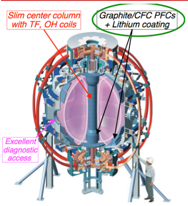
Introduction & Motivation

- 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

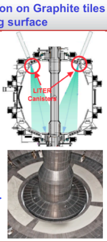
Overview of the National Spherical Torus eXperiment



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

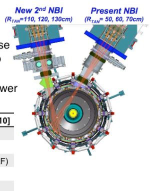
- NSTX began the FY10 run campaign April 1st, 2010
- Lithium is applied between shots via high temperature lithium evaporators (LiTERs) onto graphite PFCs
  - No Boronization (starting with the FY10 run campaign)
  - No glow discharge cleaning (GDC) between shots
  - Deposit between 200 – 800 mg / shot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



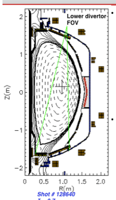
Upgraded NSTX expected to be online in FY2015

- Doubling of neutral beam heating power to 15 MW
- Increase in pulse length to 5 s
- 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 [Menard 2010]	
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

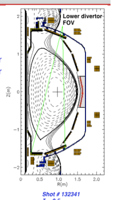


ORNL IR system currently on NSTX



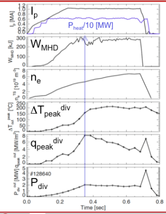
Shot # 128640
δ ~ 0.7
κ =

- 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



Shot # 132341
δ ~ 0.5
κ =

Divertor peak heat flux evolves during 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 δ_r^{sep}, small ELMs)
- Peak surface divertor temperature, ΔT_{peak}^{div} flattens as density rises
- Outer divertor heat flux peaks when W_{MHD} flat-tops; rolls over as density rises
- Total outer divertor power relatively constant (i.e. profile broadens)

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

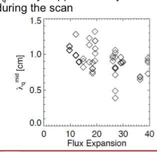
- All data is time averaged over ELMs and before lithium coatings were applied
- IR thermography measures surface temperature, which is used to estimate heat flux profile $q_{div}^{out}(r,t)$ and calculate divertor power loading: $P_{div}^{out} = \int_{R_{min}}^{R_{max}} 2\pi R_{div}^{out} q_{div}^{out}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

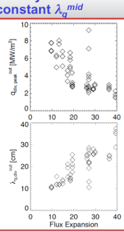
$$\lambda_q^{mid} = \lambda_{q,div}^{out} / f_{exp}, \text{ where } f_{exp} \equiv \frac{R_{mid} B_\theta^{mid}}{R_{div} B_\theta^{div}}$$

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

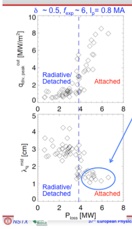
Peak heat flux decreases inversely with flux expansion with roughly constant λ_q^{mid}

- $q_{div,peak}$ decreases as flux expansion increases
- λ_q^{div} increases with flux expansion
- λ_q^{mid} stays approximately constant during the scan



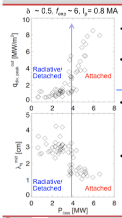


Heat flux width λ_q^{mid} largely independent of P_{loss} in attached plasmas

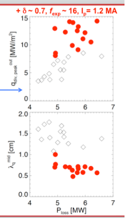


- Peak divertor heat flux increases with P_{loss}
- Apparent change in slope near P_{loss} = 4 MW in these conditions
  - Divertor transitions from a radiative/ detached divertor to an attached divertor
  - Similar to previous experiments suggesting a radiative detached divertor at low P_{loss} [Paul 2005, Maingi 2007]
- λ_q^{mid} relatively independent of P_{loss} in high heat flux 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

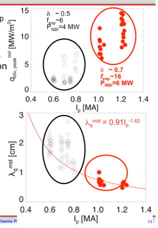


Heat flux width, λ_q^{mid} contracts with I_p

- 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_{li} different
- λ_q^{mid} found to scale accordingly:

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

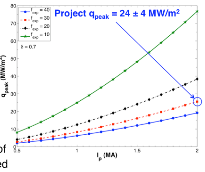
  - Suggests that for NSTX-U, with I_p = 2 MA, λ_q^{mid} = 3 ± 0.5 mm



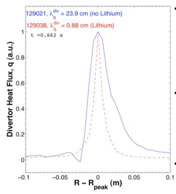
Projections for NSTX-U peak heat flux show that divertor heat flux must be mitigated

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

- 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
  - δ ~ 0.7
  - Anticipate operation with $0.5 \le n/n_{GW} \le 1$
- Functional dependence of λ_q^{mid} has been determined from experiment



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



- Under similar discharge conditions, λ_q (exponential decay length) at the divertor is reduced
  - 96% in the case shown (right)
  - 75% more typical
- Calculation of divertor heat flux/power/integral λ_q is complicated by unknown emissivity of lithium + graphite surface
- Heat flux profile appears more symmetric and Gaussian

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
- Implications for NSTX-U at full design capabilities of I_p = 2 MA and P_{heat} = 10 MW are:
  - 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
  - This will be addressed by the use of a 2 color IR camera this run campaign [McLean 2010]

FY 2010 experiments and analysis plan

- Measure I_p, P_{heat}, n_e, B_t dependences on heat flux profile with lithium at high I_p for improved scaling
- Quantify density and of heat flux profiles and asses the impact of lithium coatings
- Further development of snowflake divertor and magnetic flux expansion to mitigate heat flux
  - see Poster 1-28: V. Soukhanovskii "Snowflake divertor configuration in NSTX" for more information
- New data with LLD
  - New 2 color IR measurements → more reliable estimate of heat flux with lithium thin films due to the high emissivity of lithium
  - Including evaporative cooling
- Assess replacing lower inboard divertor C tiles with Mo
  - Improved chemical compatibility with evaporative lithium coatings
  - More relevant to fusion reactor scenarios

References

[Menard 2010]	J.E. Menard, *et al.* These Proceedings
[Kugel 2008]	H. Kugel, *et al.* Phys. Plasmas. **15** (2008) 056118
[Maingi 2009]	R. Maingi, T. Osborne, *et al.* Phys. Rev. Lett. **103**:7 (2009) 075001
[Maingi 2003]	R. Maingi, *et al*. J. Nucl, Mater. **313-316** (2003) 1005—1009
[Maingi 2007]	R. Maingi, *et al. J. Nucl. Mater.* **363-365** (2007) 196—200
[Loarte 1999]	A. Loarte, *et al. J. Nucl. Mater.* **266-269** (1999) 587—592
[Paul 2005]	S.F. Paul, *et al. J. Nucl. Mater.* **337-339** (2005) 251—255
[McLean 2010]	A.G. McLean, *et al. Rev. Sci. Instr.* Submitted (2010)

T.K. Gray is supported under an appointment to the U.S. D.O.E. Fusion Energy Postdoctoral Research Program administered by the Oak Ridge Institute for Science and Education under contract number DE-AC05-06OR23100 between the U.S. D.O.E. and Oak Ridge Associated Universities.

This work was funded by the US Department of Energy contract numbers DE-AC05-000R22725, DE-AC52-07NA27344, and DE-AC02-09CH11466