NSTX Oak Ridge National Laboratory *Supported by* U.S. Department of Energy Office of Science

Effect of lithium wall conditioning on heat flux widths in NSTX

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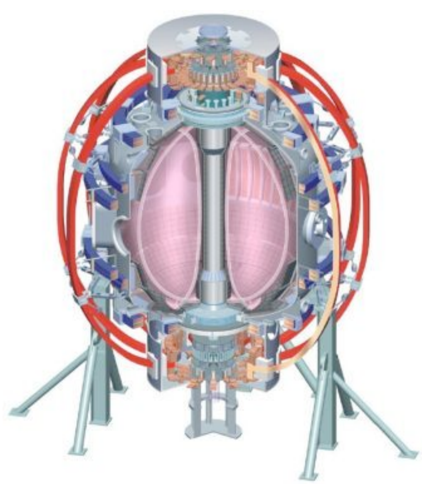

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Outline

- Introduction to NSTX
  - Motivation
  - Wall conditioning techniques
  - Definition of λ_q
- Measurements of heat flux width, λ_q with boronization
- Measurements of heat flux width, λ_q with lithium wall conditioning
- Summary and Future Work

Introduction & Motivation

- Measurements of the divertor heat flux, q and the scale length of the heat flux, λ_q are necessary for understanding thermal transport in the scrape-off layer of tokamak plasmas

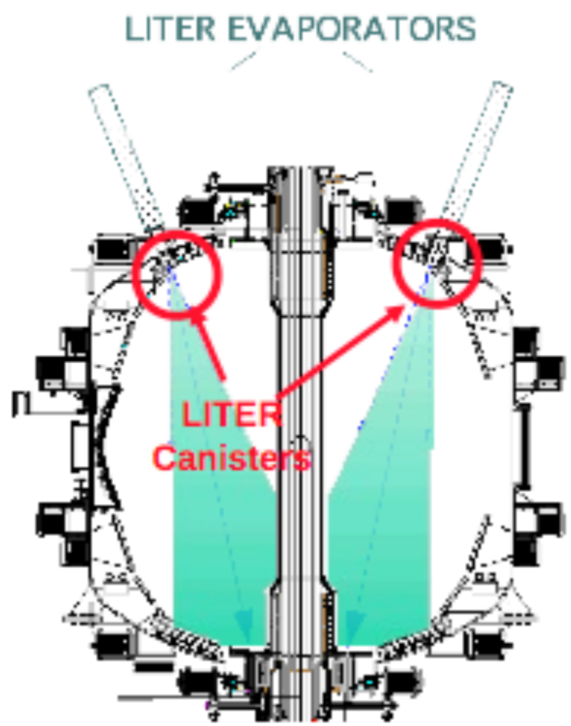
- NSTX has measured large divertor heat fluxes
  - Up to peak heat flux of 15 MW/m^2 has been measured
  - NSTX-Upgrade ($I_p \leq 2$ MA, $P_{NBI} \leq 10$ MW, $P_{RF} \leq 6$ MW, 5 sec pulse length) is planned for 2014

- NSTX has been actively exploring lithium wall conditioning techniques

- Understanding how the SOL width is altered with the addition of lithium coated PFC's

NSTX has used a variety of wall conditioning techniques

- Boronization + glow discharge cleaning used at the out set of run campaigns
  - Lithium wall conditioning used at least ½ half of the run campaigns since 2006
- Lithium wall conditioning is achieved with LiTERs
  - 2, toroidally seperated high temperature evaporators
  - Main coverage on lower, inner divertor
- In 2010:
  - No Boronization
  - No glow discharge cleaning between shots
  - Deposit between 50 – 500 mg / shot

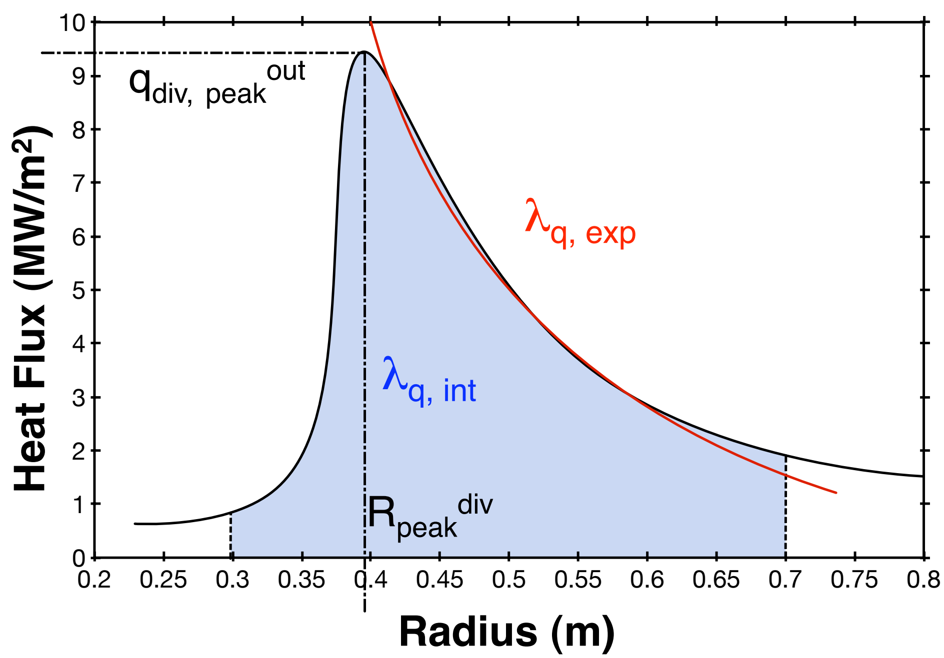


An integral heat flux width is used to determine the dependence of λ_q^{mid} on external parameters from NSTX data

- All data is time averaged over small ELMs
- IR thermography measures surface temperature of divertor tiles
- Perpendicular heat flux profile estimated from semi-infinite or finite difference models
- Define integral divertor heat flux scale length, λ_q^{div}✚

$$\lambda_q^{div} = P_{div}^{out} \Big/ \left(2\pi R_{peak}^{div} q_{div,peak}^{out}\right)$$

- λ_q^{div} related to characteristic midplane scale length through magnetic flux expansion, f_{exp}: $\lambda_q^{mid} = \lambda_q^{div} / f_{exp}$, where $f_{exp} \equiv \dfrac{R_{mid} B_\theta^{mid}}{R_{div} B_\theta^{div}}$



