NSTX

Supported by U.S. DEPARTMENT OF ENERGY | Office of Science

Physics of the H-mode Pedestal and its Possible Role in Setting the Power Flux Channel

Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
ORNL
PPPL
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Washington
U Wisconsin

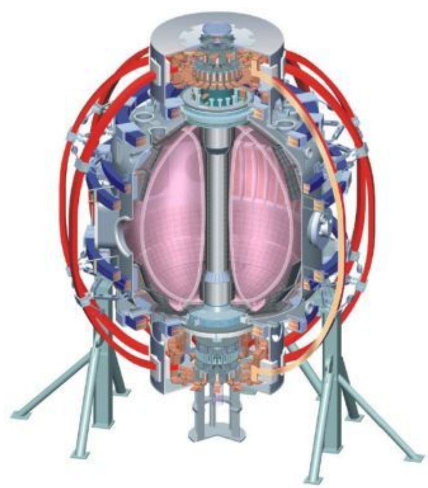
R. Maingi Oak Ridge National Laboratory

T. Gray, R. Groebner, B. LaBombard, M. Makowski, J-W. Ahn, J. Hughes, C. Lasnier, A. Leonard, P. Snyder, J. Terry, D. Whyte

20th International Conference on Plasma Surface Interactions
Aachen, Germany
May 21-25, 2012

Alcator C-Mod

DIII-D NATIONAL FUSION FACILITY



Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
NFRI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

Focused efforts have confirmed the importance of plasma current scaling for both pedestal gradients and divertor heat flux widths

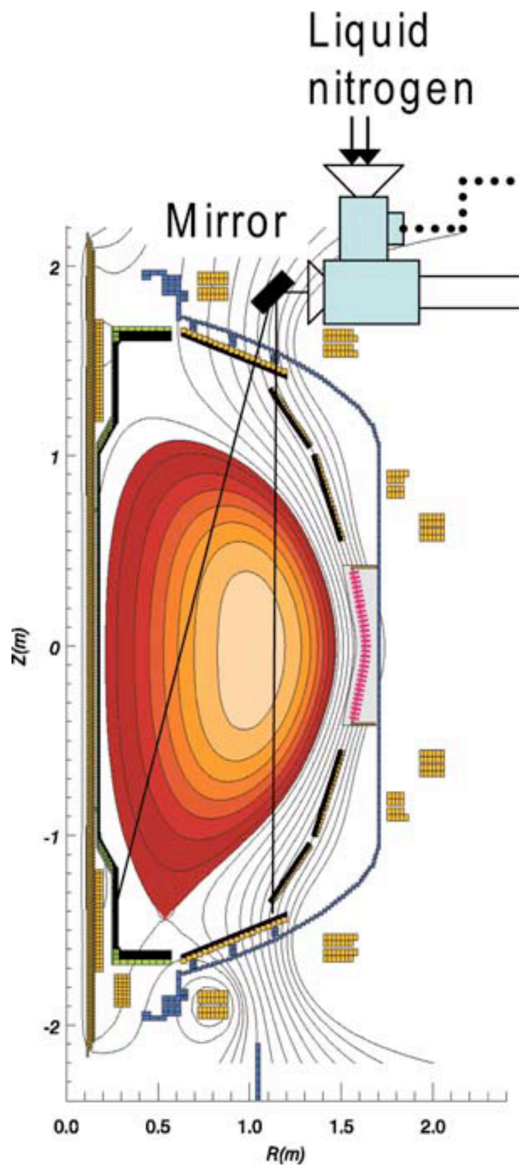
- Results of coordinated U.S. effort on the scaling of the divertor power flux width
  - Main finding: heat flux width $\lambda_q^{mid} \sim a/I_p \sim B_{pol}^{mid}$ (in near separatrix channel)
- Results of coordinated U.S. effort on the physics of the H-mode pedestal
- Correlations between the H-mode pedestal scalings and SOL heat flux footprints

Coordinated effort on SOL power flux width measurements emphasized common measurement/analysis techniques

- Common, parallel experiments in Alcator C-Mod, DIII-D, and NSTX with some level of cross-coordination
- Focus was on using IR thermography to measure heat flux profiles, and analyze midplane-mapped widths (integral power widths f/Loarte, exponentials, FWHM, Eich functions)
  - Outer divertor heat flux profiles in attached plasmas
- ELM-averaged and inter-ELM heat flux analysis done (EDA H-mode, ohmic, L-mode, I-mode in C-Mod)

- Main finding: heat flux width in near separatrix channel $\lambda_q^{mid} \sim a/I_p \sim B_{pol}^{mid}$

NSTX fast IR setup and view



- SBF focal plane array
  - 1.6 kHz 128 x 128
  - 6.2 kHz 96 x 32
  - LN2 cooled
- Retrofitted with home-made dual-band adapter to better account for emissivity effects
- Heat flux computed via 1-D conduction model and 2-D THEODOR model (in collaboration w/A. Herrmann and IPP)

Methods to characterize heat flux profile

- 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}:

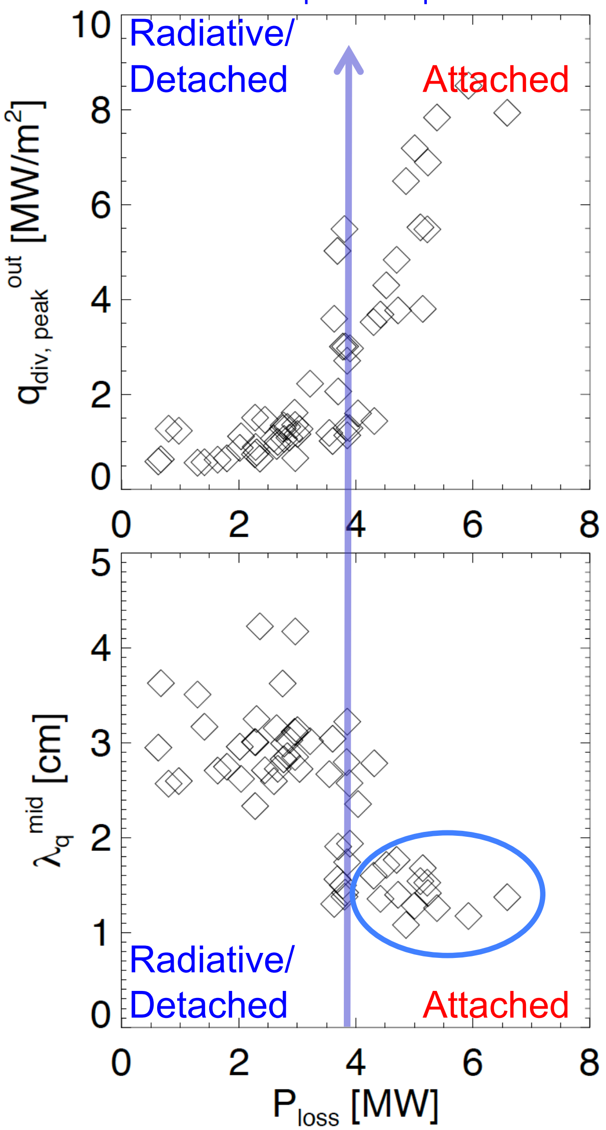
$$\lambda_q^{mid} = \lambda_{q,div}^{out} / f_{\exp} \text{ with } f_{\exp} = \frac{R_{mid} B_\theta^{mid}}{R_{div} B_\theta^{div}}$$

- Determine dependence of λ_q^{mid} on external parameters (I_p, P_{loss}, B_t, flux expansion) from NSTX data
  - *Can re-arrange equation to project for future devices*
- Other fitting functions used also: Eich functions, FWHM, exponential fit

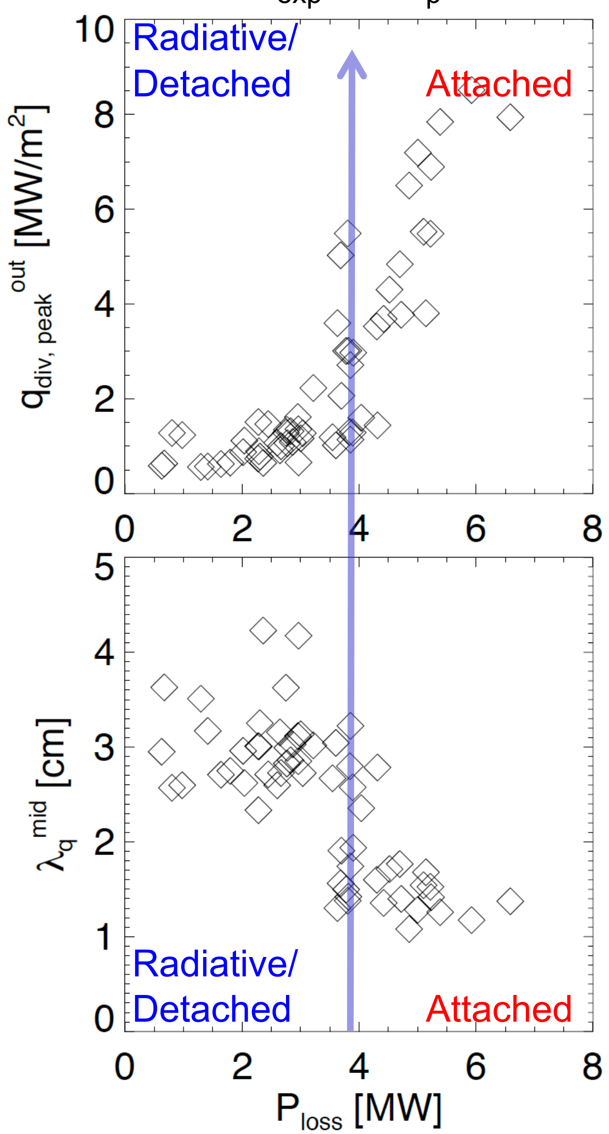
*Loarte, JNM 1999

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

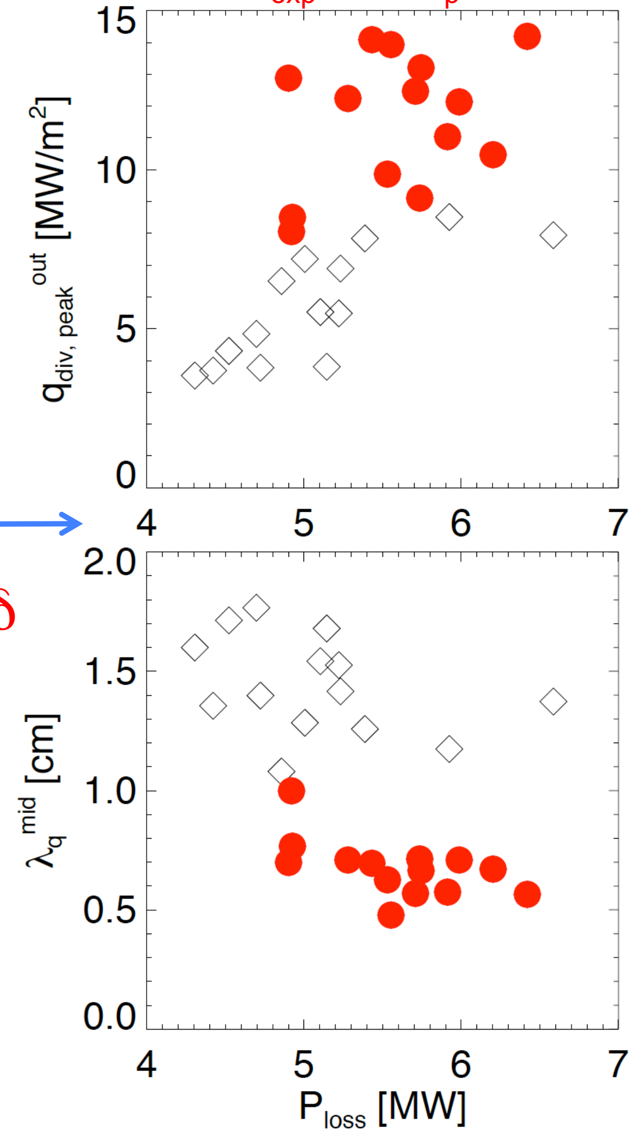
δ ~ 0.5, f_{exp} ~ 6, I_p= 0.8 MA



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

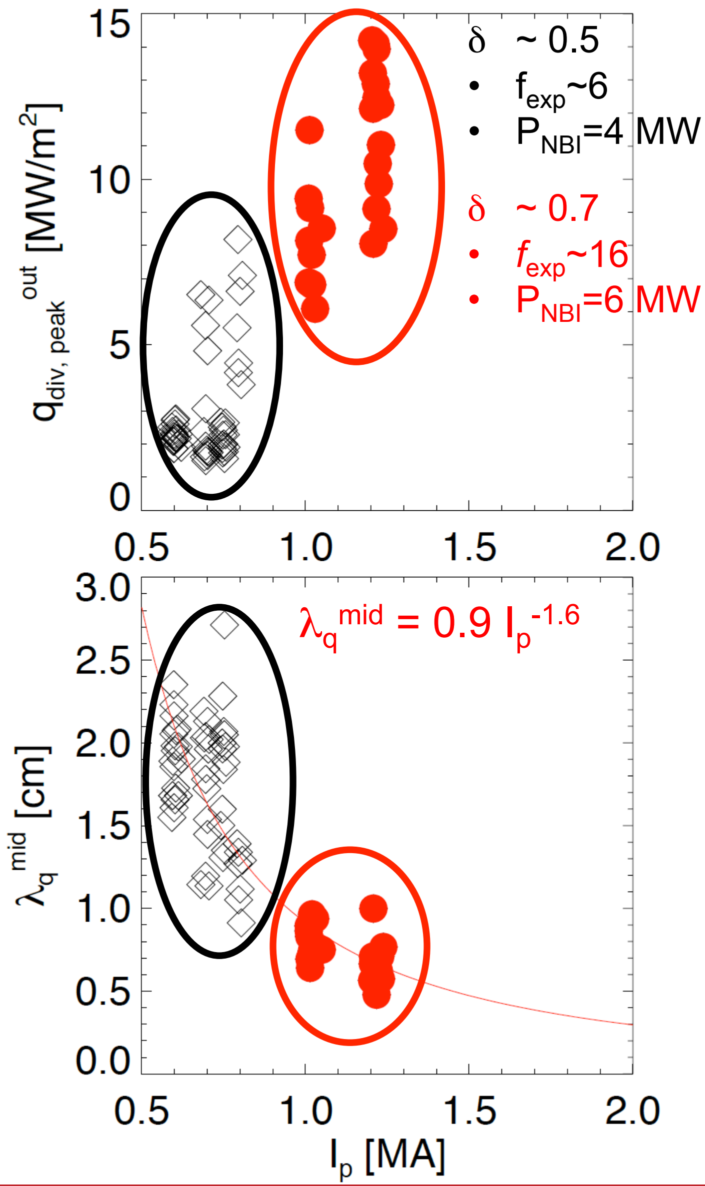


- Narrow P_{loss} plot range
- Add in high δ data
- Apparent I_p or q_{95} effect

