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Heat flux measurements and modeling for the FY10 Joint Research Milestone and implications for power producing devices

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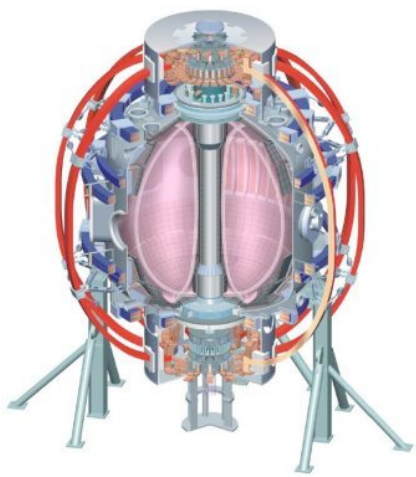
Edge Plasma Physics and PMI in the Fusion Power Plant Regime
ARIES Town Meeting
20-21 May 2010



Outline

- **Introduction**
- Status of individual and joint experiments
  - **Alcator C-Mod**
    - **Commission new diagnostics**
    - **Dedicated L-mode and H-mode experiments**
  - DIII-D
    - Several dedicated experiments, including dimensionless identity experiment with C-Mod
  - NSTX
    - Refined analysis of previous data
    - Preparation for coming run (started 3/25)
- Experimental and modeling activities

JRT Milestones Achieved for 1st and 2nd Quarters

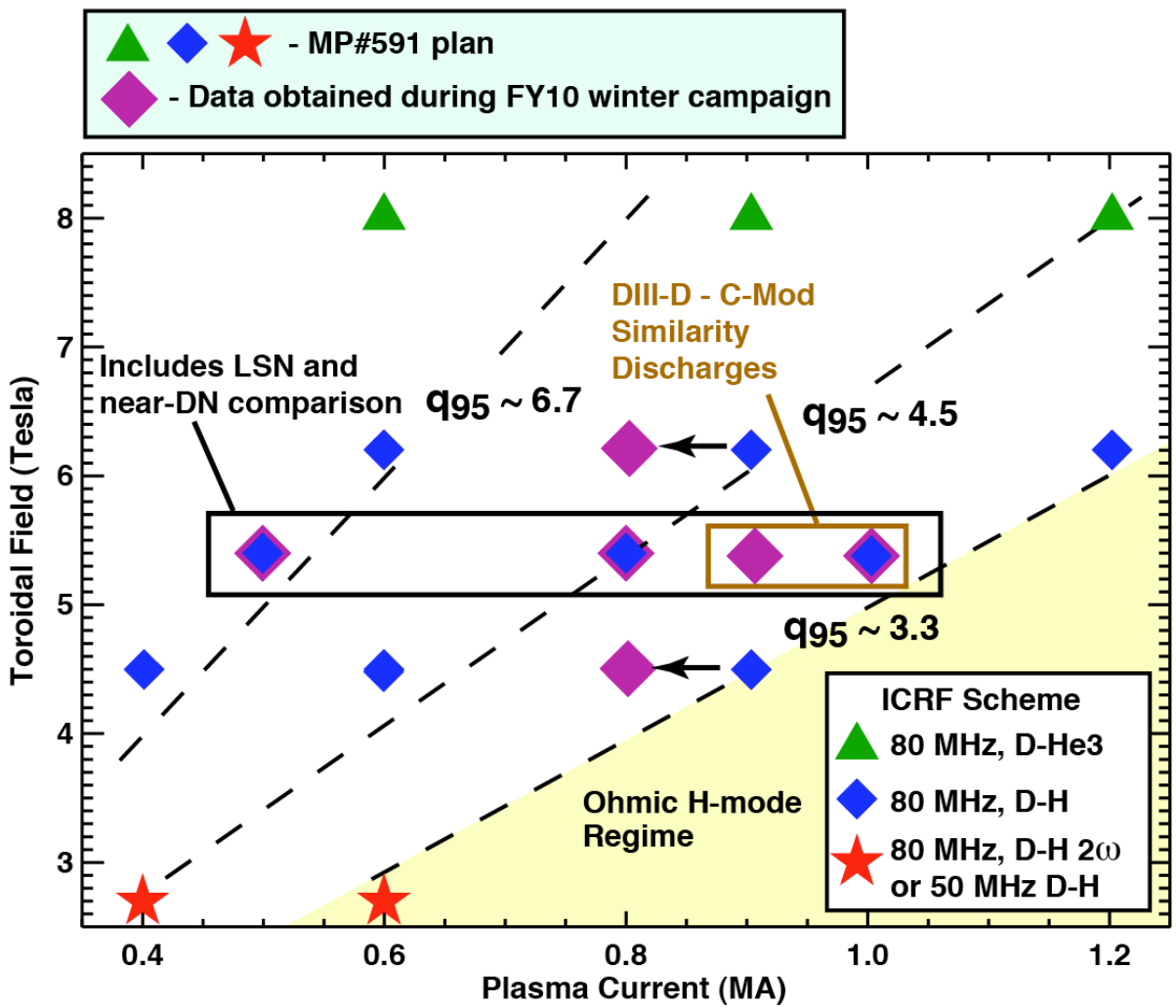
FY2010 DoE Joint Facilities Research Milestone:

Conduct experiments on major fusion facilities to improve understanding of the heat transport in the tokamak scrape off layer (SOL) plasma, strengthening the basis for projecting divertor conditions in ITER. The divertor heat flux profiles and plasma characteristics in the tokamak SOL will be measured in multiple devices to investigate the underlying thermal transport processes. The unique characteristics of C-Mod, DIII-D, and NSTX will enable collection of data over a broad range of SOL and divertor parameters (e.g., collisionality, beta, parallel heat flux, and divertor geometry). Coordinated experiments using common analysis methods will generate data that will be compared with theory and simulation.

1st Quarter Milestone	2nd Quarter Milestone	3rd Quarter Milestone	4th Quarter Milestone
Develop a preliminary research plan coordinated among the three facilities, in order to accomplish the required experiments measuring scrape-off layer characteristics and divertor heat flux, towards the goal of understanding divertor conditions projected for ITER. ✔	Initial planned experiments will have been carried out on at least one of the three facilities. ✔	Experiments will have been carried out at multiple facilities. Experimental analysis and preliminary interpretive modeling of results from multiple facilities will be in progress. An initial evaluation of the data set will be performed and research plans adjusted as appropriate.	Complete necessary experiments, data analysis and associated interpretive modeling. Prepare a joint report on the empirical understanding gained, the connections to edge transport models, and the opportunities for more detailed and extensive comparisons to theory and simulation. Identify critical research areas to improve extrapolation to ITER.

