15th ITPA SOL/Div. Group Meeting Report

Heat flux, Detachment, Fuel retention in gap

増崎　貴
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Heat Flux

- **Steady state heat flux (experiment)**
  - ✓ ITER start-up experiments in Tore Supra
    - J.P. Gunn (CEA, IRFM) et al.
  - ✓ Status report on inter-ELM heat flux analysis from JET and AUG
    - T. Eich et al.
  - ✓ US Joint research target on divertor heat flux DIII-D, C-mod and NSTX
    - A.W. Leonard et al.
- **Steady state heat flux (theory)**
  - ✓ Models of inter-ELM SOL energy transport and comparison with recent JET experiments
    - W. Fundamenski et al.
  - ✓ Heuristic drift-based model of the power scrape-off width in H-mode tokamaks with low gas-puff
    - R.J. Goldston

Heat Flux

- **ELM heat flux**
  - ✓ ELM heat flux analysis on DIII-D
    - – M. Makowski et al.
  - ✓ Impact of ELM mitigation with (R)MPs in AUG on edge parameters
    - – A. Kallenbach et al.

Motivation for this work

- In-vessel component power handling a MAJOR design and operational aspect for ITER
  - Steady state: heat flux widths for limiter start-up/ramp-down and steady state in the divertor
  - Transient: ELMs and disruptions → ELMs in this session
- ITER plasma heat load specifications (divertor and FW design!) remain uncertain
  - Adopted scaling for limiter λ_q → recent experiments do not support
  - Inter-ELM H-mode λ_q → how narrow will it really be? Is the ITER modelling strategy sound? What is the correct physics basis? What will an ITER ELM-mitigated SOL look like?
  - ELM heat load footprint: physics and scaling to ITER of the observed broadening with ELM size → minimum I_p on ITER without mitigation?

CCFE
CULHAM CENTRE FOR FUSION ENERGY

Models of inter-ELM SOL energy transport and comparison with recent JET experiments

W.Fundamenski, T.Eich (IPP), F.Militello, E.Havlickova

Culham Centre for Fusion Energy

Simple model(s) of SOL power width

SOL power width may be estimated as

$$\lambda_q \sim V_{\perp} \tau_{\|}$$

Parallel (poloidal) transport:

Model 1: (ion) convection dominates: $\tau_{\|} \sim L_{\|} / c_s$,

Model 2: (electron) conduction dominates: $\tau_{\|} \sim L_{\|}^2 / \chi_{\| e}$,

Perpendicular (radial) transport:

Model A : ion-ion (collisional) heat diffusion: $V_{\perp} \sim \sqrt{\chi_{\perp i}^{cl} / \tau_{\|}}$,

Model B : Drift ordered (Gyro-Bohm) velocity: $V_{\perp} \sim \delta c_s \sim c_s (\rho_s / \lambda_q)$,

Model C: Transport ordered velocity: $V_{\perp} \sim \delta^2 c_s \sim c_s (\rho_s / \lambda_q)^2$,

Model D : Curvature drift velocity: $V_{\perp} \sim c_s (\rho_s / R)$,

Model E : Interchange radial velocity: $V_{\perp} \sim c_s \sqrt{\rho_s / R}$,

W.Fundamenski, T. Eich, et al, NF (2011), in press

aki

Conclusions

- Many different simple models of the inter-ELM power width may be constructed, with a natural division into parallel convection and conduction families
- The recent JET data is best matched by a model based on competition between parallel electron conduction and drift-ordered (Gyro-Bohm) perpendicular convection, followed closely by marginal stability to interchange/ballooning modes
- If true, this would imply that radial transport in the near-SOL is dominated by residual levels of turbulence in the edge transport barrier, most likely driven by pressure gradient (resistive ballooning / interchange) instabilities
- Not possible to infer a unique size scaling. The error weighted size scaling is found as 0.7 ± 0.6.
- With this assumption, the power width on ITER is found in the range of ~ 5.5 mm (3.5 – 9) mapped to the outer mid-plane (in agreement with standard ITER assumptions and previous estimates)

$$\lambda_q^{i\text{-}ELM}(R_0;\zeta) = 1.63 \times (R_0/2.9)^{\zeta} \times B^{-0.57\pm0.32} q_{cyl}^{1.0\pm0.31} P_{sol}^{0.23\pm0.09} Z^{0.3\pm0.1} \ [\mathrm{mm}]$$

W.Fundamenski et al, NF (2011), in press

Heuristic Drift-Based Model of the Power Scrape-Off Width in H-Mode Tokamaks with Low Gas Puff

Robert J. Goldston
Princeton Plasma Physics Laboratory

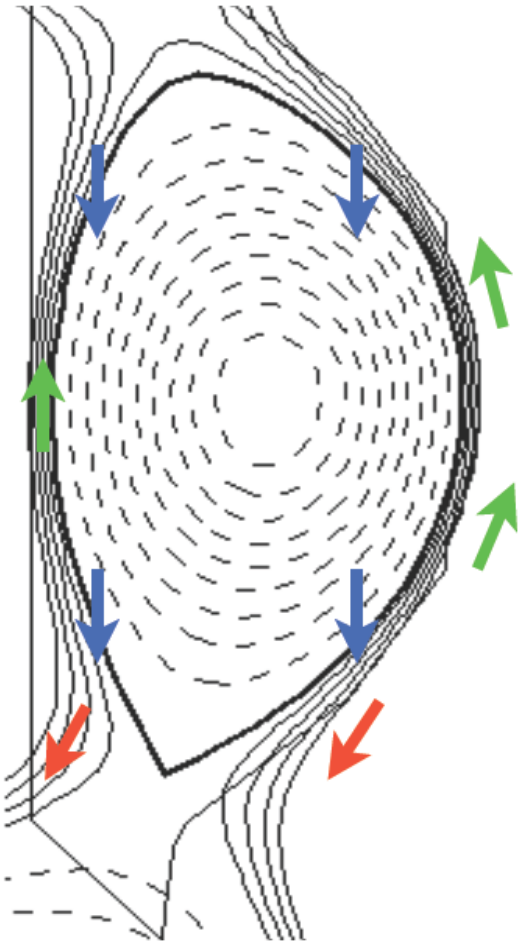
Thanks to Thomas Eich, Wojtek Fundamenski,
Sergei Krasheninnikov, Brian LaBombard, Bruce Lipschultz,
Peter Stangeby, Dennis Whyte and Michael Zarnstorff
for helpful discussions

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

Heuristic drift-based model of the power scrape-off width ...

- **Basic Ideas are Simple**
  - Particles Grad *B* and Curvature *B* drift into the SOL
  - Particles flow out of the SOL at velocity $\sim c_s/2$
  - Electrons carry heat out of SOL per Spitzer
- **Fit to Data is Fairly Good**
  - Gives reasonable predictions of I_{loss}, τ_p.
  - Fits λ_q fairly well in absolute value and scaling
- **Implications for ITER are Complex**
  - Low-gas-puff width is small
  - Heat spreading with gas puff may be very effective

