Abstract

The National Spherical Torus Experiment (NSTX) has made extensive use of evaporative lithium coatings for improved discharge performance such as reduced divertor recycling, increased plasma stored energy and duration, and the elimination of Edge Localized Modes (ELMs). Measurements of divertor heat flux are accomplished with a unique dual-band IR (DBIR) thermography system to mitigate the effects of changing surface emissivity. Measurements from the DBIR system show reduced divertor surface temperature at the outer strike point for the case with 300 mg of lithium deposition. This results in the divertor heat flux being reduced from 5 to 2.5 MW/m^2. In turn, a reduction in divertor power accounting at the outer strike point is measured with increased lithium evaporation such that $P_{div}/P_{SOL} \sim$ 0.3 -- 0.5 for discharges with 150 mg of lithium and 0.12 -- 0.2 for discharges with 300 mg of lithium. The reduction in divertor power is correlated with an increase in divertor radiation for discharges with 300 mg of lithium evaporation.

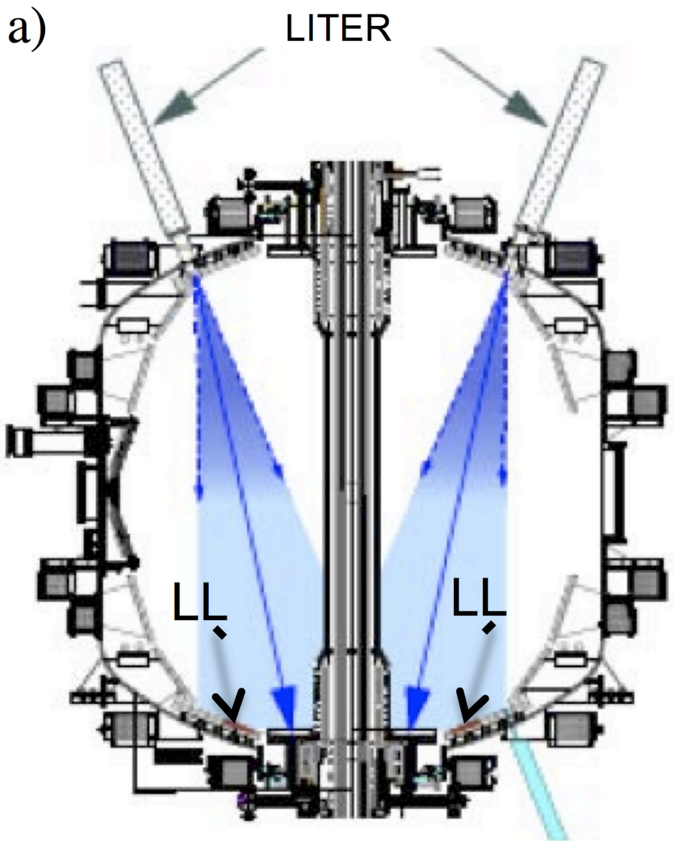
Acknowledgments

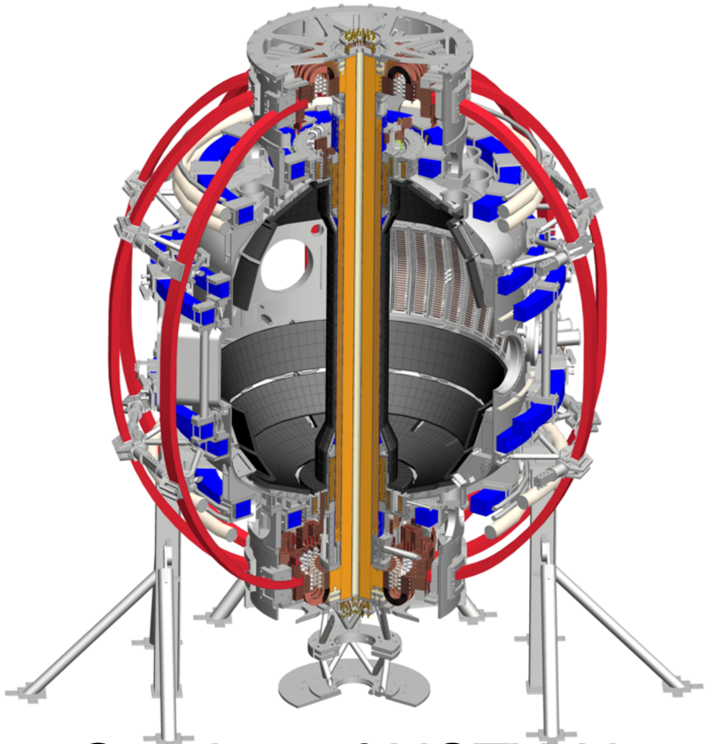
Work supported by U.S. Department of Energy contracts: DE-AC05-00OR22725, DE-AC52-07NA27344 and DE-AC02-09CH11466. The authors would also like to acknowledge a collaboration with A. Herrmann of IPP-Garching for the use of the THEODOR heat flux analysis code. As well as Marco Wischmeier and David Coster of IPP-Garching for help implementing SOLPS.

Overview of the National Spherical Torus Experiment-Upgrade (NSTX-U) and Li systems

- Lithium wall conditioning is achieved using 2 Li ovens called LiTERs
  - Located toroidally 130° apart
  - Lithium is primarily deposited on the horizontal inner divertor
    - There is an approximately gaussian distribution of the evaporated Li
- Lithium is evaporated prior to the discharge
  - Typically between 10 - 150 mg before each discharge
  - Can be greater
- Lithium wall conditioning will continued to be used in NSTX-U
  - After a period of boronized wall conditioning
- All the data in this presentation is for Lithiated graphite
  - eg: no LLD data

a)

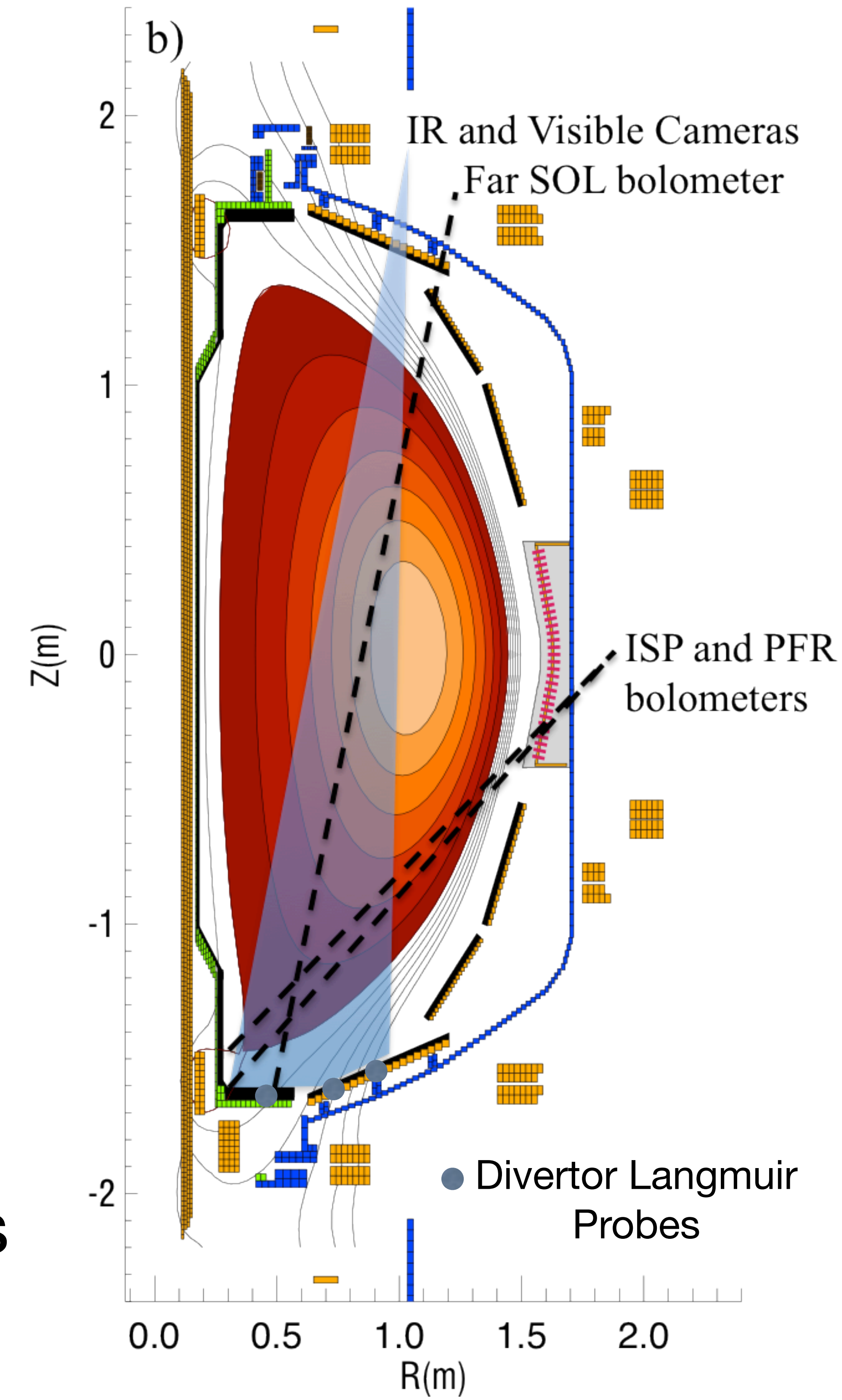




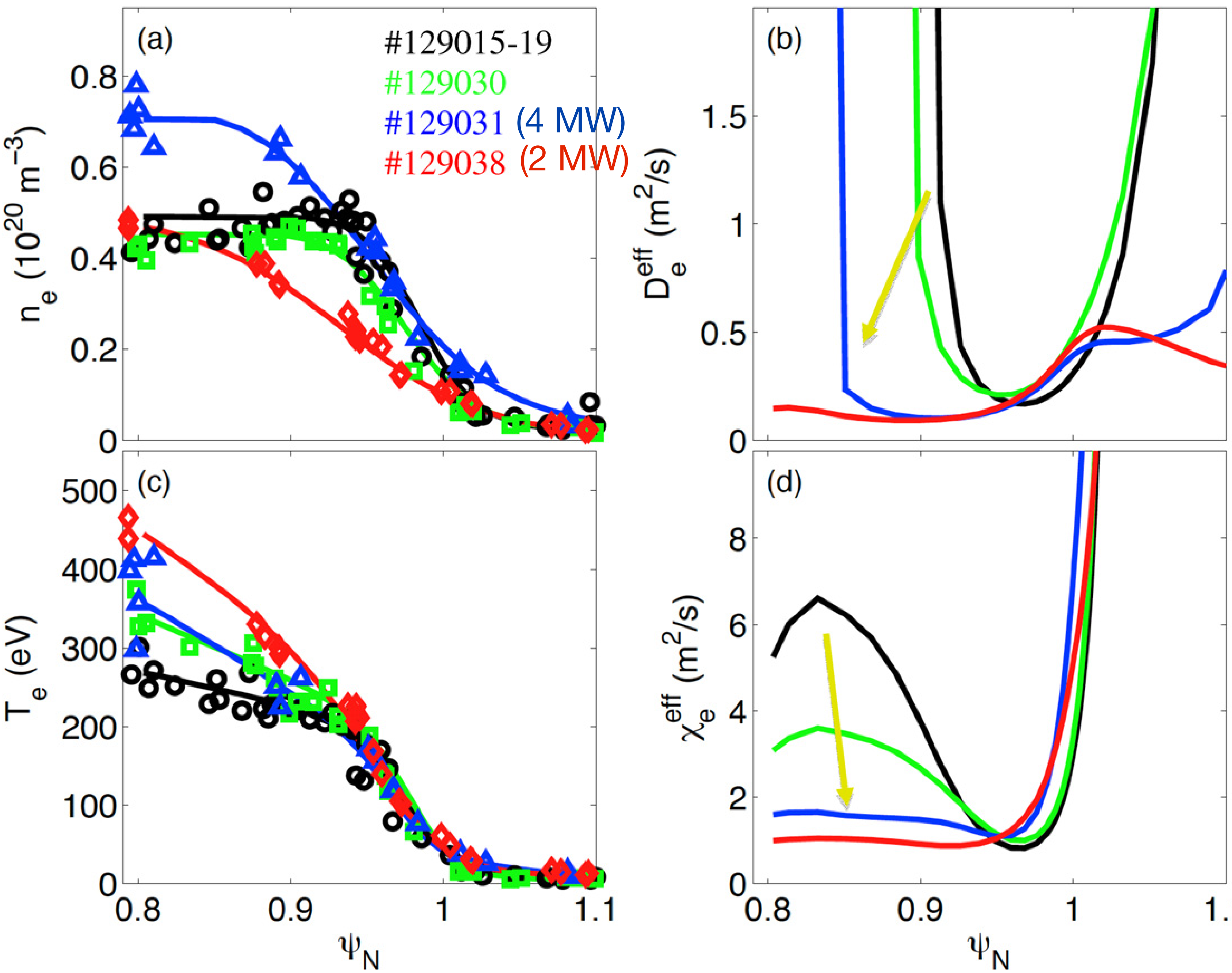
Cross-Section of NSTX-Upgrade

NSTX Divertor Diagnostics

- 2, 30 Hz IR cameras
  - 1 viewing the lower divertor, 1 the upper
  - sensitive to 6 - 13 μm
  - single band optics
- 1 Fast IR camera (≤ 16 kHz)
  - viewing the lower divertor
  - sensitive to 6 - 13 μm
  - equipped with dual band optics
- 2 Fast Phantom cameras (≤ 100 kHz)
  - each viewing nearly the entire lower divertor
  - bandpass filtered
- 2 1D CCD array cameras
  - measuring D_α and Li II emission
- 3 channels of lower divertor bolometry
  - Uncalibrated
- Flush mounted divertor Langmuir probes
  - Limited spatial coverage