✚ A. Loarte, et al. JNM. **266—269** (1999) 587—592

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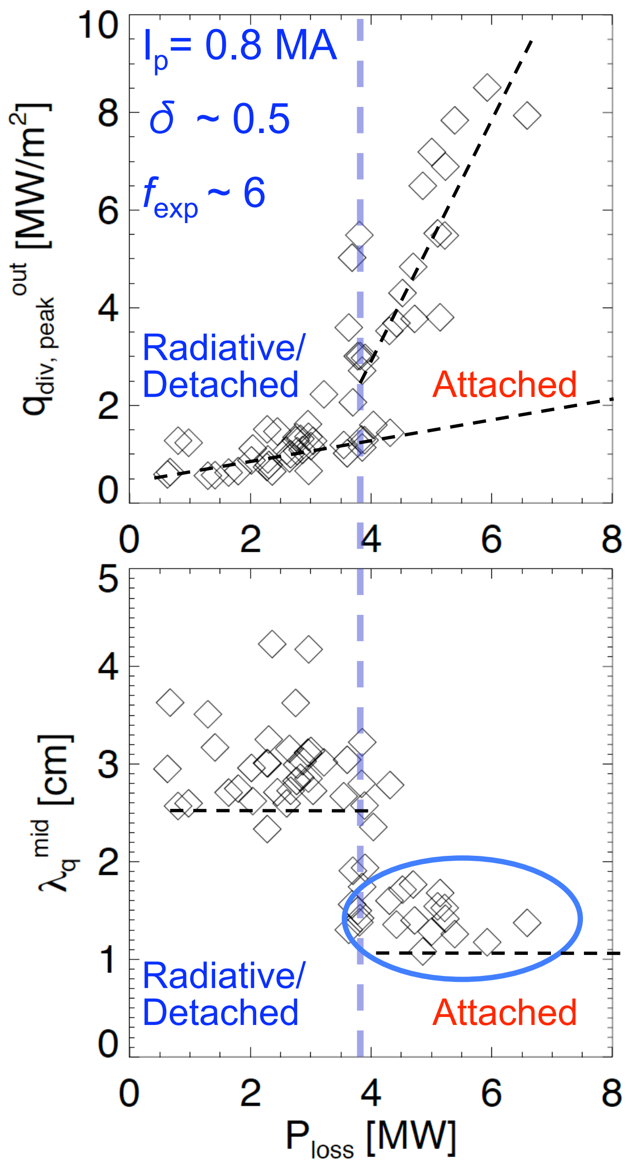
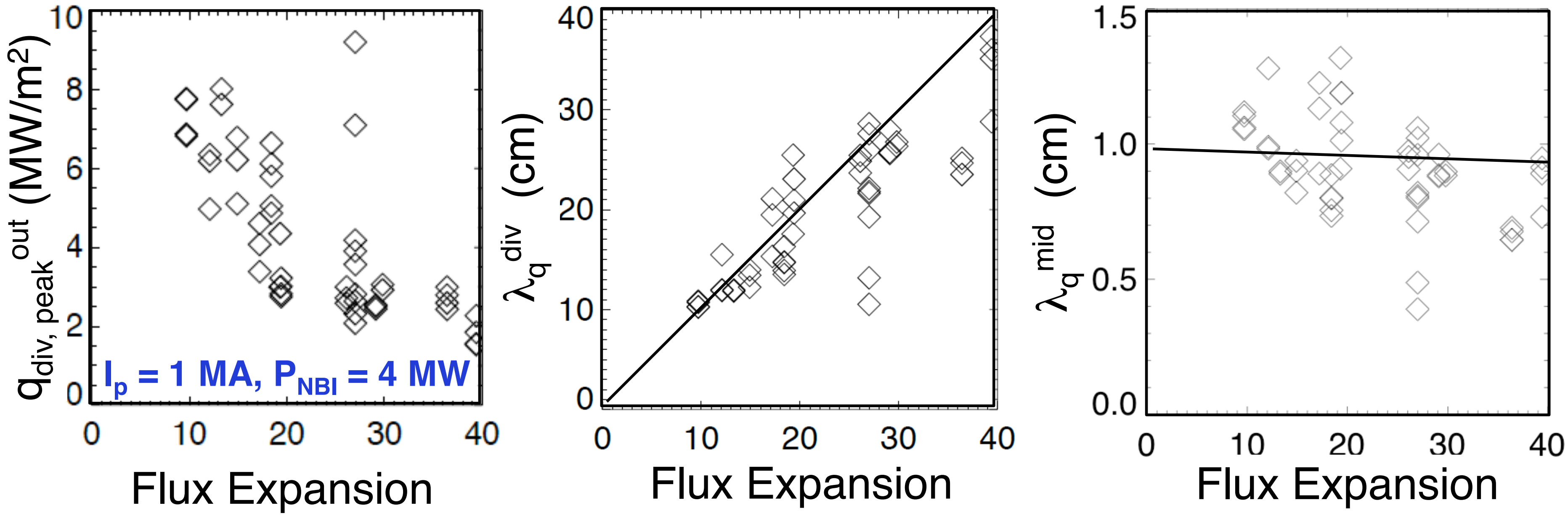
Heat flux width λ_q^{mid} relatively independent of P_{loss} in attached plasmas



- Peak divertor heat flux increases with P_{loss}
- Apparent change in slope near P_{loss} = 4 MW in these conditions
  - Divertor transitions from radiative/ detached divertor to a attached
  - Similar trend observed in previous experiments [Maingi, JNM. **363-365** (2007) 196-200]
  - Suggests the outer divertor is radiative and/or detached at low P_{loss}
- λ_q^{mid} relatively independent of P_{loss} in high heat flux regime
  - P_{loss} > 4 MW

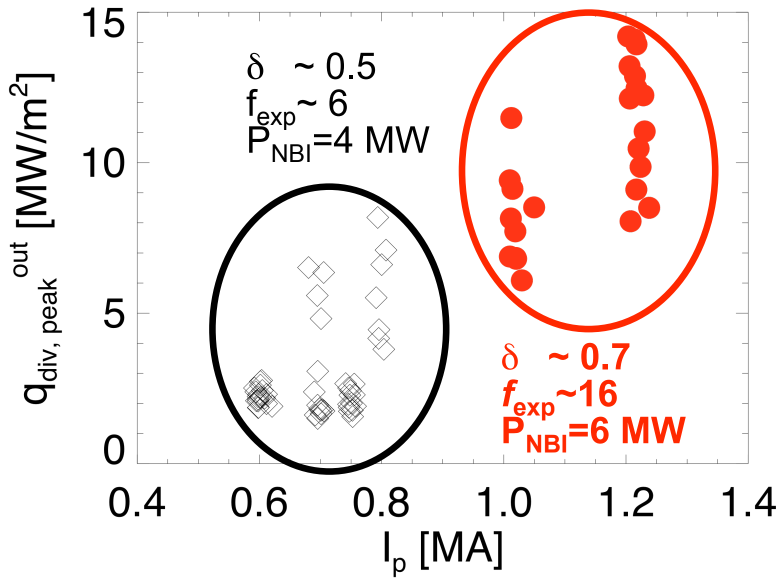
λ_q^{mid} remains relatively constant with increasing f_{exp}

