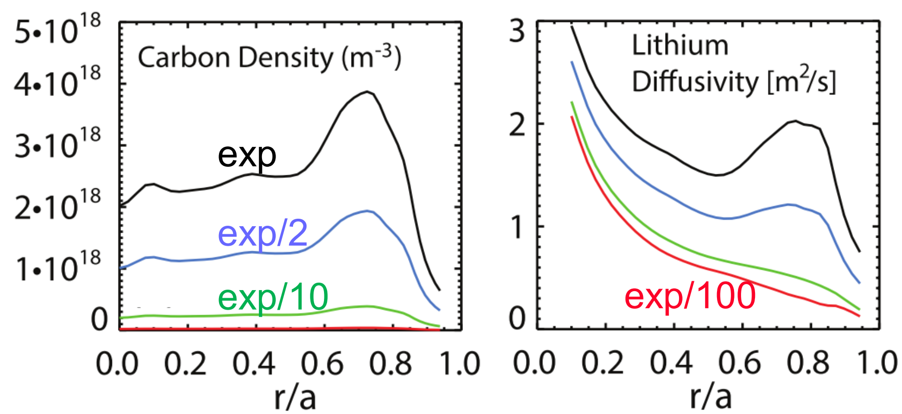
Li predicted, demonstrated to improve fusion

- Liquid metals could solve many wall issues
  - Can't break/crack, erosion not issue so can be thinner
  - Substrate only has to handle heat & neutrons, not plasma
  - Can flow or evaporate to handle heat, remove tritium
    - » Liquid lithium not addressed in this poster
- Low Recycling due to chemical bonding of H/D
  - Improved density control
  - Improved energy confinement in TFTR, NSTX, CDX-U
  - Reduced edge thermal losses, gradients, turbulence?
- **Reduce impurities**
  - Li relatively benign: Low-Z and low first ionization potential
  - Sputtering decreases with higher edge T_i for $T_i > 200$ eV
  - Getters other impurities from residual gases
  - Buries surface impurities (as solid) or dissolves (as liquid)

NSTX had very little core Li contamination

- Core Li concentration <0.1%
  - Up to 1.3 kg of Li in vessel
  - Li sputtering yield >> C
- C accumulation up to 10%
  - Got worse as Li suppressed ELMs & improved confinement
- Determined that C impurity accumulates & pushes out Li via neoclassical transport
  - D_{Li} would be 40-80% less w/o C
  - Prompt Li redeposition and low SOL penetration also important
- Understanding based on careful profile measurements & modeling
- TRANSP, NCLASS, & MIST





Ref: F. Scotti, Nucl. Fusion. **53** (2013) 083001

Experience w/ Li on C in NSTX raised questions

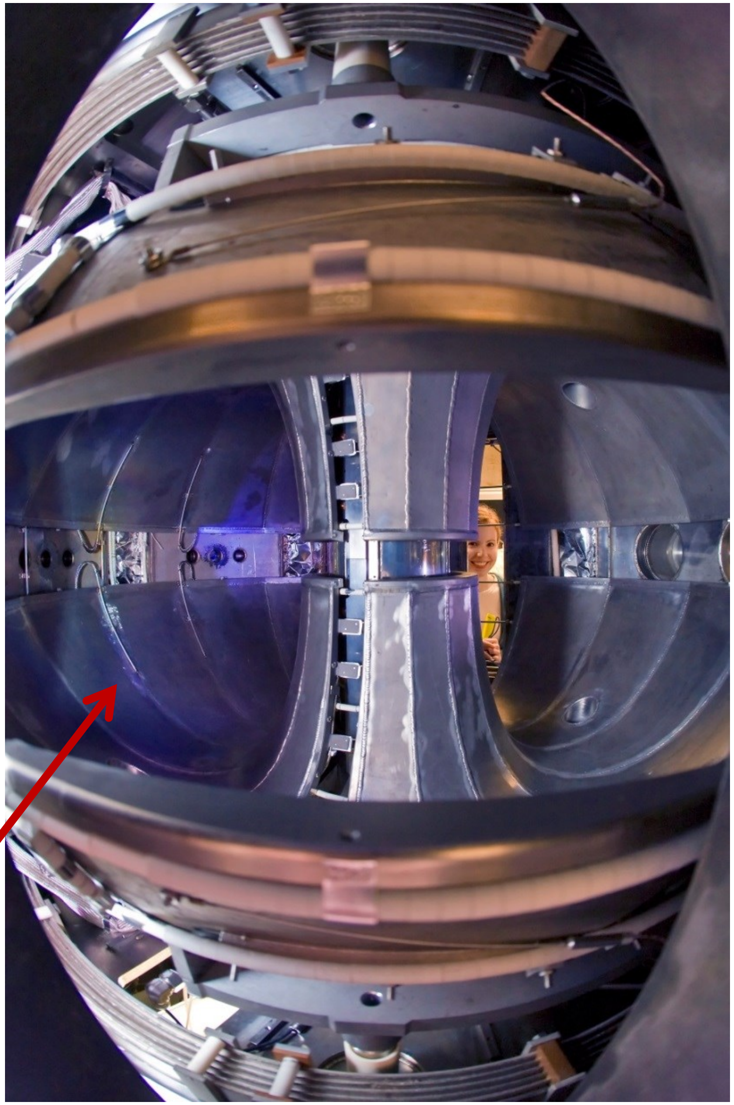
- **Will Li levels stay low in all-metal machine?**
  - NSTX <0.1% Li, but largely pushed out by C
  - Eventually NSTX-U & future devices -> all-metal walls (no bulk C)
  - What if much less C to push out Li?
- **Will Li really reduce impurities?**
  - Sputtering and evaporation higher than other materials
    - » Increases strongly with surface temperature
  - Li could potentially bring *more* impurities to surface by gettering, leaching from substrate, segregating to surface of static liquid
  - NSTX saw 3x more C in core after Li coatings (ELMs suppressed)
  - What happens w/ different impurity source? (Li on all-metal vs Li on C)
- **Neoclassical worked in NSTX, what about LTX?**
  - Large, carbon, diverted, NBI heating & fueling vs small SS limiter ohmic