Stationary EDA H-modes baseline for C-Mod H-mode experiments

- 5 runs completed in FY10 winter campaign, with focus on IR 'footprints'

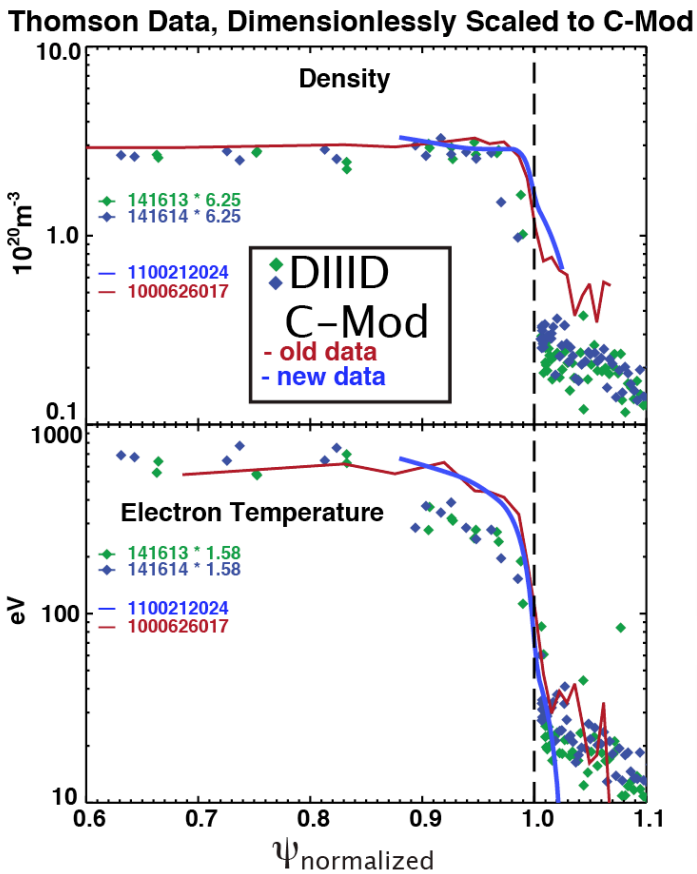


Dimensionless similarity match with DIII-D discharges attained

Current, power, field and topology variations begun

Good progress on developing IR imaging and thermal analysis tools to infer heat flux footprints

Dimensionless Similarity Discharges initiated with DIII-D



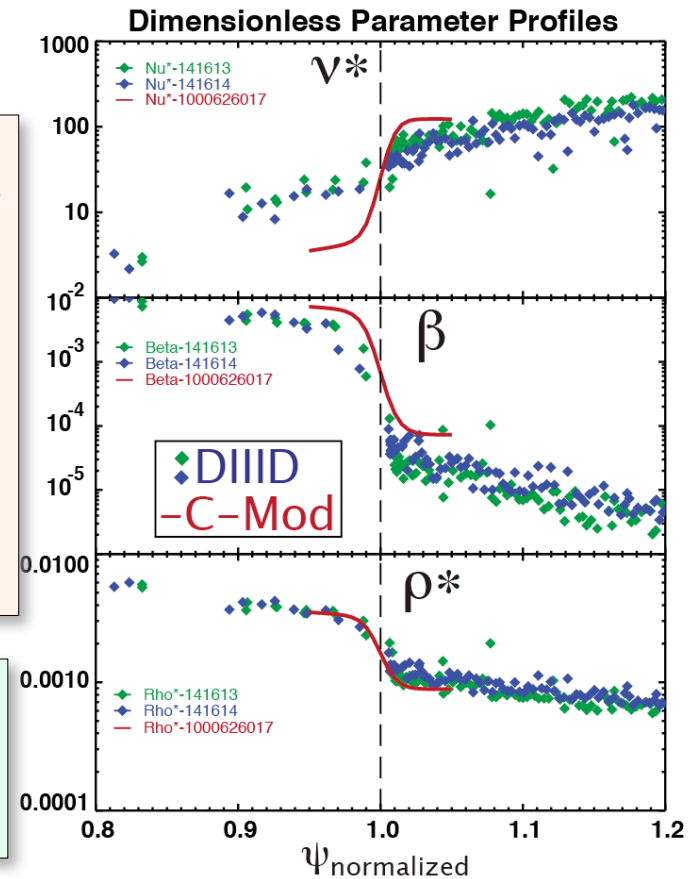
Plasma physics similarity scalings:

$$n_e\, a^2 \sim const$$

$$T_e\, a^{1/2} \sim const$$

Atomic physics similarity scaling:

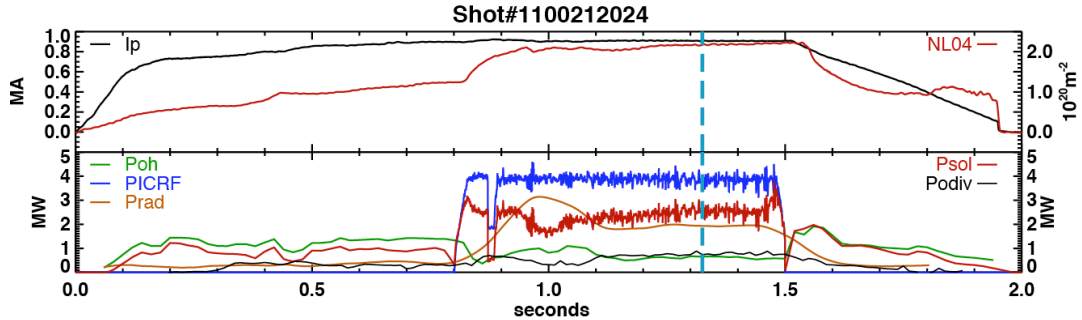
$$n_e\, a \sim const$$



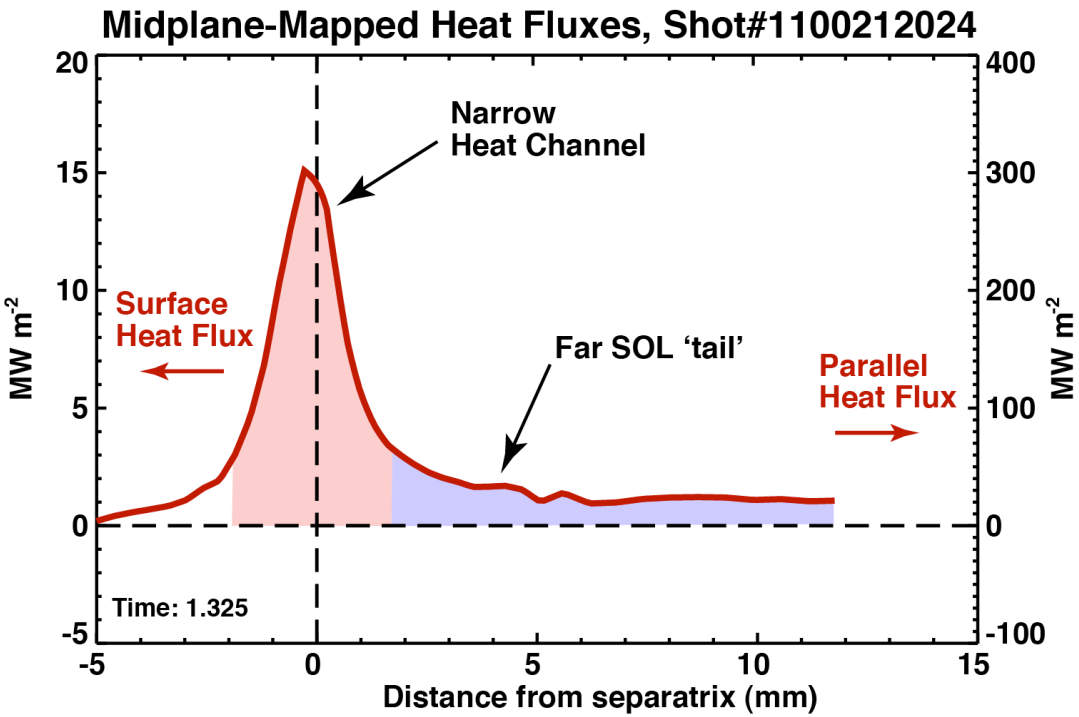
- ***Pedestal conditions of previous C-Mod similarity discharge (1000626017) attained***
- ***Higher scaled SOL density values are obtained in C-Mod versus DIII-D***

=> evidence that atomic physics breaks similarity match in SOL?