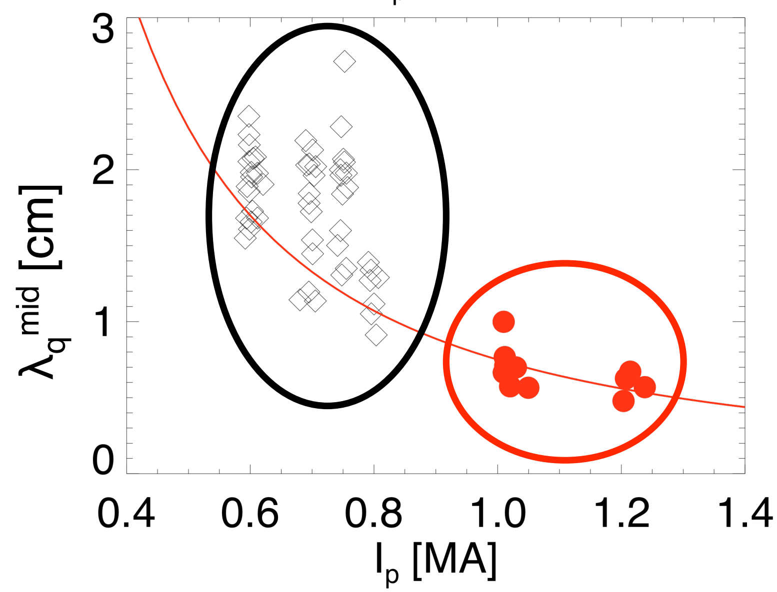


- $q_{div,peak}$ decreases as flux expansion increases
  - Indicates that magnetic flux expansion is a viable candidate to mitigate divertor heat flux
- λ_q^{div} broadens with flux expansion
  - Effectively increasing the plasma wetted area of the divertor
- λ_q^{mid} stays relatively constant during the scan
  - Decreases by 20% over a factor 4—5 scan of f_{exp}
  - Demonstrates that magnetic mapping removes dependency on f_{exp}

λ_q^{mid} contracts with increasing I_p in boronized discharges

- Combined data from dedicated I_p scans in low δ and high δ discharges
  - Upward scatter in data caused by varying fueling rates
  - Different P_{NBI}, but no P_{loss} dependence in high heat flux regime
  - Magnetic mapping of λ_q^{div} to the midplane takes into account varying f_{exp} and δ
- λ_q^{mid} found to scale ~ $I_p^{-1.6}$
  - Using lower 20 % of the data set for a conservative estimate
  - This suggests that for NSTX-U (I_p = 2 MA) λ_q^{mid} = 3 ± 0.5 mm





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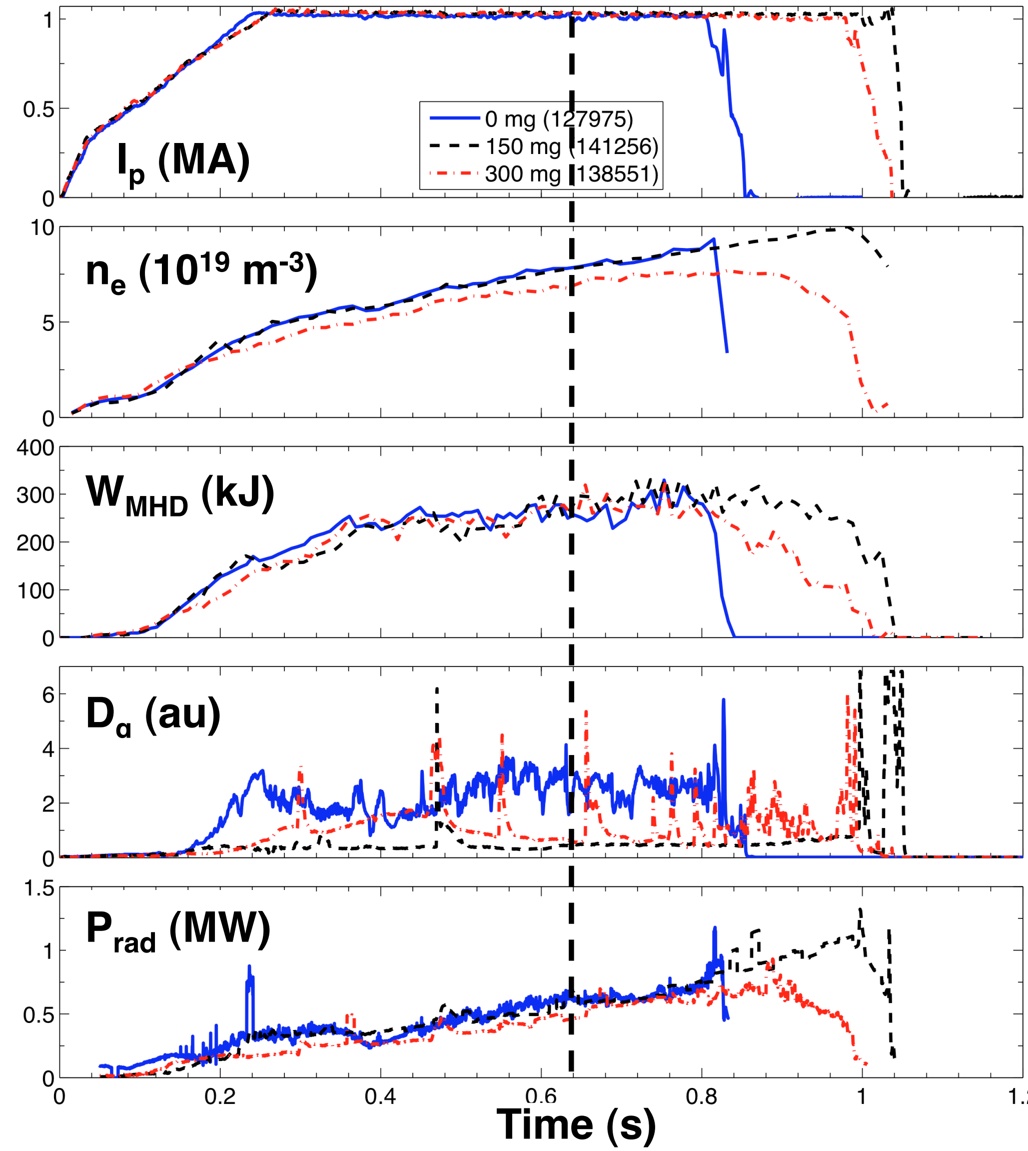
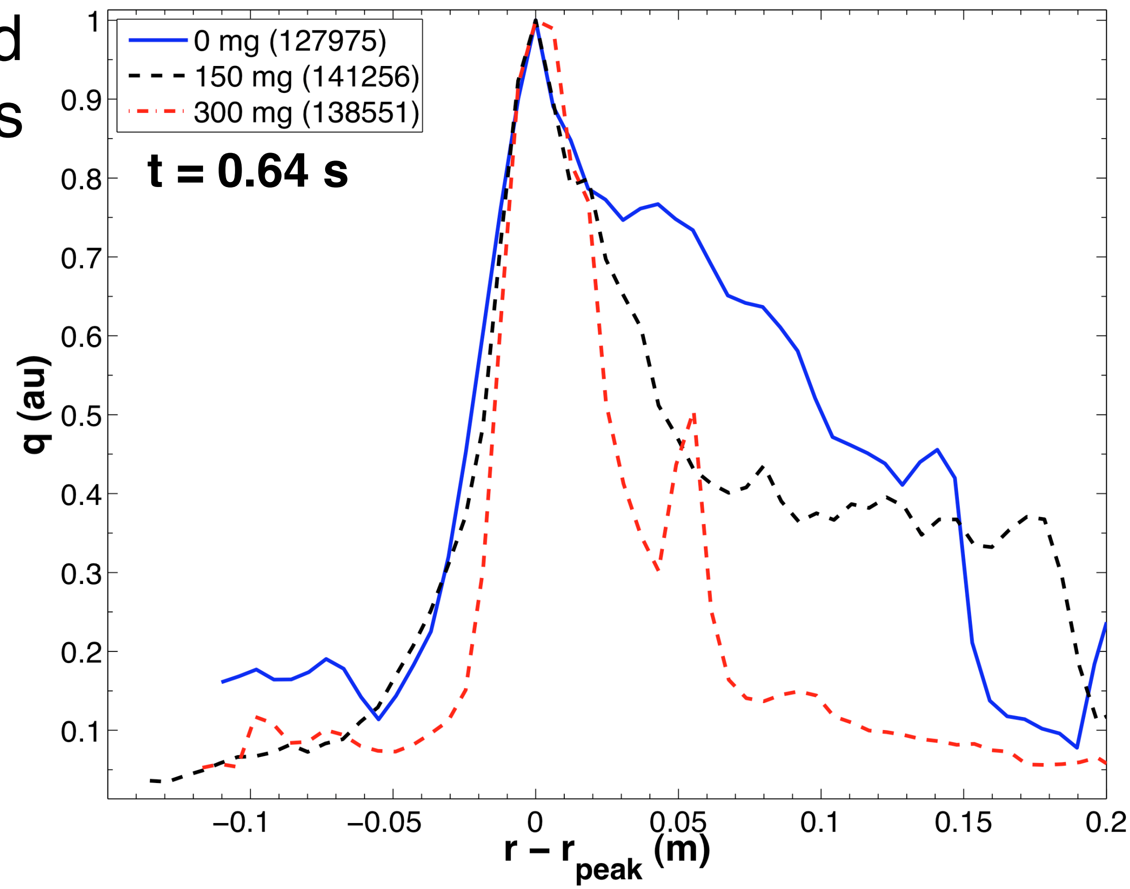
Discharges with varying amounts of lithium show similar characteristics

