Overview of NSTX divertor and plasma-material interactions, diagnosis and modeling

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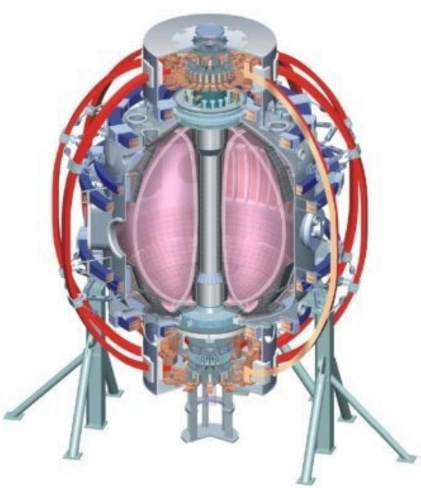
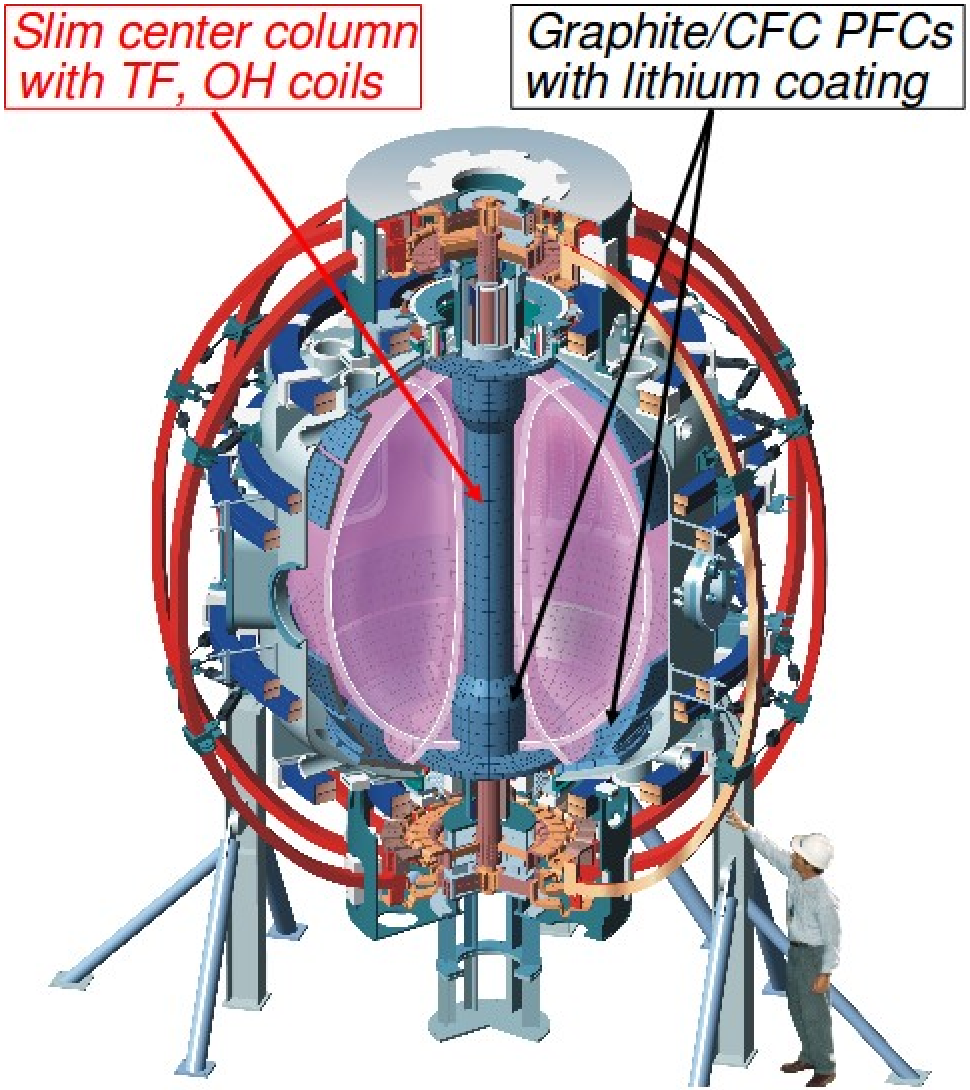


Overview

- Lithium operations in NSTX and boundary issues
- Diagnosis of SOL with Langmuir probe array
  - Hardware
  - Some initial results
  - Initial 2-point modeling of the SOL
- Dynamic plasma facing components (PFCs) in NSTX
- OEDGE interpretive modeling of NSTX
- Building a material model to inform NSTX-U decisions

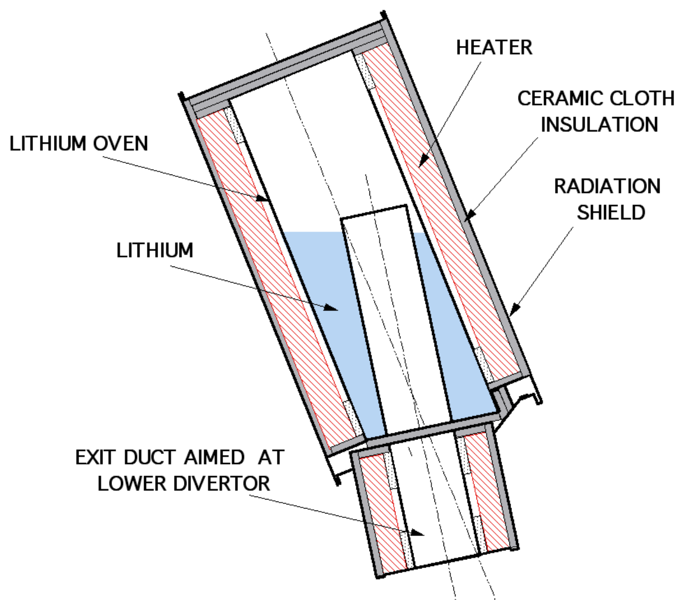
NSTX Overview of Plasma Parameters

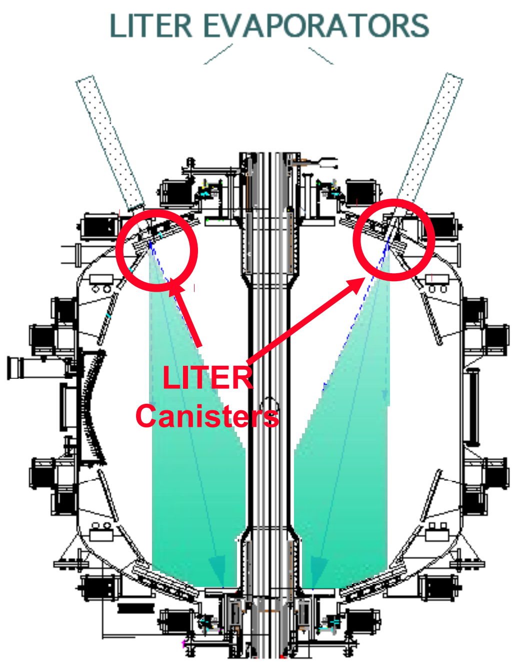


Aspect ratio A	1.27 – 1.7
Elongation κ	1.8 – 3.0
Triangularity δ	0.2 – 0.8
Major radius	0.85 m
Toroidal Field B_{T0}	0.4 – 0.55 T
Plasma Current I_p	0.7 – 1.5 MA
Auxiliary heating:	
NBI (100kV)	7 MW
RF (30MHz)	6 MW
Central temperature	1 – 5 keV
Central density	$\leq 1.2 \times 10^{20} m^{-3}$
Toroidal beta β_T	10 – 40 %

Lithium Deposition via Evaporation

- Electrically-heated stainless-steel canisters with re-entrant exit ducts
- Mounted 150° apart on probes behind gaps between upper divertor plates
- Each evaporates 1 – 40 mg/min with lithium reservoir at 520 – 630°C
- Deposits lithium on lower plasma facing surfaces
- In regular use since 2006





