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NSTX-U

Heat Flux and Scape-off Layer Wdith Scaling in NSTX and NSTX-U

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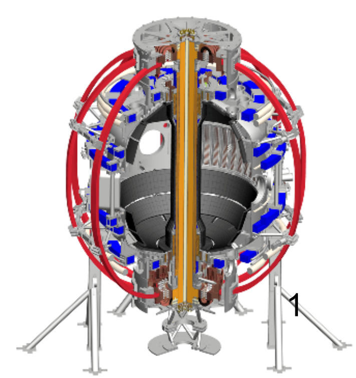

Abstract

While it has been shown experimentally that the inter-ELM scrape-off layer width, λ_q in tokamaks scales as I_p^{-1}, the underlying physical mechanism for this scaling is not yet understood. Additionally, the physics behind the broadening of the heat flux profile during detachment, described by the S parameter in the so-called Eich fitting function [Eich NF 2013], is just beginning to be explored. During the final run campaigns of NSTX, it was shown experimentally that the addition of evaporative lithium wall coatings reduced λ_q and S and correlated with a reduction in overall divertor pressure. Conversely during detachment experiments with CD_4 injection, while divertor total pressure increased during CD_4 injection, both λ_q and S increased correspondingly. This is in qualitative agreement with measurements made on other tokamaks and shows a clear scaling of λ_q and S with upstream density, which is used as a proxy for divertor density. Expected behavior and preliminary results from NSTX-U will also be presented.

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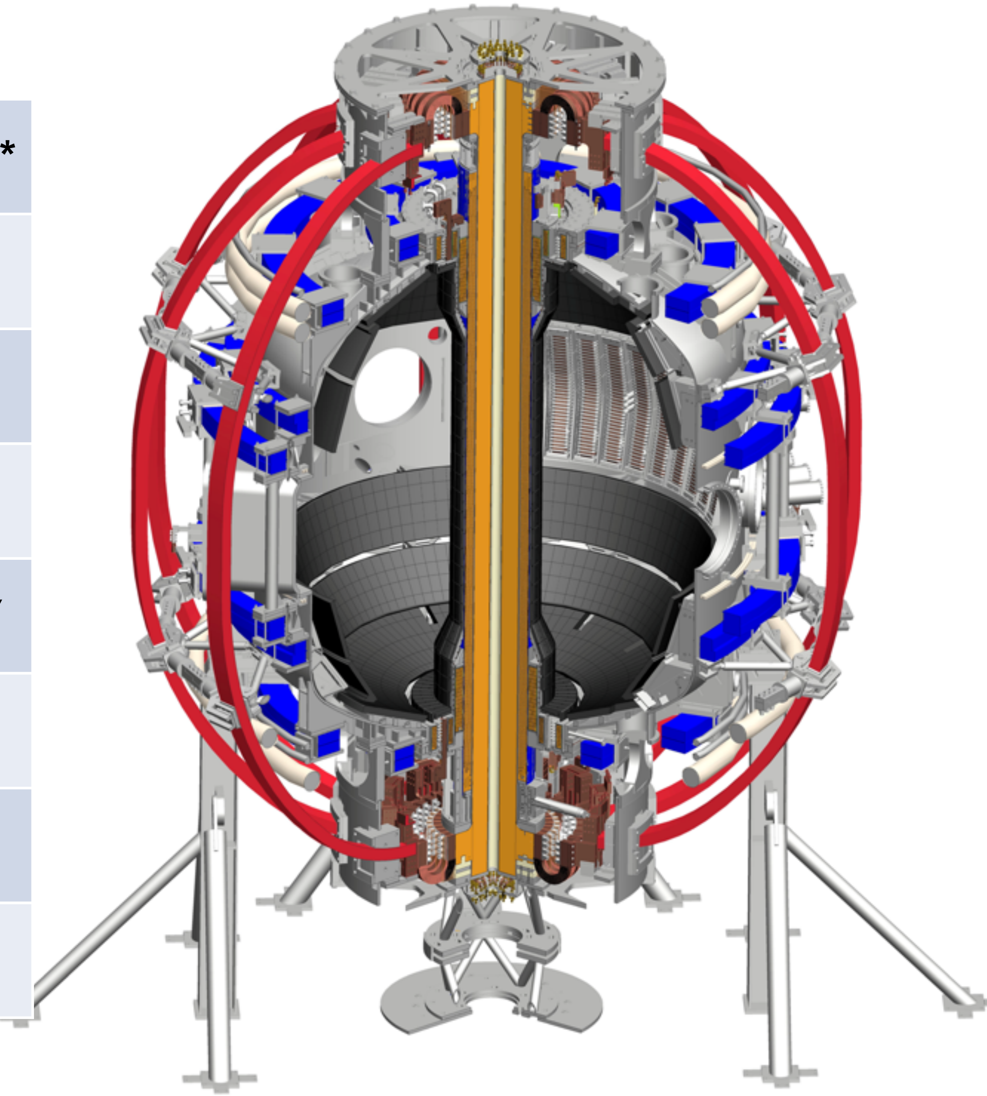
Motivation

- Mitigating divertor heat flux to acceptable material limits is one of the biggest challenges facing fusion
- This is an even greater challenge for the spherical torus due to its compact size
- Projected NSTX-U characteristics:
  - $I_p \leq 2$ MA, $P_{NBI} \leq 12$ MW, 5 second pulse
  - $q_{pk,\ Inter\text{-}ELM} > 20$ MW/m^2 [TK Gray, JNM 2011]
    - Assuming double null, $f_{exp} \sim 30$ and $f_{rad} \sim 0.5$
  - Moving to transition from graphite to high-Z PFCs (TZM Mo)
- Active program on NSTX-U to mitigate extreme heat fluxes
  - Snowflake/X-divertor
  - Lithium

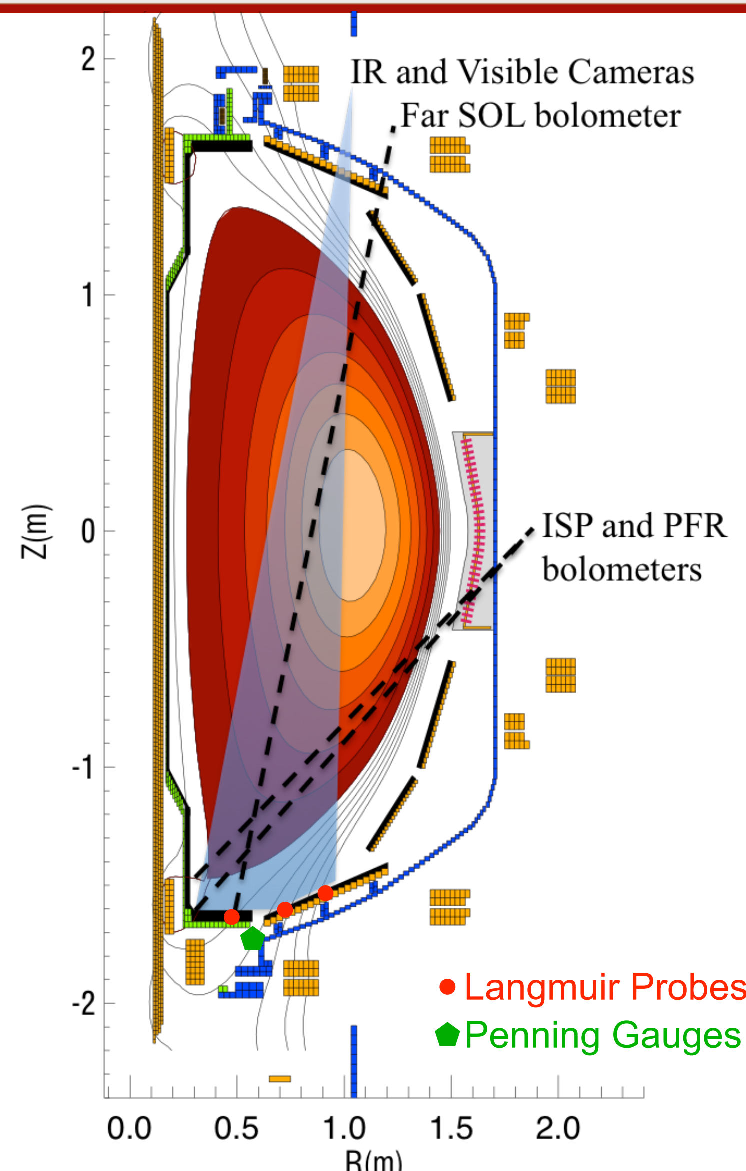
Overview of NSTX (2009-2010)