Initial Footprint Observations:
C-Mod heat flux channels are narrow with 'tail' features



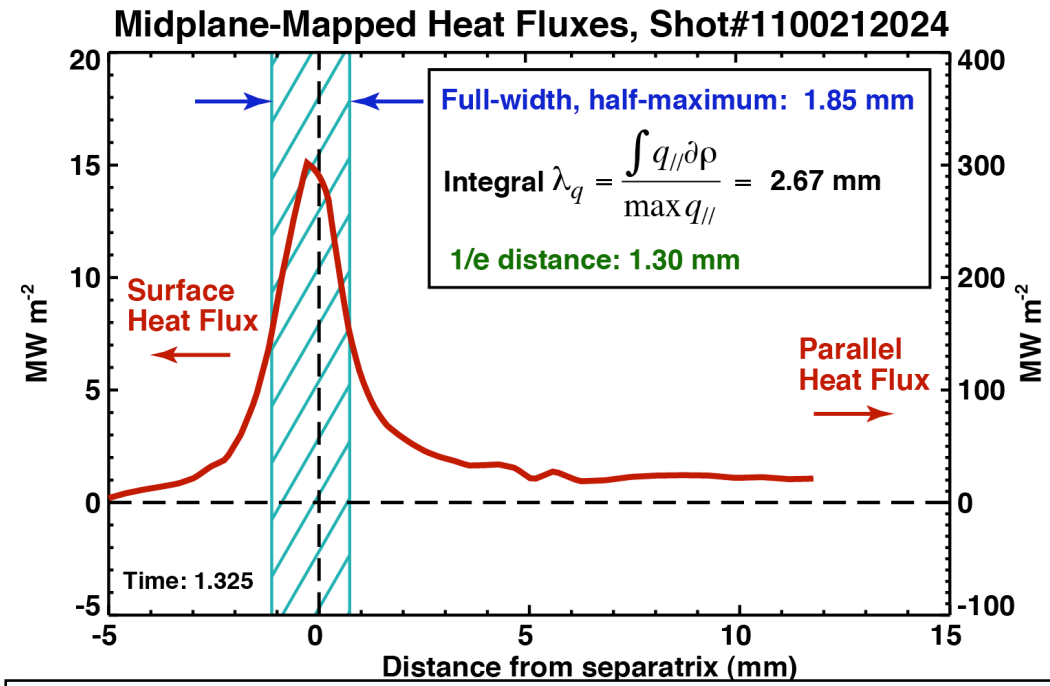
Footprint taken from similarity discharge, 1.325 s



- *Narrow with 'tail' feature*

LaBombard, PSI10

Initial Footprint Observations: C-Mod heat flux width challenges ITER empirical scalings



- ***FWHM ~ 1.85 mm***
- ***Integral λ_q ~ 2.7 mm (‘tail’ is problematic here)***
- ***1/e distance ~ 1.3 mm***

LaBombard, PSI10

λ_q scaling from JET [Kirnev, et al., PPCF 49 (2007) 689-701] is basis for ITER heat flux width scaling:

$$\lambda_q^{cond} \propto B_\phi^{-1} P_{sol}^{-0.5} n_{e,u}^{0.25} q_{95} R^2$$

…predicts integral λ_q for C-Mod shot#1100212024: λ_q^{cond} ***~ 0.55 mm!***

=> C-Mod data are already providing a valuable ‘anchor’ for R and B dependences…

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DIII-D Status

- Substantial analysis completed on dedicated experiments from FY09 (and shown here)
- New C-Mod dimensionless similarity experiment completed
- P_{heat}, I_p scans obtained in cross-sectional shape common to C-Mod, DIII-D, NSTX
- ECH vs. NBI heating compared for P_{heat} scans
  - Control room analysis indicated nearly identical profiles from ECH and NBI at same power level
- Remainder of FY focused on analysis of new dataset, and modeling of profile dependence

Divertor heat flux footprints not clearly correlated with input power in DIII-D

Peak Divertor Heat Flux

Inner and outer strike point peak heat fluxes vary linearly with input power

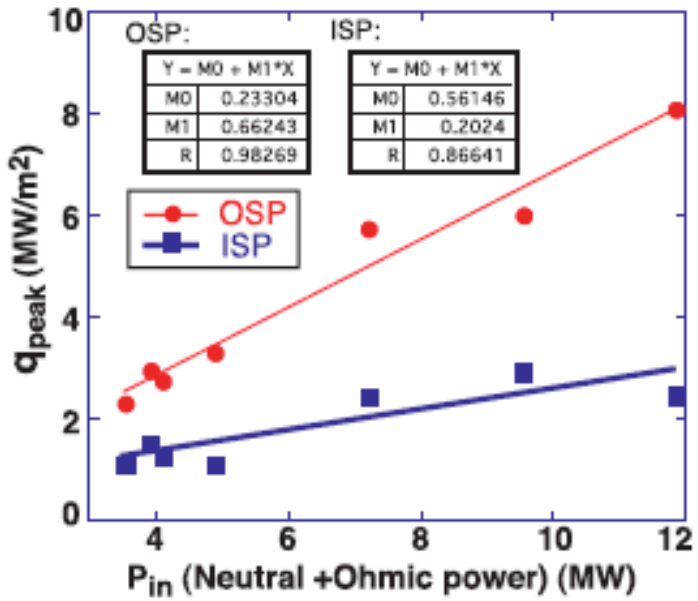
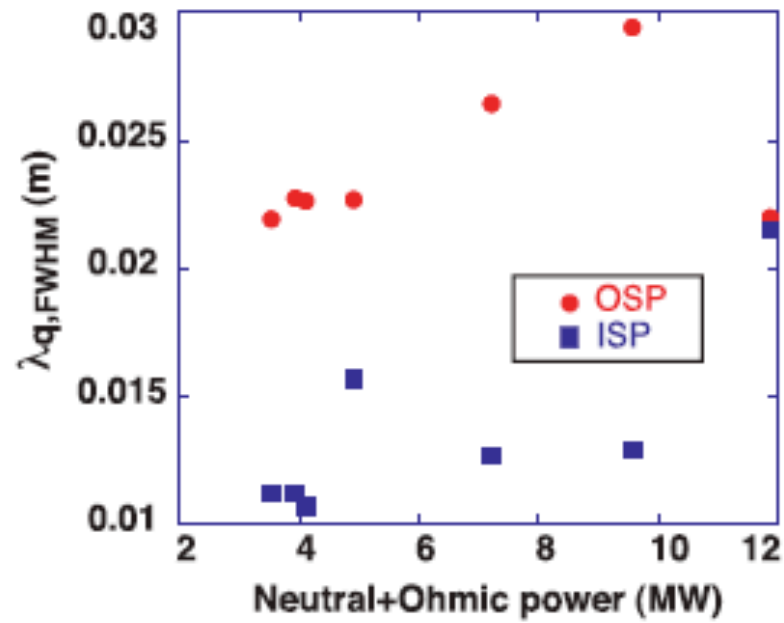


Fig. 1

Divertor Heat Flux Profile Width $\lambda_{q,FWHM}$

Weak dependence of width on input power



Lasnier, APS09, PSI10

Divertor heat flux footprints mostly independent of density, only broadening near detachment in DIII-D