Use LTX to study Li & C transport in all-metal ST

- Stainless steel PFC (no bulk C)
  - Can be entirely coated w/ Li
- 4 shells cover ~80% of surface
  - Heatable to ~350 °C for liquid Li

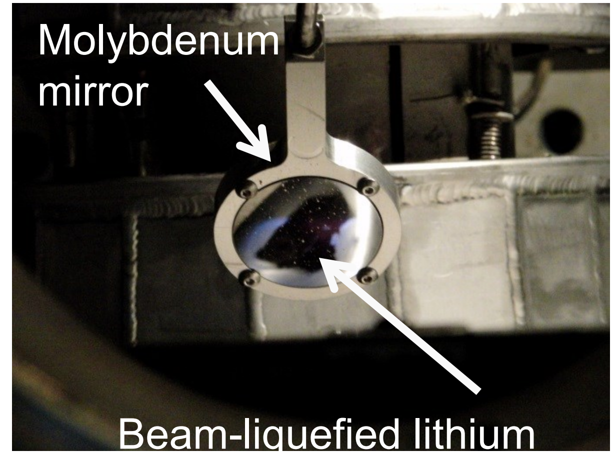
Operational Parameters	
Major Radius	R_o=0.40 m
Minor Radius	a=0.26 m
Toroidal Field	B_T=0.18 T
Plasma Current	I_p< 85 kA
Plasma Duration	t< 50 ms

Shell is 1.5 mm stainless steel liner on 1 cm copper, for good thermal conductivity and lithium resistance.

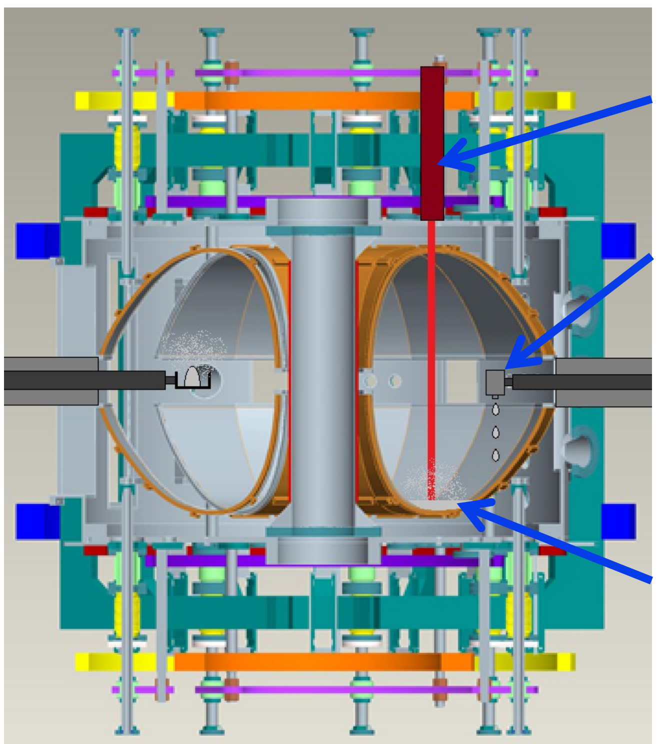


Lithium evaporated w/ 1.5 kW electron beams

- New lithium coating systems developed
  - Electron beam evaporation of lithium inventory in lower shell
  - Systems are cooled and discharges initiated in less than an hour
    - Or wait until next day



Lithium pool is imaged in a molybdenum mirror during beam heating.



Electron Gun

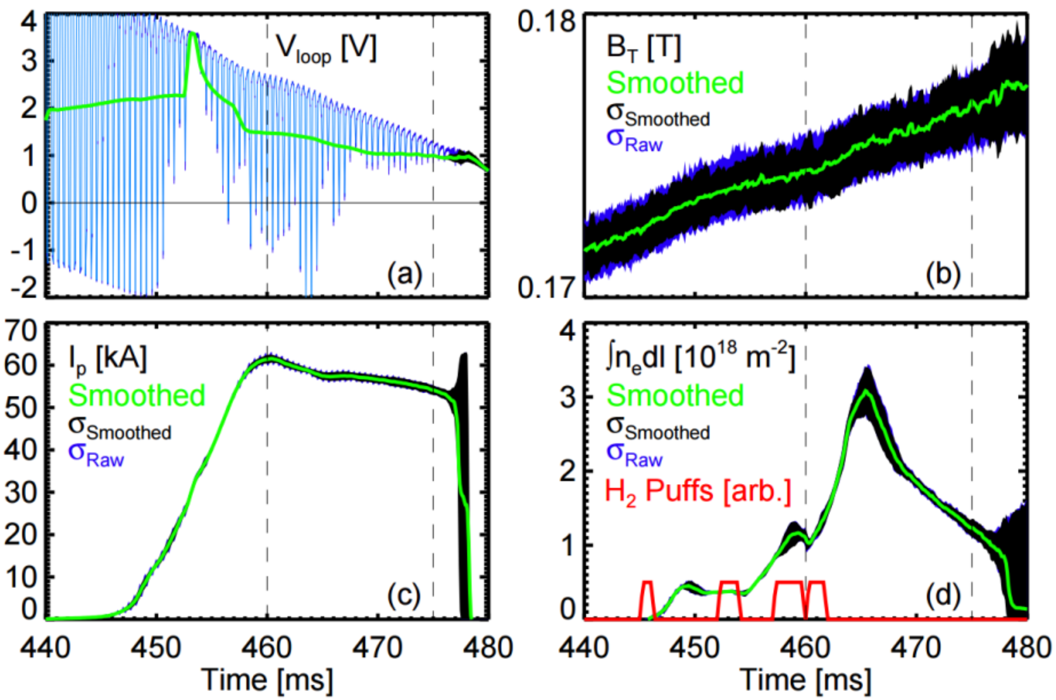
Crucible Filler

Lithium Pool

Electron beam evaporation

- Li drips from heated crucible, creating Li pool in lower shell
- Electron gun targets (preheated) Li pool, evaporation in vacuum