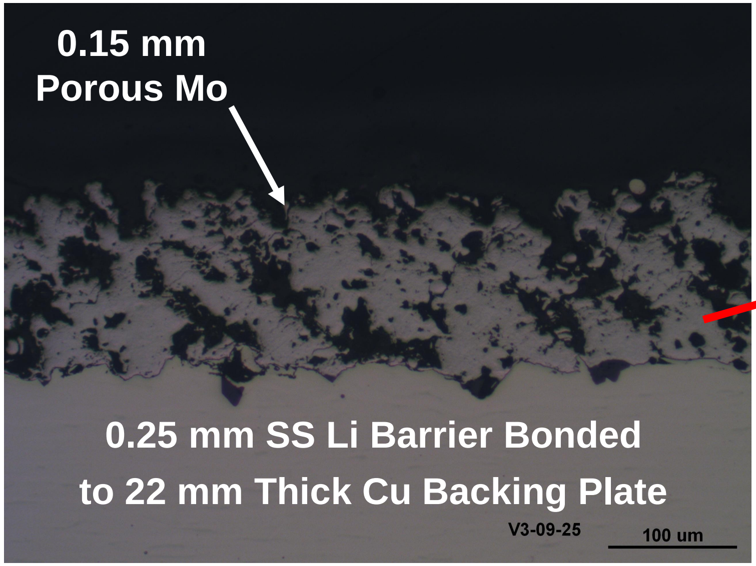
H. Kugel

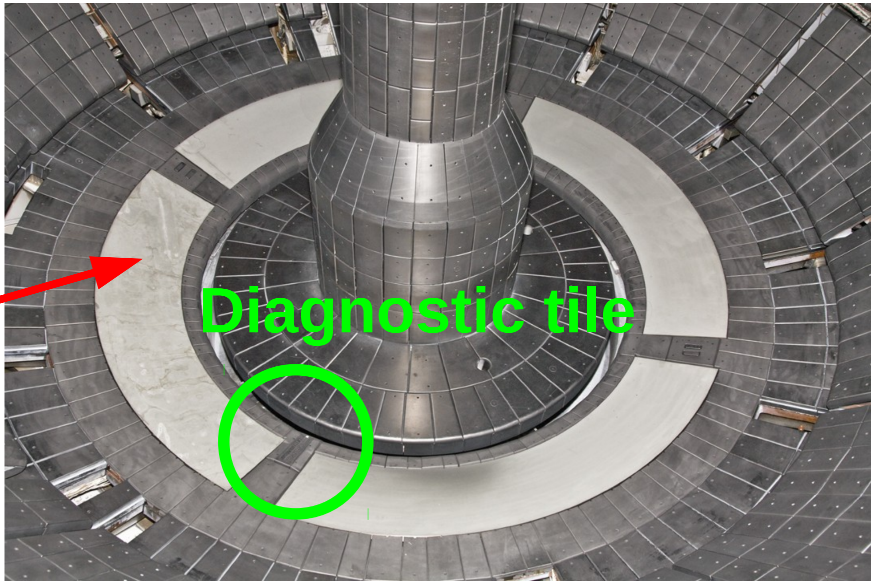
Lithiated Graphite Wall Conditions Transient

- Control room experience indicates that after 2-3 discharges, benefits of lithium-coated PFCs wanes
  - LITER evaporation rate limited
  - Shot cycle time finite
  - Limited coatings possible during regular operations
- Clean, macroscopic liquid lithium predicted to have very low recycling coefficient
  - CDX-U demonstrated improved energy confinement with large-area liquid lithium limiter (Majeski, PRL, 2006)
  - See also LTX posters in session CP9 (this afternoon).
- Motivates the installation of the liquid lithium divertor in NSTX

Liquid Lithium Divertor

Micrograph of porous Mo layer

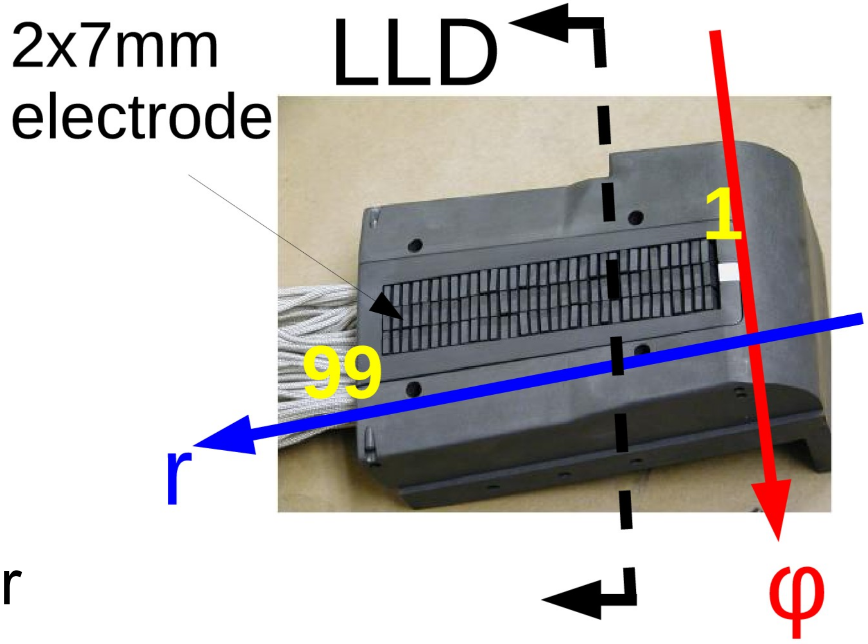




- Result of collaboration with Sandia National Laboratories
- Consists of flame-sprayed Mo surface on a thin stainless steel barrier covering a thick copper substrate
- Loaded via LITER evaporation from above
- Temperature controlled
- See H. Kugel - BP9.00041

New Langmuir Probe Array

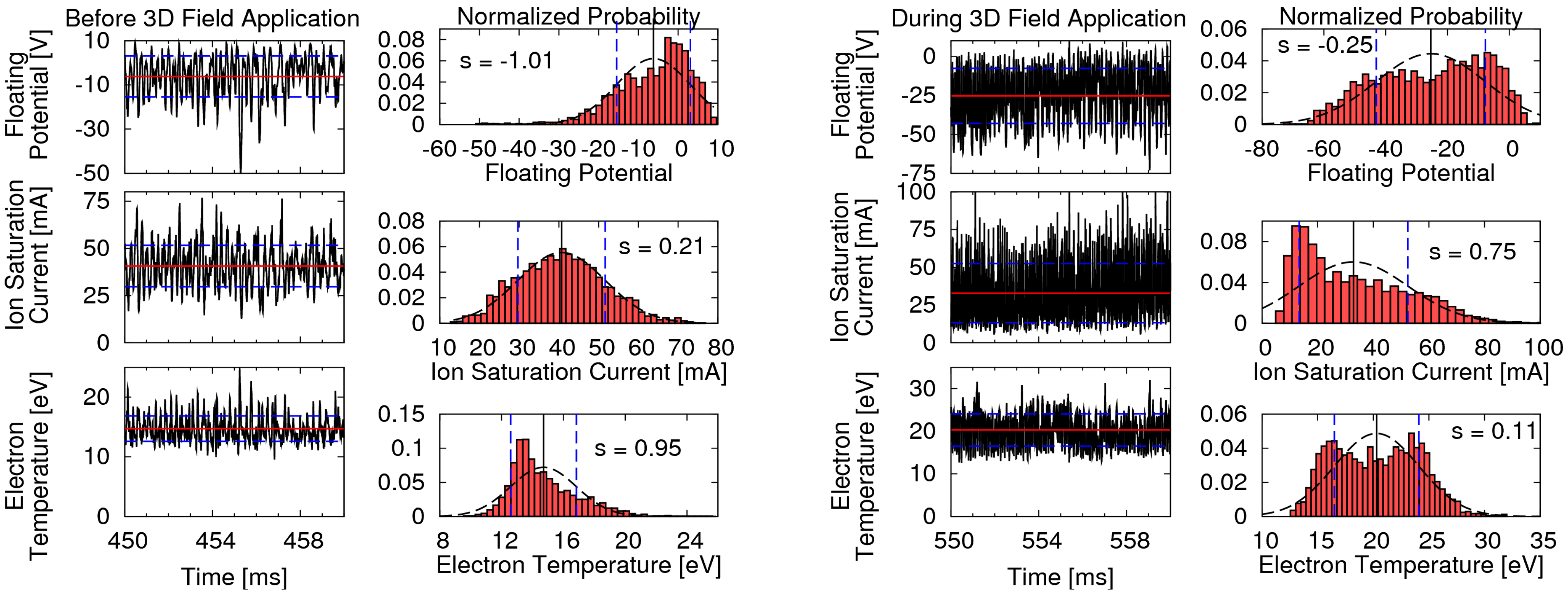
- Dense array of electrodes provides high spatial resolution
- Radially covers the LLD inboard leading edge
- Collaborative effort with U-Illinois
- Partially filled with standard swept probes, triple Langmuir probes and scrape-off-layer current monitors
- See also: J. Kallman BP9.00042 and V. Surla BP9.00046



