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Characterization of Effect of LLD on Edge Plasma Parameters using High-Density Langmuir Probe Array

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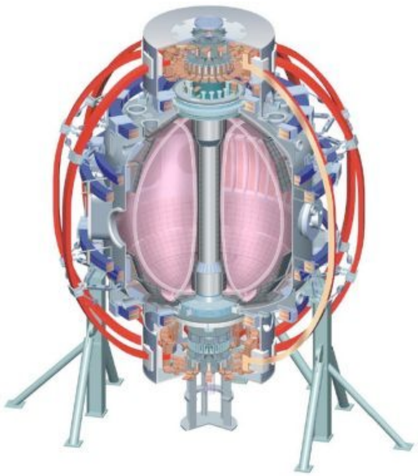

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Abstract

The NSTX Liquid Lithium Divertor (LLD) is designed to alter the edge plasma by providing a persistent particle sink with greater affinity than lithiated graphite surfaces for deuterium ions reaching the divertor target, thus lowering edge density while increasing edge temperature. In order to measure this effect, a 99-channel Langmuir probe array was designed and installed in an NSTX carbon divertor tile situated in the gap between two LLD plates. The Langmuir probes have the capability to measure the target electron temperature and density in either swept single-probe or continuous triple-probe mode. The probe array can also directly measure the incident ion flux from the plasma, which can be used to track the strike point location for applications in control system optimization and verification in conjunction with magnetic, D_α, and IR camera data. In addition, offline and in-vessel RGA measurements of reactive lithium surfaces are analyzed using mass de-convolution to relate gaseous partial pressures to lithium activity, which is then correlated with n_e and T_e measurements from the probe array.

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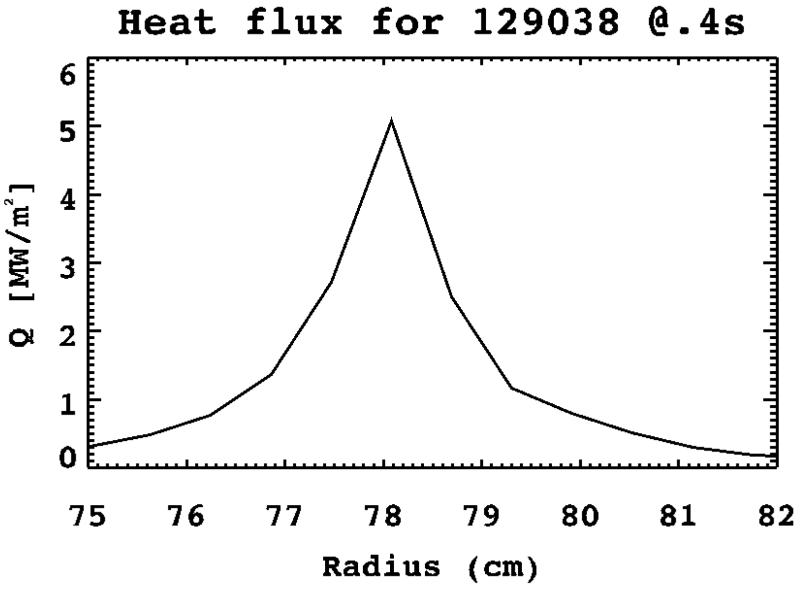
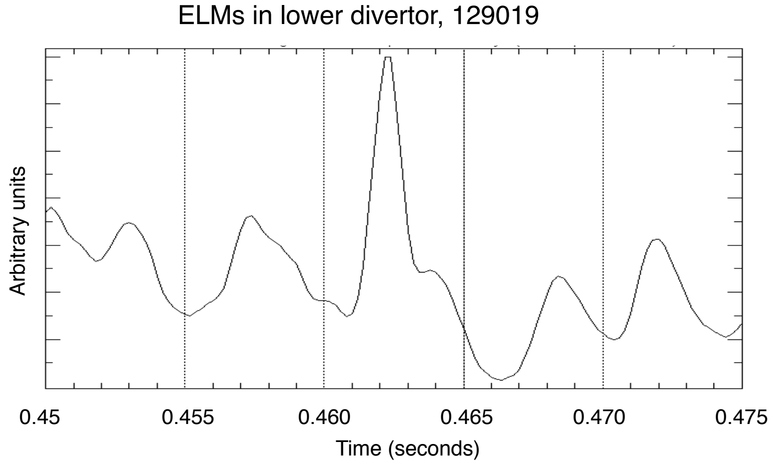
Overview

- NSTX has been conducting experiments for several years to assess the effect of lithiated wall conditions on NSTX plasmas
  - this year a liquid lithium divertor was installed
- Models predict that density and temperature in the scrape-off layer (SOL) will change due to lithium pumping of deuterium
- Previous edge diagnostic coverage in the NSTX divertor region has been limited, especially for plasma density and temperature
- A dense Langmuir probe array was developed to provide SOL measurements
- Initial data from the probes are presented
  - probe array characterizes J_{sat} profile for LLD experiments
  - SOL particle lifetime of diagnostic SGI pulse can be measured
- RGA studies from offline experiments examined for use in in-situ determination of LLD surface activation

Physics requirements for the Langmuir probe array

- Heat flux profile at outer strike point has FWHM of 10 cm
  - current IR camera resolution is 16 data points over this region
  - higher spatial resolution could allow more accurate particle flux measurements
- Edge Localized Modes (ELMs) occur on a time scale of several ms
  - temporal resolution should be sufficient to operate during transient events (single tip probes would be limited by voltage sweep rate)
  - triple probes would provide instantaneous data



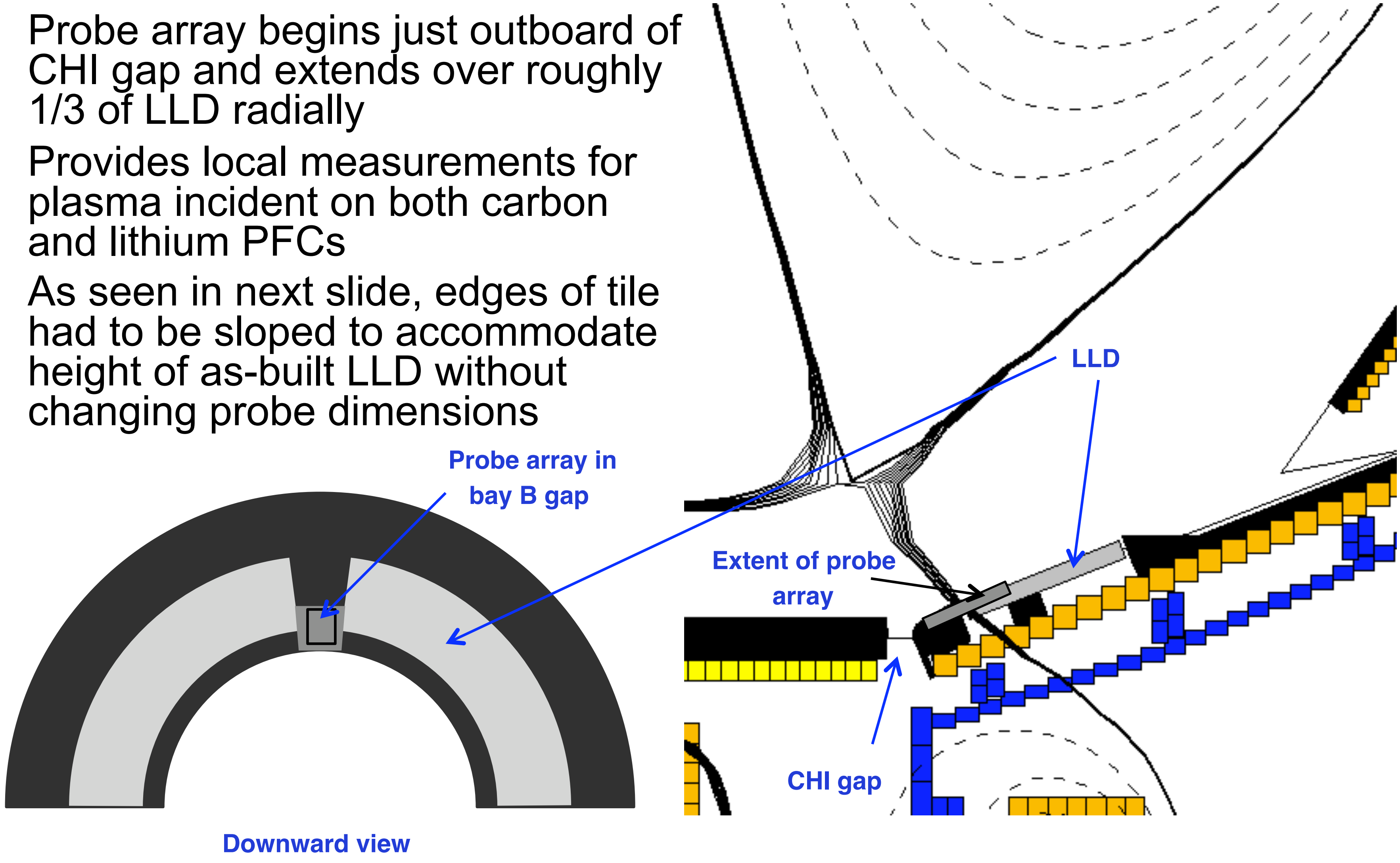


Heavy lithium depositions on divertor surfaces present materials challenge

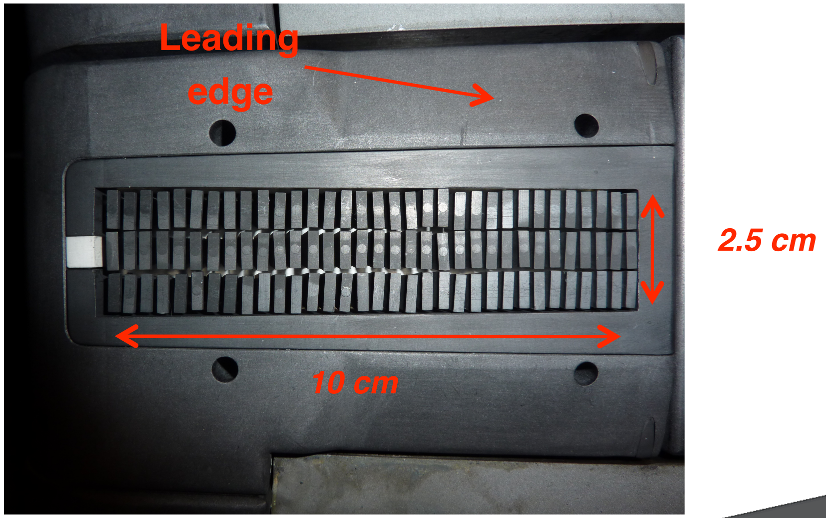
- Elemental lithium is conductive, providing a possible path for shorting electrodes to each other or ground
- Lithium also reacts with carbon in the presence of oxygen (residually present in NSTX vacua) to form lithium carbonate, an insulator
  - this effect is beneficial in avoiding grounding and direct conduction, but can provide barrier for incident electrons and ions
  - previously installed Langmuir probes show no appreciable loss of signal with heavy lithium loading, but NSTX was anticipated to deposit amounts an order of magnitude greater than previous years to fill LLD
- Strike point ablation can remove evaporated lithium, but large integral effect of continuous loading depositions is unknown
  - alternate cleaning methods, such as high current pulses to electrodes, are under investigation

