# Effect of Lithium on the Power Exhaust Channel in NSTX (PP9.00036)*

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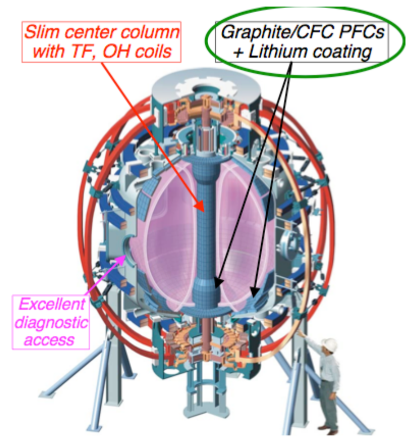
## Motivation

- NSTX has been shown to have peak heat fluxes up to 15 MW/m$^2$ where
- the heat flux width, when magnetically mapped to the midplane, $\lambda_q^{mid}$ decreases strongly with $I_p$ ($\lambda_q^{mid} \sim I_p^{-1.6}$)
- However, with lithium wall conditioning, the effect on NSTX discharges has been to:
  - Improve energy confinement [MG Bell, et. al. *Plasma Phys. Control. Fusion* **51** (2009) 124054],
  - Elimination of Edge Localized Modes (ELMs) when sufficient lithium is applied [R Maingi, et al. *Phys Rev Lett.* **103** (2009) 075001].
- $\lambda_q^{mid}$ contracts with the addition of lithium at low $I_p$
- However, at high $I_p$, $\lambda_q^{mid}$ values converge to a common value
- The addition of lithium also leads to a radiative divertor regime with sufficient lithium evaporation
- Which reduces peak divertor heat flux

## Background

- The divertor in NSTX, and ST's in general, are subject to high heat and particle fluxes
- $q_{dep} \le 15$ MW/m$^2$, $q_{\parallel} \le 300$ MW/m$^2$ have been measured in NSTX
- High heat fluxes can be moderated through:
  - Increasing the plasma wetted area through high magnetic flux expansion
    - Standard Divertor with increased magnetic flux expansion or
    - Snowflake Divertor [D.D. Ryutov, *Phys. Plasmas* 14 (2007) 64502, VA Soukhanouvskii, *et al. Nucl. Fusion* **51** (2011) 012001]
  - Increasing the parallel connection length, $L_{\parallel}$
    - Super-X divertor [M. Kotschenreuther, *et al. Phys. Plasmas* **14** (2007) 072502]
    - Snowflake Divertor
  - Detached/Radiative Divertor Operation (ITER scenario)
- Heat and particle source from the confined plasma is exhausted to an area, $A_{wet} = 2\pi R\,\lambda_{q\perp}$
  - where $\lambda_{q\perp}$ is the heat flux width
  - $\lambda_{q\perp}$ can be as small as a few mm → leading to heat fluxes of ~ 10 MW/m$^2$
- $\lambda_{q\perp}$ is determined from a competition of parallel, $\chi_{\parallel}$ and cross-field, $\chi_{\perp}$ thermal transport in the Scrape-off Layer (SOL) of diverted tokamaks