Peak heat flux drops linearly as density increases

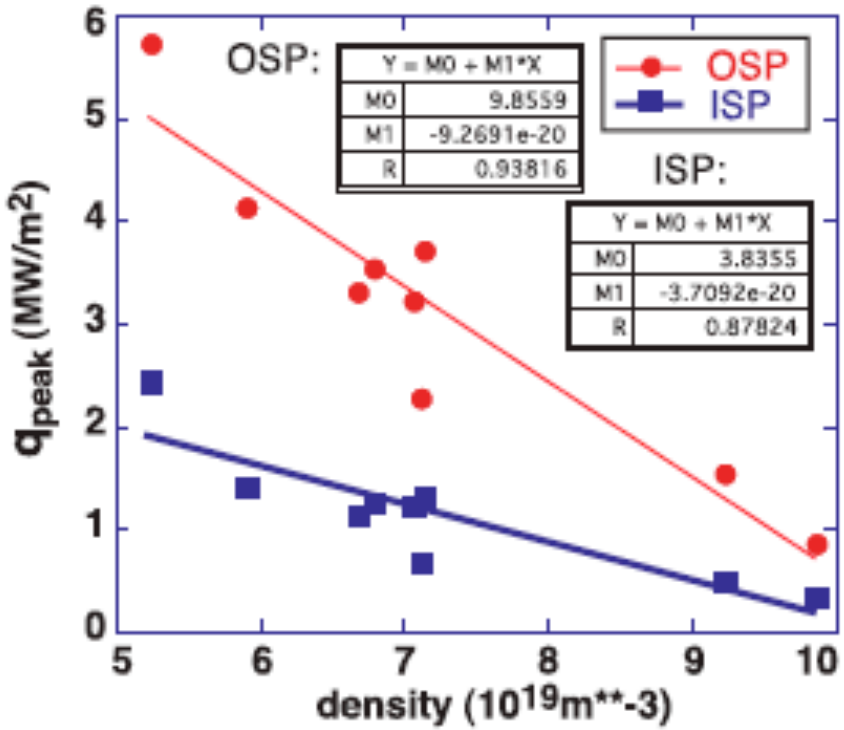


Fig. 2

The heat flux profile broadens at onset of detachment

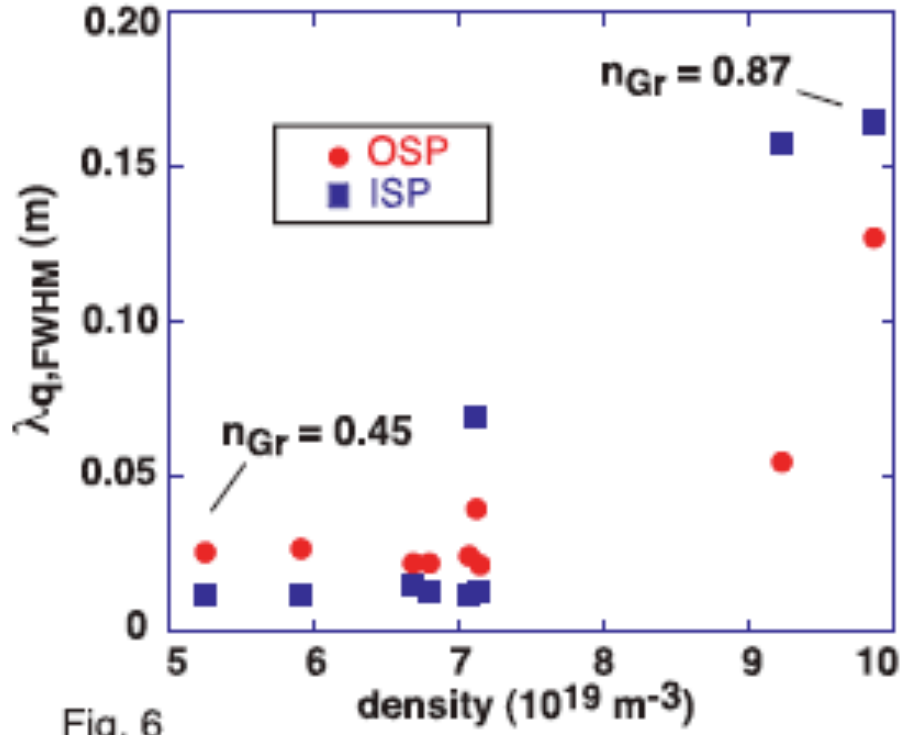
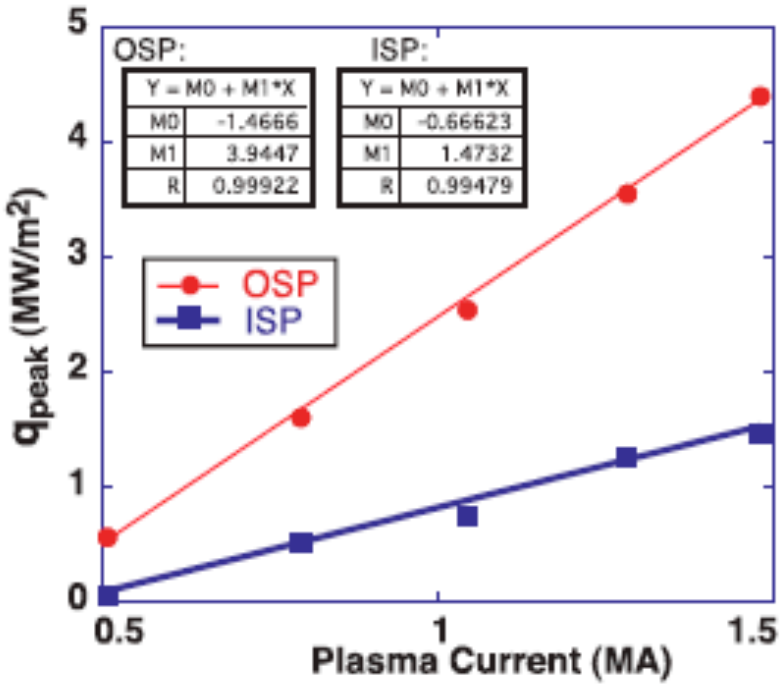


Fig. 6

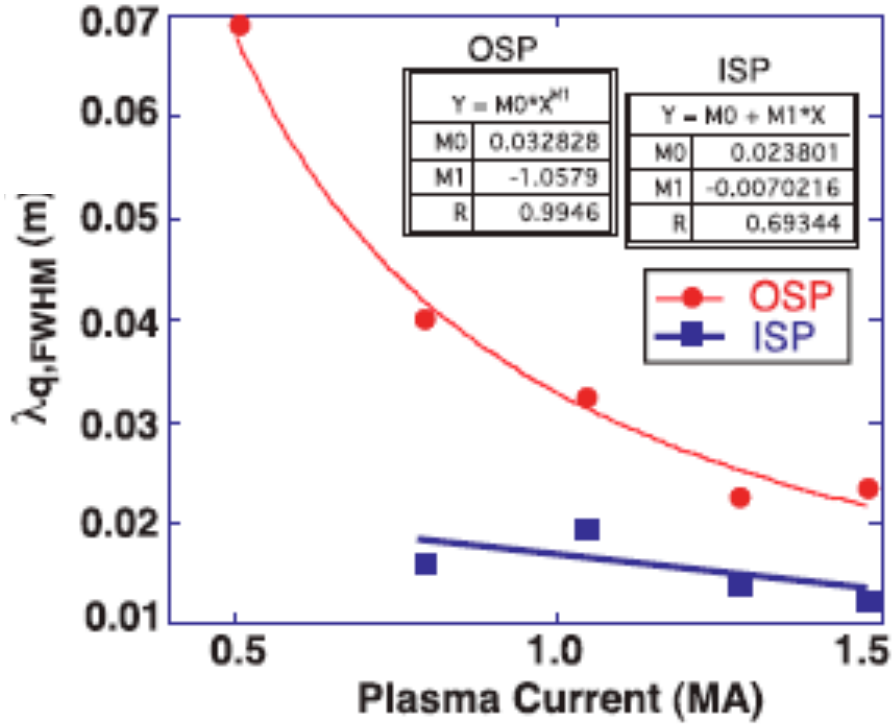
Lasnier, APS09, PSI10

Divertor heat flux footprint widths narrow with plasma current in DIII-D

Peak heat flux increases linearly with plasma current



Heat flux profile width varies inversely with plasma current.