Probe array is located near LLD to provide local measurements

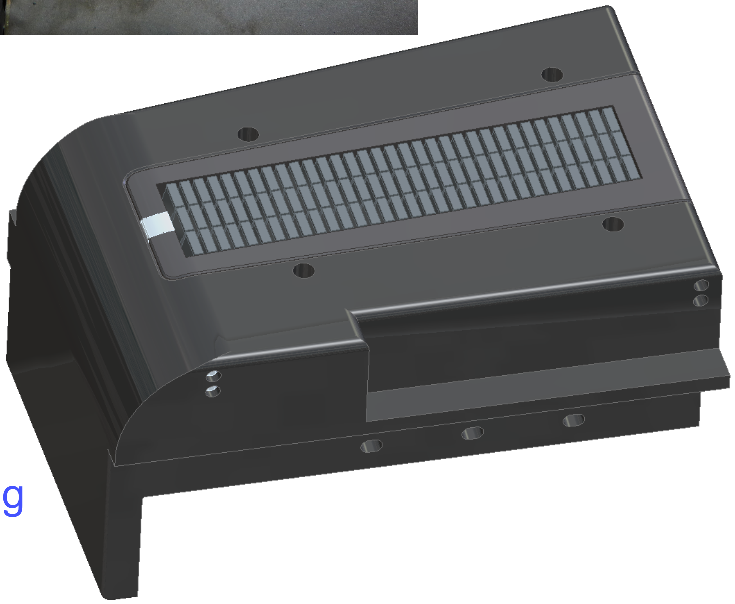
- Probe array begins just outboard of CHI gap and extends over roughly 1/3 of LLD radially
- Provides local measurements for plasma incident on both carbon and lithium PFCs
- As seen in next slide, edges of tile had to be sloped to accommodate height of as-built LLD without changing probe dimensions



Triple Langmuir probe array addresses edge diagnostic needs

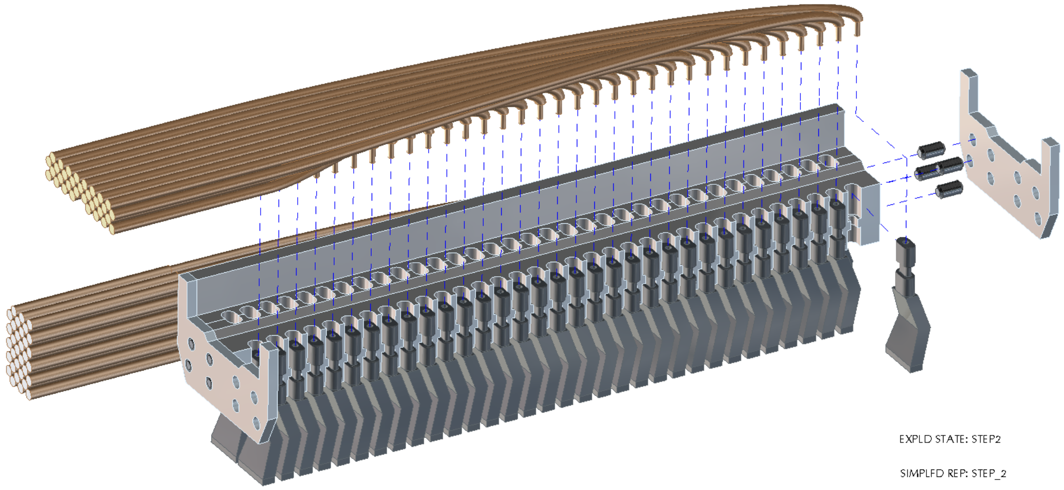


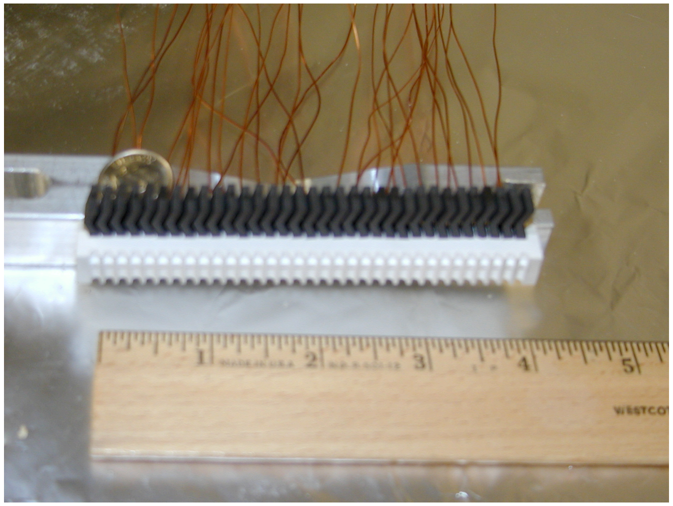
- 33 radially arrayed triple-probes provide edge temperature and density characterization on a continuous basis
    - can also be operated as swept or SOL current probes
- Probes based on MAST design involving a Macor cassette of closely spaced probes embedded in a carbon tile
    - tile mount with radial coverage of divertor (Bay B)
    - 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

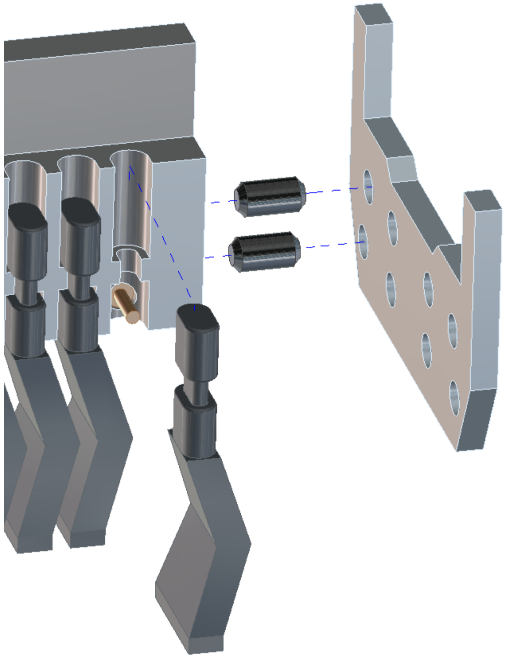
Cassette design allows for ease of probe mounting and includes channels for wire transport

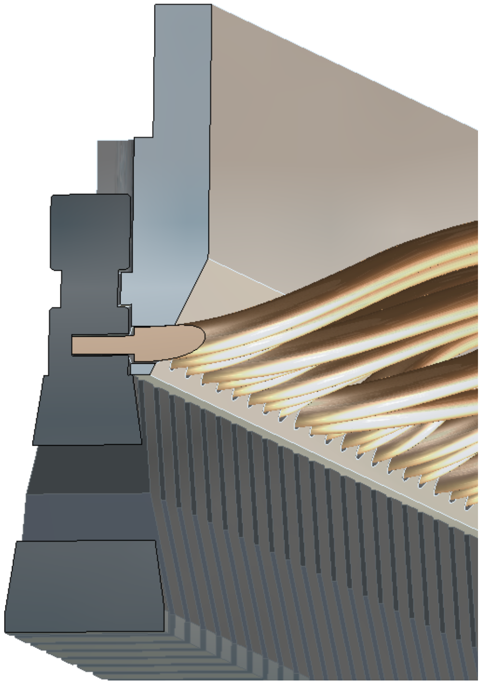




- Boron nitride cassette features interlocking segments that allow for individual probe seating and securement
  - screwless design reduces mechanical stresses on the probes
- Wiring channels allow for the wires from each group of probes to exit independently
  - wires exit on sides of edge probes and 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

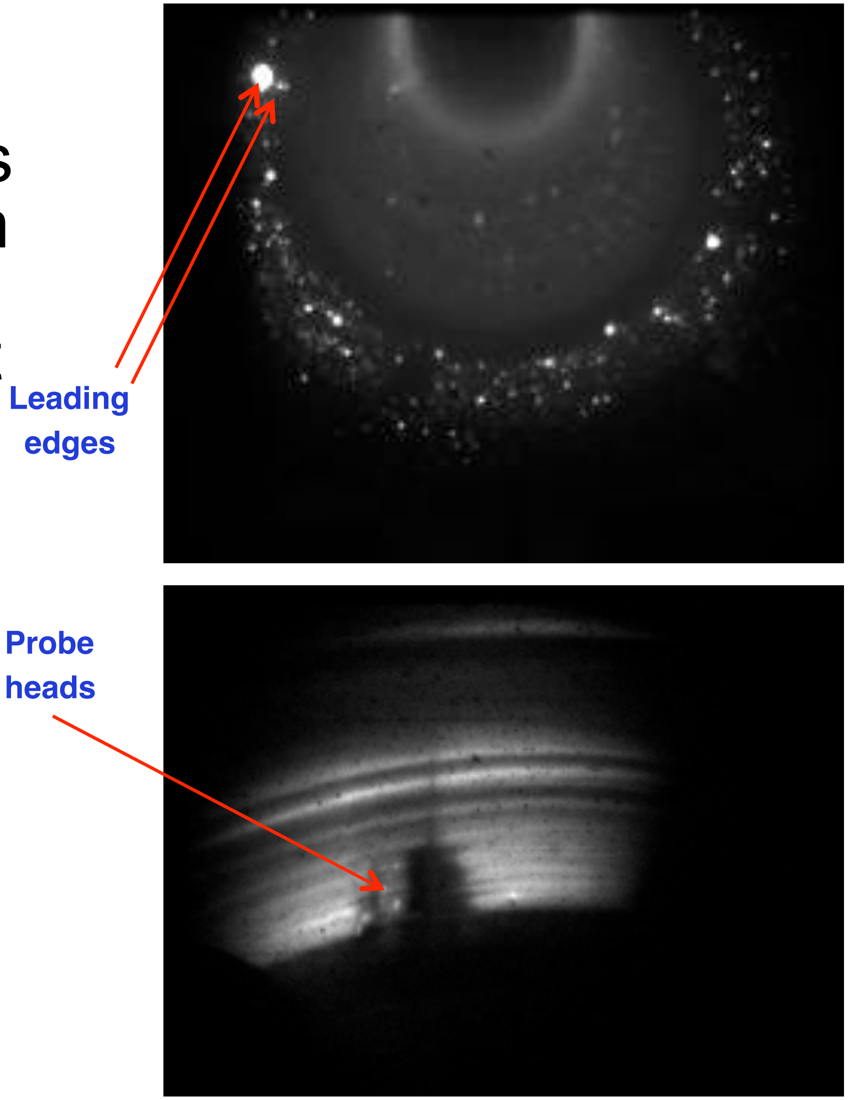




- Boron nitride offers greater lithium compatibility than original macor design
- Probes are shaped so as to minimize direct exposure of BN to plasma or lithium
  - bend prevents direct line of sight for lithium or plasma down to cassette
  - widening at probe top allows for smaller gaps and greater shielding of surfaces below
  - electrode material is vacuum compatible HK-6 Tokai graphite
- Array installed in December prior to start of NSTX 2010 run

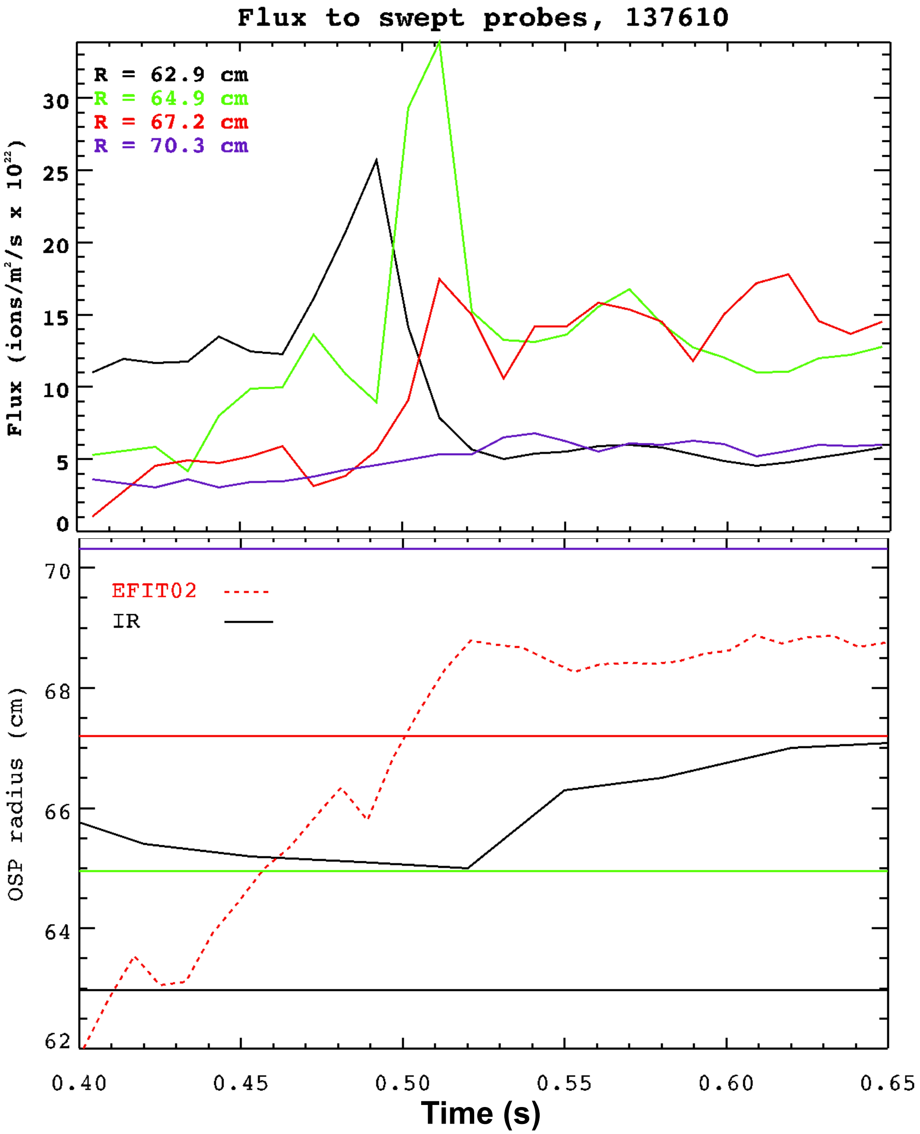
Probes continue to provide data despite significant heat and lithium fluxes