## National Spherical Torus Experiment (NSTX)

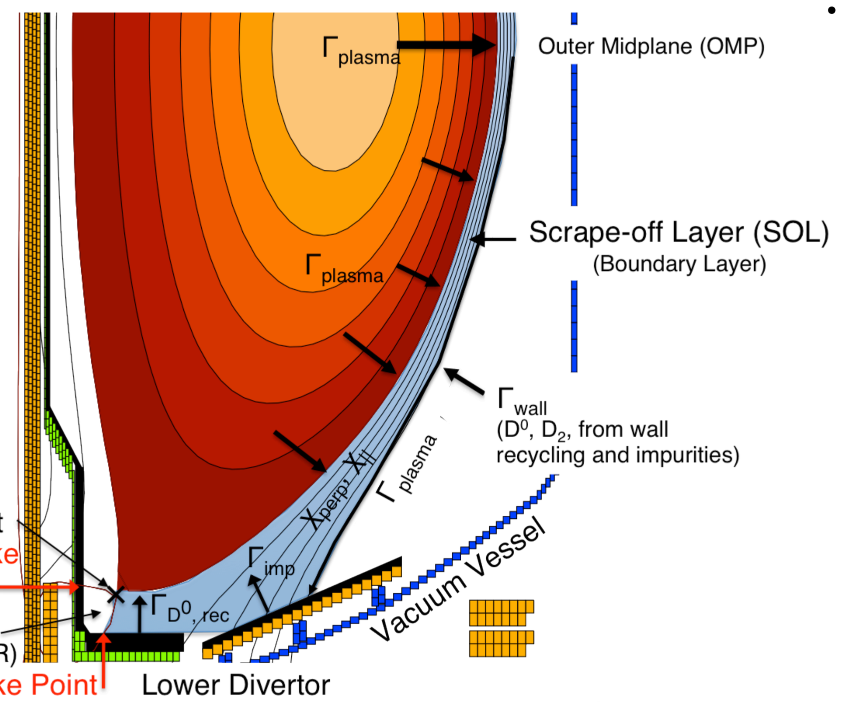



| | |
|---|---|
| R, $a_{max}$ | 0.8, 0.67 m |
| Aspect Ratio, A | 1.27 — 1.6 |
| Elongation, κ | 1.6 — 3.0 |
| Triangularity, δ | 0.3 — 0.8 |
| Toroidal Field, $B_t$ | 0.3 — 0.55 T |
| Plasma Current, $I_p$ | ≤ 1.5 MA |
| Auxiliary Heating: | |
| NBI (100 kV) | ≤ 7.4 MW |
| RF (30 MHz) | ≤ 6 MW |
| Central Temperature | 1 — 6 keV |
| Central Density | ≤ 1.2(10)$^{20}$ m$^{-3}$ |

- NSTX has used 2 wall conditioning techniques:
  1. Boronization (1999 — 2009, likely to be used in NSTX-U)
     - Performed at the start-up of each experimental campaign and periodically through out as necessary
  2. Lithiumization (2006 — current)
     - This is accomplished by evaporating lithium from 2 lithium ovens located on the top of NSTX
     - 10 — 500+ mg evaporated prior to each discharge
     - Lithium coverage is localized to the lower divertor
       - but redeposits over all PFC surfaces during discharges

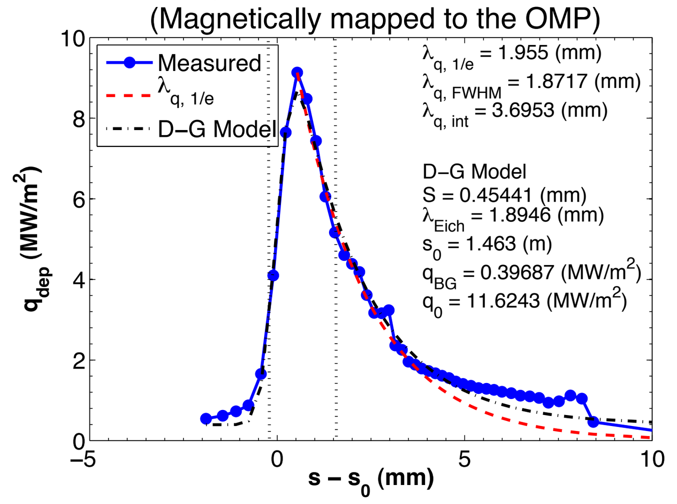
## Scrape-off Layer Physics and Analysis

Poloidal Cross Section of NSTX Plasma




- There are numerous methods for calculating heat flux width, $\lambda_q$
  - Heat flux is deduced from IR thermography measurements
    - 2D finite difference conduction model [A. Hermann et al., Plasma Phys. Control. Fus. 37 (1995) 17]
  - NSTX uses a dual-band IR camera to perform these measurements to minimize the effects of variable surface emissivity due to lithium

Example Measured Heat Flux Profile
(Magnetically mapped to the OMP)