- Similar line averaged densities
  - Slightly lower in the 300 mg discharge
- Equivalent stored energy at lower P_{NBI}
  - P_{NBI} = 6 MW for 0 mg
  - P_{NBI} = 4 MW for 150 and 300 mg discharges
  - Increase in τ_e for lithiated discharges
- Reduction in Divertor D_α with lithium
- Near elimination of ELMs leads to impurity accumulation in the core plasma
  - P_{rad} increases as a result



Divertor λ_q contracts with increasing lithium deposition

- Type V ELMs eliminated from lithiated discharges
  - Some sporadic type I ELMs are still present
  - Responsible for some of the contraction in IR profiles



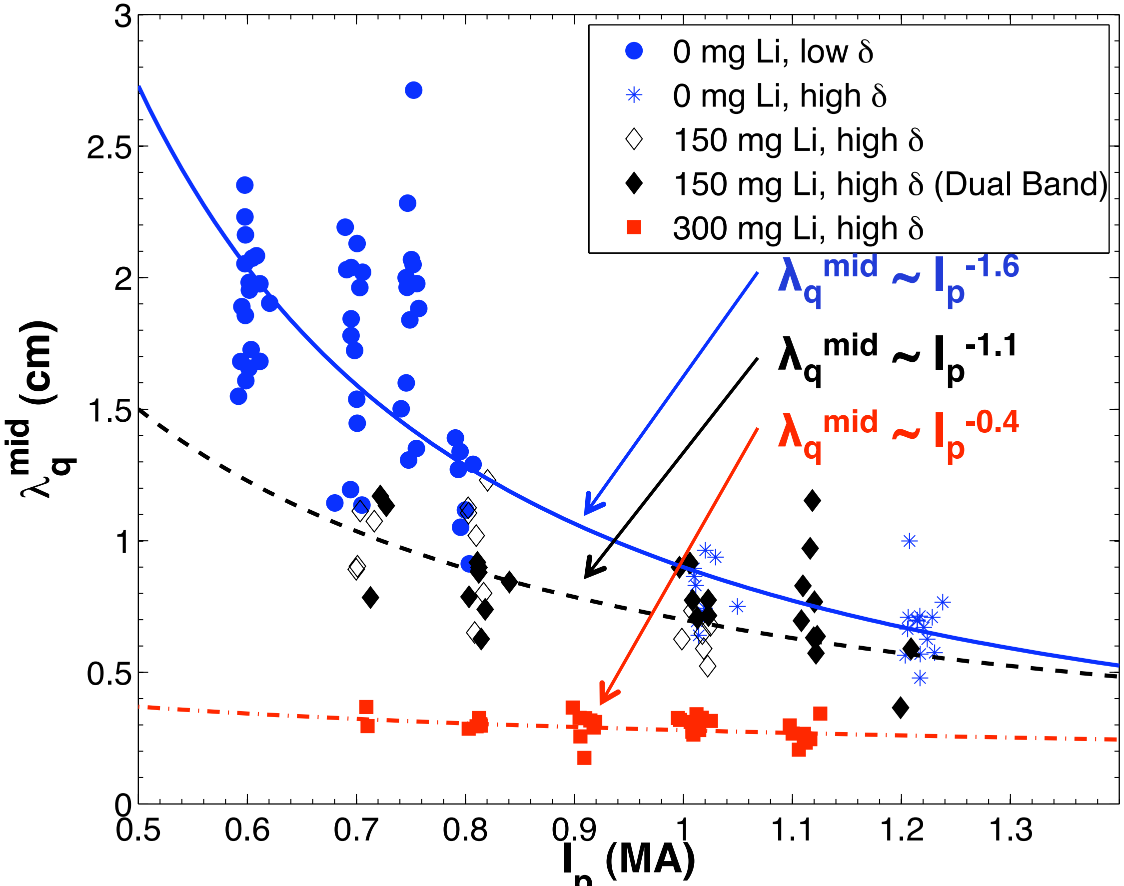
- λ_q^{div} contracts further with increasing lithium deposition