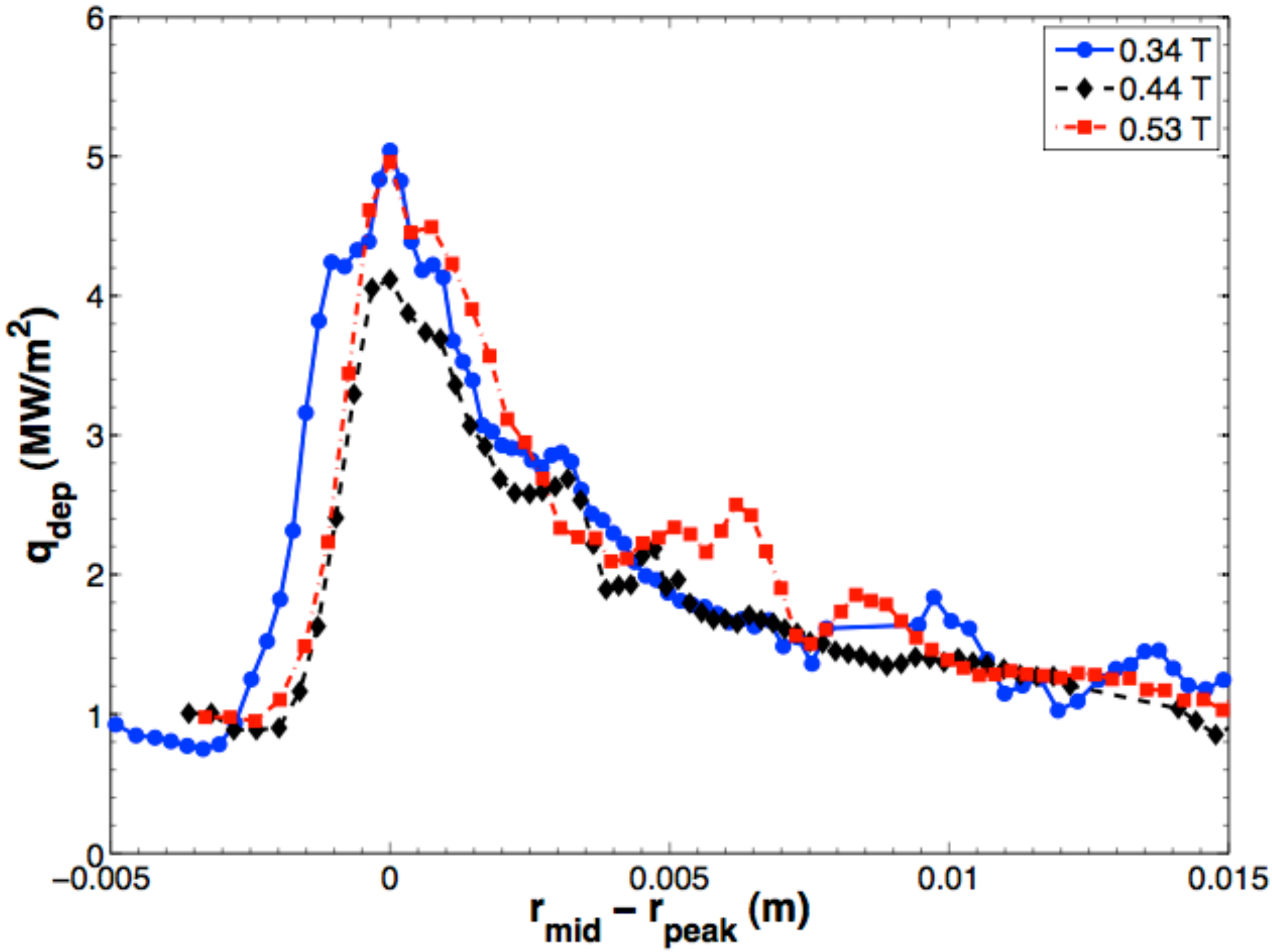


Heat flux width decreases with I_p in NSTX

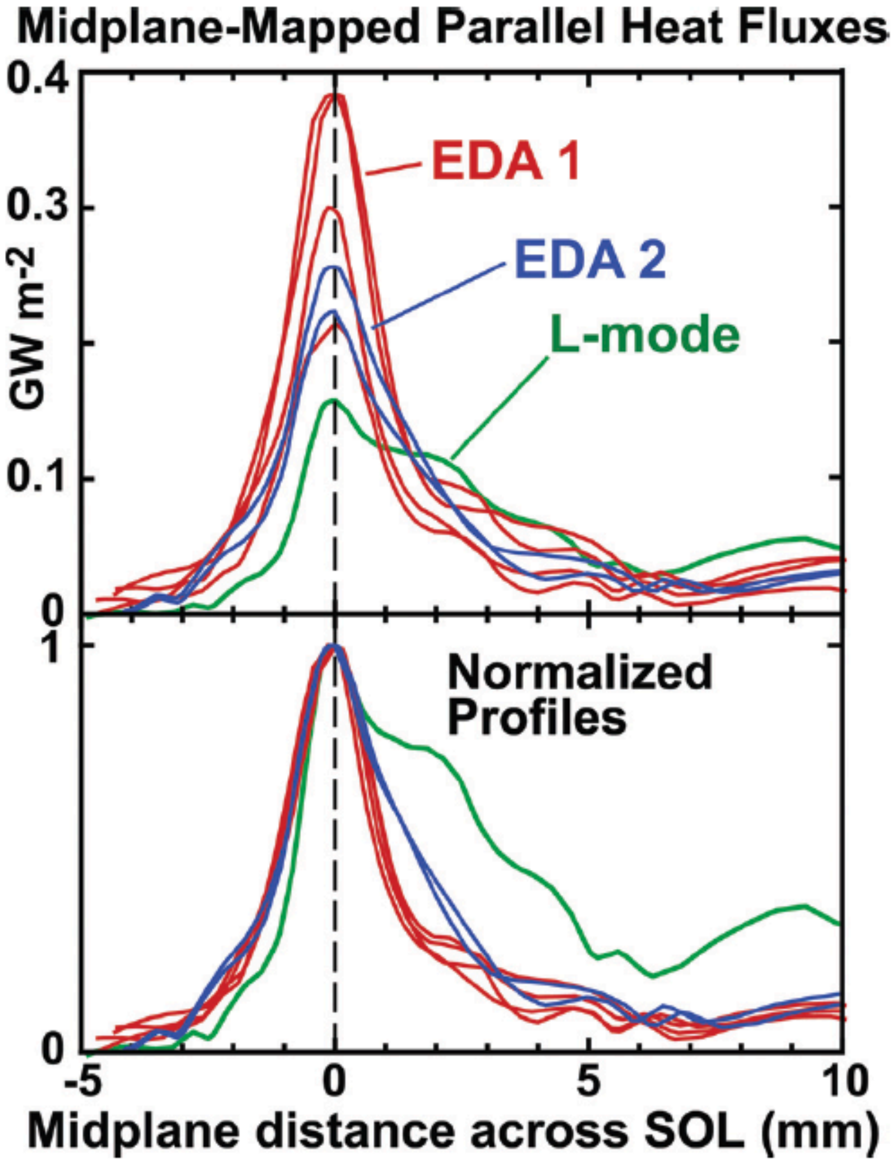
- Combined data from dedicated I_p scans in low δ and high δ discharges
  - I_p dependence also in DIII-D, JET
  - Different P_{NBI} and f_{exp}, but previous slides shows no P_{loss} or f_{exp} effect on λ_q^{mid}
  - q_{95}, $\ell_{||}$ different
- Power law fit: $\lambda_q^{mid} \sim 3$ +/- 0.5 mm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



No B_t dependence in near SOL heat flux profiles in NSTX, so I_p dependence is not a hidden q_{95} or $l_{||}$ dependence

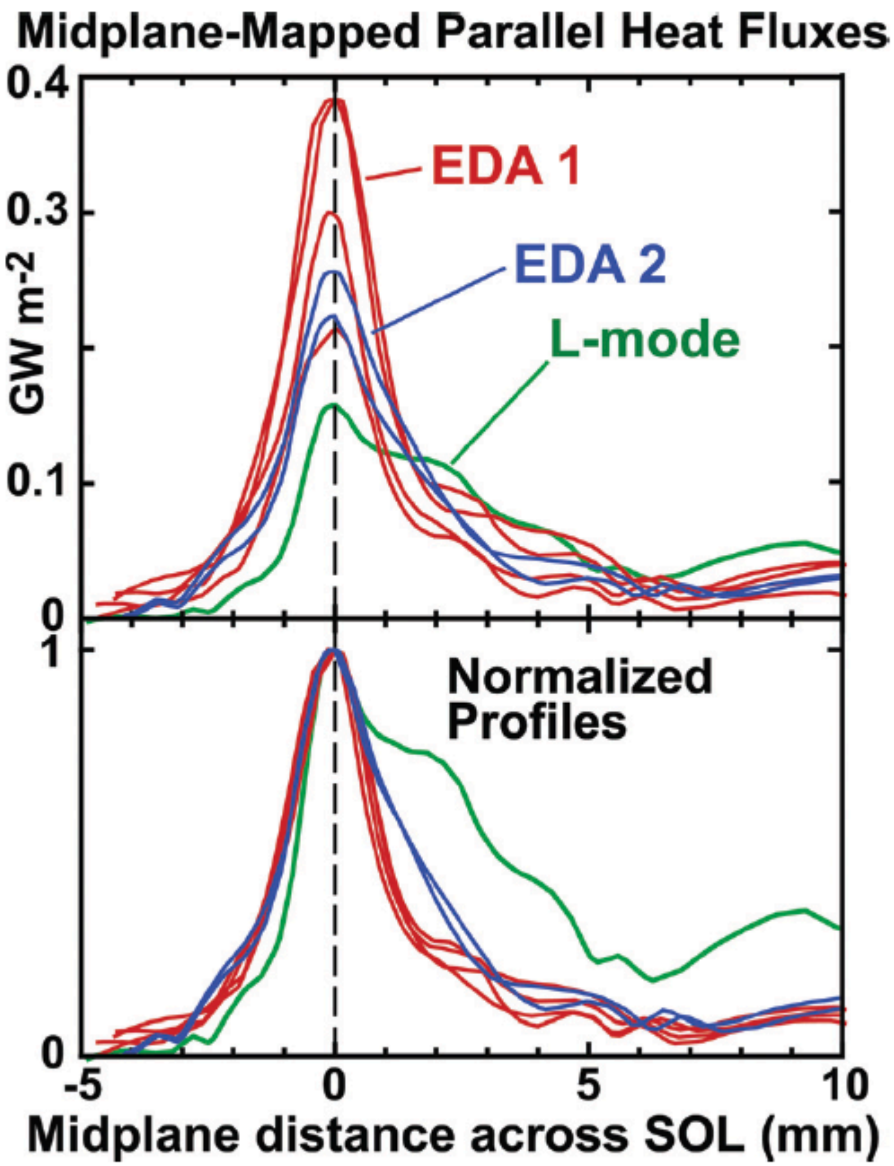


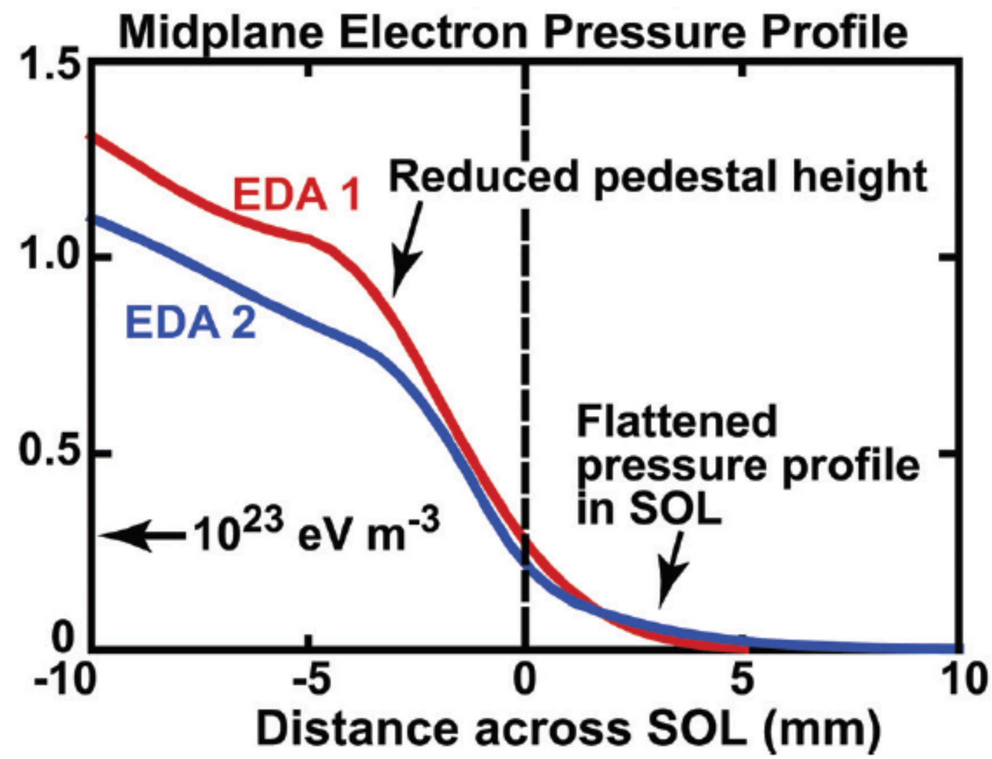
Heat flux profiles studied for several different scenarios in C-Mod



LaBombard PoP 18 (2011) 056104

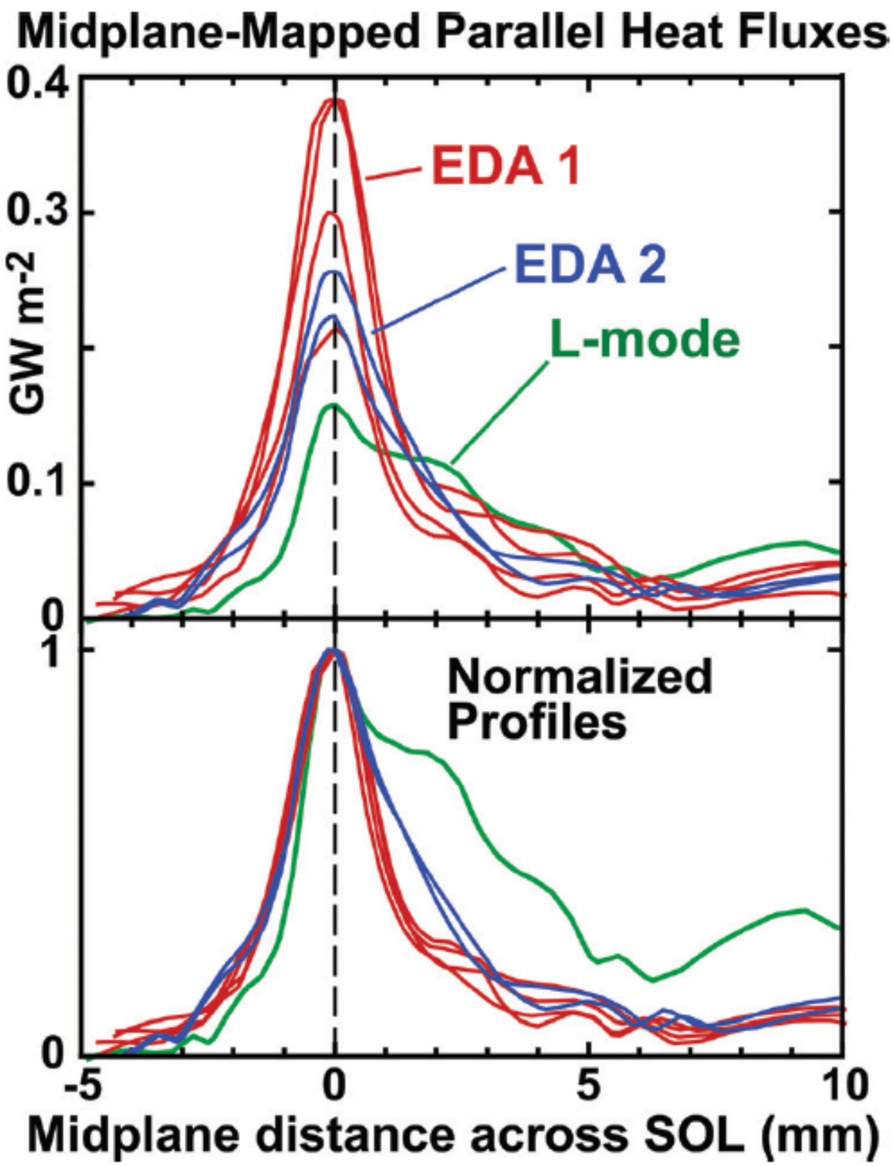
Two EDA H-modes had different pedestal performance