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

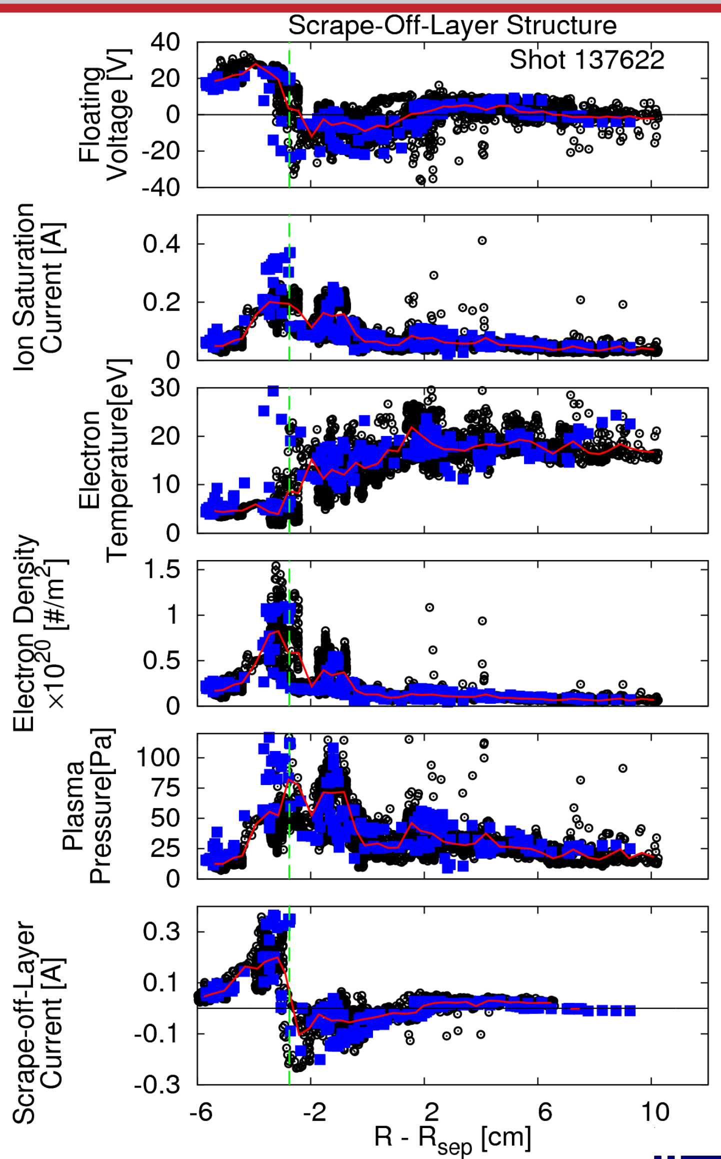
Triple Probes Complement Existing Turbulence Diagnostics

- Data example before and during application of 3D fields
- Probability density functions altered, as well as frequency
- Electron temperature becomes bi-modal
- Impact on single-probe interpretation being assessed



SOL Structure Obtained During Strike Point Sweeps

- Probe positions referenced to magnetic reconstruction
  - **Blue** points = single probe
  - **Black** points = triple probe or SOLC probe
  - **Red** line = Binned average
- Allows SOL structure to be obtained during a strike-point sweep over the array
- Provides additional means of locating the **separatrix**
  - V_F zero-crossing coincides with SOLC zero-crossing and
  - Peak pressure corresponds to this location

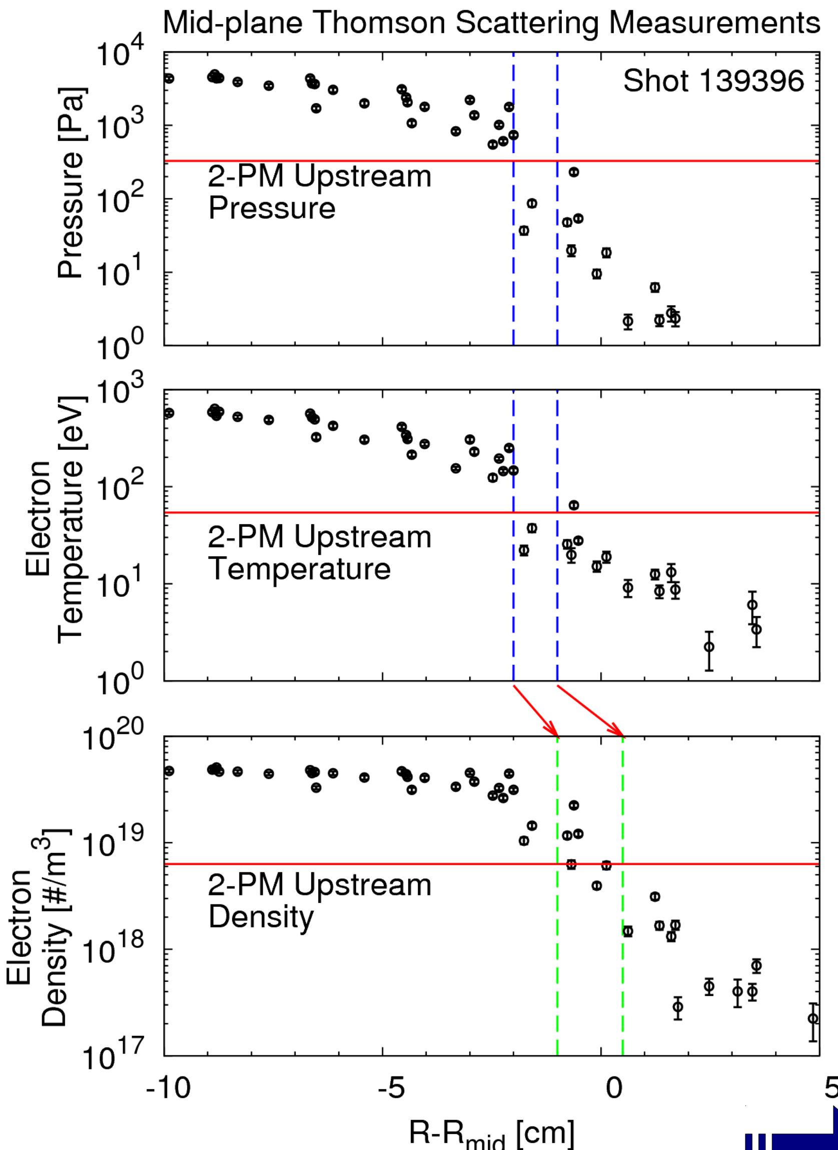


Importance of SOLC in PMI processes

- Local floating potential and SOLC intimately tied
  - Floating potential must adjust to be consistent with currents flowing through plasma
  - Equivalent to biasing the PFC to drive a current
- Enhanced sputtering in regions of positive current
  - Sheath potential energy enhanced by additional voltage between PFC and floating
  - Depending on Z of ion, impact energy can be greatly enhanced
- Enhanced heat flux in regions of negative current
  - Electrons carry bulk of plasma energy
  - Alters sheath heat transmission coefficient in the positive direction
  - Exponentially grows as surface voltage approaches plasma potential
  - Modest increase in sheath heat transmission occurs for positive current regions as well through enhanced ion energy

Upstream Separatrix Location Determined by Two-Point Model

- Simple 2-point model applied to SOL
  - Balances particle, momentum and energy in a flux tube
  - Define peak pressure along the target as the “real” separatrix location
  - Heat flux calculated with **probe data** (including floating potential effects)
  - Connection length obtained from TRACER code and magnetic soln.
  - Thomson scattering at midplane provides profile data
- Consistent location found with pressure and temperature
  - Density via 2-PM is low
  - Location improved with OSM integration (below) – discrepancy most likely due to magnetic variation in flux tube



What is the 2-Point Model?

