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XP 1001 - Recycling and pumping studies with LLD module

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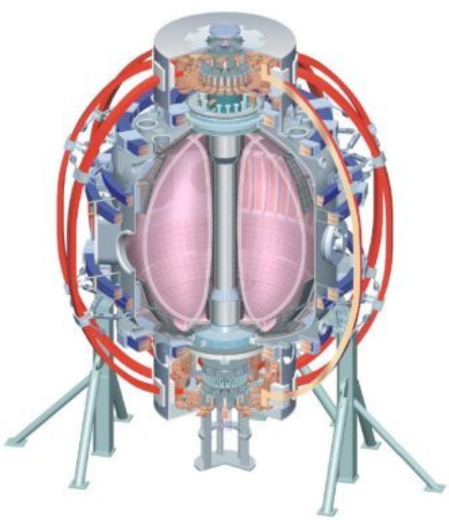
H. W. Kugel, R. Maingi, R. Raman, and NSTX Team

Lithium Research TSG Meeting
Princeton, NJ
5 March 2010



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A consistent research plan of LLD studies is emerging…

- XMP (Plasma start-up)
- XP 1000 “LLD characterization” (H. W. Kugel et al.)
- XP 1001 “Pumping and recycling with LLD”

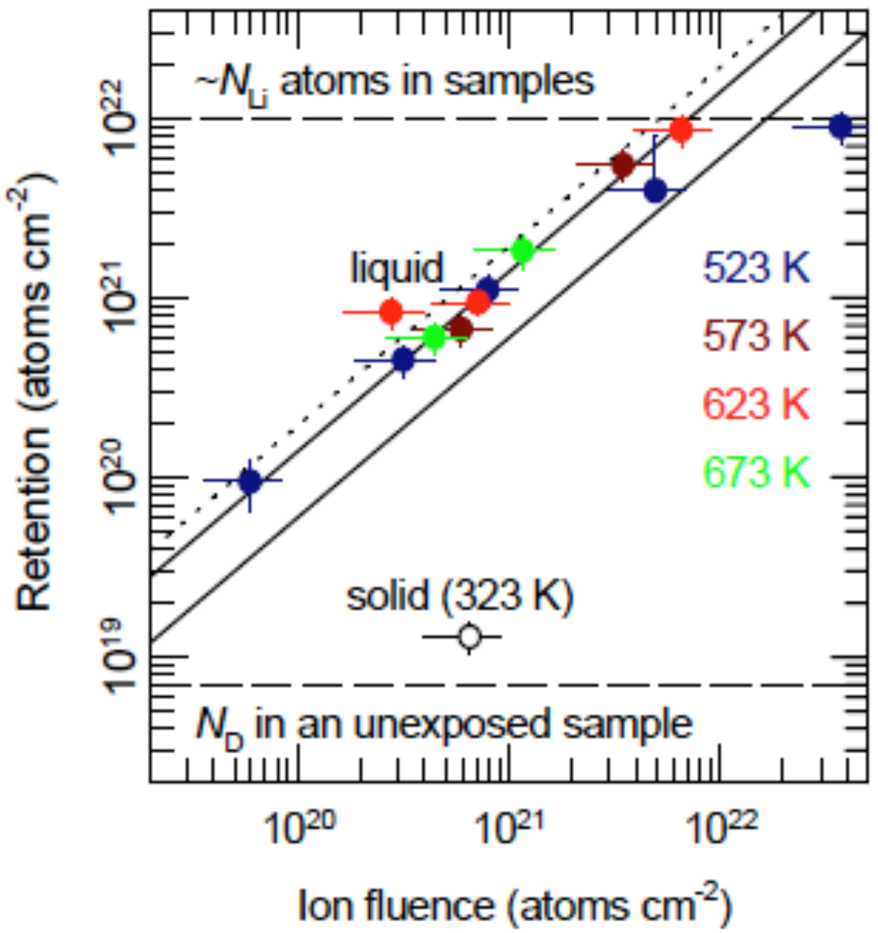
  (V. A. Soukhanovskii et al.) - *this talk*
- XP 1057 “Deuterium retention with LLD” (C. H. Skinner et al.) - *next talk*
  - Discharge-integrated and long-term retention, gas balance, detailed surface physics and chemistry using the sample probe
- XP 100? “Edge and pedestal studies with LLD” (R. Maingi et al.)
- XP 100? “Survey of physics with LLD” (S. Gerhardt et al)
- …

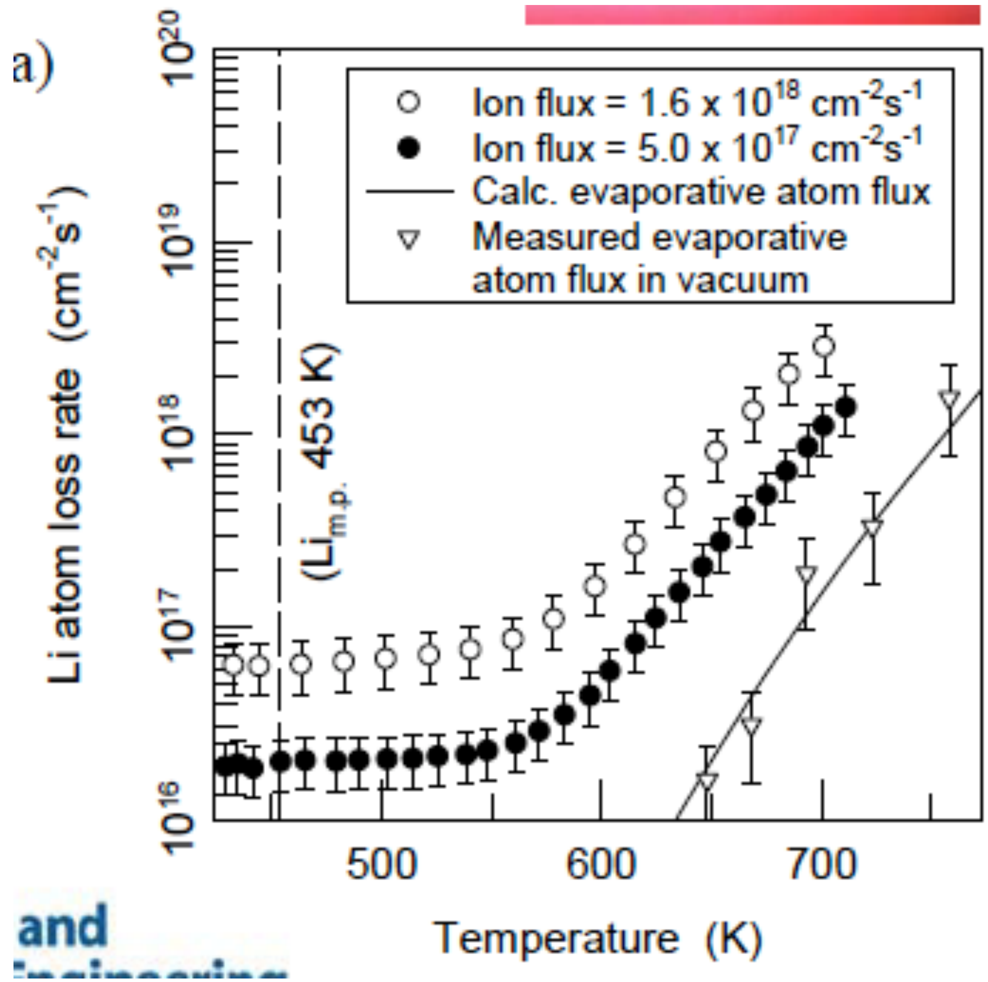
LLD pumping demonstration in XP 1000 (H. W. Kugel *et al.*) is a prerequisite to this XP