- Assume:
  - s is the radial coordinate
  - s0 the strike point location
  - That the divertor is in the attached regime
- $\lambda_{q,\,1/e}$ — exponential fit to the near SOL side of the profile
- $\lambda_{q,\,FWHM}$ — Full Width Half Maximum
- $\lambda_{q,\,int}$ — Integral width, numerically integrate the heat flux profile
  - Described by: A. Loarte, et al. *J. Nucl. Mater.* **366-269** (1999) 587
  - Assume axisymmetry for the integration

$$\lambda_{q,int} = \frac{\int (q(s) - q_{BG})\,ds}{q_{max}}$$

## Diffusive-Gaussian (D-G) Model for Heat Flux Width

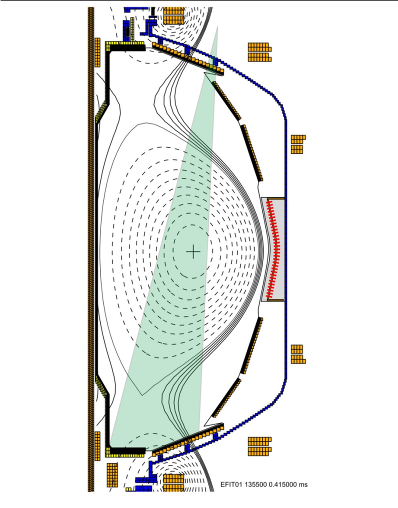
- Simple semi-empirical model [T. Eich, et al. *Phys. Rev. Lett.* accepted for publication (2011)]
- Assumes heat flux at the divertor entrance is exponential: $q(\bar{s}) = q_0 \exp\left(-\frac{\bar{s}}{\lambda_q f_{exp}}\right)$
  - $\bar{s} = s - s_0$
  - $\lambda_q$ is the 1/e folding length of the heat flux profile
  - $f_{exp}$ is the magnetic flux expansion
  - $q_0$ is the peak heat flux
- Heat then diffuses (or leaks) into the private flux region as it travels in the divertor
  - This is given by:

$$q(\bar{s}) = \frac{1}{2} q_0 \exp\left(\left(\frac{S}{2\lambda_q f_{exp}}\right)^2 - \frac{\bar{s}}{\lambda_q f_{exp}}\right) \mathrm{erfc}\left(\frac{S}{2\lambda_q f_{exp}} - \frac{\bar{s}}{S}\right) + q_{BG}$$

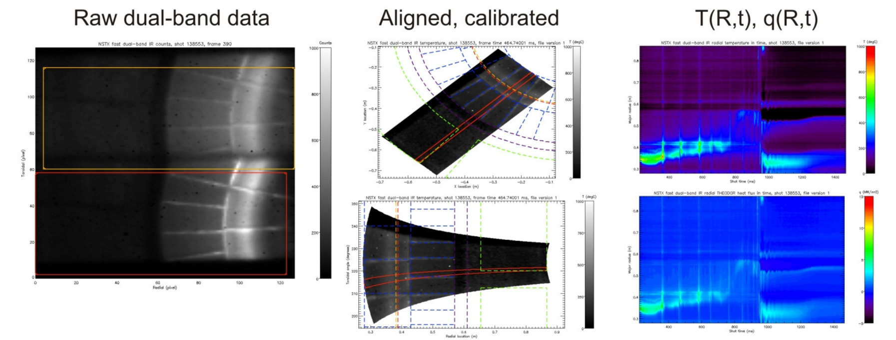
  - S is the gaussian width parameter and is indicative of the ratio of $\chi_{\parallel}$ and $\chi_{\perp}$
  - $q_{BG}$ is background heat flux due to radiation and reflections
- This model has 5 free parameters ($q_0$, $q_{BG}$, $\lambda_q$, S and $s_0$) and must be determined using a non-linear least squares fit

## Dual-Band Infrared (DBIR) Camera System

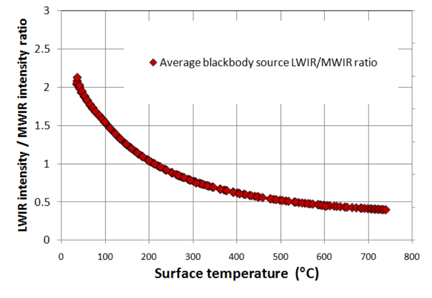
Field of View for DBIR Camera



- Standard Santa Barbara Focal Plane (Lockheed Martin) ImagIR
  - 128x128, 40μm pixel HgCdTe FPA, $LN_2$-cooled
  - QE>90% from 1.5-11 μm, 14-bit, <20 mK NETD
  - Frame rates up to 1.6 kHz
  - See Poster: PP9.00069 by AG McLean for more details
- Dual-band adapter projects 2, separate IR bands onto the camera (shown below)