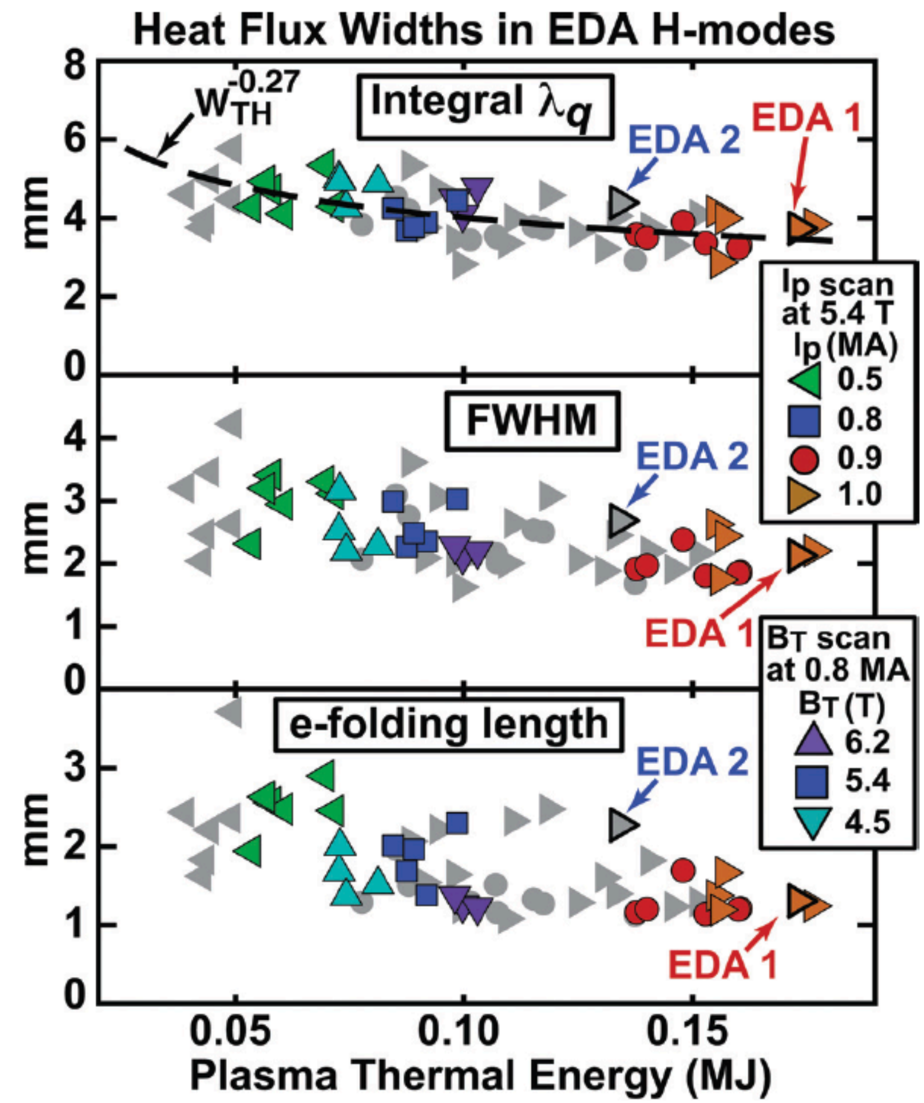




LaBombard PoP 18 (2011) 056104

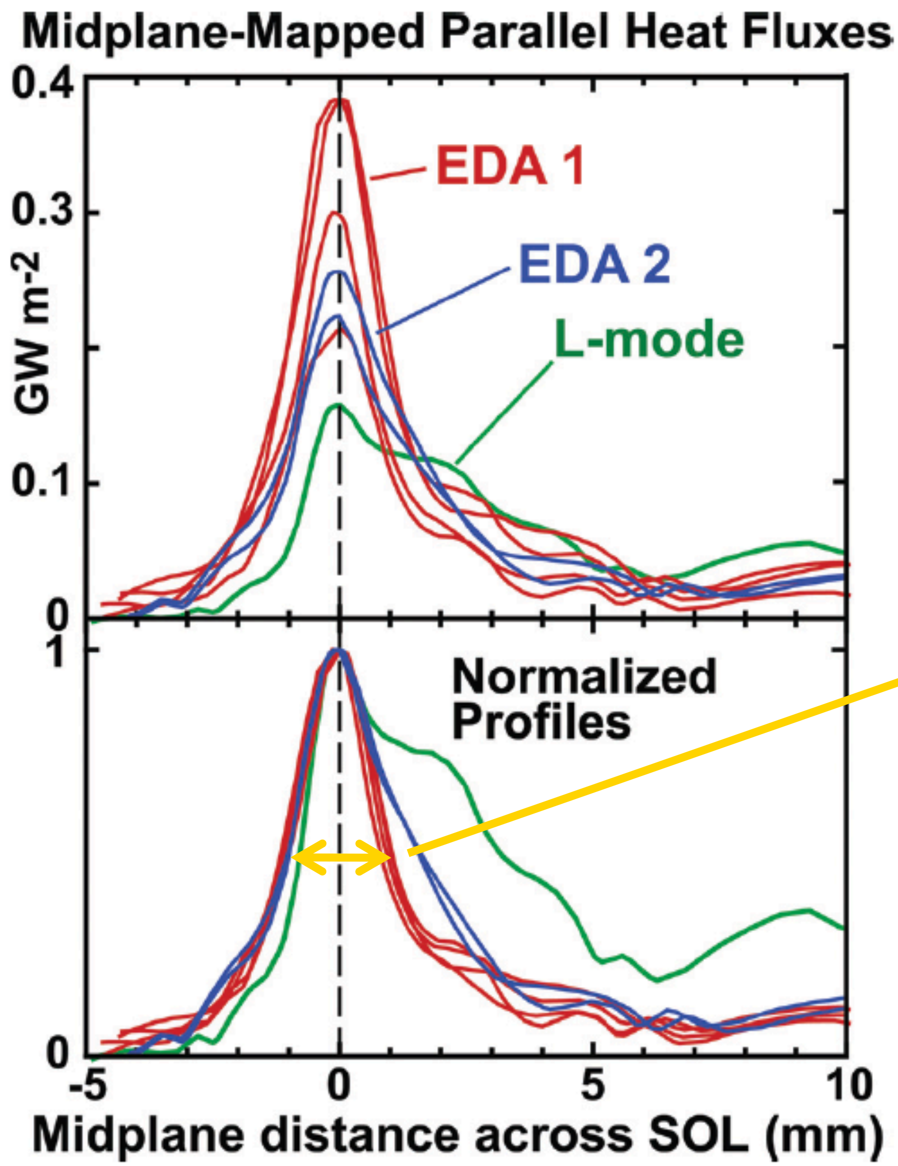
Weak dependence of heat flux widths on plasma stored energy

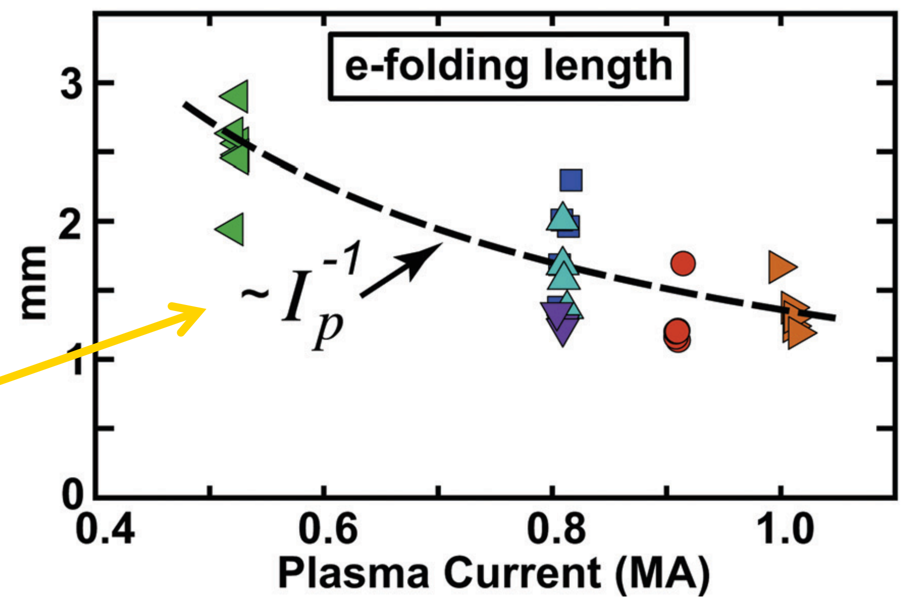




LaBombard PoP 18 (2011) 056104

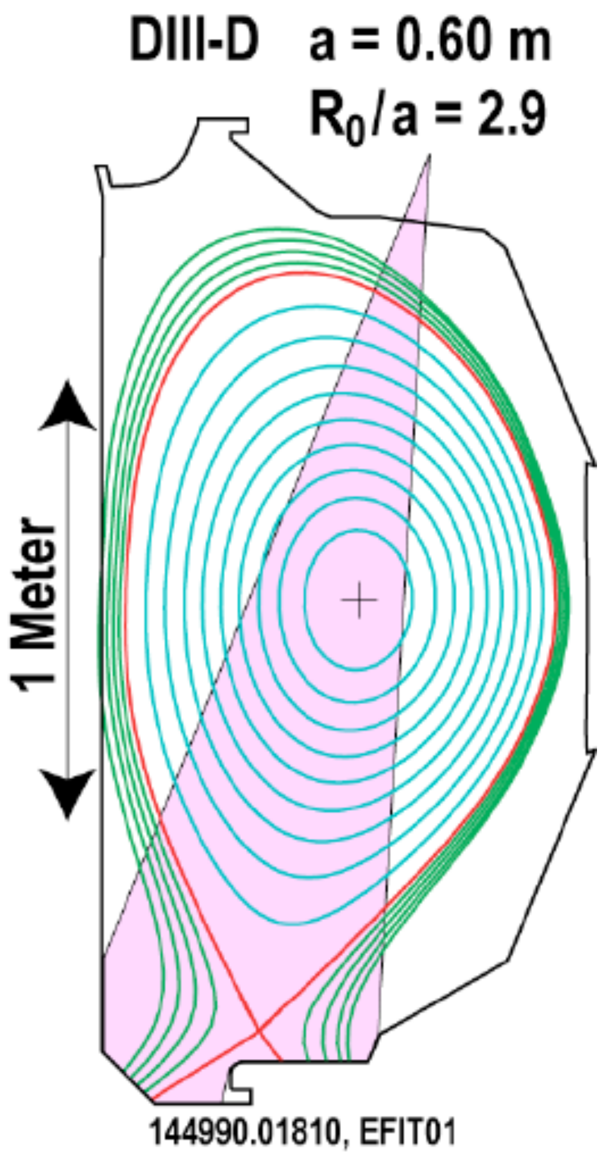
Strong dependence of near separatrix heat flux widths on I_p

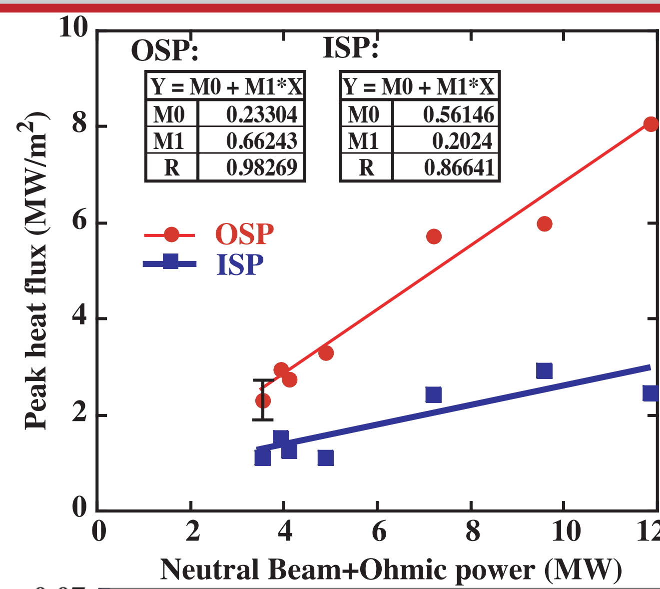


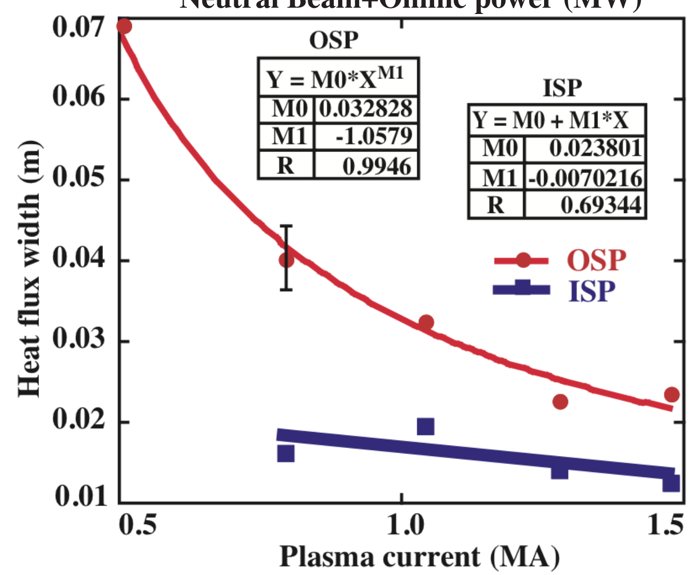


LaBombard PoP 18 (2011) 056104

Strong inverse dependence of heat flux widths on I_p also observed in DIII-D







FY 2010 JRT report, Oct. 2010

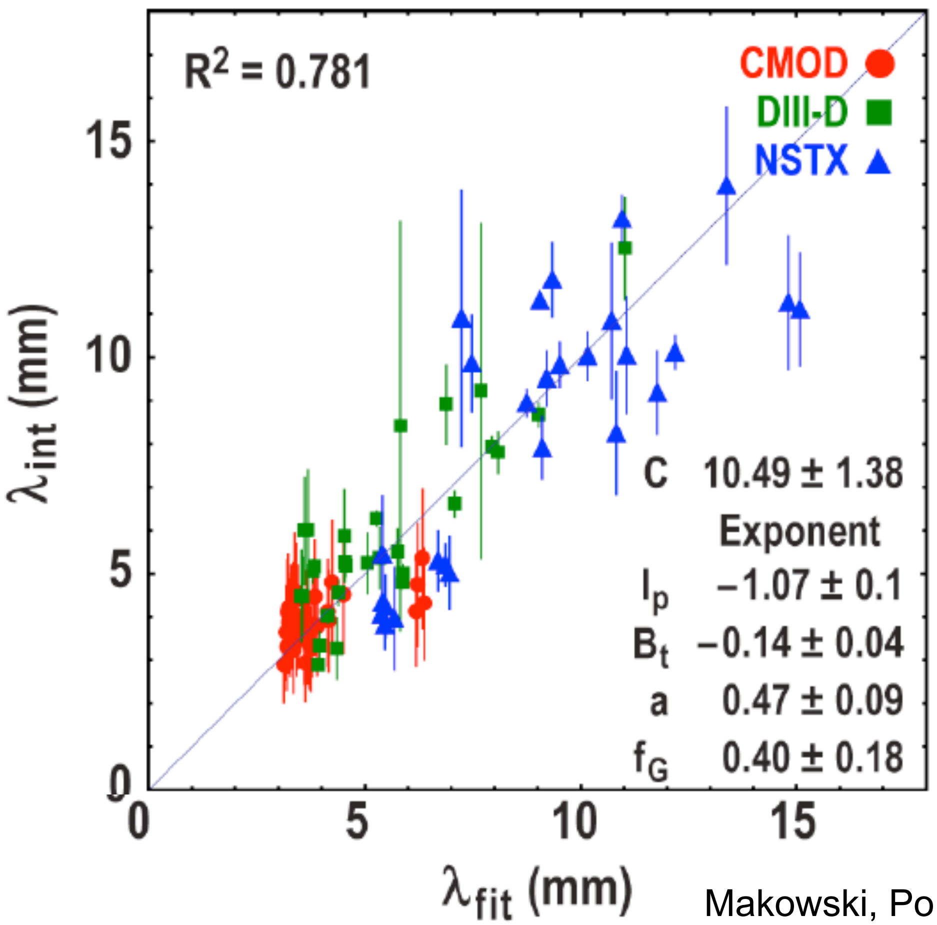
Combined scaling from US tokamaks highlights the I_p and minor radius (a) dependence