	NSTX	NSTX-U*
Plasma Current, I_p	*≤ 1.2 MA*	*≤ 2 MA*
Magnetic Field, B_t	*≤ 0.55 T*	*≤ 1 T*
Auxiliary Heating:		
Neutral Beam Injection	*6 MW*	*12 MW*
RF	*6 MW*	*6 MW*
Central Temperature	*1 — 6 keV*	*???*
Central Density	*≤ 1.2(10)^{20} m^{-3}*	*???*



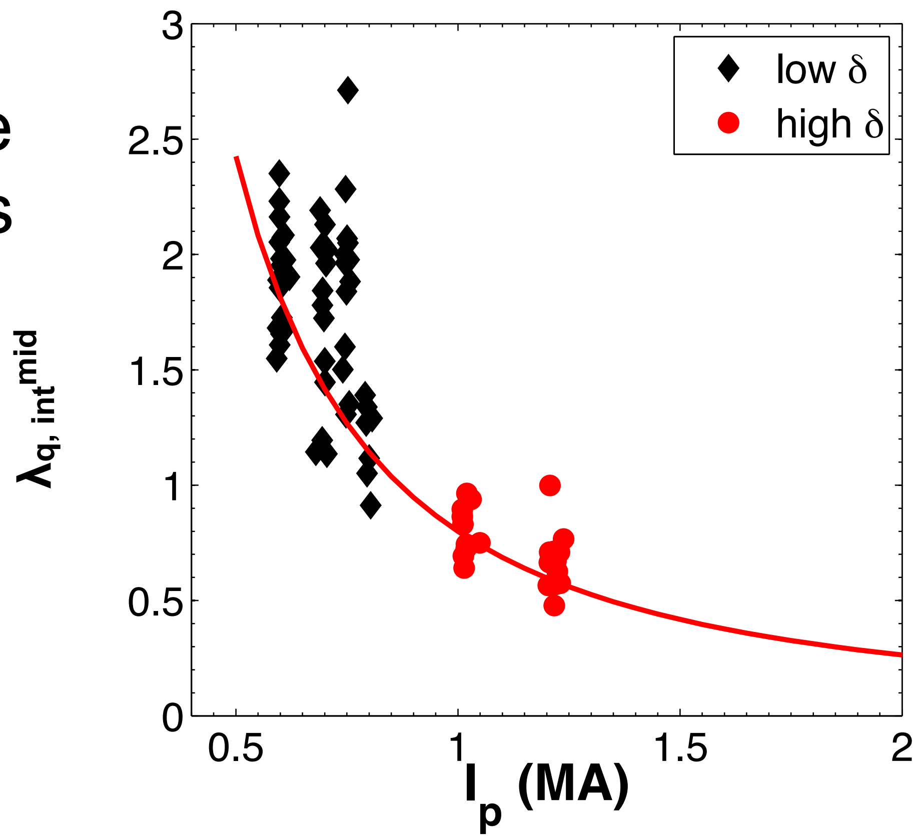
Available NSTX Diagnostics

- Lower Divertor IR cameras
  - 30 Hz IRTV
    - sensitive to 6 - 13 μm
  - 2010: Fast IR camera
    - 1.6 — 6.7 kHz
    - equipped with dual band optics
- Filterscopes
  - D_α, C II, Li II, O II
  - wide FOV of the divertor
- Flush mounted divertor Langmuir probes
- Divertor and midplane penning gauges



Previous Measurements of SOL Width

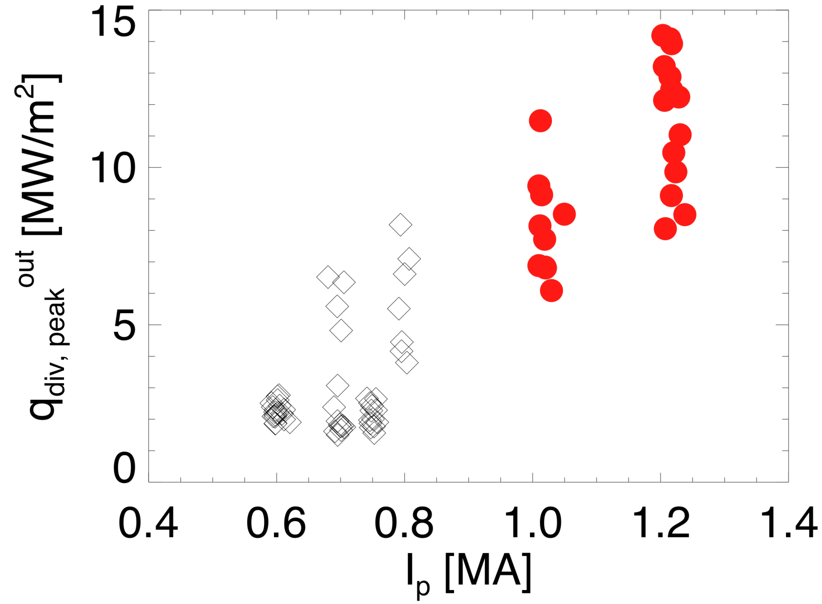
- Previous studies (no lithium) on NSTX showed λ_q has strong inverse I_p dependence in attached, H-mode plasmas [TK Gray, JNM 2011]
- True for both integral width as well as λ_q in the Diffusive-Gaussian description
- Predicts λ_q ~ 2—3 mm for NSTX-U @ 2 MA
- Addition of Li has been shown to further decrease λ_q [TK Gray, NF 2014]