- Models SOL flux tube
  - Straightened out plasma
  - No B variation
  - No radiative losses (in simple 2-PM)
  - Power enters at one end
- Balance pressure and power through flux tube
  - Assumes classical parallel-conductivity
  - Assume perfect recycling at the wall and particle balance on the flux tube
- Target power deposition modified with biased target sheath heat transmission

$$2n_tT_t = n_uT_u \qquad \text{Flux tube pressure balance}$$

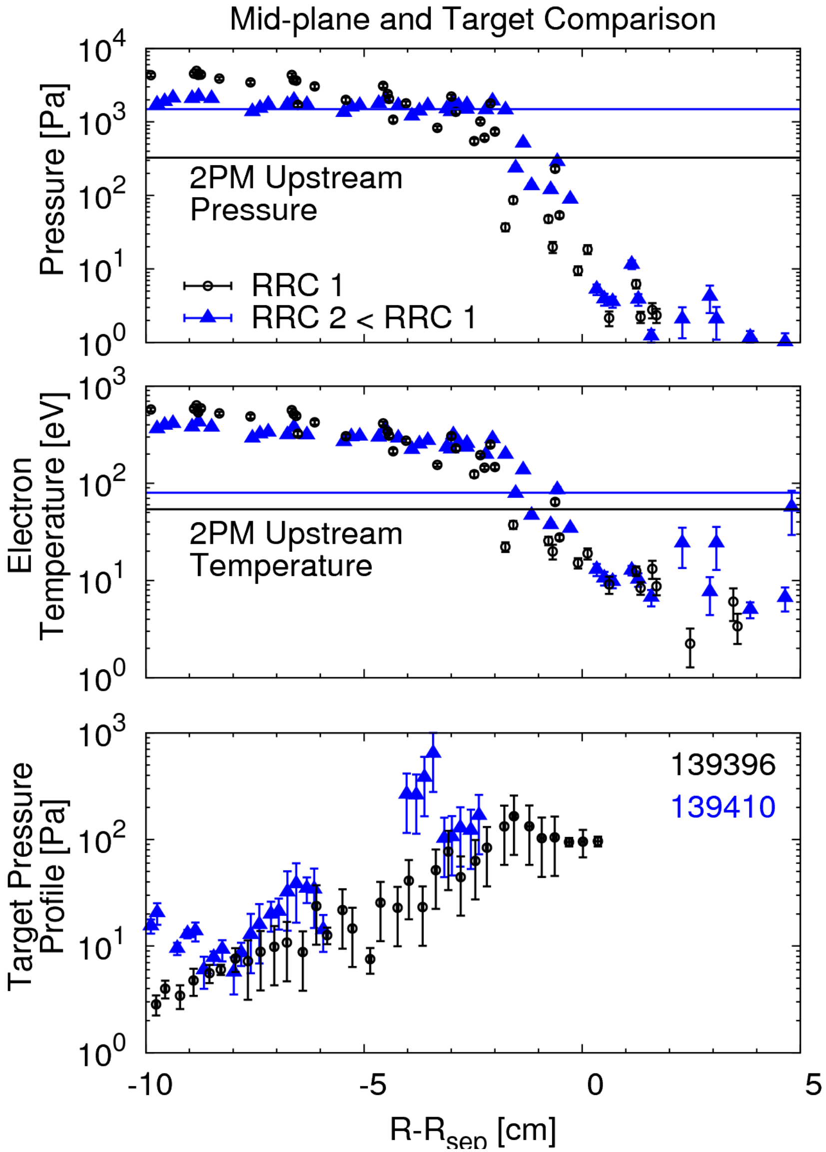
$$T_u = \left[T_t^{7/2} + \frac{7}{2}\frac{q_\parallel L}{2\kappa_{0e}}\right]^{2/7} \qquad \text{Flux tube power balance}$$

$$q_\parallel = \gamma(V_s)n_tkT_tc_{st} \qquad \text{Target power deposition}$$

$$\gamma(V_s) = -\frac{eV_s}{kT_e} + 2.5\frac{T_i}{T_e} + 2\left[\left(1+\frac{T_i}{T_e}\right)\left(\frac{2\pi m_e}{m_i}\right)\right]^{-1/2}\exp\left(\frac{eV_s}{kT_e}\right)$$

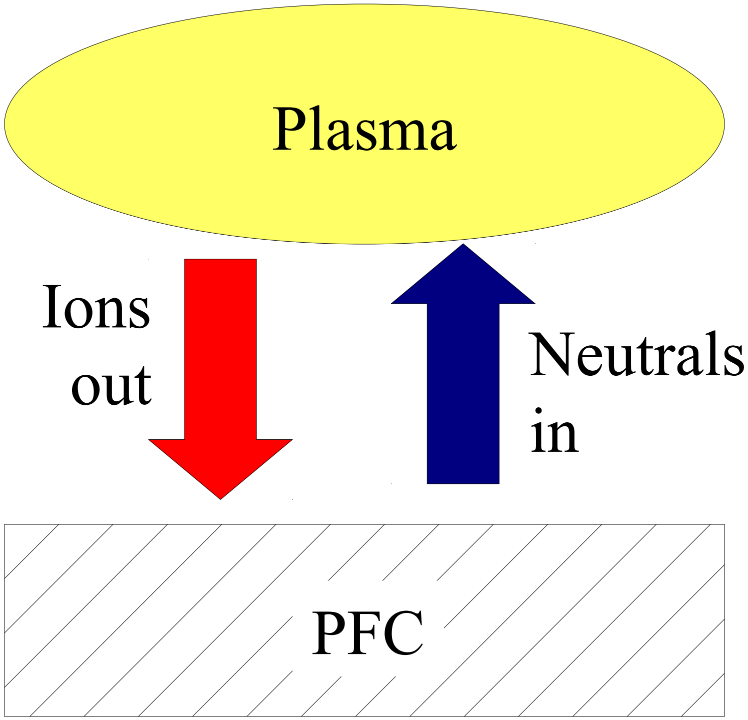
Two-Point Model Comparison of two LLD discharges

- Divertor profile exhibits higher pressure
  - $P_{t,peak}$ = 170 Pa in 139396
  - $P_{t,peak}$ = 740 Pa in 139410
  - Temperatures are comparable, but density is much larger in 139410
  - Mixture of effects – increased gas fueling, reappearance of type V ELMs
- Resulting upstream temperature is higher
  - T_u = 54 eV in 139396
  - T_u = 80 eV in 139410
- However, 2-PM is too simple
  - T_u is robust over a large set of parameters, but pressure and density affected by radiation and neutral momentum loss
  - Full strike-point profile not obtained in this discharge