- **Discharges with I_p scan at constant q_{95} showed similar dependence**

Lasnier, APS09, PSI10

Summary of DIII-D heat flux profile dependences

- $q_{peak} \propto$ input power (consistent with some previous scalings)
- $\lambda_{q,FWHM}$ depends weakly on input power if at all (previous scalings varied widely)
- $q_{peak} \propto -\overline{n_e}$ (Same as one previous scaling)
- $\lambda_{q,FWHM}$ broadens only at onset of detachment
- $q_{peak} \propto I_p$ (consistent with two previous scalings)
- $\lambda_{q,FWHM} \propto 1/I_p$ (agrees with one previous scaling)

Lasnier, APS09, PSI10

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Simplest 0-D heat flux projection based on power balance extrapolates from measured NSTX heat flux profiles

- IR thermography measures heat flux profile $q_{div}^{out}(r)$ for calculation of 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, $\lambda_{q,div}^{out}$:

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

- Assume $\lambda_{q,div}^{out}$ related* to characteristic midplane scale length through flux expansion f_{exp}: $\lambda_q^{mid} = \lambda_{q,div}^{out} / f_{\exp}$ with $f_{\exp} = \dfrac{R_{mid} B_\theta^{mid}}{R_{div} B_\theta^{div}}$

– Project NSTX-U q_{peak}^{div}: I_p=2 MA, P_{loss}=10 MW, B_t=1 T, f_{exp}=30

– For P_{loss} extrapolation, use $P_{div}^{out} = f_{div} P_{loss}$ with $f_{div} = 0.5$

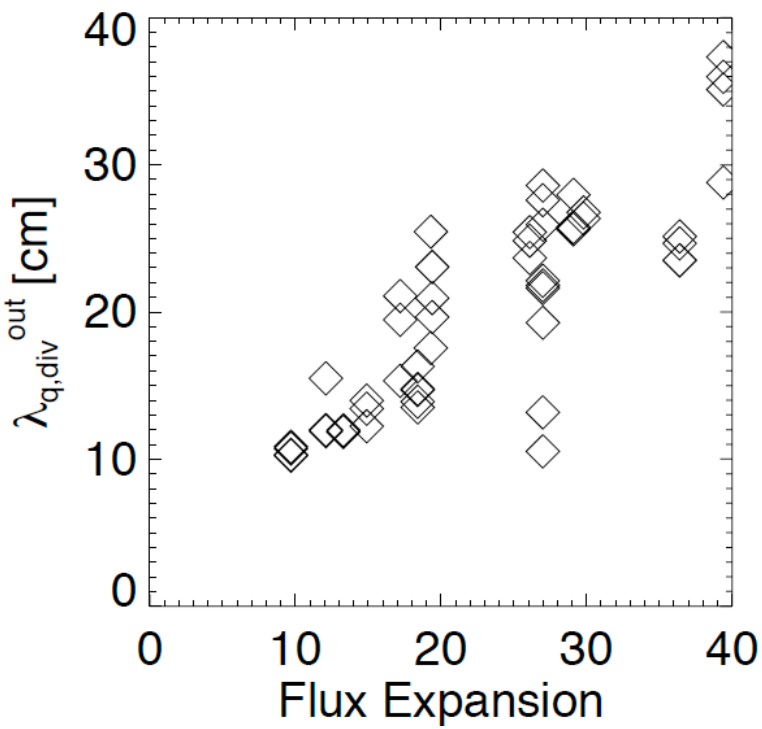
$$\boxed{q_{div,peak}^{out} = f_{div} P_{loss} \Big/ \left(2\pi R_{div,peak}^{out} f_{\exp} \lambda_q^{mid}\right) \text{ with } \lambda_q^{mid} = f(I_p, P_{loss}, B_t, f_{\exp})}$$

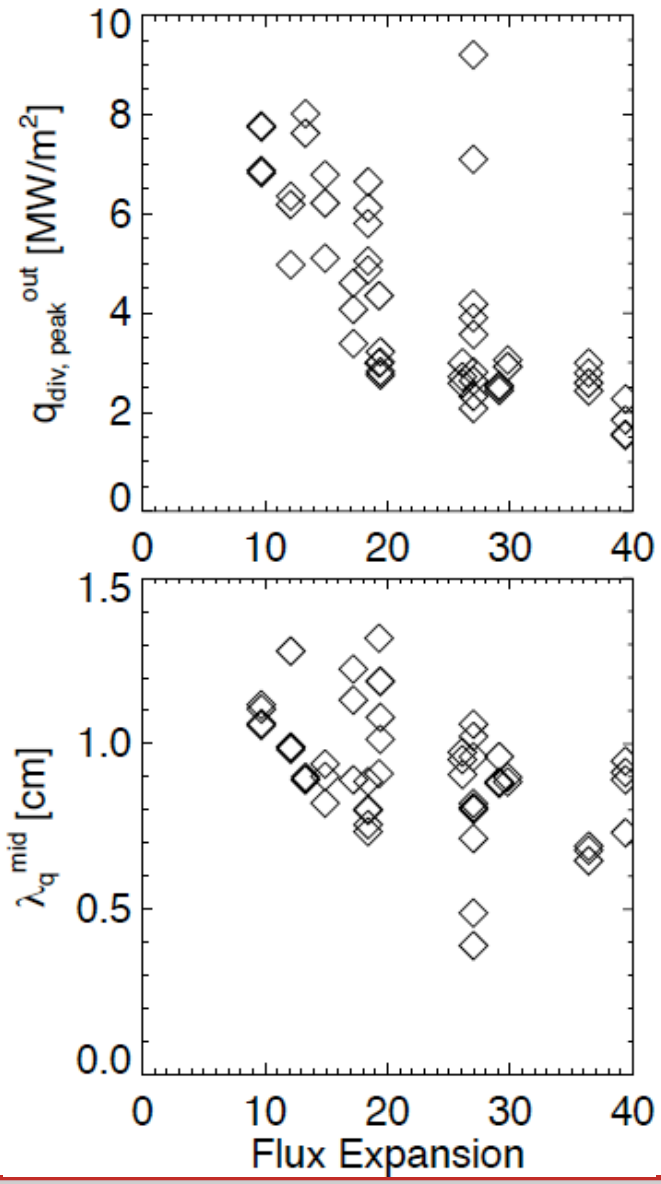
➢ Determine dependence of λ_q^{mid} on external parameters (I_p, P_{loss}, B_t, flux expansion) from NSTX data (FY10 Joint Research Target)

*Loarte, JNM 1999

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

- λ_q^{div} increases with flux expansion
- λ_q^{mid} stays approximately constant during the scan

