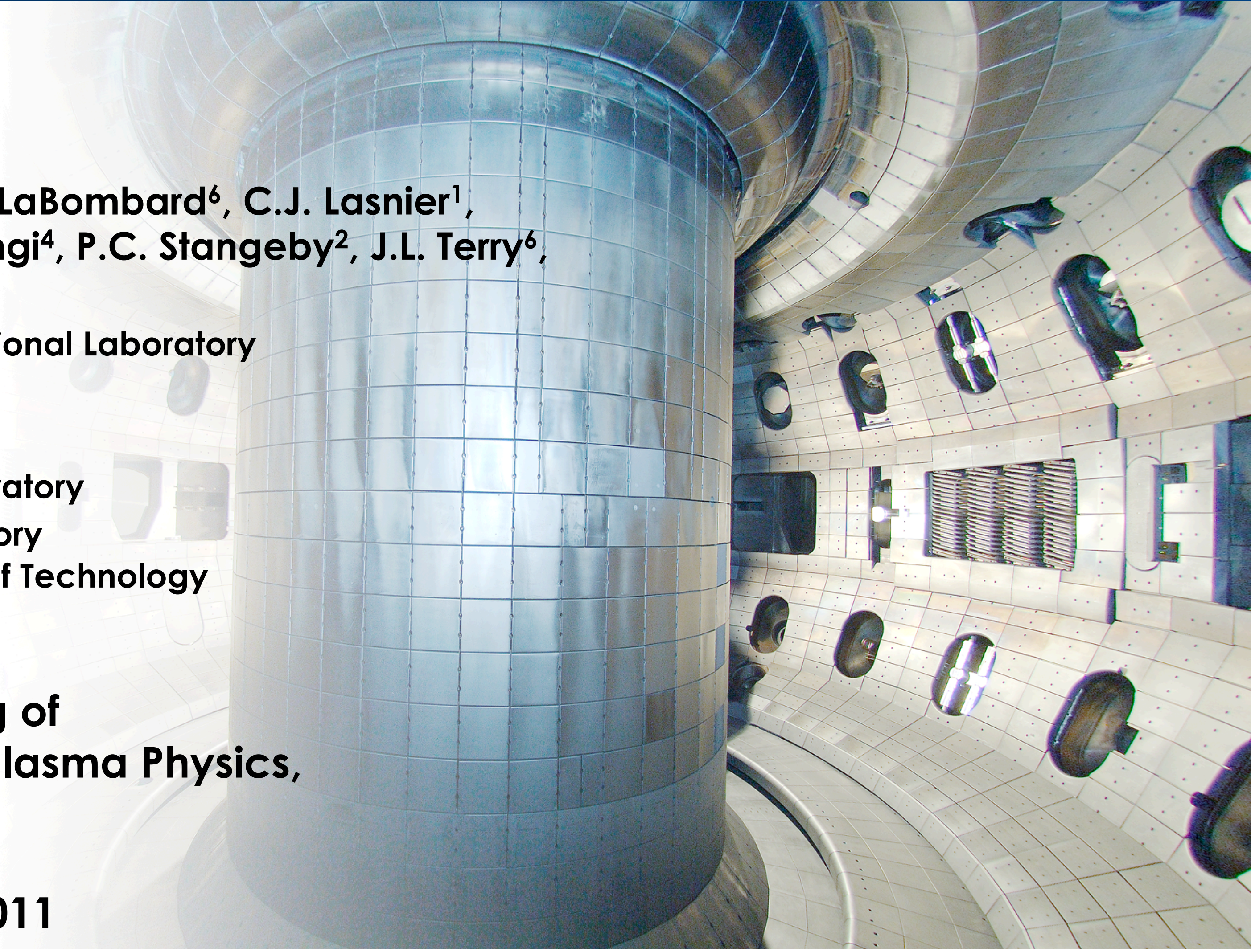
Analysis of a Multi-Machine Database on Divertor Heat Flux



by

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with

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Outline

- Motivation
- Experimental Conditions and Diagnostics
- Heat Flux Profiles
- Multi-Machine Scaling Relations
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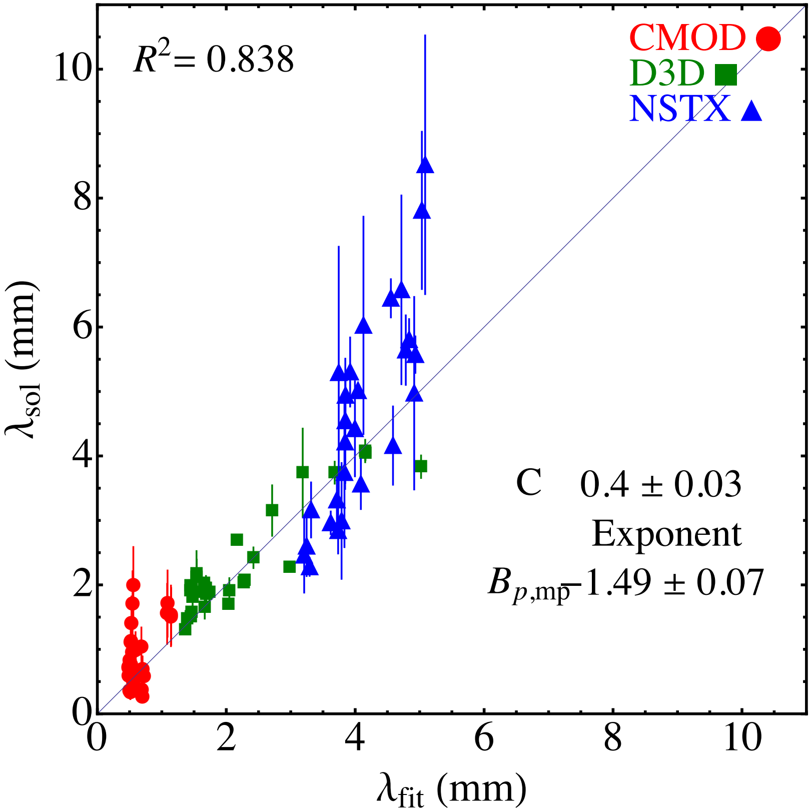
Summary of Heat Flux Width Scaling

- **Multi-machine data base predicts a scaling**

$$\lambda_q \sim \frac{a}{I_p} \sim \frac{1}{B_p}$$



- **Two-parameter fit yields independent scaling for private and common flux regions**
- **Upstream plasma profiles correlated with divertor heat flux width**
- **Heat flux width scaling consistent with drift based model**

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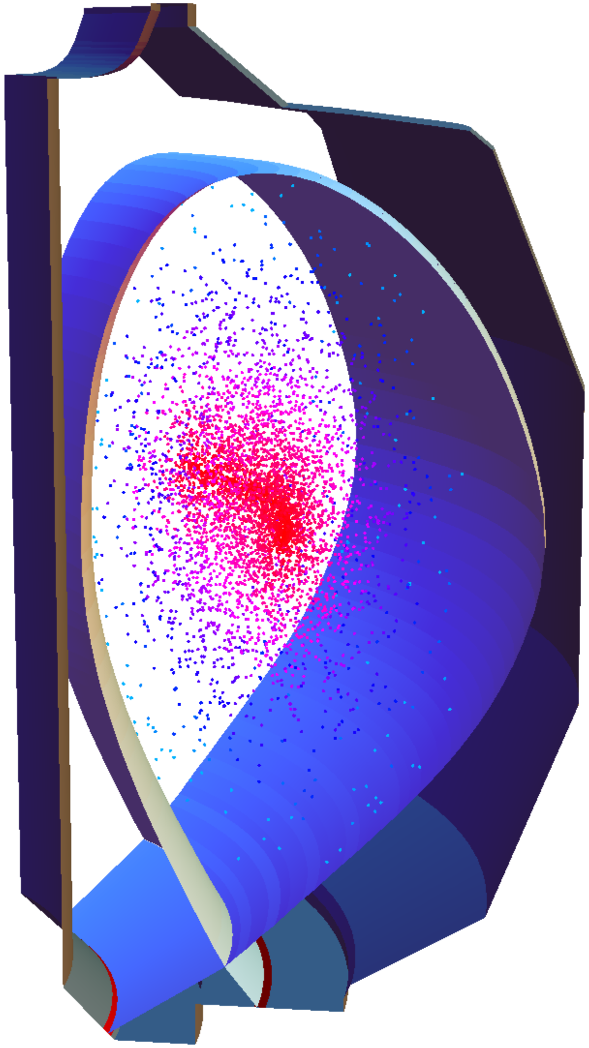
Heat Flux Width is a Critical Design Parameter

- The heat flux width is a critical design parameter for current and next-step tokamaks

- Scaling of the heat flux width with engineering and physics parameters needs a firmer physical basis than is presently available



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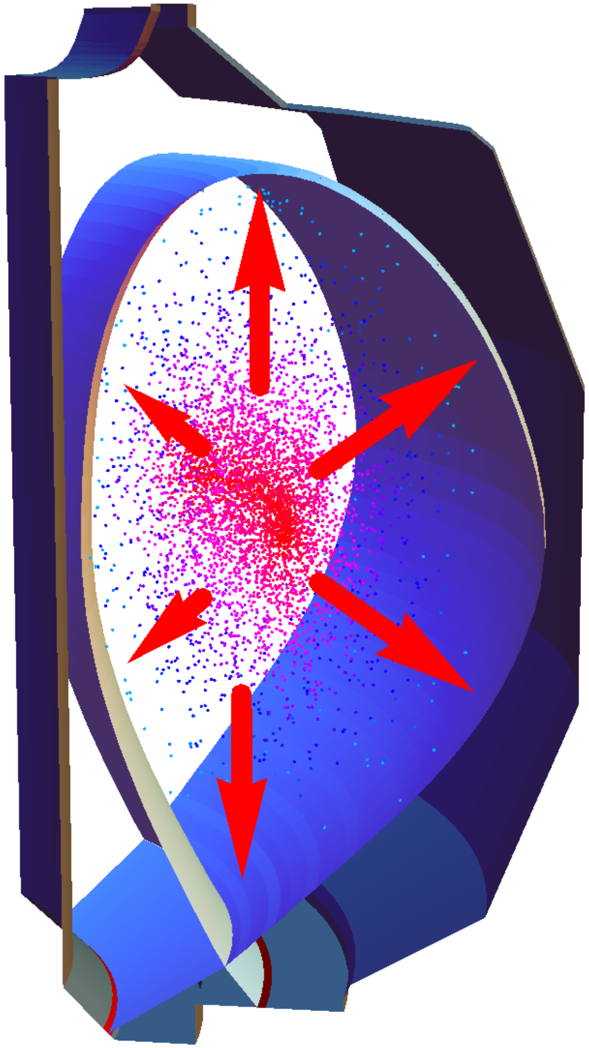