- XP 1000 "LLD characterization"
  - Crude strike point scan (R_{OSP}=0.5, 0.63 m; if warranted, 0.75, 0.35 m)
  - Two fueling scenarios - HFS and SGI
  - Two input power levels - 2-3 MW and 4-6 MW
  - Comparison between "cold" and "warm" (~ 220 C) LLD

- Anticipated deliverables from XP 1000
  - Demonstration of reduced ion density / inventory with "warm" LLD
    - Did LLD fully wet and operate as expected?
  - Data on LLD thermal regime
    - LLD steady-state heating? Heating due to plasma interaction?
  - Data on LLD impurity handling
    - Is Li, C, Fe, Mo sputtering a problem?
  - Data on LITER evaporation requirements (rate, frequency)
    - LITER between shots? Every few shots?

Liquid lithium ability to “pump” D depends on temperature and ion fluence and greatly exceeds that of solid lithium





R. Doerner, M. Baldwin, UCSD

2002 Nucl. Fusion 42 1318

Understanding of lithium coatings and LLD for density control and pumping is emerging

- Cryo-pumping (e.g., DIII-D experience)
  - Calibrated pumping rate ☺
  - Demonstrated density control ☺
  - Compatibility with radiative divertor ☺
  - Significant in-vessel hardware modifications ☹
  - Inflexibility in plasma shaping due to the need of proximity to strike point ☹
- Lithium coatings on graphite PFCs (NSTX LITER experience)
  - Flexibility in plasma shaping ☺ (LLD..?)
  - Large area pumping
  - Need for operational scenario development for each pumping and fueling rate ☹
    - Due to complex dynamic behavior of lithium coating
    - LLD: + need to satisfy thermal regime requirements
  - Multiple side effects (good and bad) on plasma core and edge
    - E.g., improved confinement, ELM stability, impurity transport, etc ☺ ☹

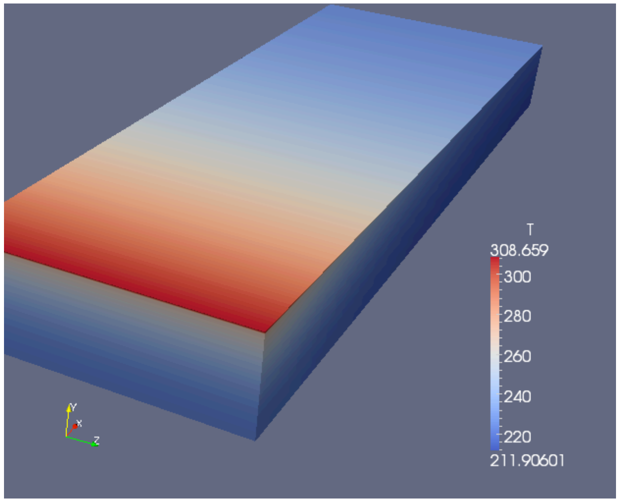
XP 1001 aims at extending XP 1000 results to wider parameter range enabling trend studies and comparison with models

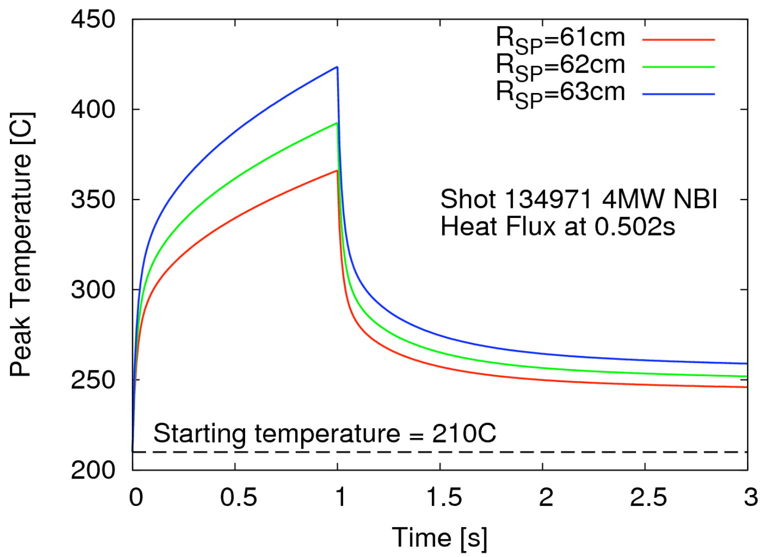
- Study neutral and ion fluxes and particle balance as functions of
  - Proximity to strike point (essentially, divertor ion flux and LLD temperature convoluted together)
  - Steady-state core ion density (n_d ~ 1-6 x 10^{19} m^{-3})
    - Use SGI fueling to vary core density
  - Response of SOL and/or divertor density to source perturbation
    - Use SGI and divertor gas puffs, measure “pump-out” times
  - Steady-state LLD temperature
    - Use heaters and/or helium system to vary LLD temperature
    - Possibly, use plasma heating to increase LLD temperature

- Based on above measurements, infer LLD particle pumping characteristics using models
  - “Simple” 0D particle balance for electrons and ions
  - 2D fluid models

Uncertainty in thermal LLD regime will be clarified in XP 1000 and through modeling

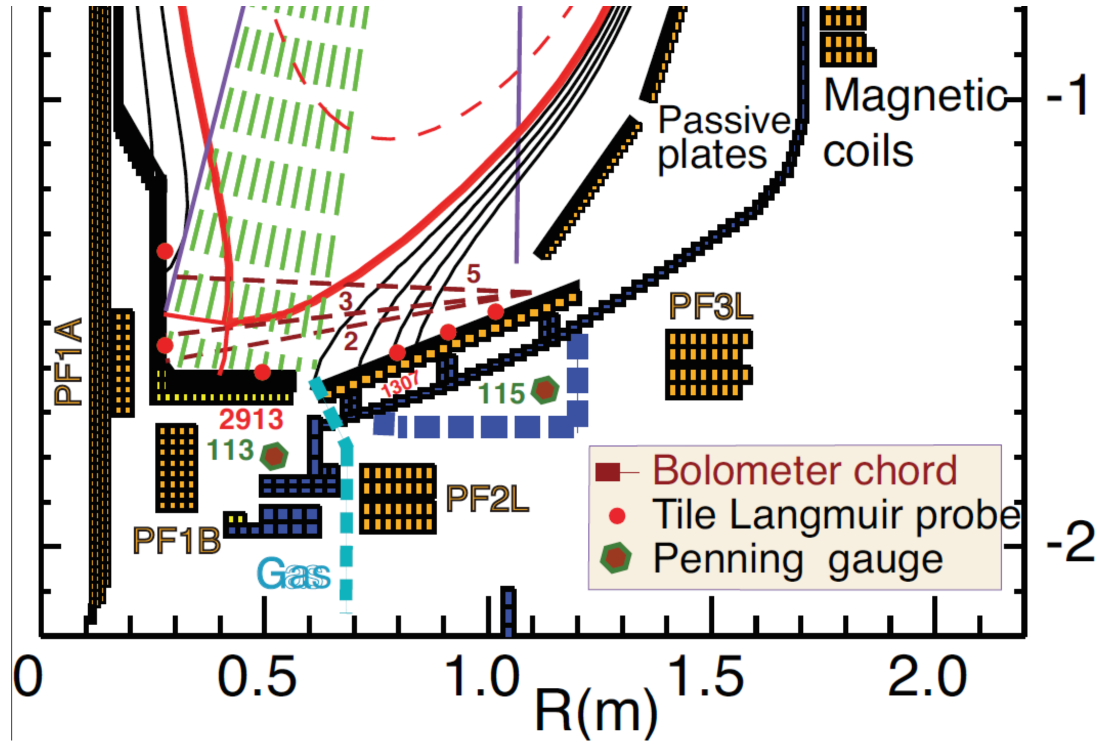
- Only ¾ of LLD can be heated to 220-250 C using heaters
- Possibility of steady-state heating with helium system TBD
- All three thermal models (Zakharov (PPPL), Nygren (SNL), Jaworski (PPPL)) show substantial LLD heating in a 1 s long 2-4 MW NBI discharge
  - Based on realistic measured divertor heat fluxes
  - Include thermal conduction in layered LLD material (Mo, SS, Cu)
  - Jaworski's calculations shown here (more in backup slides)