- NSTX bay J fast camera (w/IR filter) measurements show some afterglow from leading edges (through hole for securing bolt), but not from probe tips
- Bay F fast camera view with lithium filter shows individual probe heads as strike point causes ablation
  - a shadow is also visible where the array acts as a limiter due to its elevation relative to the LLD



Views from above

Swept probes track flux as outer strike point moves

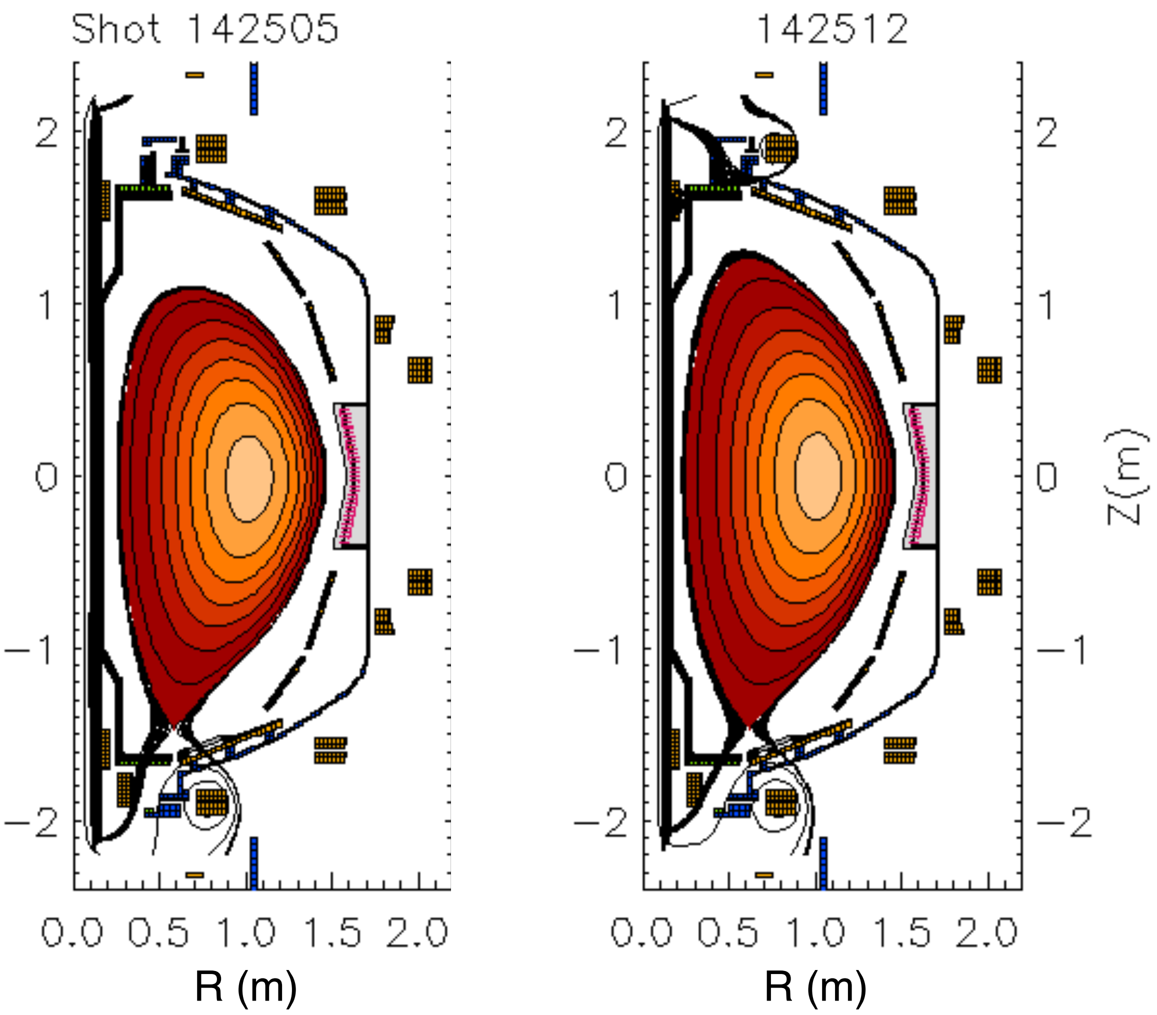


- Probe current taken at most negative voltage defined as ion saturation
- Flux to probe defined as

$$\Gamma_{probe} = n_e c_s = \frac{I_{+sat}}{eA_{probe}}$$

- Probe data in reasonable agreement with magnetic and IR camera data
  - EFIT OSP radius overestimated: increased divertor height due to LLD geometry
  - flux greatest to two probes that bound IR OSP estimate
  - probe signals at greater radii show increased flux as OSP moves outboard

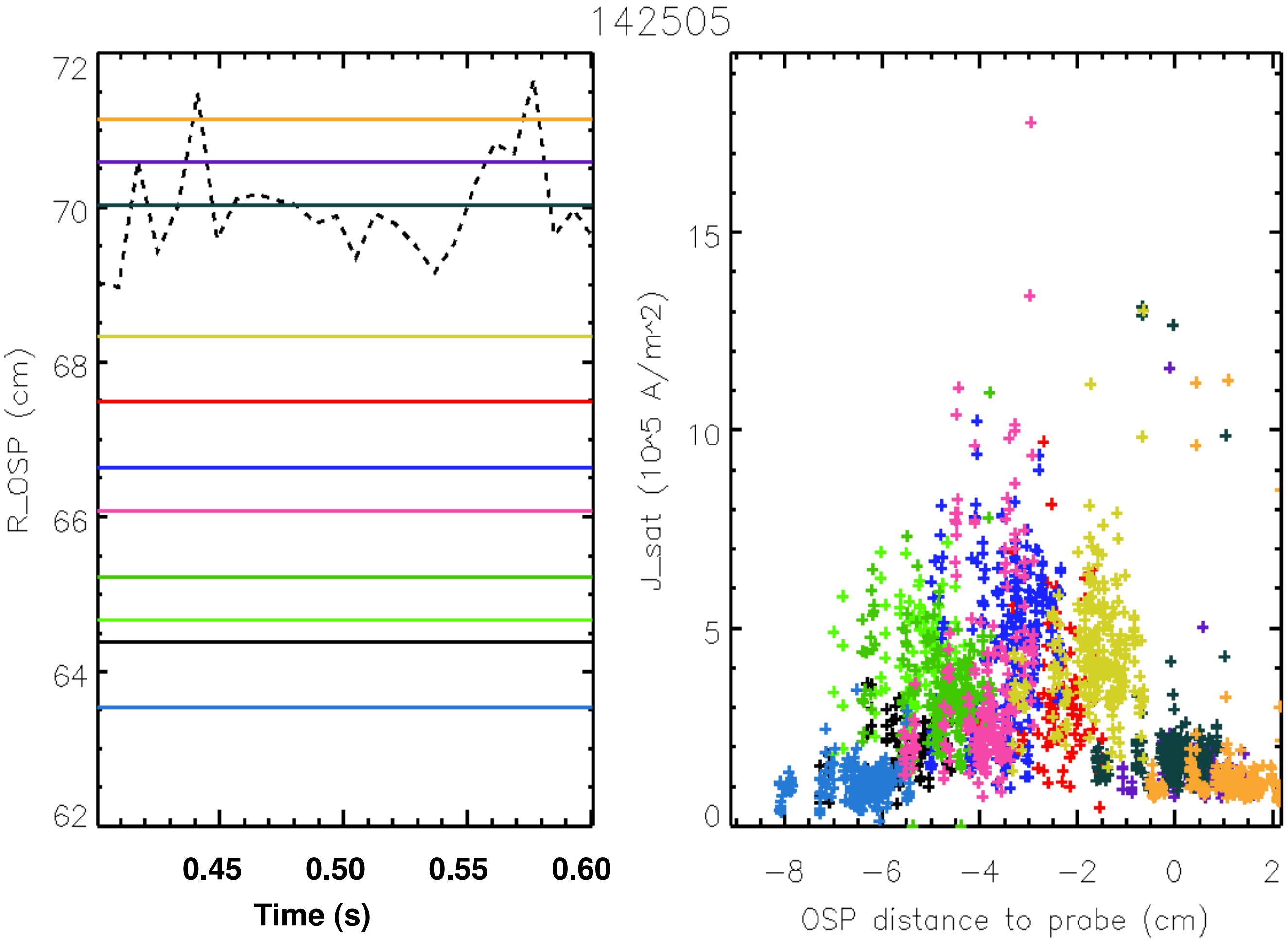
NSTX XP 1000 characterized LLD for two outer strike point (OSP) radii



- 142505 shot template uses low elongation, strike point controlled at nominal R =.73 cm
  - takes full advantage of LP array
- 142512 shot template uses higher elongation discharge shape, strike point nominally controlled at R = .78 cm
  - less coverage on LP array, but sits near center of LLD
- Run plan used initial Li evaporation, then scan in temperature throughout day

Utilizing full swept and triple probe suite, a comprehensive SOL saturation current profile can be obtained

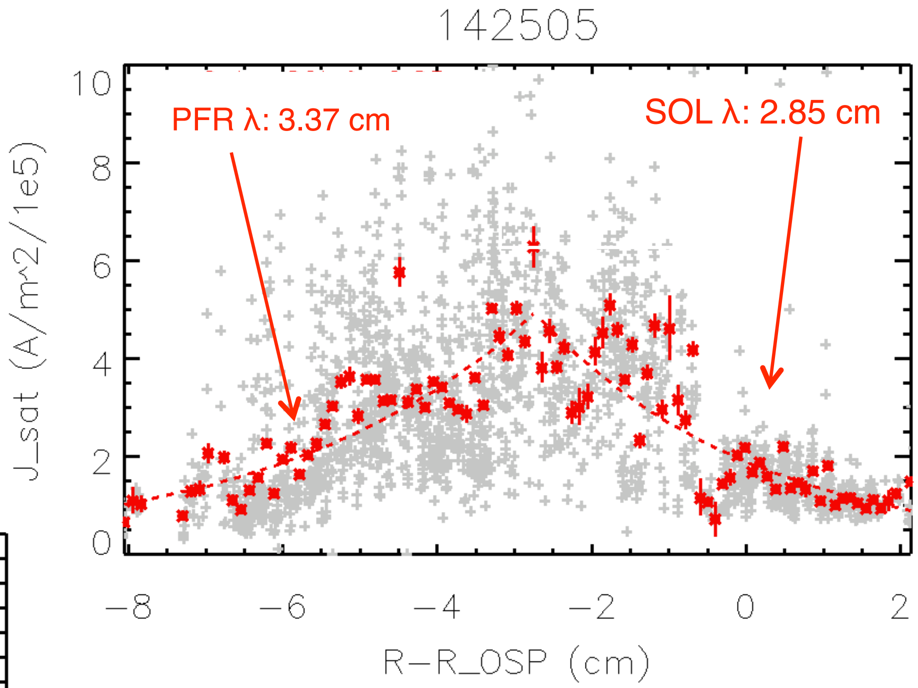
- J_{sat} is plotted for $R_{probe} - R_{OSP}$
  - strike point data taken from EFIT02 reconstruction
  - median filter applied to triple probe data to reduce noise/ ease processing
- Bottom plot shows strike point trace over time of interest as well as probe positions
  - 7 triple and 4 swept probes employed in present analysis