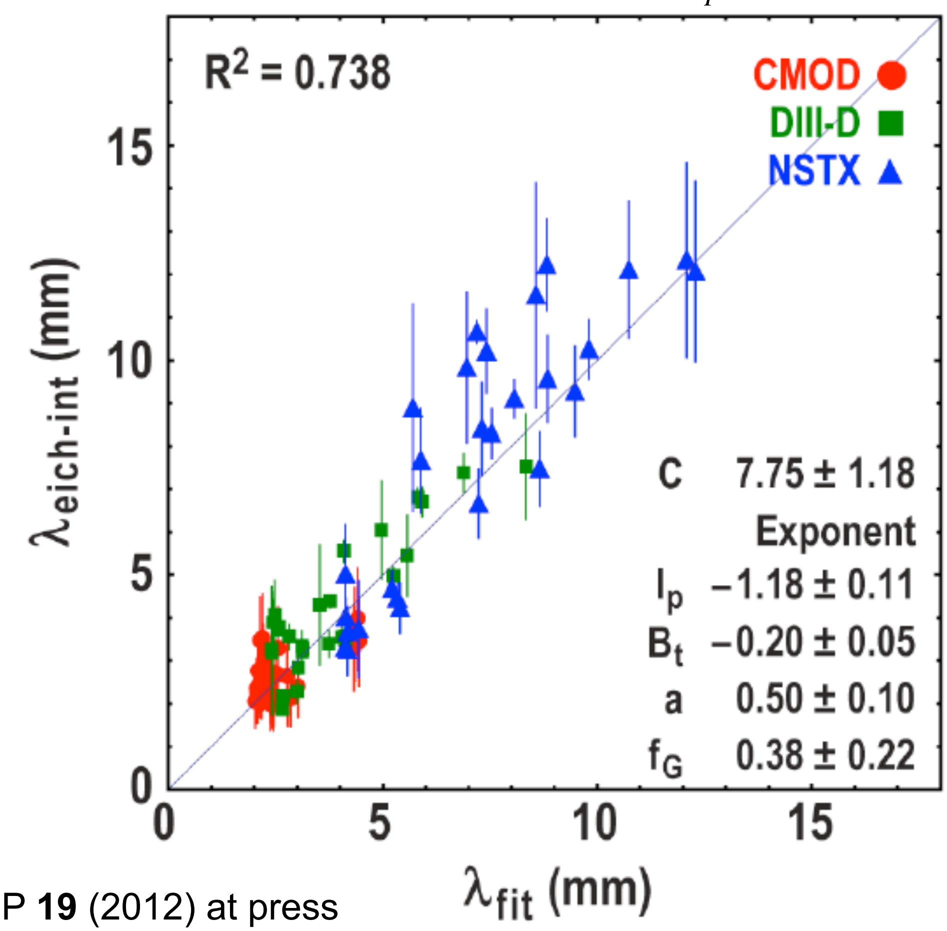
$$\lambda_{fit} = C \cdot I_p^{e_I} \cdot B_t^{e_B} \cdot a^{e_a} \cdot f_G^{e_f},$$

$$f_G = n_e / (I_p / \pi a^2)$$

$$\lambda_{eich-\mathrm{int}} = \frac{1}{q_{\parallel 0}} \int_{-\infty}^{\infty} [q_{\parallel}(s) - q_{bkg}] ds$$

$$\approx \lambda_{sol} + 1.64 w_{pvt}$$



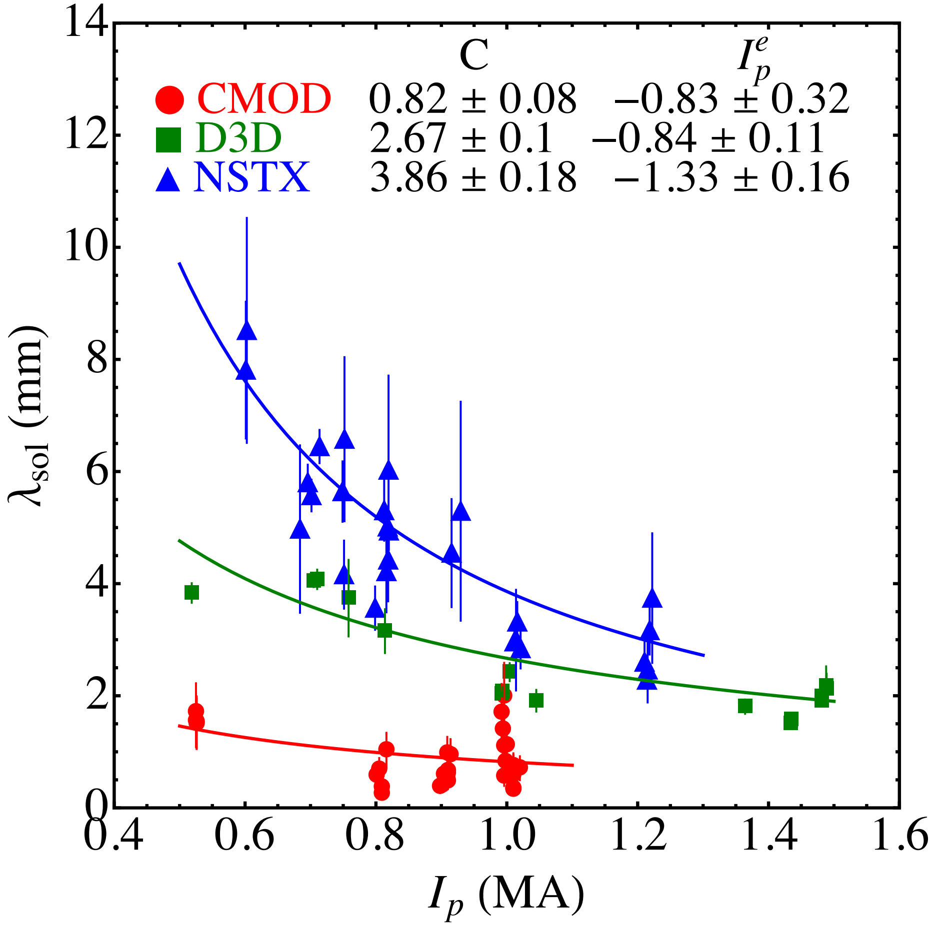


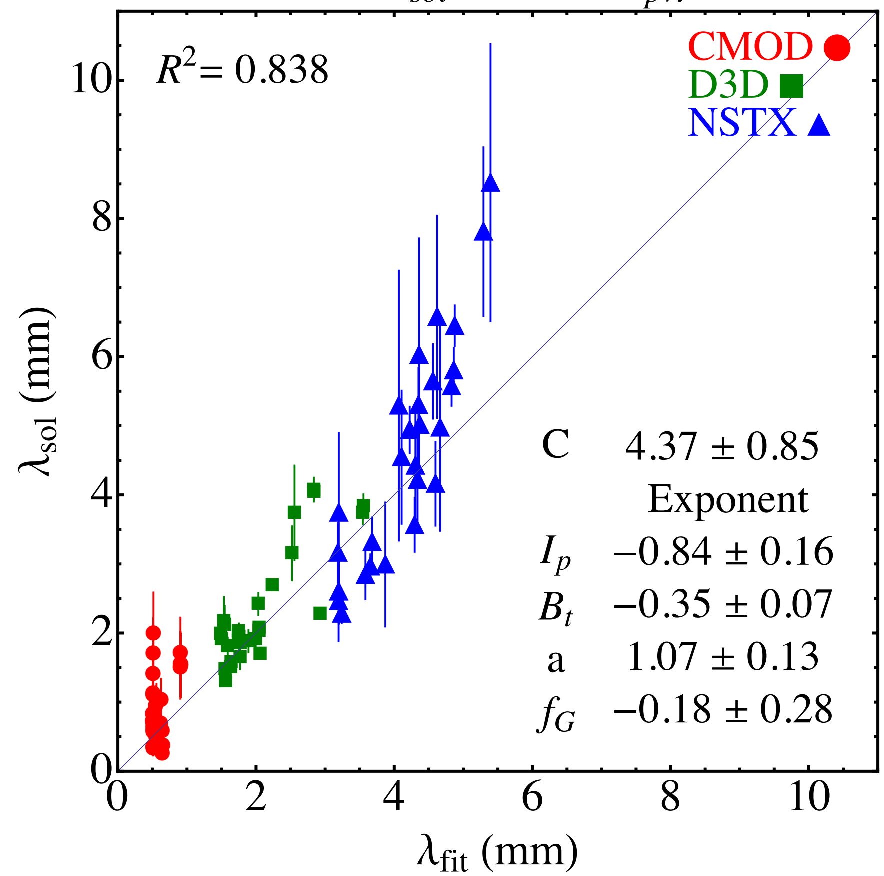
Makowski, PoP **19** (2012) at press

Combined scaling from US tokamaks highlights the I_p and minor radius (a) dependence

Makowski, PoP **19** (2012) at press

$$\lambda_{eich-\text{int}} = \frac{1}{q_{\parallel 0}} \int_{-\infty}^{\infty} [q_{\parallel}(s) - q_{bkg}] ds \approx \lambda_{sol} + 1.64 w_{pvt}$$



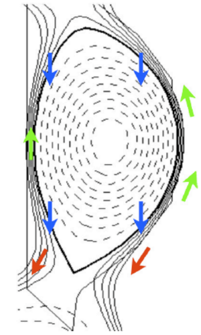


$$\lambda_{fit} = C \cdot I_p^{e_I} \cdot B_t^{e_B} \cdot a^{e_a} \cdot f_G^{e_f}, \qquad f_G = n_e / (I_p / \pi a^2)$$

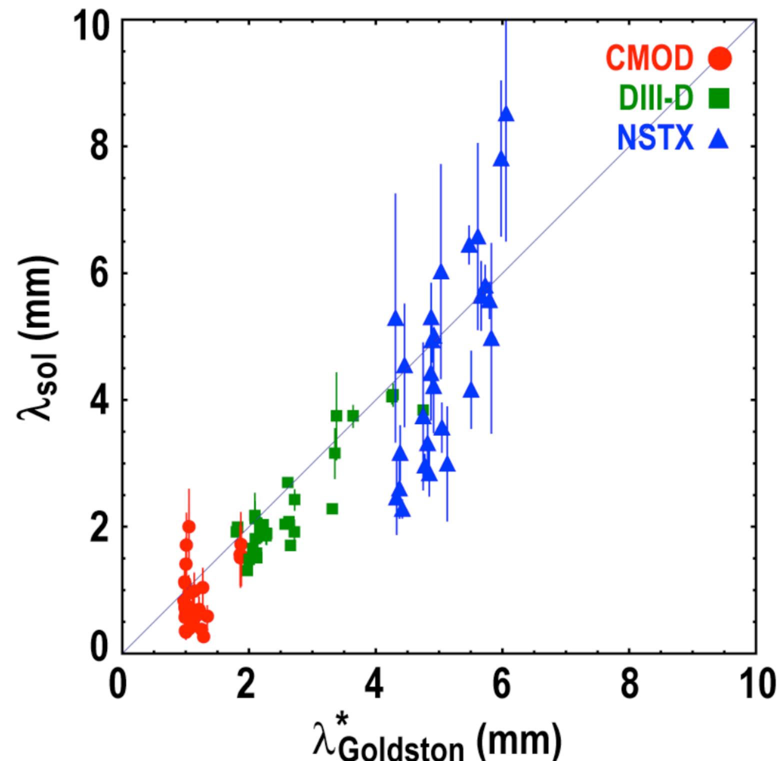
Combined US dataset in good agreement with Goldston heuristic drift model

$$\lambda^*_{Goldston} = 5671 \cdot P_{sol}^{1/8} \frac{(1+\kappa^2)^{5/8} a^{17/8} B^{1/4}}{I_p^{9/8} R} \left(\frac{2\bar{A}}{1+\bar{Z}}\right)^{7/16} \left(\frac{Z_{eff}+4}{5}\right)^{1/8} f_{mp}$$

Goldston, NF **52** (2012) 013009; P1-15 this conference



- **Physics: V_{drift}*2qR/c_s results in SOL width ~ 2 * ρ_{pol}, with temp. set by Spitzer thermal cond.**
- **Reasonable agreement with data in both absolute values and scaling**



Makowski, PoP **19** (2012) at press

Outline

- Results of coordinated U.S. effort on the scaling of the divertor power flux width
- Results of coordinated U.S. effort on the physics of the H-mode pedestal
  - Main finding (1): peeling-ballooning modes limit pedestal height in all three devices
  - Main finding (2): EPED model (using PB modes and Kinetic Ballooning Modes) predicts C-Mod and DIII-D pedestals, including observed increases in pressure gradients with I_p
- Correlations between the H-mode pedestal scalings and SOL heat flux footprints

Pedestal physics was the focus of a recent US national effort

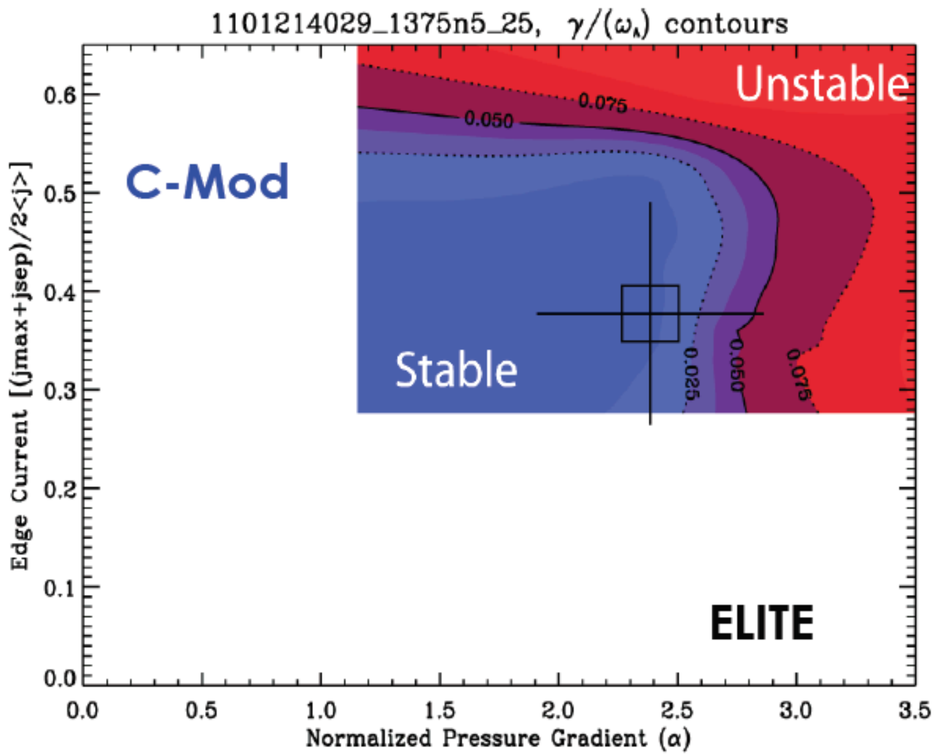
- **Research featured strong coordination of experiment, modeling and theory**
- **Main goal was to improve understanding of physics mechanisms that control the pedestal structure**
- **Dedicated pedestal experiments on C-Mod, DIII-D and NSTX**
  - Data made available to modelers
- **Development of theoretical models and codes**
  - Application of several codes to interpret experimental data
- **Focus here is on studies which compared more than one machine or more than one code**