Multiple diagnostic measurements will be analyzed

- Diagnostic set for LLD pumping studies
  - Spectroscopy
    - LADA
    - Filtered cameras
    - VIPS2 and DIMS
    - Filterscopes
  - Neutral pressure gauges
  - Tile Langmuir probes
    - "Super tile" array
    - Existing probes
  - Midplane diagnostics
    - Thomson scattering and CHERS systems
    - FIReTIP, reflectometry
    - Fast probe (?)

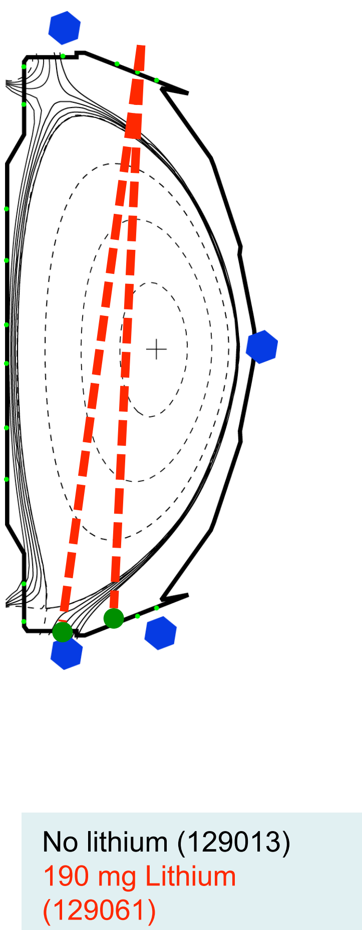


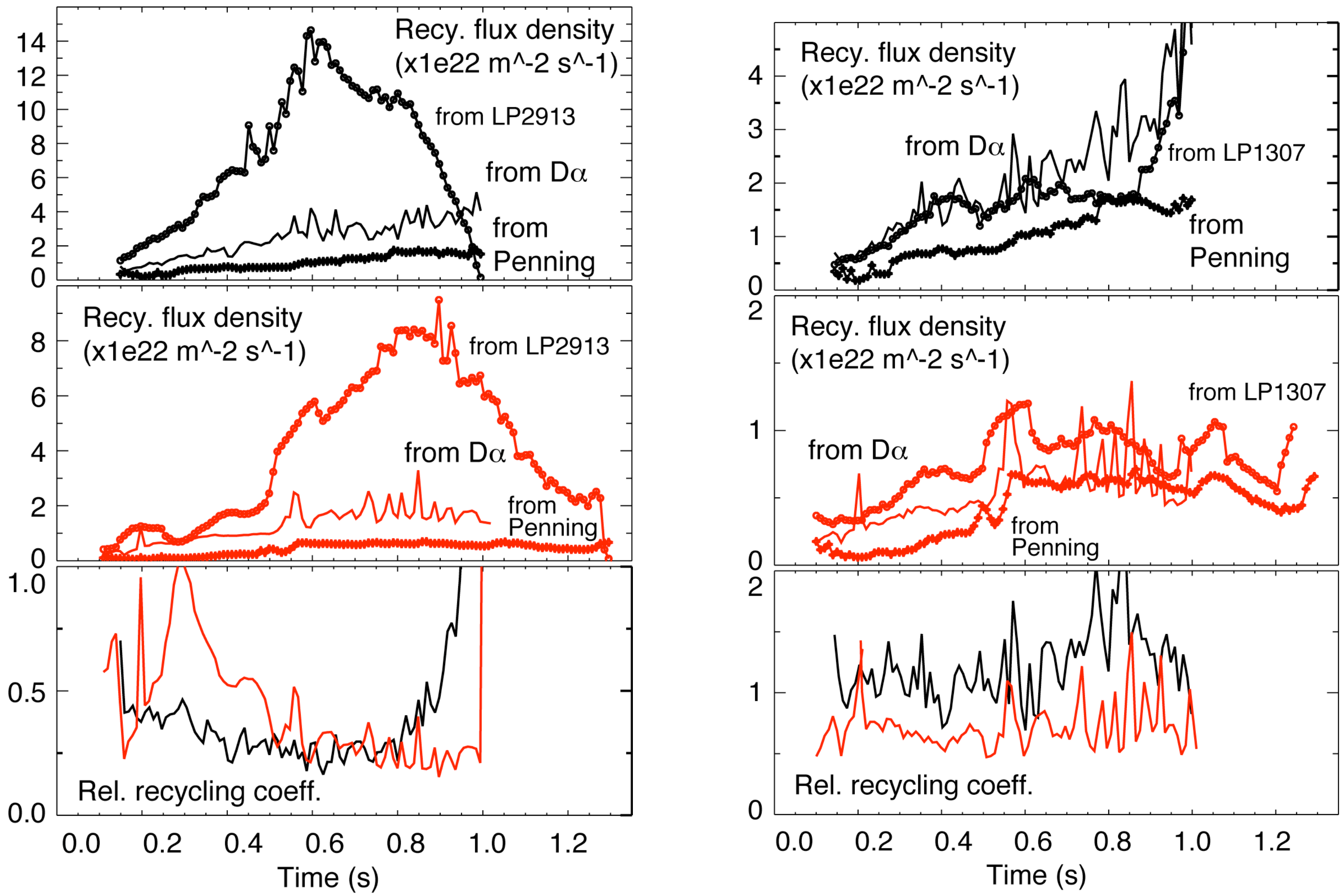
Recycling fluxes and coefficients will be measured as functions of LLD regime in this XP