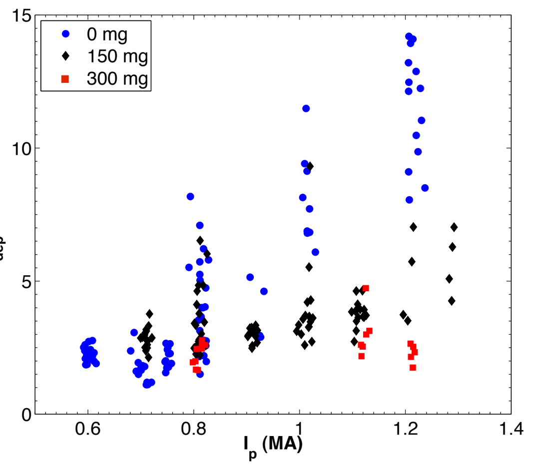


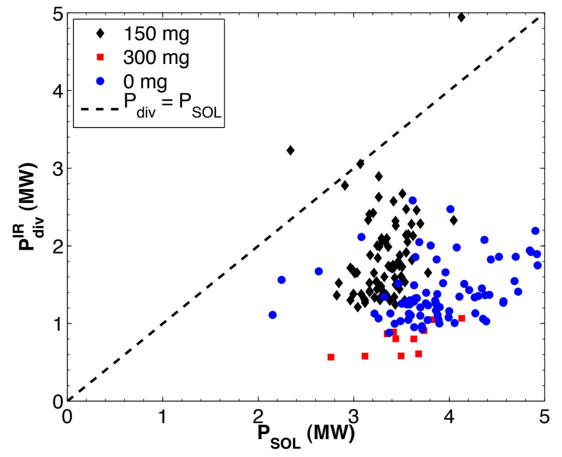

- Intensity ratio (LWIR/MWIR) calibrated:
  - *ex-situ* using a blackbody source, and
  - *in-situ* during VV bakeout and by heating the LLD

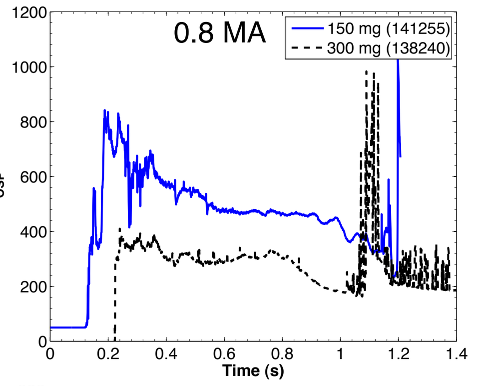


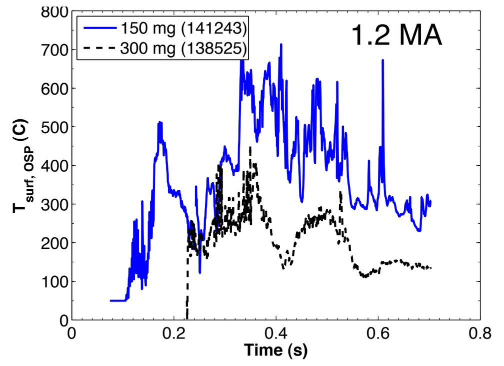

## Reduced Divertor Heat Flux with Lithium

- Inter-ELM averaged, peak heat fluxes
  - Data over a variety of $f_{exp}$ (5 - 20)
  - $P_{NBI}$ = 4, 6 MW
  - 0.5 ≤ δ ≤ 0.7
- Boronized divertor conditions yielded measured peak heat fluxes ≤ 15 MW/m$^2$
  - $I_p$ = 1.2 MA, $P_{NBI}$ = 6 MW
- Lithium discharges show heat fluxes less than half those of boronized discharges for $I_p$ > 0.9 MA
  - Low $I_p$ shots show similar heat fluxes
- The result is reduced power accounting
- $P_{div}$ / $P_{SOL}$ ~ 0.4 - 0.5 for 0 mg discharges
  - Similar, if not slightly increased, for 150 mg discharges
  - Suggest similar power accounting in these discharges
- For 300 mg discharges, $P_{div}$ / $P_{SOL}$ ~ 0.2
  - Likely the difference in divertor power is due to increased lithium radiation
    - Difficult to confirm due to a lack of calibrated divertor bolometry