Particles ∇B and curv$B$ Drift into SOL, Flow out of SOL at ~ $c_s/2$



- **Grad B and curv B drifts cross separatrix**

- **Pfirsch-Schlüter flows connect top and bottom**

- **SOL *also* empties to divertor in $\tau_{||} \sim L_{||}/(c_s/2)$**

- $\lambda \sim \langle v_d \rangle \tau_{||}$

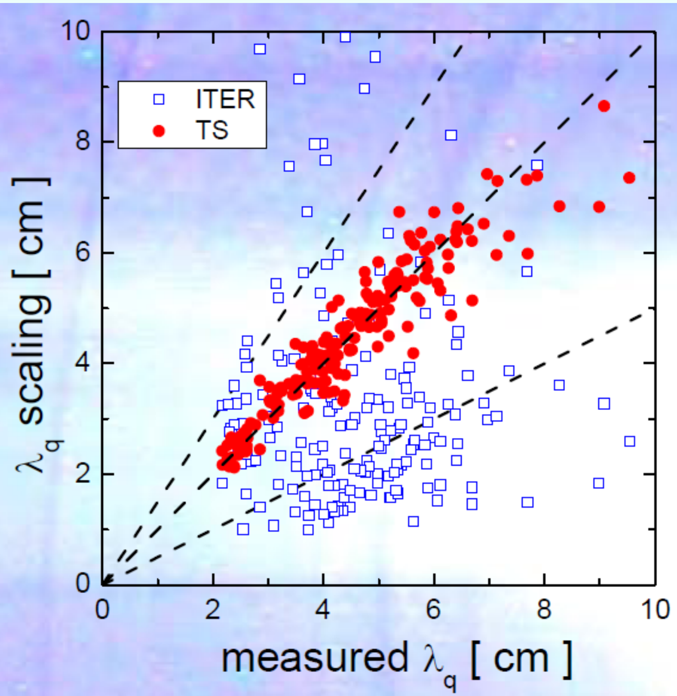
$$\Delta_{Drift} = 5671\ P_{SOL}^{1/8} \frac{\left(1+\kappa^2\right)^{5/8} a^{17/8} B^{1/4}}{I_p^{9/8} R} \left[\frac{2\bar{A}}{\left(1+\bar{Z}\right)}\right]^{7/16} \left(\frac{Z_{eff}+4}{5}\right)^{1/8}$$

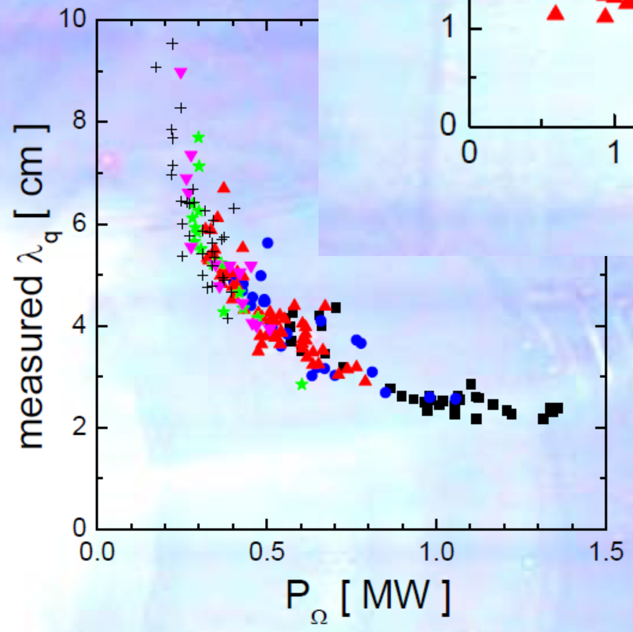
ITER start-up experiments in Tore Supra

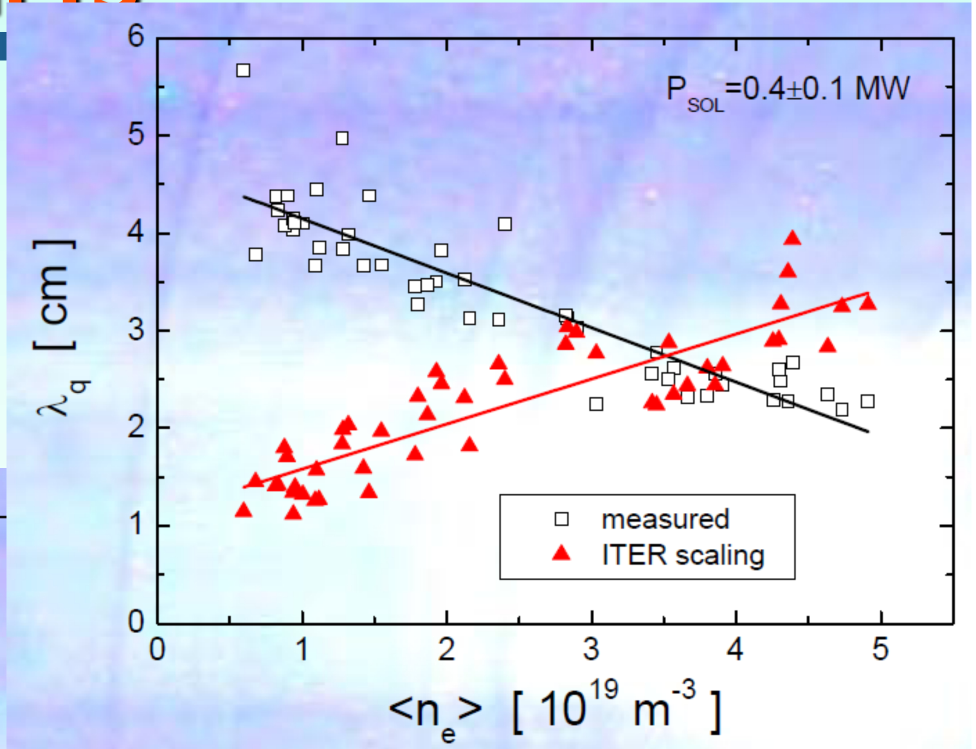
James. P. Gunn
M. Kubič, N. Fedorczak, M. Kočan
P. Devynck, P. Monier-Garbet, J.-Y. Pascal, F. Saint-Laurent

CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France.

ITER start-up experiments in TS







ITER : $\lambda_q = \left(1 \pm \frac{1}{3}\right) 3.6\times10^{-4} R^2 P_{SOL}^{-0.8} q_a^{0.5} n_e^{0.9} Z_{eff}^{0.6}$

TS : $\lambda_q = \left(1 \pm \frac{1}{10}\right) 0.025\, P_{\Omega}^{-0.7}$

Status report on inter-ELM heat flux analysis from JET and ASDEX Upgrade

- Some first results on joint efforts -

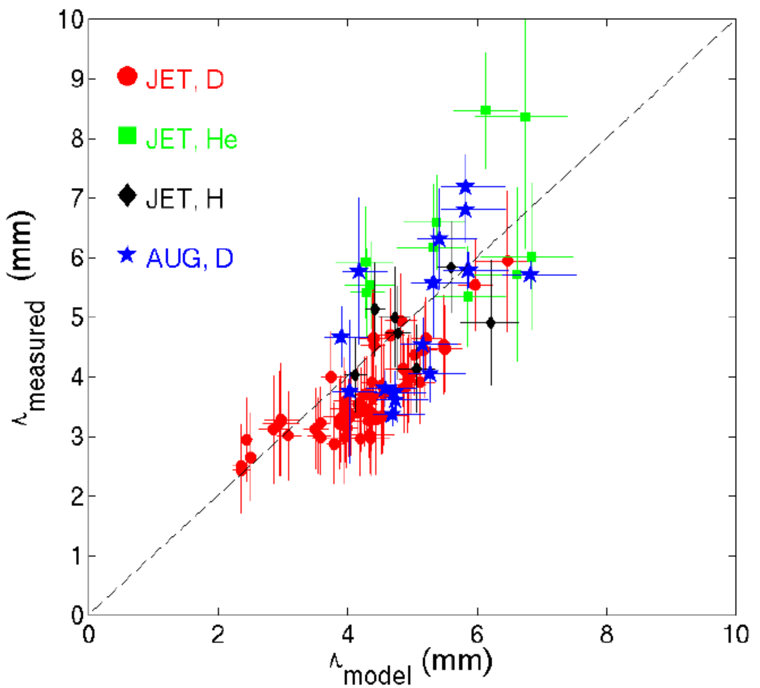
T.Eich

B.Sieglin, A.Scarabosio, A.Herrmann, S.Jachmich, S.Devaux, W.Fundamenski

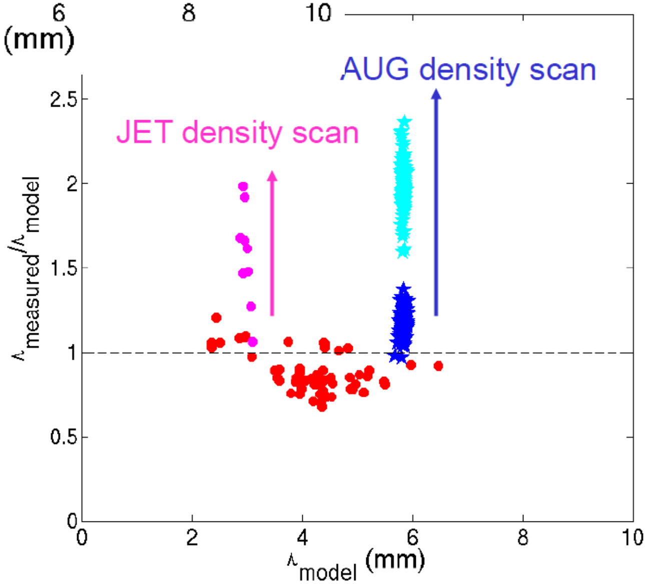
With input by A.W.Leonard,M.Makowski

Status report on inter-ELM heat flux from JET and AUG

- JET, AUGにおける計測とデータベース
  - ✓ データベース
  - ✓ 赤外線カメラ計測の検証
  - ✓ ELM cycle中のピーク熱流束位置の移動
- JET, AUGの熱流束分布特性長の評価