- Define recycling as $R_{local}=\Gamma_i^{out} / \Gamma_i^{in}$
  - Ion flux into LLD Γ_i^{in} is measured by Langmuir Probes (combined PPPL / UIUC effort)
  - Ion outflux Γ_i^{out} into SOL plasma can be estimated from measured D flux and S/XB (ionizations/photon) coefficient from ADAS
    - Need absolutely calibrated D photon flux (D-alpha cameras, LADA)
    - Need molecular emission measurements (e.g., Fulcher bands) to include contributions from molecules (DIMS)

- Recycling measurements are useful for UEDGE / Degas 2 modeling
  - calculation constraints
  - infer a global picture of LLD performance (pumping, etc)

Local *relative* recycling coefficient measurements in LITER experiments showed reduction of *R* with lithium





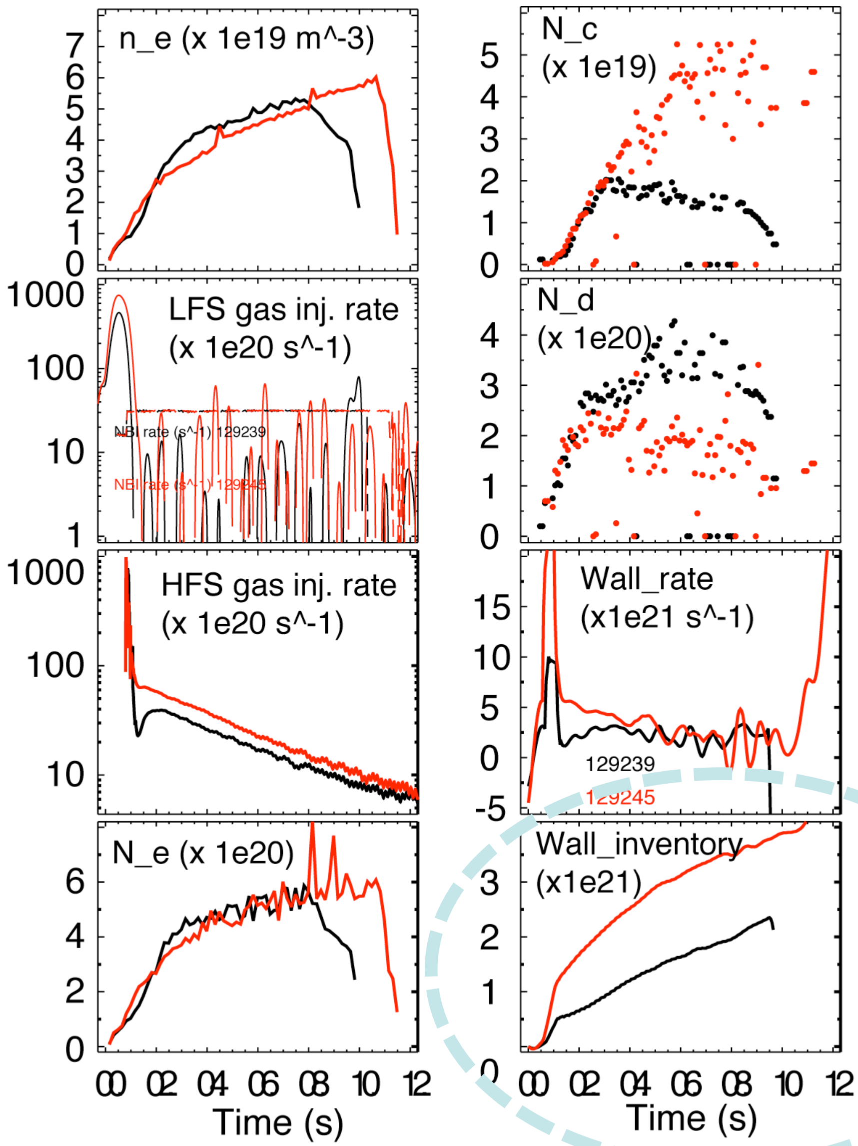
Strike point region *R* shows complex pattern

Far SOL *R* clearly reduced

XP aims at LLD pumping characterization based on measured particle balance and models

- 0D Particle balance models
  - Wall inventory model for pumping
  - "Simple" τ_p* model
    - Global τ_p* to understand LLD pumping
    - Local SOL τ_p* as LLD pumping metric
  - More sophisticated τ_p* model of core+SOL (R. Maingi - predictions for LLD pumping)
- 1D models (e.g., Onion Skin Model OEDGE)
- 2D multi-fluid models (e.g., UEDGE, SOLPS) to estimate pumping
  - May include DEGAS 2 for neutrals, lithium PSI and transport
- Kinetic models (plasma, neutrals)

Particle balance models show wall pumping in LITER experiments



- Lithium pumping is characterized by an increased “wall” loading rate and “wall” inventory
- Need to improve model for ion inventory only
- Particle balance equation for wall loading

$$\frac{dN_p}{dt} = \Gamma_{gas} + \Gamma_{NBI} + \Gamma_{NBI\_cold} + \Gamma_{NBI\_cryo} + \Gamma_{wall} - \Gamma_{pump} + \frac{dN_n}{dt}$$

Particle balance models show lithium pumping and τ_p* reduction in LITER experiments