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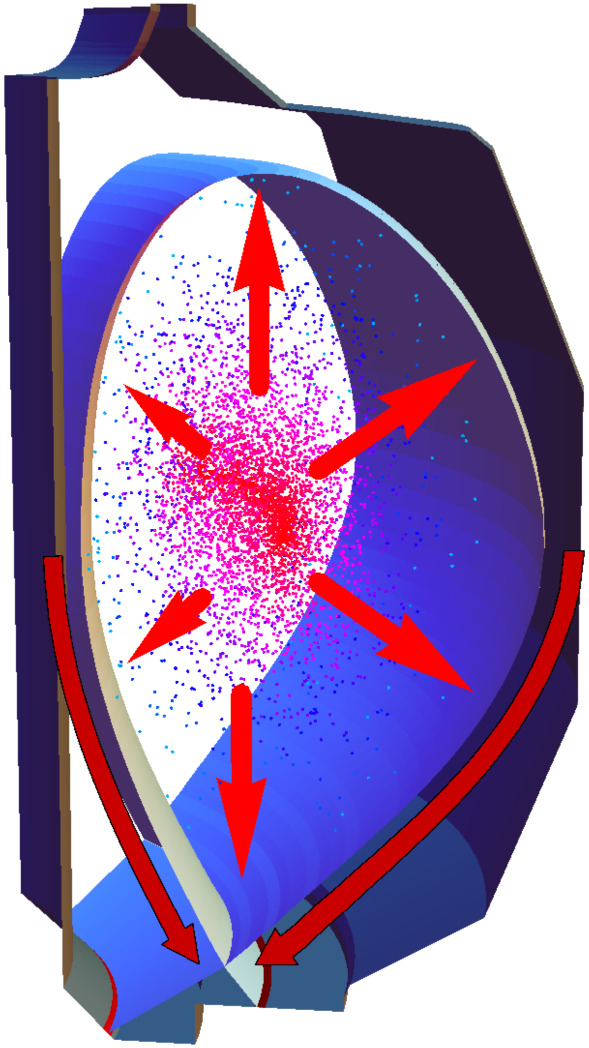

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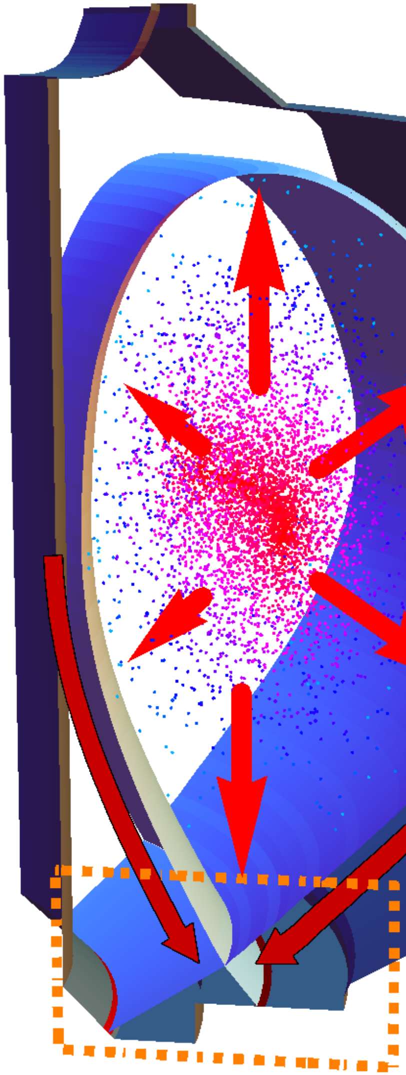

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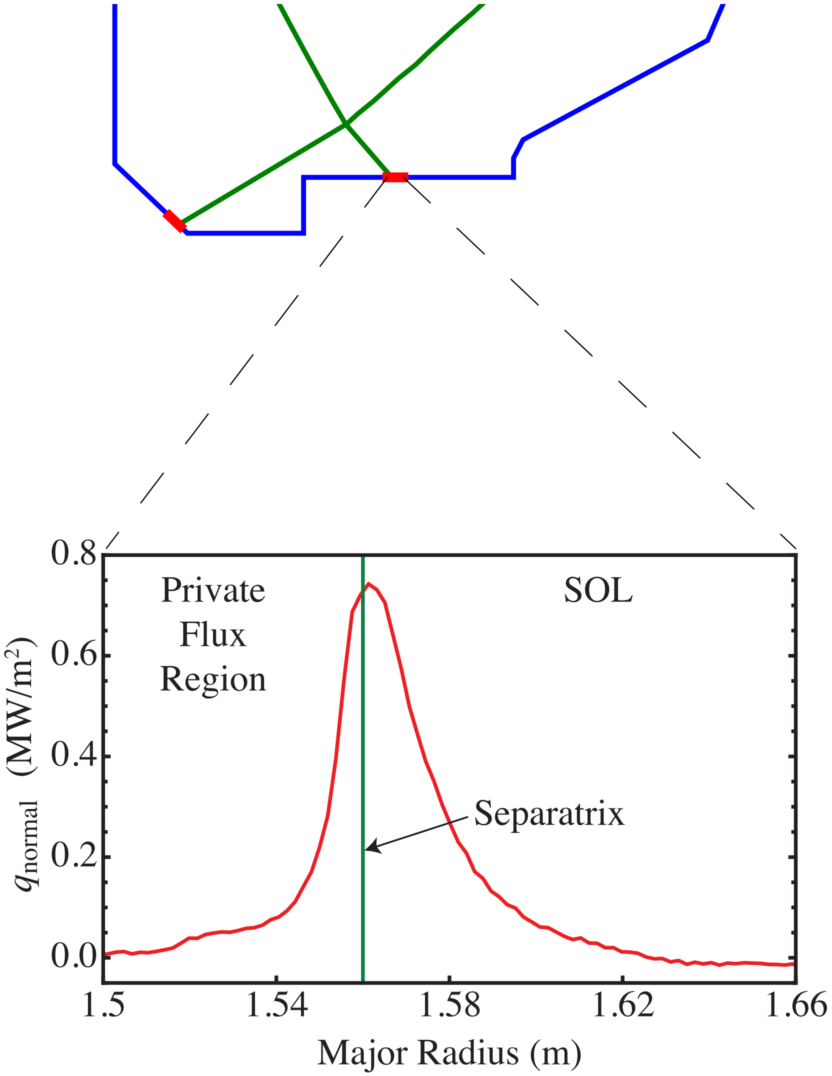
Heat Flux Width is a Critical Design Parameter

- **The heat flux width is a critical design parameter for current and next-step tokamaks**

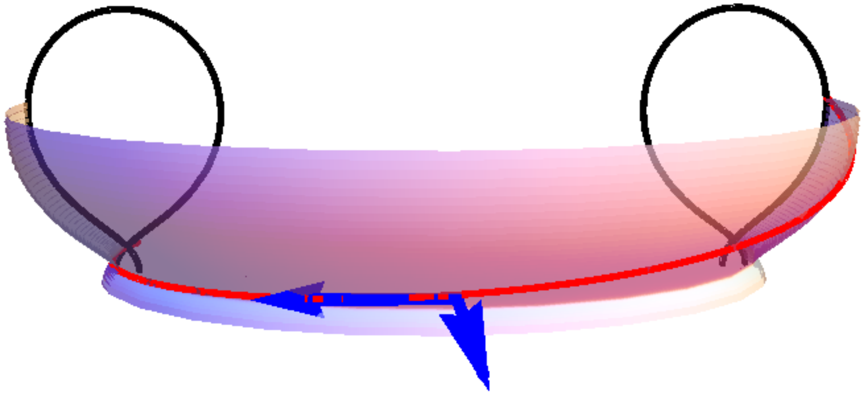
- **Scaling of the heat flux width with engineering and physics parameters needs a firmer physical basis than is presently available**

- **Volumetric heat source exhausts to an area, $A = 2\pi R\lambda_{q\perp}$ where $\lambda_{q\perp}$ is only tens of millimeters in width**

- **Resulting heat fluxes can easily exceed material limit of ~10 MW/m²**



Heat Flux Width is Dependent on Both Parallel and Cross-field Transport



- **SOL thermal transport can be cast as competition between parallel and cross-field transport**
  - Parallel physics governed by
  - conductive/convective transport and boundary conditions
  - Cross-field physics governed by drift/collisional/turbulent transport
  - Scale lengths are vastly different: $\chi_{\parallel}/\chi_{\perp} \sim 10^6$

- **Don't consider contribution from ELMs to heat flux**
  - Only contributes ~ 20% of the heat
  - Likely scales differently

Present Study is Unique in its Scope

- **Present study differs from previous ones**
  - Coordinated effort on three different devices: CMOD, D3D, and NSTX
  - Similar magnetic topology
  - Similar plasma conditions
  - Improved IR thermography providing *between-ELM* (steady-state) heat flux measurements, as in previous DIII-D work

- **Yields a cohesive data set that**
  - Allows study of underlying physics
  - Establishes a firm physics basis for extrapolation to next-step devices

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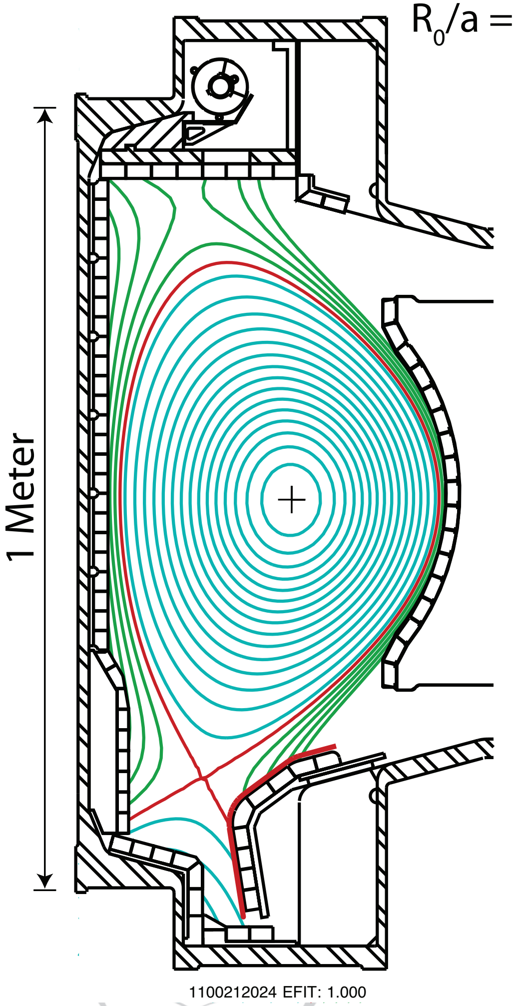
Engineering and Physics Parameters Were Varied Over a Wide Range

- **Basic magnetic configuration was the same**
  - Lower single null with grad-B drift towards the x-point
  - ELMy H-mode (EDA in the case of CMOD)
  - Attached divertor
- **Some differences exist**
  - Divertor physical geometries
  - Target is Mo in CMOD and Carbon in DIII-D and NSTX

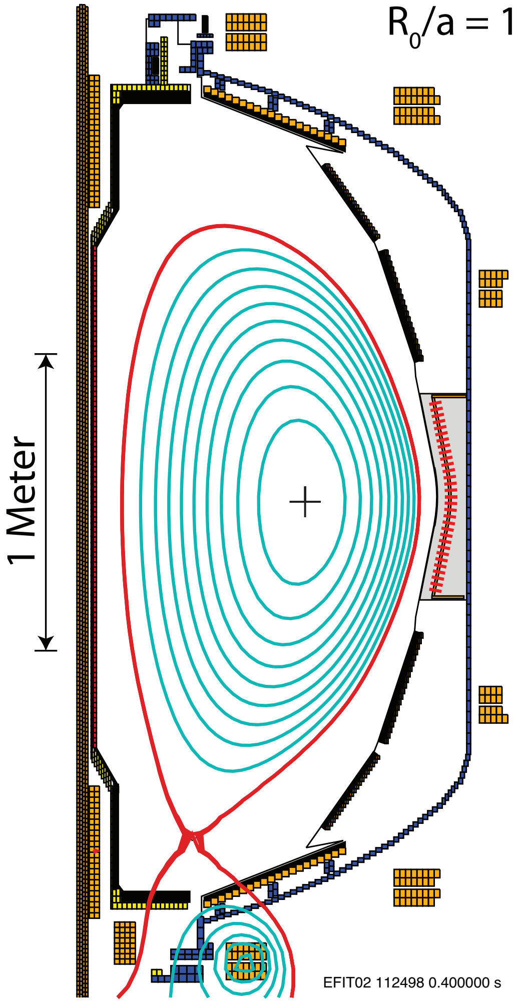
	I_p (MA)	B_t (T)	f_{GW}	a (m)	R (m)	P_{sol} (MW)
Range	3.0 x	14.7 x	3.0 x	2.7 x	2.5 x	9.8 x
CMOD	0.5 – 1.0	4.6 - 6.2	0.3 – 0.7	0.22	0.69	0.6 – 3.0
DIII-D	0.5 – 1.5	1.2 – 2.1	0.4 – 0.6	0.60	1.75	1.2 – 4.5
NSTX	0.6 – 1.2	0.42 -0.49	0.3 – 0.9	0.60	0.86	2.4 – 5.9

