NSTX Oak Ridge National Laboratory *Supported by* U.S. DEPARTMENT OF ENERGY Office of Science

Dependences of the divertor and midplane heat flux widths in NSTX

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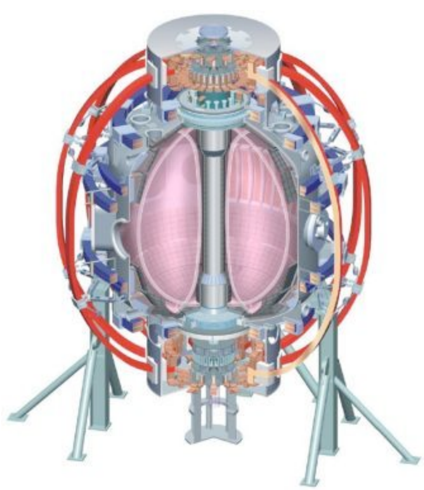

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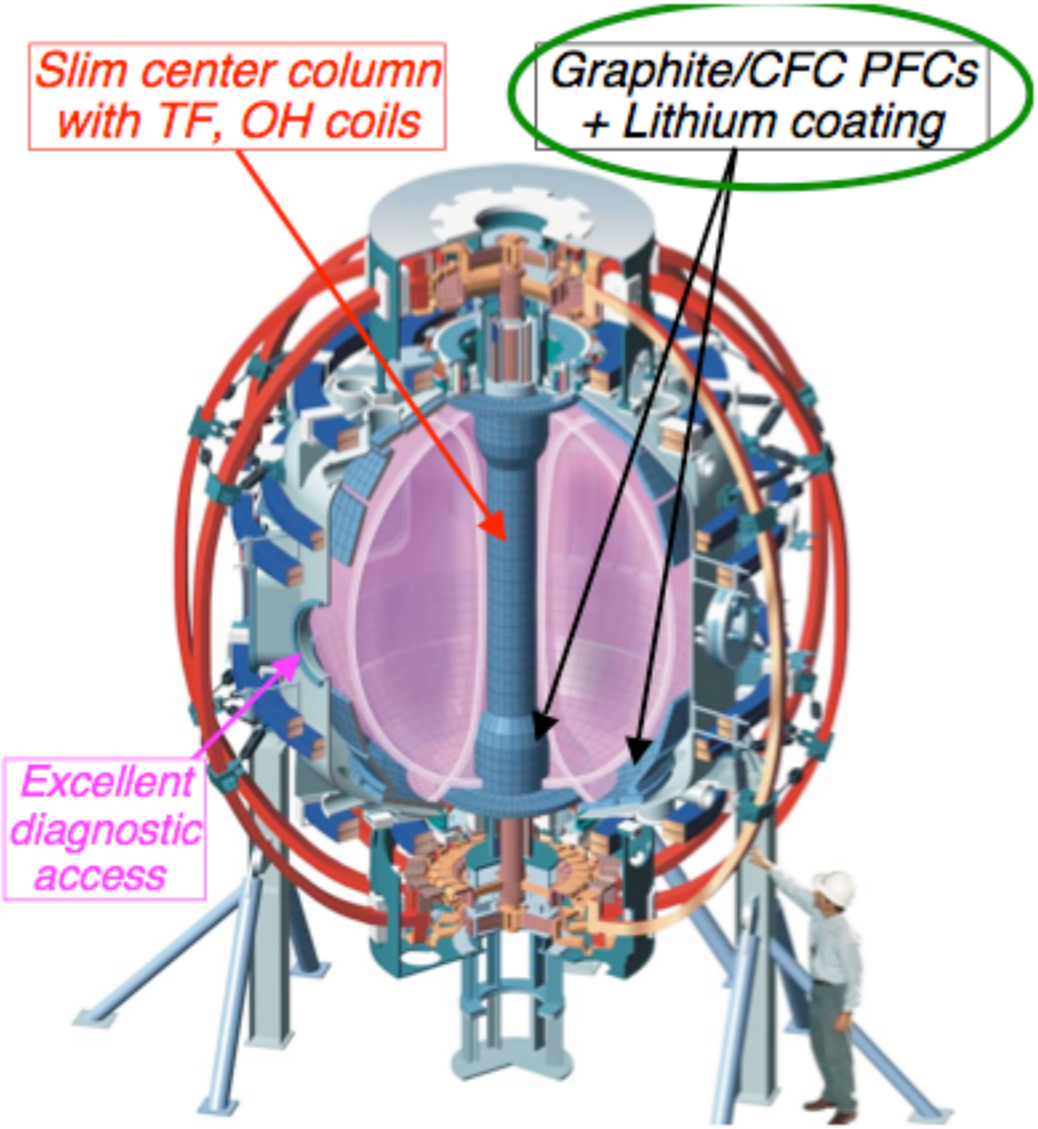
Introduction & Motivation

- Measurements of the divertor heat flux, q and the heat flux profile, λ_q are necessary for understanding thermal transport in the scrape-off layer of tokamak plasmas
- Heat loading on the divertor and plasma facing components (PFC) is also an engineering limit on the fusion reactor
  - High heat flux can also lead to PFC cracking, fatigue and subsequent impurity generation
  - Heat flux therefore limits PFC lifetime, and therefore reactor operational time between PFC replacement
- Spherical Tori (STs) are prone to large heat fluxes due to their compact design
- Part of the 2010 Joint Research Milestone (JRM) – Understanding thermal transport in tokamak scrape-off layer plasmas

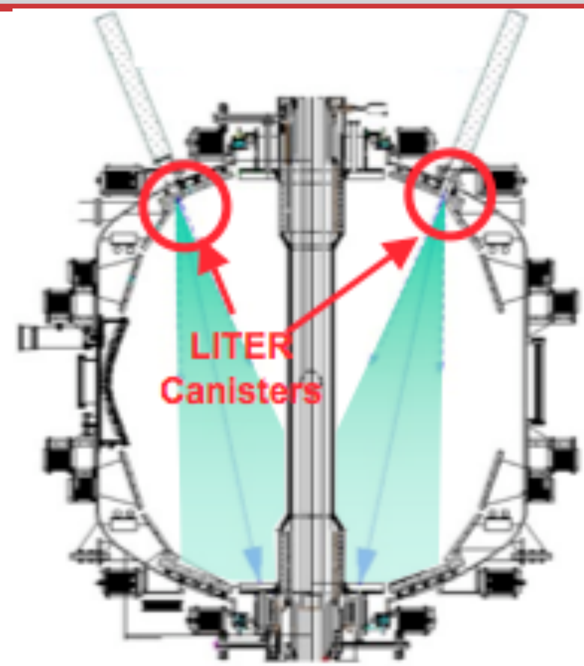
Overview of the National Spherical Torus eXperiment