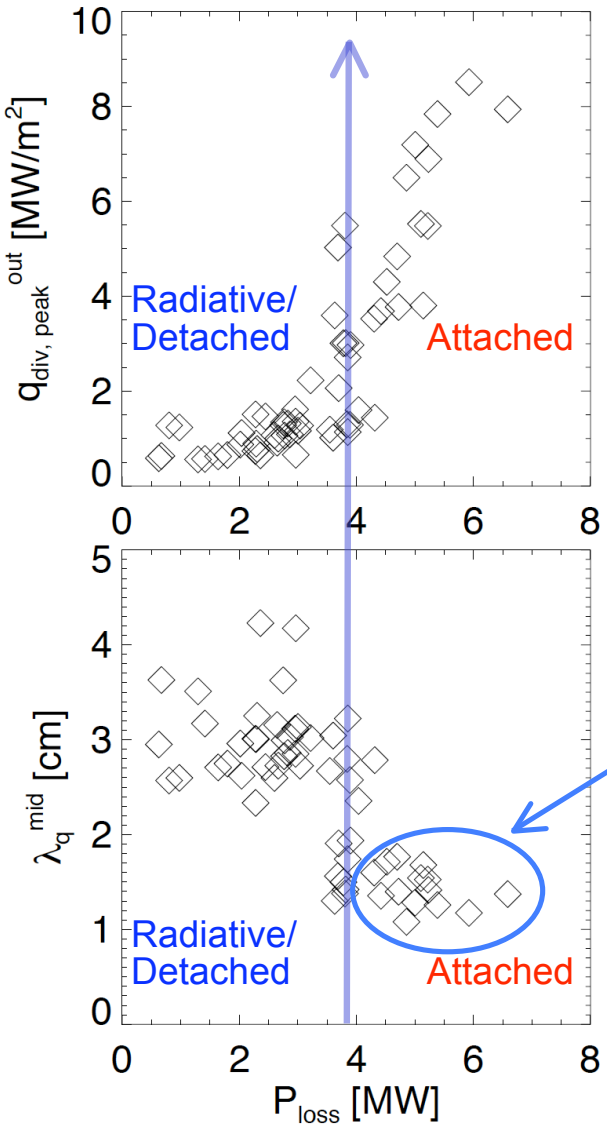




Gray, PSI10

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

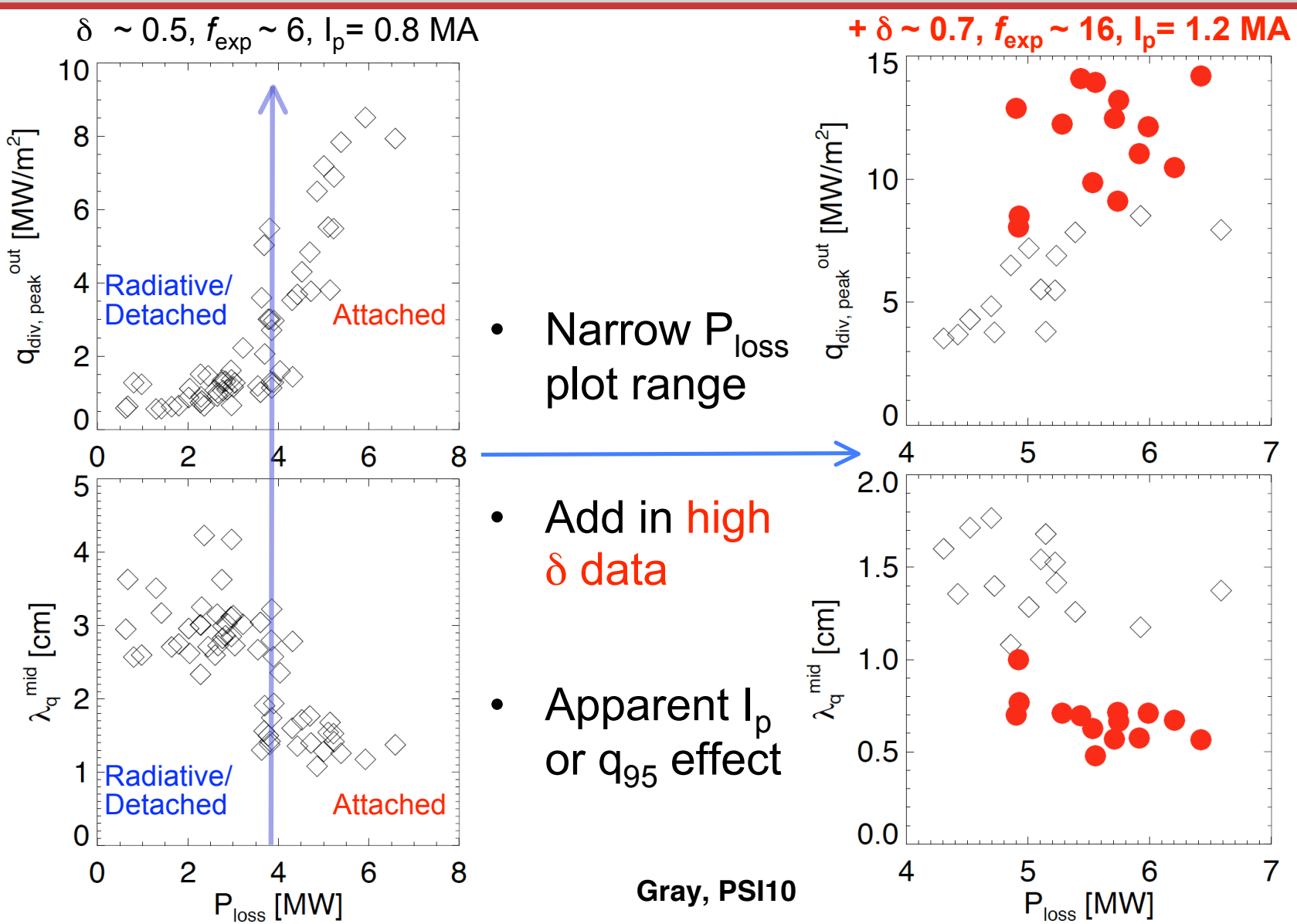
δ ~ 0.5, f_{exp} ~ 6, I_p= 0.8 MA



- Peak divertor heat flux increases with P_{loss}
- Apparent change in slope near P_{loss}=4 MW in these conditions, as divertor transitions from a radiative/detached divertor to an attached divertor
- λ_q^{mid} relatively independent of P_{loss} in high heat flux regime
- All data in this talk averaged over ELMs and before lithium coatings

Gray, PSI10

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

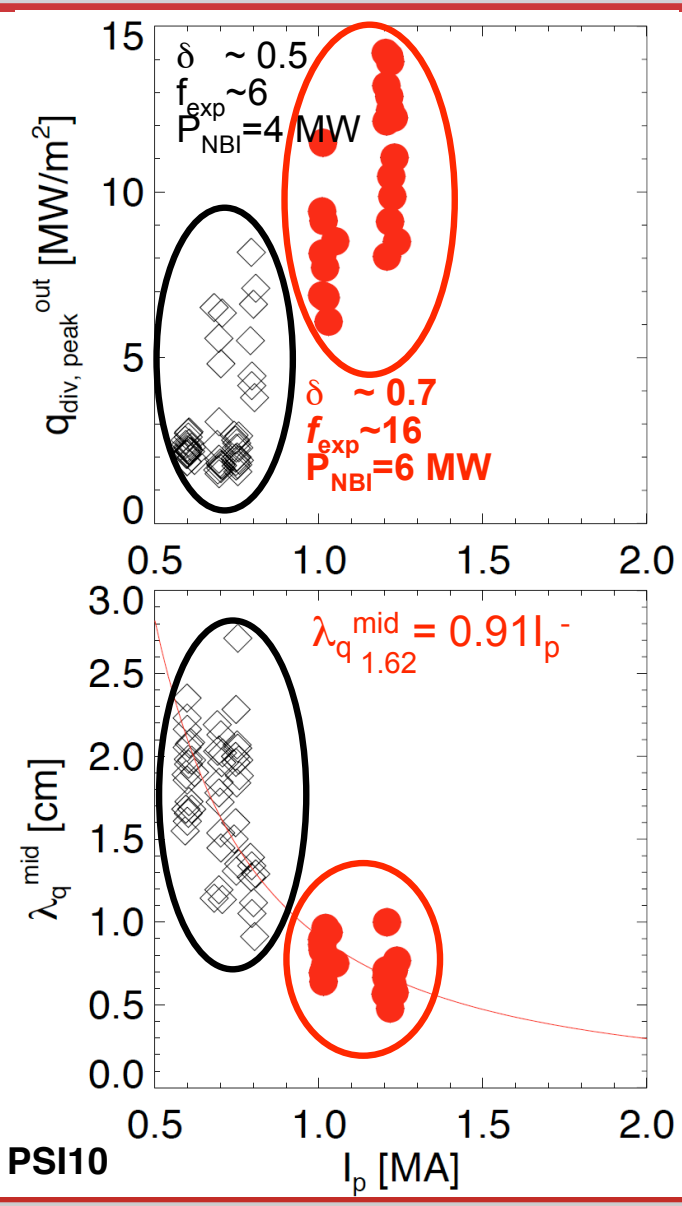


- Narrow P_{loss} plot range
- Add in high δ data
- Apparent I_p or q_{95} effect