Significant Variation in Size was Obtained

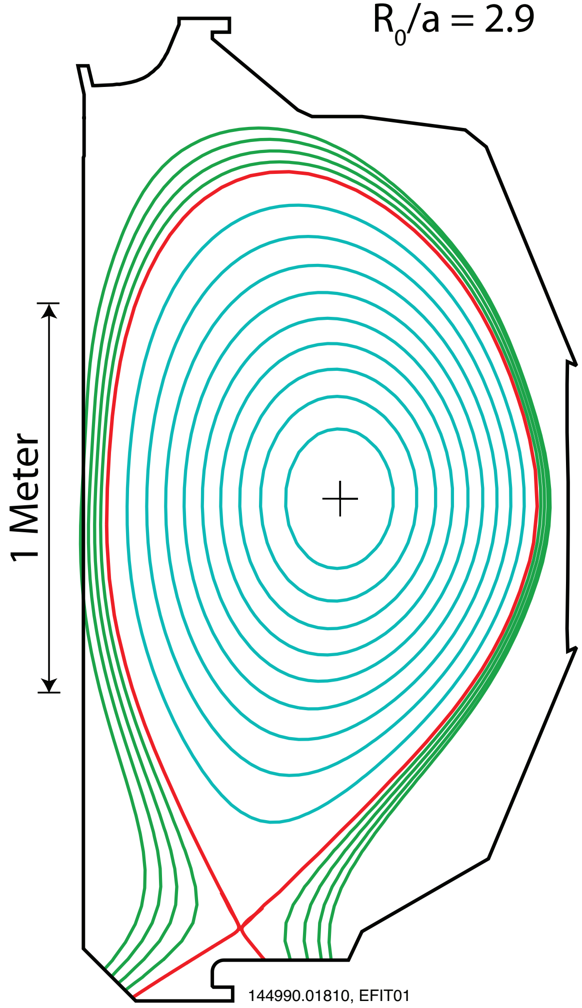
CMOD $a = 0.22$ m $R_0/a = 3.1$



NSTX $a = 0.62$ m $R_0/a = 1.4$

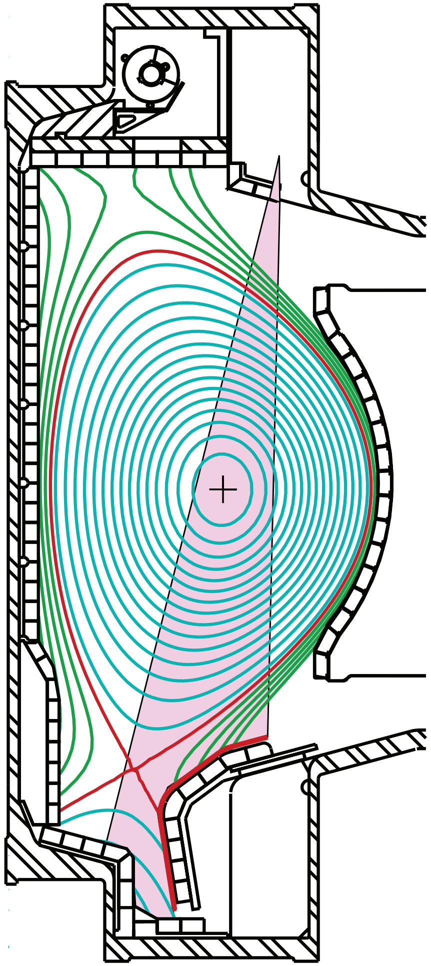


D3D $a = 0.60$ m $R_0/a = 2.9$



IR Thermography is the Primary Means of Measuring the Heat Flux

CMOD



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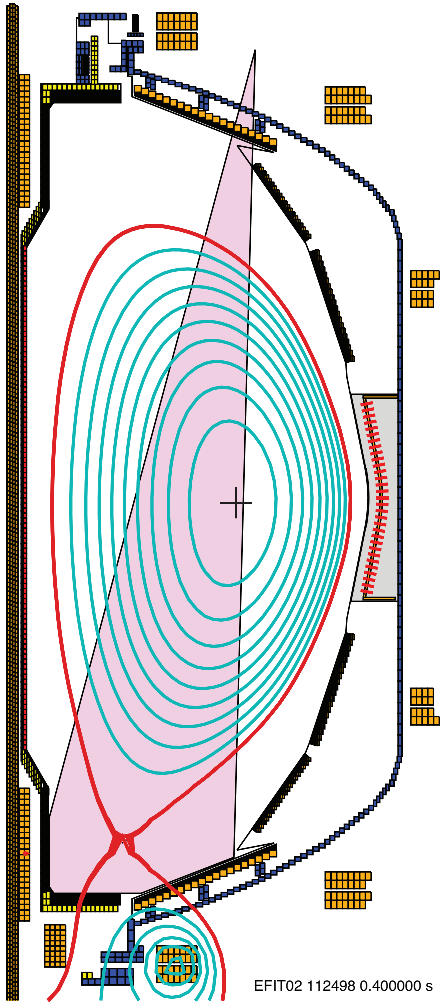
NSTX



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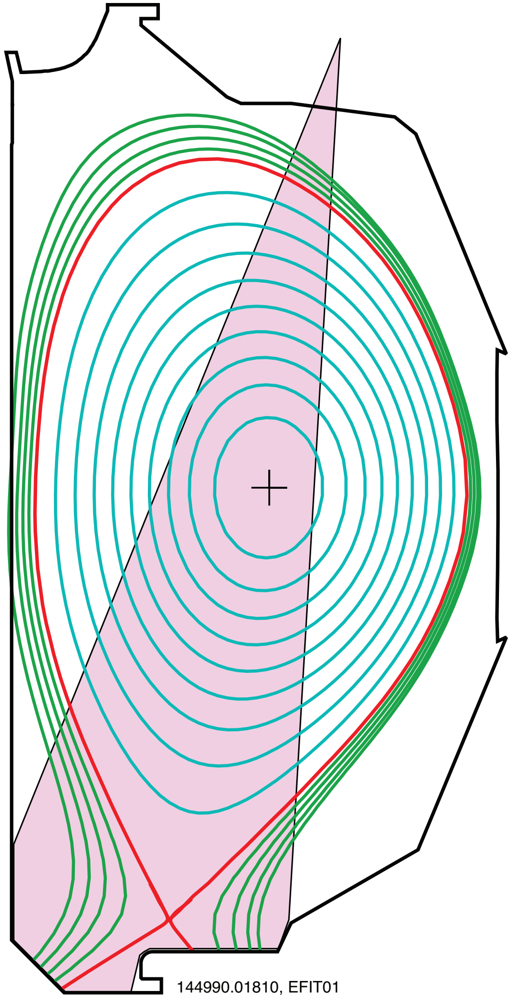
D3D



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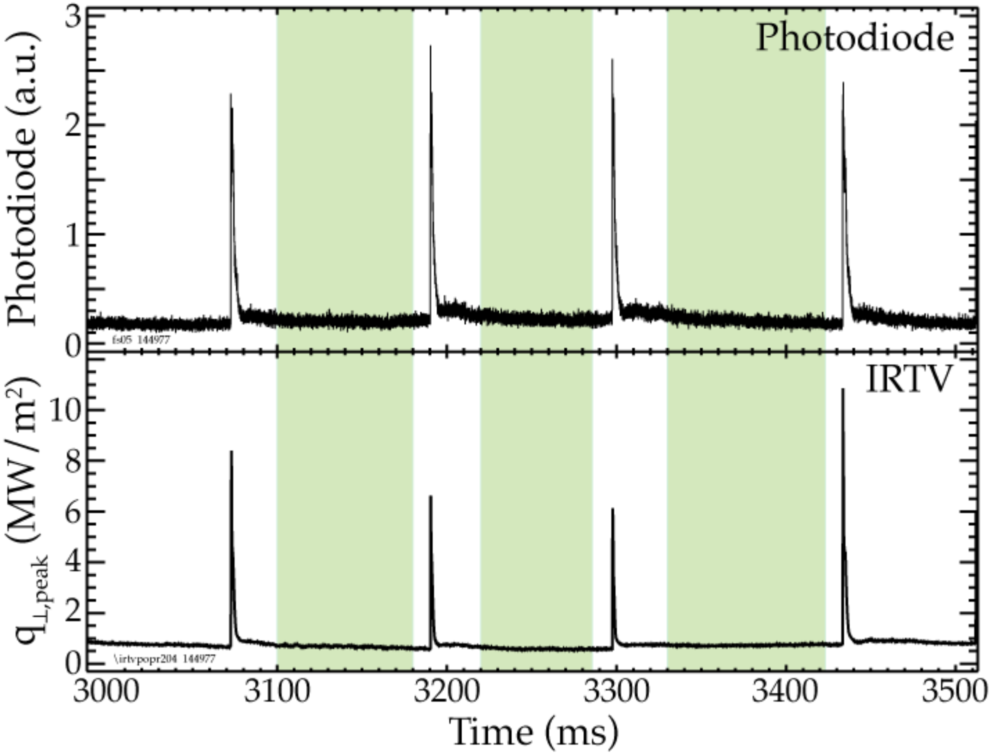
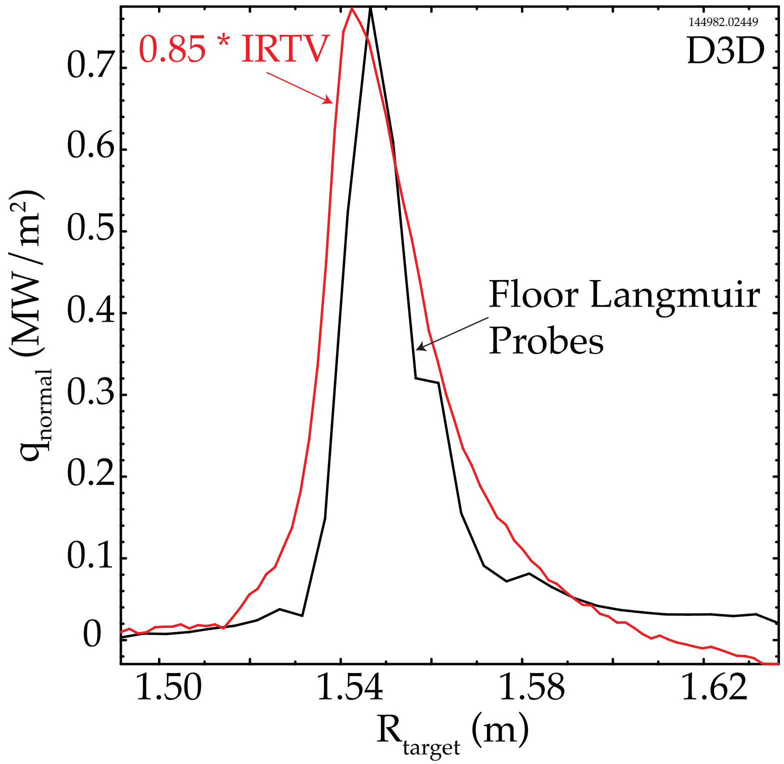
Steady-state Heat Flux Profiles are Measured Between ELMs