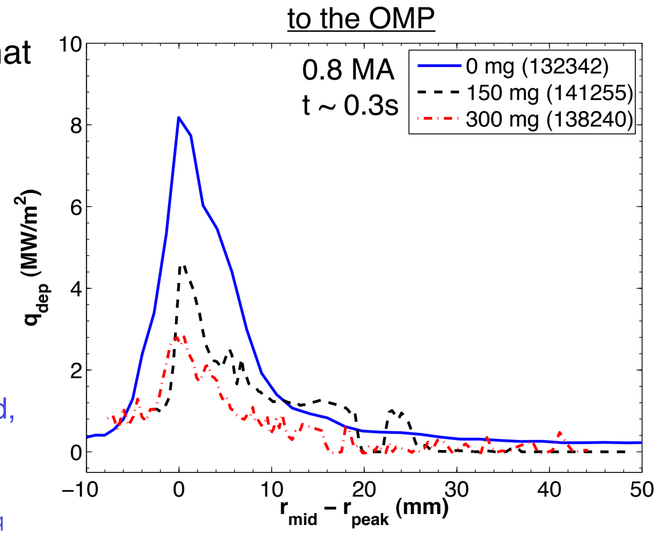




- Reduced heat flux can be seen from the reduced divertor surface temperature
- 0.8 MA Discharges (150 and 300 mg)
  - Shots are identical except for the increased lithium
  - Both discharges are ELM-free
  - $T_{surf,\,OSP}$ reduced ~150 C for the 300 mg lithium discharge (138240)
- 1.2 MA Discharges (150 and 30 mg)
  - Shots are identical except for the increased lithium
  - Presence of ELMs in both discharges complicates the analysis
  - Reduced ELMing for the 300mg discharge
    - Therefore, a lower $T_{surf}$ is expected regardless of lithium amounts
    - Though, the ELM reduction is because of the increased use of lithium

## Parametric Scaling of Heat Flux Width

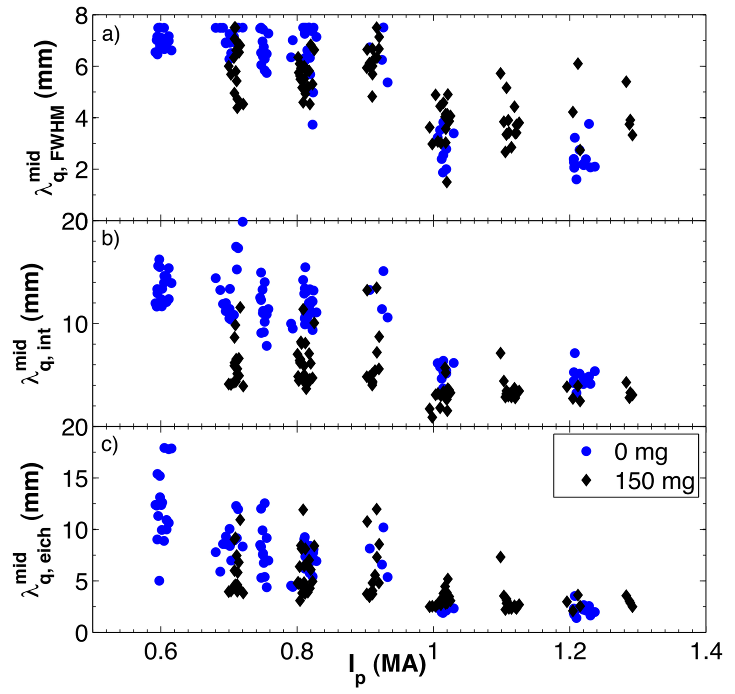
- Recently reported [TK Gray, et al. *J. Nucl. Mater.* **415** (2011) S360-S346] that $\lambda_{q,\,int}$ was reduced with increasing amounts of lithium
- Figure at left shows typical heat flux profiles (normalized) for 3 lithium evaporation amounts
  - Shots are otherwise identical ($I_p$ = 1 MA, $P_{NBI}$ = 6 MW, δ ~ 0.7, $f_{exp}$ ~ 20)
- The reduced $\lambda_q$ is counter intuitive
  - Based on power balance, as $\lambda_q$ is reduced, it would be expected for heat flux to increase
  - Instead, heat flux is reduced along with $\lambda_q$