Extensive Pedestal and Edge Transport Analysis of Lithiated NSTX Discharges has been Performed

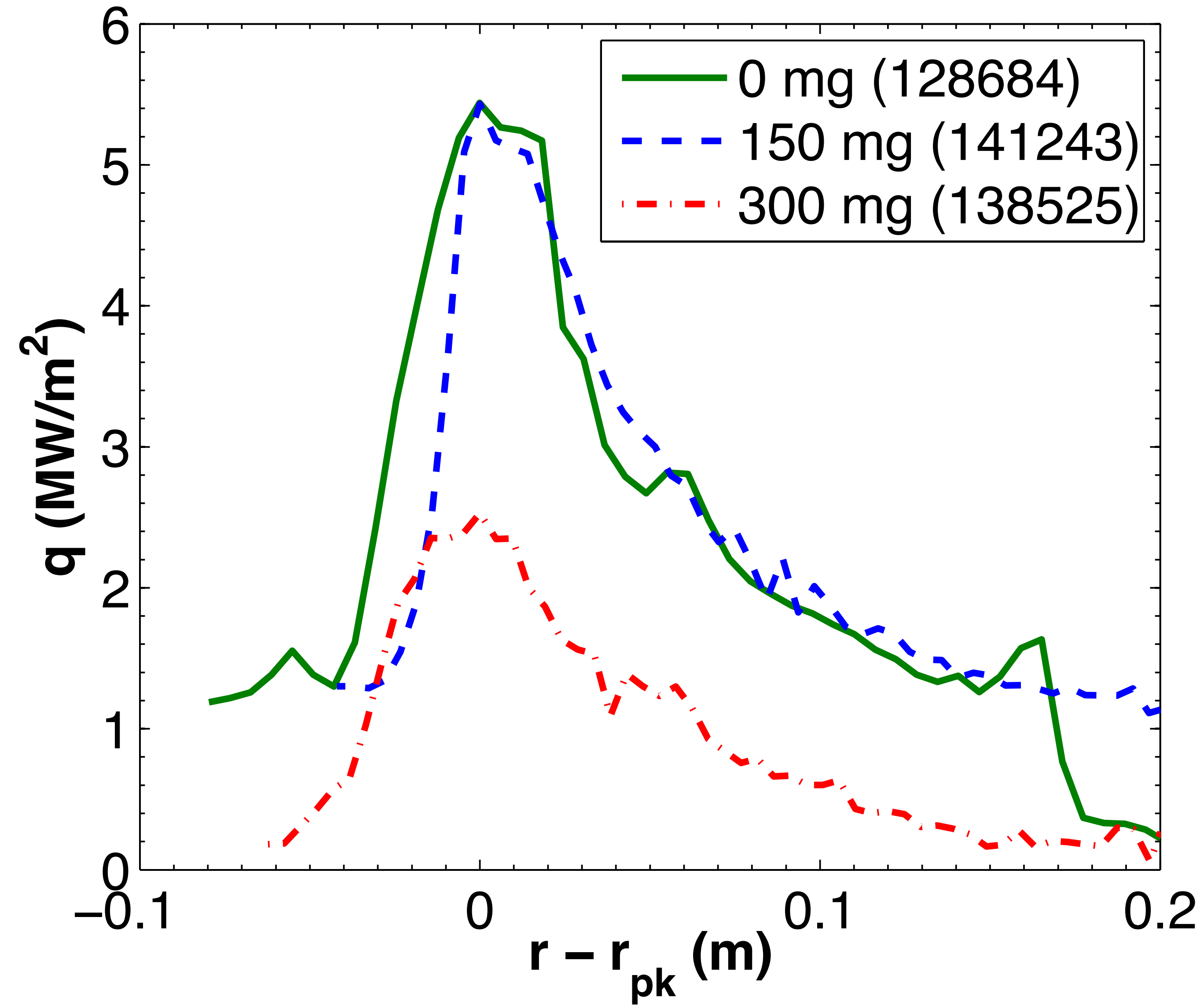


R. Maingi, et al., Nuclear Fusion. **52**, 083001 (2012)

- Composite n_e and T_e profiles are fit with modified tanh functions
  - Fits are used for SOLPS modeling
- n_e gradient is reduced at the edge
  - This leads to ELM suppression [R Maingi, PRL 2009]
- T_e edge gradient is unchanged with Li
  - But core T_e increases
- Edge D_{eff} and χ_{eff} were substantially reduced between $0.8 \leq \psi_N \leq 0.94$
  - D_{eff} and X_{eff} effectively unchanged for $\psi_N \geq 0.95$

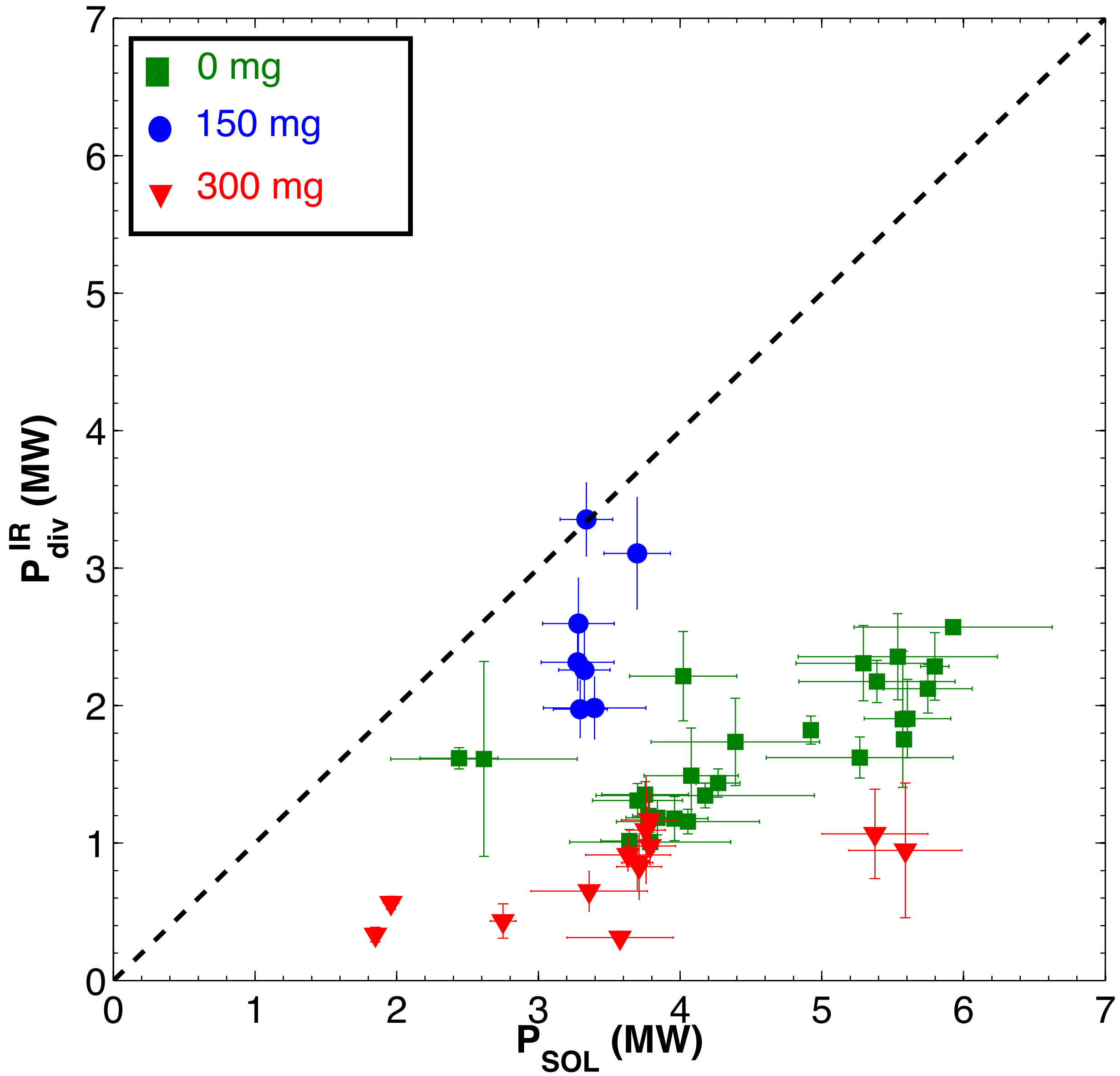
Lithium Evaporation is shown to Reduce λ_q and Peak Heat Flux

- 0 mg (boronized) and 150 mg of Li yield similar heat fluxes (inter-ELM averaged)
- λ_q contracts (slightly) with addition of 150 mg of Li
  - Likely due to the elimination of small Type V that can be ubiquitous in boronized conditions [R Maingi *et. al.*, *Nucl. Fusion* **45**(4) (2005) 264]
- With sufficient Li evaporation (300 mg), heat flux is also reduced
  - Measurements made with DBIR camera to account for surface emissivity effects
  - λ_q contracts further still



Divertor Power Accounting at the Outer Strike Point (OSP) with Heavy Lithium Evaporation is Reduced

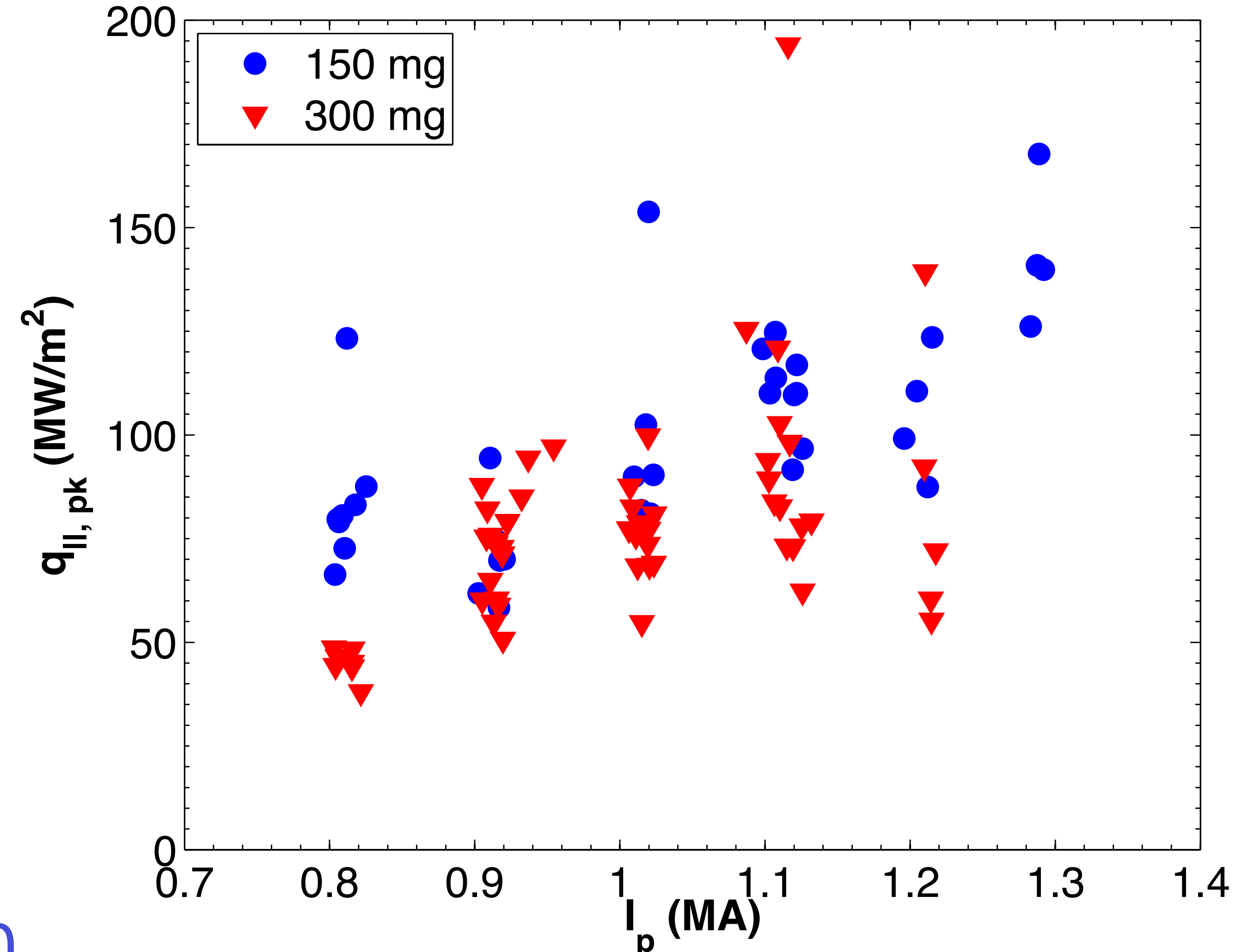
- Normally a contraction in λ_q would result in higher divertor heat flux
  - Assuming P_{SOL} is constant
- Data are averaged for each discharge
  - Limited to times early in the discharge ($\lesssim$ 0.4 sec) before P_{rad}^{core} and n_eL have increased too much
- P_{div}/P_{SOL} is similar for 0 and 150 mg of Li
  - P_{div}/P_{SOL} ~ 35 - 50%
  - Possibly improved in the 150 mg dataset
- However, measured heat flux is reduced for 300 mg of Li
  - Results in P_{div}/P_{SOL} dropping to 10 - 20%