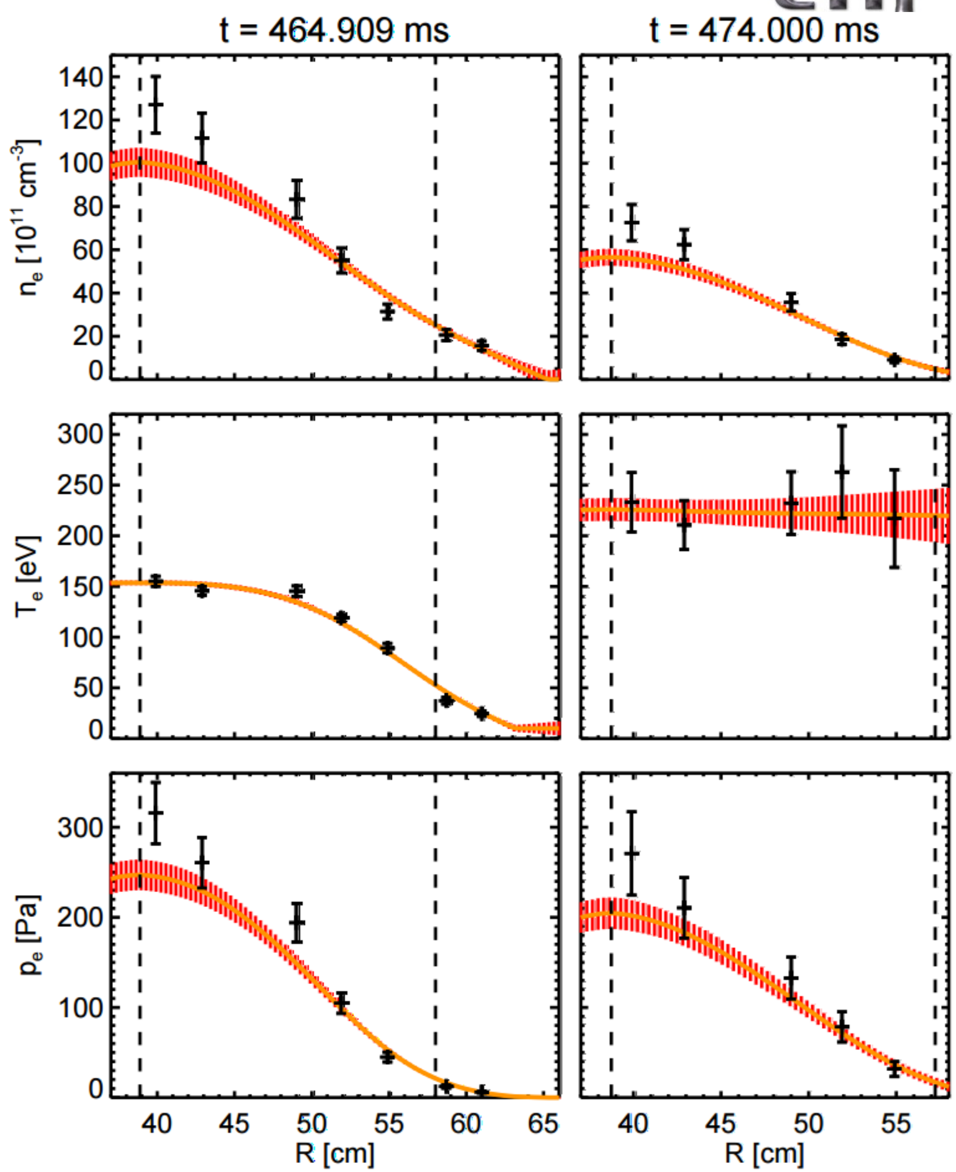
55 reproducible discharges w/ solid Li coatings



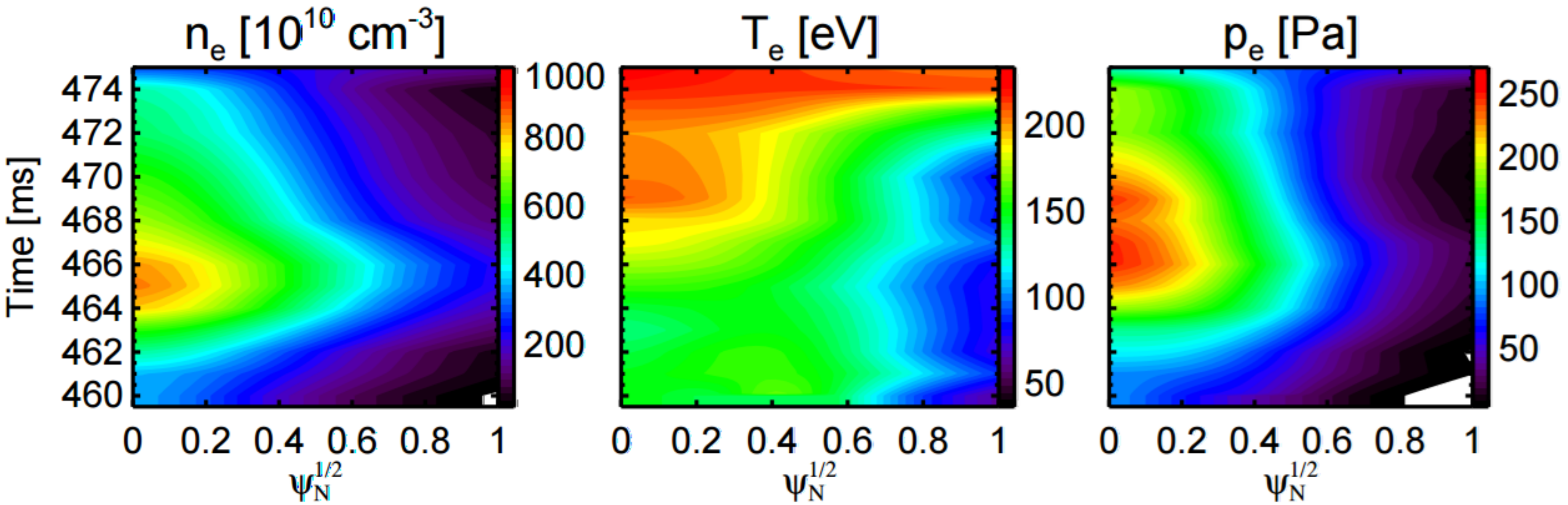
- New loop voltage programming to keep I_p ~ constant
- Large gas puff
  - Study plasma w/o fueling
  - Boost spectroscopic signals
- Smoothed median waveforms input to TRANSP