Deposited Heat Flux magnetically mapped to the OMP




Deposited $\lambda_q$ Magnetically Mapped to the Midplane

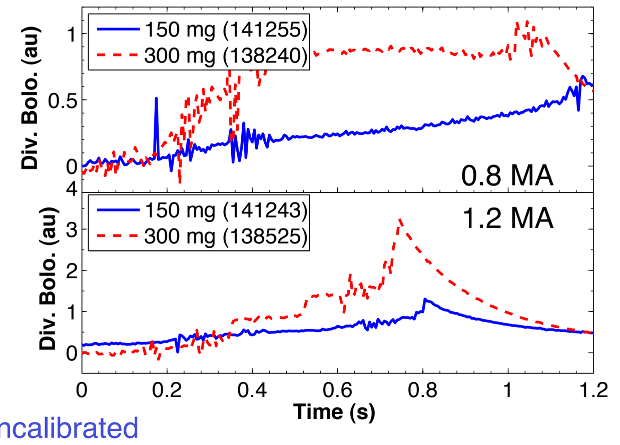
- 300 mg data not included due to the low power accounting
- The trend of reduced $\lambda_q$ is most apparent at low $I_p$ for $\lambda_{q,\,int}^{mid}$
  - where $\lambda_{q,\,int}^{mid}$ is the integral $\lambda_q$ of the deposited heat flux, magnetically mapped to the midplane
  - Though it does vary depending on the definition of $\lambda_q$ used
- At $I_p$ = 1.1 - 1.2 MA, $\lambda_q$ is observed to be nearly the same as for non-lithium discharges for all definitions of $\lambda_q$
  - Suggests $\lambda_q$ is converging to a common value at high $I_p$
- In the case of $\lambda_{q,\,Eich}^{mid}$ there appears to be little difference between discharges with 0 and 150 mg of lithium




- Given that $\lambda_{q,\,Eich}^{mid}$ is the 1/e folding length of the heat flux prior to entering the divertor in the D-G model,
  - This could indicate that the mechanism for broadening the heat flux profiles is primarily occurring in the divertor
  - Perhaps interactions with D$^0$ and $D_2$ act to diffuse heat and particle fluxes entering the divertor?
- No strong trends are seen with $\beta_N$
- A weak inverse scaling with $W_{MHD}$ exists (not shown)

## Radiative Divertor with Heavy Lithium Evaporation

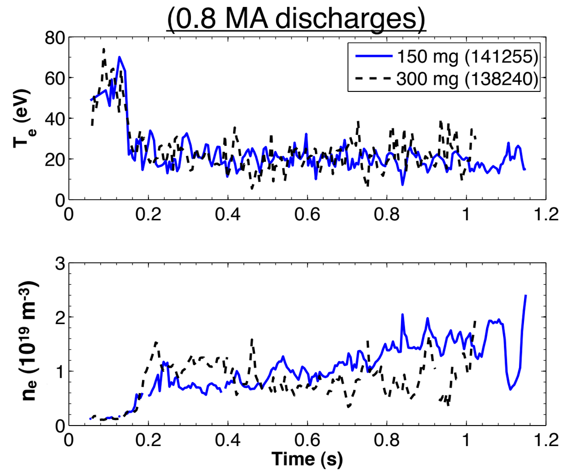
- Heat Flux profiles not the typical of detached divertor conditions
  - i.e. - profiles are not rounded off
- An increase in divertor radiation is measured with the addition of lithium




- Divertor bolometers are uncalibrated
- Can provide information about the relative change in divertor radiation, but not quantitative information