- 回帰解析
  - ✓ λ_qとプラズマパラメータ
  - ✓ Goldston-modelとの比較



$$\Delta_{Drift} = 5671\ P_{SOL}^{1/8} \frac{\left(1+\kappa^2\right)^{5/8} a^{17/8} B^{1/4}}{I_p^{9/8} R} \left[\frac{2\bar{A}}{\left(1+\bar{Z}\right)}\right]^{7/16} \left(\frac{Z_{eff}+4}{5}\right)^{1/8}$$

US Joint Research Target on Divertor Heat Flux DIII-D, C-mod, and NSTX

A.W. Leonard, T.K. Gray, B. LaBombard, C.S. Lasnier,
R. Maingi, M. Makowski, J.L. Terry

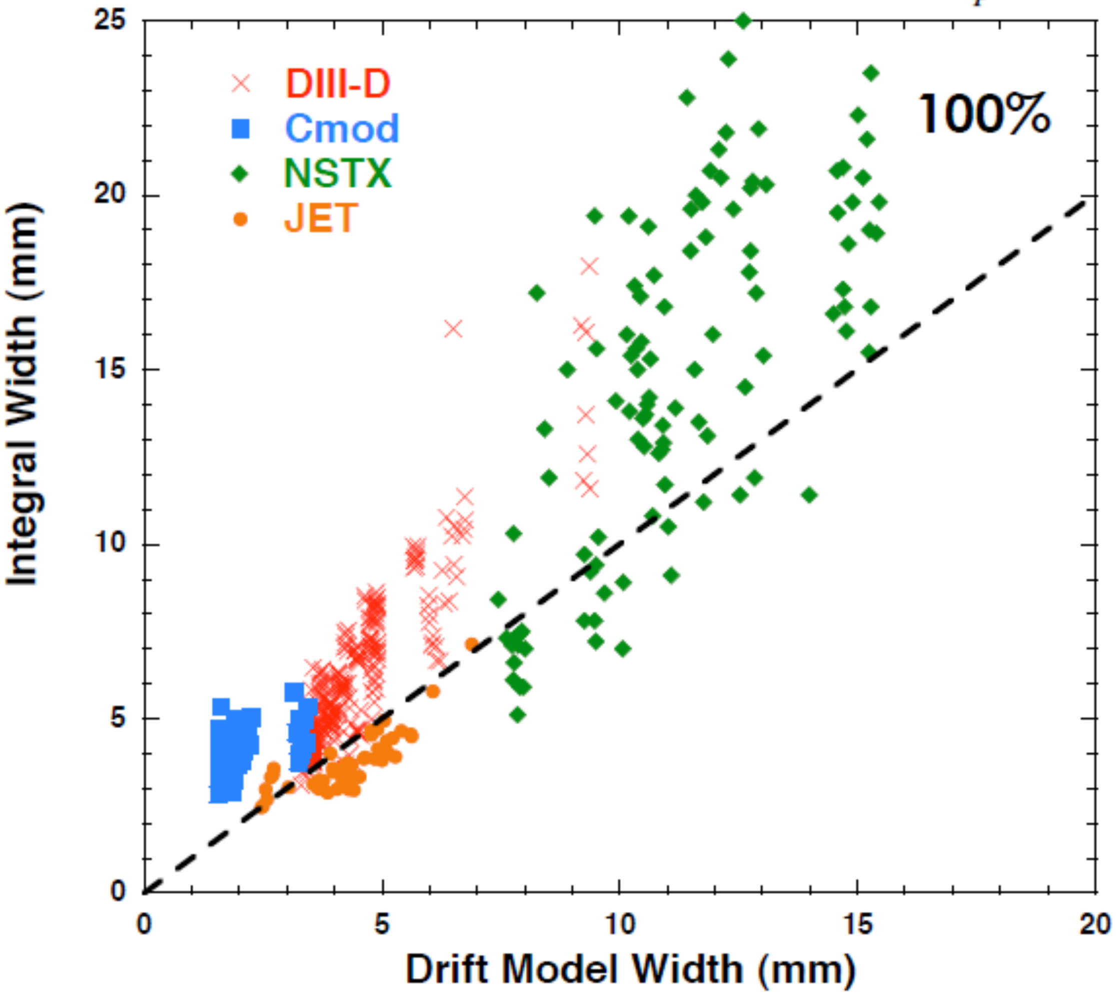
With JET contributions From T. Eich

15th Div/SOL ITPA Meeting
Helsinki, Finland
16-19 May, 2011

US joint research target on divertor heat flux

- 米国の装置におけるダイバータ熱流束計測進展への努力
  - ✓ 計測の充実
    - 赤外線カメラ設置　C-mod, NSTX, DIII-D
    - C-modではIRカメラ計測のため傾斜ダイバータ板を設置
  - ✓ 協調的実験
    - プラズマ形状を揃えたパラメータスキャン
    - 無次元比較　DIII-DとC-mod
    - 上流におけるプラズマ分布計測　揺動も
  - ✓ 理論グループの関与
    - Drift-based transport
    - Critical gradient
    - 2D transport simulation

US joint research target on divertor heat flux



- Assume; Z=1, Z_{eff} = 2, A=2
- Drift model exhibits much of the scaling trend between devices.

ELM Heat Flux Analysis on DIII-D*

M. Makowski†, C. Lasnier†, A. Leonard‡

15th ITPA Meeting on

SOL/Divertor Physics

17 May 2011

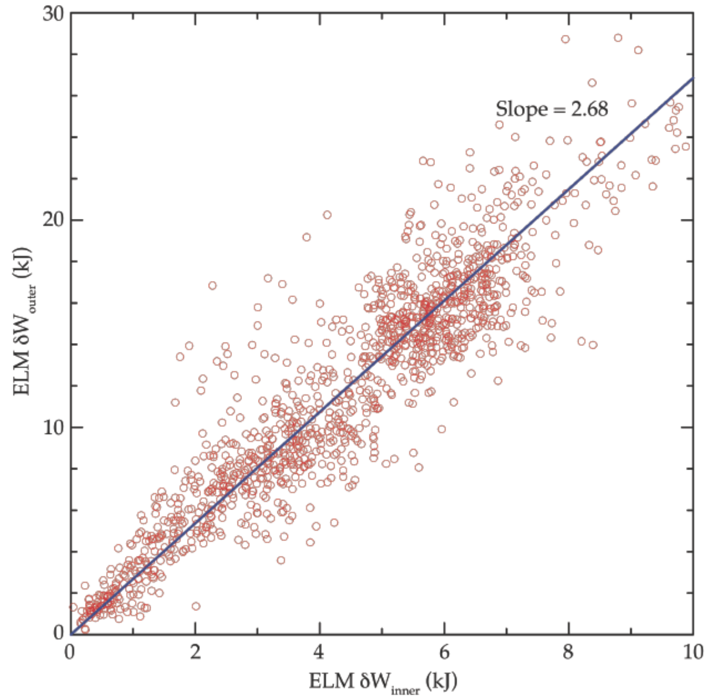
Helsinki, Finland

*Supported by the US DOE under DE-AC52-07NA27344 and DE-FC02-04ER54698.