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
Torodial 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}

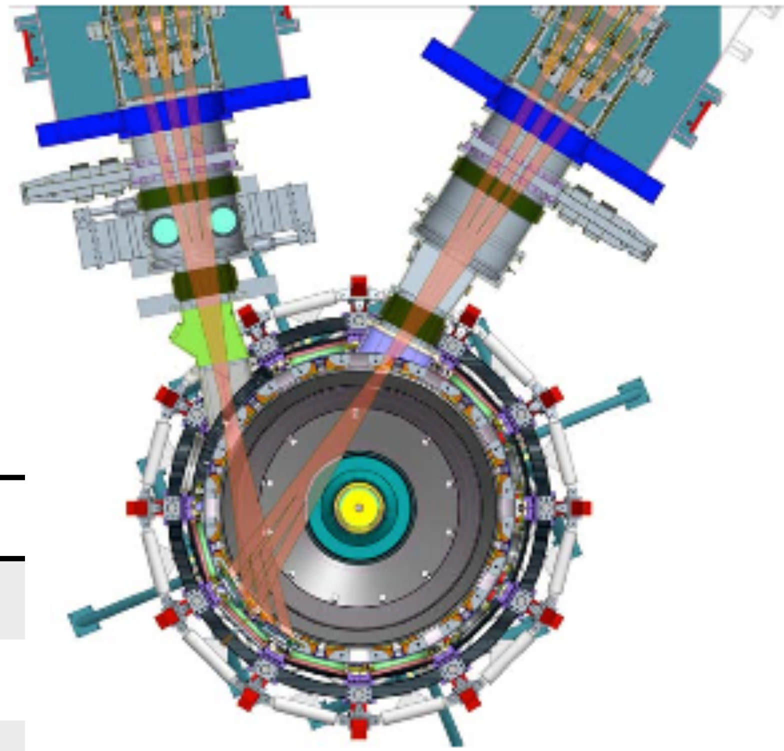
NSTX utilizes evaporative lithium position on Graphite tiles as the primary plasma facing surface

- NSTX began the FY10 run campaign April 1st, 2010
- Lithium is applied between shots via high temperature lithium evaporators (LiTERs) onto graphite PFCs
  - No Boronization (starting with the FY10 run campaign)
  - No glow discharge cleaning (GDC) between shots
  - Deposit between 200 – 800 mg / shot
    - 200 mg is typical
- Addition of a toroidal, liquid lithium divertor (LLD) in FY10 } →



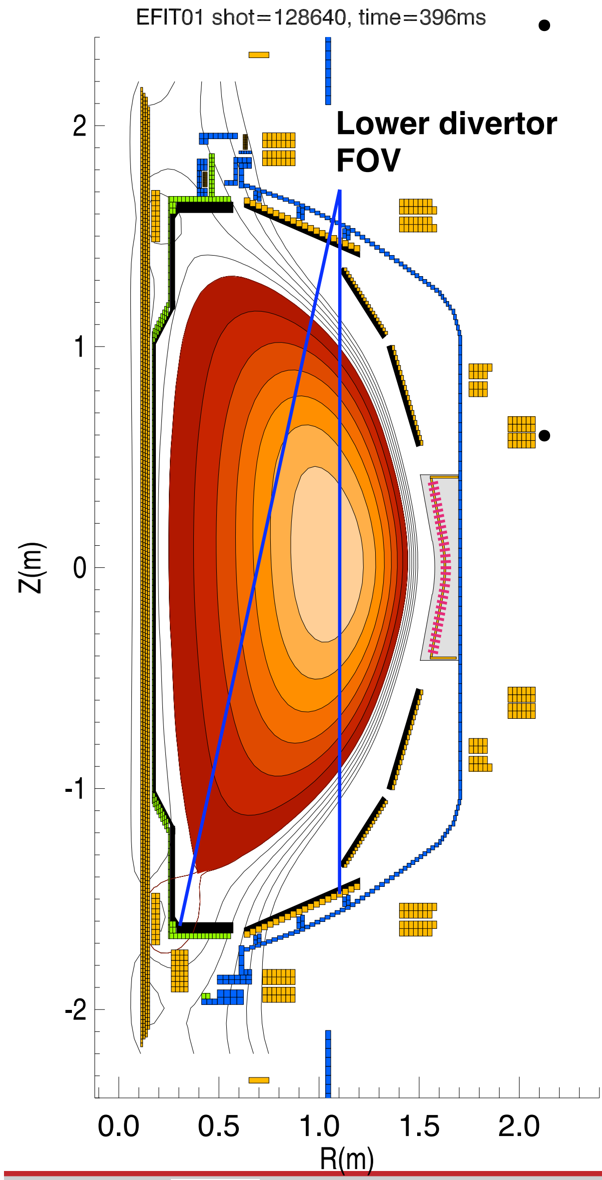
Upgraded NSTX is expected to be online in FY2014