T_e profiles flatten at edge after fueling ends

- 15-20 J single pulse Ruby laser
- 11 views, iCCD spectrometer
- Multiple shots averaged
  - TS time scanned, repeated
  - Spectra summed before fitting
  - Sum nearest neighbors (±1 ms)
- p_e constrains PSI-TRI magnetic equilibrium reconstructions
  - C. Hansen Thesis, U. Wash 2014
- Smoothing spline fits
  - Interpolate to finer radial grid
  - Extrapolate to magnetic axis
- n_e normalized w/ 1 mm interferometer
  - Assumed to be flux function, mapped to LFS w/ equilibrium
  - Good match to reflectometer

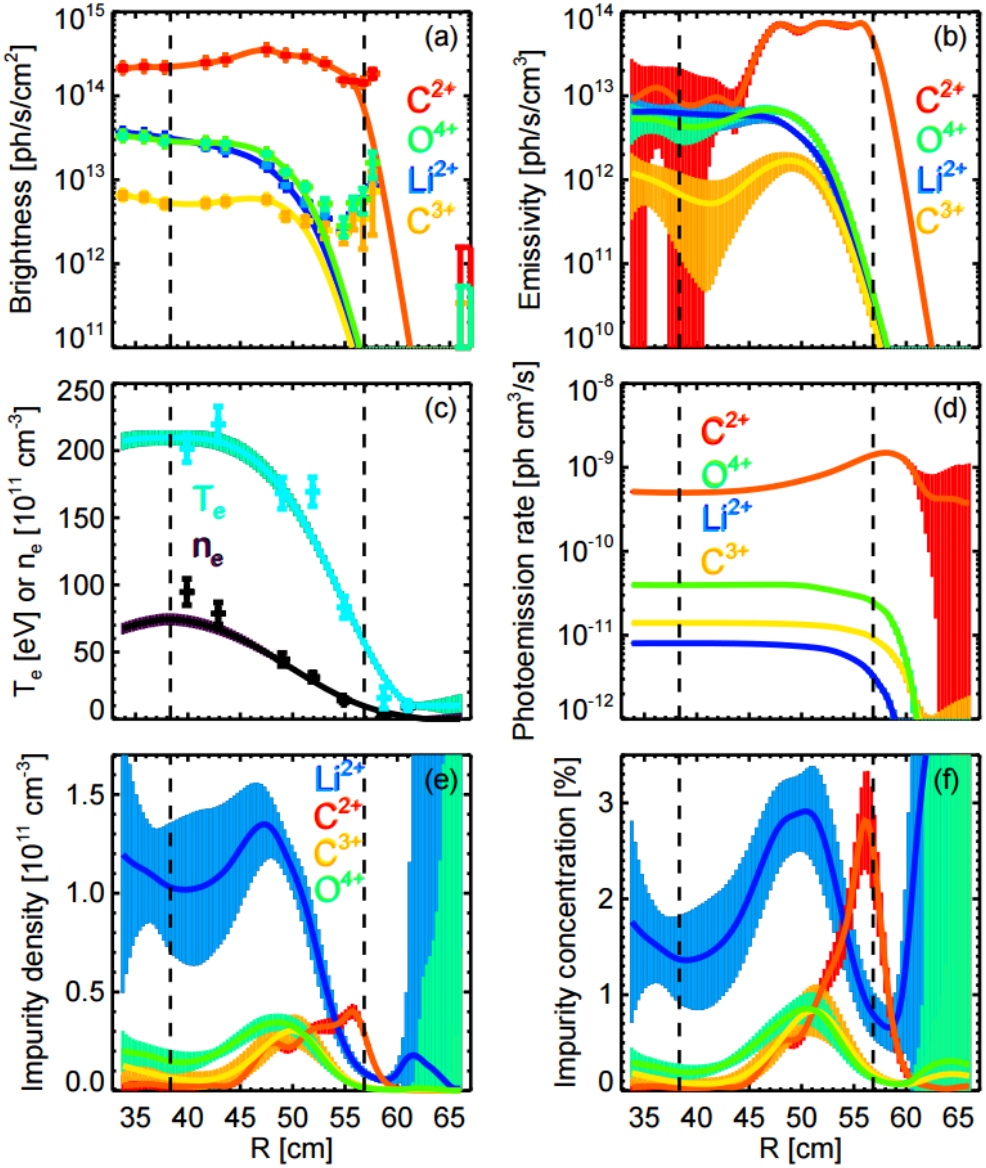


TS profiles measured throughout 15 ms "flattop"



- Centrally peaked profiles
- T_e flattens, increases after fueling ends (t > 472 ms)
  - Hot, low density edge suggests low-recycling regime
  - See P3.45 "Flat temperature profiles and the implications of very high edge temperatures in LTX" by R. Majeski
- Profiles input to TRANSP, used for impurity profiles