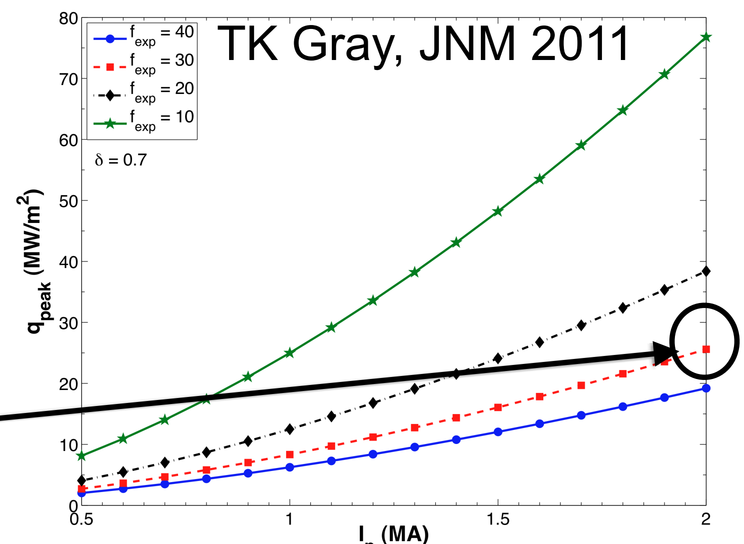


$$\lambda_q^{mid} = 0.91 I_p^{-1.62}$$

Previous Heat Flux Scaling Experiments on NSTX

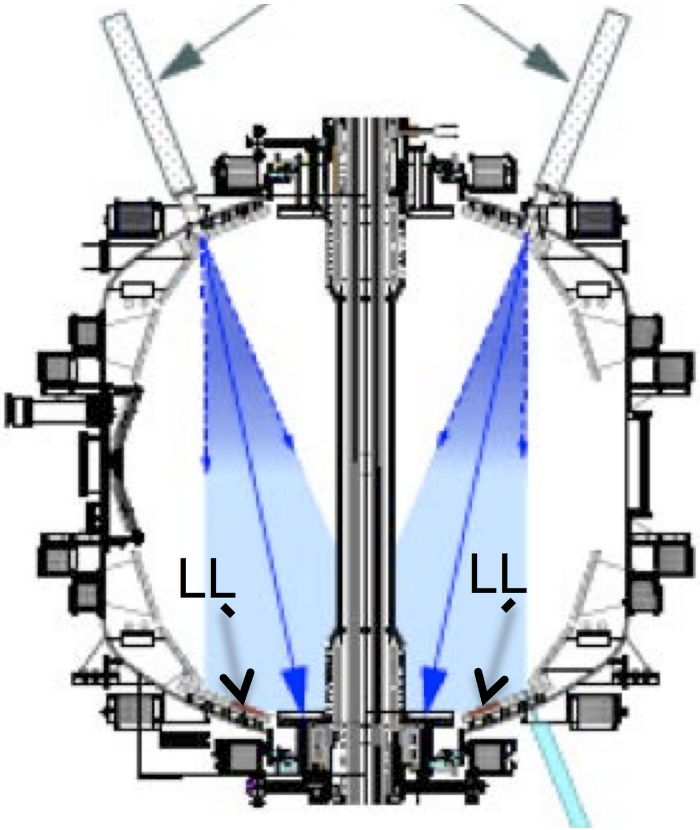
- Combined data from dedicated I_p scans in low δ and high δ discharges
  - Different P_{NBI} and f_{exp}, but previous work shows no P_{loss} or f_{exp} effect on λ_q^{mid} under attached divertor conditions
  - q_{95}, $\ell_{||}$ different
- For NSTX-U Parameters of:
  - I_p = 2 MA, B_t = 1 T
  - For P_{loss} = 10 MW
    - assuming f_{div} = 0.5
  - f_{exp} = 30
  - $\delta \sim 0.7$
  - Anticipate operation with $0.5 \leq n/n_{GW} \leq 1$
- q_{peak} = 24 MW/m^2





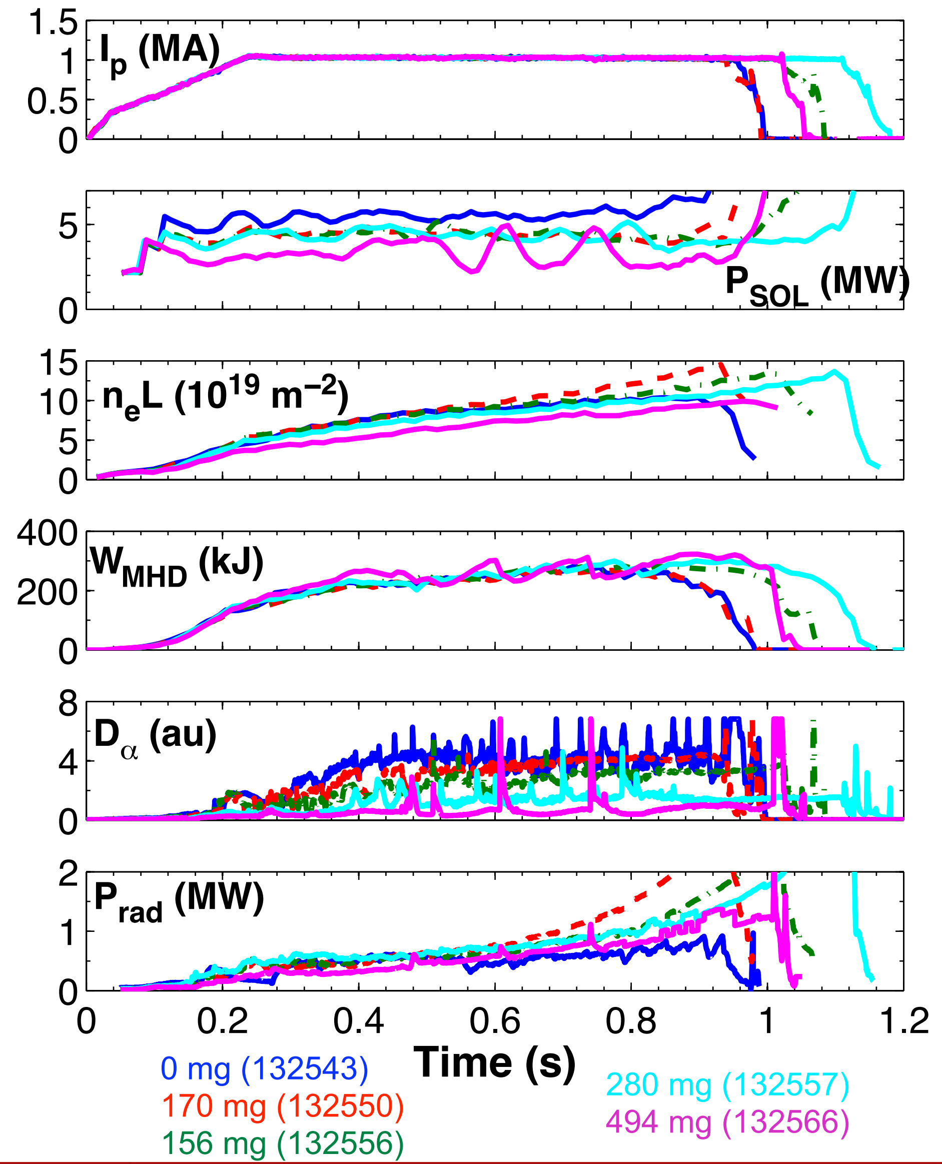
Controlled Li Introduction Experiment (2009)

- Lithium is deposited on the lower divertor prior to each discharge via 2 Li ovens called LiTERs
  - Located toroidally 130º apart
  - Li coverage in the divertor has a gaussian distribution
- Amount of Li deposited incrementally increased over the course of 2 days
- Similar experiment was performed in 2008 in a low δ discharge shape