Gray, PSI10

Heat flux width decreases with I_p in NSTX

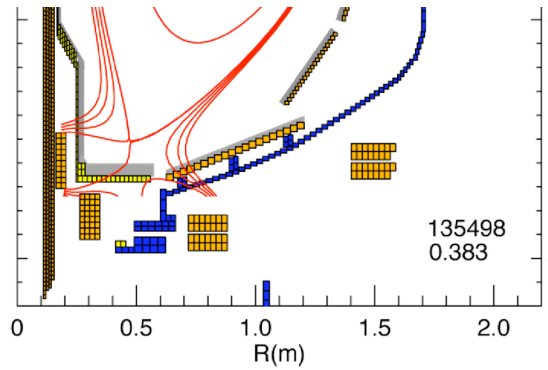
- Combined data from dedicated I_p scans in low δ and high δ discharges
  - I_p dependence also in DIII-D, JET
  - Different P_{NBI} and f_{exp}, but previous slides shows no P_{loss} or f_{exp} effect on λ_q^{mid}
  - q_{95}, ℓ_{II} different
- Power law fit: $\lambda_q^{mid} \sim 3$ +/- 0.5 mm @ 2 MA
- Lodestar group making progress on simulations (Myra, PSI10)

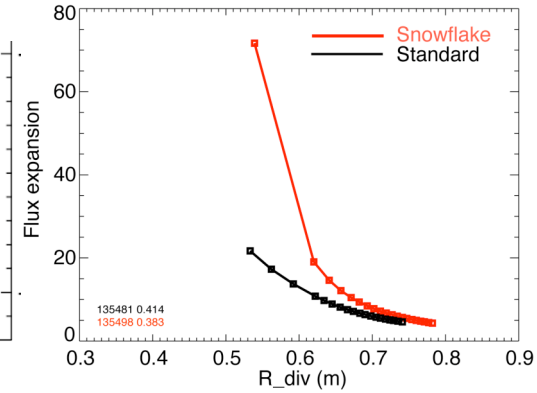


Gray, PSI10

Snowflake-like topology showed broad region of low heat flux

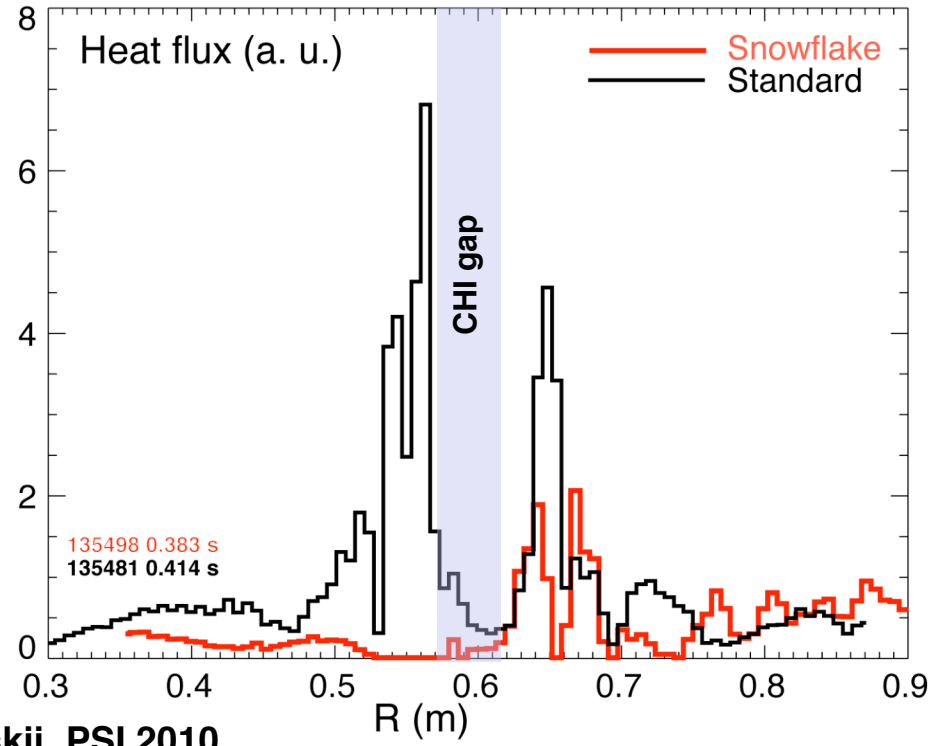
- Approximate snowflake divertor configuration achieved, with higher f_{exp} (3 mm flux surfaces shown)





- Heat flux profile made broader with reduced peak value

- Substantial high-n Balmer emission, indicative of volume recombination



Soukhanovskii, PSI 2010

Joint Modeling Activities

- Myra: Turbulence-based SOL width estimates for NSTX and C-Mod (PSI10 paper)
- Chang: XGC-0 modeling of I_p and P_{NBI} scans for all three devices
- Rognlien, et. al.: UEDGE interpretive modeling of DIII-D, and possibly C-Mod and NSTX
- Canik: SOLPS interpretive modeling of NSTX
- Umansky: possible modeling of C-Mod/DIII-D identity experiments with BOUT
- Goldston: 1-D modeling of C-Mod and NSTX, and data request for DIII-D (E.g. Goldston PoP 2010)
- Elder: 1D interpretive ODGE interpretive modeling for radially dependent transport coefficients

Electrostatic edge/SOL turbulence can probably explain the SOL width in NSTX L-mode and low power ELM-free H-mode

- Two mechanisms identified:
  - Separatrix-spanning intermittent convective cells lead to a near SOL with diffusive-type of scaling wrt $L_{||}$
  - At higher powers (poorer confinement) and longer $L_{||}$, blob transport give rise to a convective scaling
  - The transition appears to occur when $k_y \lambda_q > 1$ and results in increasing frequency of bursts
- The SOL width in high power and especially low I_p discharges on NSTX has additional broadening mechanisms. Some possibilities which could be explored theoretically and/or experimentally are:
  - divertor leg instabilities [Ryutov & Cohen]
  - hot ion losses
  - MHD activity that moves the X-pt / strike point

Myra, PSI 2010

Implications for power producing devices (preliminary)

- Much work needed for first principles projection
- Continued narrowing of heat flux footprint at higher I_p could be problematic
  - Need to understand mechanism
- For power producing devices, the possible heat flux footprint increase with R (and/or a), and with P_{SOL} would counter-balance the narrowing with I_p
- No apparent strong B_t dependence of footprint

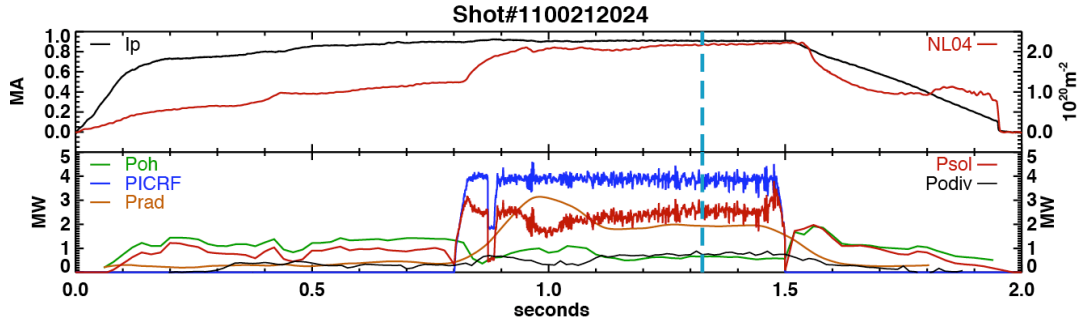
➢ *Recommend some additional experimental focus on novel divertors and heat spreading techniques*