TK Gray, et al, submitted to NF (2013)

$q_{\parallel, pk}$ is reduced over a wide range of I_p with 300 mg of Li deposited

- $q_{\parallel, pk}$ is reduced over a wide range of I_p
  - P_{NBI} = 4 MW
  - Some amount of pre-heating in the 150 mg data
  - Additional fueling was required for the 300 mg data
- Overall trend for $q_{\parallel, pk}$ to be reduced with 300 mg of Li
  - Using $q_{\parallel, pk}$ to account for changes in f_{exp} between and during discharges
  - There is some overlap between 150 and 300 mg data



What's the Physical Mechanism of Reduced Heat Flux with Increasing Li Evaporation?

A) Increased divertor radiation due to Li
- But Li is a poor radiator!
- Possibly explained by non-coronal Li radiation [S. Mirnov, JNM (2009)]

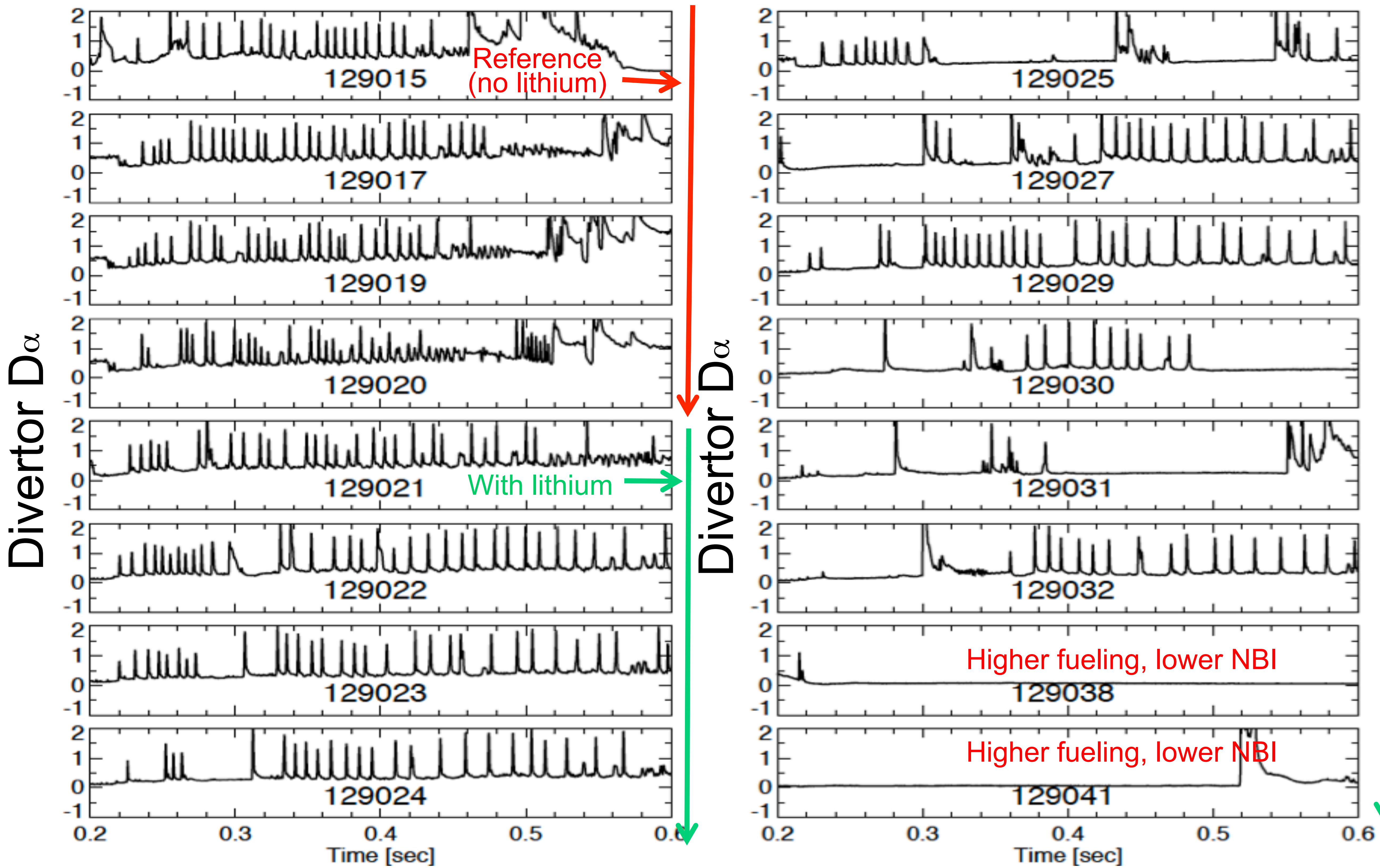
B) Li "spreading" the heat flux???
- Increased divertor n_e due to Li causes more of the incident heat flux to diffuse into the private flux region (PFR)

C) Divertor detachment onset due to Li
- Increased divertor n_e caused by more Li leads to divertor detachment

D) Upstream Profiles Modified by Li
- Its been shown that Li subtly modifies the upstream ne and Te profiles
- Under attached divertor conditions (pressure and power balance), could lead to reduced divertor heat flux

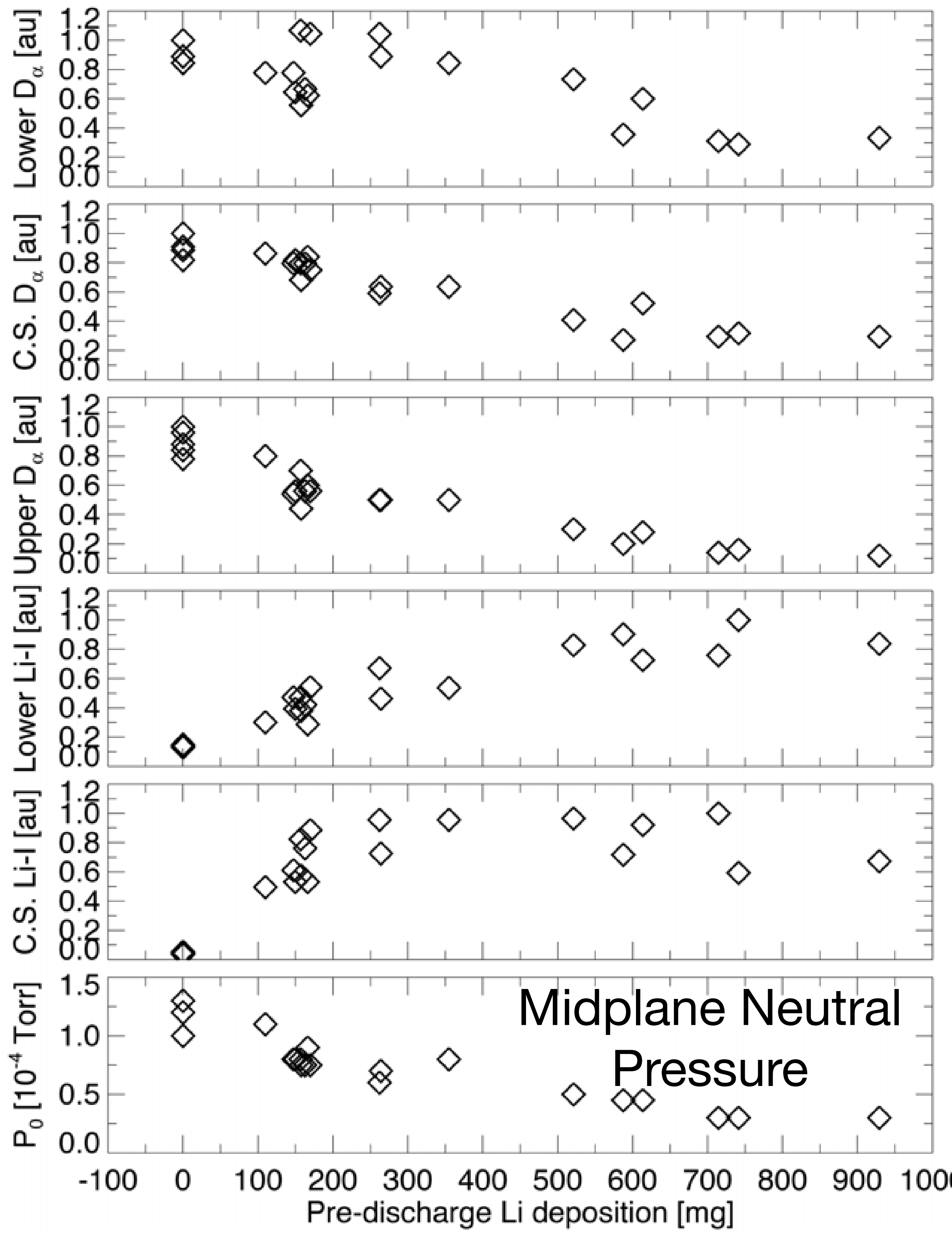
E) Some combination of all of the above?

Progressive Increase in pre-discharge Li evaporation in low δ shape resulted in elimination of ELMs



Divertor Li I Emission increases monotonically through the Li Scan

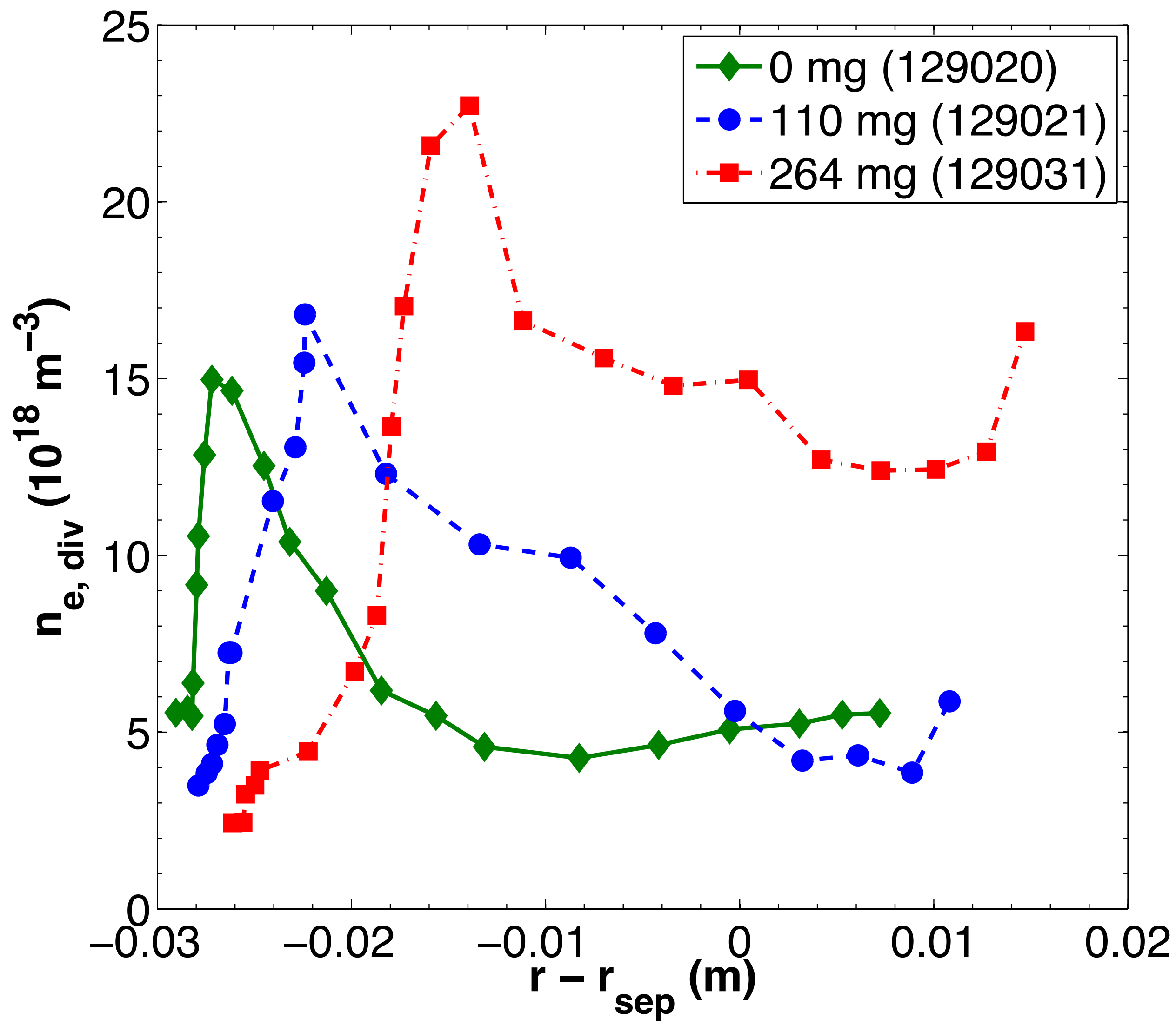
- Measurements are based on filterscopes with a wide viewing angle
  - eg: most of the divertor
- D_α emission decreases with increasing Li evaporation
  - True for both the lower and upper divertors
  - True even when CS fueling is increased
- While Li I emission increases monotonically with Li evaporation
- No VUV measurements of Li radiation
- Limited divertor bolometry coverage prevents a better understanding of divertor radiation with Li