Local Recycling Measurement

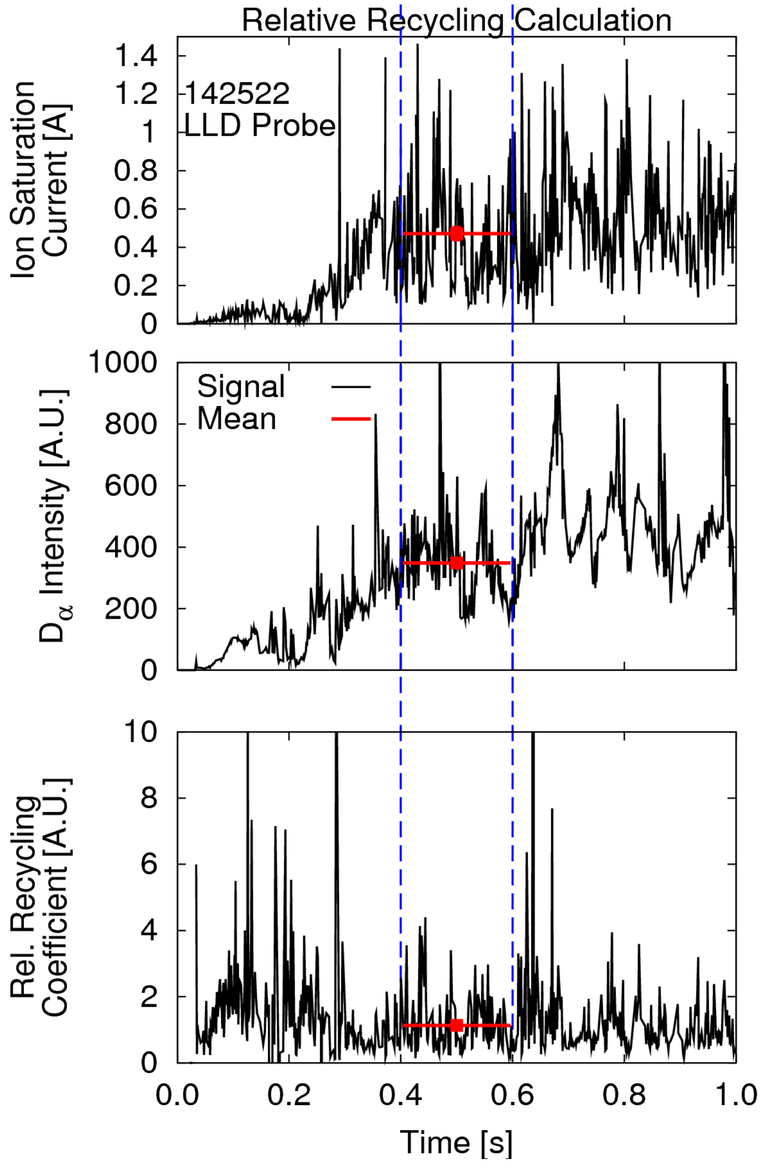
- Utilizes Langmuir probes and 1D-CCD camera D-alpha emission
  - D-alpha emission at PFC due to recycling neutrals
  - I_{sat} directly measures ion flux to probes
- Ratio provides recycling coefficient, however...
- Plasma geometry, radiation profile and reflections create significant uncertainty
  - Therefore, use the ratio in D-alpha intensity to I_{sat} as a *relative* recycling coefficient
- Relative recycling coeff. (RRC) allows trend analysis, but not absolute recycling coeff. determination



$$R = \frac{\text{Flux into plasma}}{\text{Flux into PFC}} \propto \frac{D_\alpha \text{ Intensity}}{I^+_{sat}}$$

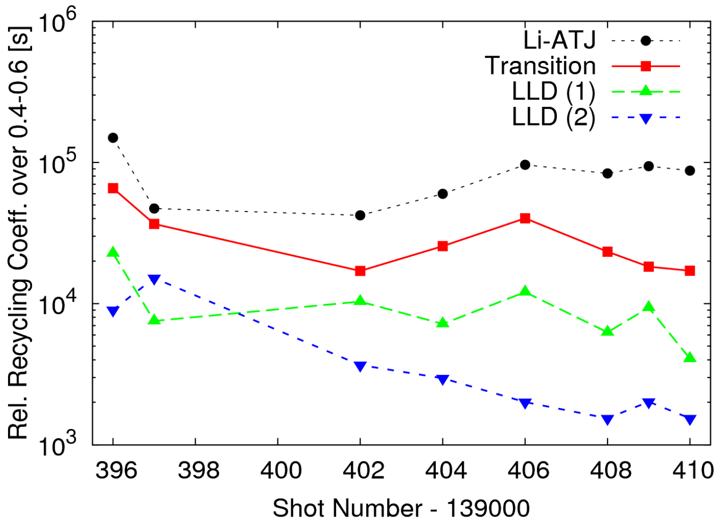
Example Relative Recycling Coefficient Calculation

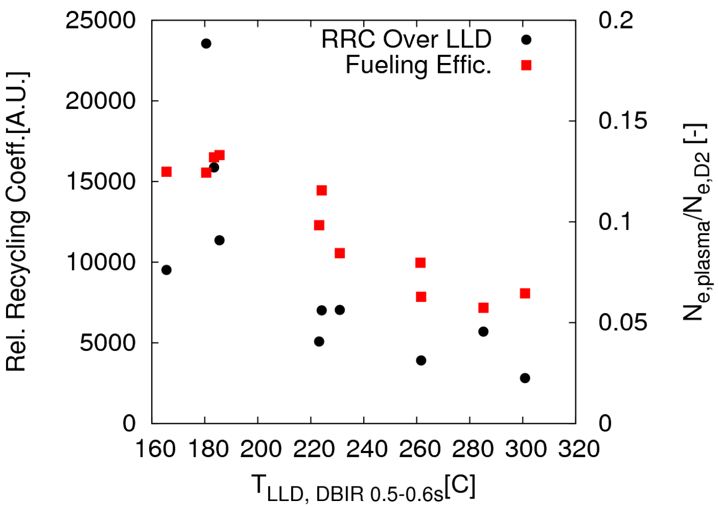
- Plasma diverts after 200ms
- Achieves stable shape by 400ms
- Measurement made during stationary discharge period from 400-600ms (mean of signal)
- Same discharge shape in both shots provides control on geometric factors
  - During first experiment, fueling rate increased (would tend to increase RRC)
  - In PFZ, dependent on PFCs on both sides of the flux tube (i.e. inboard and outboard – but both still Li-ATJ)
  - Motivates more rigorous work with OEDGE to take into account X-point and divertor leg radiation



Recycling Evolution During LLD Heating by Plasma

- During shot sequence, plasma heated the LLD
  - Melting point of Li = 180C
  - Gas puff rate increased during scan
  - Z_{eff} of carbon decreased
- Spatial variation of probes provides measurement at different PFCs
  - Probe 1 over Li-ATJ
  - Probe 2 at transition
  - Probes 3 and 4 over LLD
- Downward trend as run progressed visible in LLD probes,
  - Less apparent on Li-ATJ
  - Correlated with fueling efficiency decrease, and
  - Trends downward with temperature
  - But fueling was increased in sequence
  - Changes in both I_{sat} and D_{α}





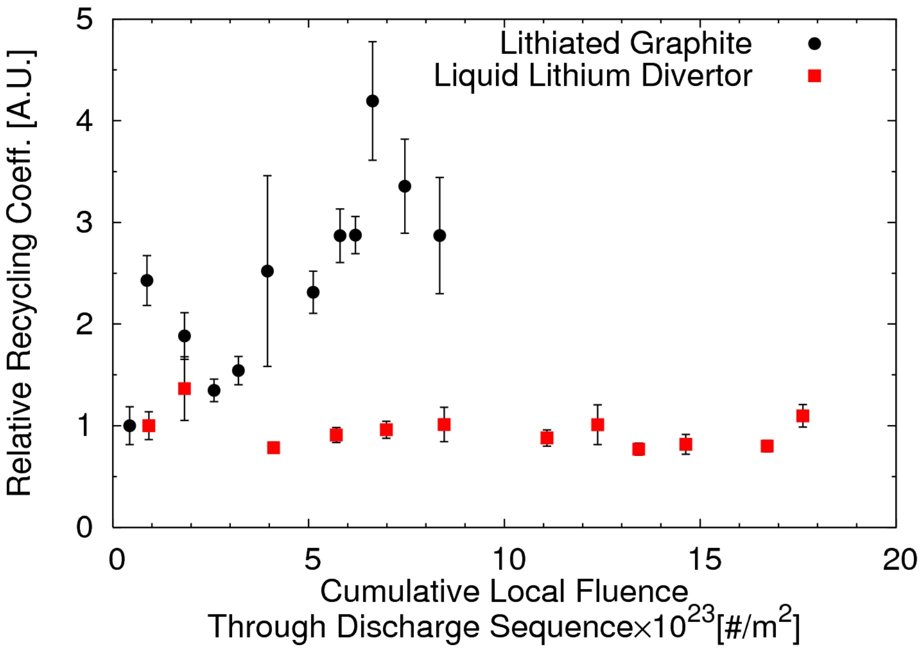
A. McLean – DB-IR
M. Bell – Fueling Eff.