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

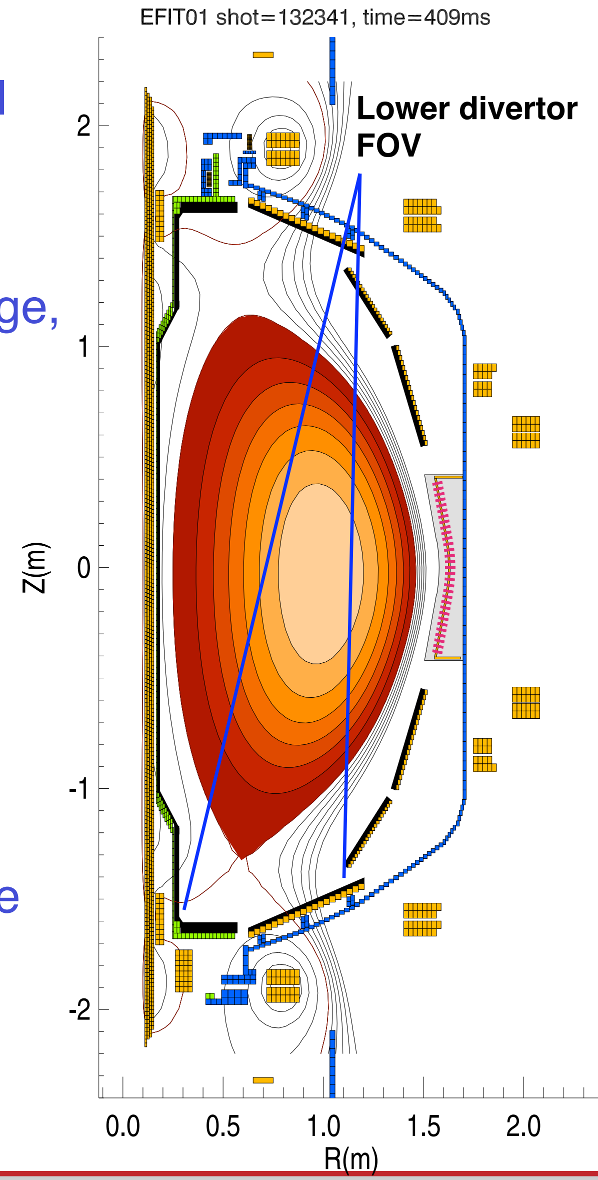


NSTX-U Operating Parameters	
Plasma Current, I_p	≤ 2 MA
Toroidal Field, B_t	≤ 1 T
Heating Power, P_{heat}	15 MW (NBI) 5 MW (RF)
Pulse Length	≤ 5 s
P/R, R/A	20 MW/m, 0.4 MW/m^2

ORNL IR Cameras currently installed 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)
  - 2 color system designed to be less sensitive to emissivity changes
    - MWIR: 4—6 µm and
    - LWIR: 7 – 10 µm



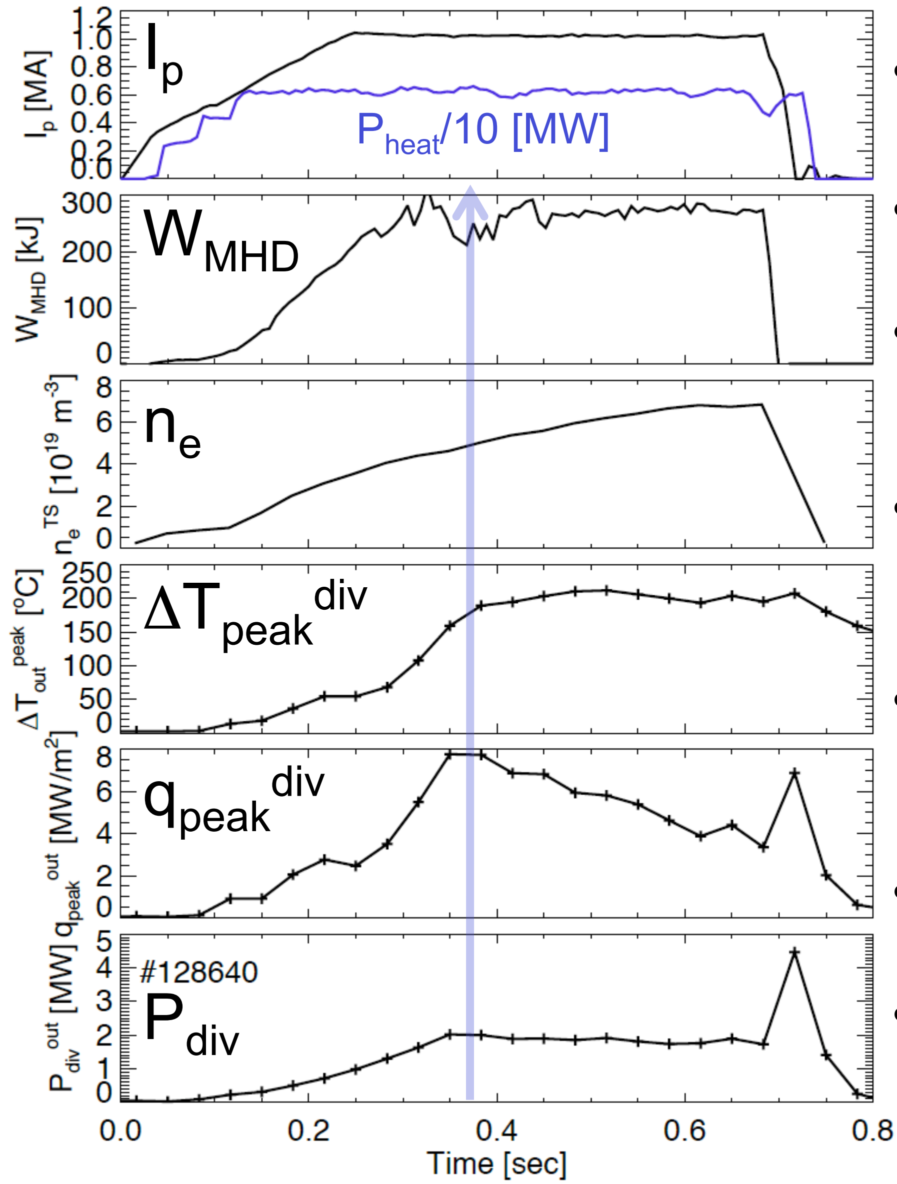
Determine dependence of λ_q^{mid} on external parameters from NSTX data

- All data is time averaged over ELMs and before lithium coatings were applied
- IR thermography measures surface temperature, which is used to estimate heat flux profile $q_{div}^{out}(r,t)$ and calculate divertor power loading: $P_{div}^{out} = \int_{R_{\min}}^{R_{\max}} 2\pi R_{div}^{out} q_{div}^{out} dr$
- Define characteristic divertor heat flux scale length, $\lambda^{out}_{q,div}$ [Loarte 1999]: $\lambda_{q,div}^{out} = P_{div}^{out} \Big/ \left(2\pi R_{div,peak}^{out} q_{div,peak}^{out}\right)$
- Assume $\lambda^{out}_{q,div}$ related to characteristic midplane scale length through flux expansion, f_{exp} such that:

$$\lambda_q^{mid} = \lambda_{q,div}^{out} / f_{\exp}, \text{ where } f_{\exp} \equiv \frac{R_{mid} B_\theta^{mid}}{R_{div} B_\theta^{div}}$$