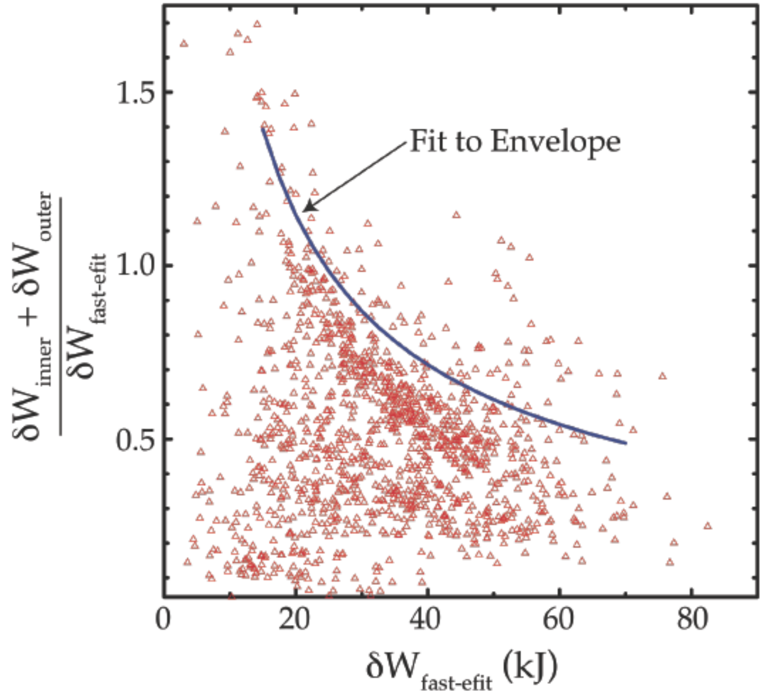
†Lawrence Livermore National Laboratory

‡General Atomics

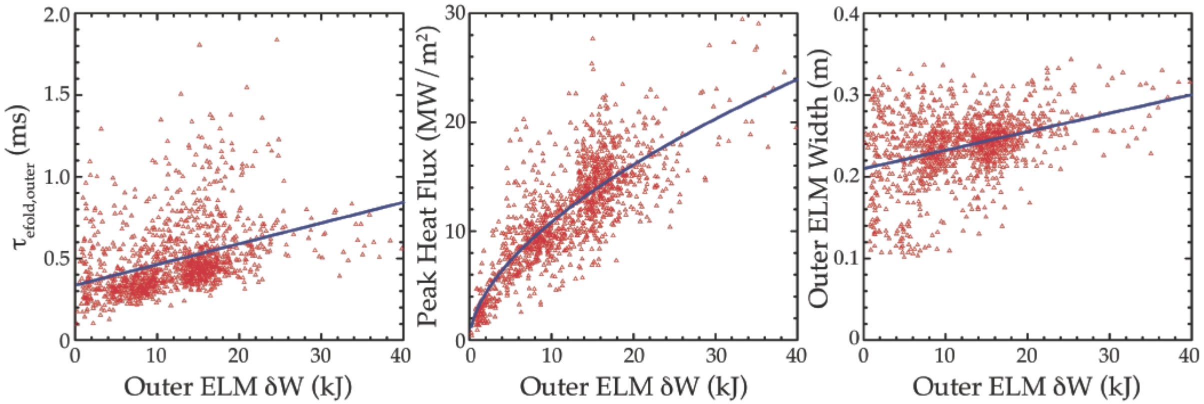
ELM heat flux analysis on DIII-D



- Although the inner peak is higher, its width is narrower and it decays faster
- Strong correlation between inner and outer ELM energies
- About 75% of the energy is in the outer peak
- This is contrary to previous results
- Bump contributes a significant amount of energy to outer peak
- α inner vs outer?

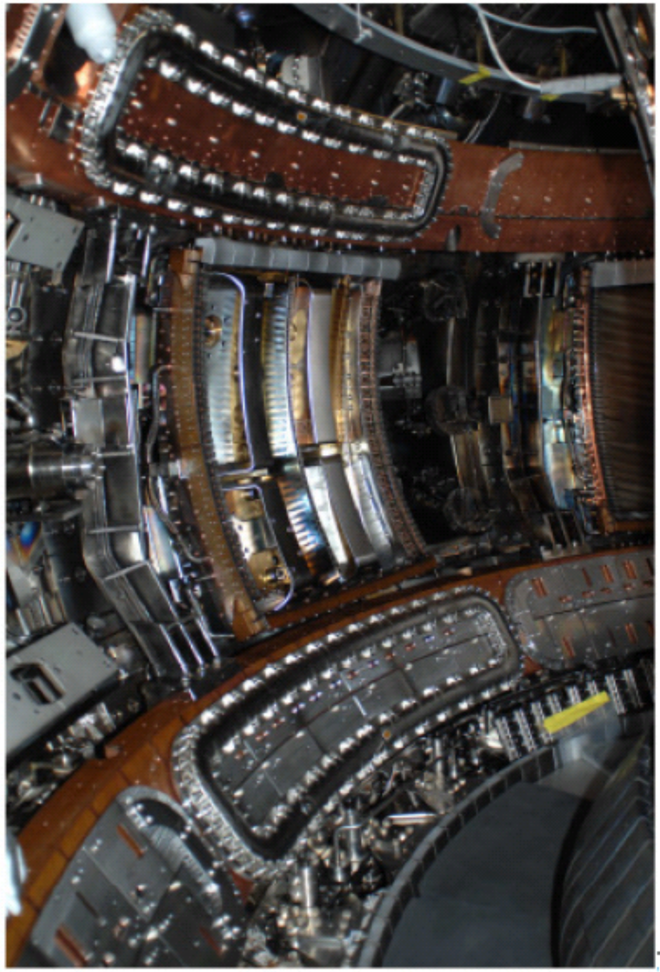


ELMサイズが大きくなるとダイバータへ流れる熱の割合が減っている



ELMサイズが大きくなるとピーク熱流束は減。しかし、幅が増・減衰時間が長くなっている。

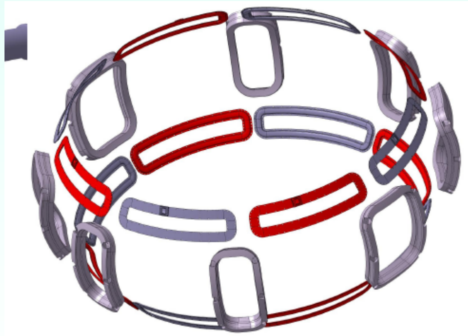
Impact of ELM mitigation with (R)MPs in ASDEX Upgrade on edge parameters