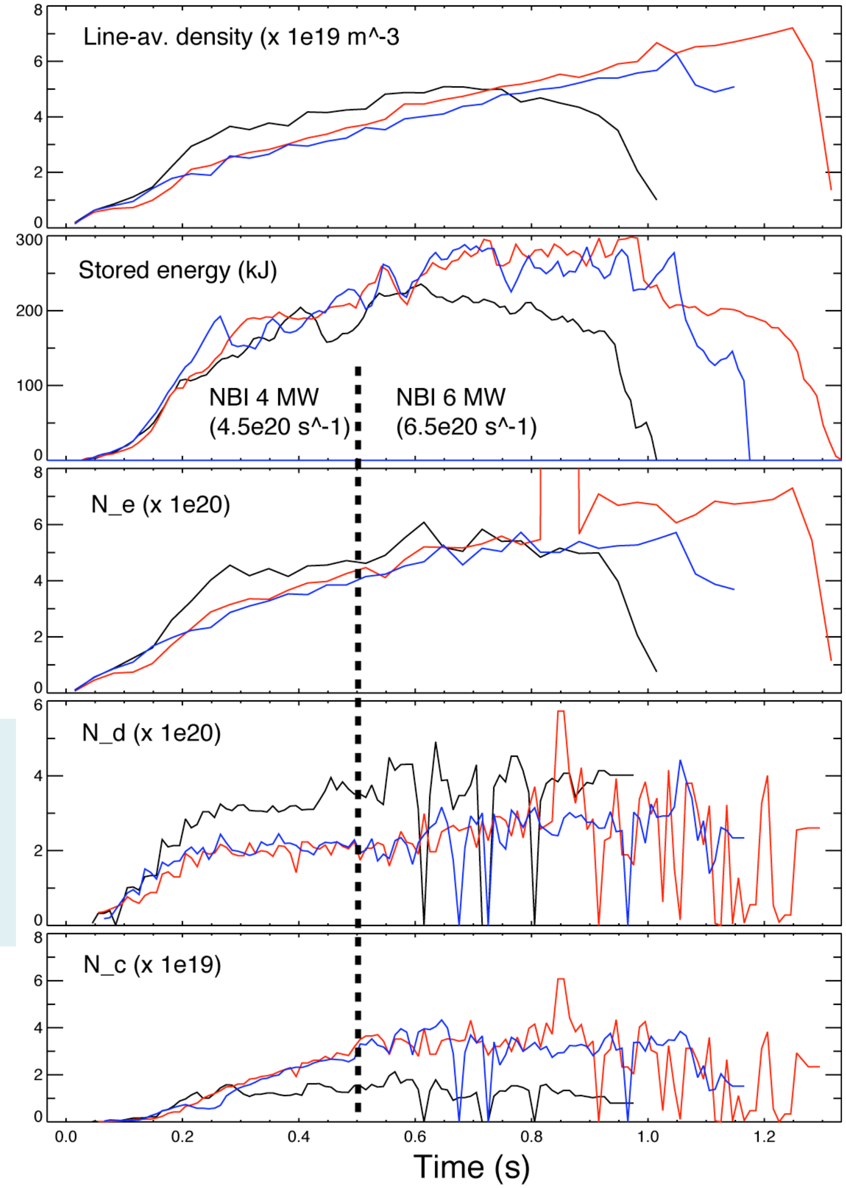
- Particle balance model

$$\frac{dN_p}{dt} = \eta_{gas} S_{gas} + \eta_{NBI} S_{NBI} + S_{recy} - \frac{N_p}{\tau_p}$$

$$\frac{dN_e}{dt} = S - \frac{N_e}{\tau_p^*}$$

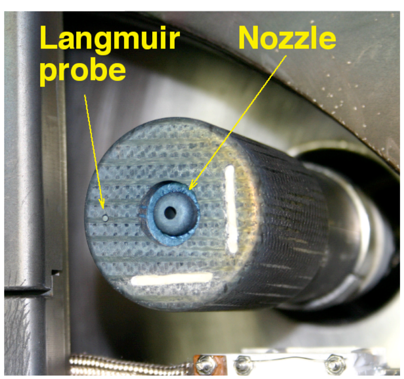
- "Steady-state" τ_p* estimated to be
  - ~ 250 ms w/ LITER
  - ~ 300-350 ms w/o LITER
  - HFS fueling 20-30 T-l/s
  - Interestingly, same ion inventory with more lithium albeit lowered recycling

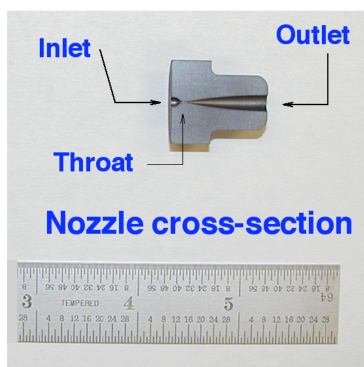
No lithium (129013)
190 mg Lithium (129061)
600 mg lithium (129064)

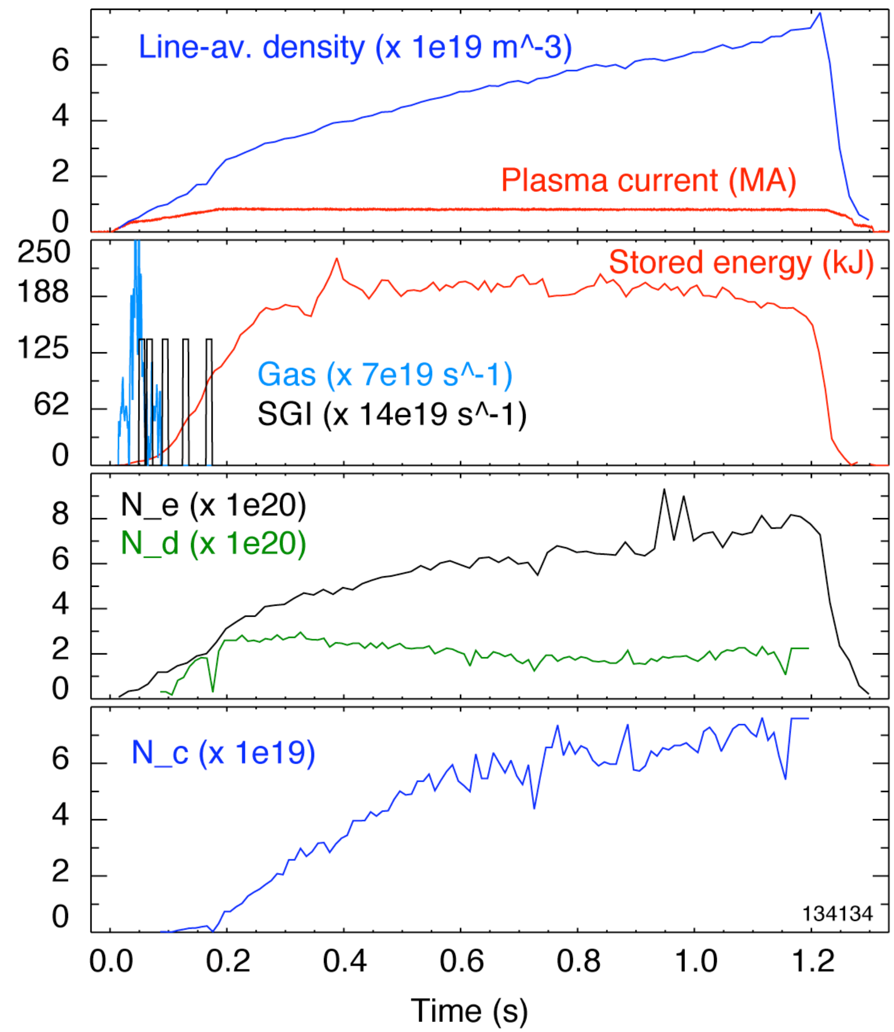


SGI fueling will be used to produce controlled steady-state ion density in XP 1001

- Used SGI-only fueling
- LITER rate 6-9 mg/min
- Ion density nearly constant
- N_i also nearly constant, while N_e is rising due to carbon
- τ_p* estimated to be 0.3-0.4 s