Lithiated Graphite Exhibited Increase in Recycling

- Single LITER evaporation of 7.5gm
  - Plasma shape and fueling comparable
  - Discharges repeated through entire day
- Systematic rise in relative recycling coefficient on lithiated graphite, but not on the LLD
- Multi-shot ion fluence indicates LLD has “reservoir” effect compared to Li-graphite

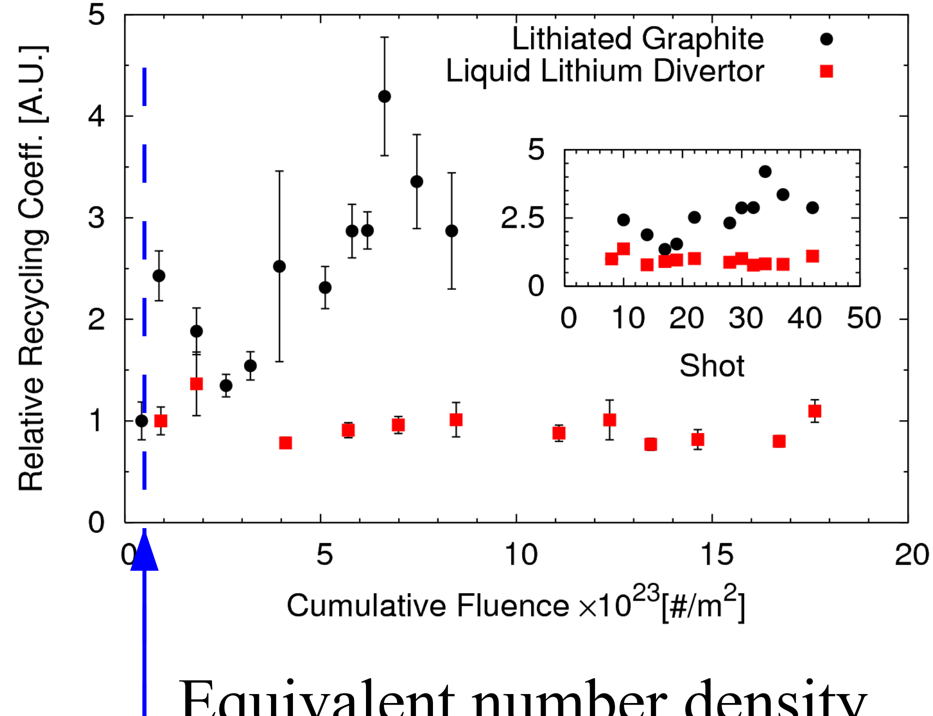
$$R = \frac{\text{Flux into plasma}}{\text{Flux into PFC}} \propto \frac{D_\alpha \text{ Intensity}}{I_{sat}^{+}}$$

$$\begin{aligned} N_{inc} &= \text{Cumulative Fluence} \\ &= \sum_{Shots} \left(\int \frac{I_{sat}^{+}}{eA_{probe}} \mathrm{dt} \right) \end{aligned}$$



Simplified Model for Recycling and Material Saturation

- PISCES-B data showed that Li absorbs D until converted to LiD (M. Baldwin, NF, 2002)
- LITER evaporation deposited 7.5gm, but amounts to 3.5×10^{22} $\#/m^2$ in vicinity of LLD
- Simple fluence comparison would suggest the PFC should be saturated within the first discharge...
- Yet recycling continues to trend upward



Equivalent number density of deposited Li

$$N_{dep} \approx \frac{\eta m_{Li}}{\pi\left(R_o^2 - R_i^2\right)} \cdot \frac{A_v}{M_{Li}}$$

$$N_{dep} \approx \frac{0.05 \cdot 7.5\text{gm}}{0.9425\text{m}^2} \cdot \frac{6.022 \times 10^{23}\#/\text{mol}}{6.941\text{gm}/\text{mol}}$$

$$N_{dep} \approx 3.5 \times 10^{22}\#/\text{m}^2$$

Simple Model of Recycling as Function of Saturation

- Define saturation level, θ
- Assume recycling proportional to saturation level
- Only 1-R particles are absorbed
- Solve ODE for saturation as a function of incident fluence

$$\theta = \frac{N_D}{N_{Li}} \qquad 0 \leq \theta \leq 1$$

$$R(\theta) = \frac{R_{max} - R_{min}}{\theta_{max} - \theta_{min}}\theta + R_{min} = \frac{\Delta_R}{1}\theta + R_{min} \qquad R_{max} \leq 1$$

$$\frac{\mathrm{d}N_D}{\mathrm{d}t} = [1 - R(\theta)]\Gamma_{inc}$$

$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = [1 - R(\theta)]\frac{\Gamma_{inc}}{N_{Li}}$$

$$N_{inc} = \Gamma_{inc} \cdot t$$

$$\theta(N_{inc}) = \frac{(1 - R_{min})}{\Delta_R}\left[1 - \exp\left(-\frac{N_{inc}}{N_{Li}}\Delta_R\right)\right]$$

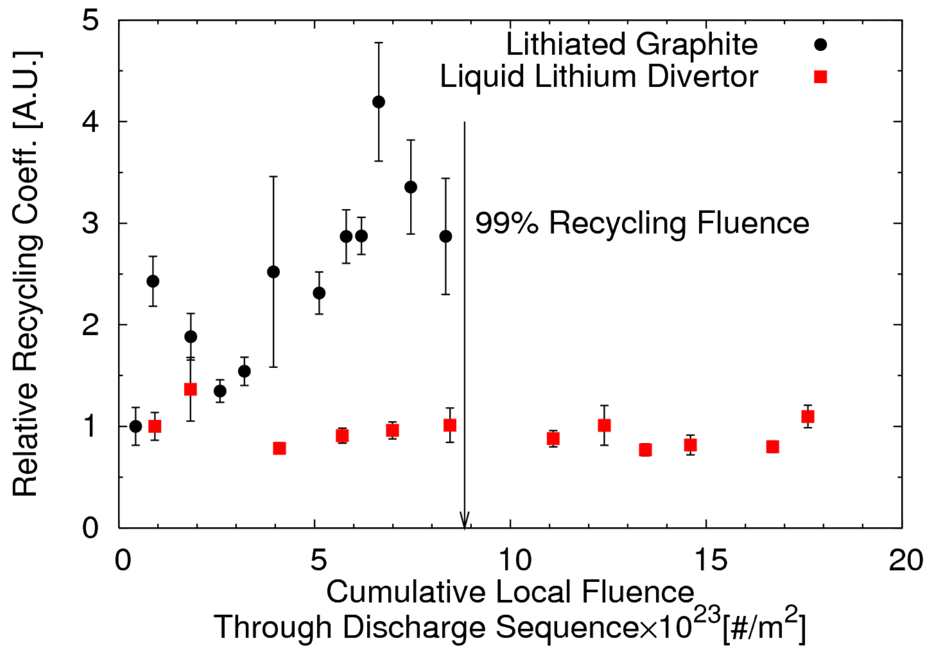
Can Predict 99% Recycling Fluence

- Change in saturation slows exponentially as material fills up
- Fluence to reach 99% recycling surface calculated as about 26 times the available lithium deposited
  - Assumes Rmin = 0.90 from J. Canik SOLPS modeling
  - Rmax = 1.0
  - Predicts the Li-ATJ may have more pumping ability beyond what was tested

$$0.99 = R(\theta_{99} = 0.9) \quad \text{for } R_{min} = 0.90$$

$$N_{inc}|_{R=0.99} = \frac{1}{\Delta_R} \ln\left(\frac{1}{1-\theta_{99}}\right) \cdot N_{Li}$$