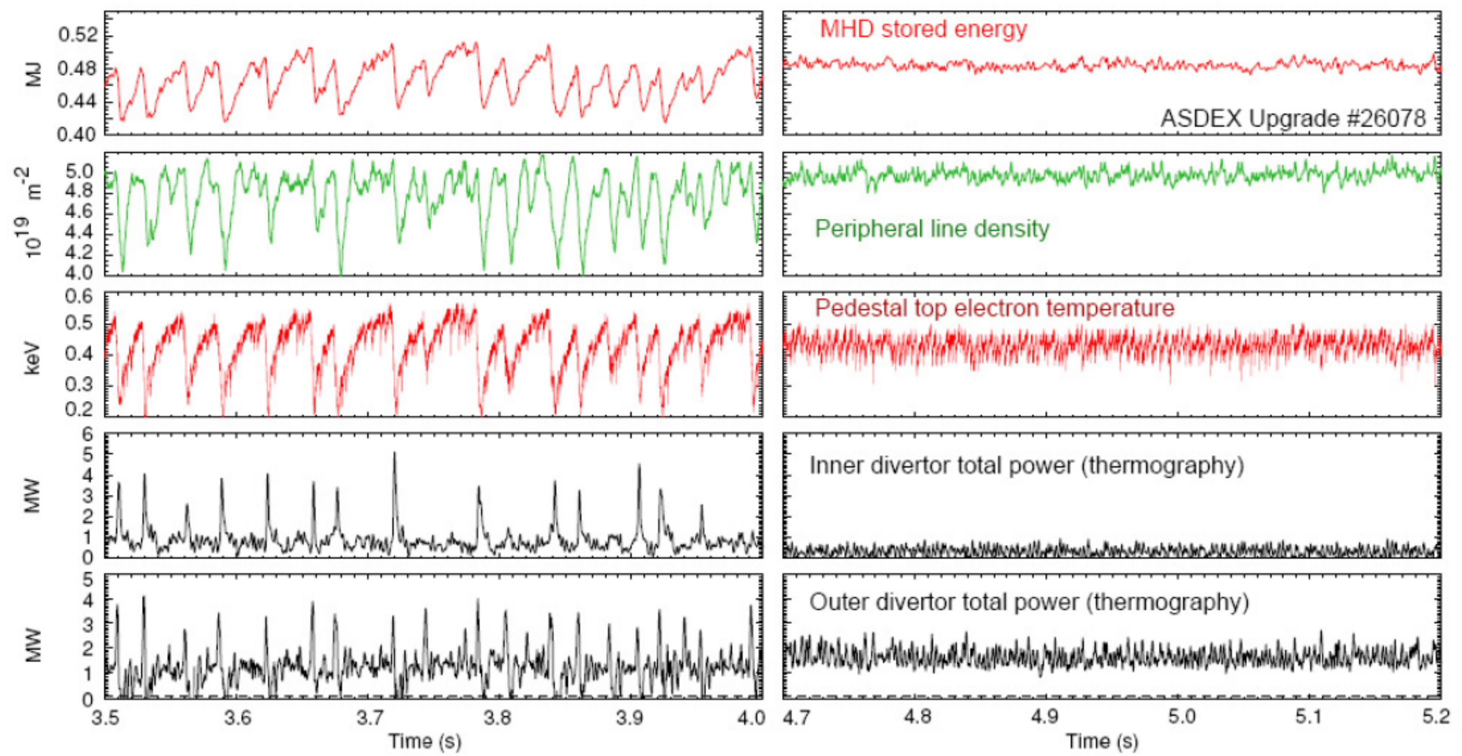


Arne Kallenbach for the ASDEX Upgrade Team
special thanks to Wolfgang Suttrop

Impact of ELM mitigation with (R)MPs in AUG ---

- 8個のサドルコイルを設置
- 共鳴・非共鳴によらず、ELM低減
- 比較的高い密度領域（~0.7n_G）でELM低減を観測
- 閉じ込め劣化、密度ポンプアウト、タングステンの蓄積は観測されず。





Much reduced excursions of W_{MHD}, $\overline{n}_e$, $T_{\mathrm{e,ped}}$, P_{div}!

Detachment

- **Simulations of detached L-mode plasmas in DIII-D, AUG and JET with UEDGE**

  M. Groth et al.

- **Extension of SOLPS4 grid up to first wall -Current status- May 2011**

  S. Wiesen et al.

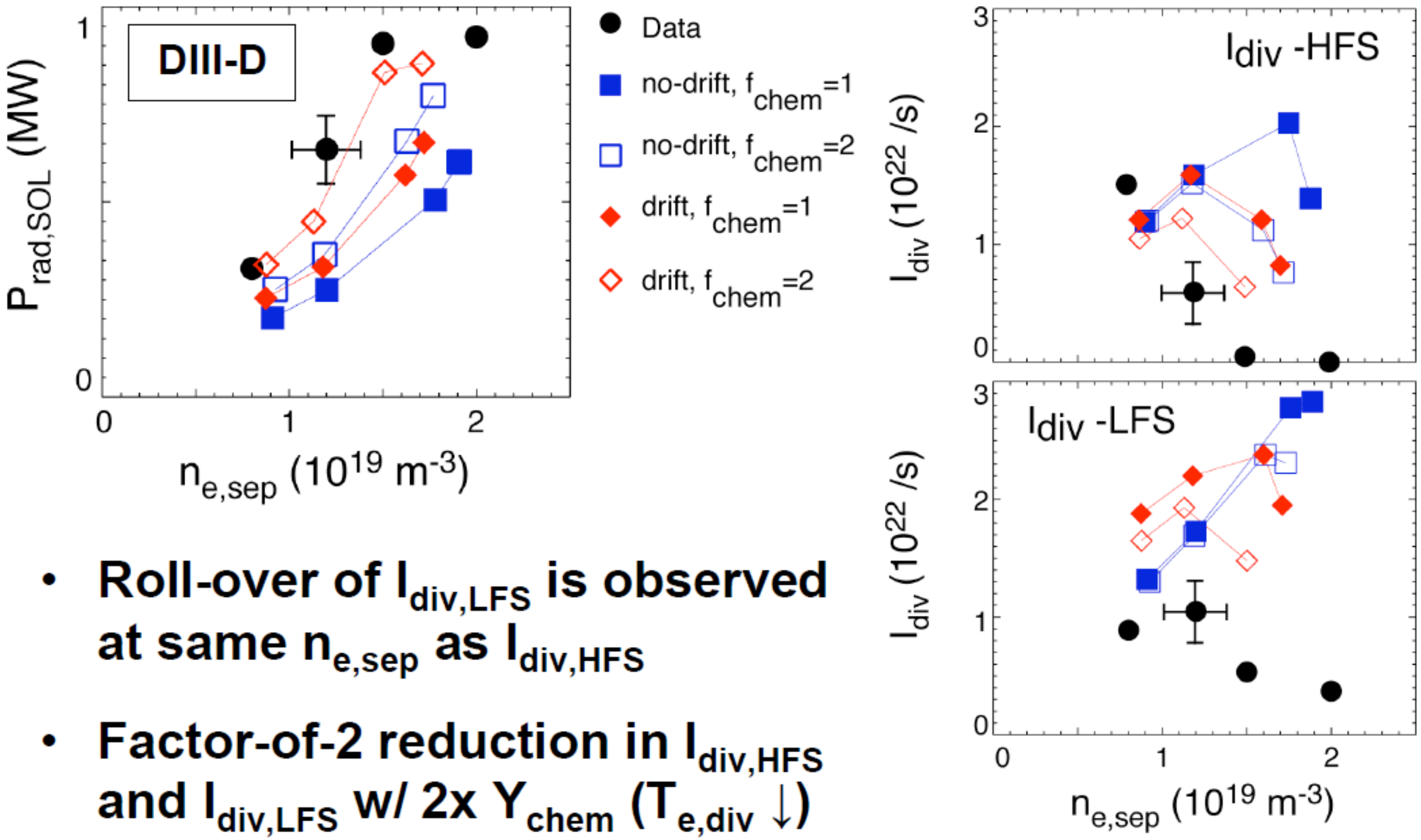
- **SOL current contribution to heat flux**