- This effect is confirmed by dual band IR measurements

	0 mg	150 mg	300 mg
λ_q^{div} (cm)	14.1	13	7
λ_q^{mid} (cm)	0.98	0.74	0.37

Scaling of λ_q^{mid} with I_p Relaxes with Increased Lithium Deposition

- With out lithium, λ_q^{mid} has shown a strong contraction with I_p
- As increasing amounts of lithium are deposited, this trend relaxes
  - $\lambda_q^{mid} \sim I_p^{-0.4}$ at 300 mg
- Suggests reduced perpendicular transport in the SOL
  - Modeling with XGC0 suggests $\lambda_q^{mid} \sim I_p^{-1}$ with neoclassical transport [JRM 2010 Final Report]



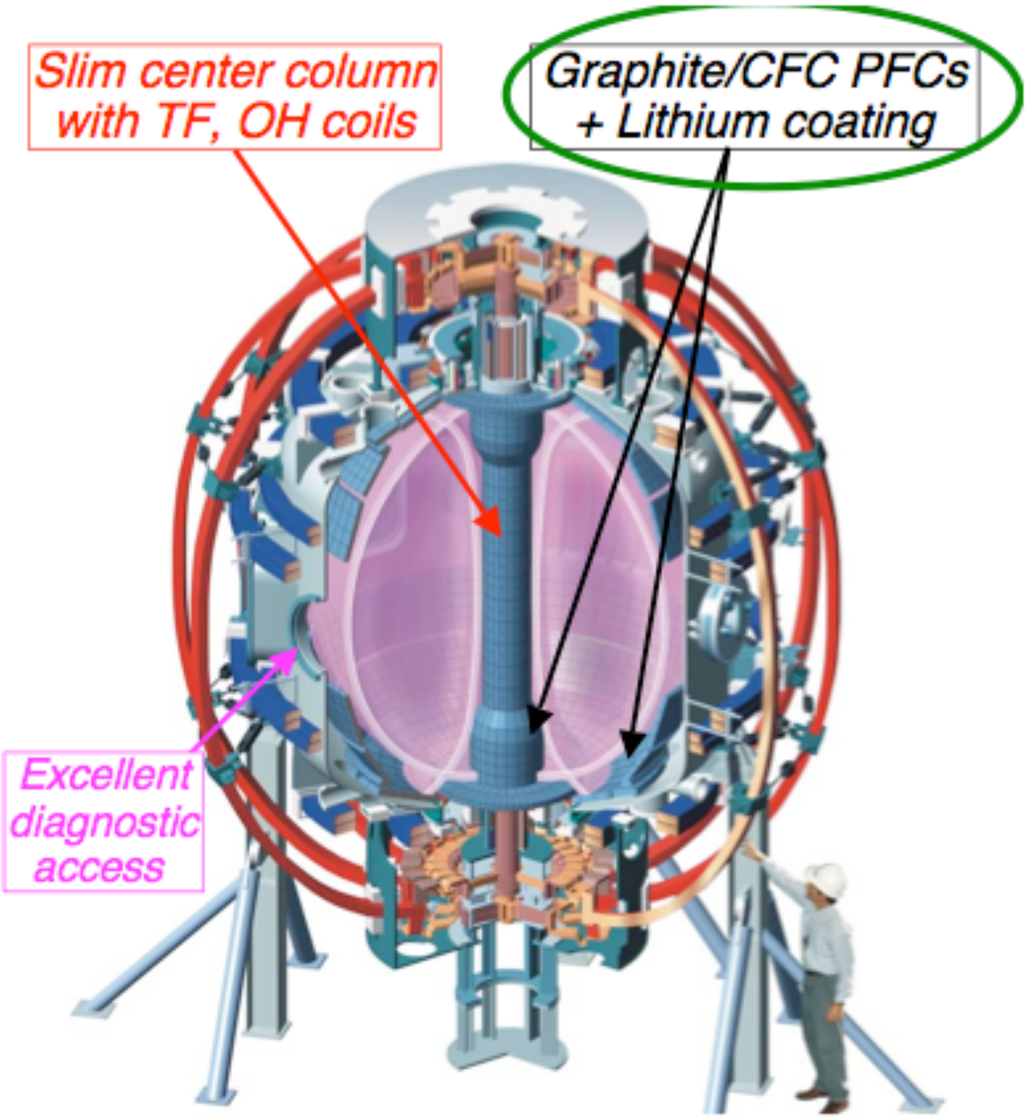
- LSN Discharges, during I_p and W_{MHD} flattops
- P_{NBI} = 4 MW (some 6 MW data in 0 mg discharges)
- $4 < n_e^{LD} < 7(10)^{19}\ m^{-3}$

Summary and Discussion

- When boronization is used, $\lambda_q^{mid} \sim I_p^{-1.6}$
  - This is a stronger dependence than seen on traditional aspect ratio tokamaks
    - DIII-D: $\lambda_q^{mid} \sim I_p^{-1.2}$ [C. Lasnier, JNM 2011]
    - C-MOD (near sep.): $\lambda_q^{mid} \sim I_p^{-1}$ [B. Labombard, JNM 2011]
    - JET: $\lambda_q^{mid} \sim I_p^{-1}$ [G. Kirnev, PPCF **49** (2007) 698]
- The addition of evaporative lithium coatings correlates with a contraction of λ_q^{mid}
  - Partially due to the elimination of Type V ELMs
  - λ_q appears broader due to time averaging
- However, λ_q continues to contract after the elimination of type V ELMs
  - Resulting in $\lambda_q^{mid} \sim I_p^{-0.4}$
- More transport analysis is required to fully understand the contraction of λ_q^{mid}