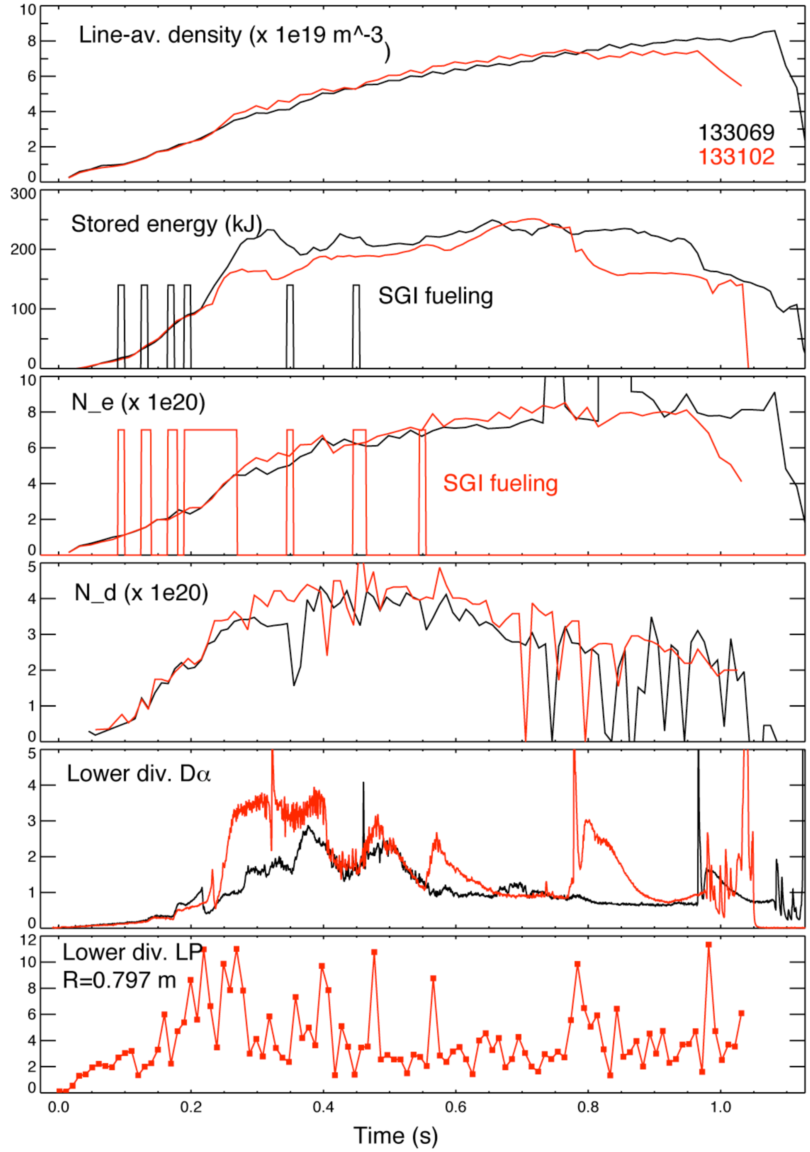




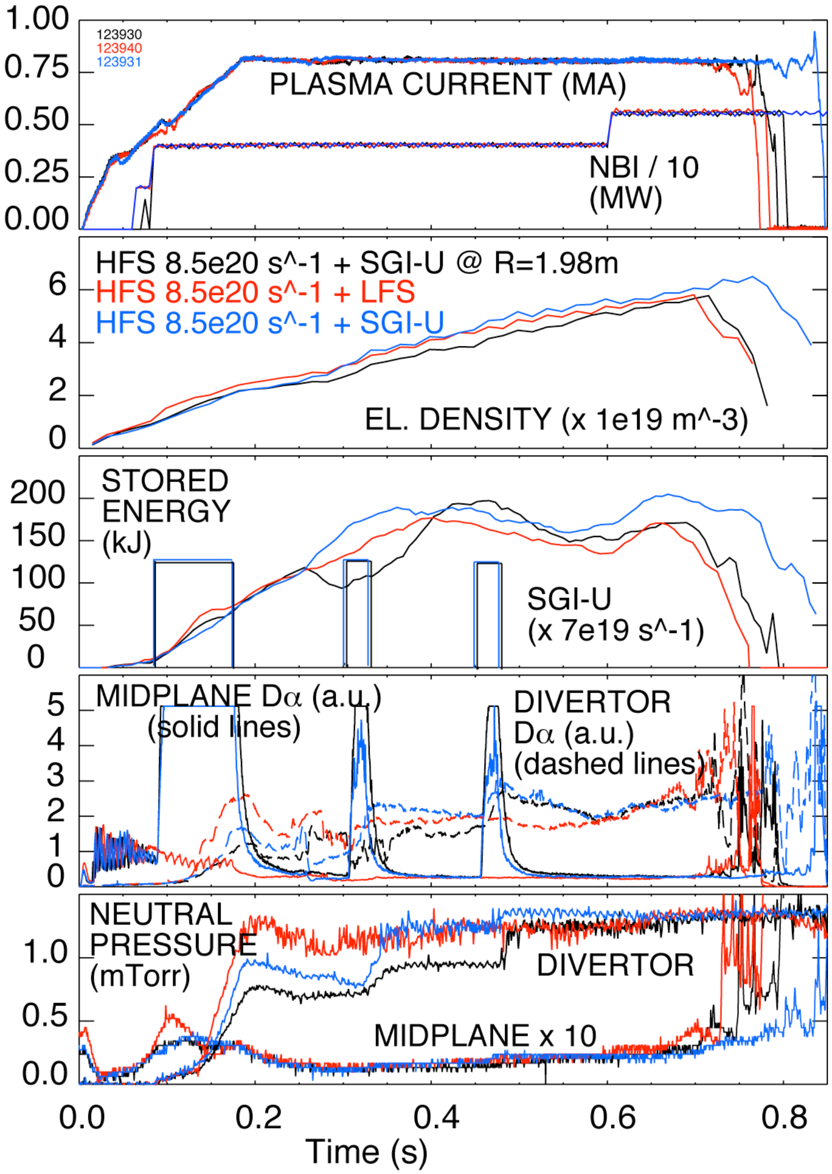


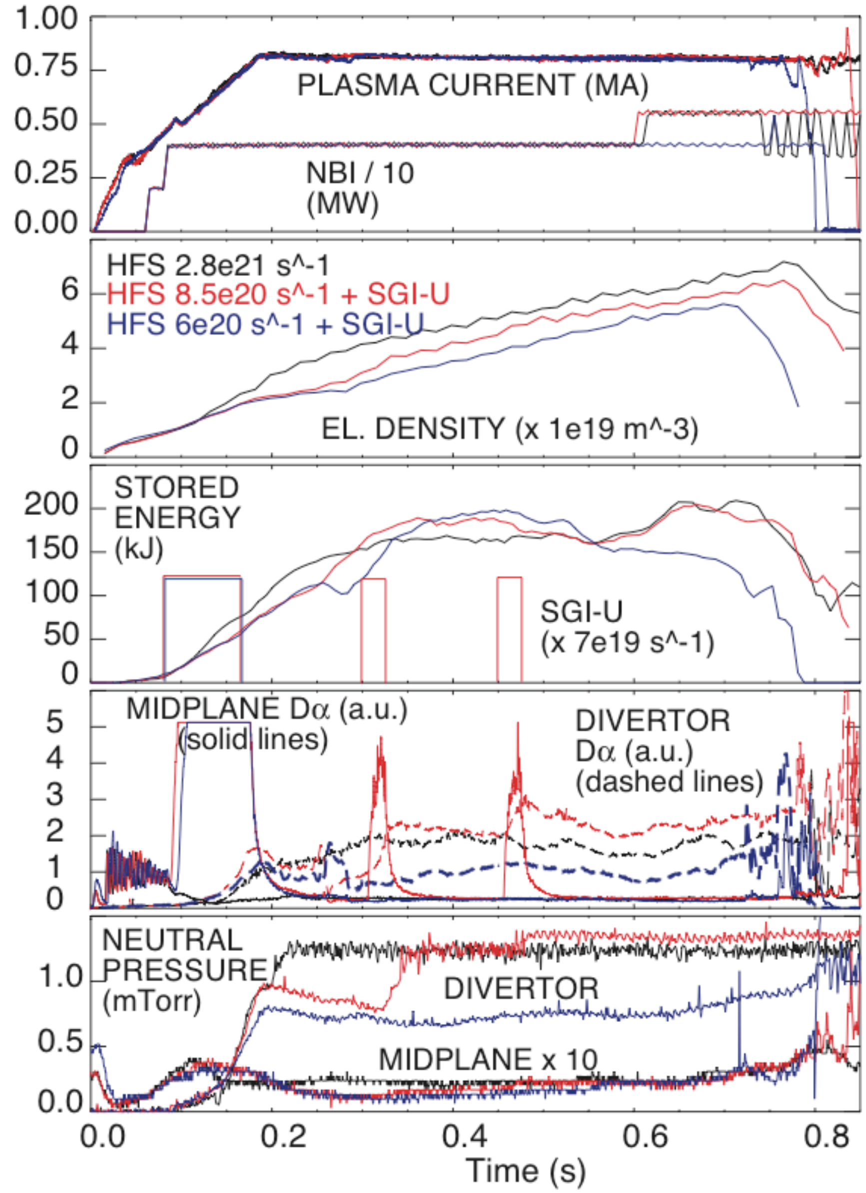
SGI singular gas pulses will be used to measure "pump-out" (edge " τ_p* ")