R. Maingi, et al., Nuclear Fusion. (2012)

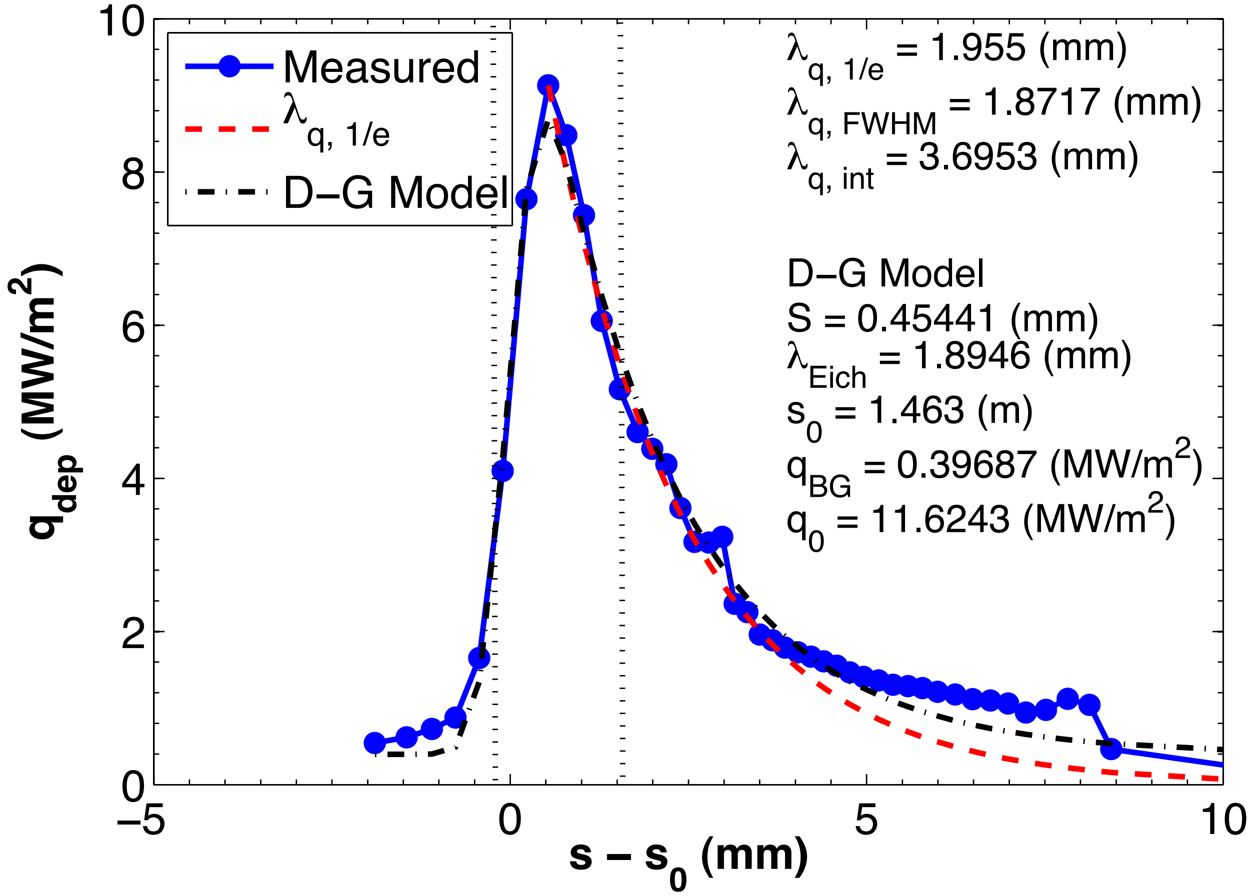
Divertor n_e at the Outer Strike Point Increases for Increasing Li Evaporation

- Using the natural strike point sweep over a single probe location to measure the divertor ne profile
  - This is necessary due to the limited divertor probe coverage in NSTX
  - Limits the analysis to times early in the discharge
    - This is when the strike point is being swept out for the low-δ shape
    - Strike point is mostly stationary after this initial movement
- Divertor n_e increases ~ 50% between 0 and 264mg of Li
  - It's assumed this is due to Li being "trapped" in the divertor/SOL plasma
  - Core Li concentration < 0.1% $n_{e, core}$ [Podesta, NF. 2012]
- The n_e profile is also much broader in the 264mg discharge
  - Qualitatively similar to the broader heat flux profiles
- The mechanism for the broader n_e profile is unclear



Constant P_{NBI} = 4 MW
Constant f_{exp} ~ 20

There are numerous definitions for the SOL width, λ_q



- **Integral: $\lambda_{q,\,int}$**
  - Numerical integration of radial heat flux profile
  - Assumes axisymetric heat deposition profile

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

- **Diffusive-Gaussian (D-G) Model[Eich2012]**
  - Simple semi-empirical model
  - Assumes λ_q is an exponential in the SOL before entering the divertor

$$q(\bar{s}) = q_0 \exp\left(-\frac{\bar{s}}{\lambda_q f_{exp}}\right)$$

  - The exponential "diffuses" into the private flux region as it enters the divertor
  - No mechanism for this diffusion is put forth
    - But is clearly observed in all divertor footprints
  - 5 free parameters which require nonlinear least squares fitting to determine

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

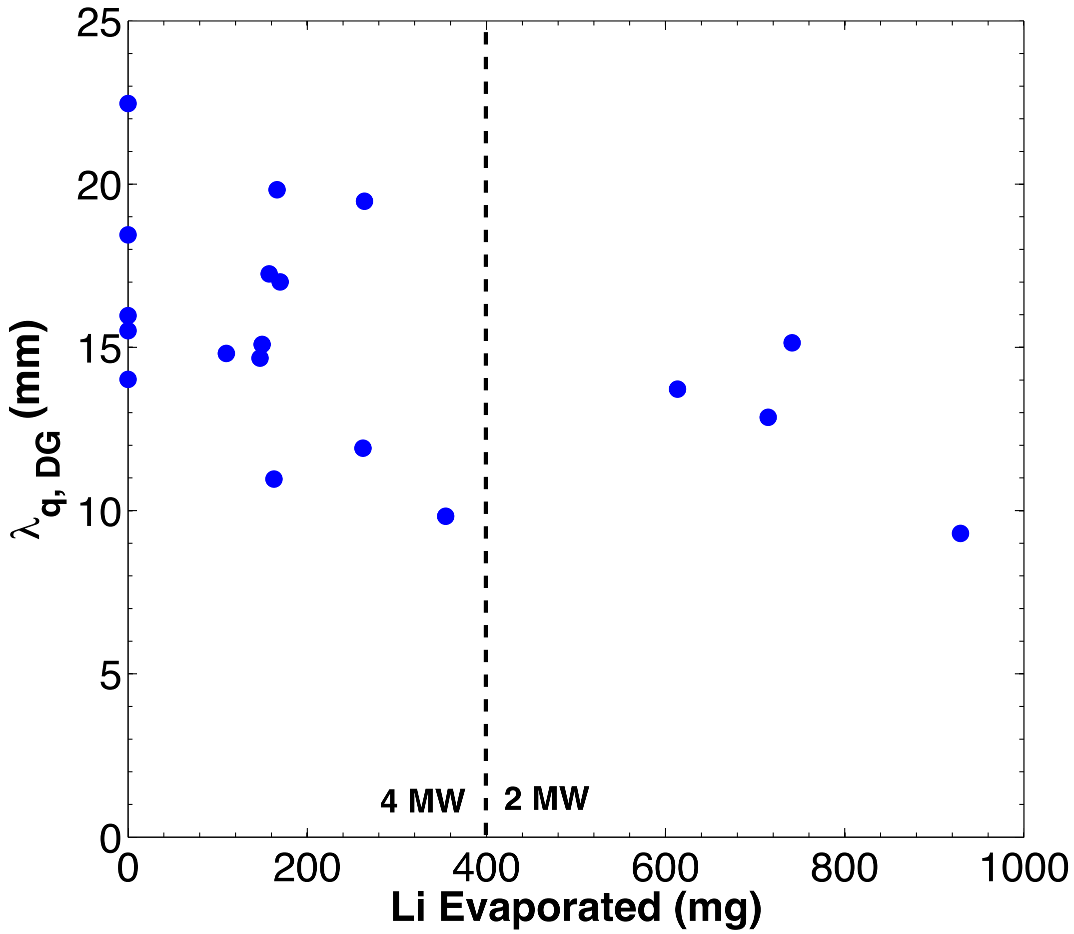
s = radial coordinate
s_0 = Strike Point Location
$\bar{s} = \mathrm{s} - \mathrm{s}_0$
q_0 = peak heat flux
q_{BG} = background heat flux
λ_q ($\lambda_{q,\,Eich}$) = e-folding length of q in SOL
S = Gaussian diffusion parameter

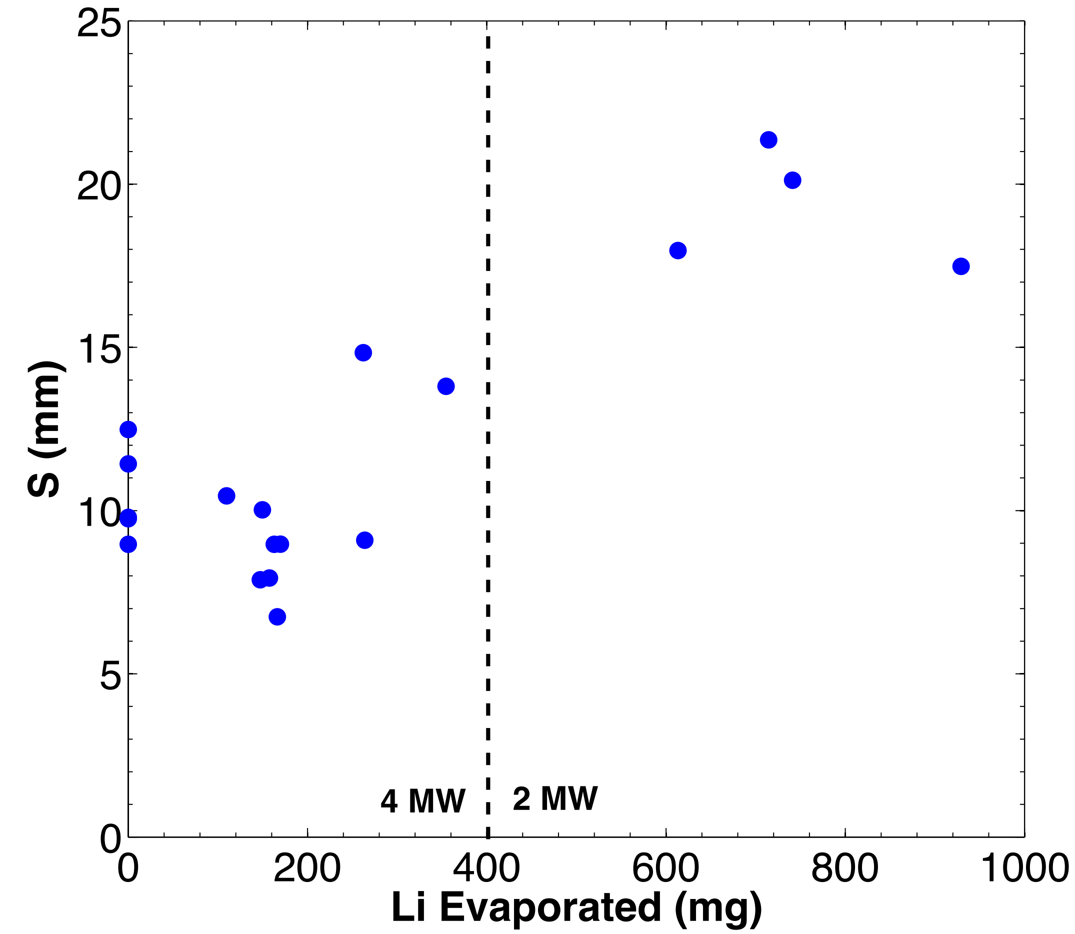
Increased Li deposition leads to decreased $\lambda_{q,\,DG}$ and increased S overall