Back-up Slides

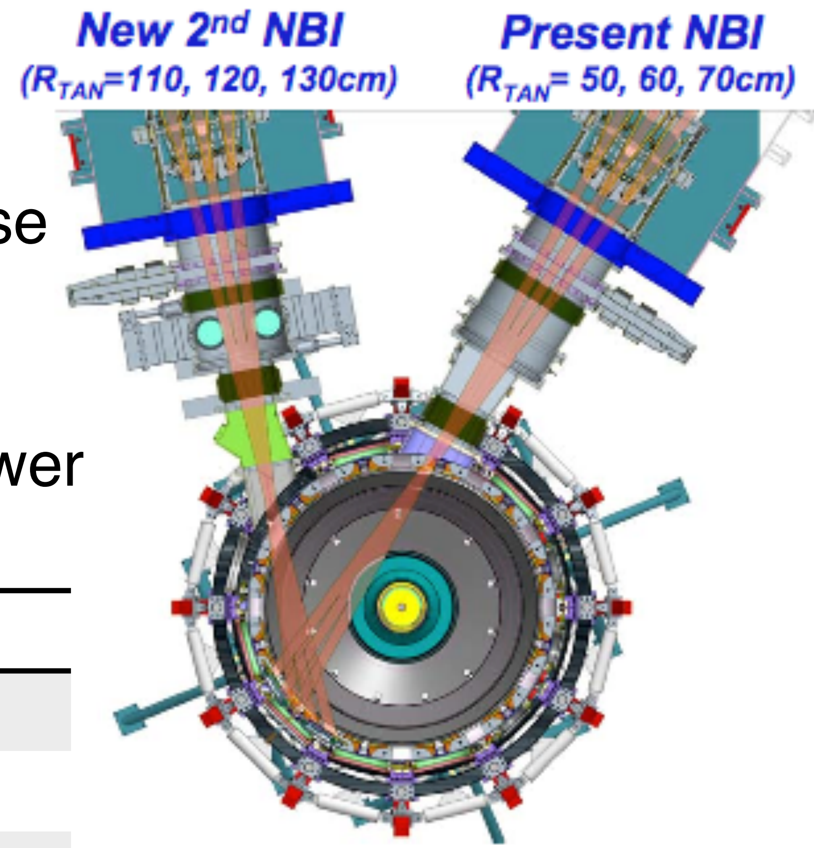
Overview of the National Spherical Torus eXperiment



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	$\leq 1.2(10)^{20}$ m^{-3}

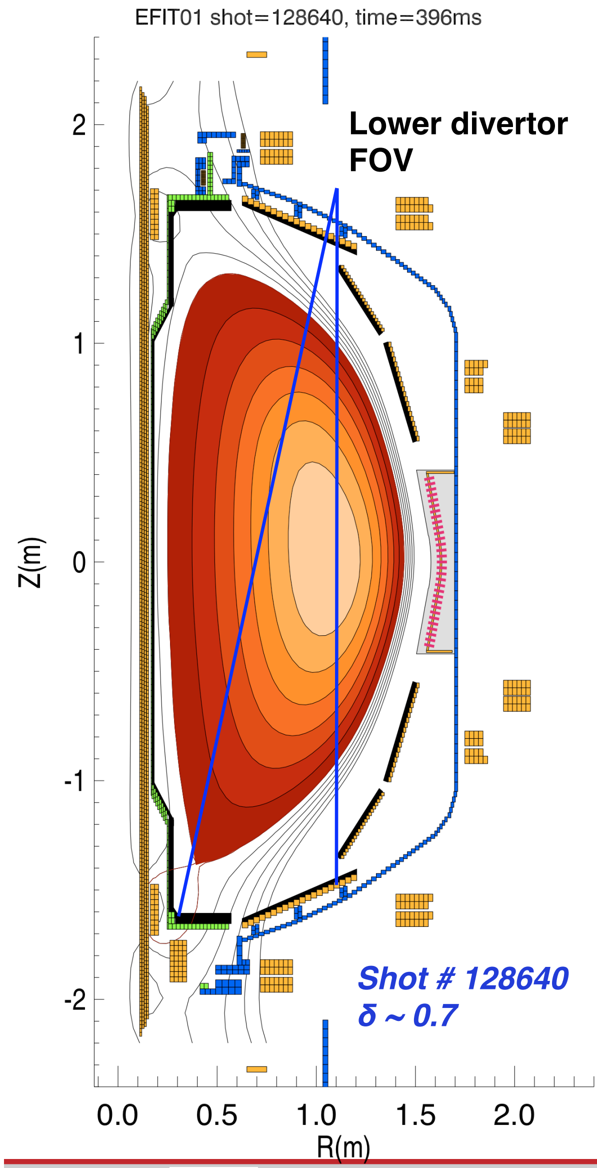
Upgraded NSTX expected to be online in FY2014

- Doubling of neutral beam heating power to 15 MW
- Increase in pulse length to 5 sec
- Will represent a significant increase in expected power deposited onto the divertor
- Techniques to handle the high power densities in NSTX-U are required

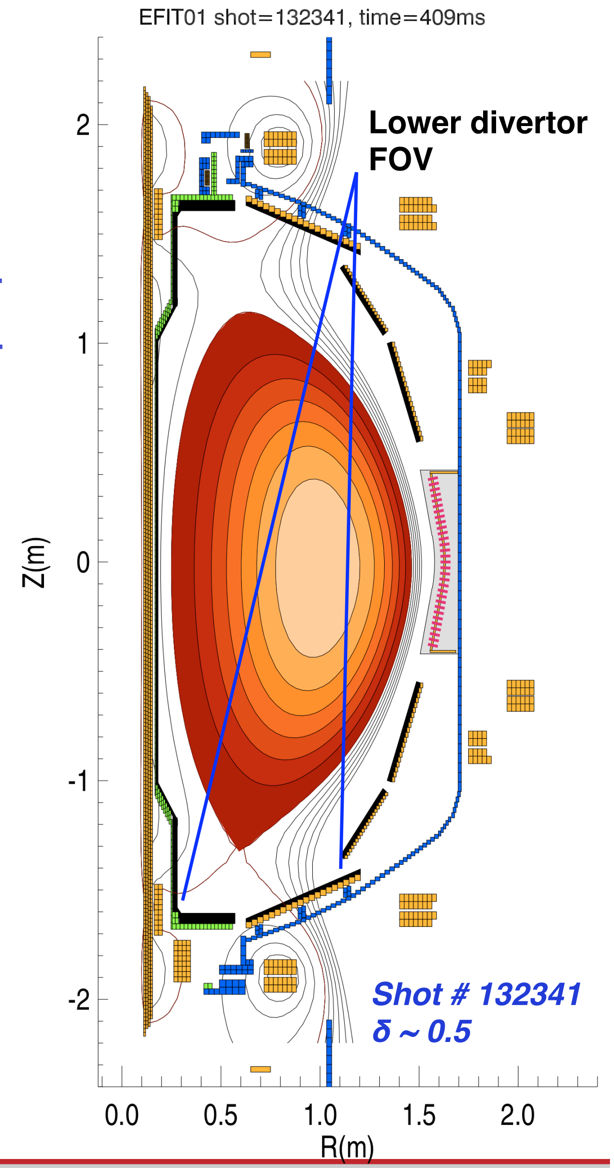


NSTX-U Operating Parameters	
Plasma Current, I_p	≤ 2 MA
Toroidal Field, B_t	≤ 1 T
Heating Power, P_{heat}	15 MW (NBI) 5 MW (RF)
Pulse Length	≤ 5 s
P/R, R/A	20 MW/m, 0.4 MW/m^2