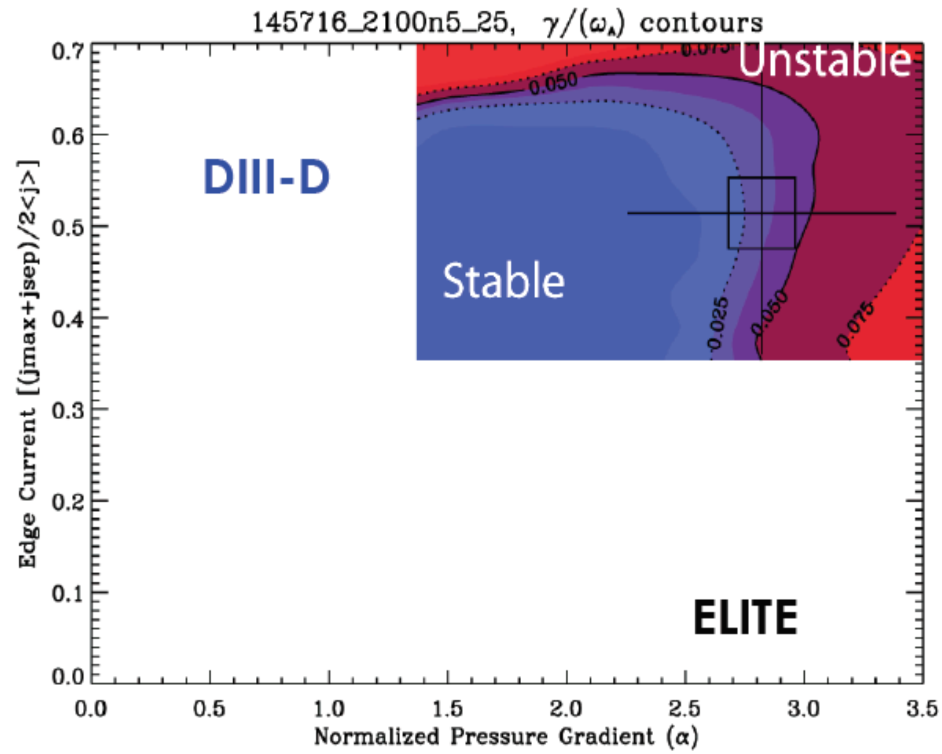
High level summary of the effort, and outstanding issues

- **We have improved quantitative understanding of several physics processes**
  - Peeling-ballooning stability, bootstrap current, width scaling
- **EPED model predicts pressure pedestal height in moderate aspect ratio tokamaks to ~20% accuracy**
  - Enabled by improved quantitative understanding (discussed above)
  - *Issue: Need measurements of KBM and comparison with simulations*
- **A number of transport processes may be operative in the pedestal**
  - Understanding these processes is required to predict time evolution of pedestal
  - *Issue: Need very significant work in use and development of codes to model transport, particularly from gradient-driven micro-instabilities*
- **Evidence exists for roles of a pinch and of neutral fuelling in density pedestal**
  - Improved understanding required to answer ITER concerns about pedestal density
  - *Issue: Need way to measure pinch in pedestal*

Type I ELM onset predicted by peeling-ballooning model for Alcator C-Mod, DIII-D, and NSTX

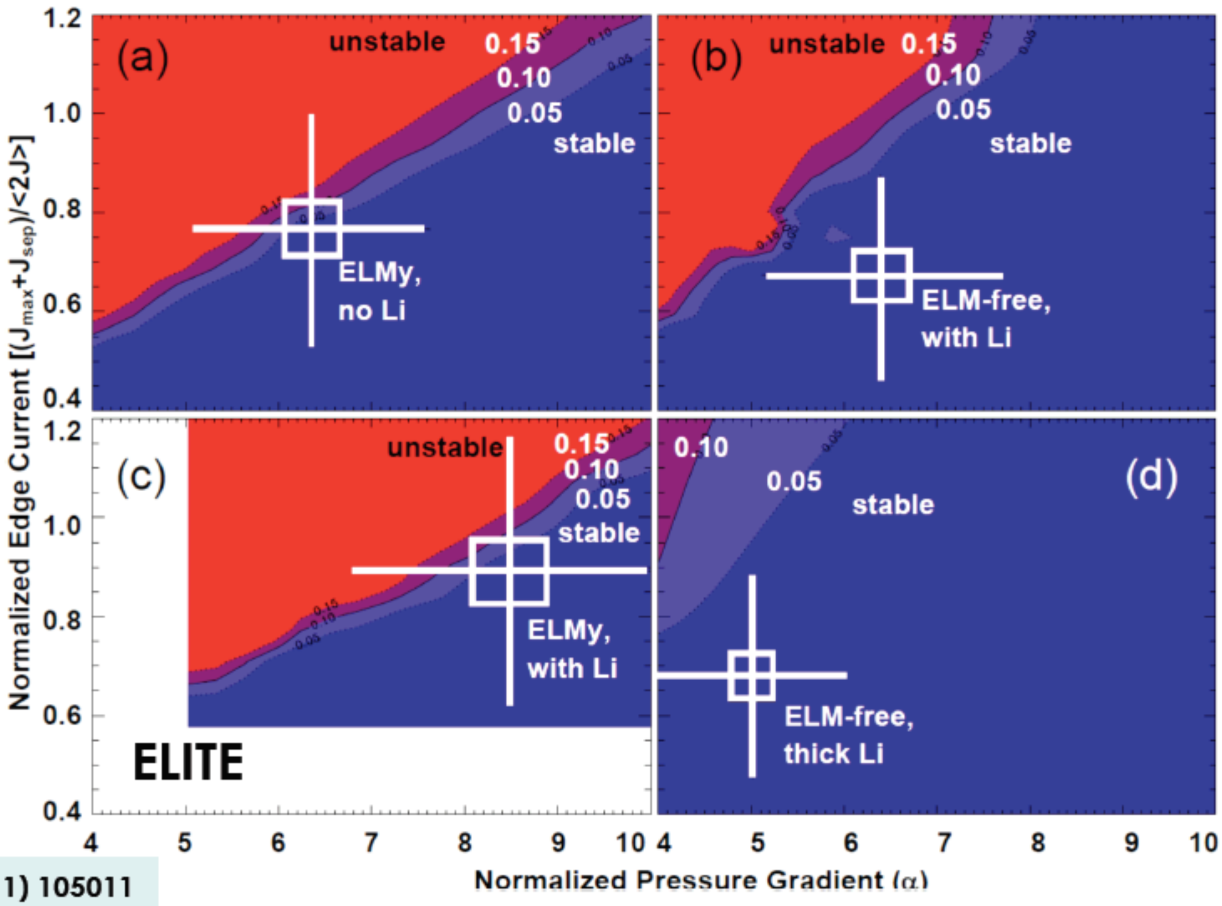
- Type I ELMs observed in C-Mod, DIII-D, NSTX near predicted stability boundaries (diamagnetic stabilization included)
- Type I ELM limits maximum pedestal size





ELM-free operation in NSTX afforded by thick lithium wall coatings consistent with peeling-ballooning physics

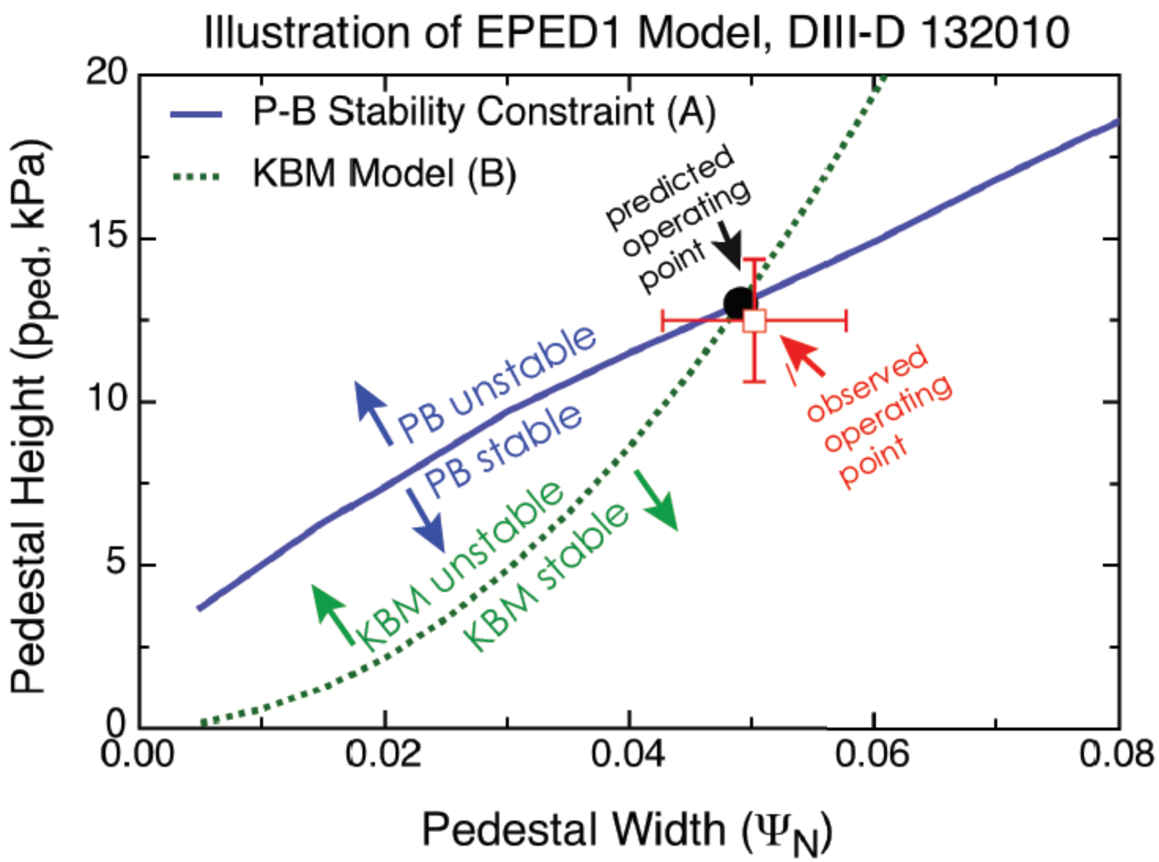
- Stable operation consistent with peeling-ballooning theory
- Kink/peeling stability improved by increase of the separation of the peak of the bootstrap current and the separatrix



Boyle, PPCF 53 (2011) 105011

A model for pedestal height has been developed and tested

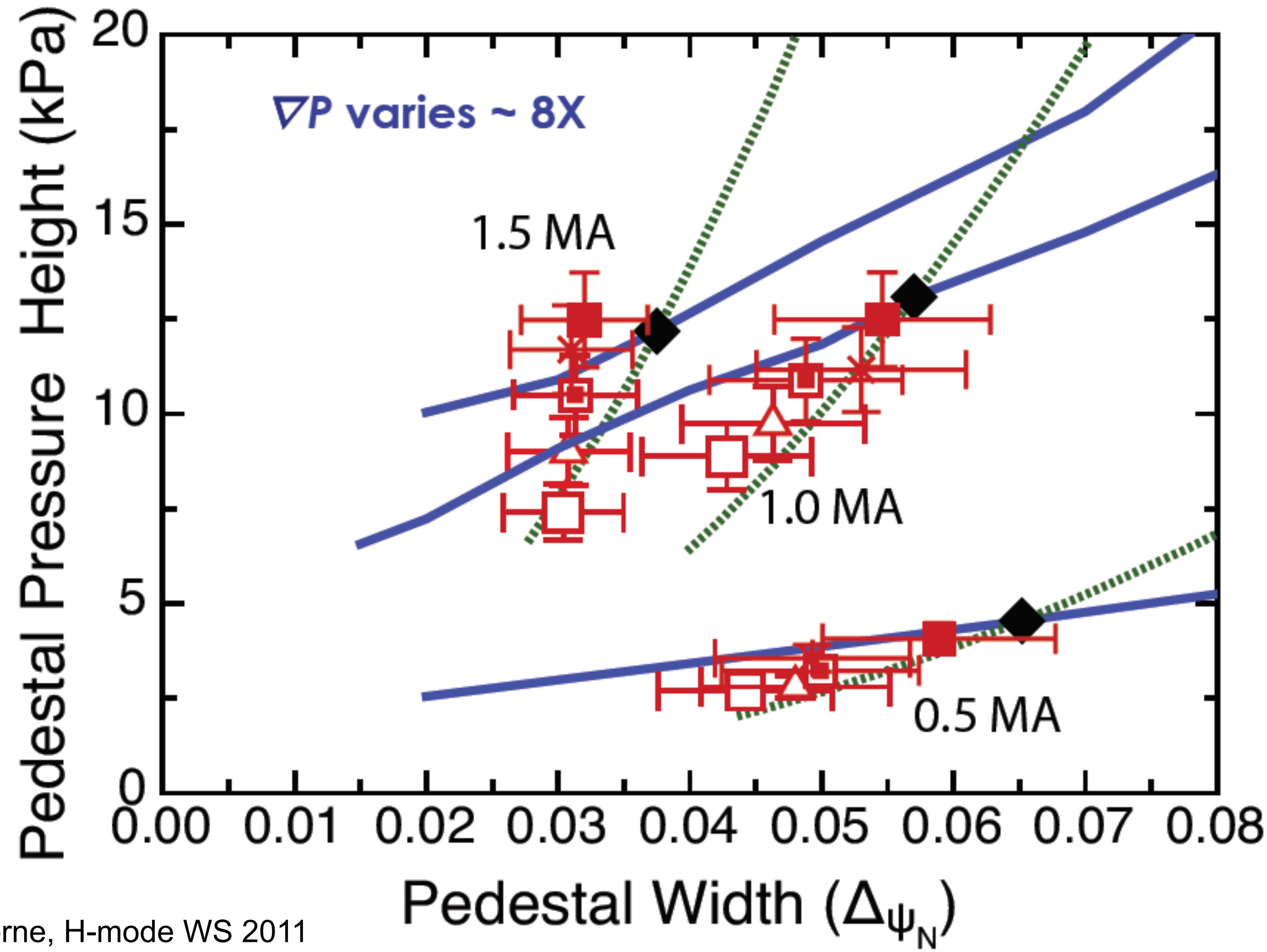
- **EPED model combines peeling-ballooning (PB) stability and a model for limit on pressure gradient**
- **Limit on Grad P from model of kinetic ballooning modes (KBM)**
  - Proposed to provide hard limit to pressure gradient
- **Combined models for PB and KBM predict a unique operating point**
- **And, predict a pedestal width scaling** $\Delta_{\psi_N} = \beta_{p,ped}^{1/2} G(\nu_*, \varepsilon \ldots)$