Impurity profiles from HAL visible spectrometer

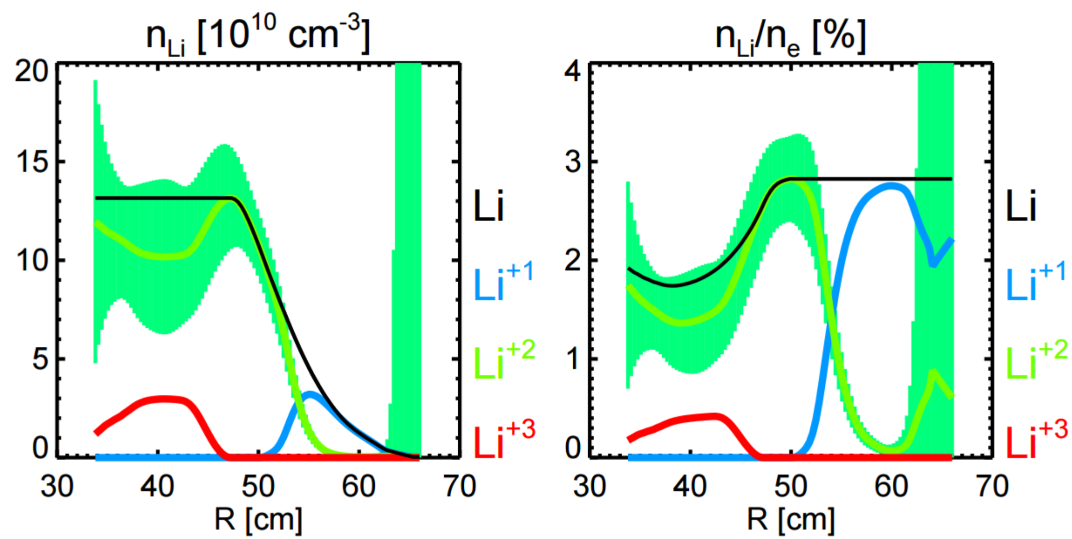


- 13 toroidal views
  - High-throughput, Accurate-wavelength, Lens-based (HAL)
  - Li III 450 nm, C III 465 nm, C IV 580 nm, O V 650 nm
- Smoothing spline to log(Br) for inversion
  - Edge views vignetted, spectra overlap other lines
  - Brightness forced to drop at edge
- TS profiles interpolated in time, averaged over 2.5 ms HAL frames for ADAS rates

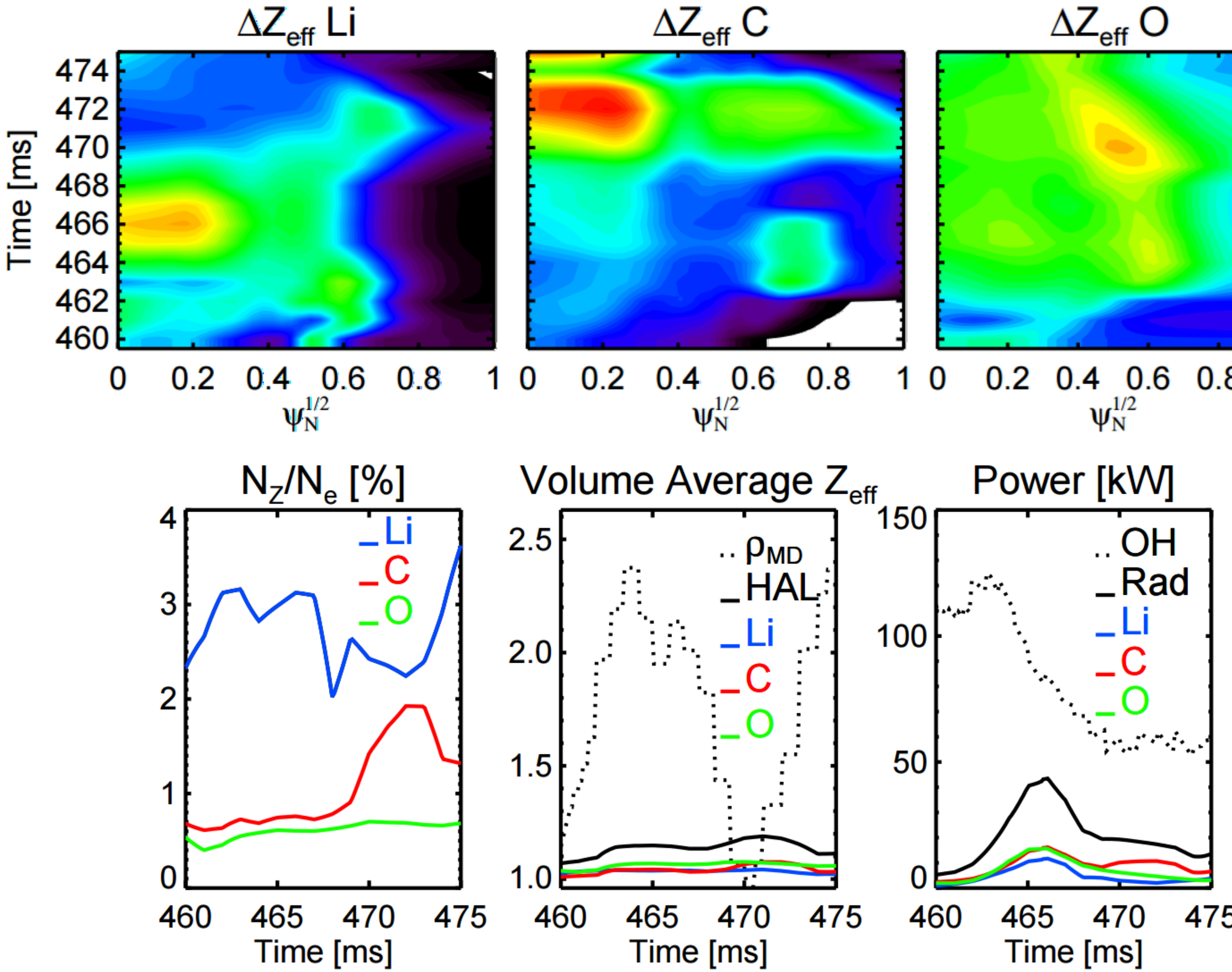
Simple model used for unmeasured charge states

- HAL does not measure all impurity charge states
  - Li^{3+} needs NBI, other high states in VUV, not visible
  - Low states emit near edge, hard to invert profiles
- In core, extend peak measured **density**