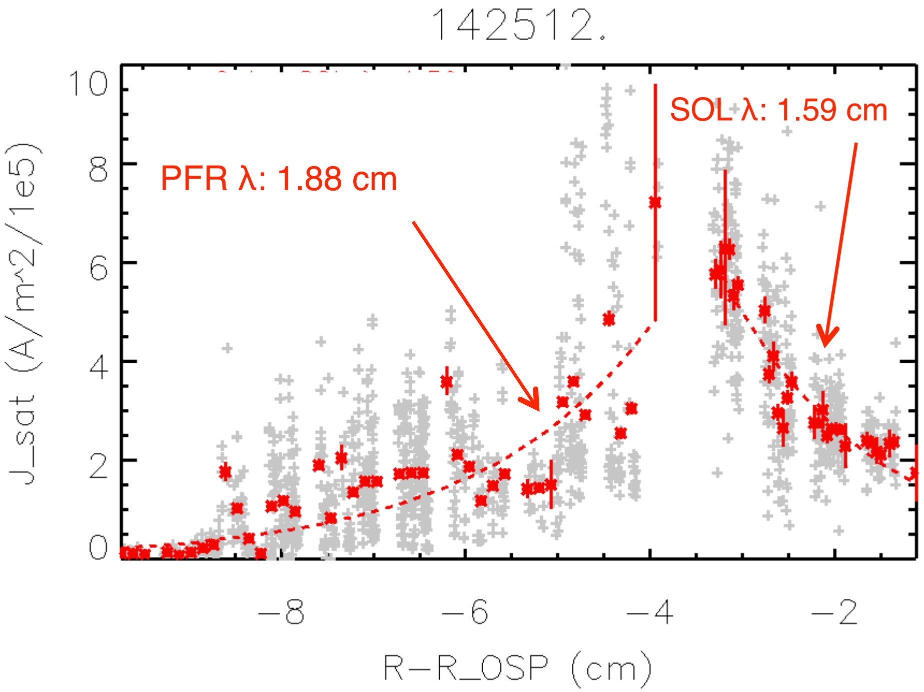


- ELM-free periods utilized for present analysis, but triple probes run at 250 kHz digitization time for potential intra-ELM data

Current density profile can then be fit to provide scale lengths at divertor target

- Raw probe data is binned for both private flux region (PFR) and SOL profiles separately
- Bin values are averaged (red points), providing error bars through counting statistics

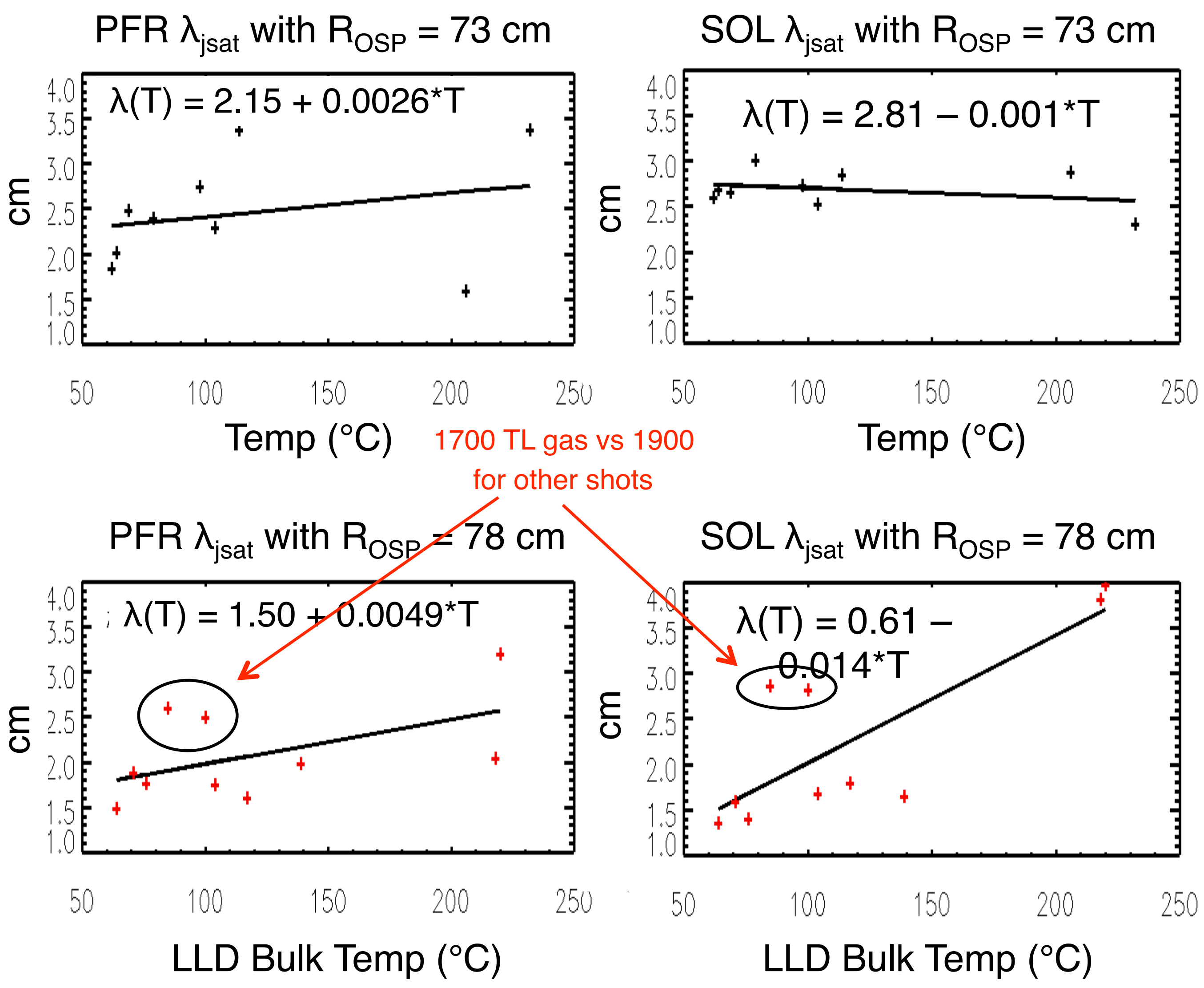




- Exponential behavior assumed, allows for a determination of current density scale lengths both in SOL (outer) and private flux region (inner)
- Current density is directly related to flux to probes, can be utilized in determination of recycling coefficient in combination with D-α data (see M.A. Jaworski’s poster: BP9.00052)

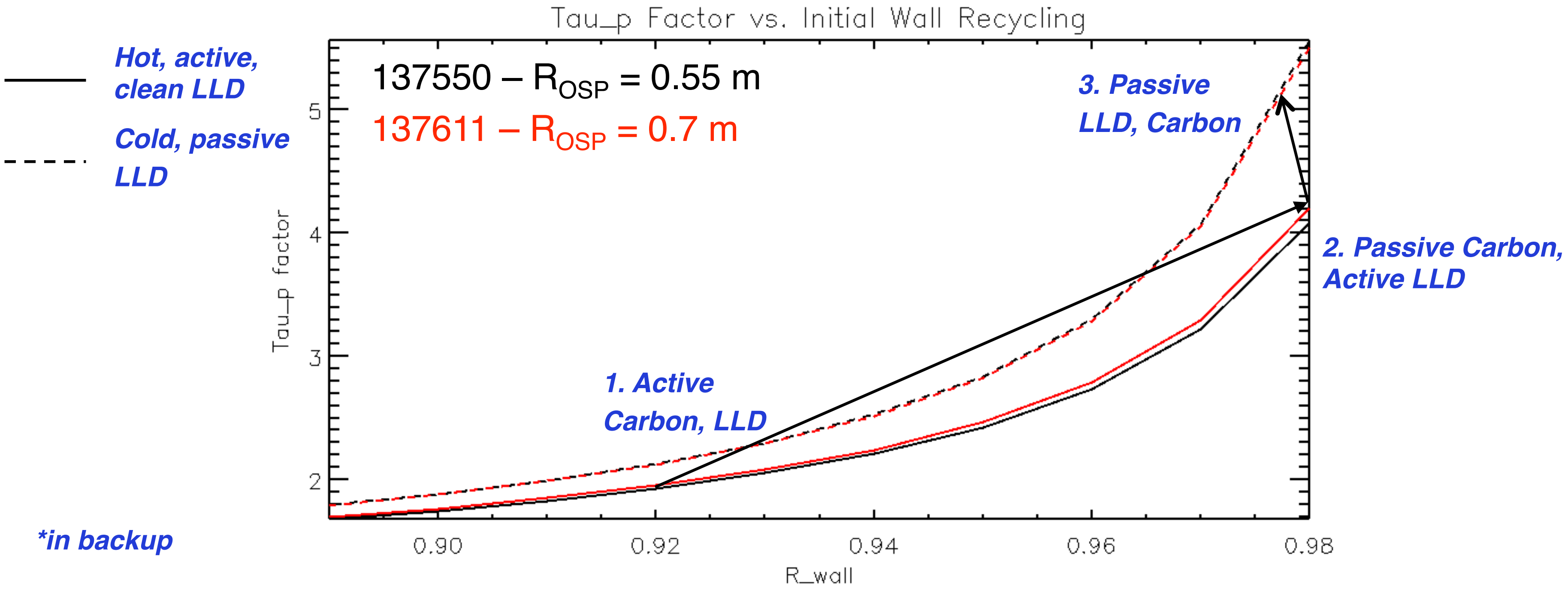
Current density profiles examined for dependence on LLD temperature during scan

- Both PFR and SOL scale lengths examined for 73 and 78 cm OSP radius
- Very little dependence evident for 73 cm shots
- Slight dependence for 78 cm shots
  - circled data points show potential relation to plasma fueling; suggests future line of research
- Lack of data points at intermediate temperatures complicates interpretation
  - 78 cm shots suggest binary SOL regime → where is the transition temperature?



0D model* predicts changes to particle lifetime with and without LLD presence – related to SOL lengths?

- Scan in Rp, recycling of carbon walls
  - according to J. Canik, should be 92% for pumping, 98% for passivated
- Run initially for two cases
  - R = .63 (137550), R = .7 (137611)
- XP should provide expected particle lifetimes for active/inactive LLD with and without actively pumping carbon tiles
- XP 1000 roughly duplicates this – as initial Li evaporation passivates throughout day, LLD should retain pumping capacity
  - is this a better metric than simply temperature scan than utilized above?