Snyder PoP 16 056118 (2009)

We have tested predictions of width scaling and of this operating space

EPED model predicts pressure gradient observed during pedestal buildup for a range of plasma currents

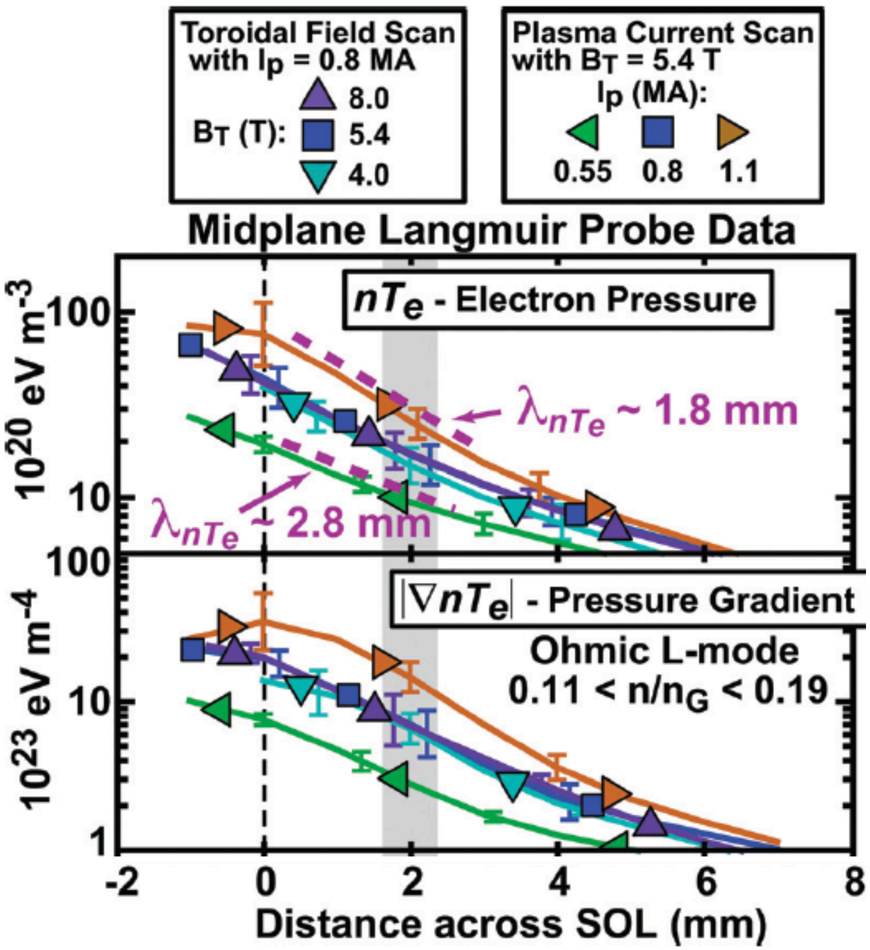


Osborne, H-mode WS 2011

Outline

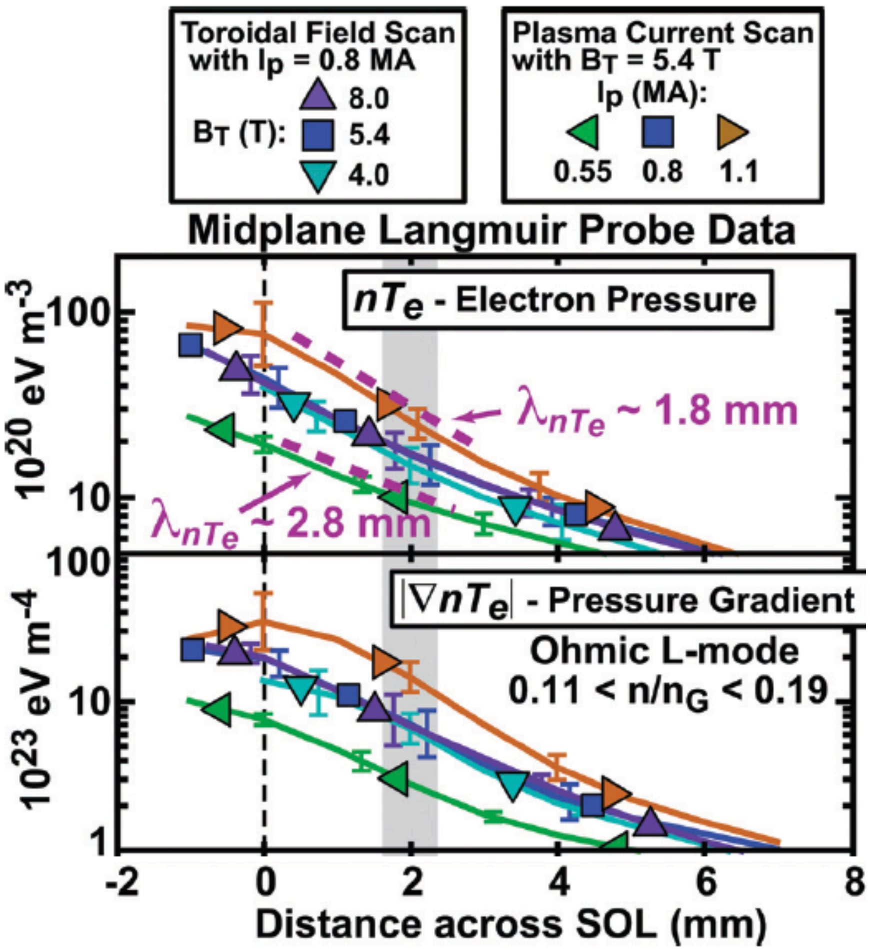
- Results of coordinated U.S. effort on the scaling of the divertor power flux width
- Results of coordinated U.S. effort on the physics of the H-mode pedestal
- Correlations between the H-mode pedestal scalings and SOL heat flux footprints
  - Does the KBM physics that appears to restrict gradients just inside the separatrix extend across the separatrix to the heat flux channel?

C-Mod: pressure gradients appear continuous across separatrix, with a strong I_p dependence

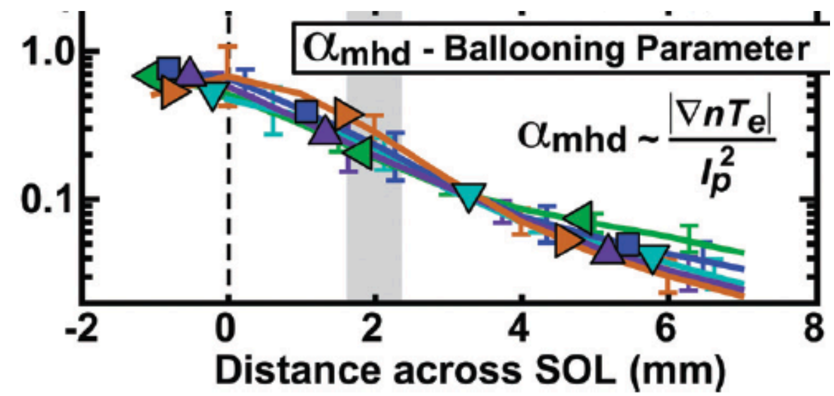


LaBombard PoP 18 (2011) 056104

C-Mod: Normalizing gradients to ballooning parameter α_{MHD} aligns the I_p variations – importance of ballooning mode physics?



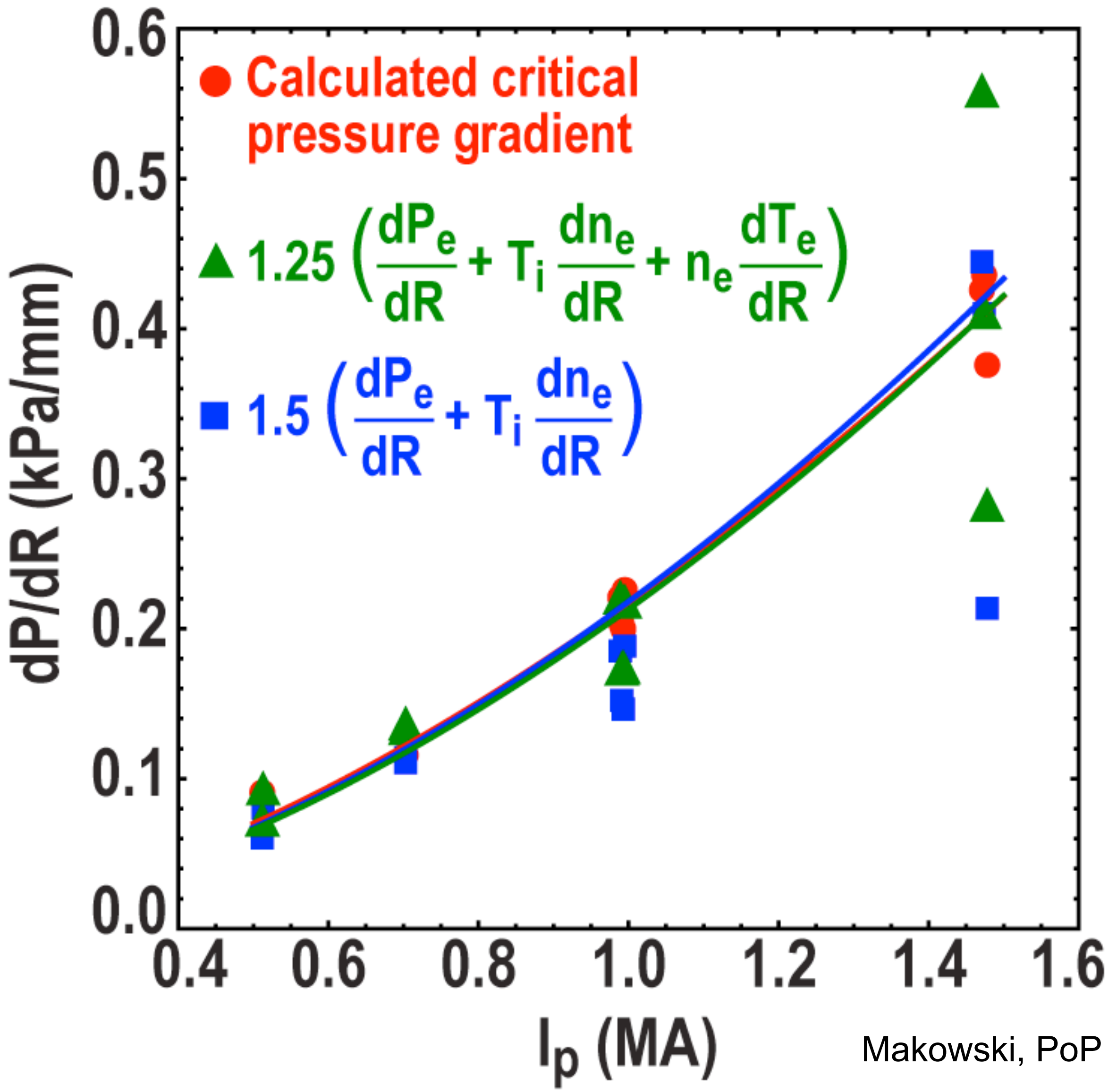
- α_{MHD} $=4R\mu_0 q_{95}^2(dP/dr)/B_t^2$ (MHD ballooning parameter) *Connor, PRL 1978*



- *New data on C-Mod I-mode SOL widths: Terry, O-14*

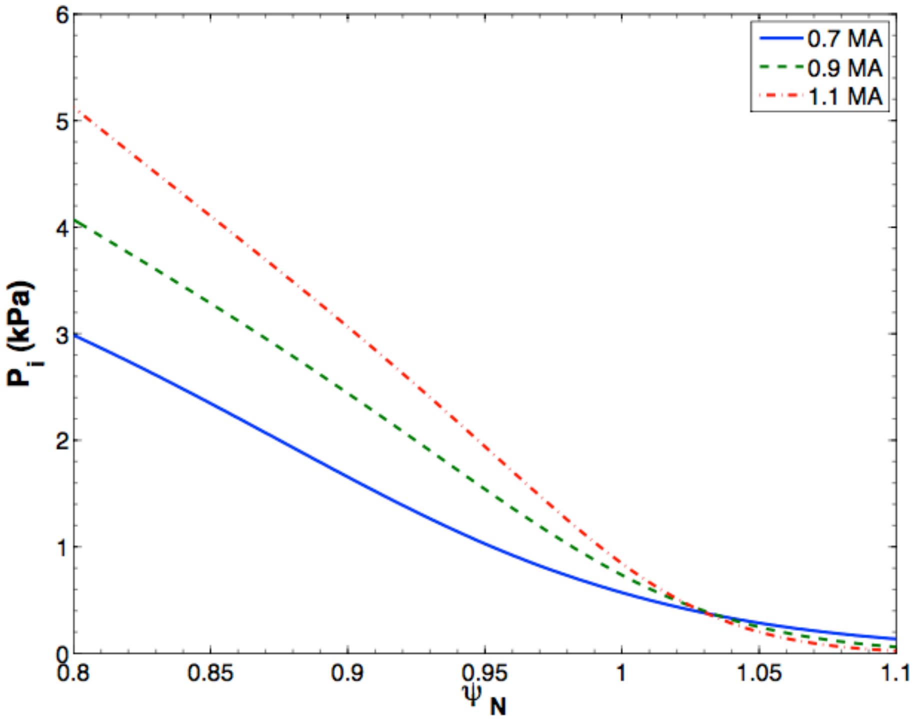
LaBombard PoP 18 (2011) 056104

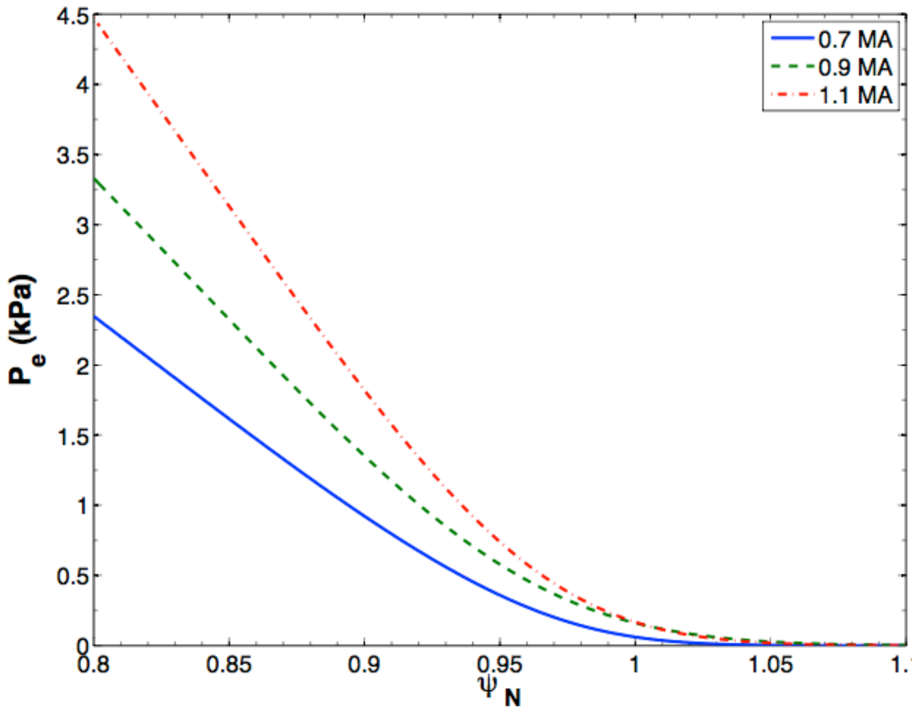
DIII-D: measured gradients near separatrix very close to those predicted to destabilize Kinetic Ballooning Modes