- Divertor heat flux fitted to a diffusive-gaussian function [Eich, PRL 2012]:

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

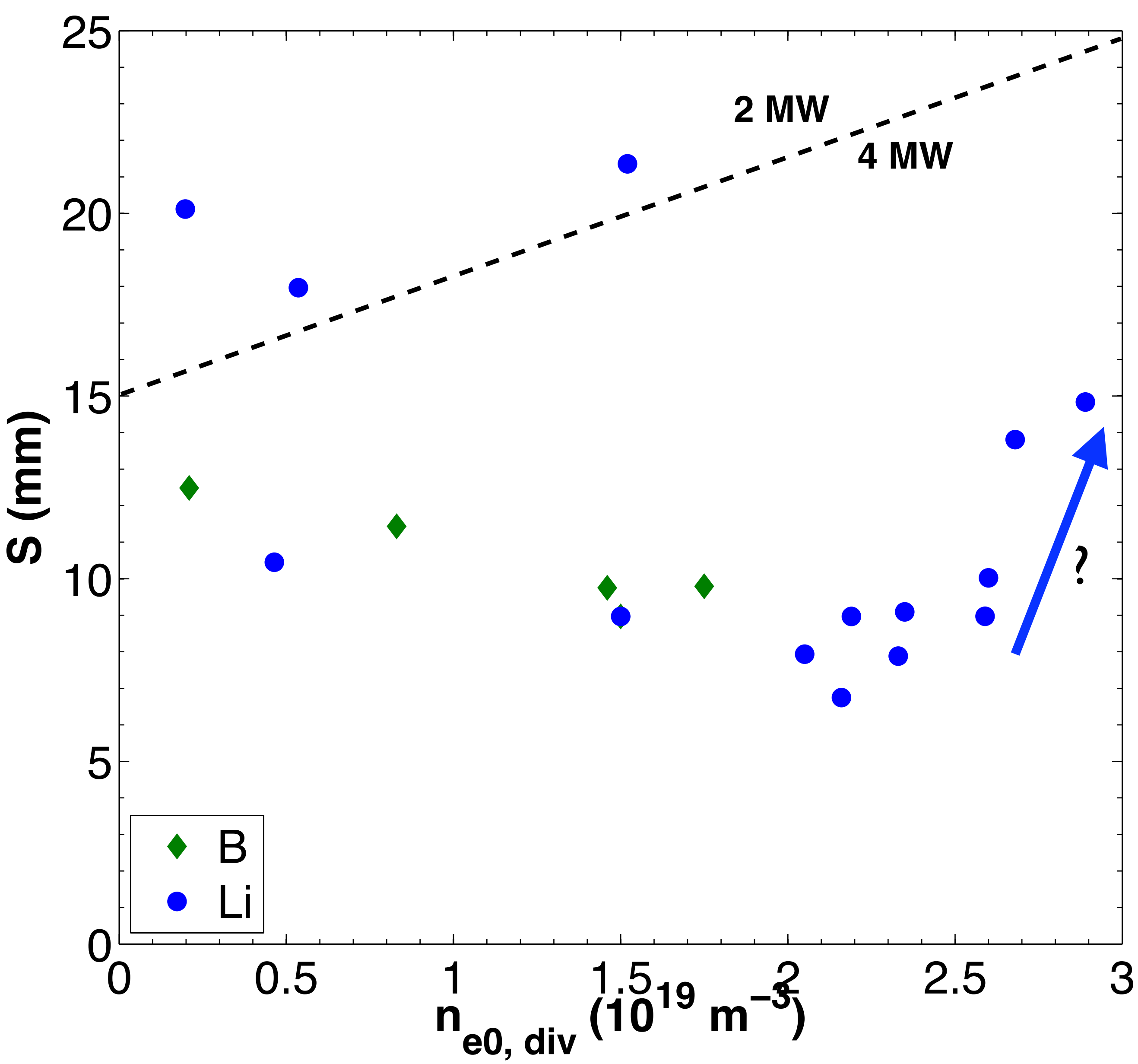
- $\lambda_{q,\,DG}$ contracts continuously with increasing Li deposition
- S decreases initially between 0 - 200 mg of Li
- S then increases substantially from 200-1000 mg of Li
  - In agreement with data shown earlier for 0 ➔ 150 ➔ 300 mg





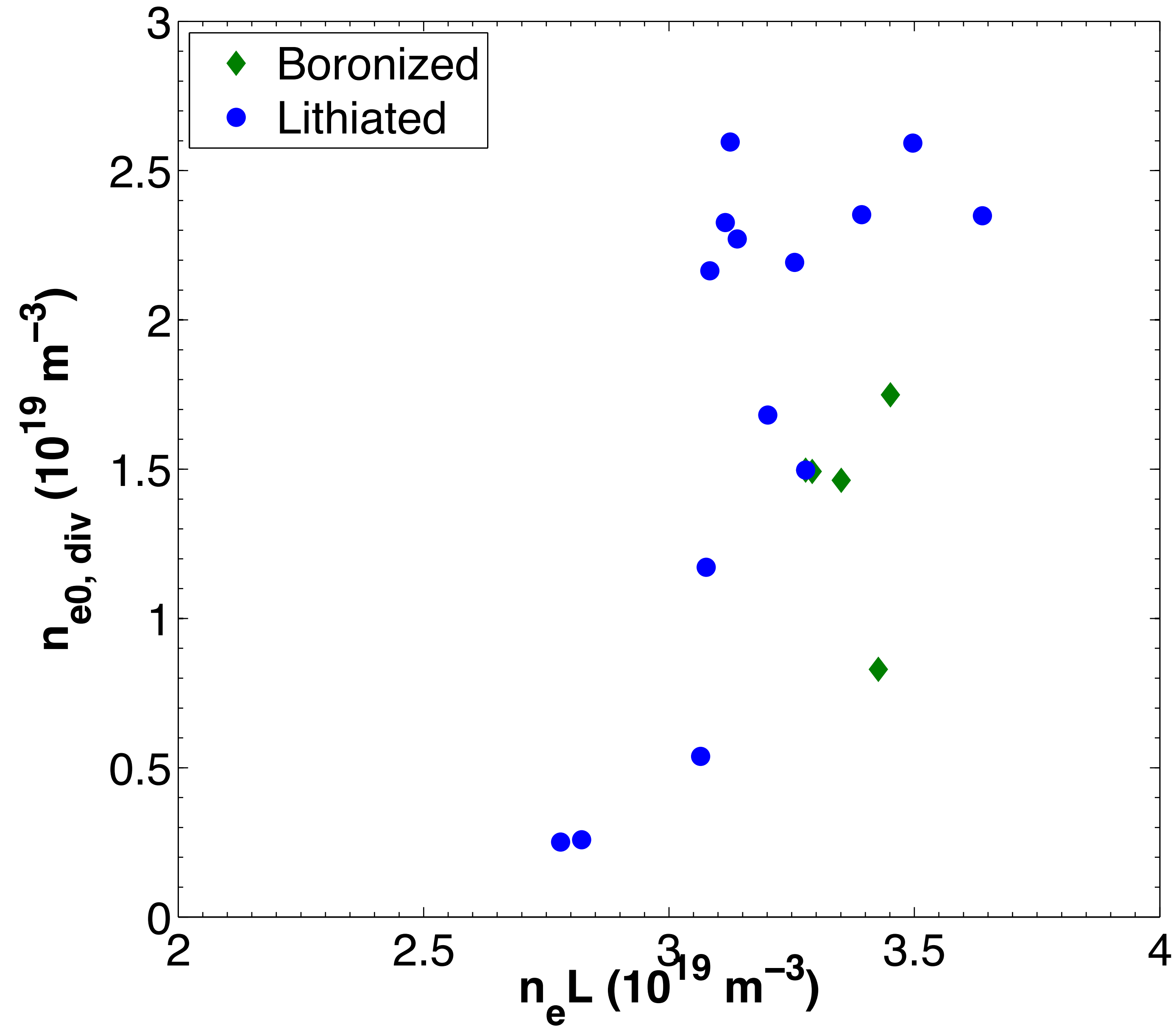
Inconclusive Evidence that Increased Divertor n_e Leads to Broadening of the Heat Flux Profile

- Clear delineation between discharges with varying P_{NBI}
- Possible indications of increases in S at n_e > 2.5(10)^{19} m^{-3}
  - Only a few data points
  - These are the data points for Li evaporation amounts > 200 mg
- A larger scan in divertor density with Li is needed to address this issue
  - Possible avenue for further SOLPS modeling before NSTX-U comes on-line



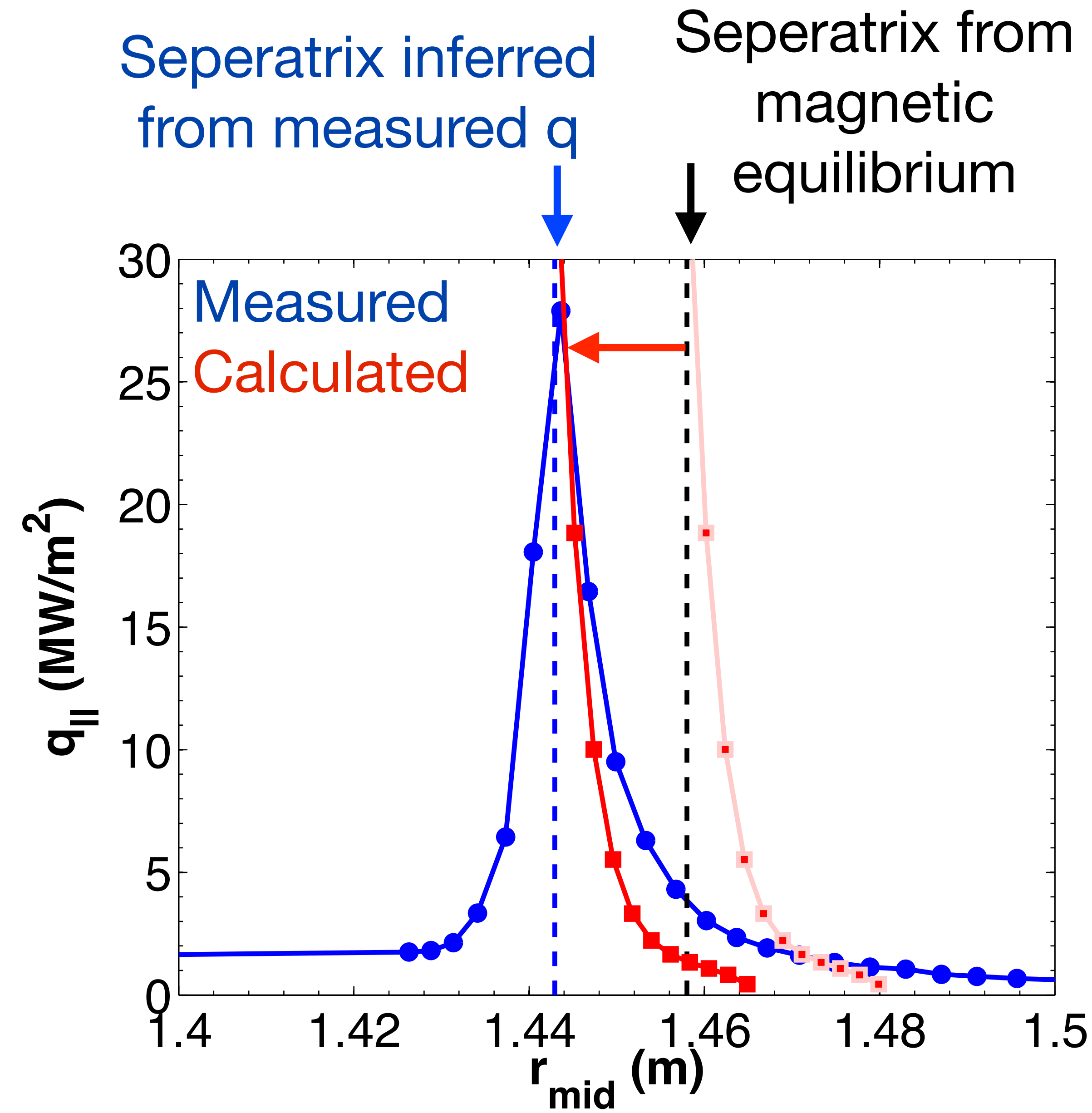
No evidence of Divertor Detachment During the Progressive Li Scan