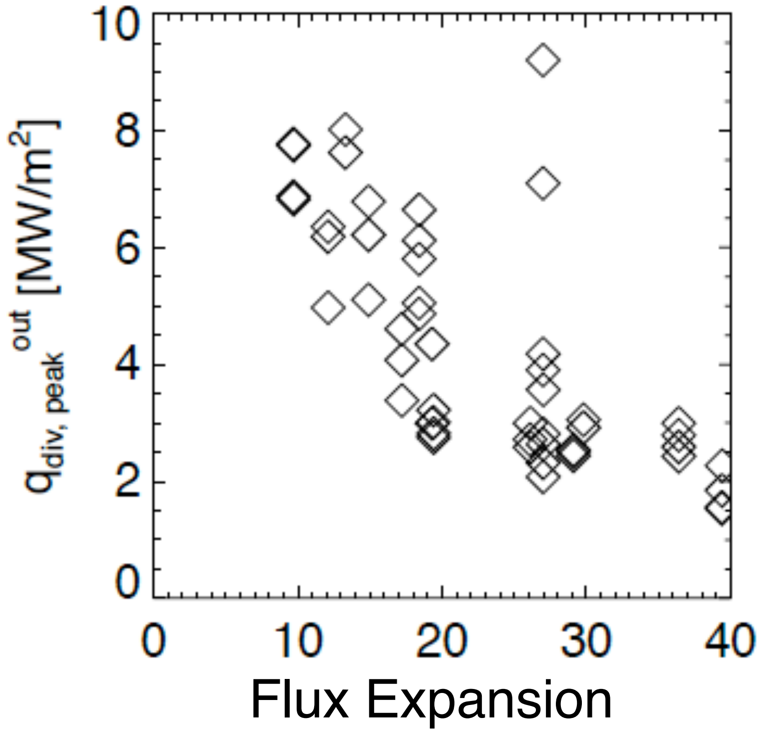
$$\therefore \quad q_{div,peak}^{out} = P_{div}^{out} \Big/ \left(2\pi R_{div,peak}^{out} f_{\exp} \lambda_q^{mid}\right) \quad \text{with } \lambda_q^{mid} = f(I_p, P_{loss}, B_t, f_{\exp})$$

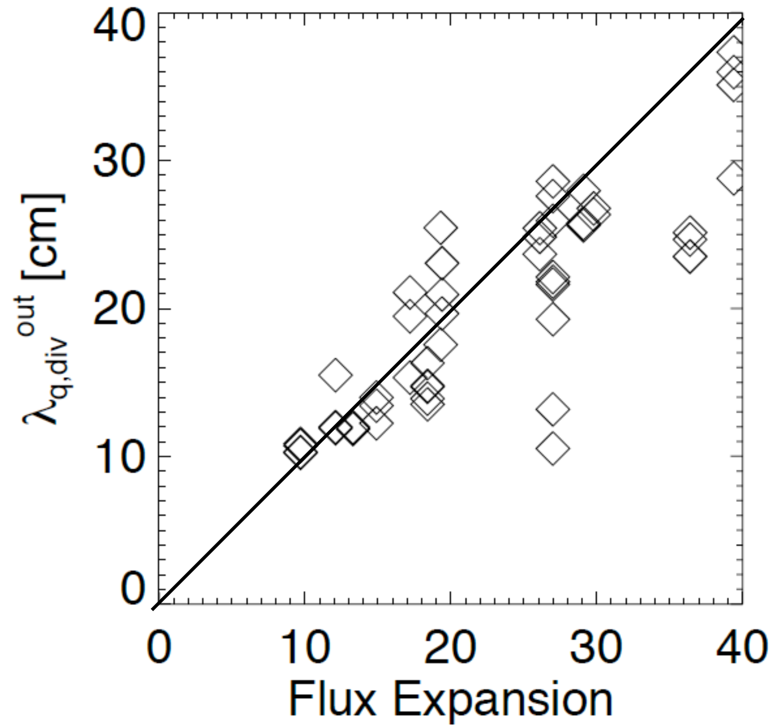
Divertor peak heat flux evolves during a discharge



- I_p flat-top at 0.25 sec
  - L-H transition at 0.13 sec
- Stored energy usually flat-tops after I_p flat-top
- Density ramps throughout the discharge (large d_r^{sep}, small ELMs)
- Outer divertor heat flux peaks when W_{MHD} flat-tops
  - q_{div} rolls over as density rises
- Total outer divertor power is relatively constant
  - Heat flux profile broadens
- Data is taken over 100—200 ms after W_{MHD} flattens
- Should be a conservative projection for NSTX-U

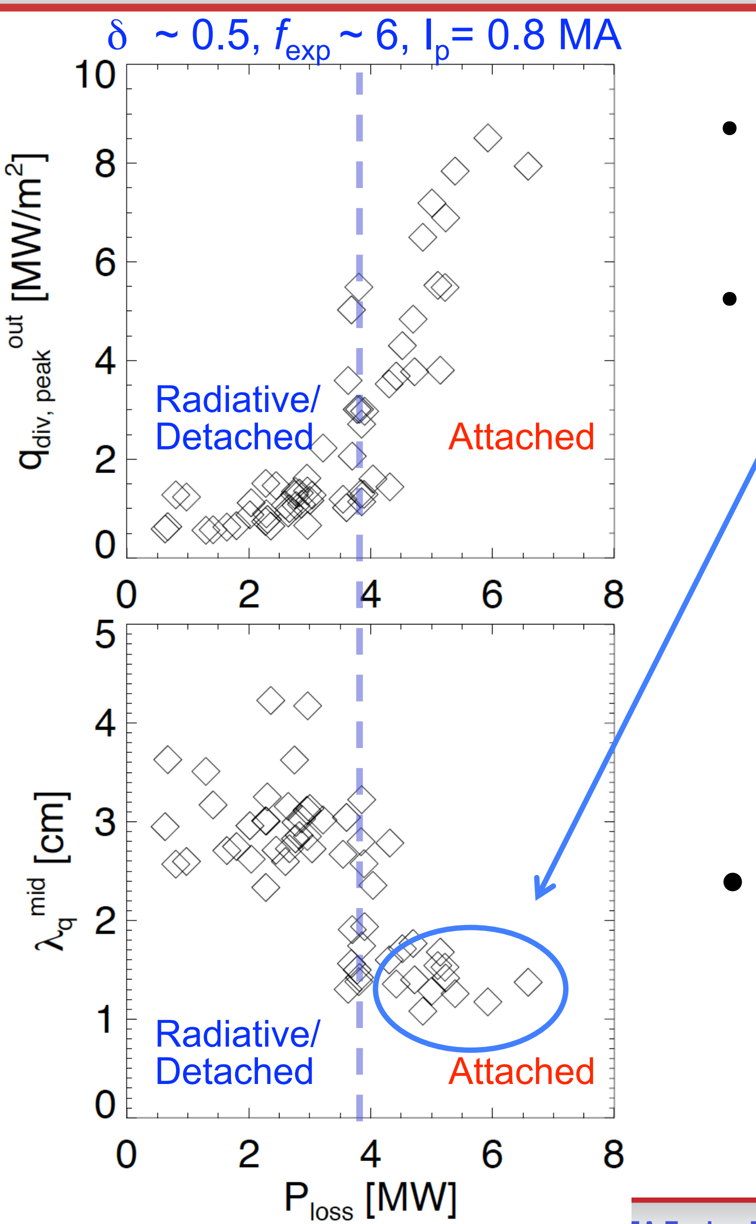
Peak heat flux decreases inversely with flux expansion with roughly constant λ_q^{mid}