1. Active Carbon, LLD

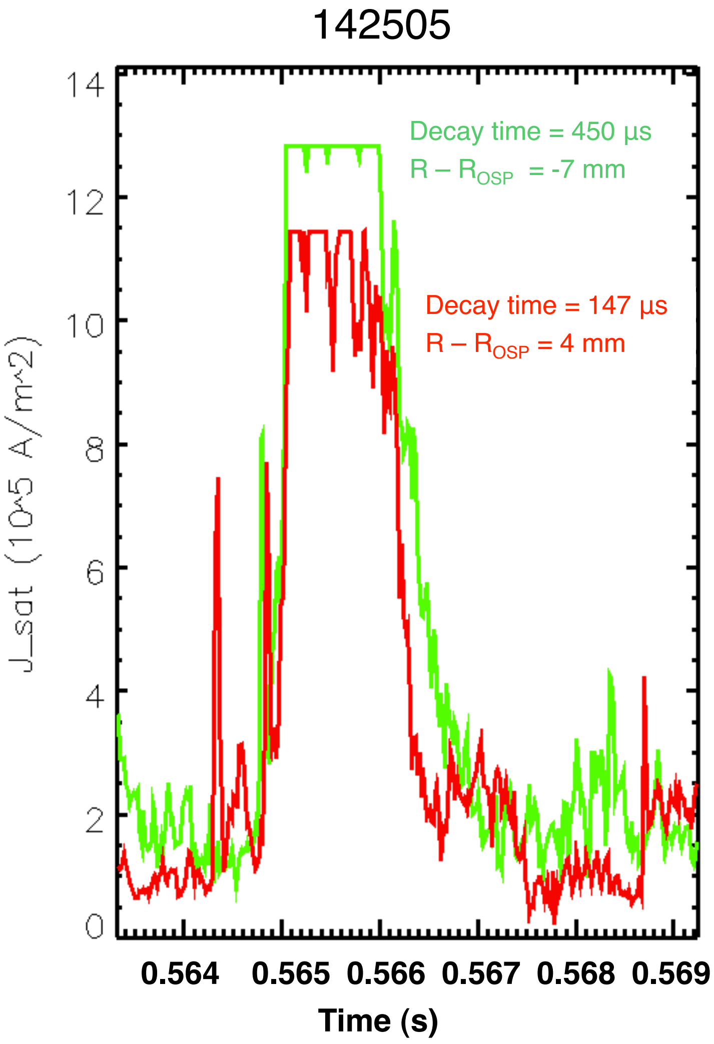
2. Passive Carbon, Active LLD

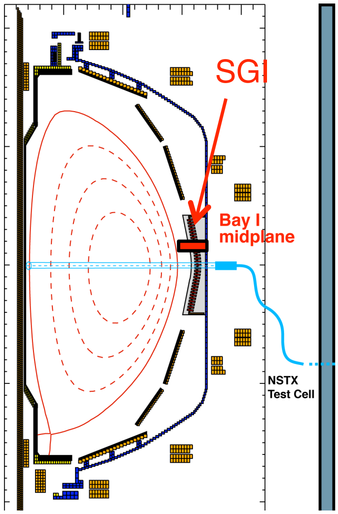
3. Passive LLD, Carbon

in backup

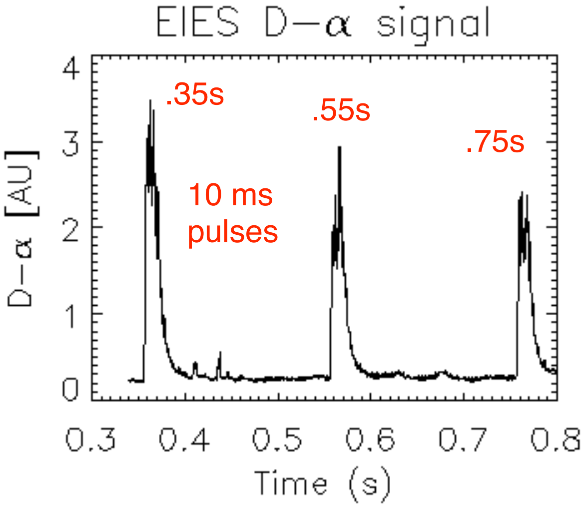
Supersonic Gas Injector (SGI) pulses utilized as controlled gas source to attempt to measure particle lifetimes in SOL

- EIES system detects D-α emission during and after SGI pulse
- As D puff ionizes and moves through SOL, should be visible on LP array
- In most cases, SGI puff triggers an ELM that is clearly visible, but measurement is of ELM decay time rather than lithium pumping



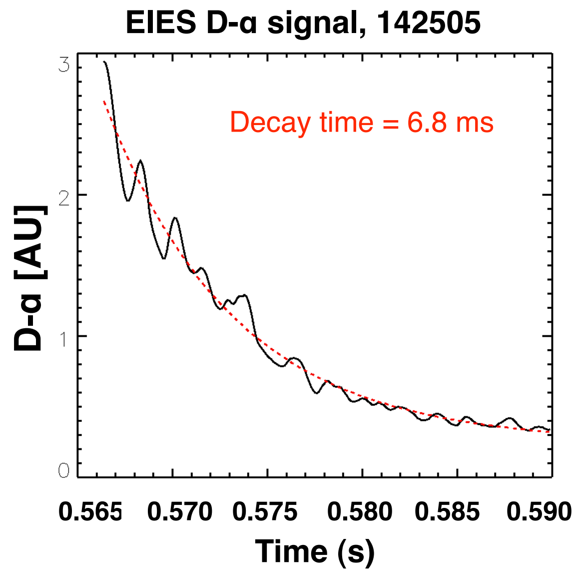


Edge Impurity Emission Spectroscopy (EIES) - Bay I midplane view

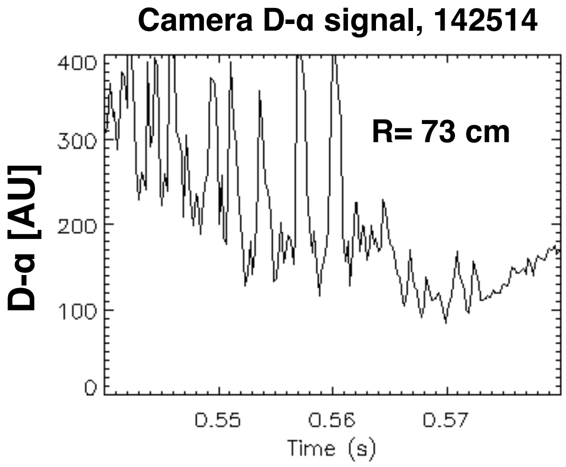


More analysis necessary if SGI is to be used in global particle confinement measurement

- Proximity of SGI to EIES sightline inhibits ability to draw global conclusions
  - signal is a local view of light from the gas jet itself
- Pulse is nominally a square wave, but full physical characterization of nozzle has not been performed
  - decay of EIES signal is a function of nozzle closure time
- Downward viewing camera can better aid in global measurement, but ELMs, turbulence make fitting difficult
- Pulse is generally not visible on probes when ELMs are not present


EIES D-α signal, 142505

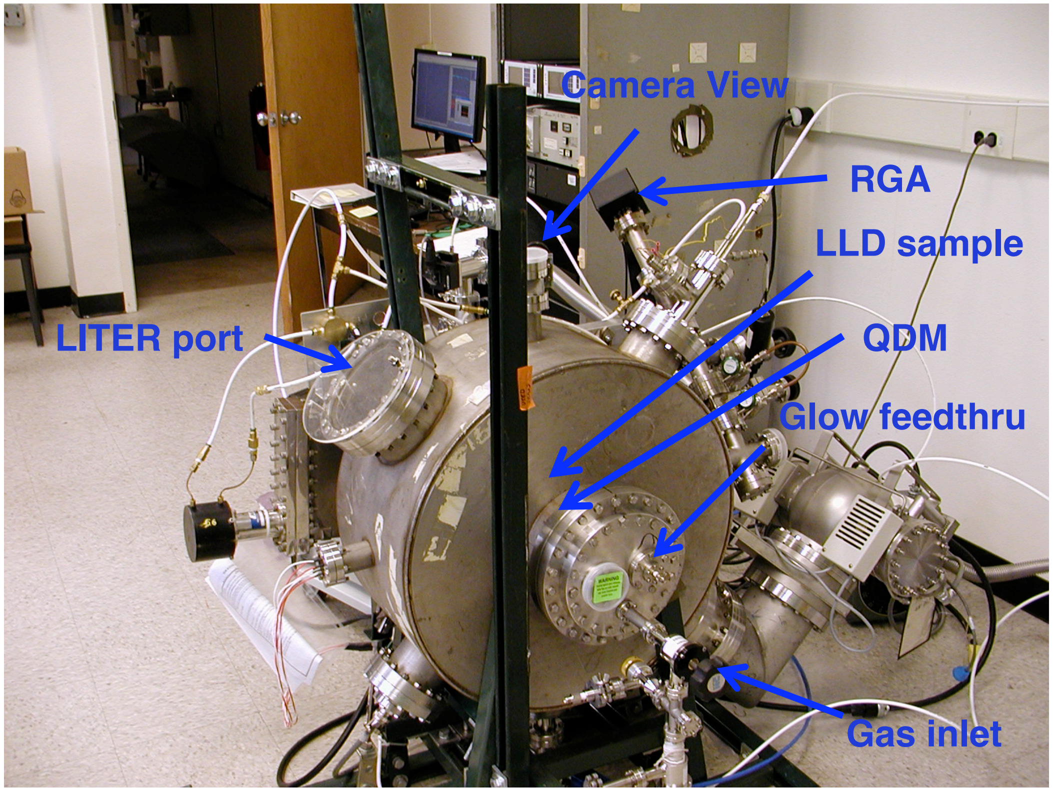
Decay time = 6.8 ms

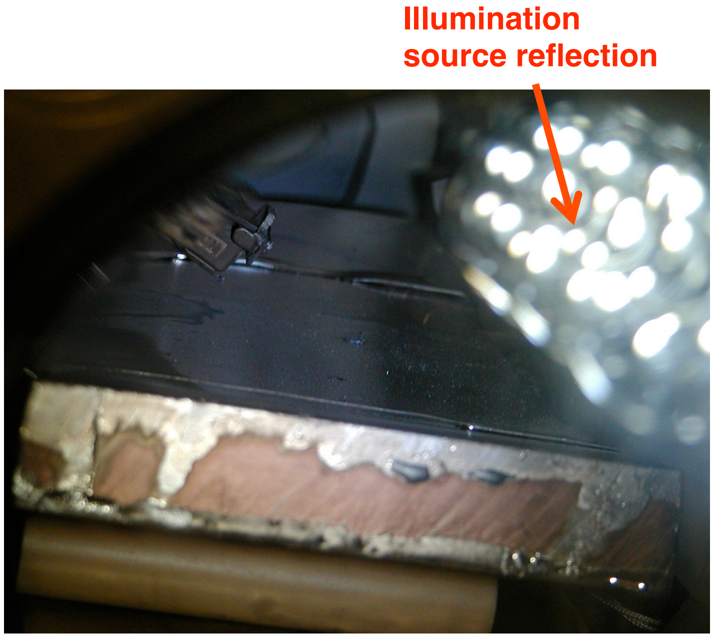

Camera D-α signal, 142514

R= 73 cm

Offline RGA experiments also performed to look for more viable metrics to identify Li activation state

- Evaporations performed on ‘proto’-LLD sample and RGA spectra taken after various evaporation/ passivation/reheating cycles