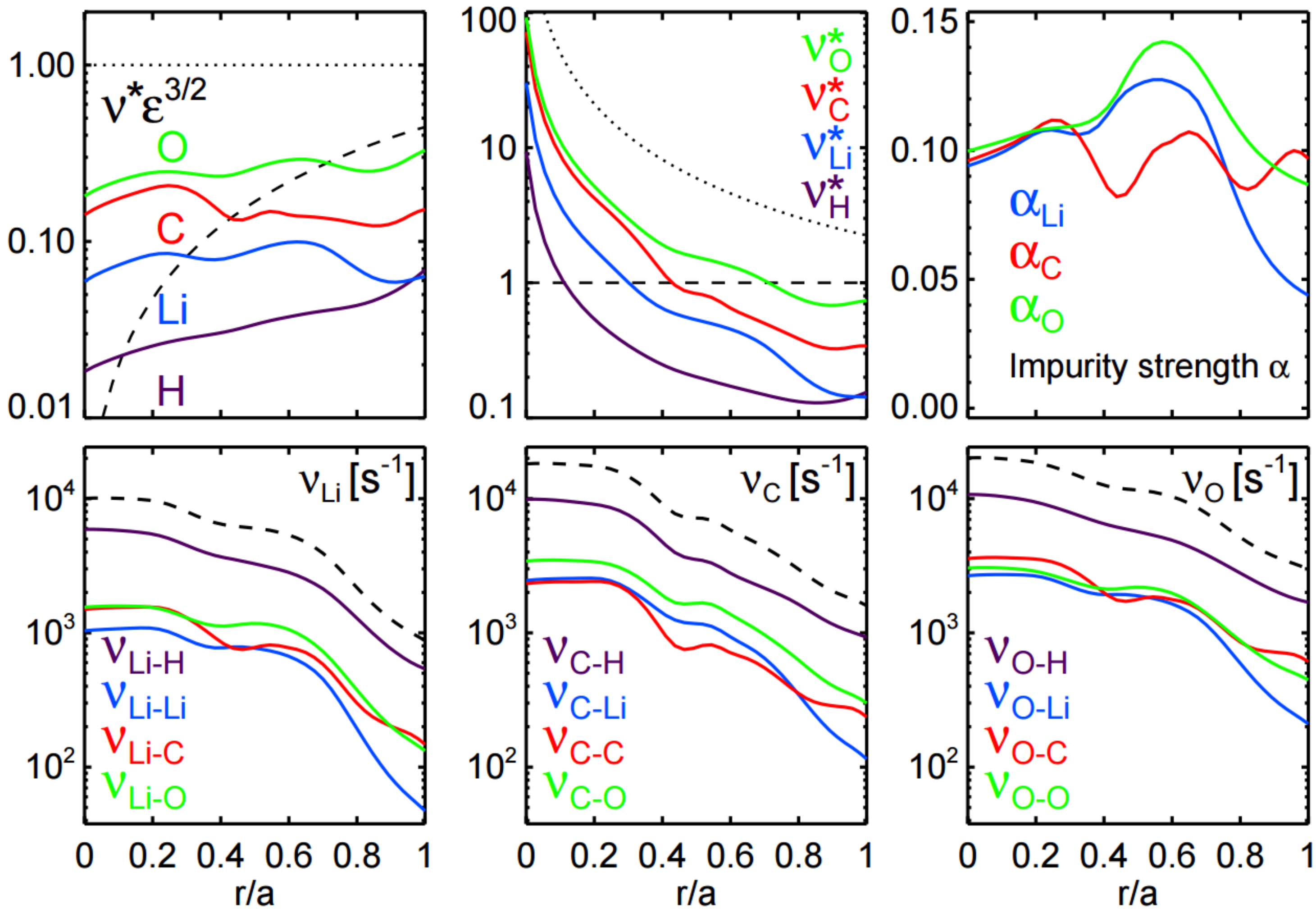
  Fill in w/ next highest state (Li^{3+}, C^{4+}, O^{5+})
- In edge, extend peak **concentration**
  - Fill in w/ next lowest state (Li^{+}, C^{+}, O^{3+})
- Uncertainty weighted time interpolation & gaussian smoothing (σ_t=0.5 ms) of concentration