- Measure dynamic SOL density response to singular flat-top SGI pulses ("pumpout") at various LLD temperatures, plasma densities
  - Use FIReTIP channel 7 (R_{tang} ~ 150 cm) at midplane (n_e)
  - Use divertor Langmuir probes (Γ_i, n_e)
  - Use neutral pressure gauges (Γ_n, n_0)
- Example - Two shots compared
  - 14 mg/min Li evaporation, 10 min clock cycle
  - HFS at 700 Torr + SGI
  - Higher SGI and **lower SGI** fueling rate
- Accordingly, higher N_e, N_d and **lower** $\boldsymbol{N_e}$ **,** $\boldsymbol{N_d}$ obtained
  - Carbon inventory the same (not shown)
- Divertor D_α and Langmuir Probe I_{sat} correlated with SGI pulses, showed density pump-out



Discharges without lithium conditioning never showed pump-out with SGI singular gas pulses





XP 1001 would also produce good scans and data for pedestal, SOL and divertor studies

- Effect of LLD on SOL / divertor transport
  - Impurity sources
  - What can we say about parallel heat transport?
    - T_e gradients?
  - What can we say about radial ion and impurity transport?
    - Use GPI to characterize blob velocity and size

- Effect on pedestal
  - Relate (n_e, p_e) pedestal structure (height and width) and collisionality to recycling measurements and pumping (e.g., via Mahdavi model)
  - Further quantify ion transport vs source effect

Tentative run plan

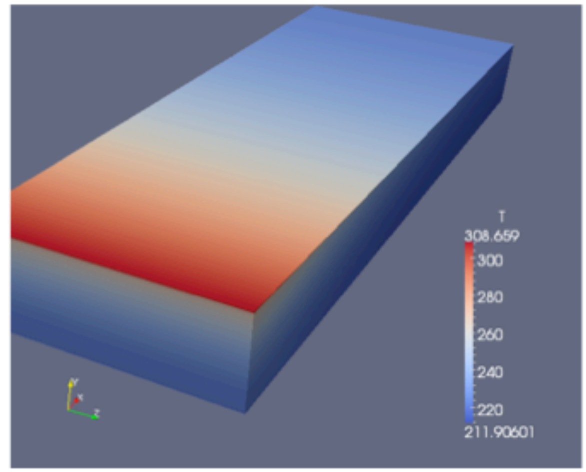
- Target – SGI-only 0.7-1 MA, 3-5 MW NBI H-mode from XP 1000
  - Fine-tuning – 2-3 shots
- Ion density scan with pulsed SGI – 10 shots w/ cold LLD, 10 shots w/ warm LLD
  - Obtain a proportional range of ion fluxes to divertor plate
  - Can probably support $n_d \sim 1\text{-}6 \times 10^{19}$ m^{-3} in steady-state
  - May include different R_{OSP} (0.5, 0.55, 0.63 m, etc)
  - May include 2-3 shots with LDGIS gas injection
- LLD at different temperature – up to 10-15 shots
  - Desirable to go beyond 220 C ! (e.g., 250, 300 C)
- Total – 1-1.5 days

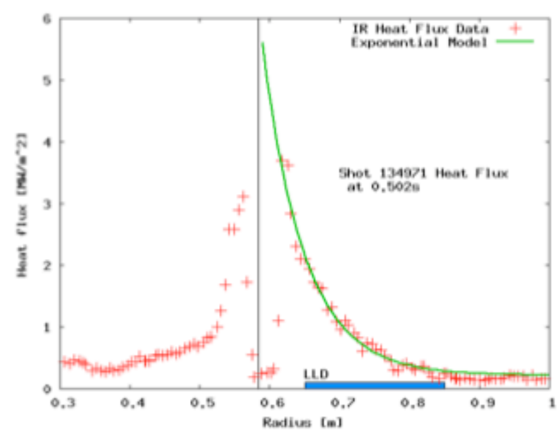
Backup

Details of LLD thermal regime calculations by M. Jaworski (1)

Working model for LLD temperature rise

- Implemented model making estimates of temperature rise
  - Using OpenFOAM computational system to perform thermal analysis
  - Toroidal symmetry assumed (wedge modeled)
  - Using IR heat flux measurements for input (J. Kallman and R. Maingi)
  - LLD geometry and materials used (additional porous material model based on Jaworski **JNM** 2008)
- Conservative/Pessimistic boundary conditions
  - Constant heat flux for 1s pulse duration
  - No radiation or evaporative cooling (both negligible)
  - Insulated boundaries – how hot can it get?
- End result is upper-bound on temperature during heat pulse

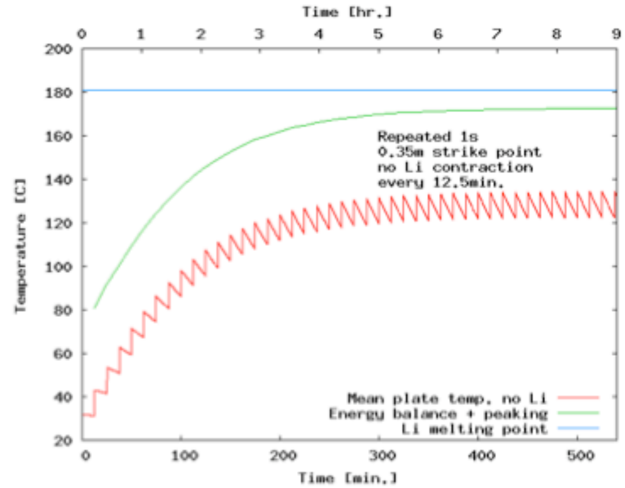


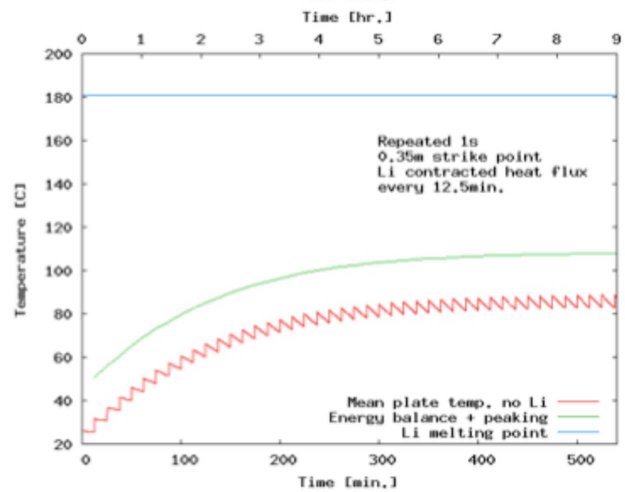


Details of LLD thermal regime calculations by M. Jaworski (2)