ORNL IR system currently on NSTX

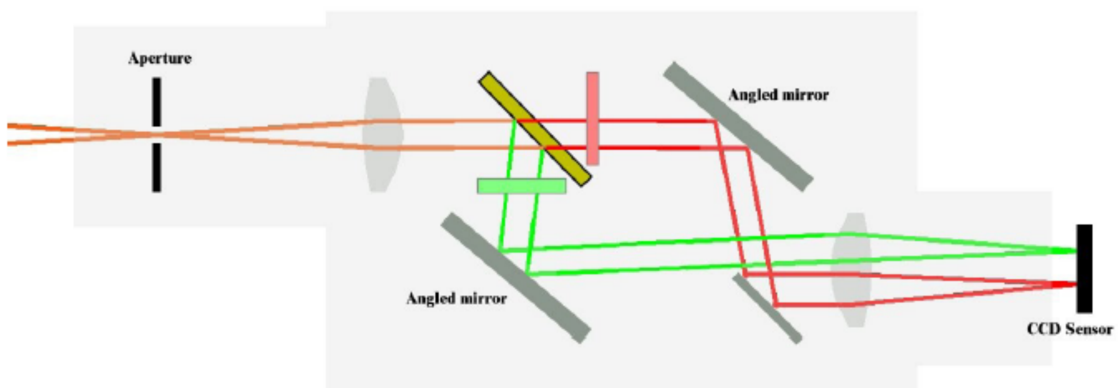


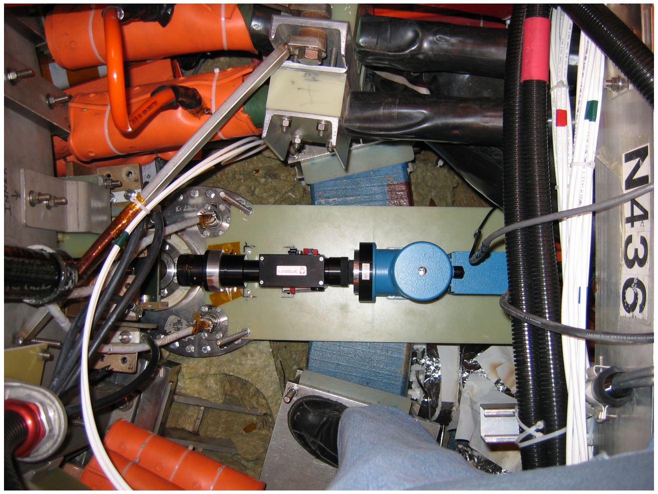
- Two slow (30 Hz) IR cameras
  - Indigo Omega, 160x128 pixel
  - uncooled microbolometer
  - 15° FOV of lower divertor
  - 7-13 µm, 12-bit, 0-700°C range, ZnSe window
- One fast (1.6-7.0 kHz) IR camera
  - Santa Barbara Focal Plane, 128x128 pixel
  - LN_2-cooled
  - 15.5° FOV of lower divertor (Bay H)
  - 8-12 µm, 14-bit , ZnSe window



A two-color infrared imaging adaptor for the fast IR camera on NSTX [6]

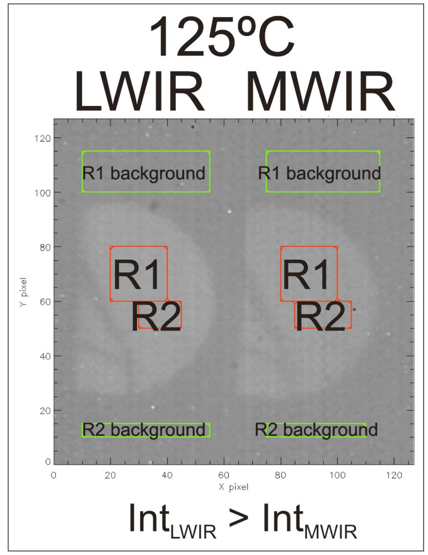
- Use of the LLD in NSTX will make assumptions of high surface emissivity (applicable to graphite) inaccurate
  - Complications include: Surface coating changes in real time during plasma shots, emissivity changes due to H-absorption in Li, reflections from Li surface, deposition of Li on C surfaces, erosion/transport of Li and C
- Two-color camera measures temperature based on the ratio of integrated IR emission in two IR bands, not single band intensity
- Image split into medium wavelength IR (4-6 µm) and long-wavelength IR (7-10 µm) using a dichroic beamsplitter, filtered with bandpass filters, projected side-by-side into the NSTX fast IR camera (1.6 kHz full frame)

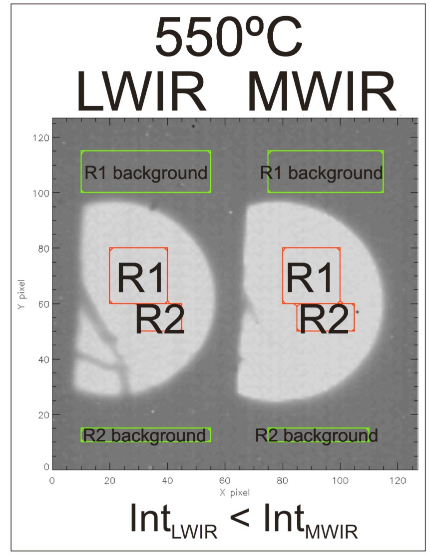




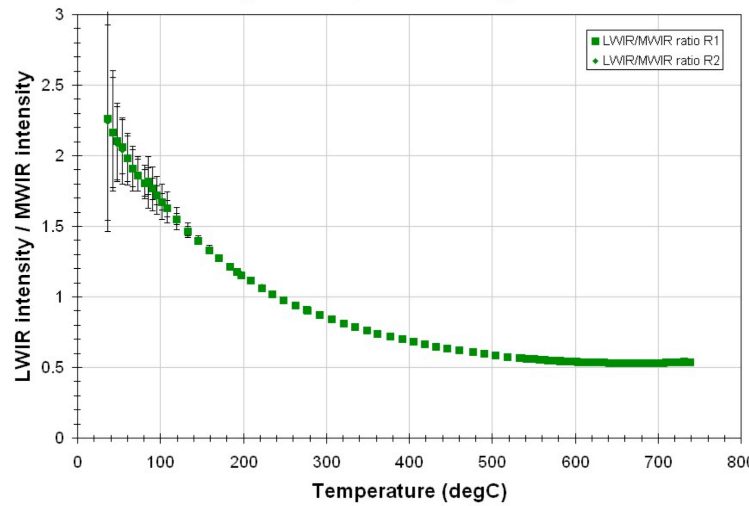
Calibration and physics application of two-color IR