2-4 % Li, 0.6-2% C, 0.4-0.7% O, Z_{eff}<1.2

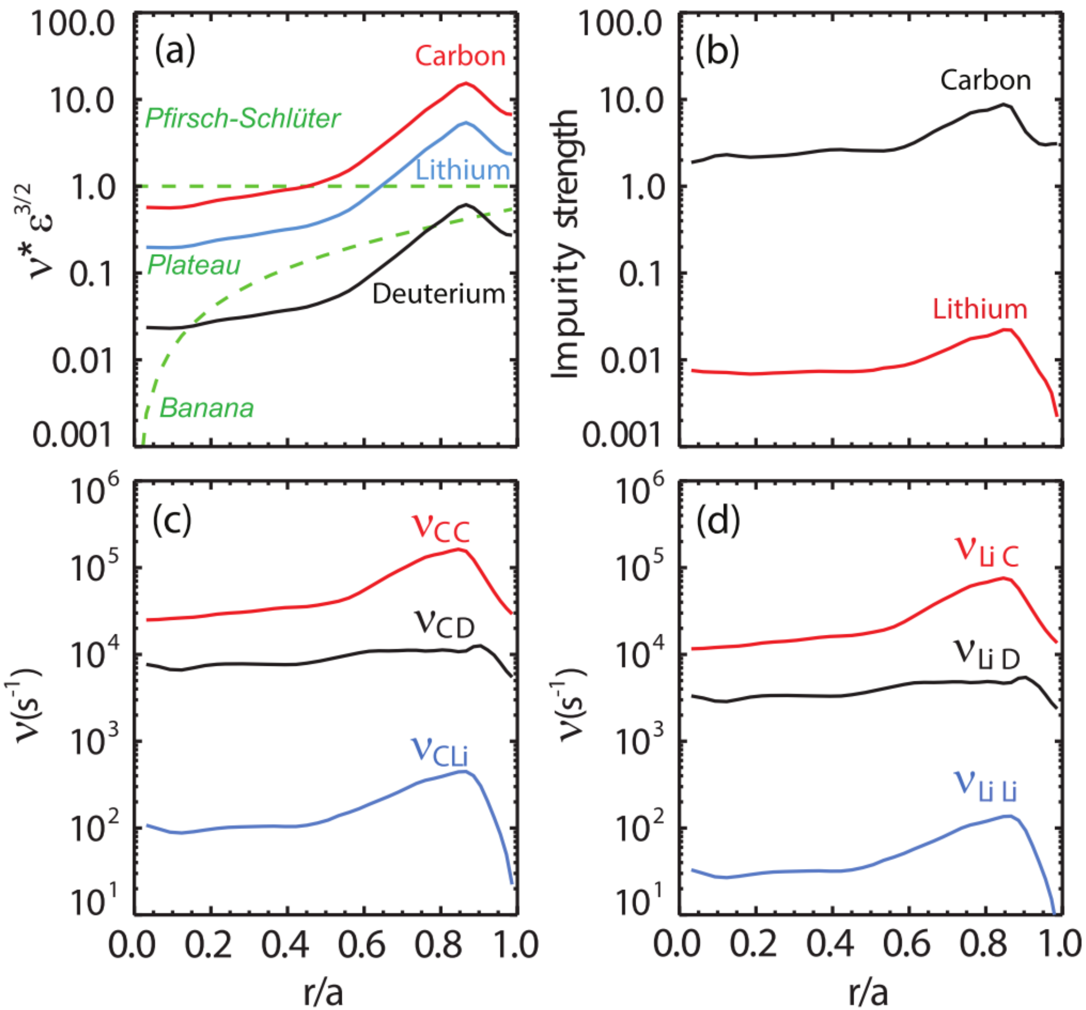


Impurity collisions dominated by main ions



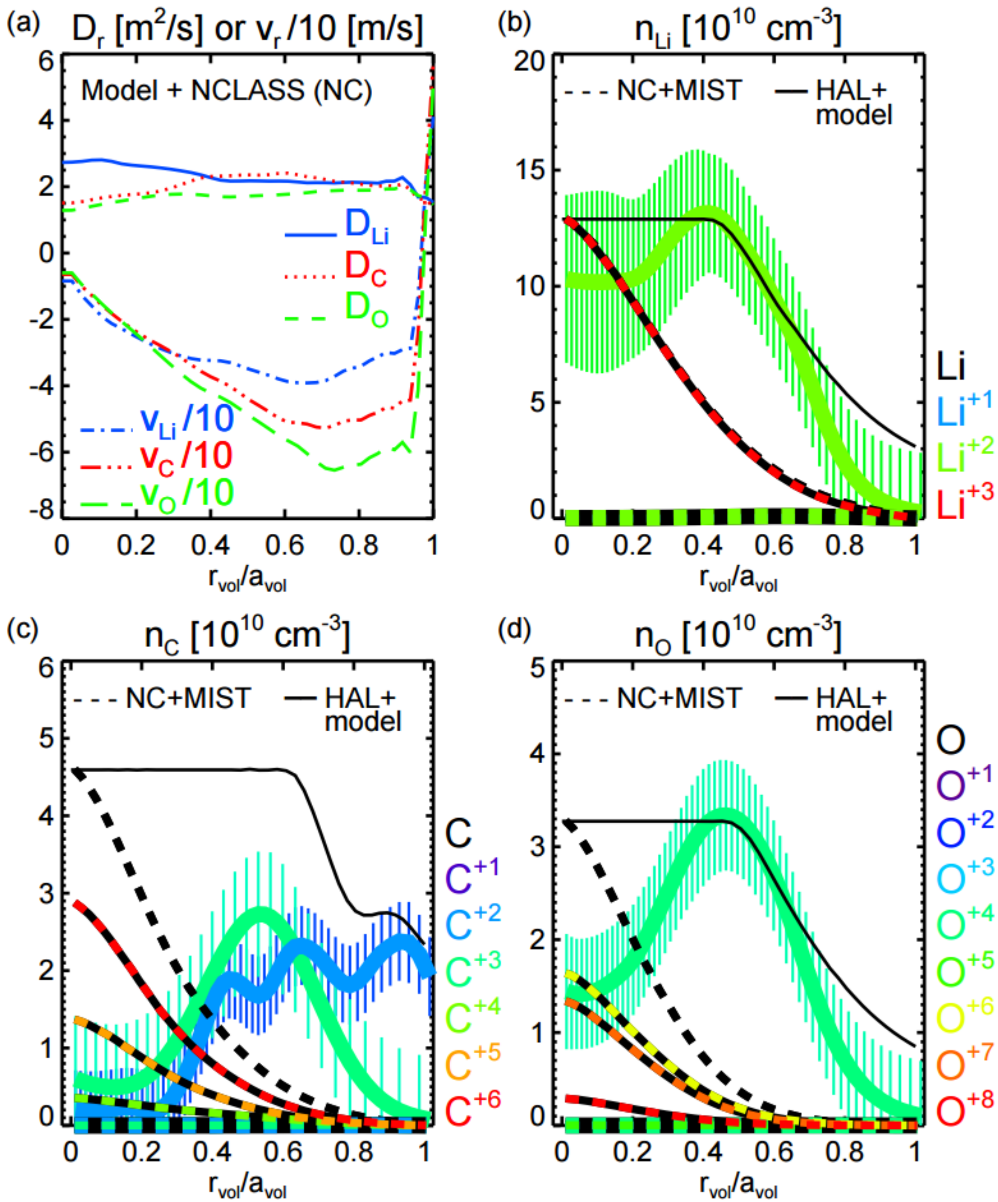
- Impurity strengths $\alpha<0.2$ through discharge, total<0.5