  - X-divertor and super-X divertors (Kotschenreuther, Valanju, Mahajan)
  - Snowflake divertors (Ryutov, Umansky)
  - Induced divertor leg turbulence? (Ryutov, Cohen)

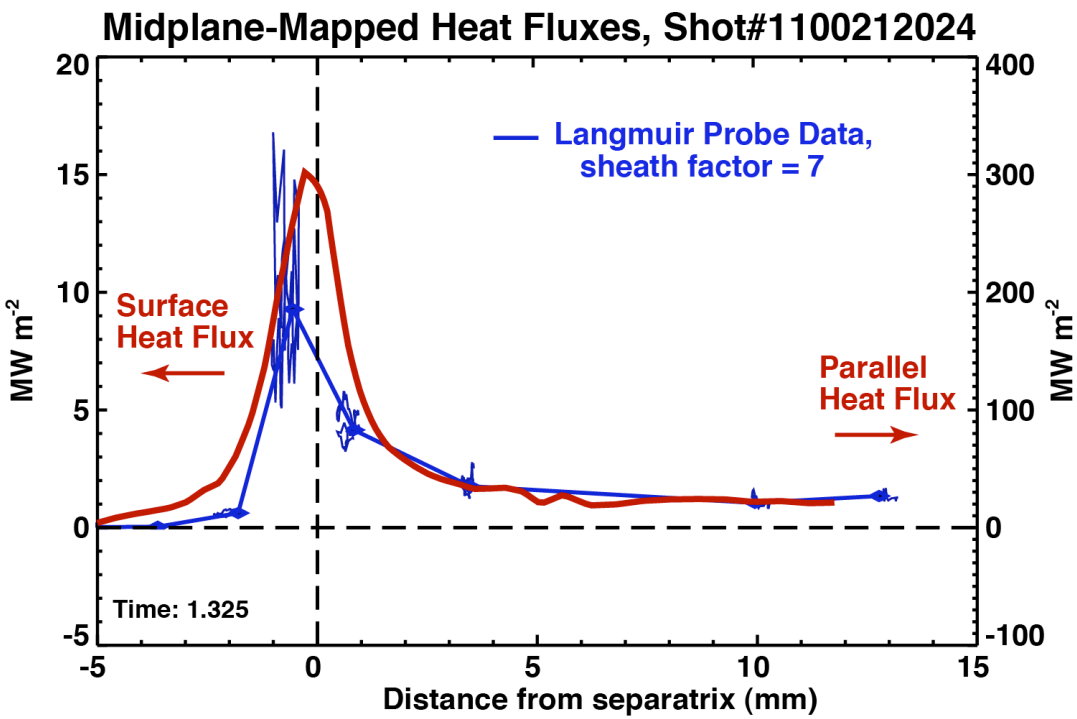
- Joint Research Milestone report available ~ Oct. 2010

Backup

Initial Footprint Observations:
C-Mod heat flux channels are narrow with 'tail' features



Footprint taken from similarity discharge, 1.325 s



- *Narrow with 'tail' feature*
- *'tail' consistent with LP data*

LaBombard, PSI10

C-Mod Plans: 2nd half of FY10

April-June -- Manned vessel access

- *Replace Ramped Tiles in strike-point region (repair Tungsten tiles)*
- *New & improved set of Calorimeters, Surface TCs and Tile TCs sensors/cables*
- *Repair damaged Langmuir probes on outer and upper divertors*
- *New Langmuir probe array on Ramped Tiles*
- *Clean IR periscopes, install 'landmark' tiles in divertor view*
- *Bundle data for modeling studies*

May -- PSI Meeting, San Diego

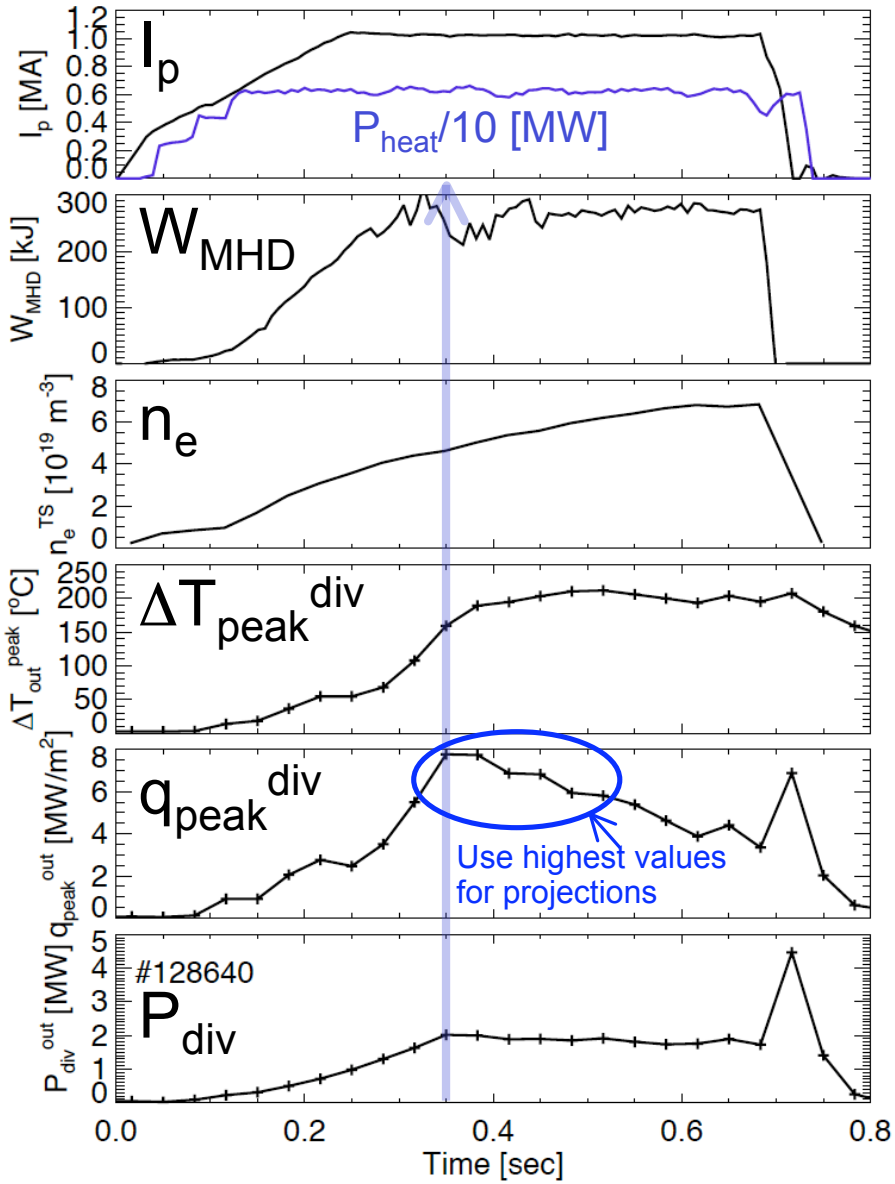
July-September -- Summer run campaign

- *Revisit L-Mode heat flux footprints (MP#570)*
- *Continue H-Mode footprint studies (MP#591)*
- *Assemble empirical scalings, connections to 'upstream' measurements*
- *Joint Facilities Research final report*

FY11 --

- *Continued boundary heat transport studies…*

Divertor peak heat flux evolves during discharge in NSTX



- 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 divertor temperature rise 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)

NSTX FY 2010 experiment 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
  - Separate during and between ELM profiles
- Continue snowflake divertor development
- Continue 2D interpretive modeling of scenarios