- Data averaged for early times in each discharge
  - Same technique as used previously to obtain $n_{e,\,div}$ profiles
- No roll-over in peak divertor density ($n_{e0,\,div}$) as would be expected for “textbook” detached divertor conditions
- But, the data is a limited scan of divertor and core density
  - $2.5 \leq n_eL \leq 4(10)^{19}\ m^{-3}$
  - Since the data are all limited to times early in the discharge



Interpretive Modeling of the Discharges is Necessary to Better Understand SOL Power Balance

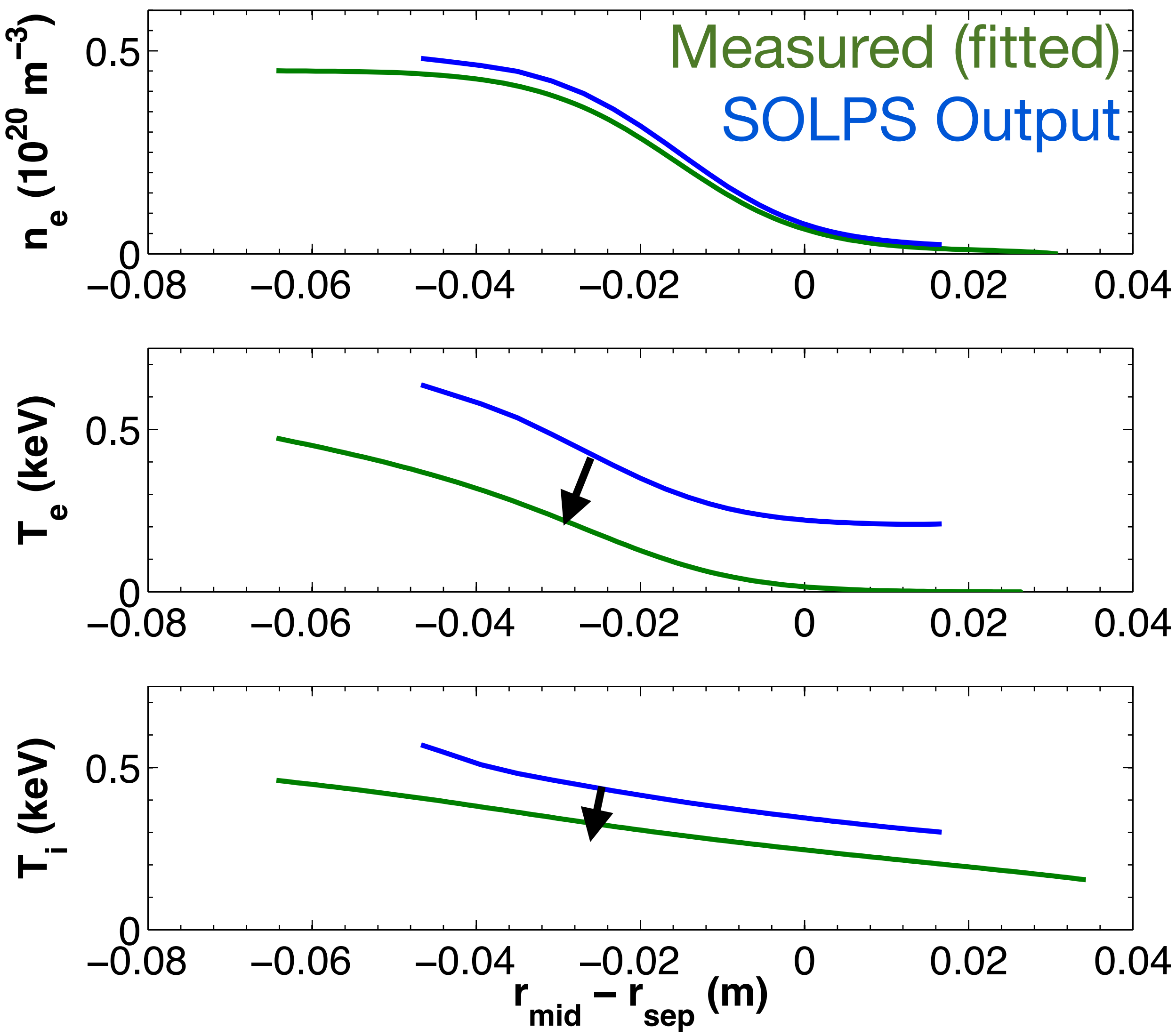
- Assuming attached divertor conditions, the parallel heat flux can be inferred from upstream n_e and T_e
- However, there's consistently a difference in seperatrix location between the divertor $q_{||}$ and the magnetic equilibrium
  - True regardless of divertor wall conditioning used
- Shifting the upstream data can partially resolve this
  - But still a poor comparison away from the seperatrix
  - The shift in upstream data to match heat flux varies from 1-3 cm for various shots



129020, 0.38 sec
(boronized shot!)

Constraining the SOLPS simulations to experimental values has been the limiting factor in further investigations

- Determining the correct $D_\perp^{eff}$ and $\chi_\perp^{eff}$ to match the experimental midplane n_e, T_e and T_i has been troublesome
  - $D_\perp^{eff}$ less so
- This hampers further use of SOLPS to interrogate the underlying physics
  - D only simulations
- Work is ongoing to resolve this issue
  - Once the midplane profiles are in agreement, contributions from C and Li can be added into the simulations



Conclusions and Ongoing Work

- With sufficient Li deposition, divertor power accounting drops to 12 - 20 % P_{SOL}
  - Lower Li deposition amounts may actually improve divertor power accounting
- The reduction in P_{div}/P_{SOL} is due not only to contracted heat flux profiles with Li, but also reduced divertor T_{surf} measured with the dual-band IR thermography system
  - There does appear to be a threshold amount of Li deposition required to achieve heat flux reduction
- Increased Li deposition leads to increased divertor electron density
  - Li is trapped in the divertor and SOL plasmas ($n_{Li,\ core}$ < 0.1%)

What's the Physical Mechanism of Reduced Heat Flux with Increasing Li Evaporation ... Revisited

A) Increased divertor radiation due to Li
- ➡ NSTX didn't have the necessary diagnostics to properly address this
- ➡ Will attempt to address with continued modeling and future experiments on NSTX-U

B) Li "spreading" the heat flux???
- ➡ Some initial indications that this may be happening ... but there's not nearly enough data to back up this claim
- ➡ More data at a wider range of divertor densities is needed

C) Divertor detachment onset due to Li
- ➡ Based on divertor probe measurements, Li doesn't appear to be causing divertor detachment

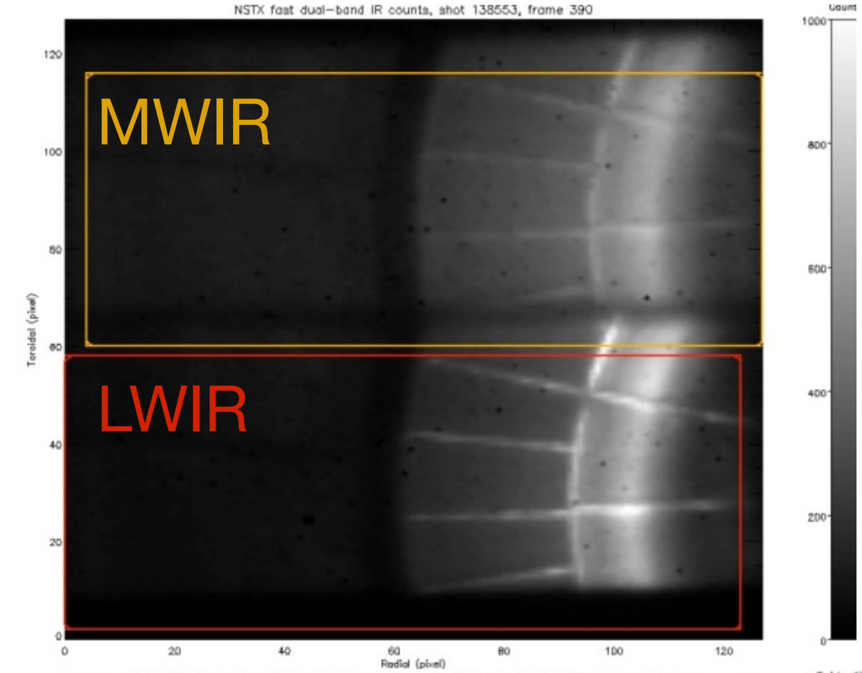
D) Upstream Profiles Modified by Li → This is still under investigation
- ➡ Somewhat limited since all previous Li scans occurred before the dual-band IR system was installed (eg - no absolute measure of divertor T_{surf})

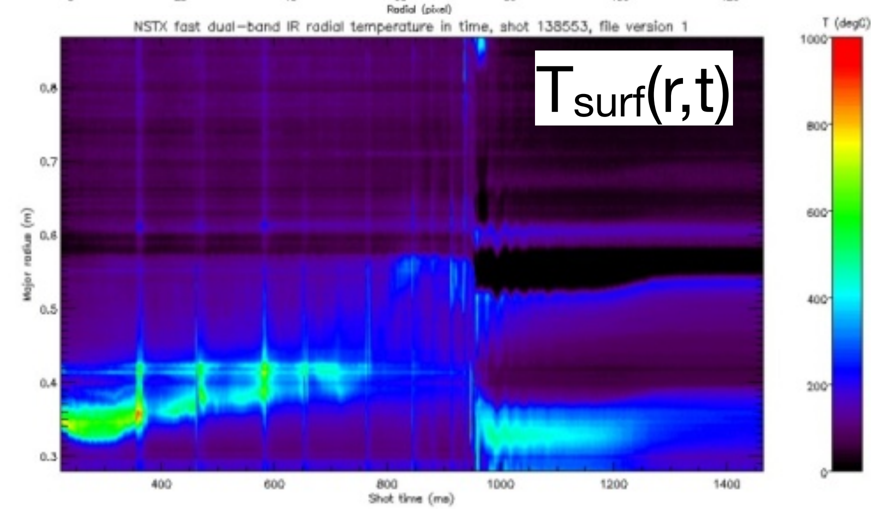
E) Some combination of all of the above or none of the above?