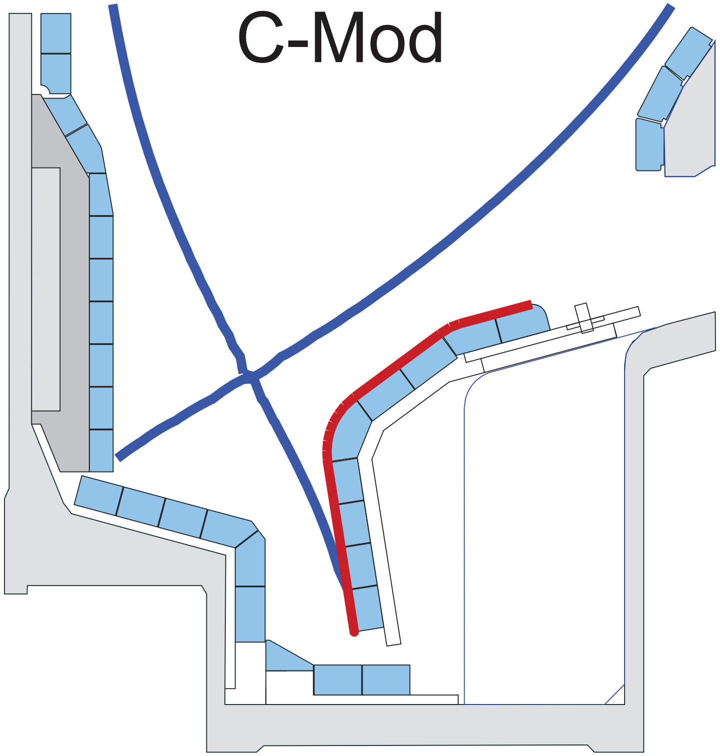
- **Fast infrared camera measures the surface temperature between ELMs**
  - Supplemented by probe and slower thermocouple measurements
- **No profile broadening due to strike point motion**





Codes Are Used to Convert Surface Temperature to Heat Flux

- **Temperature is converted to heat flux by solution of the 2D, time-dependent, non-linear heat diffusion equation**
  - Anisotropic in the case of carbon (THEODOR code)
  - Finite element code used for curved divertor in CMOD (QFLUX_2D)



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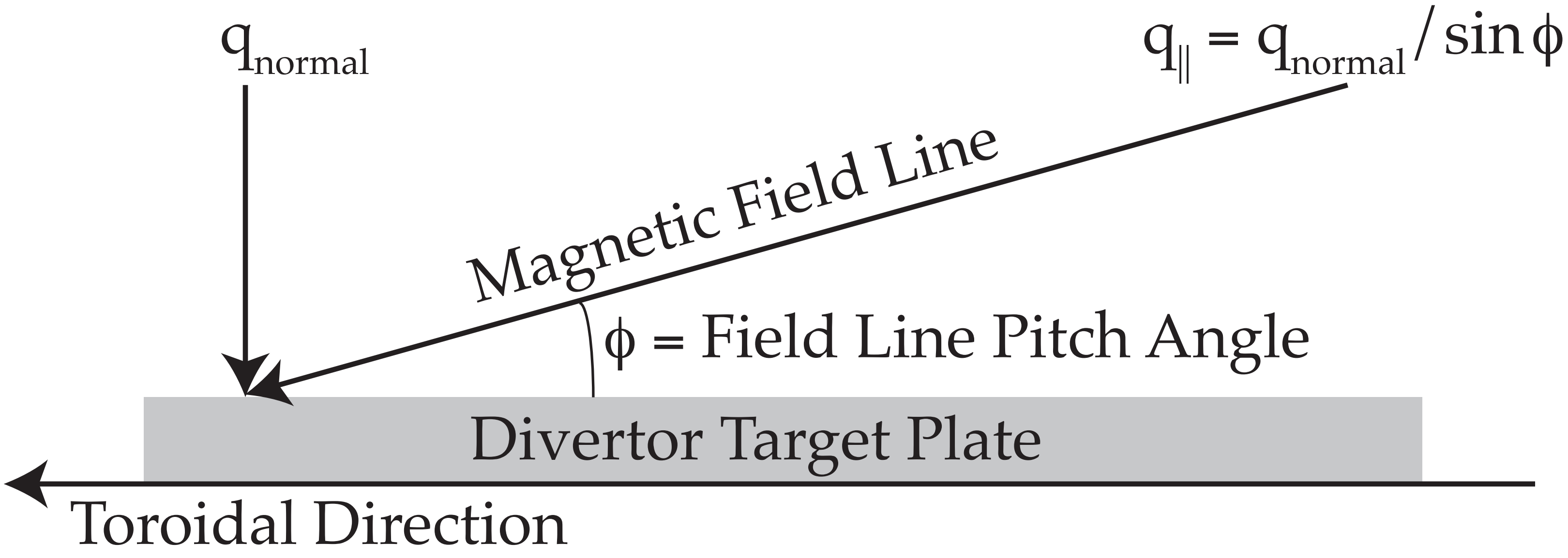
Parallel Heat Flux is Used to Compare Different Devices

- **To reconcile differing divertor geometries, the parallel heat flux, mapped to the outer midplane, is used for inter-machine comparisons**
- **Typically, ϕ is a few degrees**



$q_{\parallel} = q_{normal} / \sin\phi$

M.A. Makowski/APS/November 2011

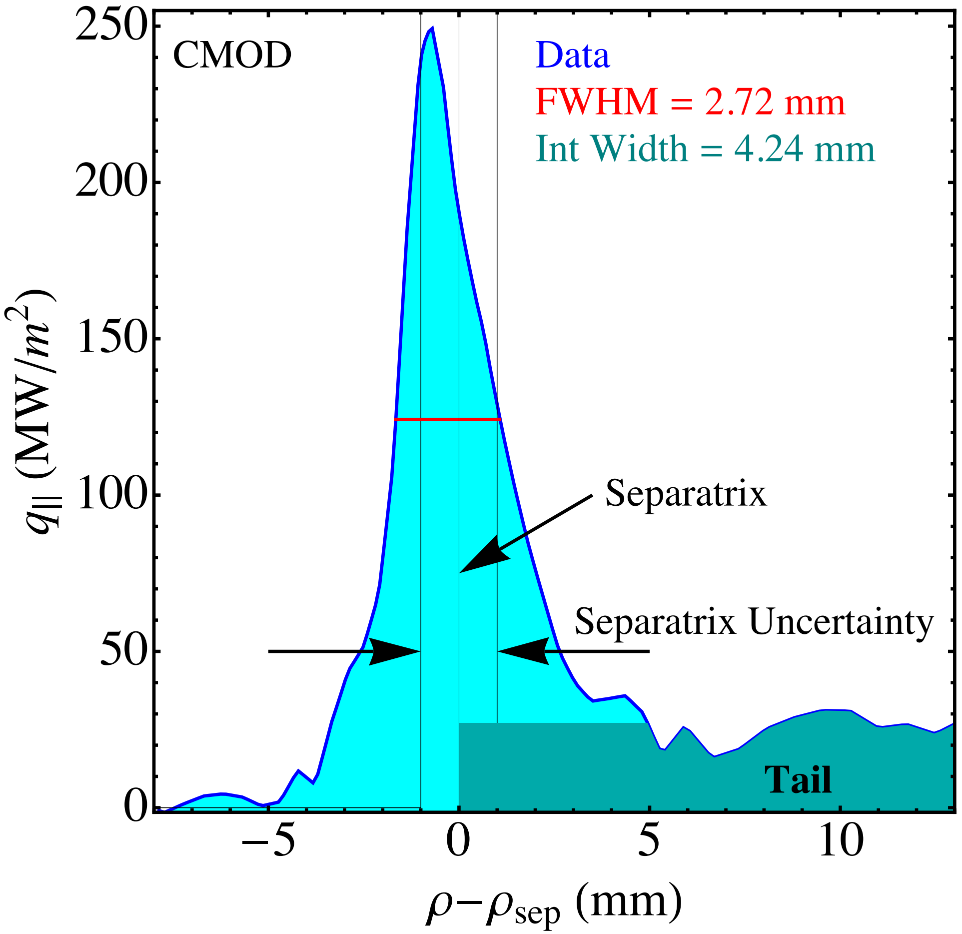
The Traditional Way to Characterize the Heat Flux Profile is with the Integral Width

- **Integral width is a *single parameter* measure of a profile**

$$\lambda_{q,\mathrm{int}} = \frac{1}{q_{\parallel,0}} \int q_{\parallel}(R_{mp})\, dR_{mp}$$

- **The integral width captures the contribution to the heat flux from the "tail" such as in CMOD profiles**

- **Integral width includes contributions from both the private and common flux regions**



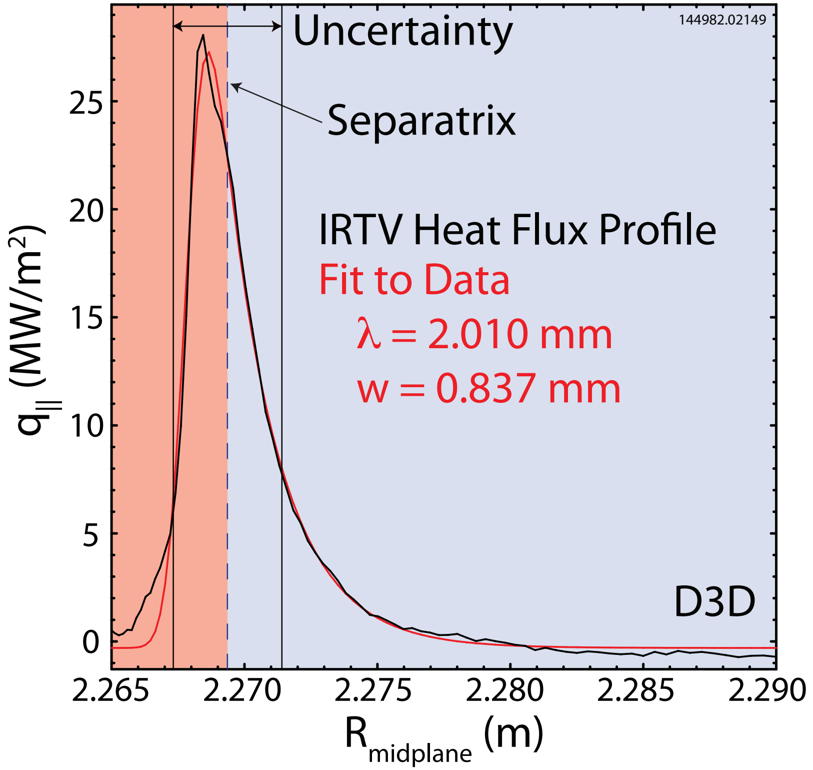
The Eich Function is a Two-parameter, Semi-empirical Fit to the Entire Profile

- **Eich* has developed a *two-parameter*, semi-empirical profile fit-function:**

$$q_{\parallel}(s) = \frac{q_{\parallel,0}}{N\sqrt{\pi w_{pvt}^{2}}} \int_{0}^{\infty} e^{-(s-s')^{2}/w_{pvt}^{2}}\, e^{-s'/\lambda_{sol}}\, ds' + q_{bkg}$$