- Calibration accomplished *ex-situ* using a 0-750˚C blackbody source
  - Useful, low error LWIR/MWIR ratio from ~100-600˚C
- Additional i*n-situ* calibration during heating of LLD plates from 0-320˚C
  - Shows extended useful range due to losses in MWIR channel
- True radial view of NSTX lower floor
  - View of inner divertor (graphite), CHI gap, and LLD plates



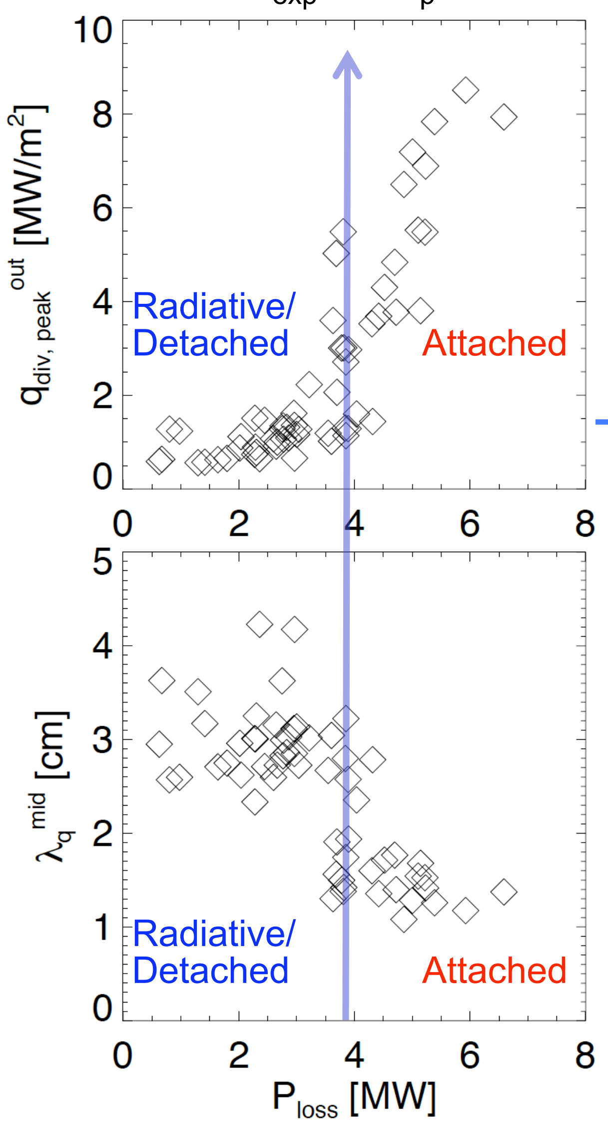


SBFP 2-color intensity ratio calibration, blackbody source, 22 us integration time



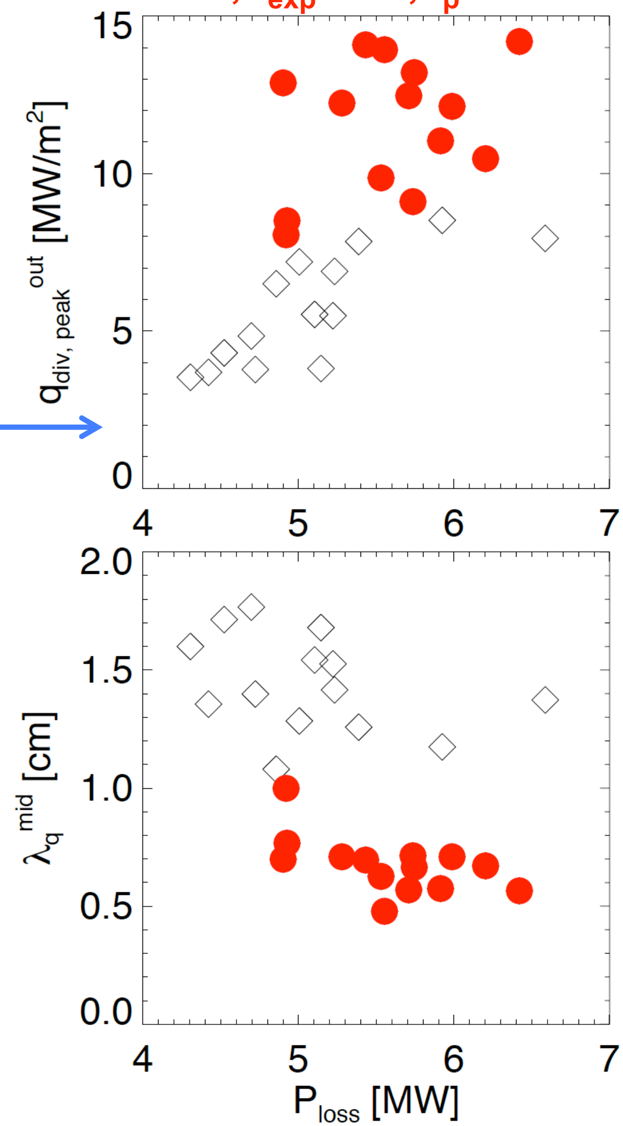
Heat flux width λ_q^{mid} largely independent of P_{loss} in attached plasmas

$\delta \sim 0.5$, $f_{exp} \sim 6$, $I_p = 0.8$ MA



- Add in high δ data
- Narrow P_{loss} plot range
- Apparent I_p or q_{95} effect at higher triangularity
- λ_q^{mid} is reduced for higher δ, higher I_p discharges

+ $\delta \sim 0.7$, $f_{exp} \sim 16$, $I_p = 1.2$ MA



Elimination of small, Type V ELMs is responsible for part of the contraction in SOL width

- λ_q^{div} is related to the upstream electron temperature scale length, λ_{Te}^{mid}
- In boronized discharges, $\lambda_{Te,\ ELMs} > \lambda_{Te,\ no\ ELMs}$ measured with midplane reciprocated probe
  - Probe plunge acts to average over all ELMs and blobs
  - Whereas λ_{Te} measured by Thomson scattering is instantaneous (misses ELMs)
- Therefore, SOL width can appear broader when averaging over ELMs