$$N_{inc}|_{R=0.99} \approx 25.6 \times N_{Li}$$

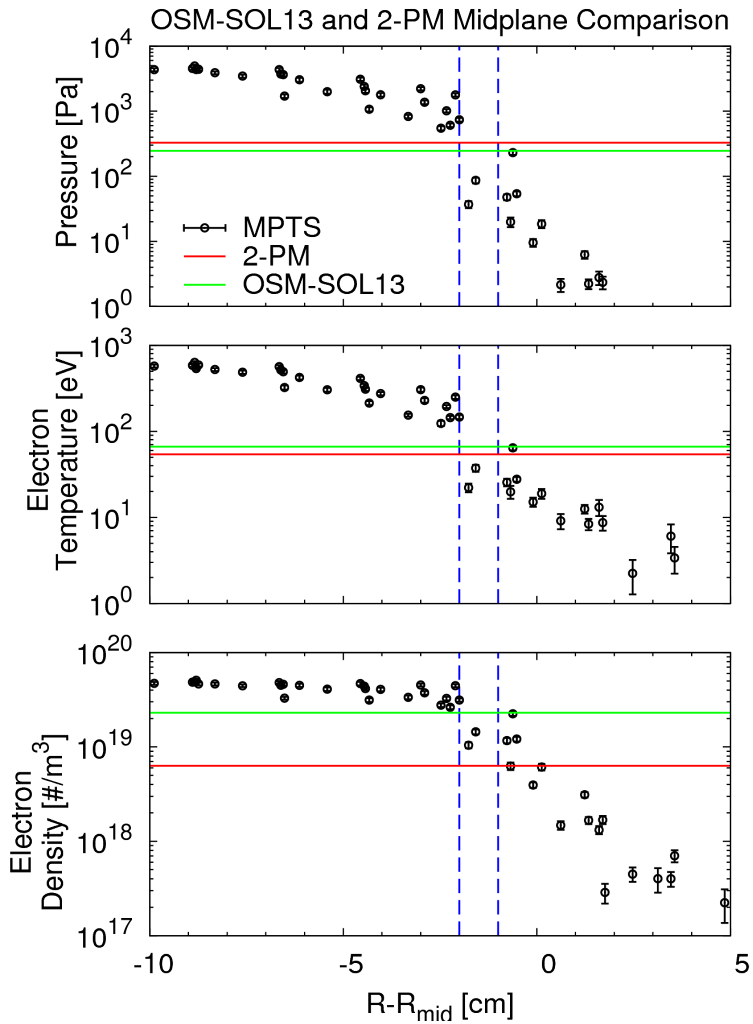


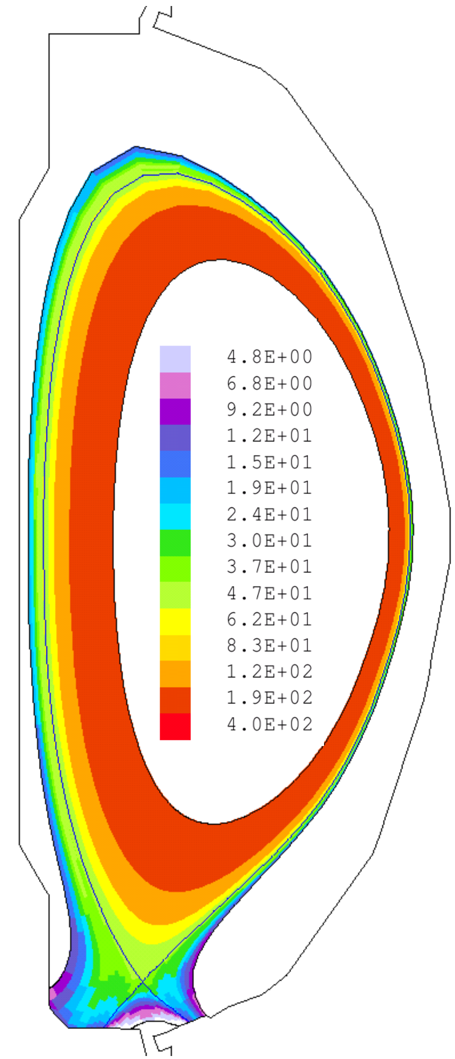
More Rigorous Analysis Available with OEDGE code suite

- Confront your model with *all* available data simultaneously
- Onion-skin method (OSM)
  - Generalization of the 2-point model – integrates fluid equation along a flux-tube
  - Assumes parallel transport >> perpendicular
  - Allows individual flux-tube solution
- Eirene
  - Neutral transport code
  - Determines background neutral pressure in machine and interaction with plasma solution
  - Takes a wall model as input for calculating the recycling from the surface
- DIVIMP
  - Monte Carlo impurity model – utilizes sputtering tables to determine launch probabilities – tracks impurities and radiation cause by them

OSM Temperature Integration Improves Upstream Separatrix Location

- Separatrix location consistent in all three quantities
  - Mid-plane density finds consistent separatrix location with T_e and P_e
- Testcase run to develop work flow (proof-of-principle test)
  - Outboard Ne and Te obtained by probes
  - Core profile determined by MPTS
  - Inboard profile mimicked for this test case
  - Plasma solution found via pseudo-self consistent fluid model along flux-tubes
  - No neutral solution yet, simple ionization model





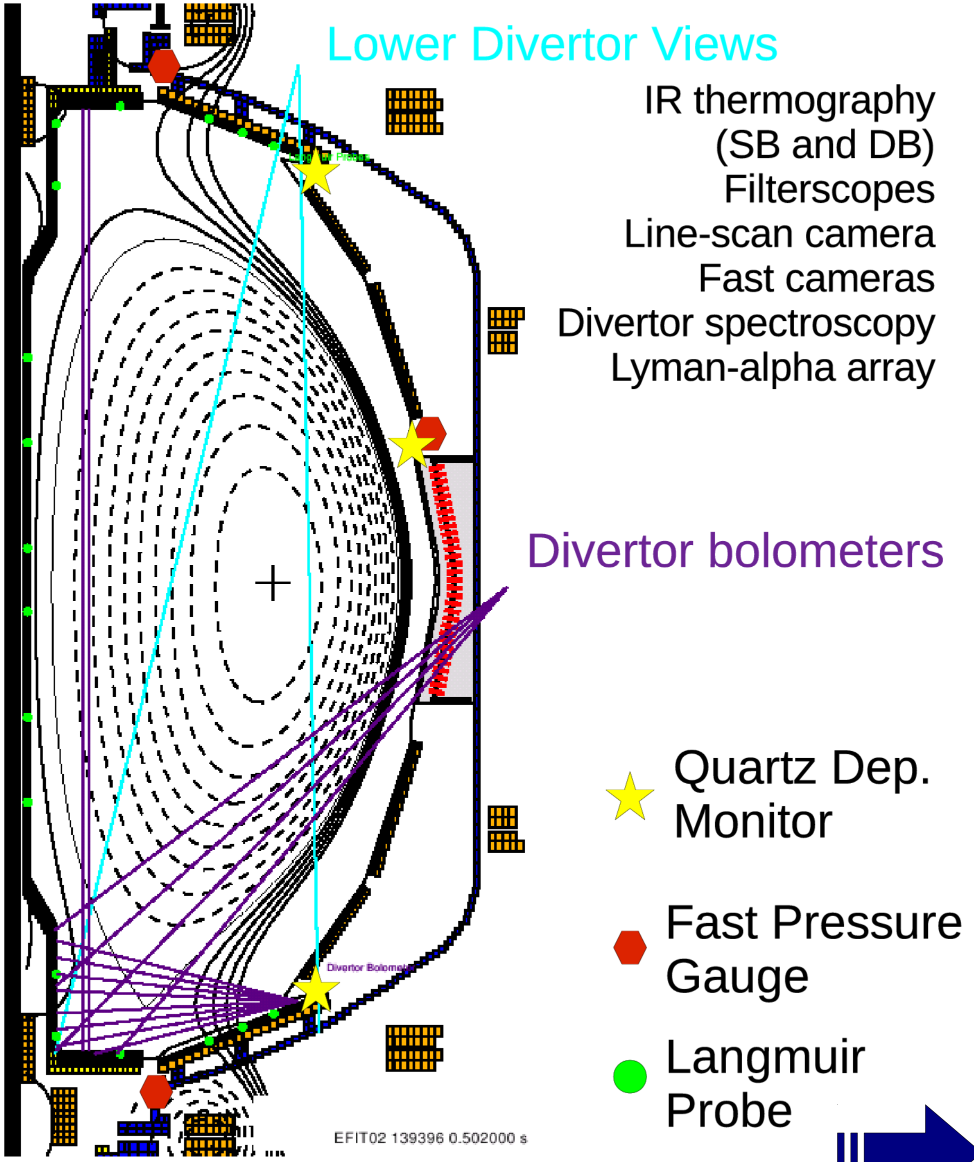
T_e solution

Option SOL-13 – Pseudo Self-Consistent Integration

- Integrates only some of the conservation equations along the flux tube
  - Integrates T(s) along flux tube with a prescribed radiative power loss along flux tube
  - Utilizes ionization model to integrate Γ(s) (particle flux) in similar fashion
  - Solves for density and velocity based on pressure balance and flux
- Primary difference with SOL-22 option is that SOL-22 integrates all three conservation equations simultaneously
- For the case run shown, no radiation is prescribed and only the ionization is set as a decaying exponential with decay length of 8cm (compared to 14m distance to mid-plane very close to separatrix)