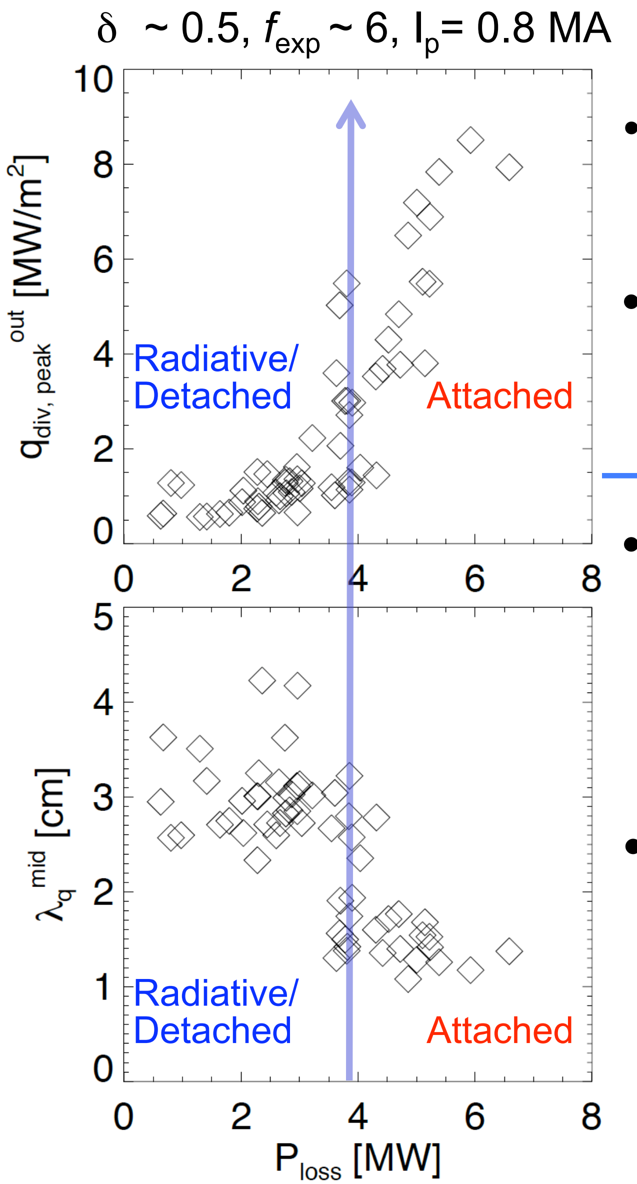
- $q_{div,peak}$ decreases as flux expansion increases
- λ_q^{div} broadens with flux expansion
  - Effectively increasing the plasma wetted area of the divertor
- λ_q^{mid} stays approximately constant during the scan
  - Decreases by 20% over a factor 4—5 scan of f_{exp}

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

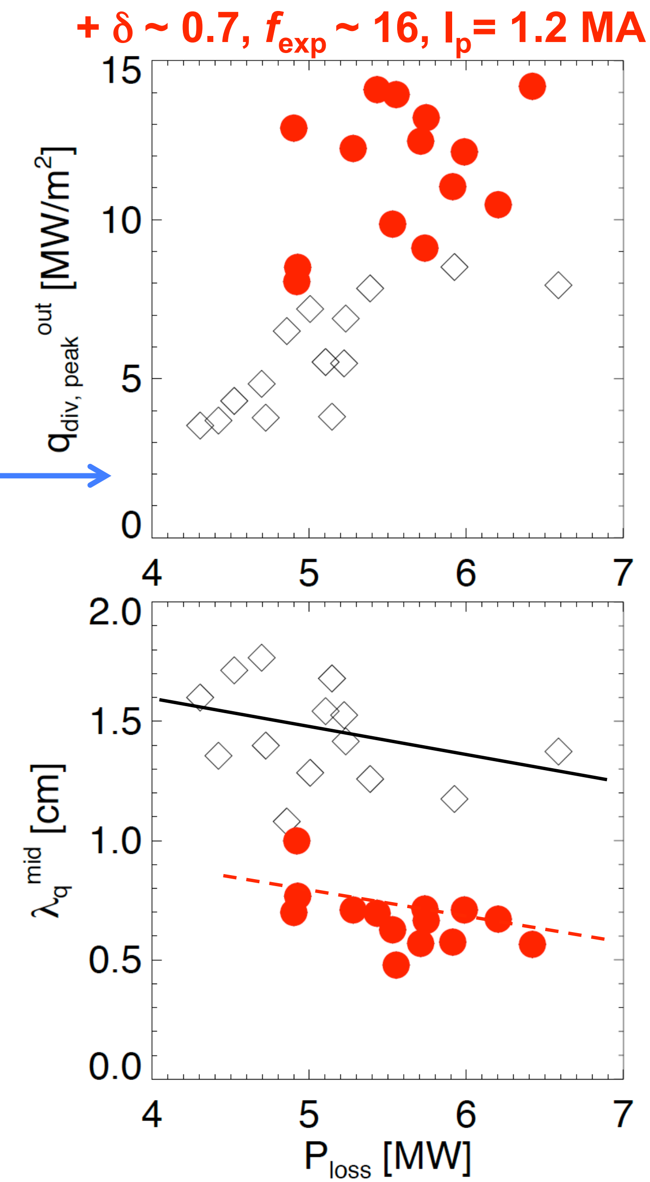


- Peak divertor heat flux increases with P_{loss}
- Apparent change in slope near P_{loss} = 4 MW in these conditions
  - Divertor transitions from a radiative/ detached divertor to an attached divertor
  - Similar to previous experiments suggesting a radiative detached divertor at low P_{loss} [Maingi 2007]
- λ_q^{mid} relatively independent of P_{loss} in high heat flux/attached regime
  - P_{loss} > 4 MW