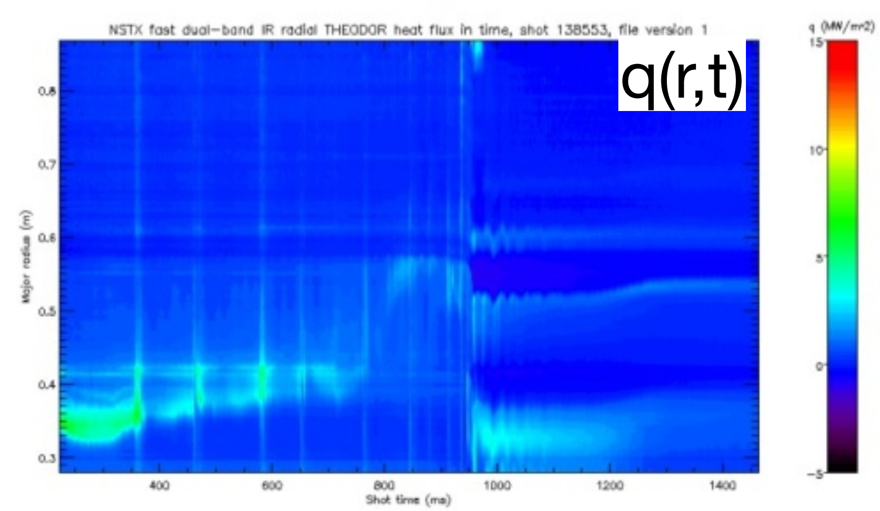
- Given that new data on NSTX-U is 1+ years away at best, we're currently relying on:
  - Analysis of older NSTX data to better understand the underlying mechanisms at work
  - As well as interpretive 2D modeling of these discharges
  - Progress in modeling has been slow, but is still ongoing

The Dual-Band IR Camera Allows Measurement of Divertor Surface Temperature with Variable Surface Emissivity

- The addition of lithium complicates the measurement of divertor surface temperature, T_{surf}
  - Li emissivity (clean) ~ 0.1
  - Graphite ~ 0.8
  - Lithium and Carbon are eroded and redeposited constantly through out the discharge
- Using a Santa Barbra Focal Plane Camera
  - 128x128 pixels
  - frame rate ≤ 16 kHz (typical operation at 1.6 kHz with dual band optics)
- 2 different IR wavelength bands are imaged simultaneously[McLean 2012]
  - MWIR: 7 - 10 μm
  - LWIR: 10 - 13 μm
- The ratio of the 2 bands yields $T_{surf}(r,t)$
  - Assumes the surface emissivity is similar across both wavelength bands
  - Not a bad assumption for a diffuse, grey body emitter
- Once T_{surf} is known, heat flux can be calculated
  - 2D finite difference calculation (THEODOR)

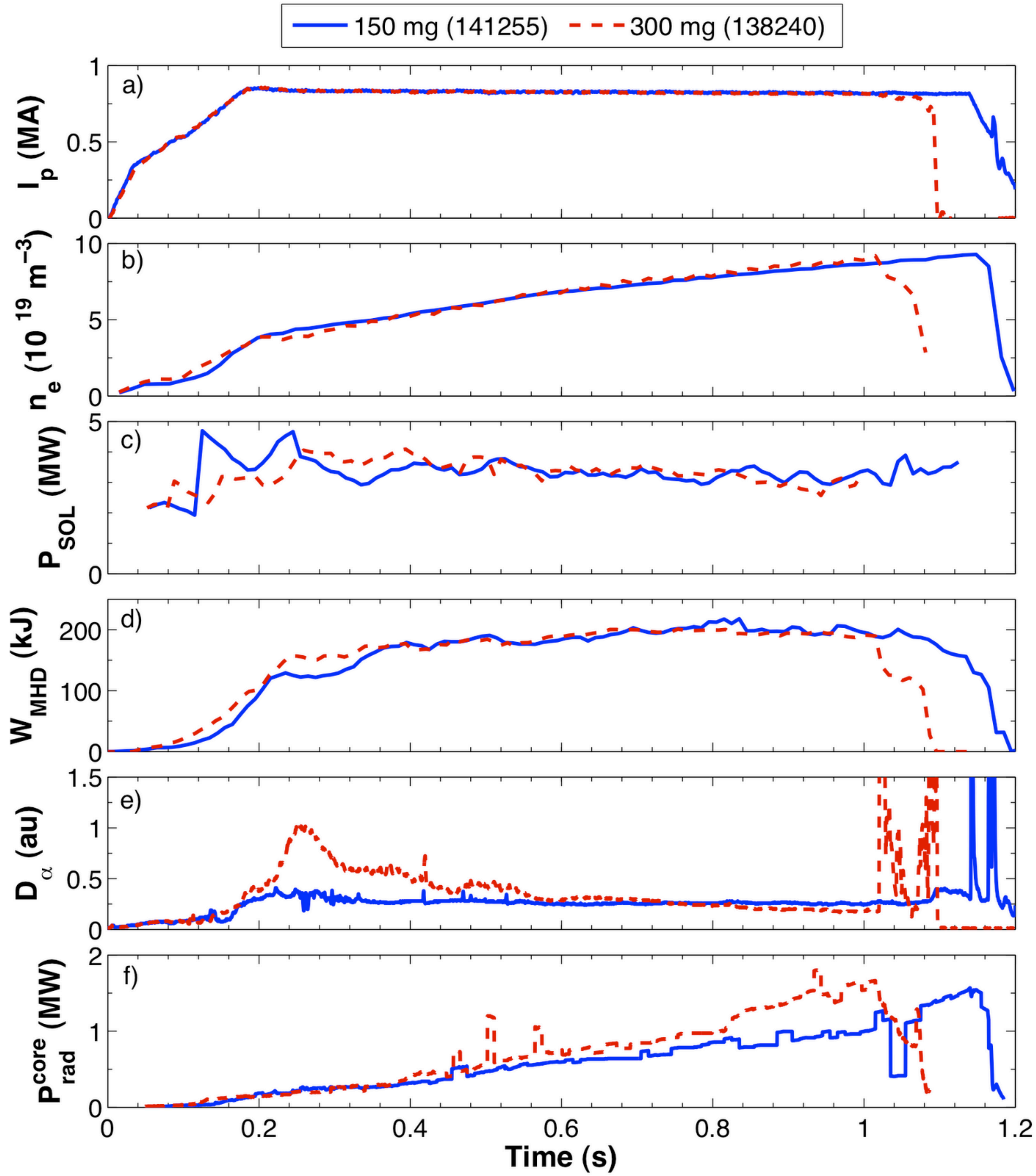






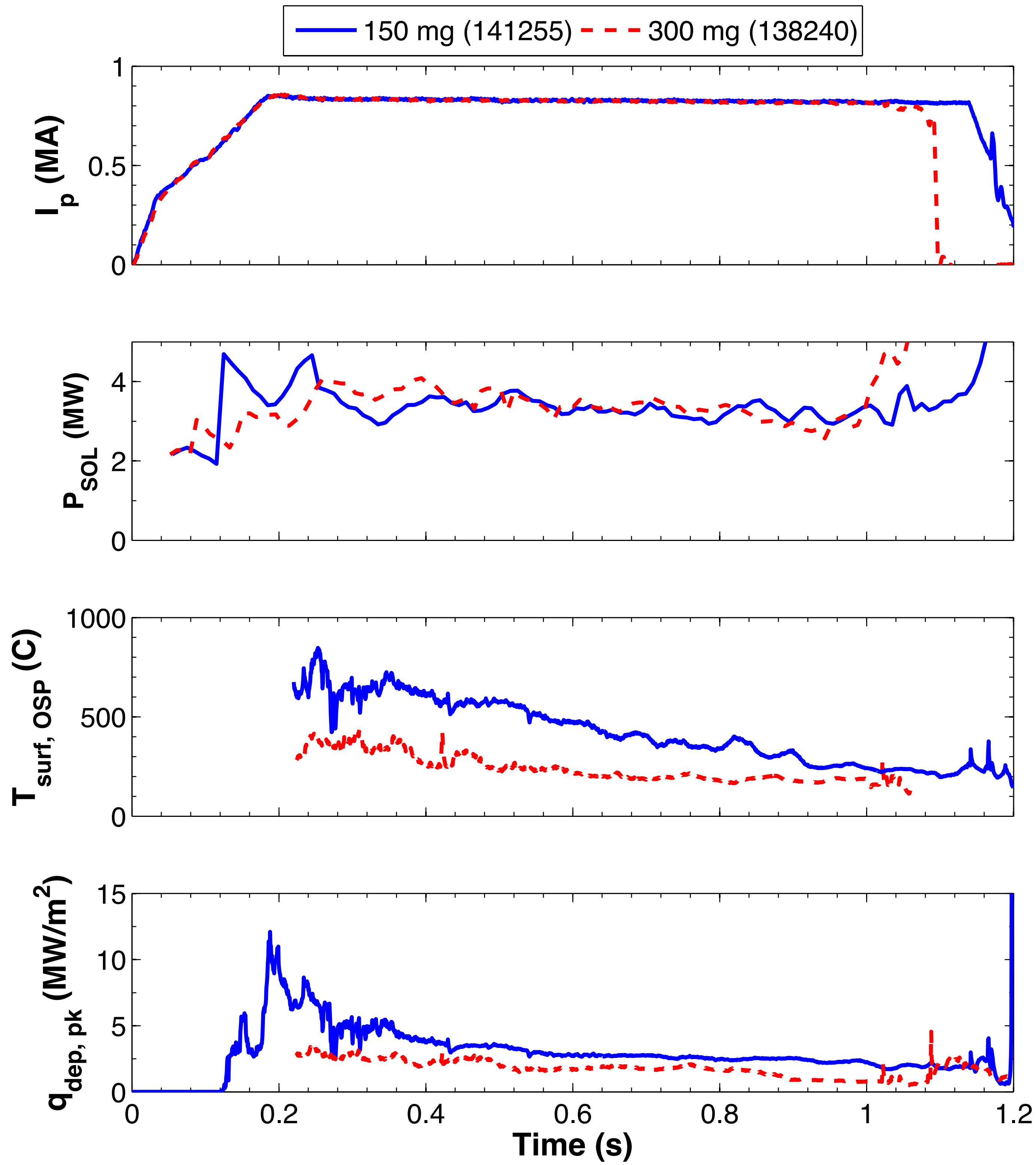
Comparing shots that are nearly identical, other than lithium coverage, provides a means to study the effect of lithium

- No ELMs in either shot
  - Boronized shots are ELMy and would have higher divertor heat flux because of this
- I_p = 0.8 MA
- P_{nbi} ~ 4 MW
  - Some pre-heating (~ 5MW) used in the 150mg shot (141255)
  - P_{SOL} is similar after ~ 0.25 s
- high δ, f_{exp} ~ 20
- increased center stack gas puffing in the 300mg shot
  - required to sufficiently fuel the discharge and avoid locked modes
- Higher P_{rad}^{core} in 300 mg discharge after t = 0.6 s



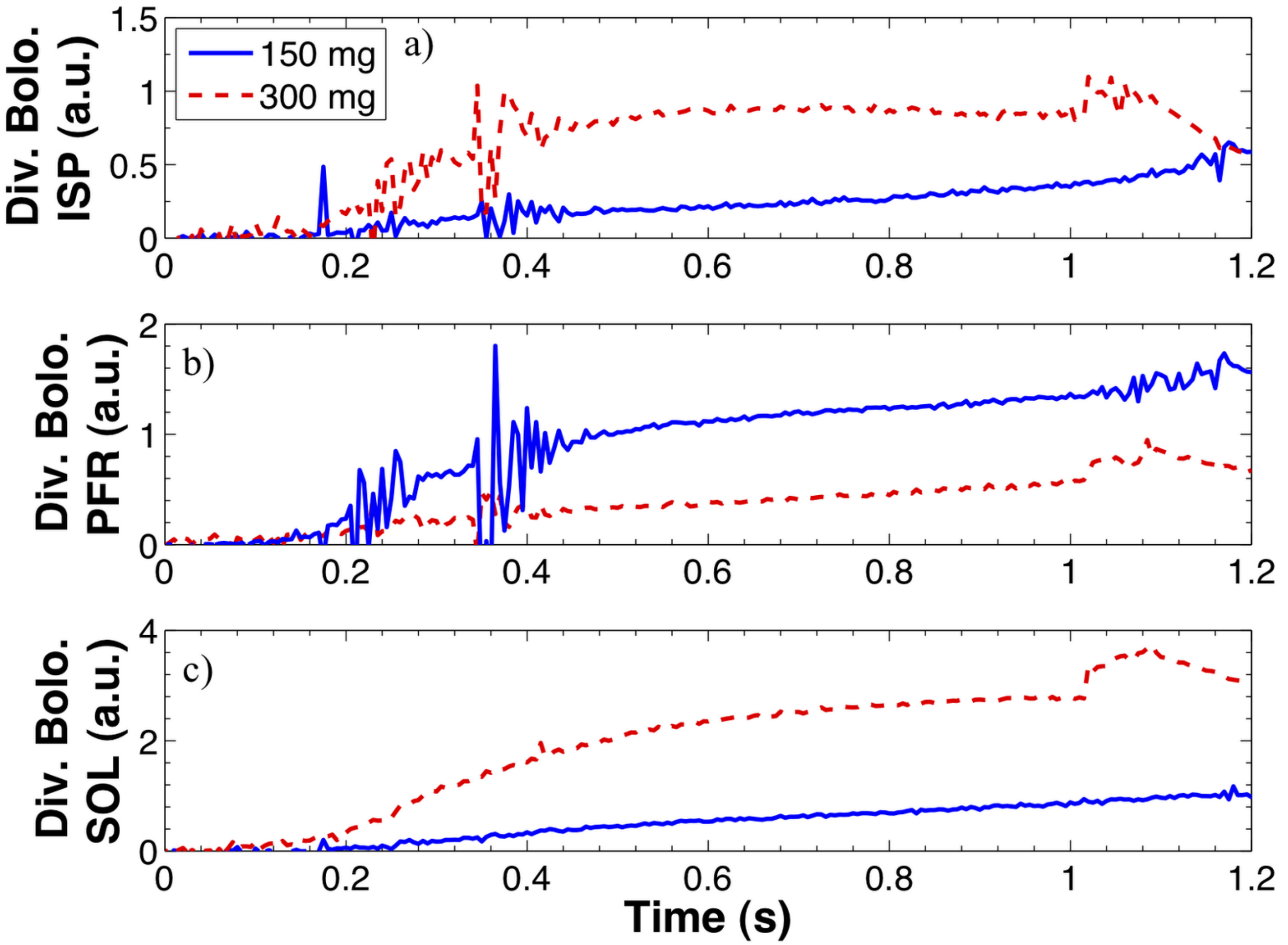
Clear reduction in divertor surface temperature and heat flux with increased lithium evaporation