Wide Range of Diagnostics Available for Constraints

- Each new diagnostic provides means for constraining the model
  - e.g. divertor spectroscopy provides impurity information
  - e.g. QDMs provide impurity redeposition/transport
  - e.g. Pressure gauges provides information on neutrals
- HDLP not shown in figure
  - Inboard coverage by Langmuir probes could still be improved
  - Mid-plane reciprocating probe also not shown



First Sanity Check: LLD Plate Heating

- Thermocouples measure LLD plate temperatures in bulk copper
  - Treat each LLD plate as a 90lb. Calorimeter
  - Rise in mean temperature yields energy deposited over entire discharge
- Estimate plasma heating time by the time spent diverted
- Plate heating and Langmuir probe-based heat flux calculations show particle heating accounts for ~90% of total heat input

$$\Delta E_{plate} = V_{plate}\rho_{Cu}C_{p,Cu}\Delta T$$

$$\Delta E_{plate} = 5222\text{cm}^3\ 8.94\frac{\text{g}}{\text{cm}^3}\ 0.384\frac{\text{J}}{\text{g}\cdot\text{K}}\Delta T$$

$$\Delta E_{plate} = 17.9\ \text{kJ/K}\ \Delta T$$

$$\Delta E_{div} = \Delta E_{plate} \cdot \frac{2\pi}{\theta_{plate}}$$

$$\Delta E_{div} = \Delta E_{plate} \cdot 4.36$$

$$\bar{P}_{div} = \frac{\Delta E_{div}}{\tau_{div}}$$

where $\tau_{div} =$ Period of time plasma is diverted

For shot 139396

$$\tau_{div} \approx 0.85[\text{s}] \qquad \Delta T_{plate} \approx 8[\text{C}]$$

$$\bar{P}_{div} \approx \frac{4.36 \times 143[\text{kJ}]}{0.85[\text{s}]} \approx 735[\text{kW}]$$

$$P_{OSM-LP} = 674[\text{kW}] \approx 92\% \text{ of } \bar{P}_{div}$$

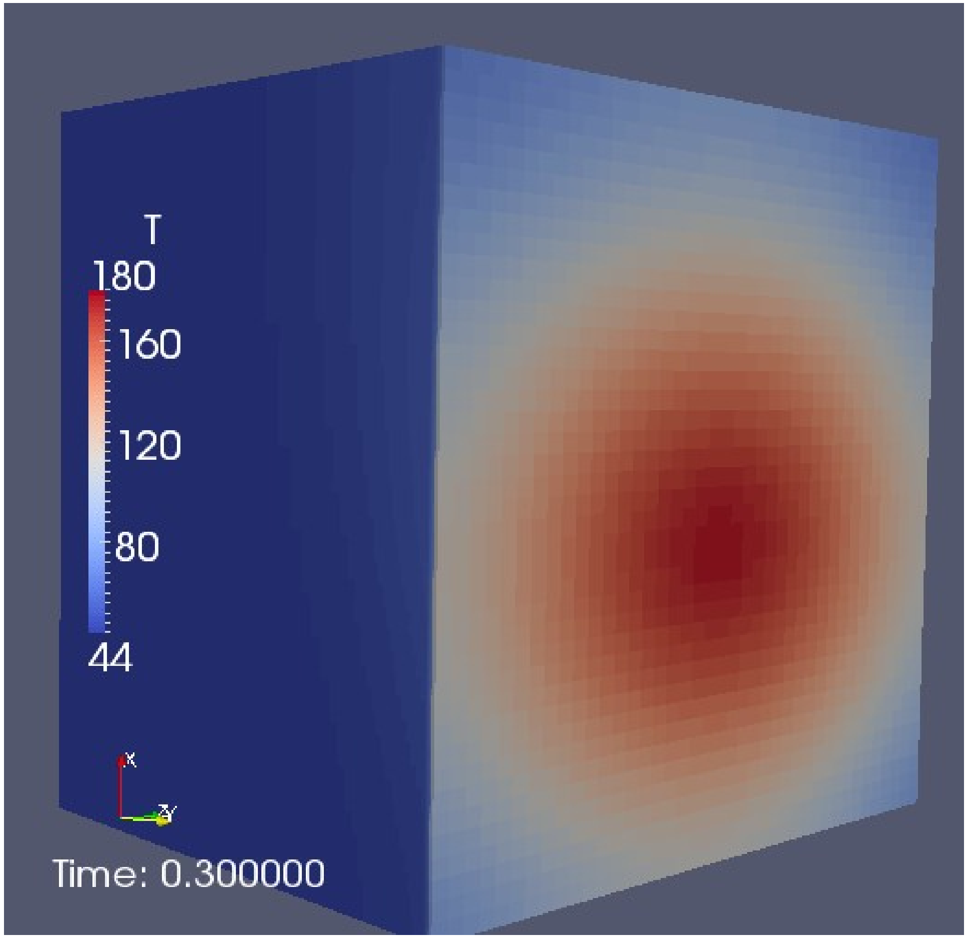
Study Methodology

- Take all available data to constrain the plasma and impurity levels
- Determine best material model (e.g. recycling coeff.) to best match available data
- Construct recycling coefficient database for lithiated graphite as well as lithium-coated moly/LLD for range of operating scenarios
  - Local plasma temperature, density
  - PFC bulk and front-face temperature
- Create model to describe the resulting behavior based on the plasma response to the PFCs
  - Supplement with sample diagnosis as it becomes available (see MAPP probe poster BP9.00088)
  - Other offline experiments and modeling as appropriate

Determining LLD Plate Front-Face Temperature Response with Offline Experiments

- Diagnostic neutral beam exposures of LLD sample piece
  - Obtained front-face temperature response to ~1.5MW/m^2 heat flux
  - See T. Abrams BP9.00045 for experiment details
- Perfect material bonds not present in sample
  - Tests show much larger temperatures than expected
  - Preliminary estimates indicate resistive layer exists between LLD layers (equivalent to x20 reduction in porous moly conductivity)
- Bench-marked model in the works for future predictive capability

OpenFOAM LLD Sample Model



Extending the Recycling Model

- Simple model may explain steady trend in Li-ATJ data
- Better modeling of the PFCs will depend on extracting actual values of recycling coefficient, not relative recycling
- Some temperature scans already performed
  - Include surface evaporation and recombination
  - Sputtering of lithium and deuterium
  - Sputtering of other impurities
- Informs on PFC choice and conditioning method for NSTX-U and other machines
  - Does liquid lithium saturate in a similar fashion?
  - What are the limits in temperature for “low” recycling to persist?
  - Is there a feasible liquid lithium PFC in a high-performance machine or pilot plant?

Summary

- NSTX divertor is rich in physics topics and phenomena
- Measurements to date indicate LLD interaction with the bulk plasma is subtle and requires careful analysis
  - Some indications of SOL changes via Langmuir probe measurements, however...
  - Complicated by multiple variable changes (e.g. fueling rate)
  - Latest set of data under analysis
- Relative recycling measurement indicates LLD and Li-ATJ PFCs evolve in time over the period of several discharges
  - Corroborates "control room" wisdom that Li wall effects are short lived
  - Analysis of cumulative fluence to PFCs motivates a simple recycling model based on material saturation
  - While encouraging, should be improved with "real" recycling analysis
- OEDGE analysis of NSTX plasmas ramping up after initial test runs – major goal is to develop detailed understanding of lithiated PFCs and the impact on the global plasma

Reprints