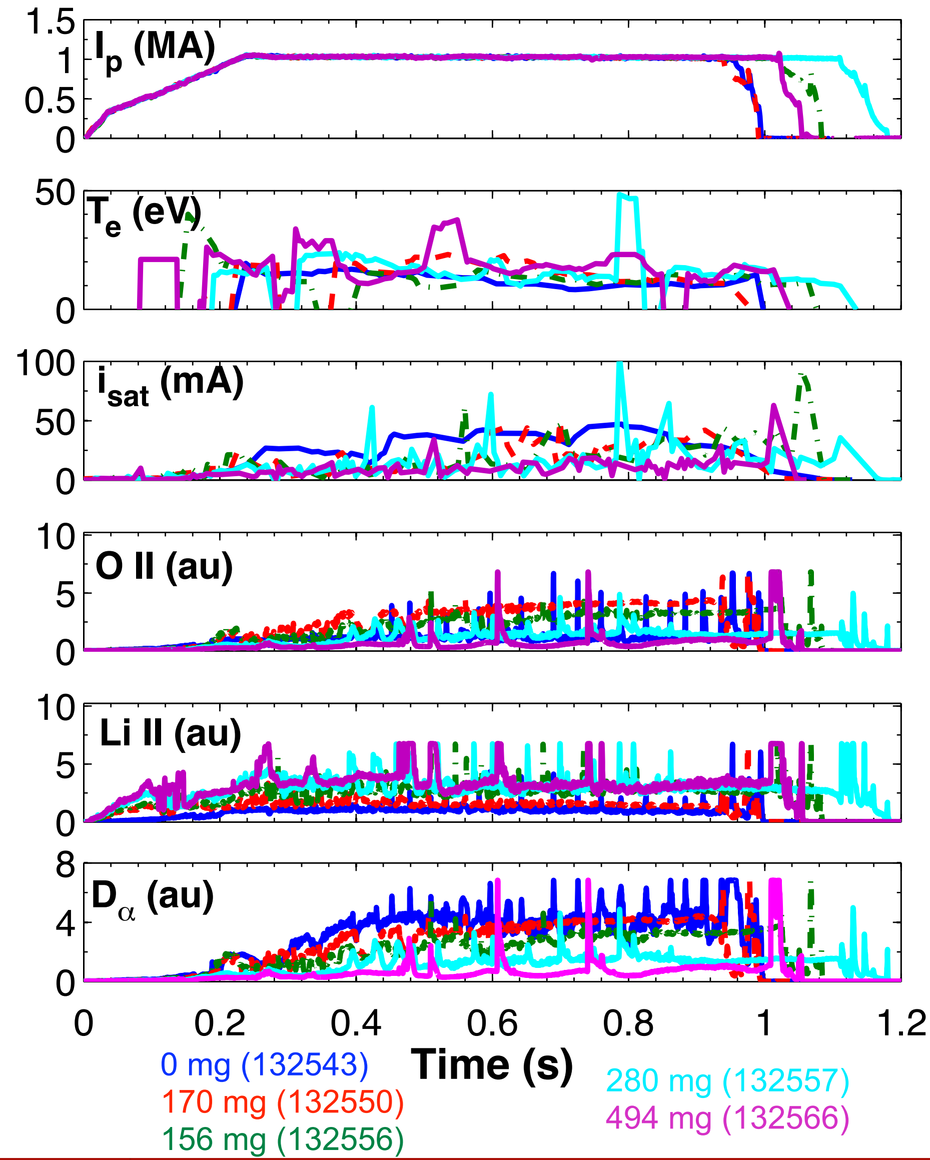
Introduction of Lithium into NSTX in 2009

- 22 shots used (132540 — 132569)
  - 8 boronized shots
  - The remaining shots (starting with 132550) have increasing pre-shot Li evaporation
  - I_p = 1 MA, P_{NBI} = 4 — 6 MW, δ ~ 0.7
- With the addition of Li:
  - ELM frequency was reduced but not completely eliminated
  - Similar stored energies
  - Core P_{rad} increases
  - n_eL decreases at high Li depositions
- IRTV data is single band
  - Quantitative heat flux measurements are unreliable due to addition of Li
  - ELM averaged (30 Hz)
  - Profile analysis limited to H-mode phase



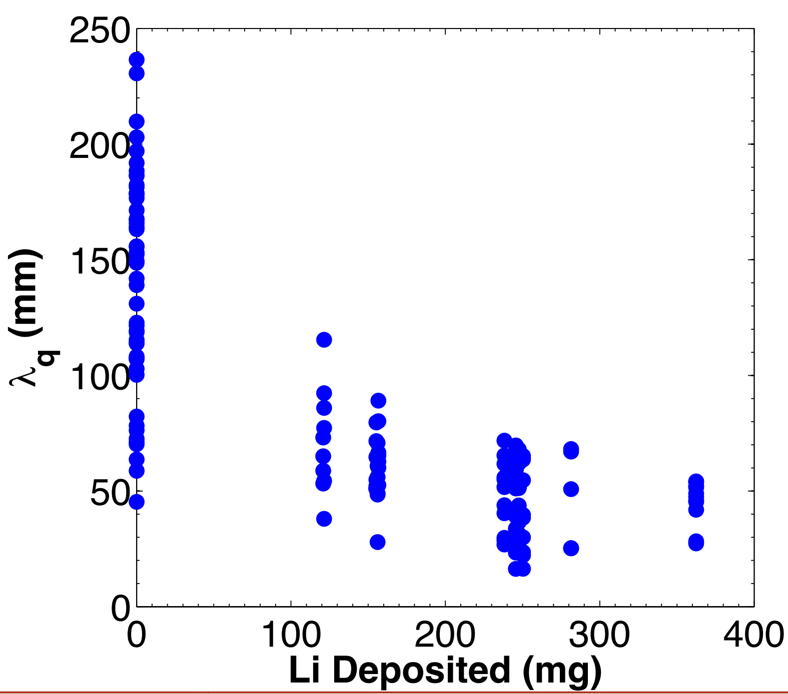
Divertor plasma continually evolves with addition of Lithium

- D_α decreases monotonically indicative of reduced recycling
- Divertor pressure is reduced
- Li II emission increases, but saturates after the initial Li introduction
- Reduction in inter-ELM i_{sat} in far-SOL
  - probe @ r = 50 cm
  - r_{OSP} ~ 35 cm
- T_e is similar or slightly higher than the non-lithium reference
  - Classical probe interpretation
  - Error is estimated to be ±5 eV
- O II emission initially increases with the first addition of Li (shot 132550)
  - Returns to pre-lithium levels after several shots

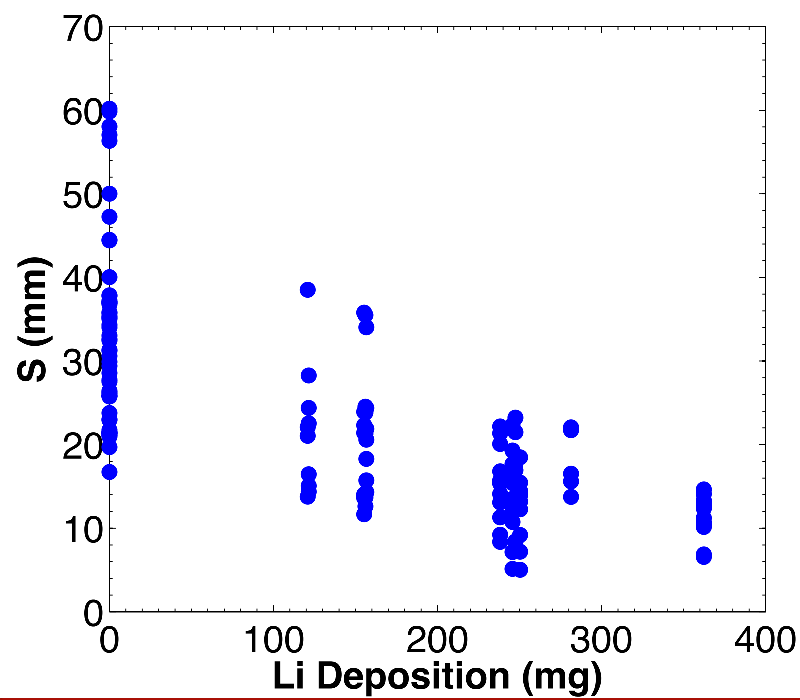


ELM averaged λq and S both decrease with addition of Li

- Decrease in λ_q with Li has been previously reported [TK Gray, JNM 2011]
  - Scatter in the data due to increasing n_eL during each shot