- **The function is a convolution of a Gaussian and an Exponential**
  - Gaussian: Characterized by w_{pvt} and models diffusion into the private flux and SOL regions
  - Exponential: Characterized by l_{sol} and models transport in the SOL

**T. Eich, accepted for publication, PRL.*



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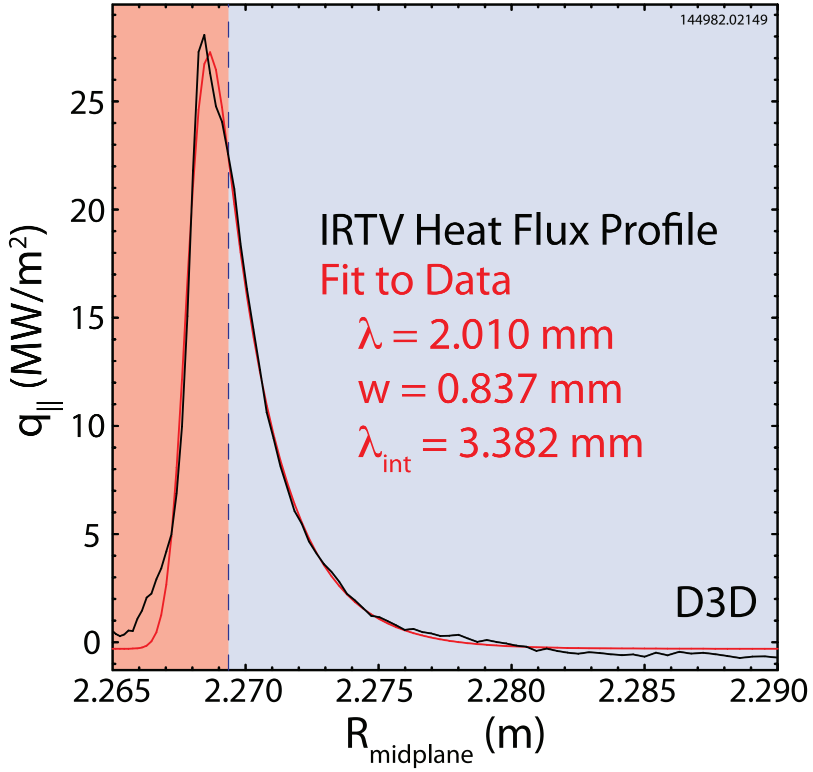
- **The function is a convolution of a Gaussian and an Exponential**

- **Integral width of Eich profile is**

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



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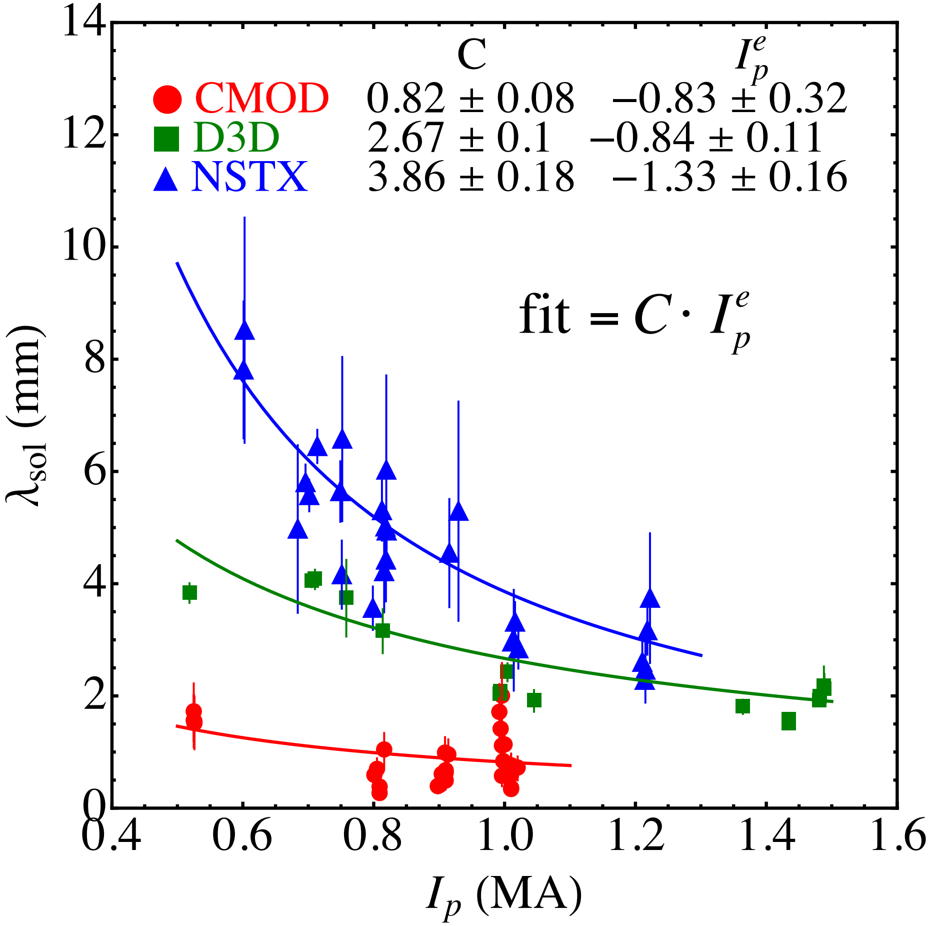
Primary Dependence Found is Approximately Inverse with I_p

- **All three machines independently demonstrate an inverse I_p dependence with slightly different exponents**

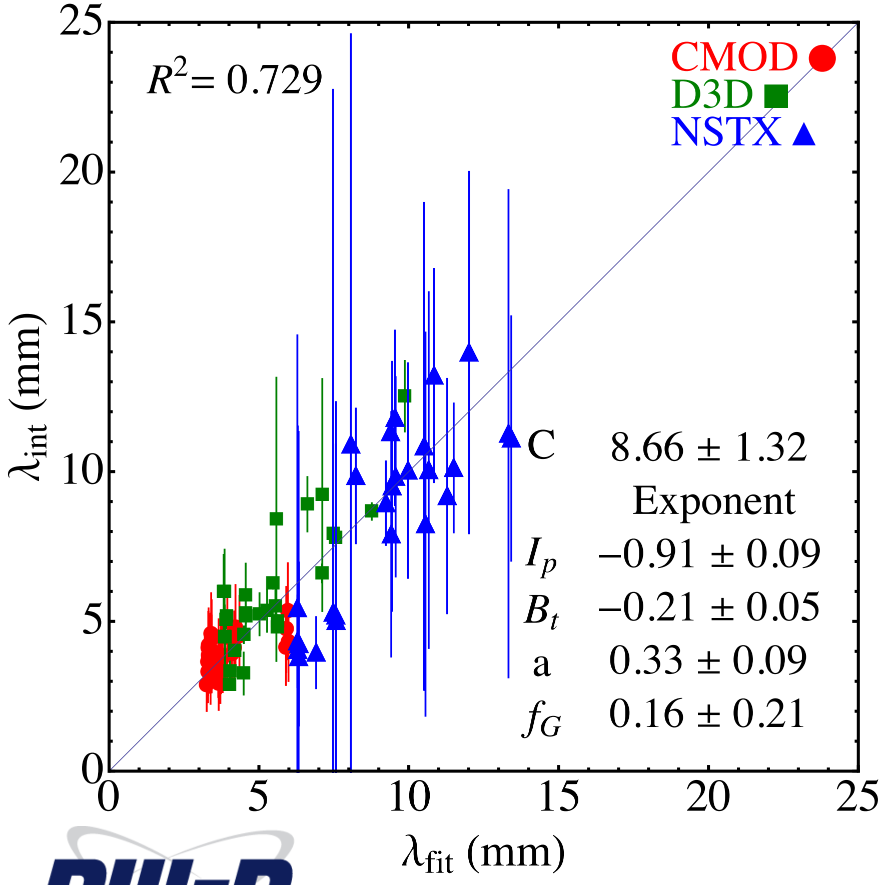
- **This dependence persists in the multi-machine scaling**
- **Secondary dependencies (B_t, P_{sol}, …) vary from machine to machine and**
  - With choice of heat flux width
  - Weighting of data



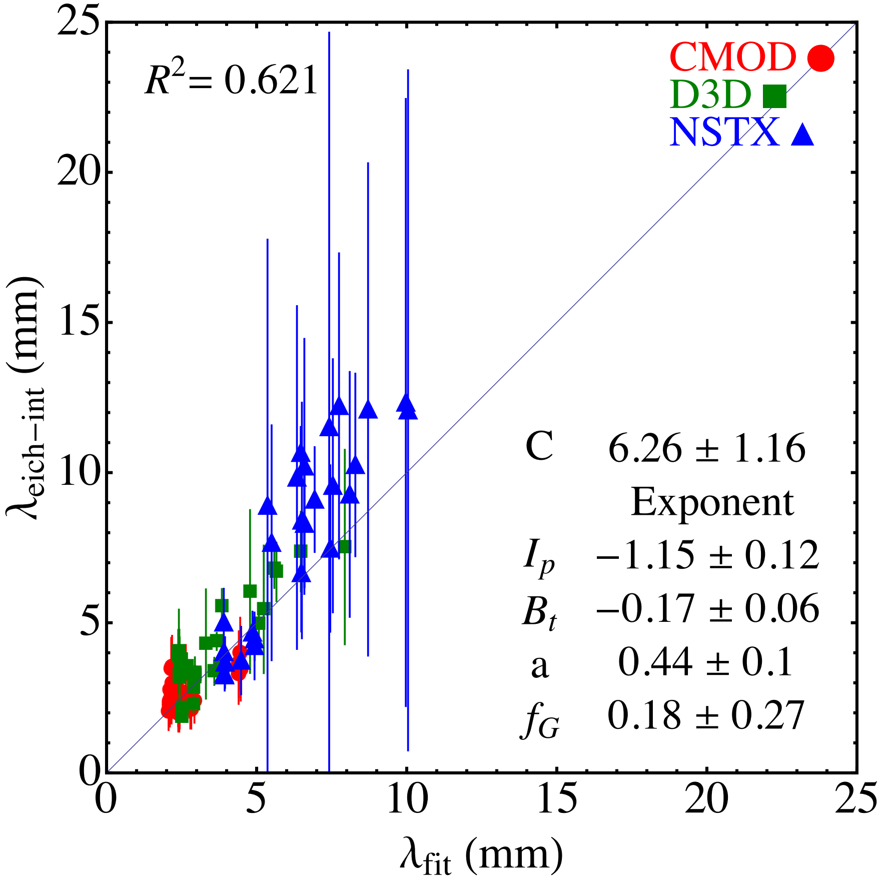
Similar Dependencies Obtained with Different Measures of Width