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

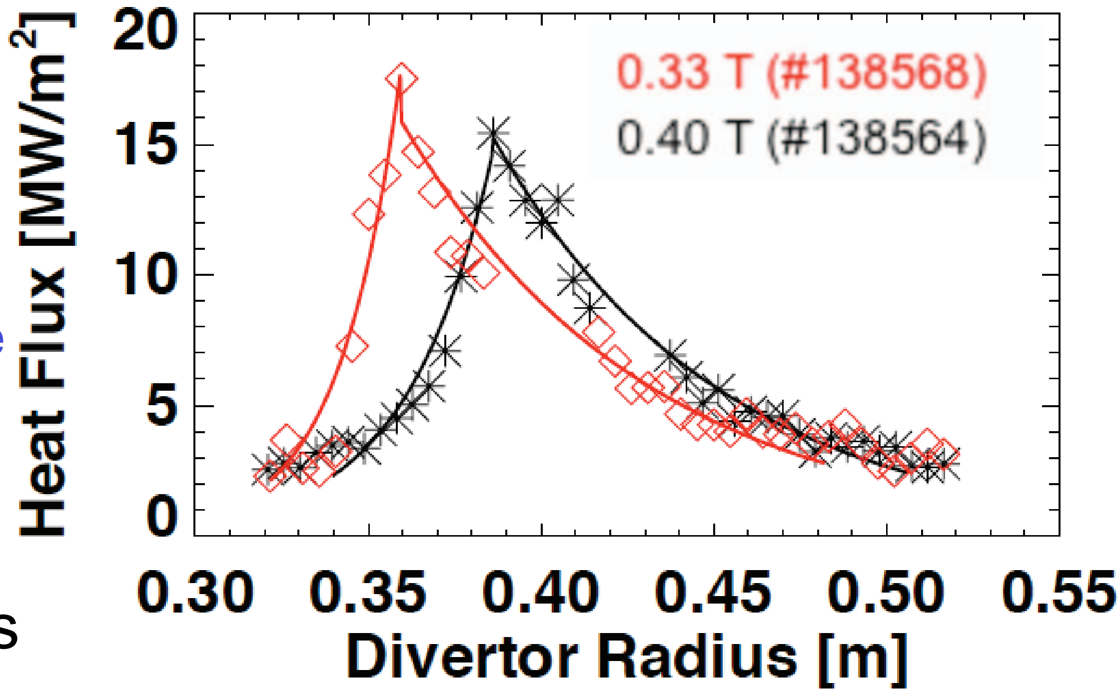


- Add in high δ data
- Narrow P_{loss} plot range
- Apparent I_p or q_{95} effect at higher triangularity
- λ_q^{mid} is reduced for higher δ, higher I_p discharges



Changes in $B_t(0)$ don't appear to effect divertor heat flux profiles

- Preliminary measurements from a scan of toroidal magnetic field, $B_t(0)$ appear to have minimal impact on the heat flux footprint
  - All other parameters were kept constant
  - Limited ranges of B_t are accessible in NSTX
- Suggestions that $L_{||}$ does not have a large impact on the divertor profiles



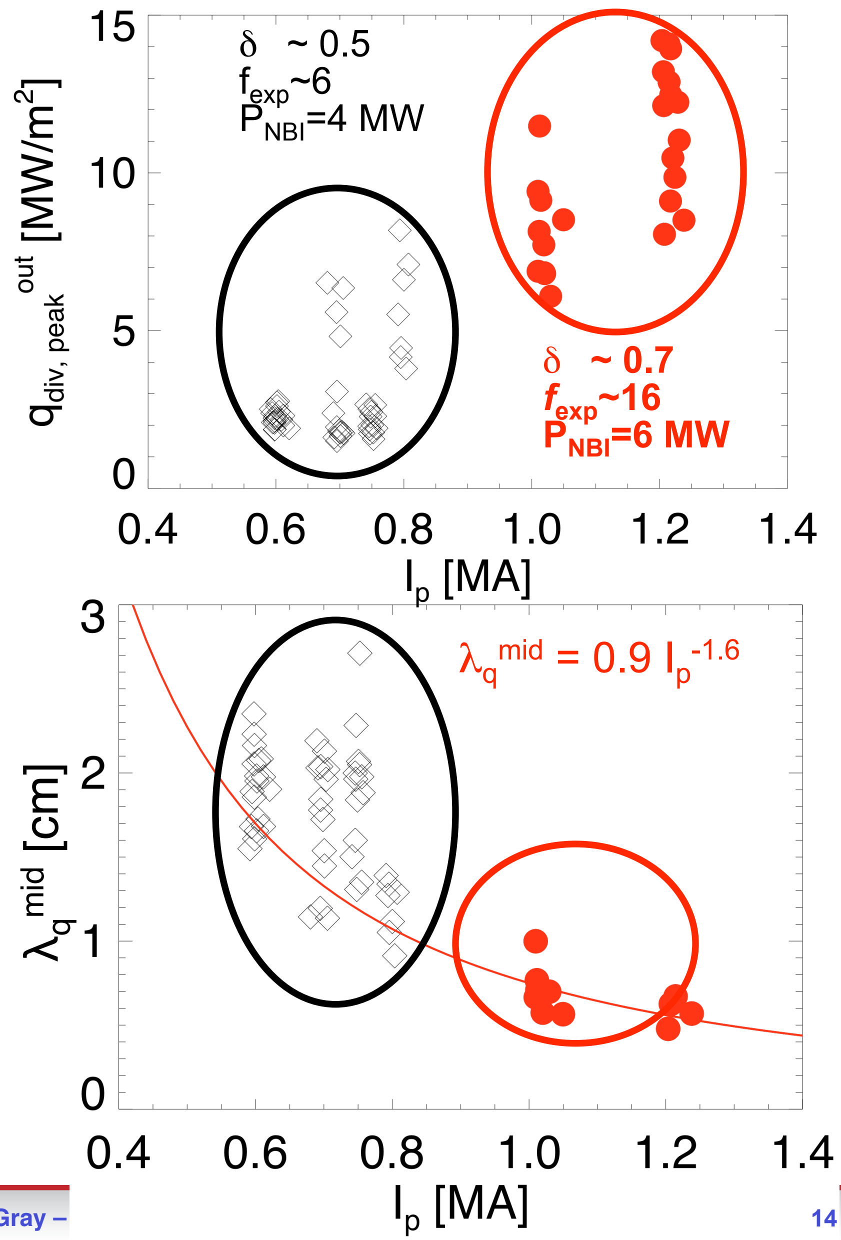
Heat flux width, λ_q^{mid} contracts with I_p