  V. Rozhansky et al.

Simulations of detached L-mode plasmas in DIII-D, AUG, and JET with UEDGE

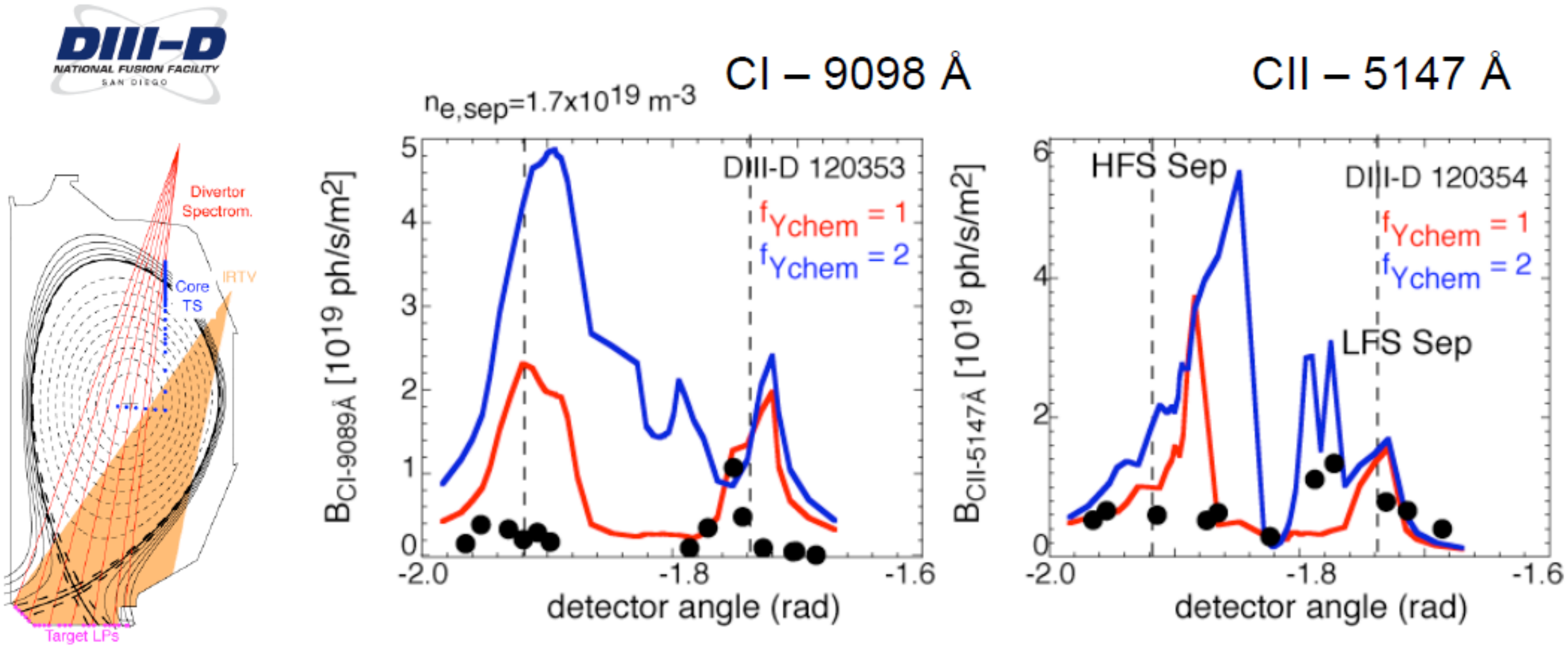
M. Groth, G.D. Porter, T.D. Rognlien, M.E. Rensink,
S. Wiesen, M. Wischmeier,
S. Jachmich, H.W. Müller, J.G. Watkins, B.D. Bray,
S. Brezinsek, N.H. Brooks, M.E. Fenstermacher,
C. Fuchs, R.A. Groebner, A. Huber, A.W. Leonard, A. Meigs,
and the DIII-D and AUG teams, and the JET-EFDA contributors*

DIII-D: drifts + raising Y_{chem} by 2x reproduces $P_{rad,SOL}$, and moves I_{div} and P_{div} toward measurements



- **Roll-over of $I_{div,LFS}$ is observed at same $n_{e,sep}$ as $I_{div,HFS}$**
- **Factor-of-2 reduction in $I_{div,HFS}$ and $I_{div,LFS}$ w/ 2x Y_{chem} ($T_{e,div}$ ↓)**

Carbon source from the inner divertor leg too high by factors of ~ 10 assuming Haasz-Davis yields



- **CII emission from inner leg factors of 10 to 20 higher than observed experimentally; outer leg within a factor of 2**

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JÜLICH FORSCHUNGSZENTRUM

Extension of SOLPS4 grid up to first wall – current status – may 2011

S.Wiesen[1], P.Boerner[1], M.Baelmans[2], D.Reiter[1], W.Dekeyser[2], S.Brezinsek[1], A.Huber[1]

[1]FZ-Juelich, [2]KU-Leuven

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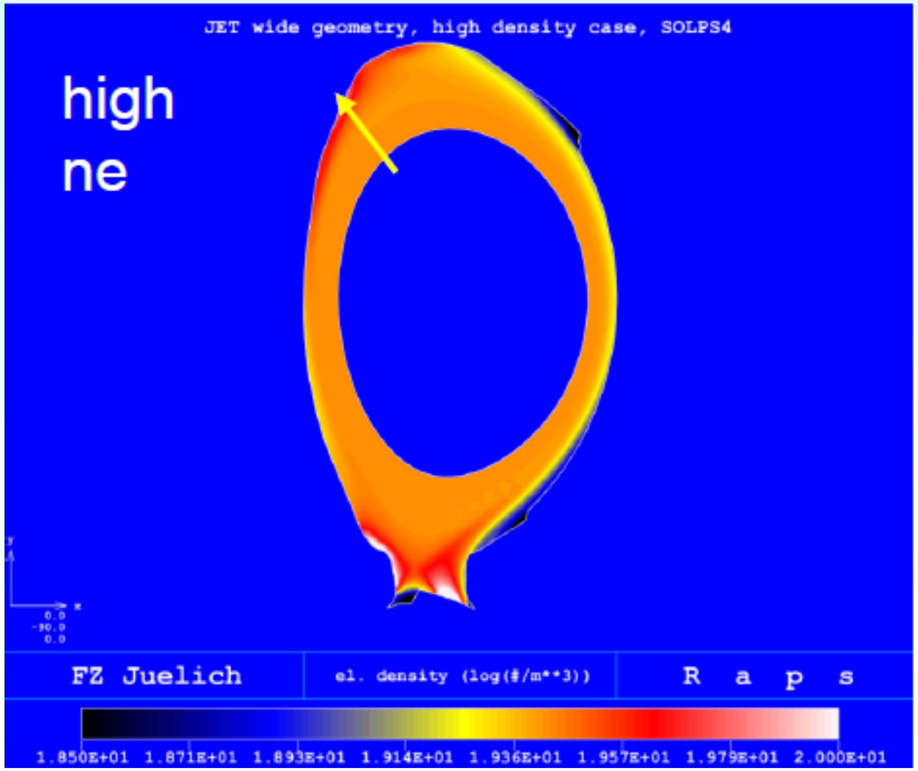


- *SOLPS4 shows enhanced recycling with increasing density at upper HFS and on top inner baffle*

→ can we detect this in the JET experiment?
(similar effect in vertical target configuration? effect on flow symmetry?)

Fuel Retention in Gap

- **Tritium retention in gaps of the tiles in JT-60U**

  M. Yoshida et al.

- **Erosion/deposition, and retention in gaps in KSTAR**

  Suk-Ho Hong et al.

- **Studies of hydrocarbon cracking and transport into gaps in TJ-II**

  F.L. Tabarés

Scientific Research in Priority Areas
Tritium for Fusion
2007 - 2011

JAEA

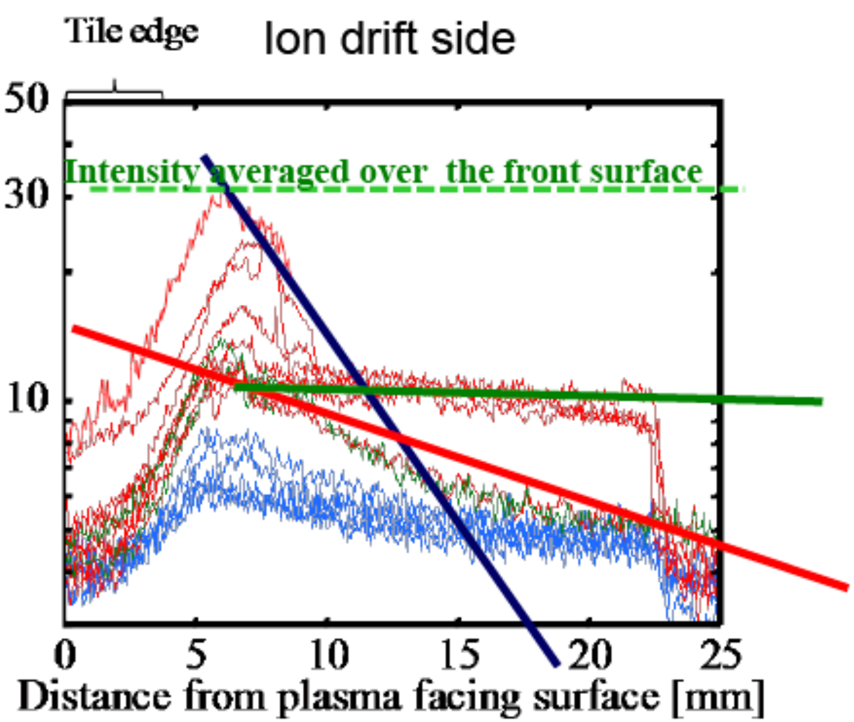
Tritium retention in gaps of the tiles in JT-60U