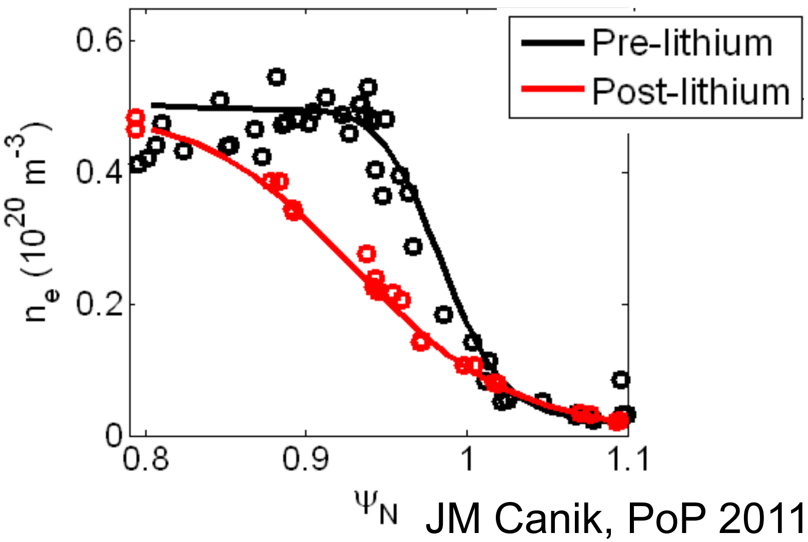


- Unclear whether the decrease S is due to either:
  - Decrease in collisionality
  - Decrease in recycling

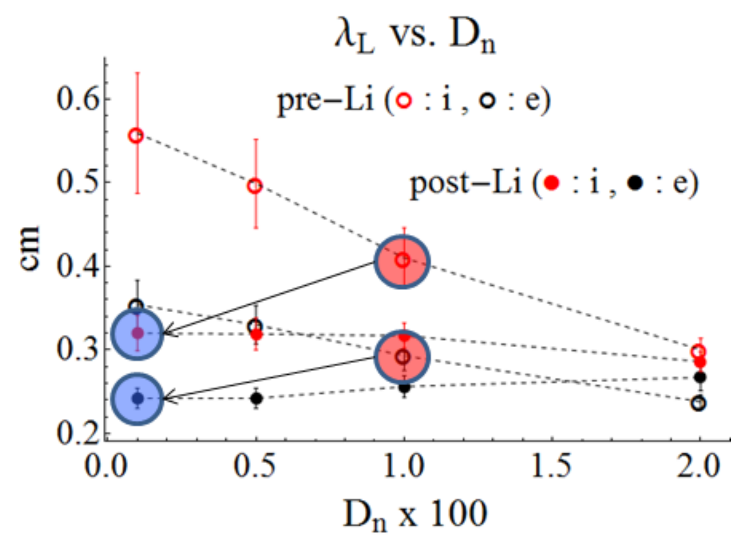


Simulations with SOLT qualitatively describe the observed contraction of λq with Li

- SOLT is a fluid turbulence code
- Density diffusion D_n used to match to simulation results to experimental power crossing the seperatrix
  - D_n is not driving the heat flux
  - it's damping the turbulence which drives the heat flux
- Turbulent (blob) heat transport is weaker for the broader, post-Li profiles
- Weaker turbulence ⇒ less cross-field transport
- Post -Li footprints are smaller than Pre-Li footprints (arrows) at the shot powers (circles)
- Pre/post Li trend qualitatively agrees with experiment