- **Predominant scaling is ~ $a^{0.4}/I_p$**

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



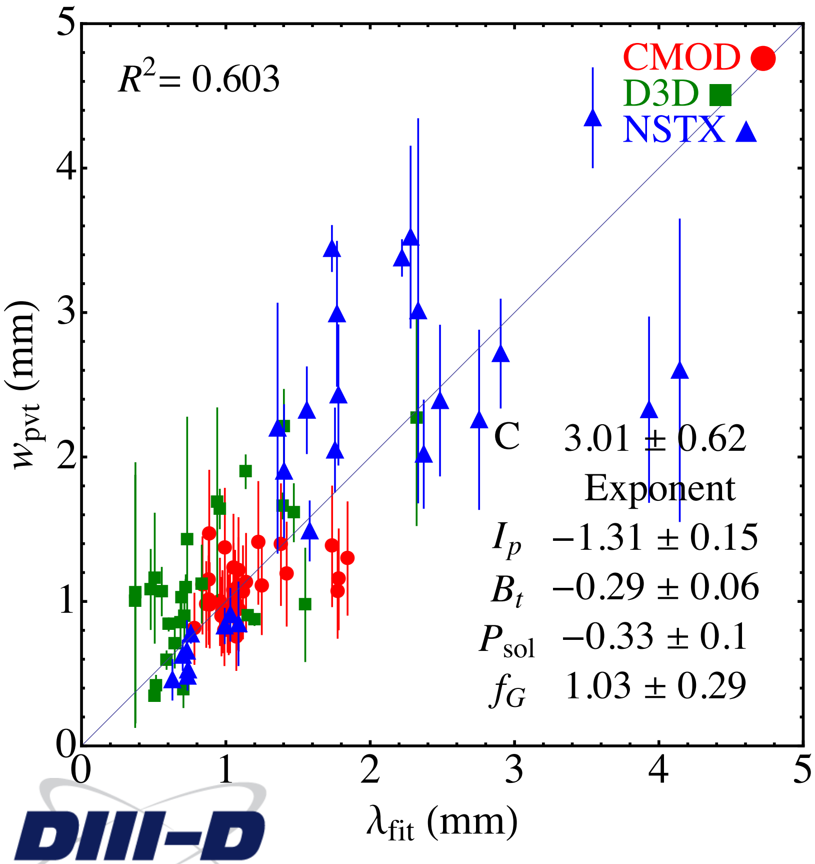
C	8.66 ± 1.32
	Exponent
I_p	−0.91 ± 0.09
B_t	−0.21 ± 0.05
a	0.33 ± 0.09
f_G	0.16 ± 0.21

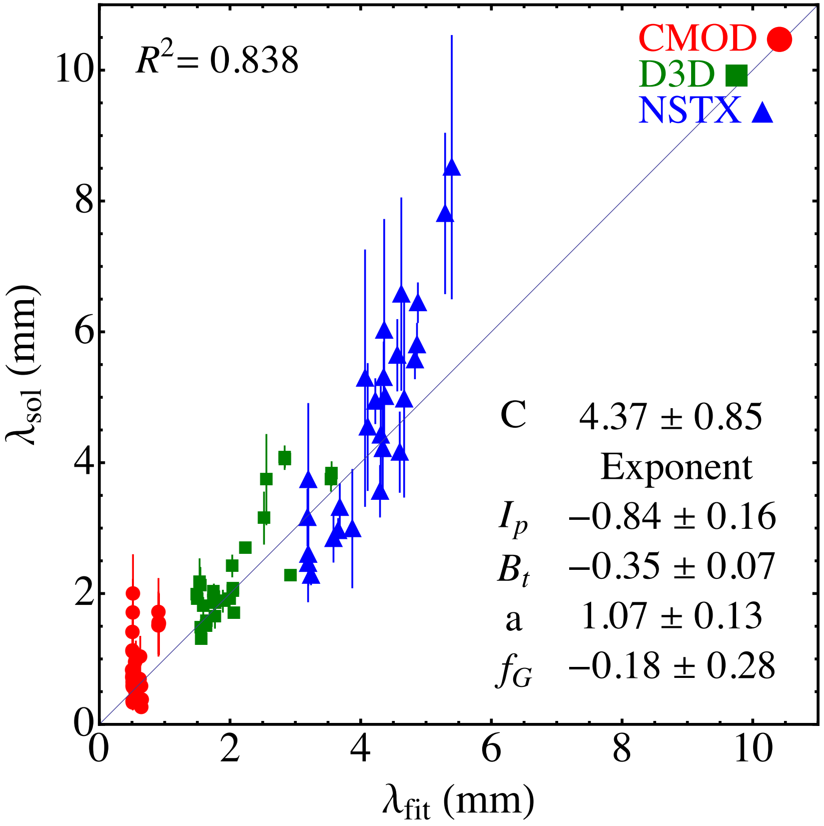


C	6.26 ± 1.16
	Exponent
I_p	−1.15 ± 0.12
B_t	−0.17 ± 0.06
a	0.44 ± 0.1
f_G	0.18 ± 0.27

The Eich Parameters w_{pvt} and λ_{sol} have Different Parametric Dependencies

- **Private flux (w_{pvt})**
  - Strong dependence on I_p, f_G
  - Weak dependence on B_t, P_{sol}
- **SOL (l_{sol})**
  - Strong dependence on I_p, a
  - Weak B_t and no f_G dependence



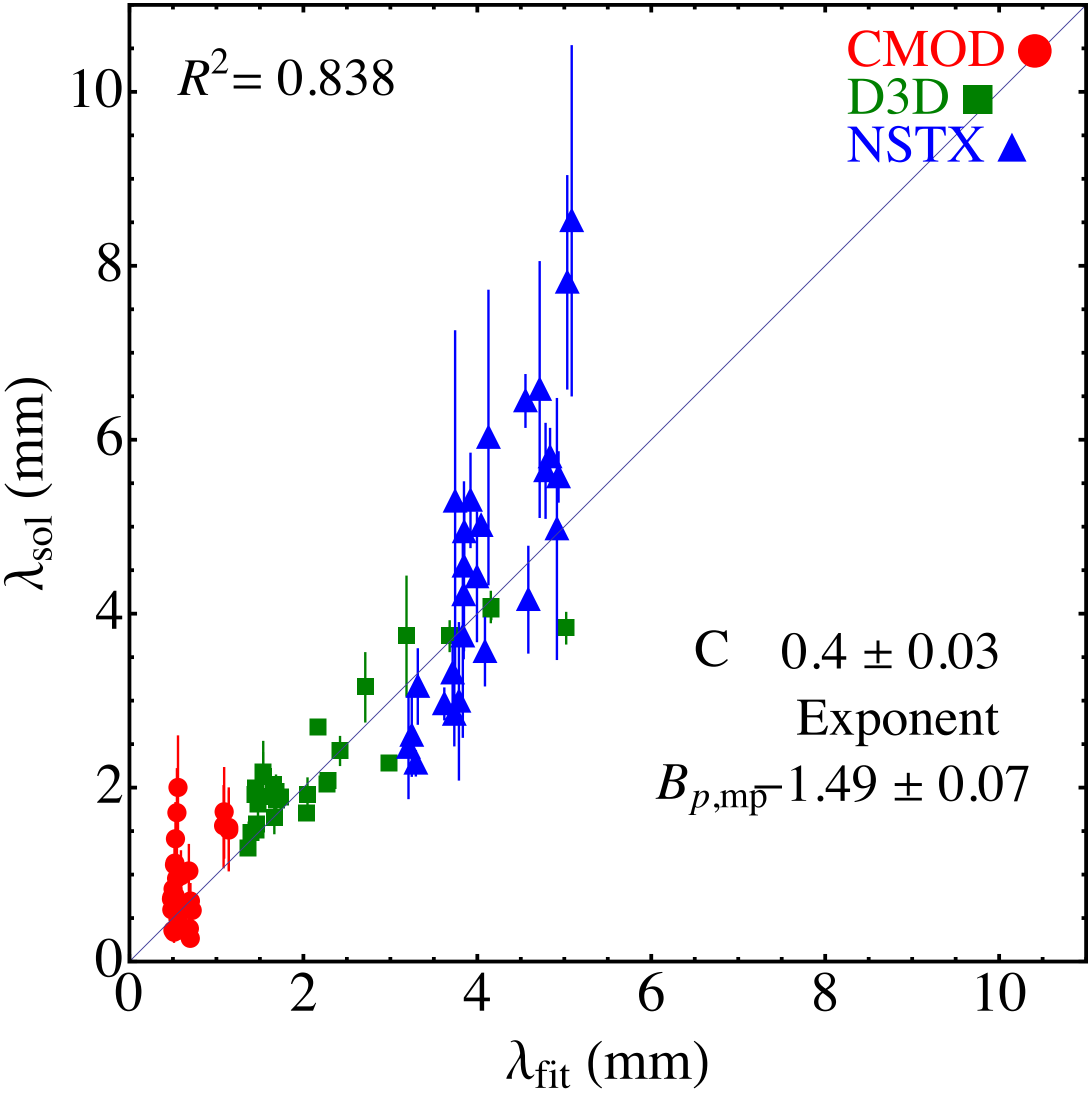


Scaling with a/I_p Suggest B_{pol} as Fundamental Dependence

- **Scaling of λ_{sol} with a/I_p suggests B_{pol} as a regression variable**

- **Resulting scaling is independent of all other variables, including minor radius, *a***

- **Has same value of correlation coefficient as 4 parameter regression**



Data from this Study is Consistent with JET/ASDEX-U Results*

- **Result of JET/ASDEX-U study are similar to those of this study**
  - Weak size scaling
  - No dependence on P_{sol}

$$\lambda_{JET-\mathrm{int}} = C \cdot B_t^{e_b} q_{cyl}^{e_q} P_{sol}^{e_p} R^{e_r}$$