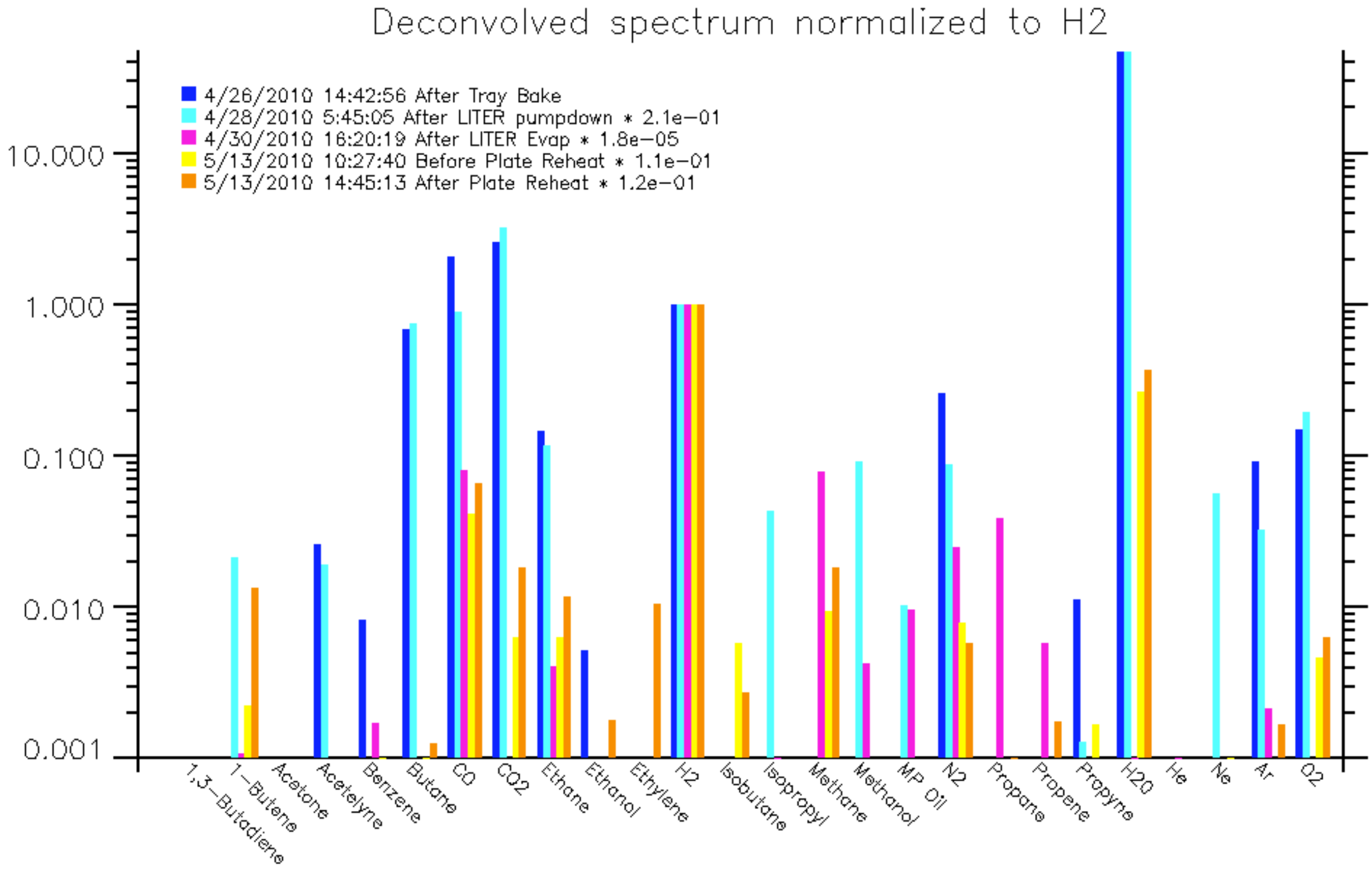




- View of sample with evaporated Li coating through side port

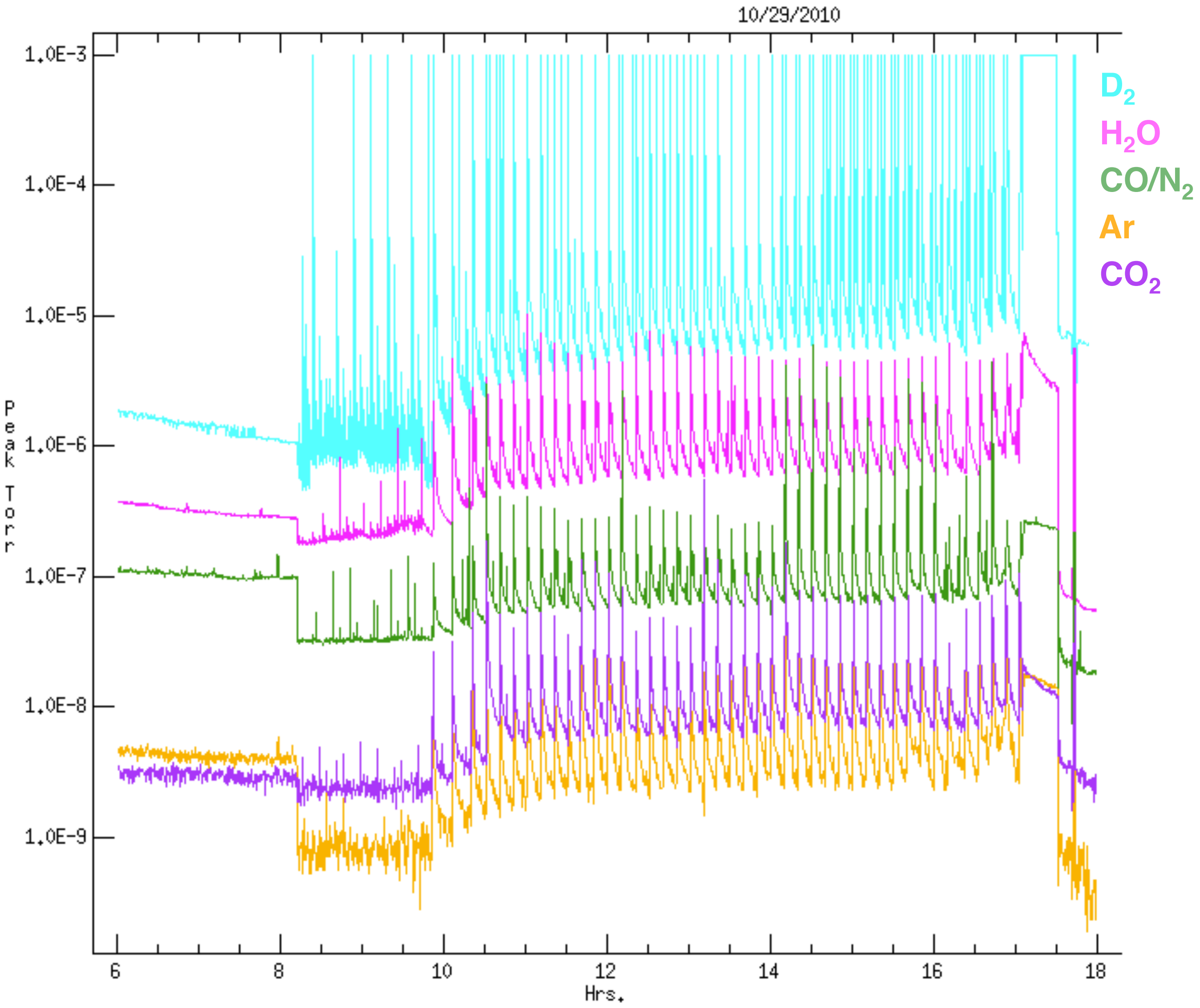
RGA de-convolution software developed and applied to spectra obtained

- SVD decomposition used to resolve RGA spectrum based on NIST cracking patterns
- Main signature of active Li is absence of water peak
- Possible hydrocarbon signatures present, many possible contributors to mass 28 confound RGA analysis without available spectroscopy to further resolve species



Variations in NSTX vacuum conditions during operation further complicates potential for RGA analysis in-situ

- NSTX shot cycle and NBI cycling prevent trend characterization of vacuum conditions
- Factors such as shot power, duration, location, and vacuum vessel temperature affect amount of residual gas seen on analyzer



Heating experiments under controlled conditions can provide data on surface behavior during heating

- Several heating tests performed under static vacuum conditions; figure below is after initial round of Li experiments
  - compare to Baldwin JNM plot on left
- After repeated bouts of deposition and passivation, however, surface quality is difficult to examine under operational conditions

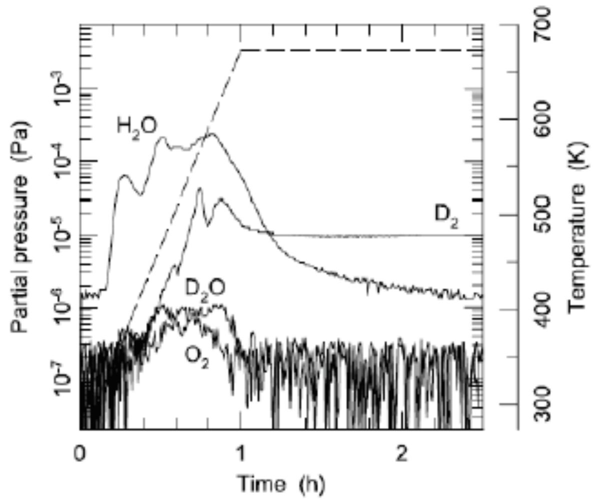
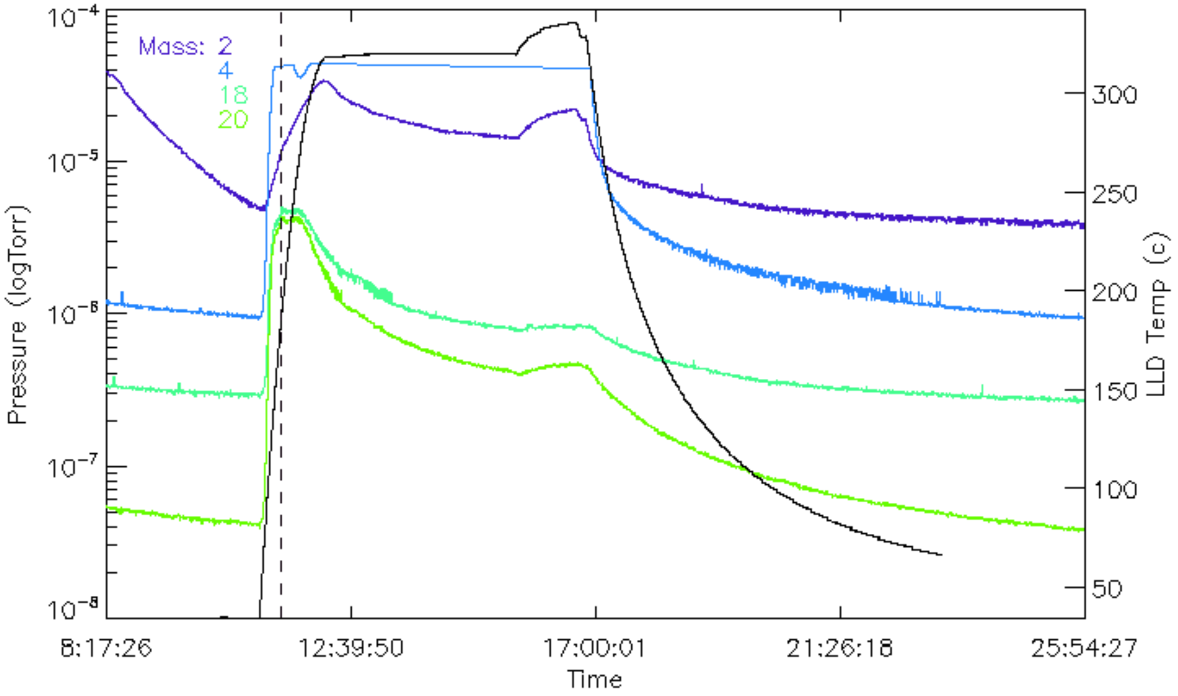


Fig. 2. Outgassing profiles for masses 4 (D_2), 18 (H_2O), 20 (D_2O) and 32 (O_2) taken on a sample of Li–LiD using the programmed temperature sequence indicated by the dashed line.