Makowski, PoP **19** (2012) at press

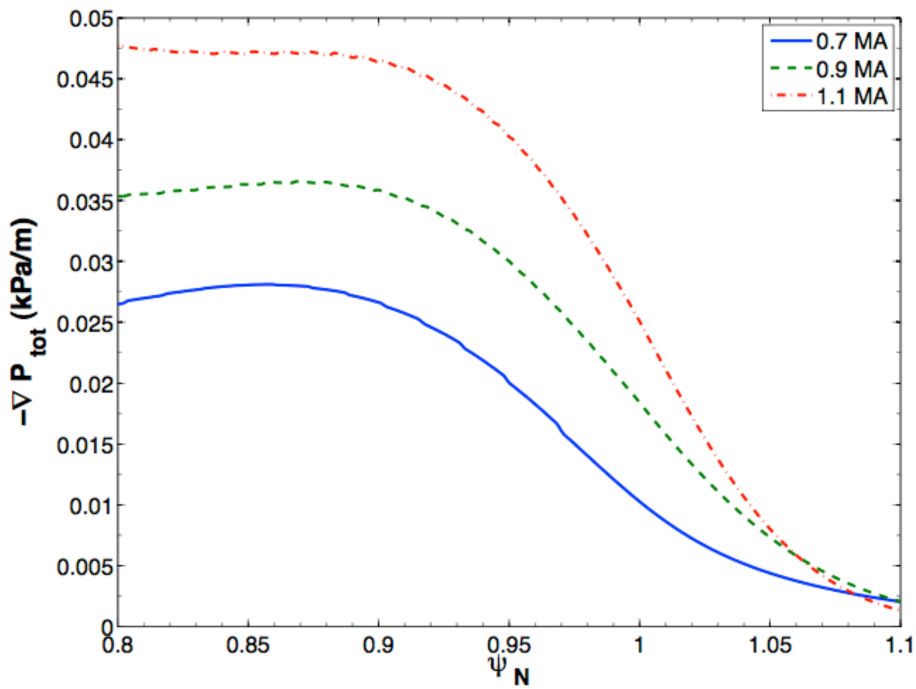
NSTX: Electron and Ion pressure profiles strongly depend on I_p

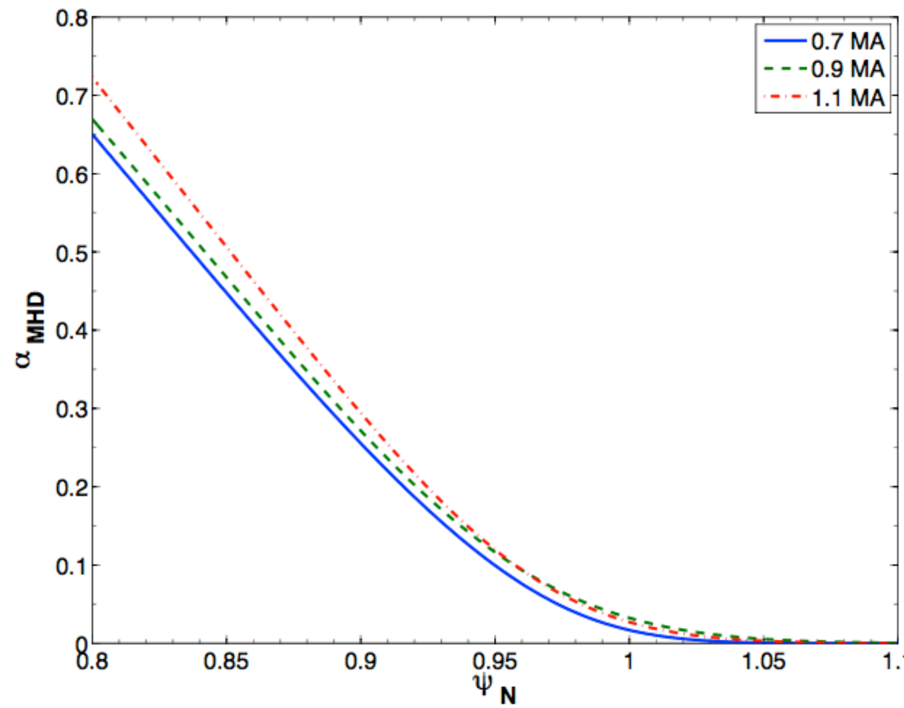




NSTX: pressure gradients strongly scale with I_p, but normalizing with α_{MHD} aligns profiles, as in C-Mod

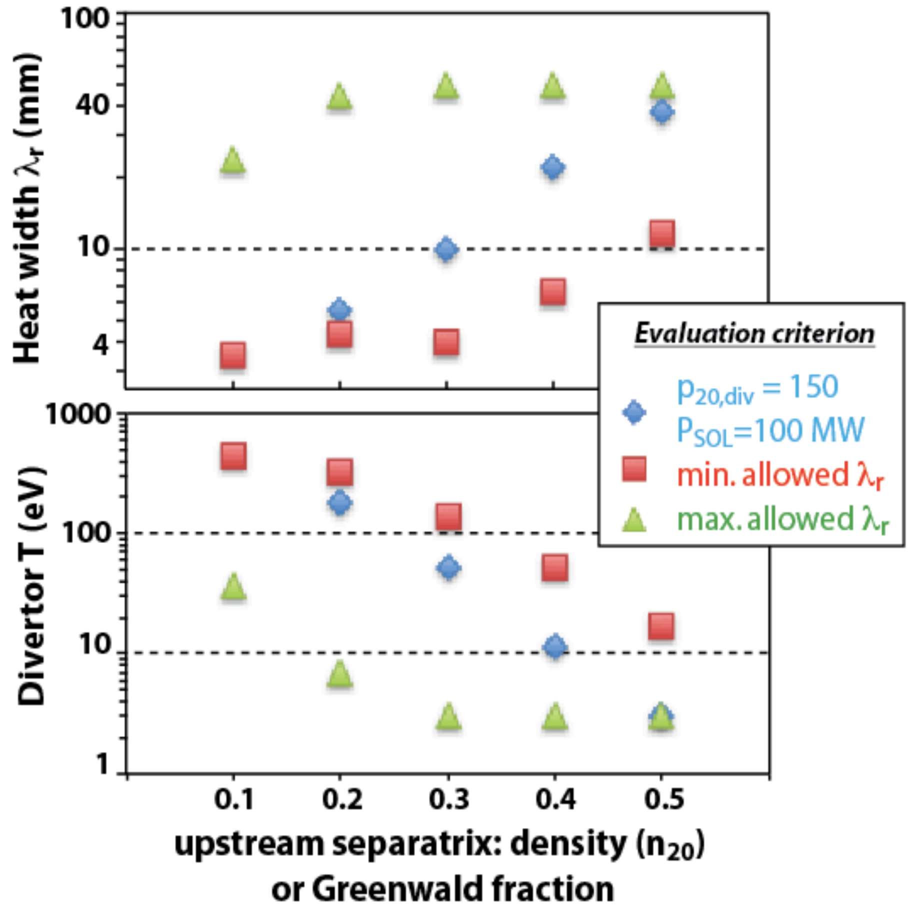
Units conversion factors will be fixed





Recent model by Whyte predicts a much wider footprint in ITER: $\lambda_q^{mid} \sim$ 1-3 cm

- $\lambda_q^{mid} \sim B_{pol}^{mid}$ results in a 1 mm SOL width for ITER (i.e. assuming no KBM effects)
- Recent model by D. Whyte (P1-37) predicts a much wider ITER SOL heat flux footprint
  - Assumes a 5% ratio of pedestal to separatrix pressure
  - Assumes pressure balance on the open field lines
  - Assumes collisionless sheath power transmission in a high recycling, attached divertor with $T_{div} \sim$ 5-20 eV

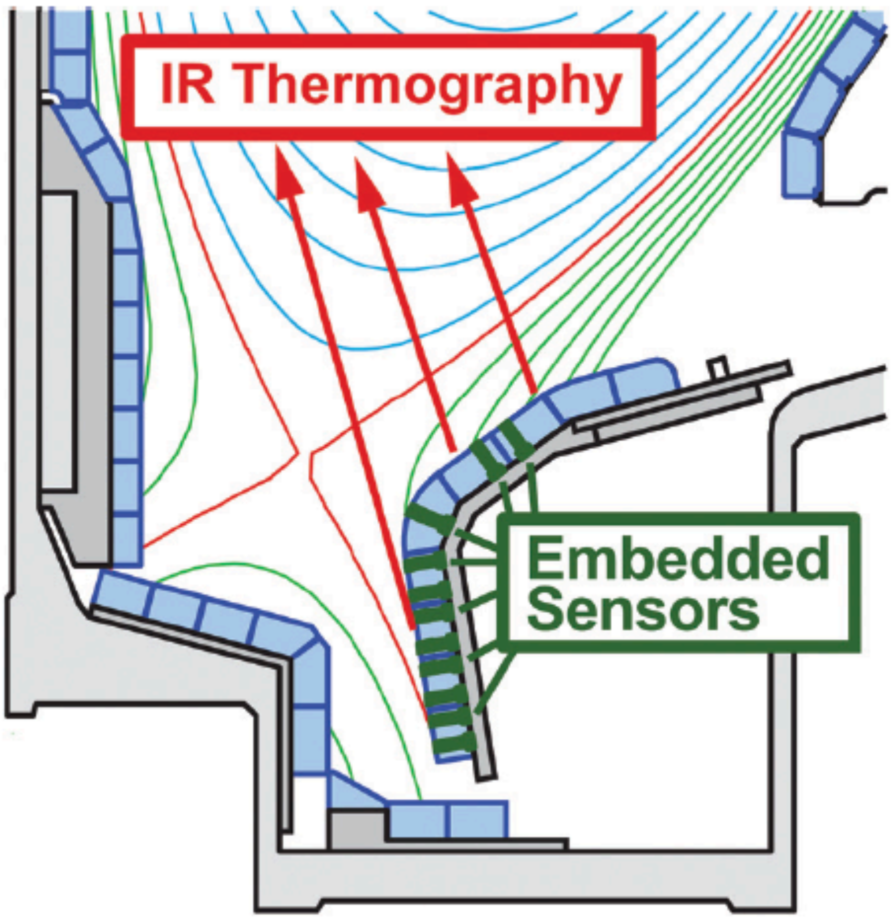


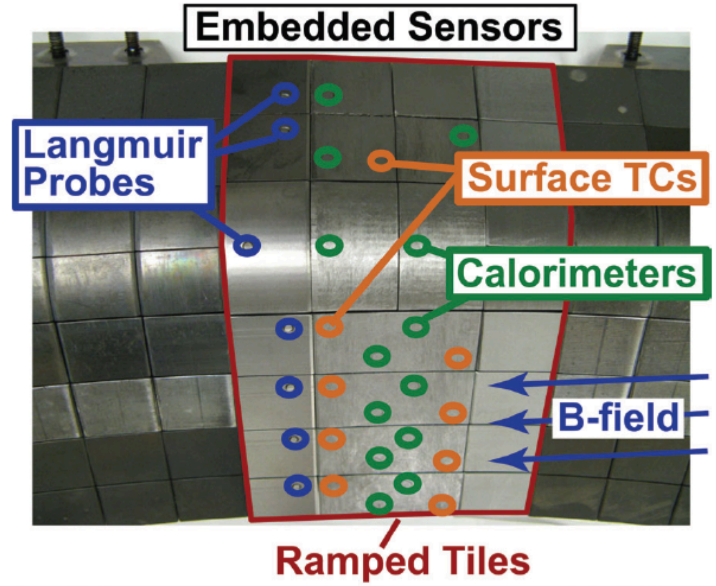
Summary and Conclusions

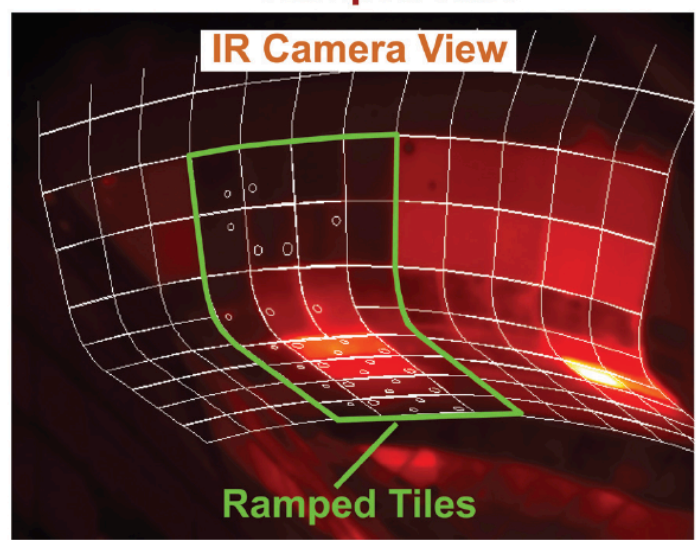
- Results of coordinated U.S. effort on the scaling of the divertor power flux width identified an $a/I_p \sim B_{pol}^{mid}$ dependence of the mapped SOL heat flux width
  - Data agree well with Goldston drift-based model
- Results of coordinated U.S. effort on the physics of the H-mode pedestal confirmed the importance of I_p in pedestal scalings
  - Confirmed the importance of EPED/KBM physics in C-mod and DIII-D, with continuing assessment for NSTX
- I_p dependence of upstream profiles appears to be organized by α_{MHD}
  - Not inconsistent with ballooning mode physics playing a key role in extending 'pedestal physics' into the SOL

Backup

Many new diagnostics installed in Alcator C-Mod for this study



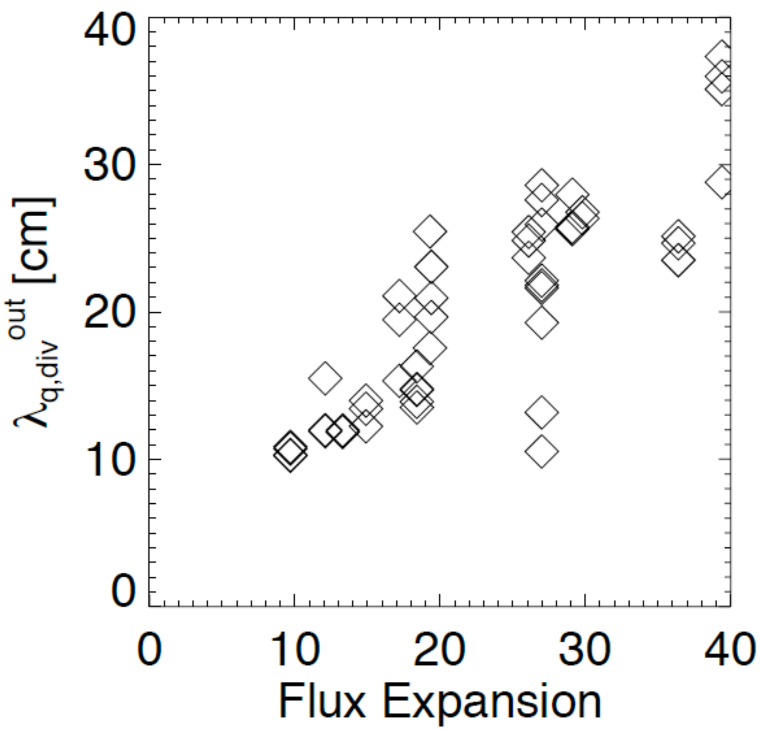




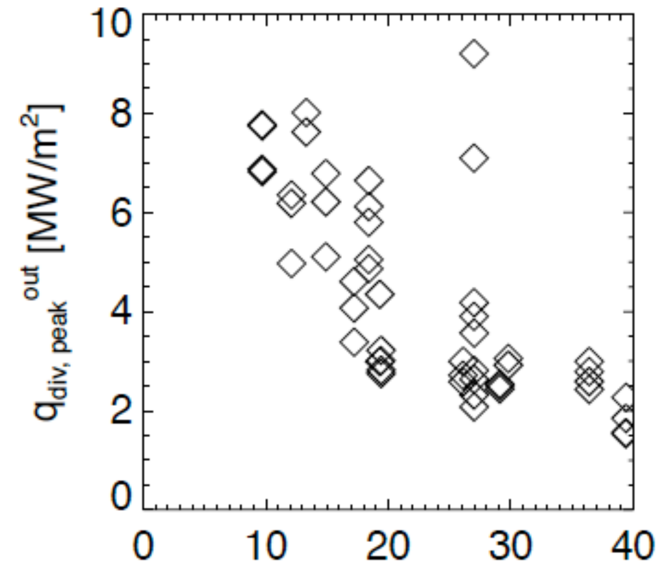
LaBombard PoP 18 (2011) 056104

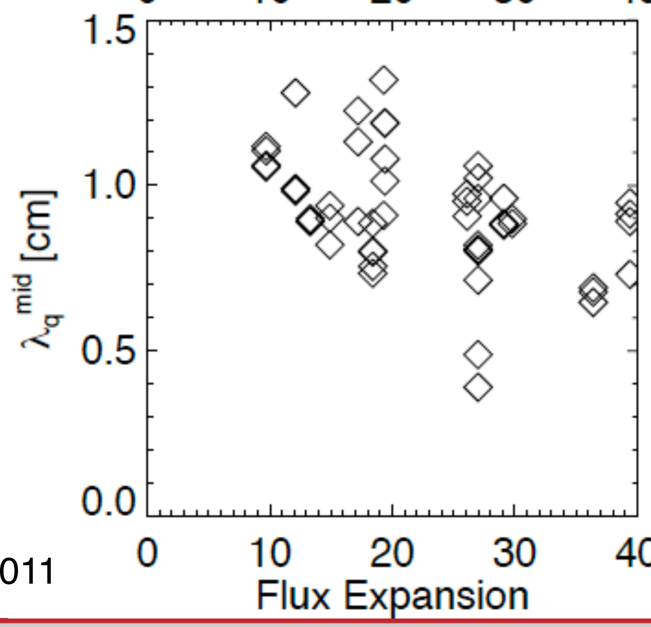
Peak heat flux decreases inversely with flux expansion with roughly constant λ_q^{mid} in NSTX