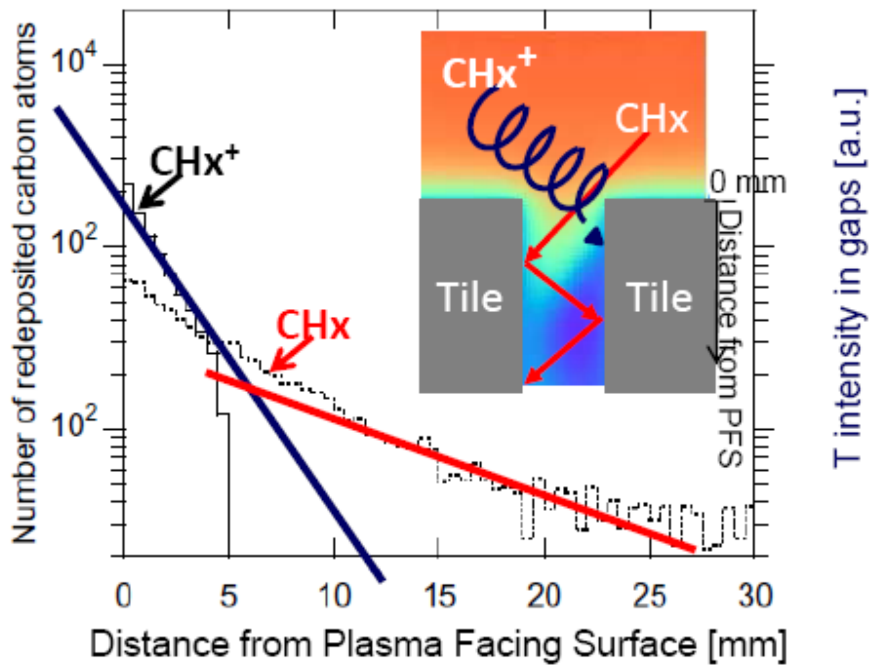
M.Yoshida[1], T.Tanabe[1], T.Hayashi[2], T.Nakano[2], K.Masaki[2], K.Itami[2]

[1]Kyushu University, Japan
[2]Japan Atomic Energy Agency, Japan

Tritium retention in gaps of the tiles in JT-60U

Tritium profile in tile gaps at first wall is very similar to Carbon deposition profiles observed and simulated for divertor region (Monte Carlo simulation by Ohya et al)





K. Inai, K. Ohya / Journal of Nuclear Materials 363–365 (2007) 915–919

Erosion/deposition, and retention in gaps in KSTAR.

Suk-Ho Hong[1,2,5,†], Sang-Joon Park[2,‡], Jae-Myung Choe[2], Young-Mu Jeon[1], Seung-Jae Yang[3], Sun-Taek Lim[2], Sooseok Choi[4], Young-Gil Jin[2], Chong Rae Park[3], and Gon-Ho Kim[2]

[1]National Fusion Research Institute, 113 Gwahangno, Yusung-Gu, Daejeon, 305-333, Korea
[2]Department of Nuclear Engineering, Seoul National University, Seoul, Korea
[3]Department of Materials Science and Engineering, Seoul National University, Seoul, Korea
[4]Center for Advance Research in Fusion Reactor Engineering, Seoul National University, Seoul, Korea
[5]Center for Edge Plasma Science (cEps), HanYang University, Seoul 133-791, Korea

[†]Email: sukhhong@nfri.re.kr
[‡]Present address: Department of Electrical Engineering, HanYang University, Seoul, Republic of Korea

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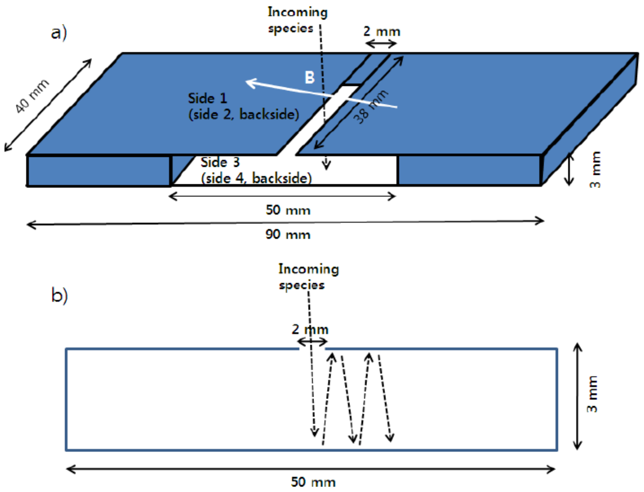
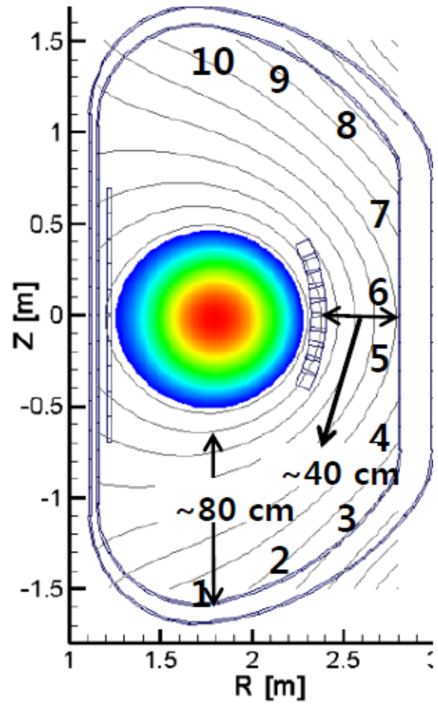
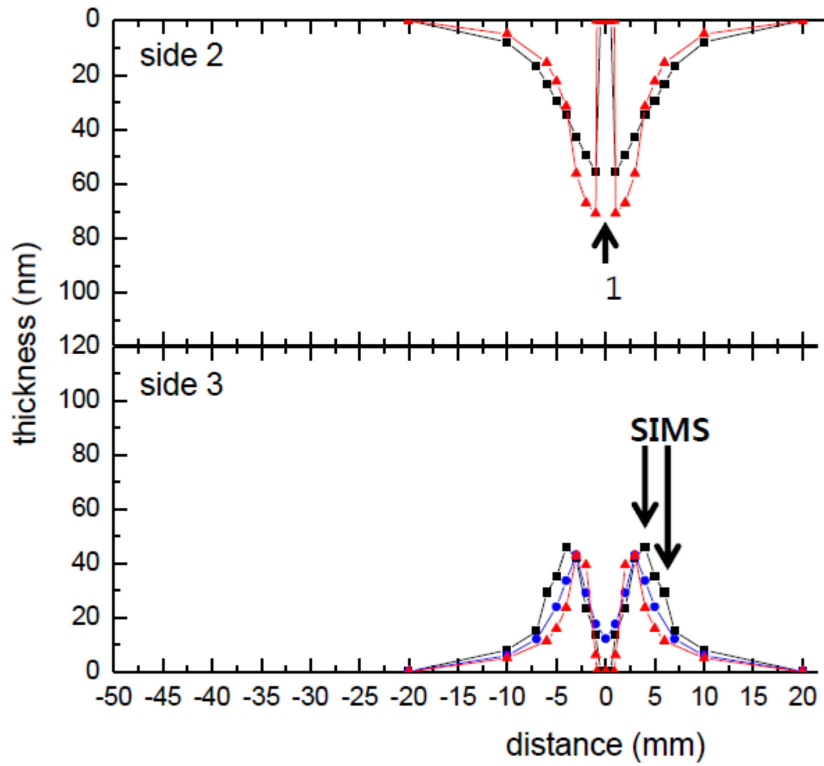
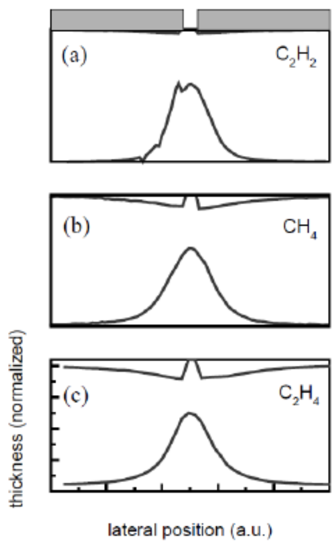
Erosion/deposition, and retention in gaps in KSTAR