Baldwin. JNM (2002)

RGA data from 4/16/10 heating test



Conclusions

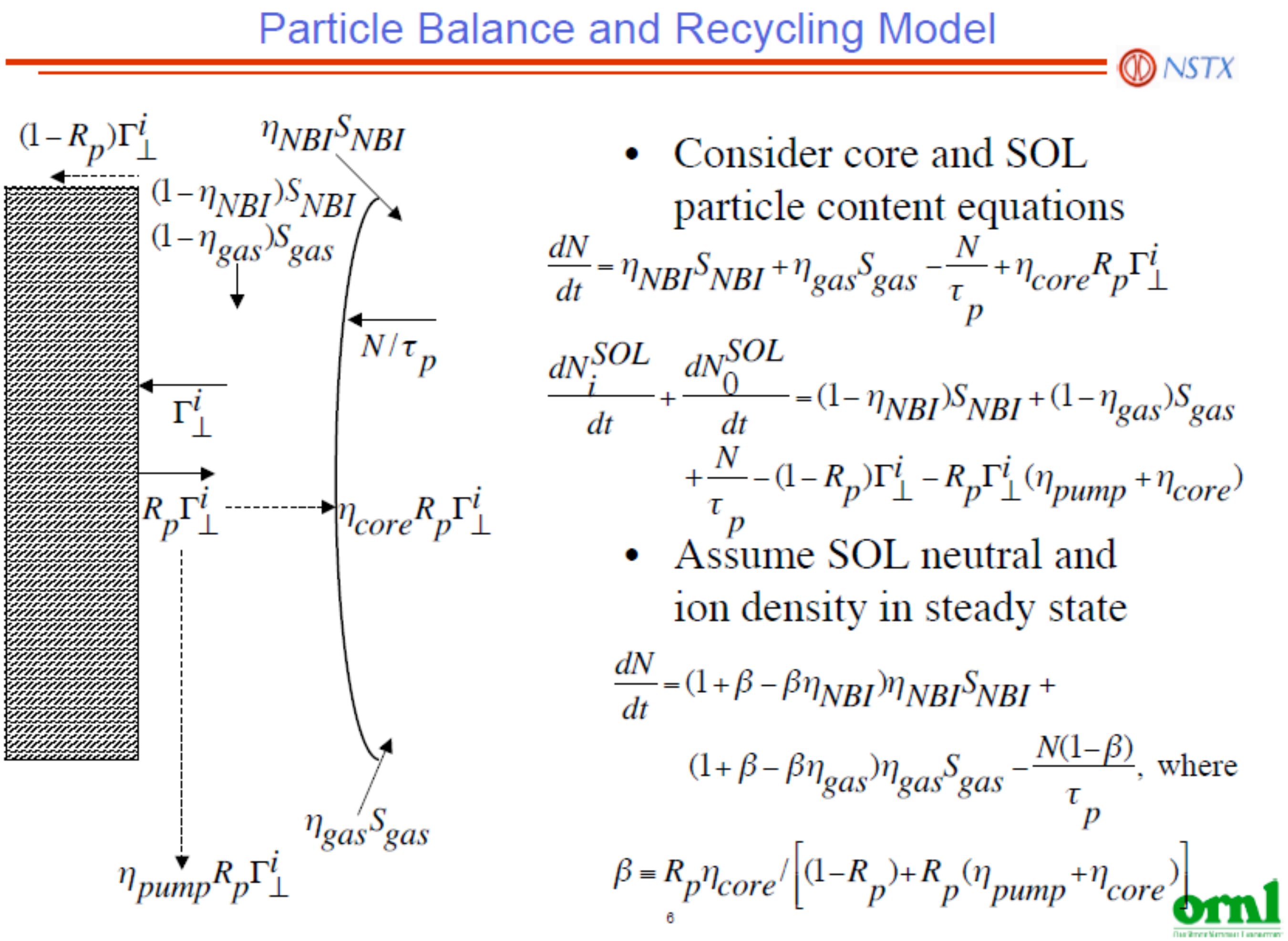
- High-density Langmuir probe array is able to provide high temporal and spatial resolution profiles for in-depth analysis of divertor target properties in NSTX
- Probes can be used as additional verification method to complement IR and magnetics for strike point tracking
- SGI pulses do not offer clear measurement for use in particle pumpout times
- RGA analysis can be useful for determining initial lithium conditions, but is of less utility during actual plasma operations

Future work

- Determine temperature and density profiles from initial current density measurements
- SOL profiles and dependencies do not match theoretical predictions of simple models – necessary to conduct more thorough 2D transport analysis on discharges with many complementary diagnostic data sets
  - despite some gaps in the temperature scan, a wealth of data for this purpose were obtained during XP 1000
- More analysis necessary to determine if SGI data can be used in concert with 0D model, but most signs point to necessity of 2D modeling regardless

0D Model – Backup

Model developed by R. Maingi, ORNL



Particle Balance and Recycling Model

- Consider core and SOL particle content equations

$$\frac{dN}{dt} = \eta_{NBI}S_{NBI} + \eta_{gas}S_{gas} - \frac{N}{\tau_p} + \eta_{core}R_p\Gamma_\perp^i$$

$$\frac{dN_i^{SOL}}{dt} + \frac{dN_0^{SOL}}{dt} = (1-\eta_{NBI})S_{NBI} + (1-\eta_{gas})S_{gas} + \frac{N}{\tau_p} - (1-R_p)\Gamma_\perp^i - R_p\Gamma_\perp^i(\eta_{pump}+\eta_{core})$$

- Assume SOL neutral and ion density in steady state

$$\frac{dN}{dt} = (1+\beta-\beta\eta_{NBI})\eta_{NBI}S_{NBI} + (1+\beta-\beta\eta_{gas})\eta_{gas}S_{gas} - \frac{N(1-\beta)}{\tau_p}, \text{ where}$$

$$\beta \equiv R_p\eta_{core}/\left[(1-R_p)+R_p(\eta_{pump}+\eta_{core})\right]$$

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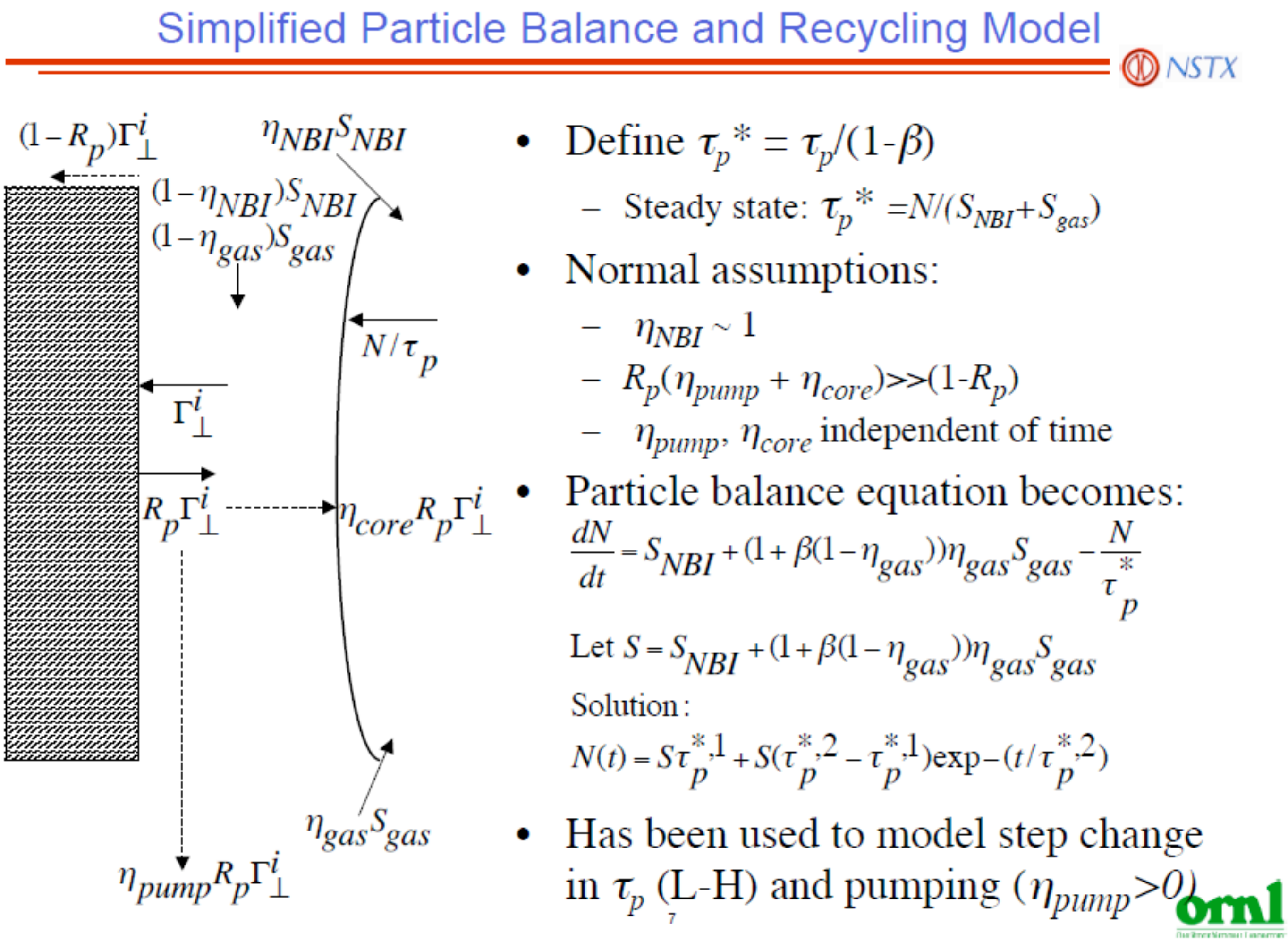
0D Model II



Simplified Particle Balance and Recycling Model

NSTX

- Define $\tau_p{}^* = \tau_p/(1\text{-}\beta)$
  - Steady state: $\tau_p{}^* = N/(S_{NBI}+S_{gas})$
- Normal assumptions:
  - $\eta_{NBI} \sim 1$
  - $R_p(\eta_{pump} + \eta_{core}) >> (1\text{-}R_p)$
  - η_{pump}, η_{core} independent of time
- Particle balance equation becomes:

$$\frac{dN}{dt} = S_{NBI} + (1+\beta(1-\eta_{gas}))\eta_{gas}S_{gas} - \frac{N}{\tau^*_p}$$

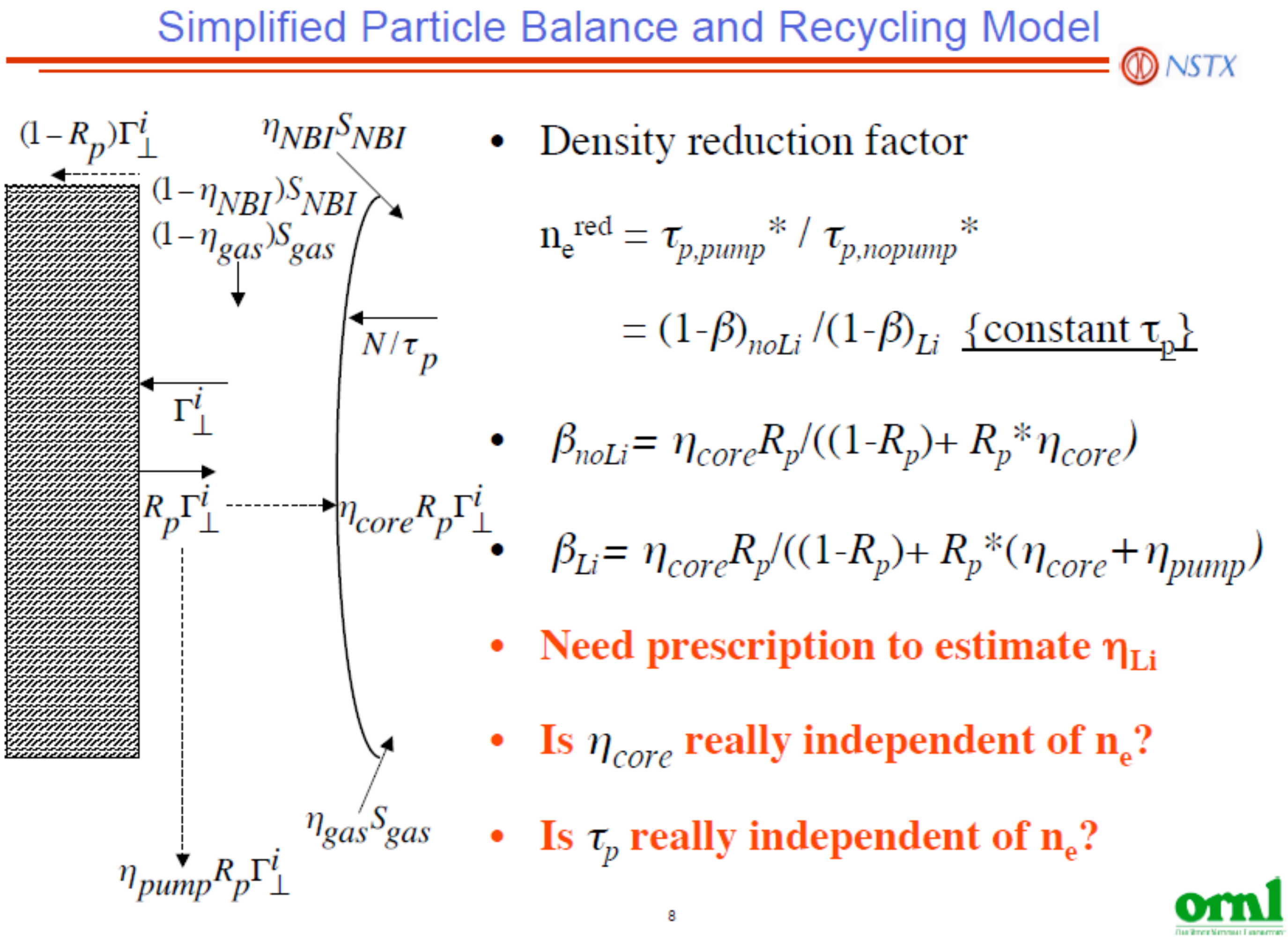
Let $S = S_{NBI} + (1+\beta(1-\eta_{gas}))\eta_{gas}S_{gas}$