- No ELMs in either discharge
- T_{surf} at the outer strike point stays below 400 C for 300 mg of Li
  - Peaks around 800 C for 150 mg
- Results in a heat flux that never peaks above 3 MW/ m^2 with heavy lithium evaporation
- This is consistently the trend in discharges that used heavy Li evaporations

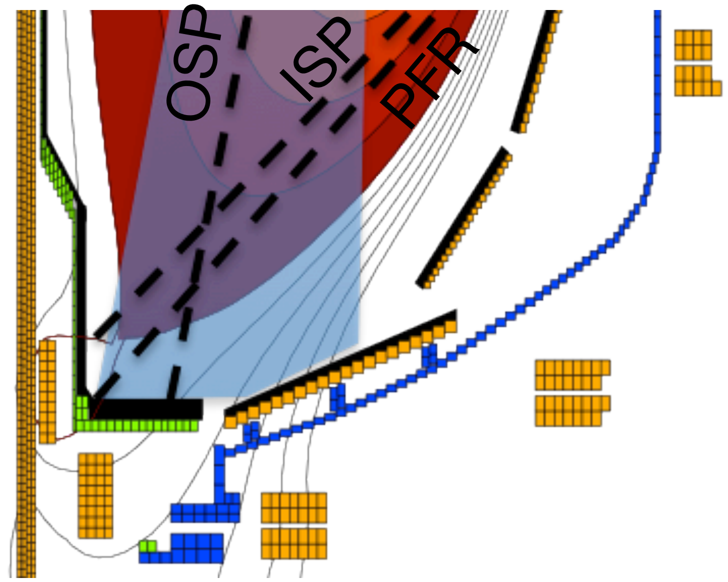


Divertor radiation measurements show an increase in radiation near the inner and outer strike points

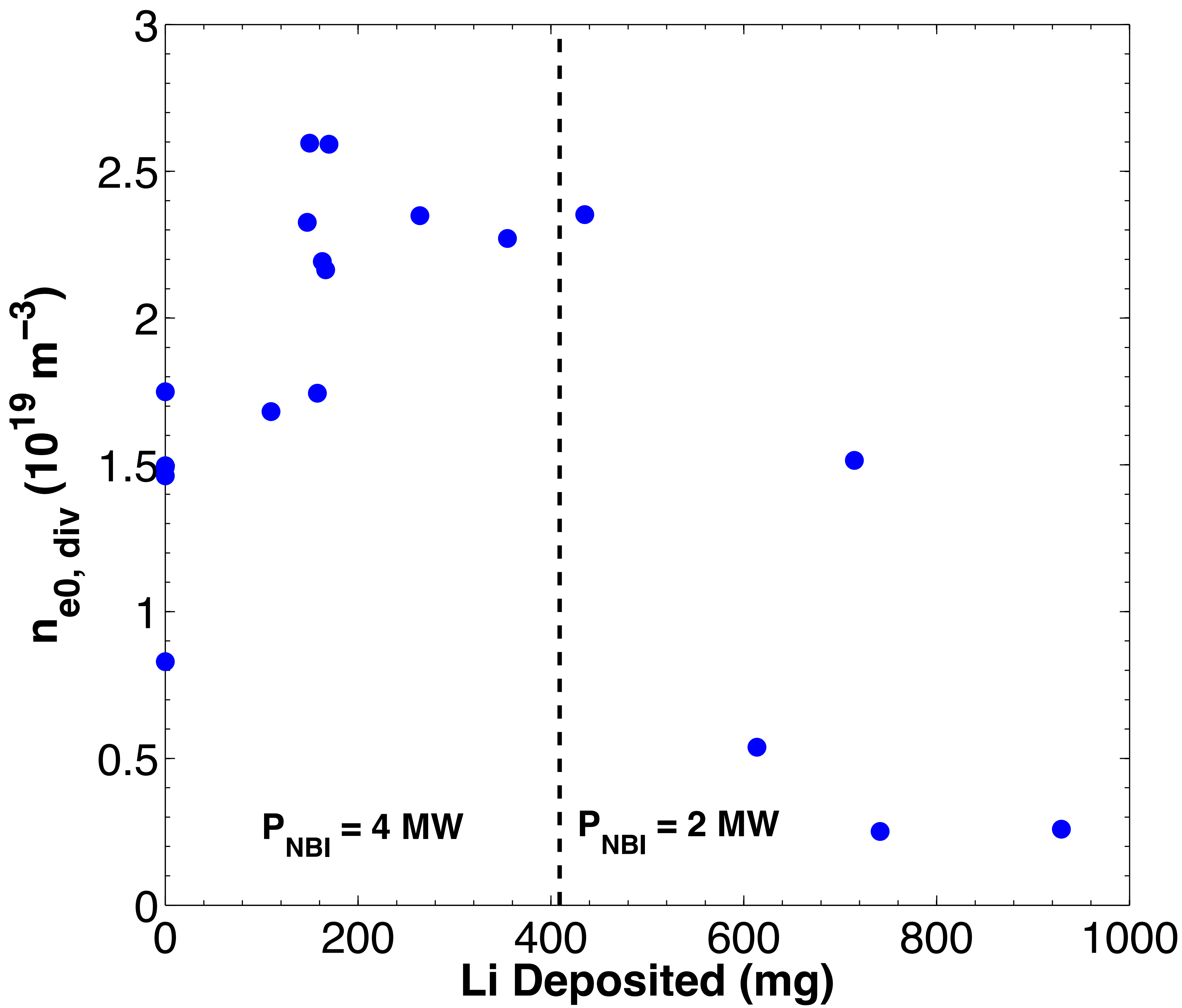
- Radiation at the Inner Strike Point (ISP) and in the far SOL increases substantially with increased Li deposition
  - P_{rad}^{core} similar between the 2 discharges for early times
- However, radiation from PFR region is decreased for higher Li depositions
  - This could be due to changes in radiation at the x-point
  - Without more extensive bolometric coverage in the divertor, its difficult to reach any conclusions about the cause



Divertor Bolometer Chords

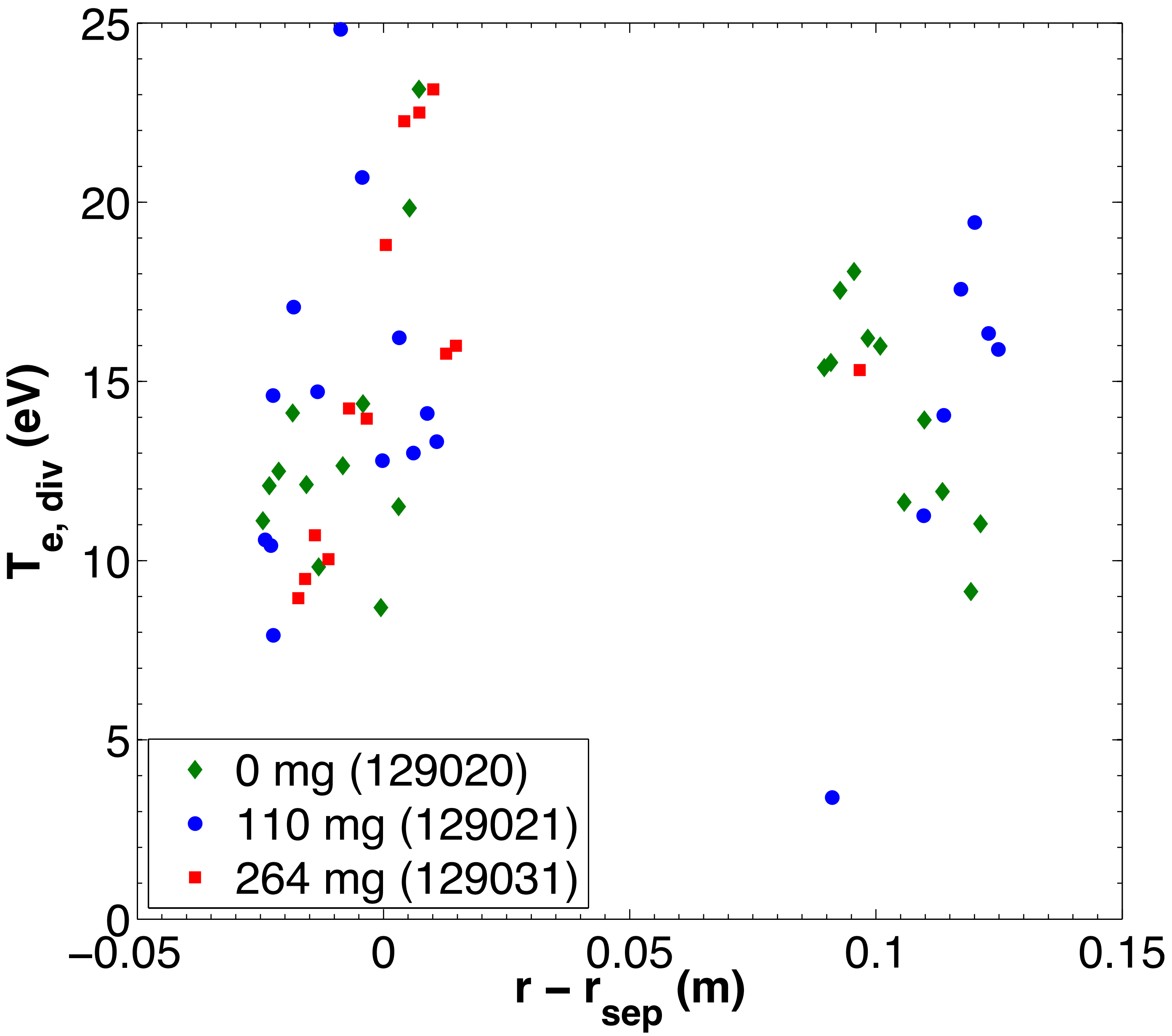


Divertor n_e increases with increased Li evaporation

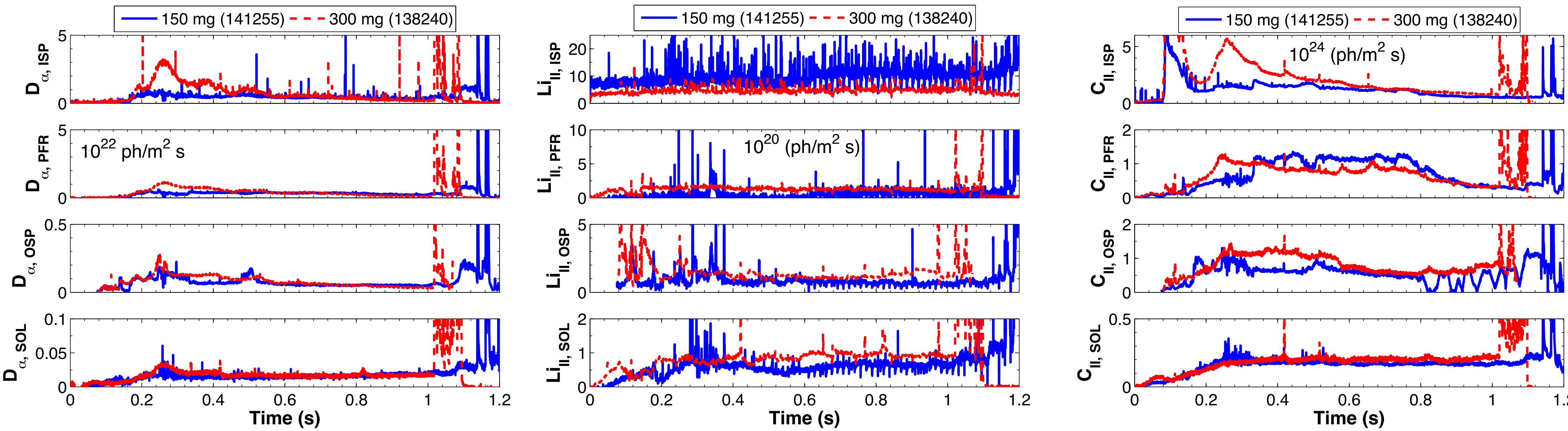


Divertor T_e Profiles are Difficult to Interpret

- Using the natural strike point sweep to obtain T_e profile
  - Same procedure as performed for the n_e profiles
  - However, 2 probes used to get a more complete T_e profile
- No discernible T_e profile
  - At best, $T_{e,\,div}$ is "constant"
  - Similar regardless of Li used



Increased visible line emission can partly explain the increases seen in divertor bolometer. Doesn't explain decrease in the PFR



- Increases in D_α and C II emission may explain increased radiation at the ISP
- Overall, Li II emission is fairly constant to slightly elevated in these 2 discharges
- No evidence of decreased PFR line emission
  - Only measuring D_α, Li II and C II in these discharges