$$C = 3.19 \pm 1.49$$

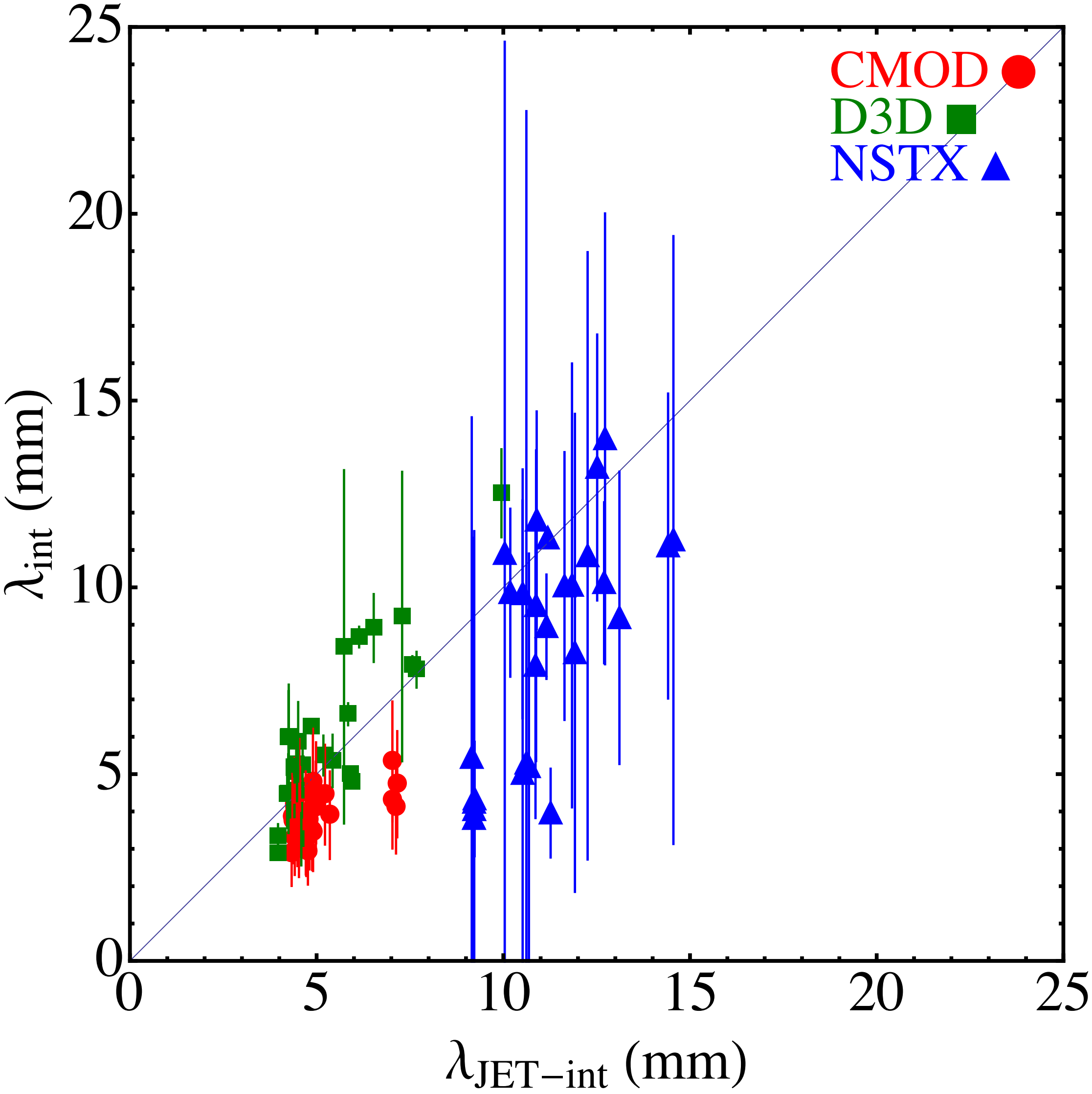
$$e_b = -0.47 \pm 0.21$$

$$e_q = 0.82 \pm 0.25$$

$$e_p = -0.05 \pm 0.09$$

$$e_r = -0.39 \pm 0.18$$

***Eich, NO.00014**



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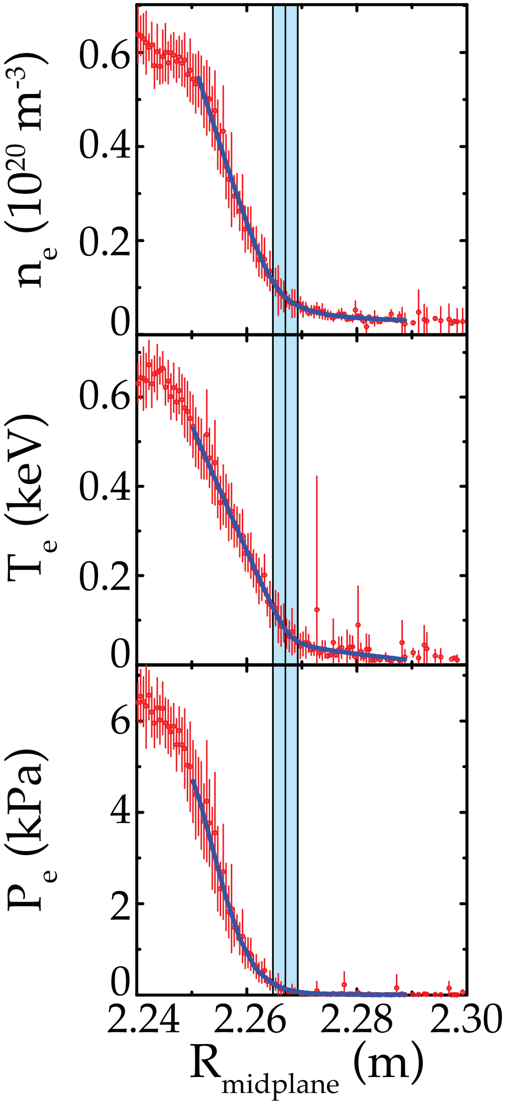
High Quality Upstream Plasma Profile Data has been Obtained

- **High quality Thomson data has been obtained for upstream plasma profiles on D3D this year**



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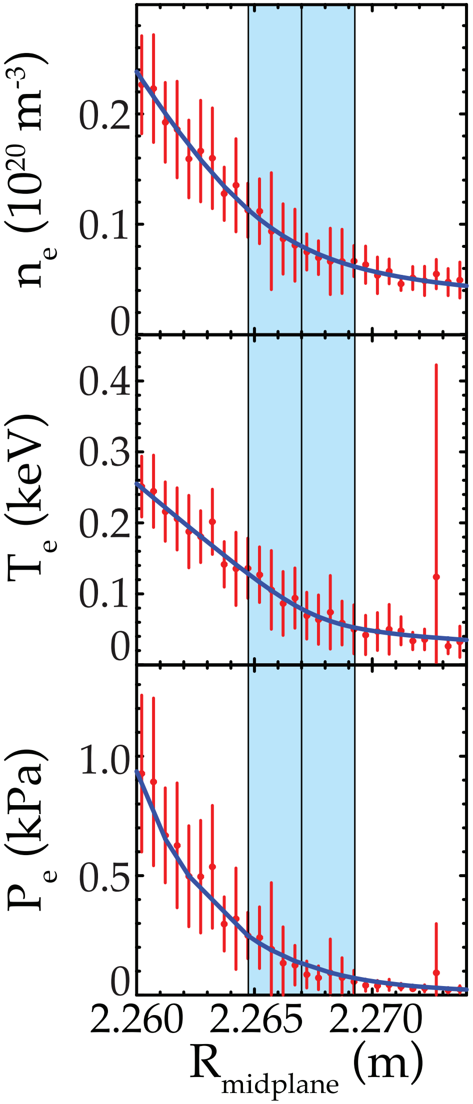
- **Relevant region for SOL models is quite small: ~10 mm**

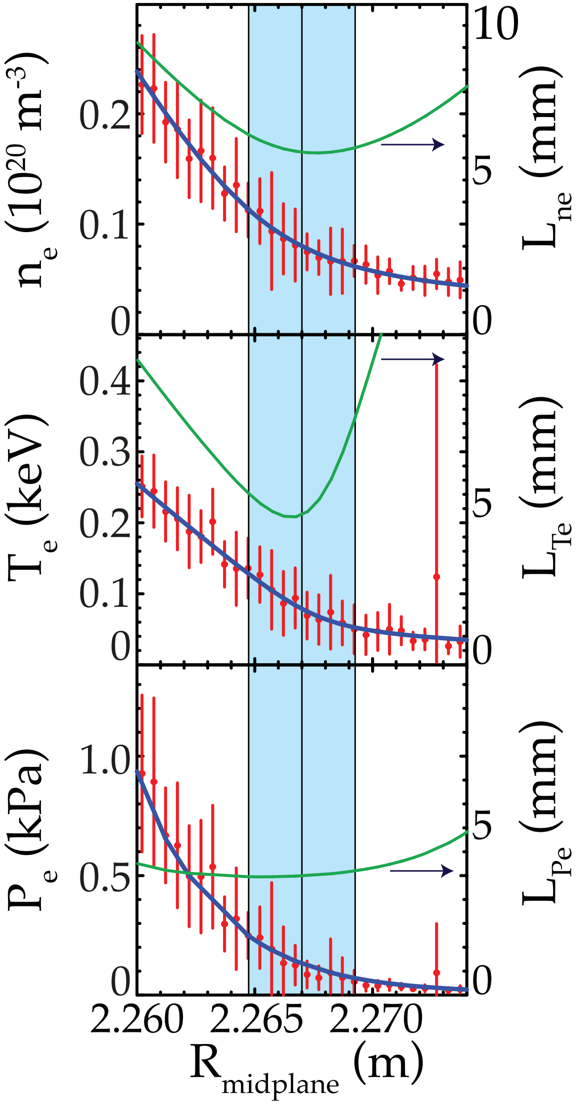


High Quality Upstream Plasma Profile Data has been Obtained

- **High quality Thomson data has been obtained for upstream plasma profiles on D3D this year**
- **Relevant region for SOL models is quite small: ~10 mm**
- **Can extract accurate gradient scale lengths: L_{ne}, L_{Te}, L_{pe}**

$$L_{ne} = \left(\frac{1}{n_e} \frac{dn_e}{dR} \right)^{-1}$$

- **Possible to evaluate the validity of simple models for parallel heat flux**



Profile Scale Lengths Generally Consistent with Parallel Physics Models of Heat Flux Width*

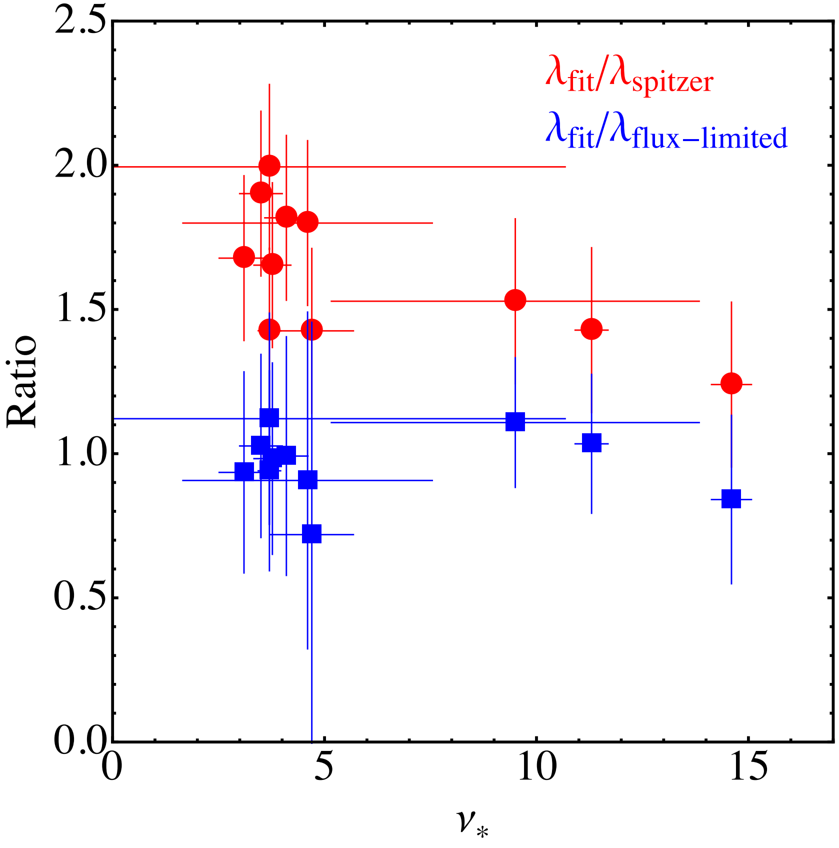
- **Parallel physics models generally predict that the heat flux width is proportional to the gradient scale lengths of the profiles of n_e, T_e, or P_e (or a combination of them)**

- **Models *relate* scale lengths to the heat flux width, but *do not predict* what determines the width**

- **Flux-limited model agrees better than Spitzer model**

$$\lambda_{\text{spitzer}} = \frac{2}{7} L_{Te}, \quad \lambda_{\text{flux-limited}} = \left(\frac{1}{L_{ne}} + \frac{1.5}{L_{Te}} \right)^{-1}$$

P.C. Stangeby, GO4.00009



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What Sets the Heat Flux Width??