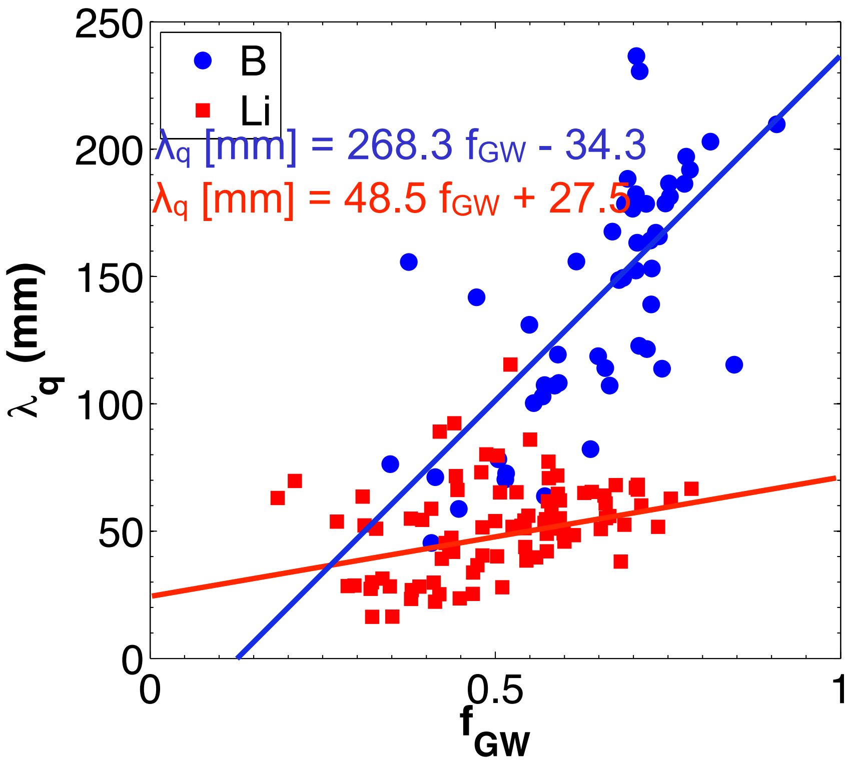


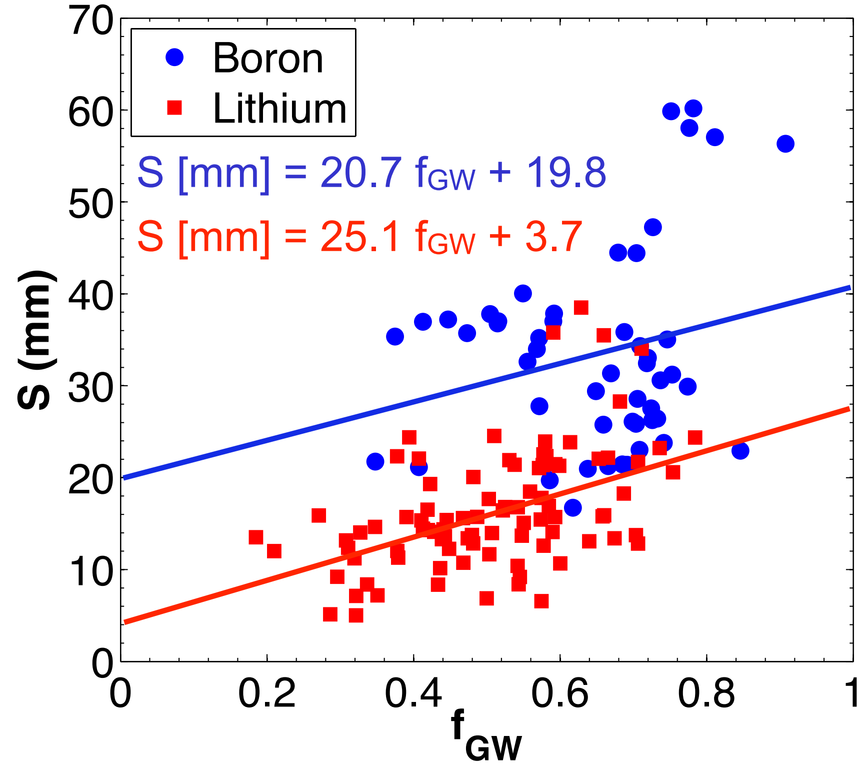
JM Canik, PoP 2011



*DA Russell, PoP (2015)

λ_q and S both increase with upstream density



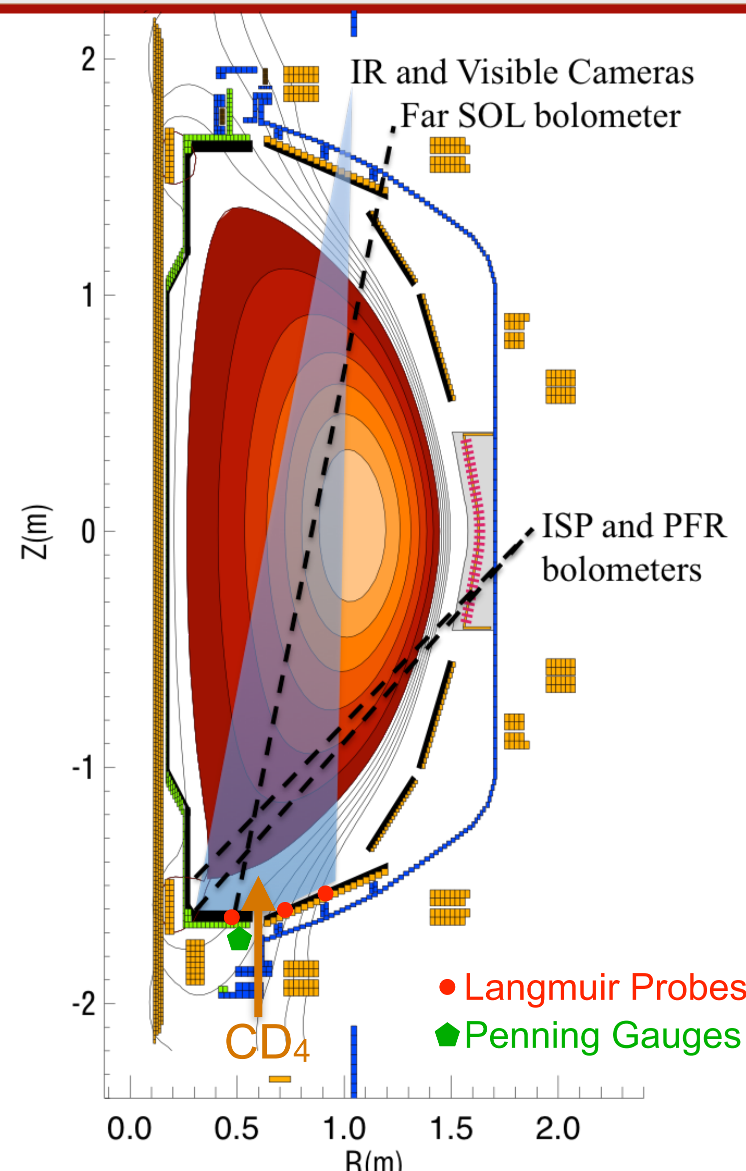


- Rate of change of λ_q w.r.t. f_{GW} is greatly reduced with Li compared to B

- Rate of change of S w.r.t. f_{GW} is similar, perhaps higher, between B and Li discharges
  - Poor linear fit of B data

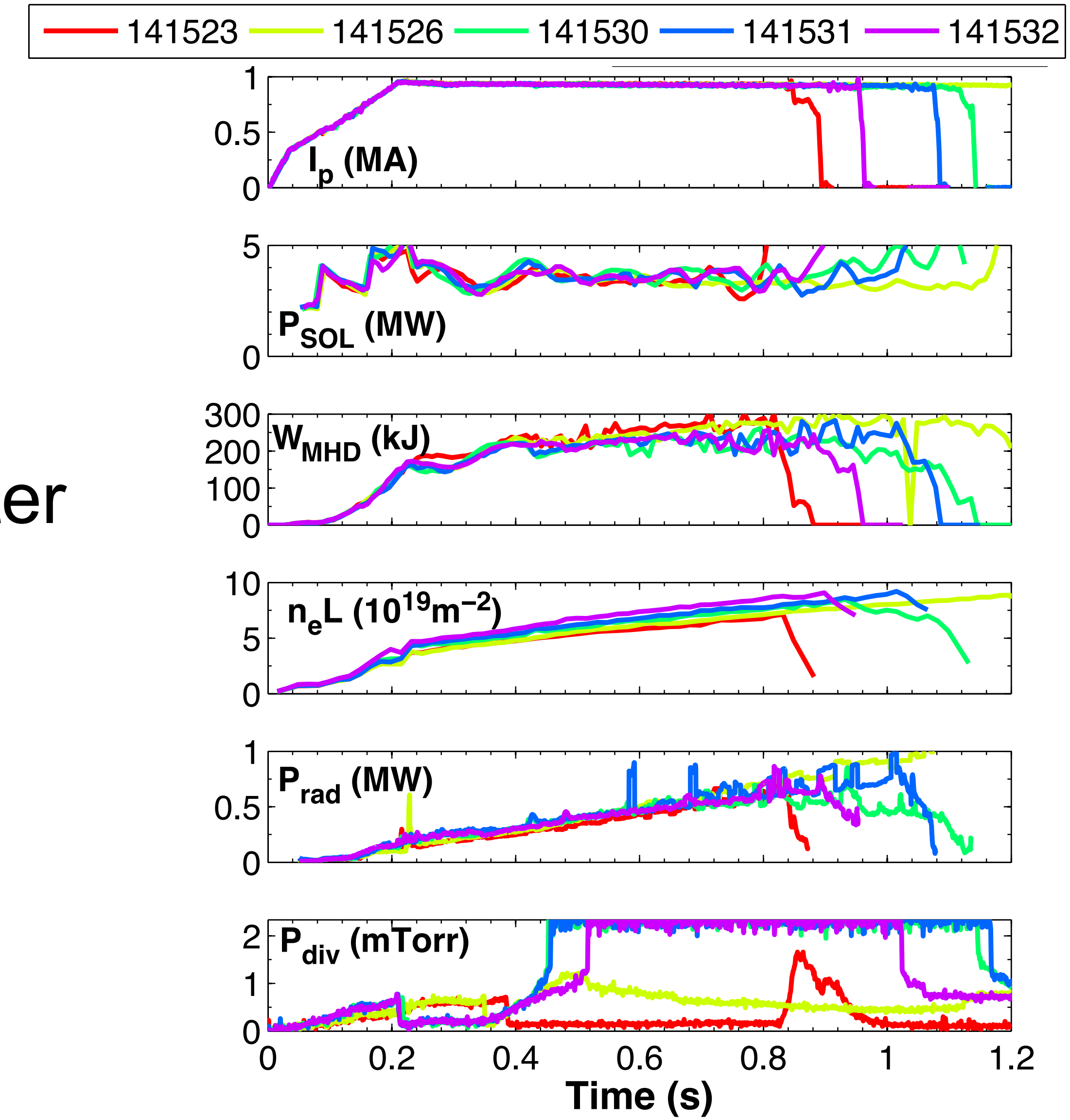
Divertor Detachment using CD_4 (2010)