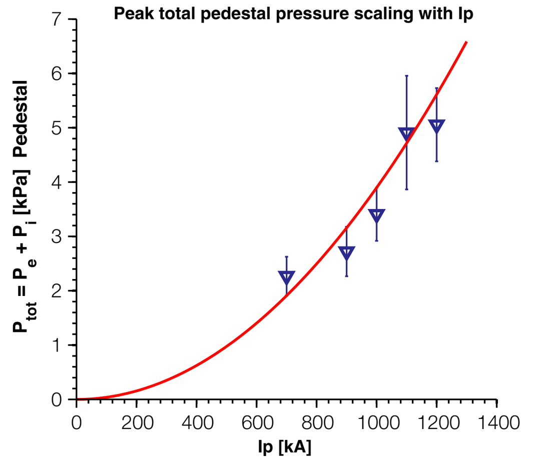
- Inboard Langmuir probes show no difference in divertor $T_e$
  - Using the "classical" probe interpretation
  - However, there is evidence of bi-modal electron distribution in the divertor
- Increase in divertor $n_e$ early in time
  - Strike point motion has been accounted for
- Not indicative of detachment
- Points to a radiative divertor regime with heavy lithium evaporation

Divertor $T_e$ and $n_e$
(0.8 MA discharges)

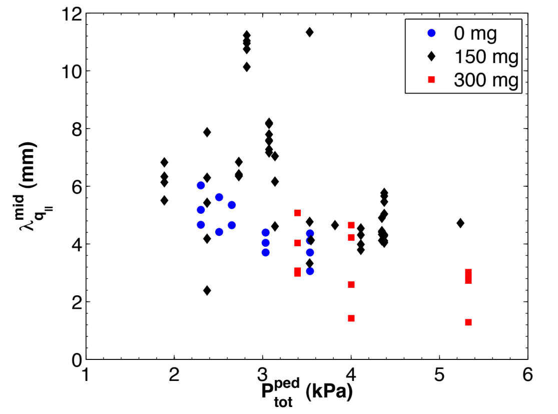



## Preliminary Pedestal Analysis

- $P_{tot}^{ped}$ has been shown to be proportional to $I_p$
  - A Diallo, et al. *Nucl. Fusion.* **51** (2011) 103031
- One of the biggest impacts of lithium has been to modify the pedestal in NSTX [R Maingi, et al. *Phys Rev Lett.* **103** (2009) 075001]
- No clear trend is observed with $n_e^{ped}$ or $T_e^{ped}$
  - likewise for seperatrix quantities ($n_e^{sep}$, $T_e^{sep}$, $P_e^{sep}$)




- *Preliminarily,* $\lambda_{q\parallel}^{mid}$ is found to scale inversely with $P_{tot}^{ped}$
  - Most of the data shown are for $n_e/n_{GW}$ > 0.5
  - Lower density data still to be analyzed




## Conclusions

- Reduction in $\lambda_{q,\,int}^{mid}$ at low $I_p$
- However, $\lambda_{q,\,int}^{mid}$ values converge to similar values for high $I_p$ discharges
- $\lambda_{q,\,Eich}^{mid}$ from the D-G model shows no difference with increased lithium evaporation
  - This suggests that the broadening of the heat flux profile occurs in the divertor region when lithium is not used
- While $\lambda_{q,\,int}^{mid}$ is reduced with increasing lithium, so is the deposited heat flux
- This appears due to the divertor surface temperature "clamping" with heavy lithium evaporation
  - Consistent with reduced power accounting in the divertor
- This suggests that sufficient lithium coverage, the divertor transitions to a radiative regime
  - Work to quantify the divertor operating regime with heavy lithium conditioning is still on-going
- There is also evidence that $\lambda_{q\parallel,\,int}^{mid}$ is inversely correlated with $P_{tot}^{ped}$
  - This could explain the difference in $\lambda_{q\parallel,\,int}^{mid}$ with different lithium amounts at low $I_p$

## Future Work

- Further analysis of divertor conditions (through Langmuir Probes and spectroscopy) to determine divertor regime with heavy lithium use
- Pedestal analysis for a larger number of discharges currently in the $\lambda_q$ SOL database
- SOLPS simulations of heavy lithium discharges
  - Determine why power to the divertor is reduced and
  - Determine where the power is being deposited
- Investigate use of lithium for NSTX-U
  - Primarily concerned with the effect of NSTX-U's increased discharge length to 5s