- **Competition between parallel and cross-field physics determines the heat flux width**

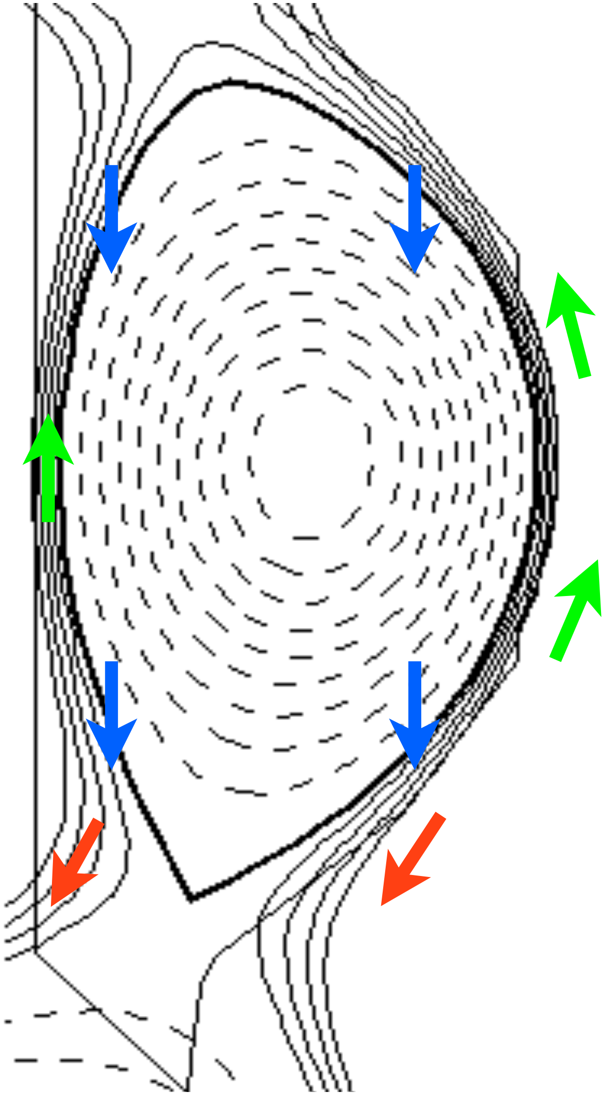
- **Scaling of the heat flux width indicates the dependencies, but not the underlying physics mechanisms**
  - Result is that the heat flux width depends strongly on B_p

- **Parallel physics yields a simple relation between the divertor heat flux width and SOL profiles**

- **Examine two possible models for SOL transport expected to scale with B_p**

Drift Based Model of SOL Flows Quantitatively Predicts the Heat Flux Width

- This is a first principals model with no free parameters but is based on a heuristic derivation*
- Magnetic drifts carry particles into the SOL
- Parallel flows assumed in the SOL
- The penetration of the drift into the SOL determines the *density* scale length
- Anomalous electron thermal diffusivity is needed to provide heat exhaust
- Factors of order unity may apply



******Goldston, accepted for publication, Nuc. Fusion***

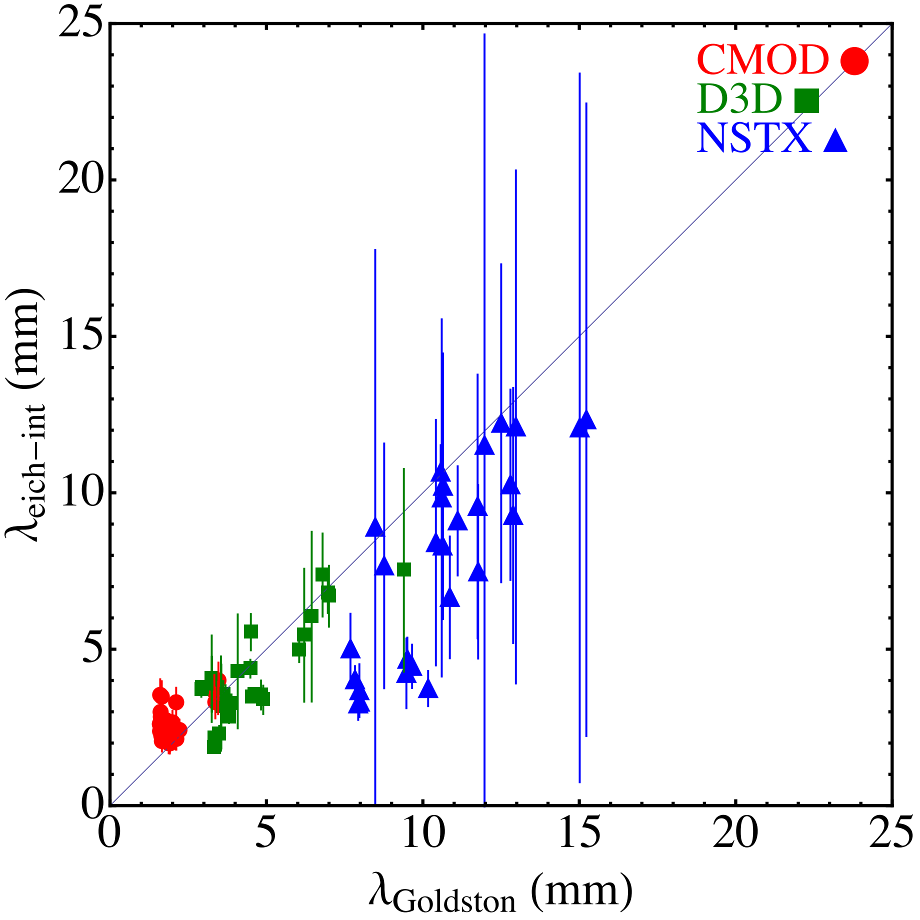
Our Results are Consistent with Drift Based Theory of Heat Flux Width

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

- **Observed size scaling is consistent with drift based theory of heat flux width**

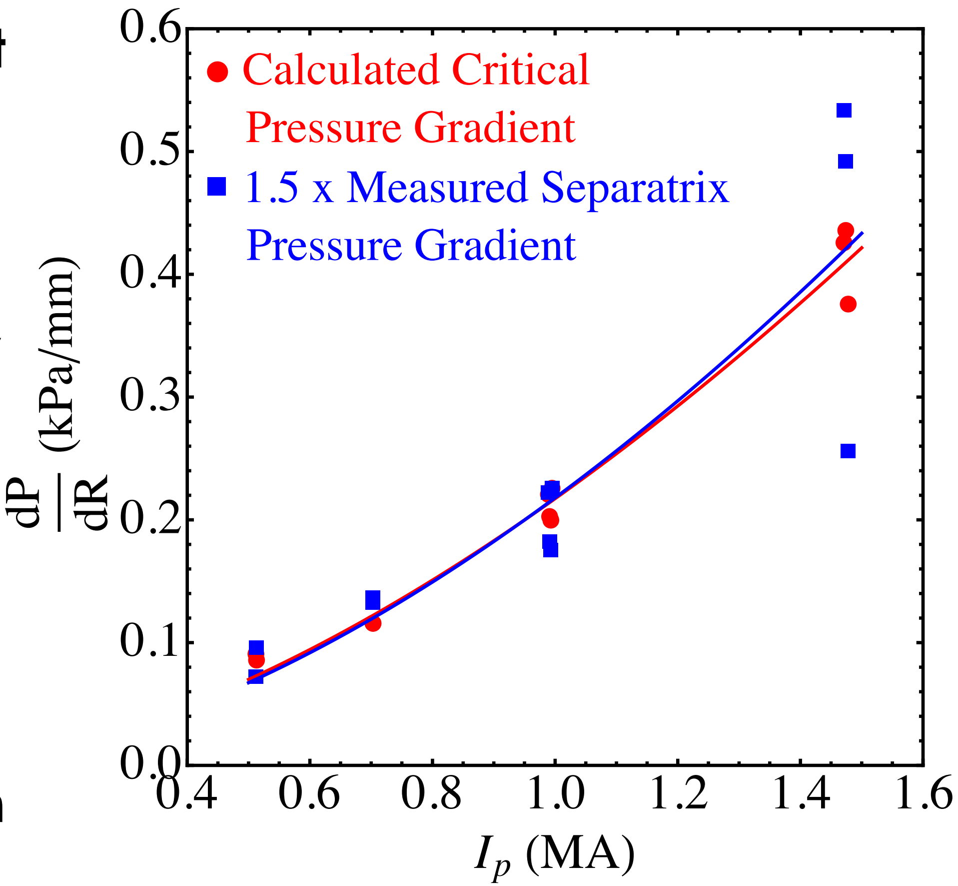
- **Predicts that the heat flux width is proportional to the poloidal gyroradius ~ $B^{-1}_{p,mp}$**

$$\frac{a^{17/8}}{I_p^{9/8} R} \approx \frac{a^2}{I_p R} = \frac{a}{R} \frac{1}{B_p}$$



The Kinetic Ballooning Mode (KBM) is a Leading Candidate for Setting the Edge Pressure Gradient*

- **Estimate the KBM critical gradient at the separatrix by the ideal ballooning mode stability limit**
- **Measured and calculated pressure gradients scale similarly**
  - Factor of 1.5 is within the uncertainty of measurements and calculation
- **For a complete model of the heat flux width, need**
  - A more accurate calculation of the KBM limit
  - A model for the separatrix pressure



***Snyder, CI2.00005**

M.A. Makowski/APS/November 2011

Outline

- Motivation
- Experimental Conditions and Diagnostics
- Heat Flux Profiles
- Multi-Machine Scaling Relations
- Plasma Profile Analysis
- Comparison with SOL Models
- **Conclusion and Summary**

Implications for Next Step Devices

- **Inverse I_p dependence dominates scaling of heat flux width**
  - This has important implications for high plasma current next step devices

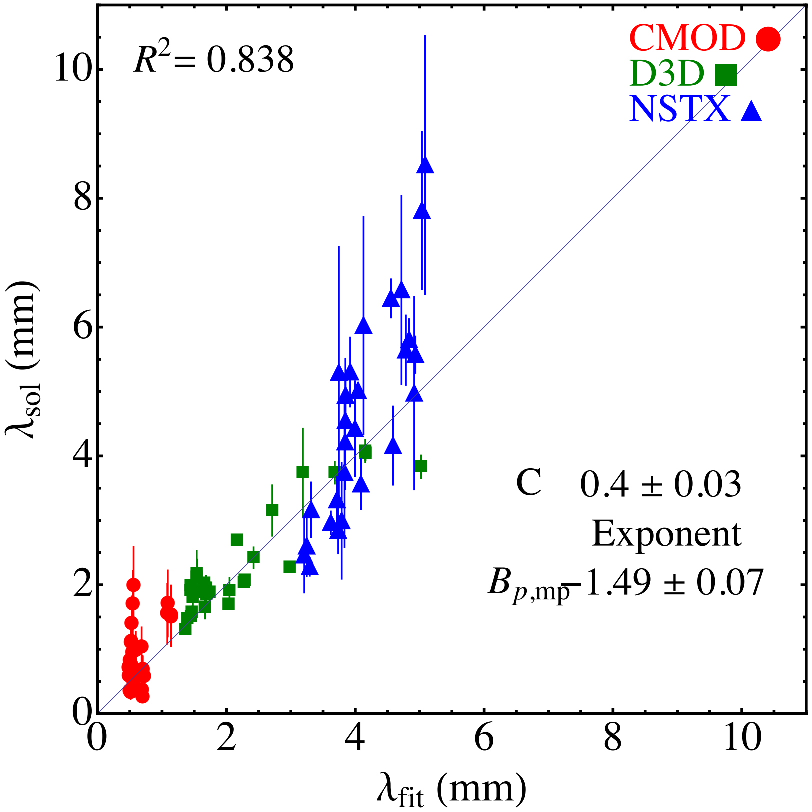
- **Regardless of secondary dependencies, heat flux widths are consistently smaller than currently used scaling relations**
  - Results here predict a width of the order of 1 mm for ITER
  - This is substantially less than the present estimate of 5 mm

Summary

- **Multi-machine data base predicts a scaling**

$$\lambda_q \sim \frac{a}{I_p} \sim \frac{1}{B_p}$$

- **Two-parameter fit yields independent scaling for private and common flux regions**



- **Upstream plasma profiles correlated with divertor heat flux width**
- **Heat flux width scaling consistent with drift based model**