Solution:

$$N(t) = S\tau^{*,1}_p + S(\tau^{*,2}_p - \tau^{*,1}_p)\exp-(t/\tau^{*,2}_p)$$

- Has been used to model step change in τ_p (L-H) and pumping (η_{pump}>0)

0D Model III



Simplified Particle Balance and Recycling Model

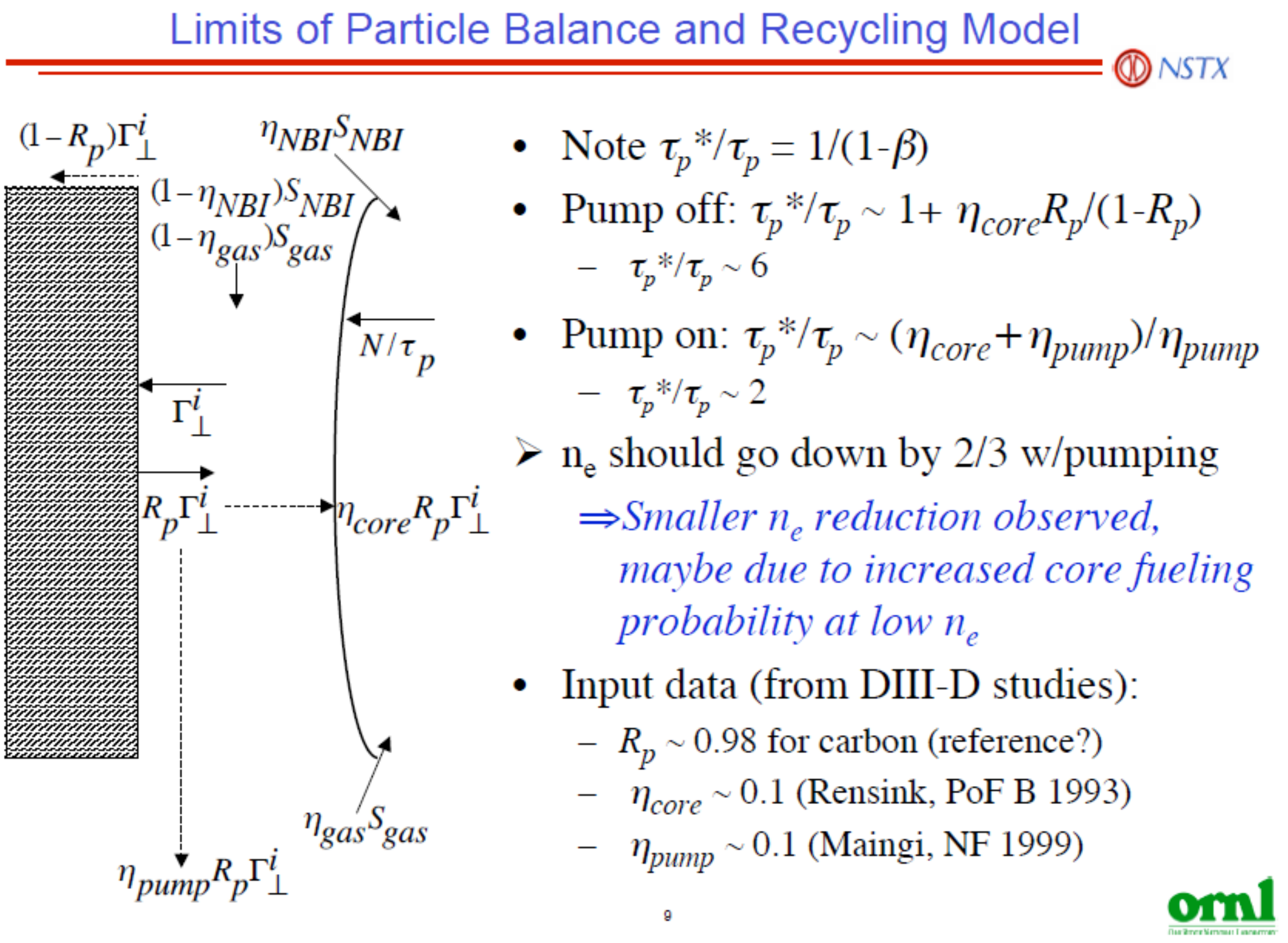
- Density reduction factor

$$n_e^{red} = \tau_{p,pump}^* \,/\, \tau_{p,nopump}^*$$

$$= (1-\beta)_{noLi} /(1-\beta)_{Li} \quad \underline{\{\text{constant } \tau_p\}}$$

- $\beta_{noLi} = \eta_{core}R_p/((1-R_p)+ R_p{}^*\eta_{core})$
- $\beta_{Li} = \eta_{core}R_p/((1-R_p)+ R_p{}^*(\eta_{core}+\eta_{pump}))$
- **Need prescription to estimate η_{Li}**
- **Is η_{core} really independent of n_e?**
- **Is τ_p really independent of n_e?**

0D Model IV



Limits of Particle Balance and Recycling Model

- Note $\tau_p{}^*/\tau_p = 1/(1-\beta)$
- Pump off: $\tau_p{}^*/\tau_p \sim 1+ \eta_{core}R_p/(1-R_p)$
  - $\tau_p{}^*/\tau_p \sim 6$
- Pump on: $\tau_p{}^*/\tau_p \sim (\eta_{core}+\eta_{pump})/\eta_{pump}$
  - $\tau_p{}^*/\tau_p \sim 2$

➢ n_e should go down by 2/3 w/pumping

⇒Smaller n_e reduction observed, maybe due to increased core fueling probability at low n_e

- Input data (from DIII-D studies):
  - $R_p \sim 0.98$ for carbon (reference?)
  - $\eta_{core} \sim 0.1$ (Rensink, PoF B 1993)
  - $\eta_{pump} \sim 0.1$ (Maingi, NF 1999)

9

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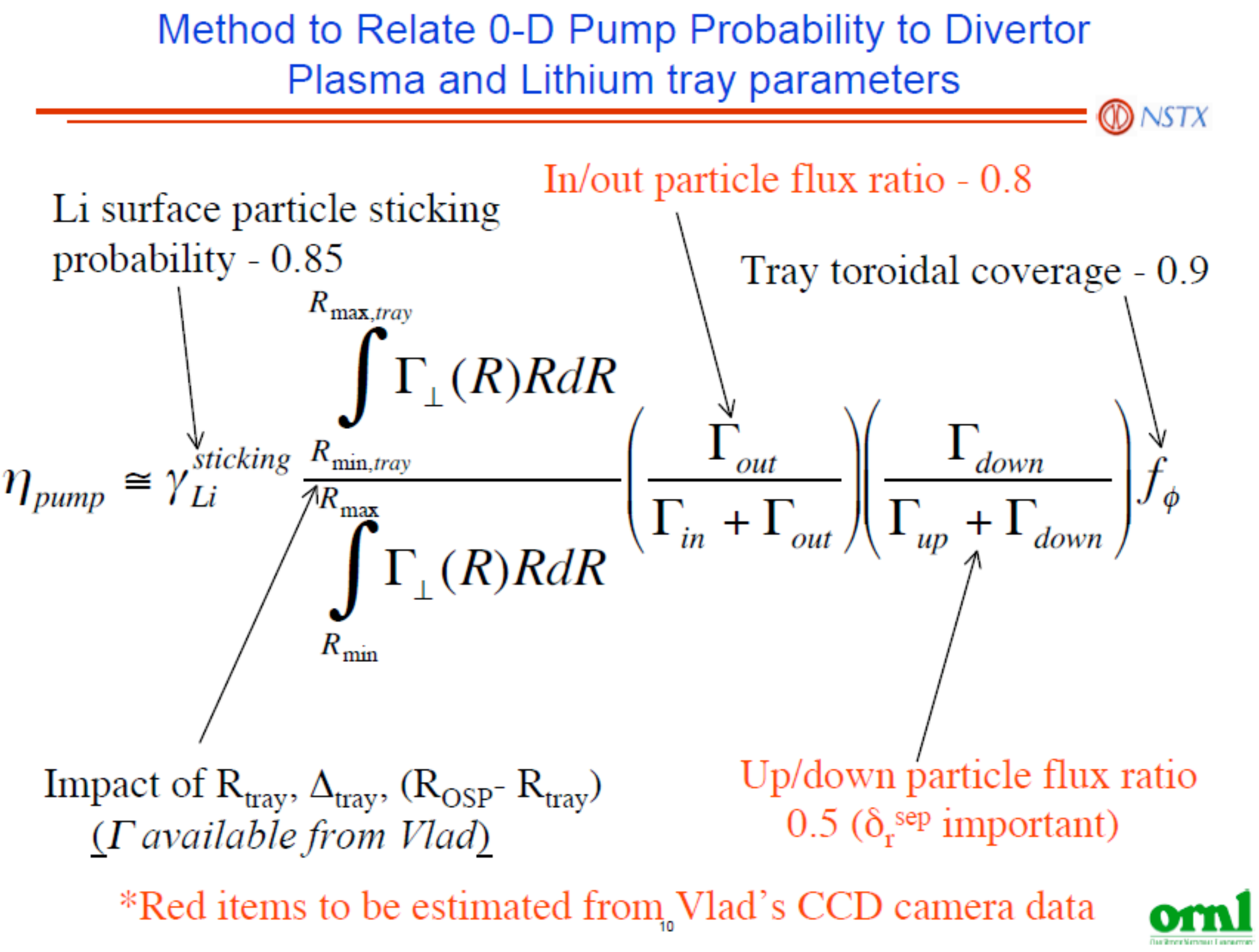
0D Model V



Method to Relate 0-D Pump Probability to Divertor Plasma and Lithium tray parameters

Li surface particle sticking probability - 0.85

In/out particle flux ratio - 0.8

Tray toroidal coverage - 0.9

$$\eta_{pump} \cong \gamma_{Li}^{sticking} \frac{\int_{R_{\min,tray}}^{R_{\max,tray}} \Gamma_{\perp}(R)RdR}{\int_{R_{\min}}^{R_{\max}} \Gamma_{\perp}(R)RdR} \left(\frac{\Gamma_{out}}{\Gamma_{in}+\Gamma_{out}}\right)\left(\frac{\Gamma_{down}}{\Gamma_{up}+\Gamma_{down}}\right) f_{\phi}$$

Impact of R_{tray}, Δ_{tray}, (R_{OSP}- R_{tray})
(*Γ available from Vlad*)

Up/down particle flux ratio
0.5 (δ_r^{sep} important)

*Red items to be estimated from Vlad's CCD camera data