LTX contrasts with NSTX, where C dominated



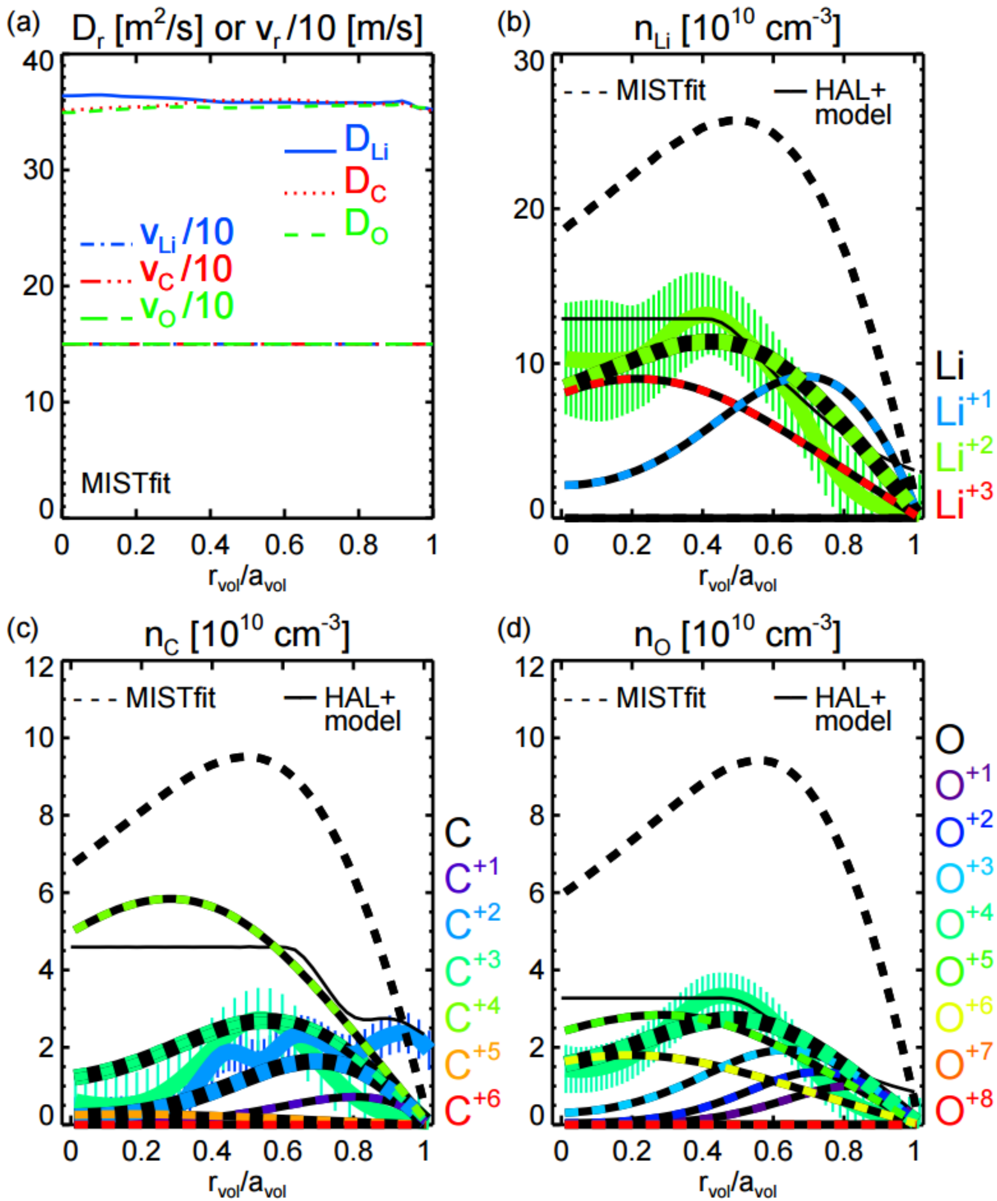
- Carbon impurity strength $\alpha_C > 2$, Lithium $\alpha_{Li} < 0.02$

MIST runs w/ NCLASS D & v don't match data



- NCLASS run using TRANSP output
- D & v similar across species, D ~ 2 m²/s
  - Contrast to NSTX
- Time-independent MIST simulations using NCLASS D & v do not match shapes of measured profiles
  - Show most impurities in high charge states

Varying D and v can match measured profiles



- Non-linear fits vary MIST D & v to match measured charge state profiles
  - Many different D & v profiles can fit data
  - Need D>10-15 m^2/s
  - v>0 (outward) in most fits, can have v=0
    - NCLASS: v<0 (inward)
  - Simple charge model plausible but neither confirmed/refuted

Summary & Conclusions

- Impurity and electron profiles measured in LTX
  - Solid Li coatings on all-metal PFCs surround ~ entire plasma
  - Refurbished TS and new HAL spectrometer measurements
  - T_e flattens w/ hot edge after fueling terminated
  - Simple model used to estimate unmeasured charge states
    - ~2-4% Li, 0.6-2% C, 0.4-0.7% O, Z_{eff}<1.2
    - Li levels low, >>NSTX; C levels low w/o C PFCs, <<NSTX
    - O levels low despite solid Li coatings oxidizing to Li_2O
- Impurity transport assessed w/ TRANSP, NCLASS, MIST
  - All impurity transport dominated by collisions w/ main H ions
  - Impurity strength, NCLASS D & v similar across species
  - MIST time-independent simulations w/ NCLASS D & v do not match measured profiles, need D > 10-15 m^2/s (>>D_{NC}~ 2 m^2/s)
    - Contrast to NSTX, where C "pushed out" Li, D_{Li} >> D_C, impurity transport well described by neoclassical

Future Work

- Enhance analysis to better account for unmeasured states
  - Use hard-to-invert low charge state measurements as constraints
  - Incorporate VUV spectrometers, filterscopes
  - Improve profiles; use reflectometer, Langmuir probes, HAL T_i
  - Time-dependent MIST (STRAHL?) simulations
- Extend analysis to other experiments on LTX
  - Full/partial liquid Li walls, Li coatings w/ more surface impurities
  - Different programming of field coils, loop voltage, and fueling
- Upgrades in LTX-β will enable improved transport studies
  - Neutral beam core fueling & heating, higher current & fields, longer discharges, between-shots Li coating
  - CHERS, improved spectroscopy views, upgraded & edge TS, profile bolometer, time-resolved VUV