Possible use for *starting* temperature scan

- Temperature of unheated plate will ratchet
  - Thermal calculations very preliminary here
  - Unknown emissivity and effective radiating surface area (geometric and B.B. used here)
- Fiducial temperature profile used here
  - 1 MW/m2 inboard, 0.6 MW/m2 outboard without Li
  - Contraction to half this due to Li effect (both via. R. Maingi)
  - 12.5 minute shot cycle
  - Potential to transition unheated plate to liquid state within a shot
- More operational data needed and small experiments in C128 to make a better estimate





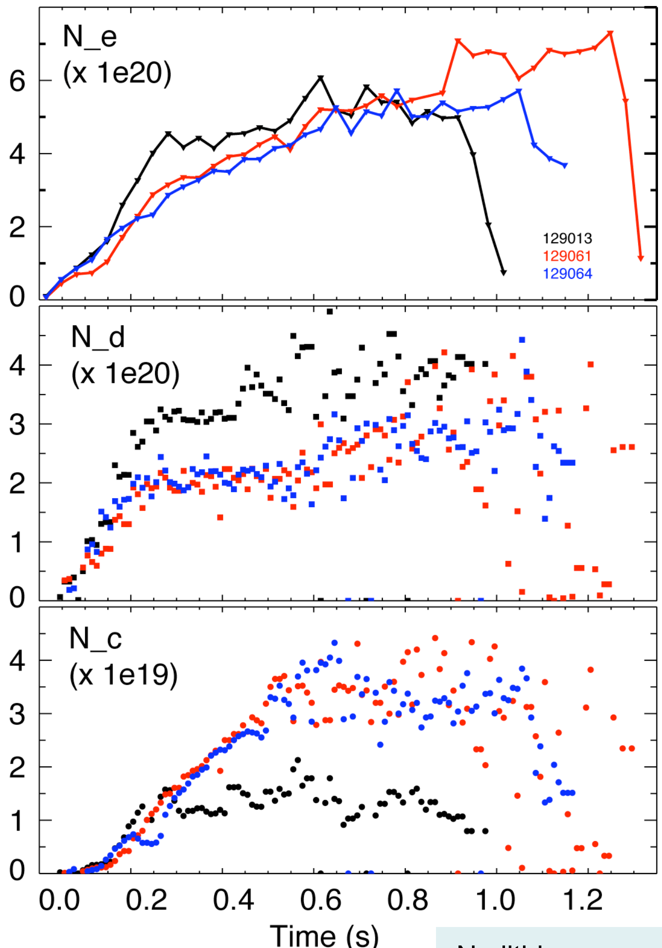
Summary of APS 2009 poster "Modifications in SOL and divertor conditions with lithium coatings…" by V. A. Soukhanovskii *et al.*

- Evaporative lithium coatings on carbon PFCs modify divertor and SOL sources
  - Lower divertor, upper divertor and inner wall recycling was reduced by up to 50 %
  - Local recycling coefficients reduced on inner wall and far SOL, remained similar in the outer strike point region
  - Lower divertor carbon source from physical sputtering also reduced
  - Divertor lithium influx increased, however, lithium was retained in divertor

- SOL transport regime changes from high-recycling to sheath-limited
  - Apparently small parallel T_e gradient
  - Detached inner divertor re-attaches, X-point MARFEs disappear

- Pedestal and core confinement improvement leads to
  - Reduction of ion inventory (density) by up to 50 % due to surface pumping
  - Effective screening of lithium from core plasma
  - Carbon and high-Z impurity accumulation
  - P_{rad} increases in the core, P_{SOL} significantly reduces

Ion inventory is well controlled in discharges with lithium, core carbon accumulates, lithium is screened out



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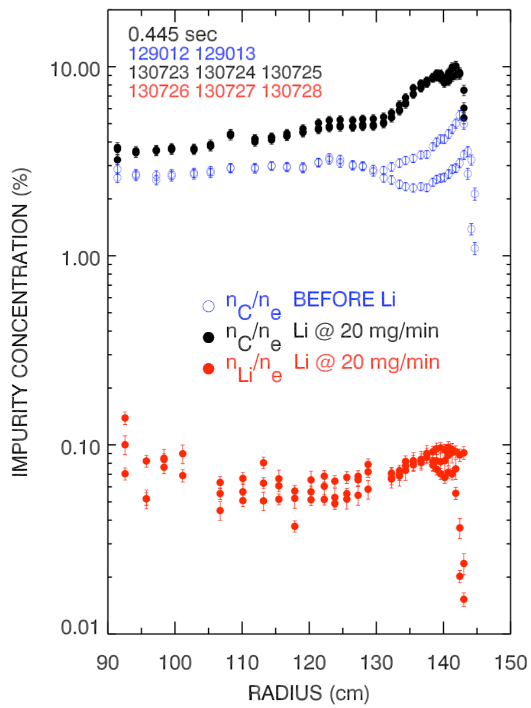

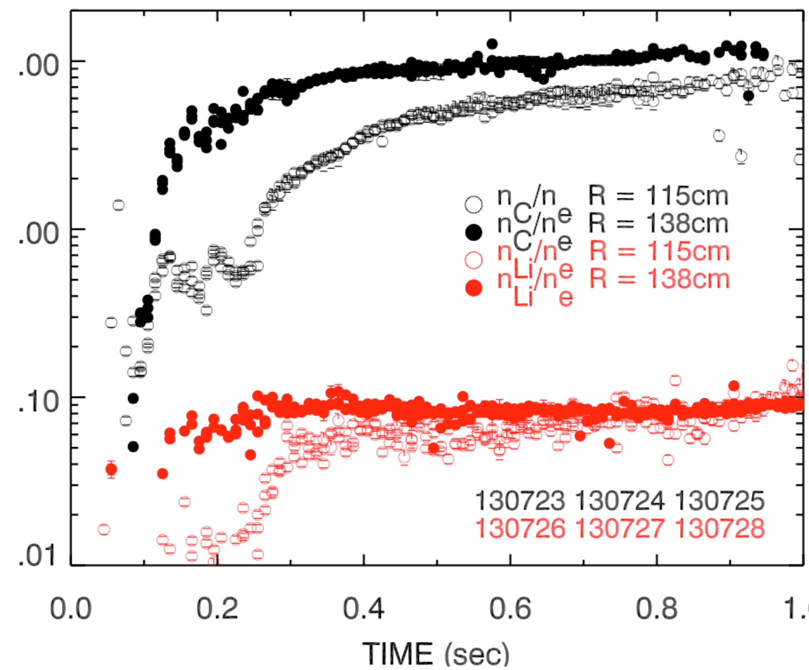

- Impurity density profiles from CHERS
  - C VI, n = 8-7 transition, 529.1 nm
  - Li III, n = 7-5 transition, 516.7 nm
- Lithium concentration much lower than carbon concentration
  - $n_C/n_{Li} \sim 100$
- Carbon increases with Li evaporation