- I_p = 1 MA, P_{NBI} = 4 MW, δ ~ 0.7
- CD_4 was injected in the lower divertor at pre-programmed intervals
- Li wall conditioning (~ 100 mg) was used prior to each shot

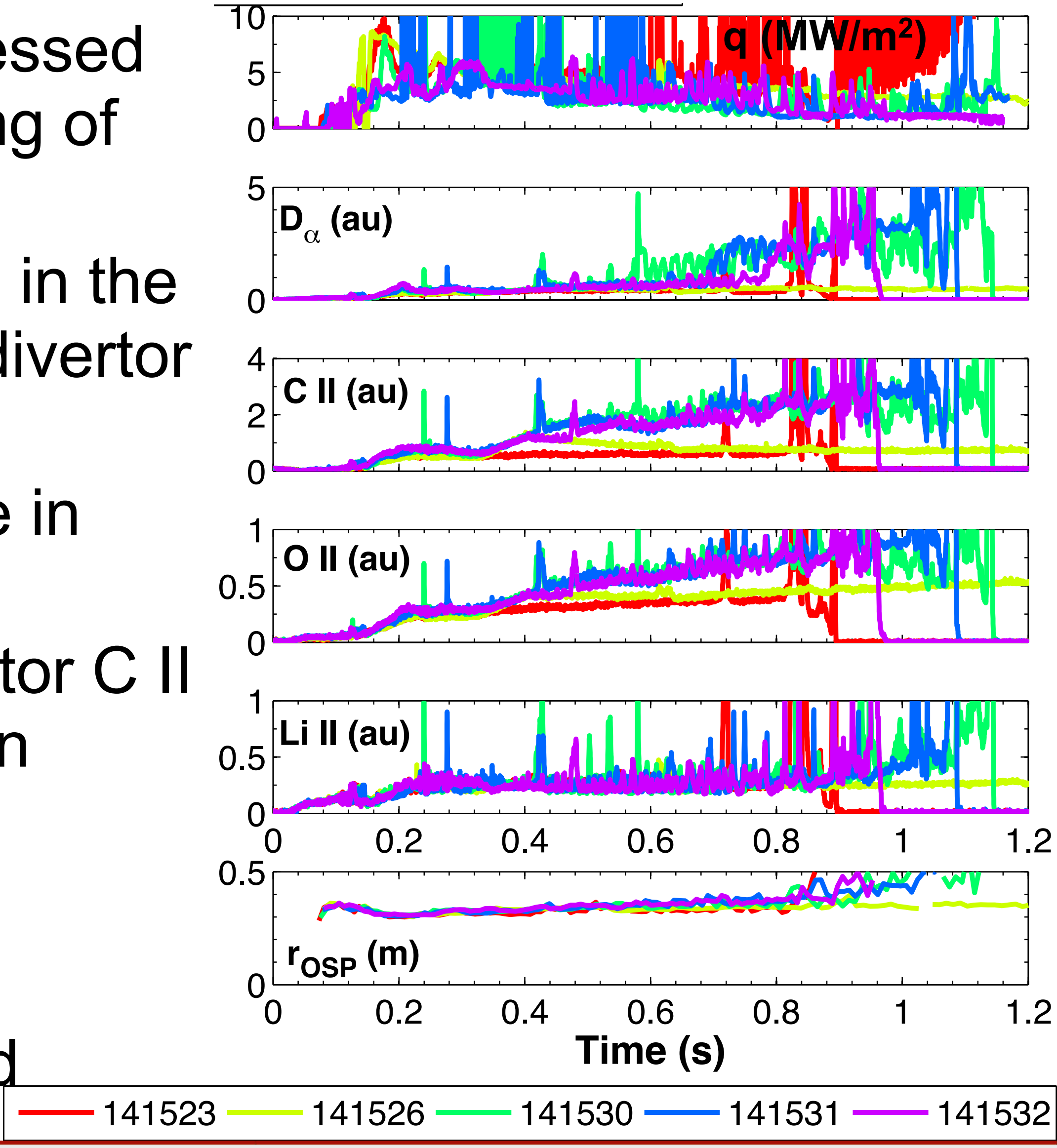


Overview of CD_4 Injection Shots

- Reference discharge without CD_4 injection (141523)
- Injection of CD_4 in the divertor leads to a faster rate of rise in core n_eL
- P_{SOL}, W_{MHD} and P_{rad} otherwise similar between shots

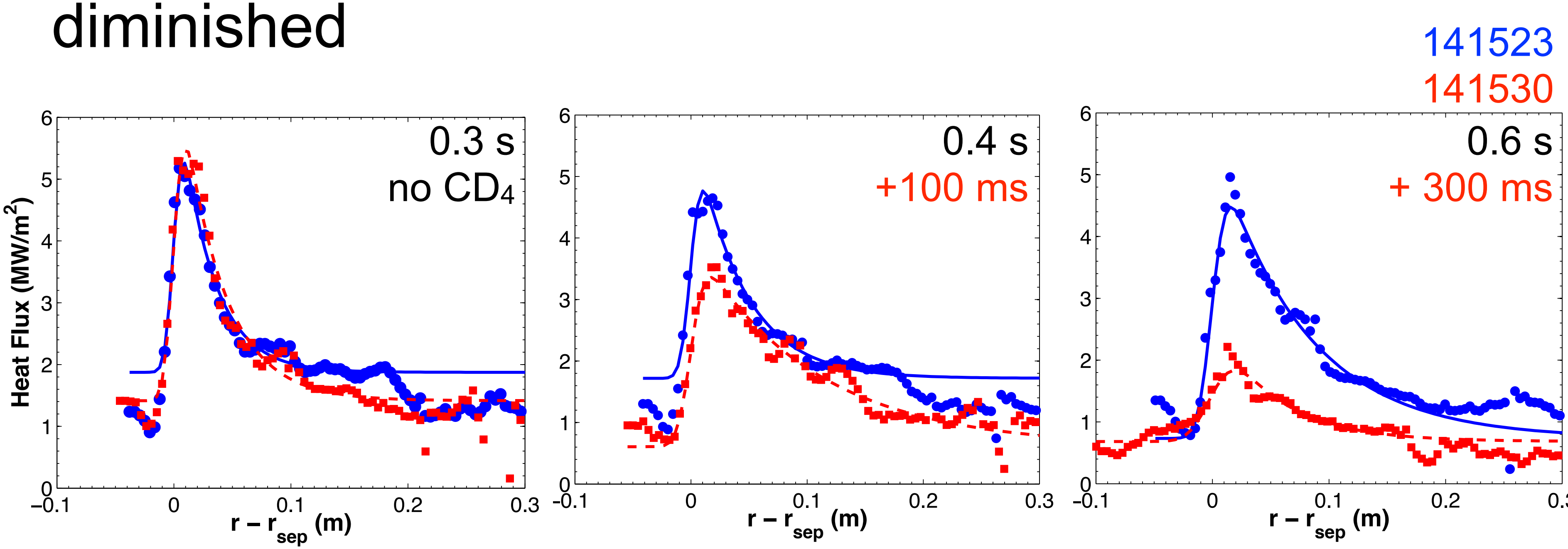


- ELMs were initially suppressed since each shot has 100 mg of pre-shot Li evaporation
- However, ELMs return late in the discharges with sufficient divertor gas injection
- No corresponding increase in inter-ELM D_α emission
- Expected increase in divertor C II emission with CD4 injection
- Increase in O II emission correlated with rise in C II emission
- Li II emission is unchanged