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



Gray, JNM 2011





Goldston model

- Heuristic drift-based model derived (NF 52 2012 013009)

$$\lambda = 5671 \cdot P_{\mathrm{SOL}}^{1/8} \frac{(1+\kappa^2)^{5/8} a^{17/8} B^{1/4}}{I_p^{9/8} R} \left(\frac{2\bar{A}}{(1+\bar{Z})}\right)^{7/16} \times \left(\frac{Z_{\mathrm{eff}}+4}{5}\right)^{1/8} \quad \text{all units SI}$$

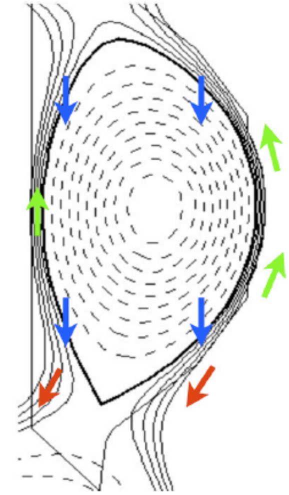


Table 1. Comparison with recent experimental data in deuterium.

	JET low λ	JET high λ	NSTX, 1 MA	DIII-D, 1 MA	C-Mod, 1 MA
P_{SOL} (W)	1.05E + 07	1.05E + 07	5.50E + 06	4.30E + 06	2.00E + 06
B_t (T)	3.00E + 00	2.00E + 00	4.40E − 01	2.00E + 00	5.40E + 00
κ	1.68E + 00	1.68E + 00	2.25E + 00	1.75E + 00	1.65E + 00
a (m)	9.50E − 01	9.50E − 01	5.90E − 01	5.95E − 01	2.20E − 01
I_p (A)	3.00E + 06	1.20E + 06	1.00E + 06	1.00E + 06	1.00E + 06
R (m)	2.95E + 00	2.95E + 00	8.70E − 01	1.76E + 00	6.80E − 01
Z_{eff}	2.00E + 00	2.00E + 00	2.00E + 00	2.00E + 00	2.00E + 00
λ (exp't)	4.00E − 03	6.10E − 03	8.00E − 03	6.30E − 03	3.50E − 03
λ (model)	2.83E − 03	7.18E − 03	9.15E − 03	5.08E − 03	1.75E − 03

Summary of FY2010 JRT main modeling results

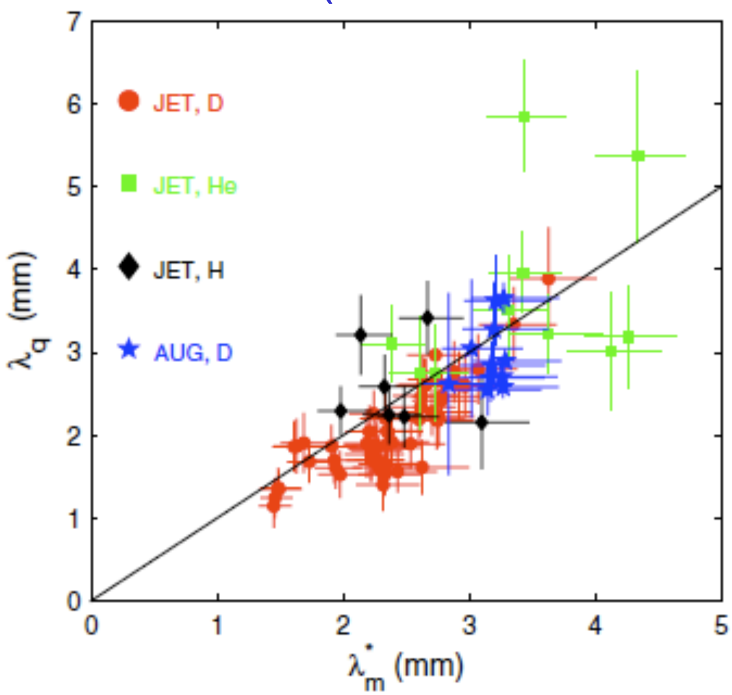
- Modeling of Alcator C-Mod and DIII-D with UEDGE
  – Modeled similarity expt. discharges
  – C-Mod profiles matched with transport coefficients that increased wih radius
  – Drift effects important in both devices
- Modeling of Alcator C-Mod and NSTX with SOLT
  – In C-Mod, computed SOL width was ~ 1mm, less than data; single mode found unstable that may correspond to QC mode
  – In NSTX, trend of heat flux width decreasing with I_p reproduced, but not as strong as data: importance of X-point spreading identified
  – Transition from diffusive to convective radial transport identified
- Modeling of DIII-D and NSTX with XGC0
  – $1/I_p$ scaling of heat flux width with neoclassical transport alone
  – Heat flux widths 50% smaller than measured ones

Follow-on work in FY2011 and FY2012 to date: Eich

- ASDEX-Upgrade and JET:
  - Eich (PRL 107 (2011) 215001) described new formula and $1/I_p$ scaling

$$q(\bar{s}) = \frac{q_0}{2}\exp\left[\left(\frac{S}{2\lambda_q f_x}\right)^2 - \frac{\bar{s}}{\lambda_q f_x}\right]\operatorname{erfc}\left(\frac{S}{2\lambda_q f_x} - \frac{\bar{s}}{S}\right) + q_{BG}$$

  - good agreement with Goldston drift-based model (NF 52 2012 013009)



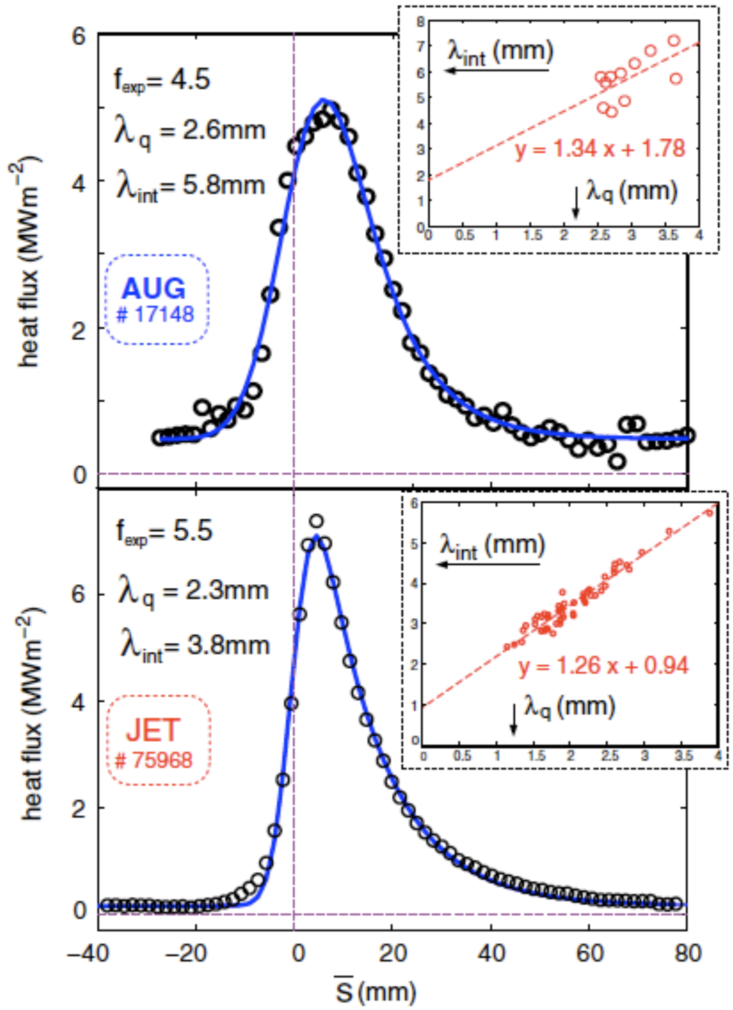
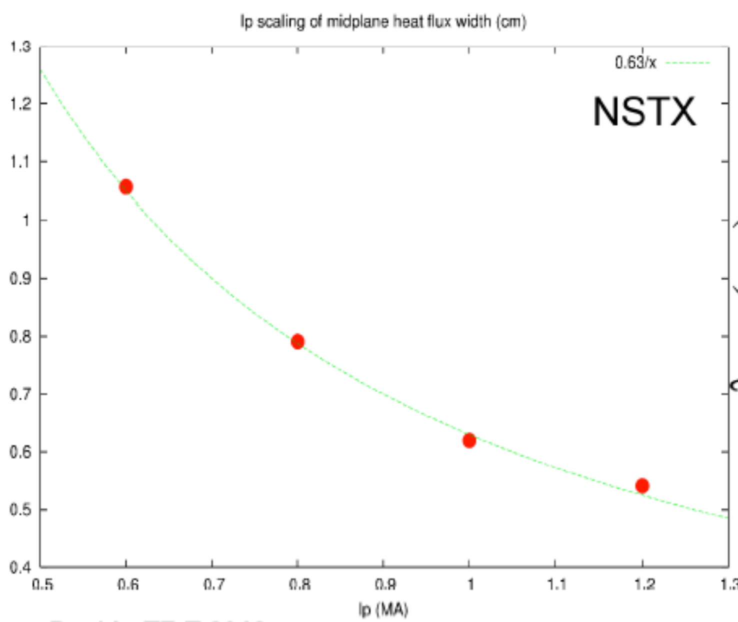


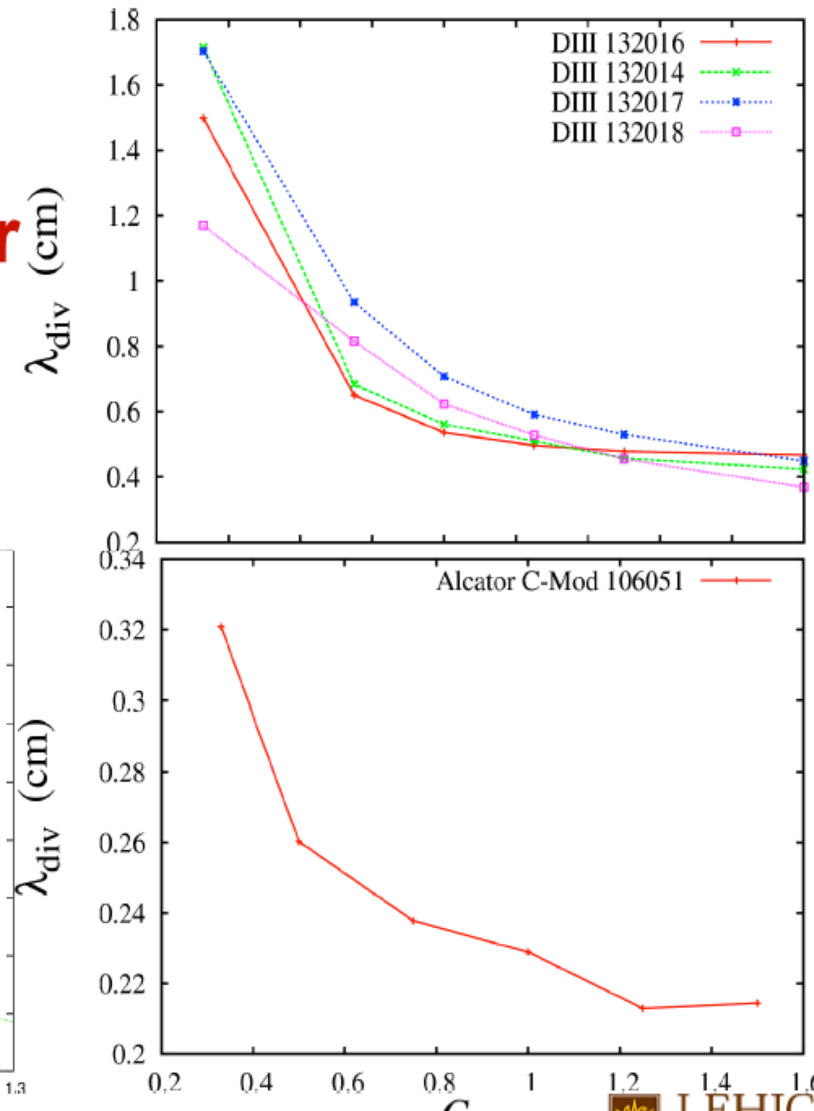
FIG. 2 (color online). Heat flux profiles measured on the outer divertor target and fits using Eq. (2). The inserts show the relation between λ_q and λ_{int} which are well expressed by a linear fit.

Neoclassical simulations with XGC-0 code

Neoclassical heat load width is broader at smaller plasma currents: Heat load width



Pankin TF-T 2010



•Pankin IAEA 2010, G-Y Park

LEHIGH UNIVERSITY

Summary of FY2010 JRT main experimental results

- Alcator C-Mod: EDA H-mode, L-mode, Ohmic
  - In FY2010 report: found a $1/I_p$ scaling of heat flux width near the separatrix in L-mode; H-mode scaling weaker because of far SOL
  - Just after JRT (APS 2010), reported $1/I_p$ in near SOL H-mode
  - Installed large number of new diagnostics
- DIII-D: ELMy H-mode with NBI or ECH
  - In FY2010 report: found a $1/I_p$ scaling of heat flux width near the separatrix in H-mode
- NSTX: ELMy H-mode and ELM-free H-mode
  - In FY2010 report: found a $1/I_p^{\alpha}$ scaling of heat flux width near the separatrix in H-mode, $\alpha \sim 1.6$
  - No appreciable B_t or P_{heat} dependence