- Combined data from dedicated I_p scans in low δ and high δ discharges
  - Different P_{NBI} and f_{exp}, but previous slides shows no P_{loss} or f_{exp} effect on λ_q^{mid}
  - I_p dependence also in DIII-D, JET
  - q_{95}, $L_{||}$ re varied (constant B_T)
- λ_q^{mid} found to scale accordingly:

$$\lambda_q^{mid} \approx 0.9 I_p^{-1.6}$$

  - Suggests that for NSTX-U, with I_p = 2 MA and PNBI = 10 MW:

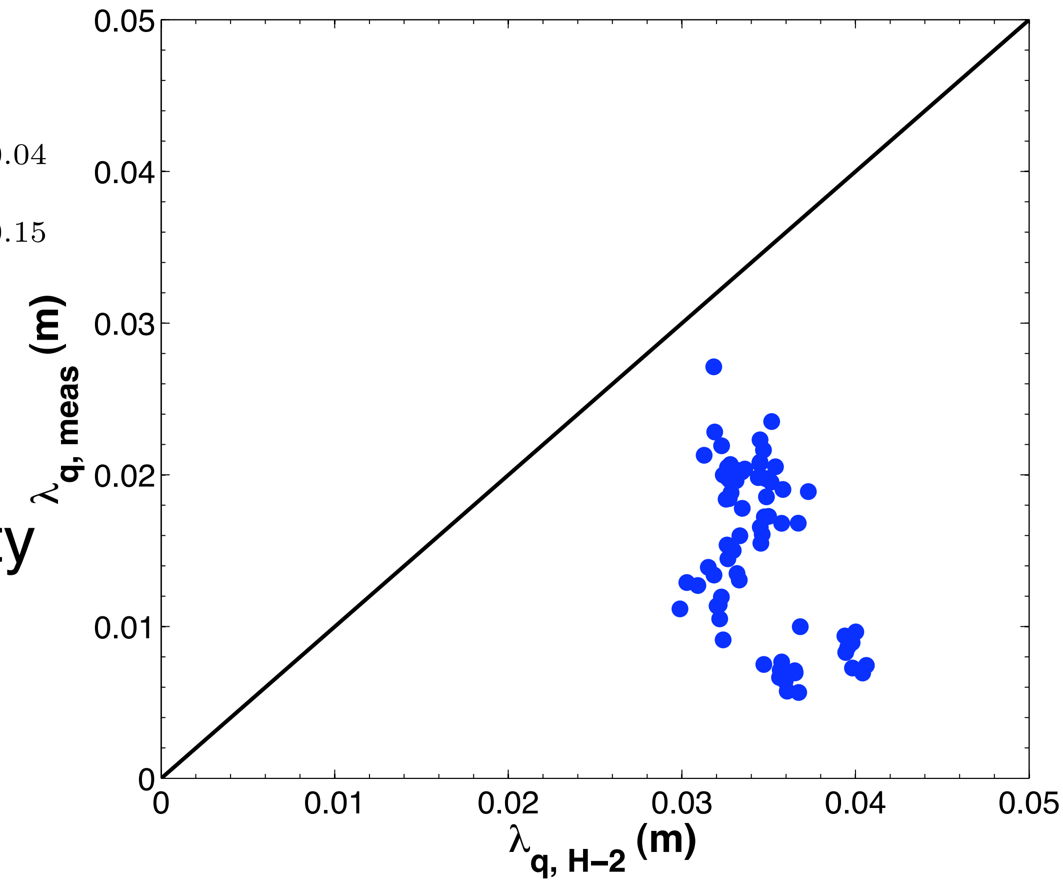
$$\lambda_q^{mid} = 3 \pm 0.5 \text{ mm}$$



Previous H-mode scalings over predict the measured λ_q^{mid}

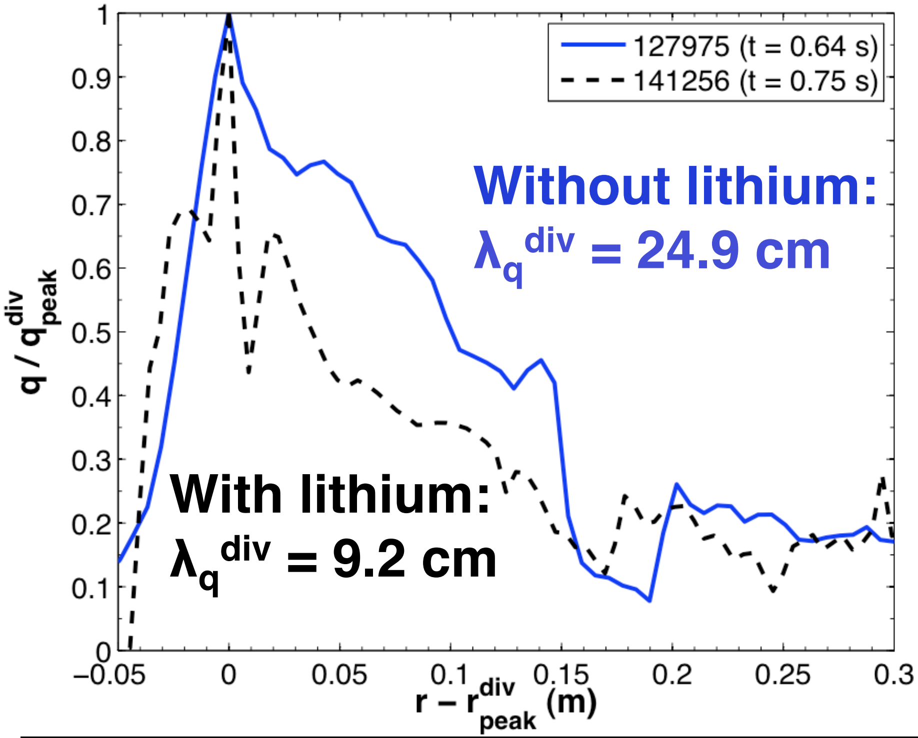
- H-2 scaling [Loarte 1999]
  - Used AUG, DIII-D and JT-60U data

$$\lambda_q^{H-2}[\mathrm{m}] = (5.3 \pm 1.4)10^{-3}\mathrm{P_{TOT}}[\mathrm{MW}]^{0.38\pm0.04} \mathrm{B}[\mathrm{T}]^{-0.71\pm0.08}\mathrm{q}_{95}^{0.30\pm0.15}$$