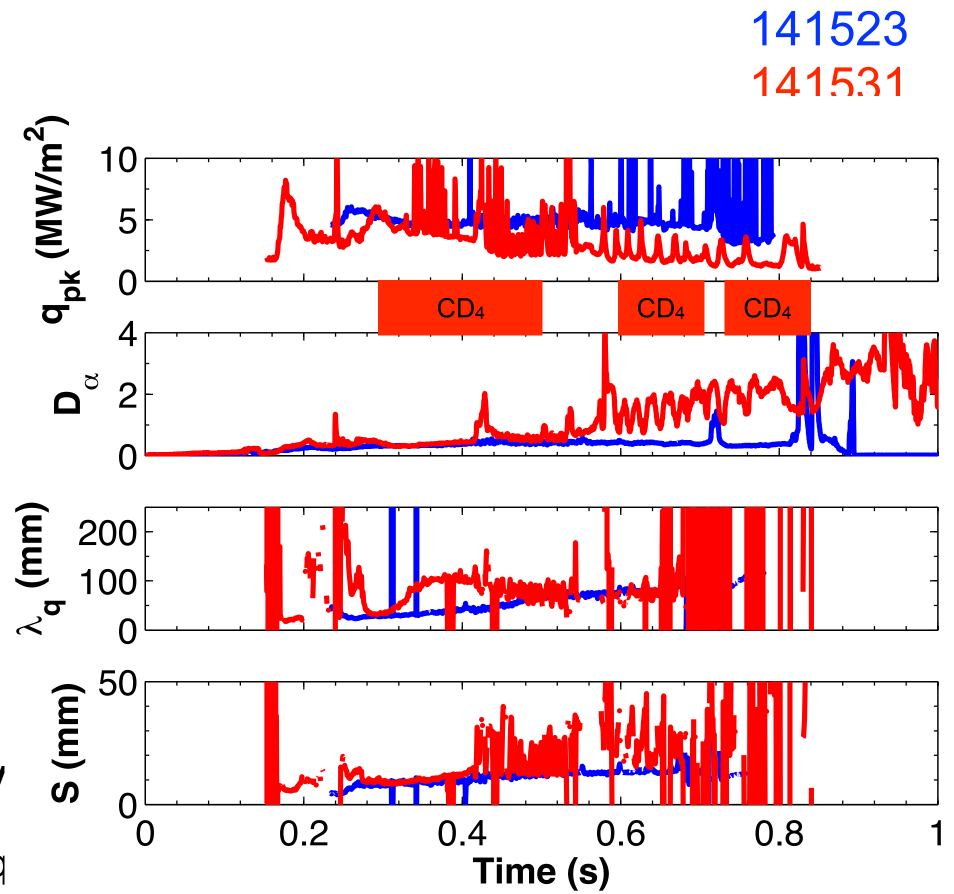


Evolution of Heat Flux profiles during CD_4 Injection

- Heat flux profiles averaged over 12 ms (20 frames
- Average peak heat flux is reduced 50% with CD4 injection
- Diffusive-Gaussian fits are problematic nearing detachment (t = 0.6 s) as the quality of the IR data is diminished



- Inter-ELM heat flux is reduced with CD4 injection
- But ELMs return due to increased density
- λ_q and S continually increase during reference discharge (141523) due to increasing core density
- λ_q is increased by a factor of 3-4 after CD_4 injection
- S doesn't appear to be affected by gas injection until ~ 100ms after λ_q
- However, analysis of λ_q and S late in the discharge is problematic due to poor quality heat flux data



Conclusions

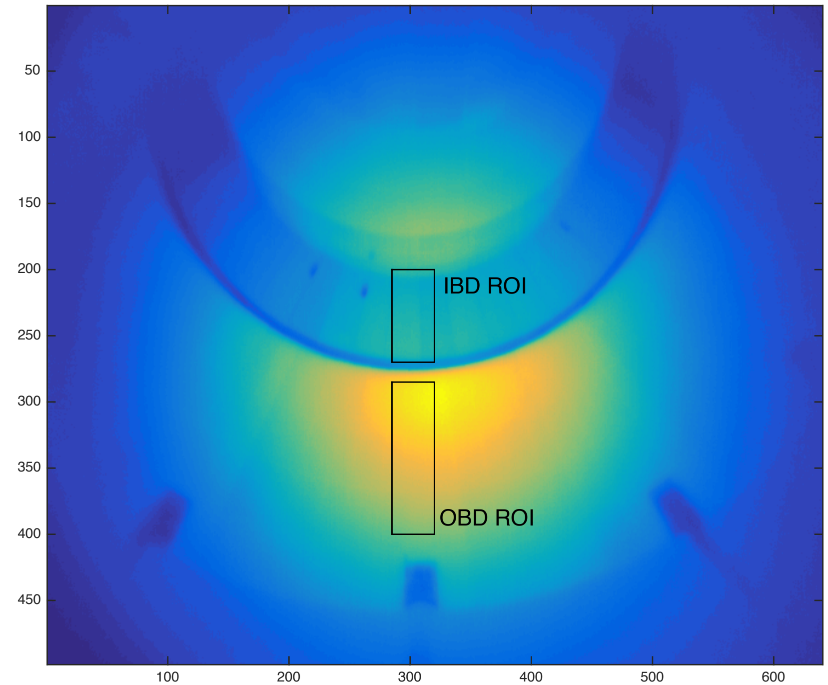
- Addition of Li evaporative coatings reduces both λ_q and S
- Reduction in λ_q is in qualitative agreement with a reduction in turbulence based on SOLT modeling
- Physics behind the reduction in S with Li is less clear
- λ_q increases x 3-4 with divertor CD_4 injection
- Behavior of S is less clear
    - Increase in S is delayed compared to increase in λ_q
    - Increase in S is observed as detachment is approached and fit quality is diminished

Upcoming NSTX-U Experiments

- SOL Thermal Transport
  - Simultaneous measurement of mid plane SOL and divertor turbulence with BES, GPI, Langmuir probes and fast cameras
- Controlled Li Introduction
  - Similar to 2008 and 2009 experiments
  - First use of dual-band IR camera during Li introduction experiment
- Reference Discharges for high-Z divertor upgrade

NSTX-U Heat Flux Diagnostics

- Lower and Upper divertor views with fast IR camera
  - Dual-band optics available for both
- Wide-angle IR camera viewing the lower divertor
  - 30 Hz
  - 640x512 pixels, single band
- Additions in FY17:
  - Calorimeters in high Z tiles
  - Additional IR cameras to cover inner strike points
  - Improved core and divertor bolometry for power balance



Wide-angle IR view of lower divertor during bake-out

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