- Over predicts the magnitude of λ_q^{mid}
- Under predicts the severity of the contraction with I_p
  - $\lambda_q^{H-2} \sim I_p^{-1}$
- Possibly due to the different aspect ratio

Resultant divertor heat flux profile is narrowed with use of lithium coatings



Under similar discharge conditions:

- $\lambda_{q,non\text{-}lithium} \sim 2\ \lambda_{q,lithium}$
- High δ, 1 MA, 4 MW NBI, $f_{exp} \sim 18$
- Appears consistent across I_p and P_{NBI} scans

- For the discharge with lithium, the fast, 2 color IR camera is used
  - Frames are averaged together to yield a similar integration time as the slow, single color IR camera
- Narrowing of the heat flux profile appears with 2 color IRTV camera
  - Confirms earlier trends with single color, IRTV system [Gray 2010]
  - Not simply an effect of changing surface emissivity
  - Believed due to the elimination of small type V ELMs

Experiments on NSTX have successfully mapped out the behavior of the divertor heat flux with many engineering parameters

- By magnetically mapping the divertor heat flux profile, λ_q^{div} to the midplane, it's dependencies on heating power and flux expansion are eliminated
  - Yielding only $\lambda_q^{mid} \approx f(I_p)$
- λ_q^{mid} contracts strongly with increasing plasma current
  - This has been observed on DIII-D and JET as well
- Magnetic flux expansion appears to be a viable method to spread the heat flux out on the divertor
- Implications for NSTX-U at full design capabilities of I_p = 2 MA and P_{heat} = 10 MW are:
  - $q_{div,\, peak}$ = 24 MW/m^2, $\lambda_q^{mid} \sim$ 3 mm with f_{exp} = 30
  - Operations with a large magnetic flux expansion will be necessary to mitigate the expected large heat fluxes
  - Or operating with a detached divertor via divertor gas puffing will be necessary
- The full effect of thin lithium coatings is still being explored, but initial results show a further contraction of λ_q^{div} that is not yet understood

Future experiments and data analysis

- Measured I_p, P_{heat}, δ_r^{sep}, n_e, B_t dependences on heat flux profile with lithium using the new 2 color IR Camera
  - More reliable estimate of heat flux with lithium thin films due to the low emissivity of lithium
  - Determine how λ_q^{mid} scales with I_p in lithiated discharges
- Further development of snowflake divertor and magnetic flux expansion to mitigate heat flux
  - see Poster EXD/3-32: V. Soukhanovskii, "Snowflake divertor configuration in NSTX" for more information
- Effect of 3D magnetic fields on the heat flux profile
  - See Poster EXD/P3-01: J-W Ahn, "Effect of non-axisymmetric magnetic perturbations on divertor heat and particle flux profiles"
- Assess replacing lower inboard divertor C tiles with Mo
  - Mo offers improved chemical compatibility with evaporative lithium coatings
  - Metal walls are more relevant to fusion reactor scenarios

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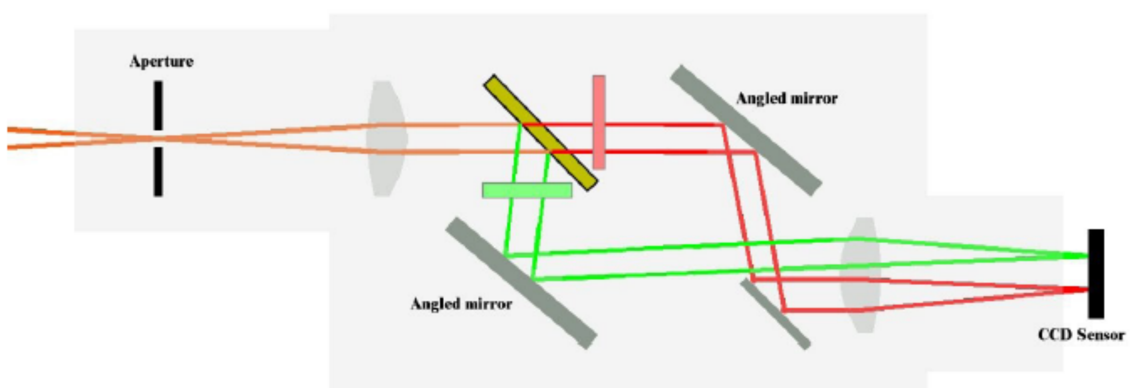
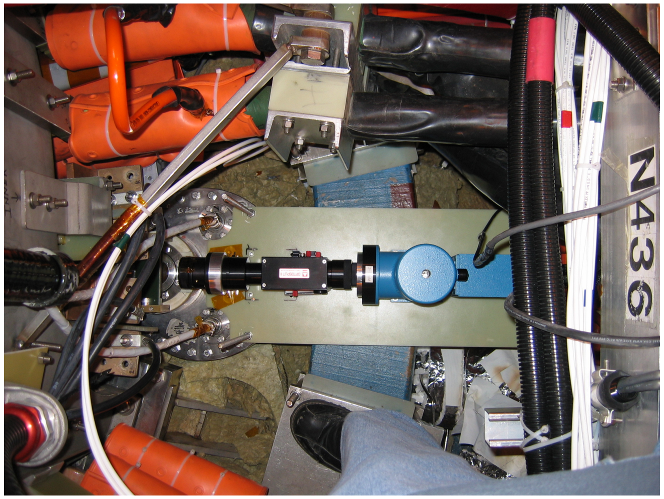
Request for Reprints

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 *in-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