Cavity structure couponを用い、第一壁に飛来する主たる炭化水素種の同定・粒子束等の計測

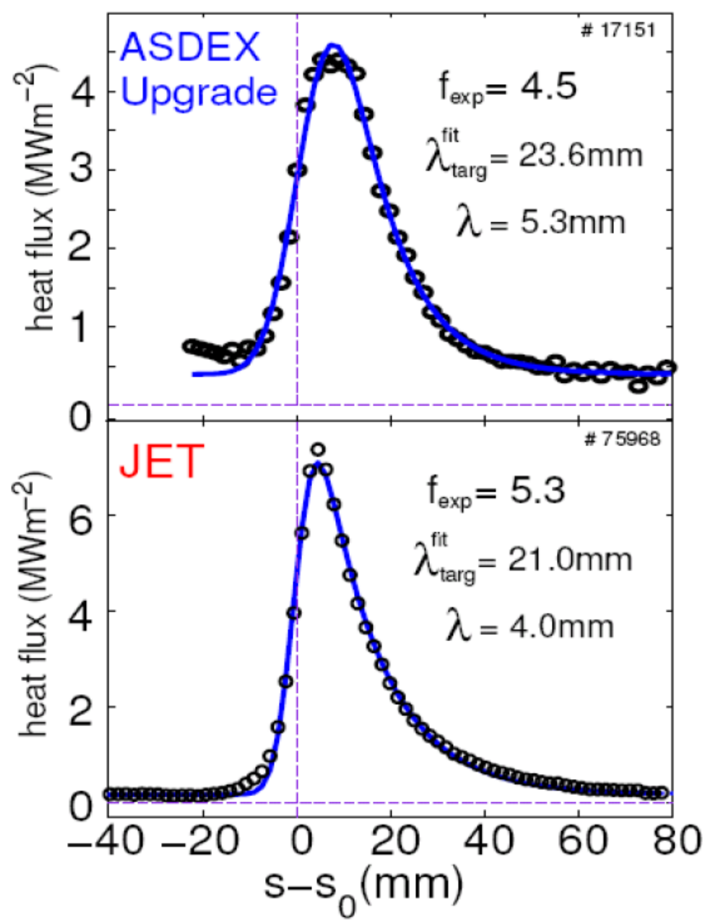




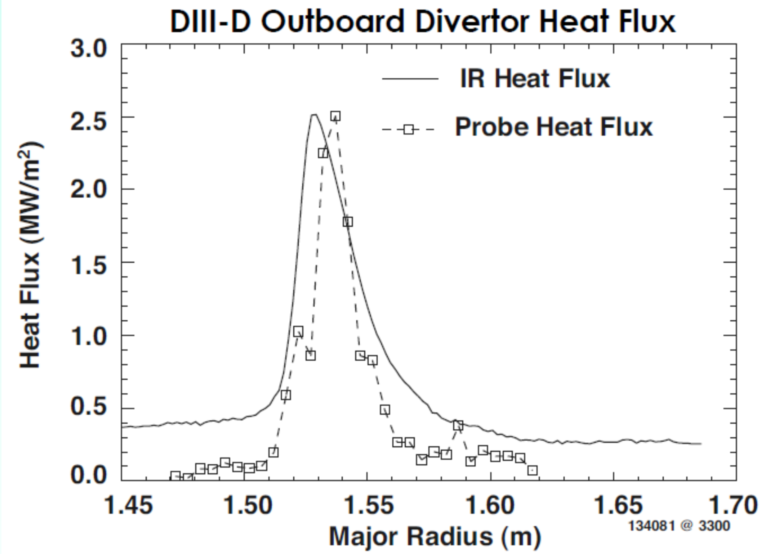


ITER start-up experiments in TS

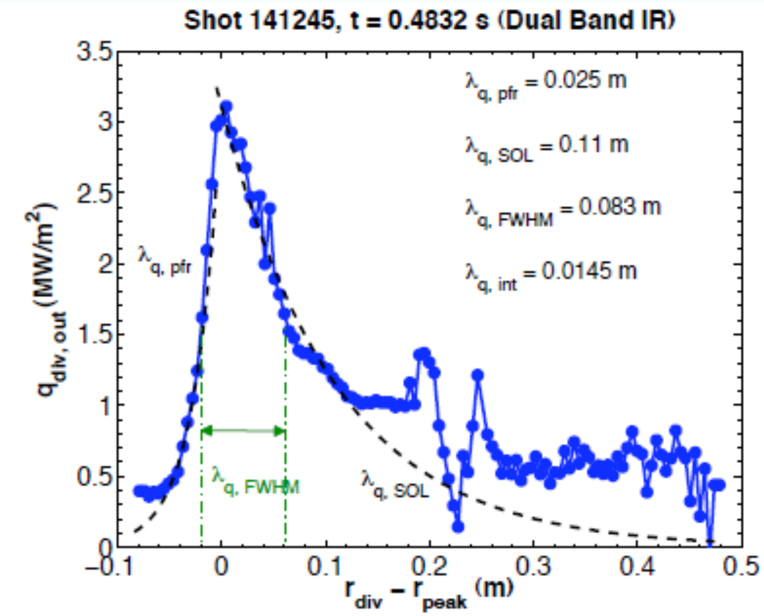
- ITERにおけるプラズマ立ち上げ時のリミタ配位時における壁（リミタ）熱負荷予測
- 静電プローブ（Tunnel probe）及び実時間平衡計算（セパラトリクス位置計算）による静電プローブ位置制御
- 離散的なリミタ設置によるSOL3次元構造形成（拡大？）
- SOL熱流束幅予測　1999年のスケーリング　X点ダイバータトカマクにおけるL-mode放電のデータから構築　リミタ配位トカマクデータ少ない
- HFS、LFSリミタ配位で、それぞれプラズマパラメータを変えてデータベース構築
  - ✓ HFSリミタ配位ではLFSに比べて低い熱流束・広いSOL
  - ✓ この違いはblob輸送の違いによる　LFSで大
- 熱流束分布は必ずしも指数関数的ではない　どのように定義するのか
  - ✓ HFSリミタ配位時に比べてLFSリミタ配位時は位置の誤差が大きいため、今回はHFSリミタ配位時のデータのみで議論する
- 熱流束と熱流束分布特性長λ_qの関係を取得　λ_qの増大→熱流束の低下
- ITERスケーリングは、TSのデータを予測できない
  - ✓ TSではohmic powerに対する依存性でスケールできる
  - ✓ 密度に対する依存性は、真逆



ASDEX Upgrade
17151
f_{exp}= 4.5
λ_{targ}^{fit}= 23.6mm
λ = 5.3mm
heat flux (MWm^{-2})
JET
75968
f_{exp}= 5.3
λ_{targ}^{fit}= 21.0mm
λ = 4.0mm
heat flux (MWm^{-2})
s−s$_0$(mm)



DIII-D Outboard Divertor Heat Flux
IR Heat Flux
Probe Heat Flux
Heat Flux (MW/m^2)
Major Radius (m)
134081 @ 3300



Shot 141245, t = 0.4832 s (Dual Band IR)
$\lambda_{q,\ pfr}$ = 0.025 m
$\lambda_{q,\ SOL}$ = 0.11 m
$\lambda_{q,\ FWHM}$ = 0.083 m
$\lambda_{q,\ int}$ = 0.0145 m
$\lambda_{q,\ pfr}$
$\lambda_{q,\ FWHM}$
$\lambda_{q,\ SOL}$
$q_{div,\ out}$ (MW/m^2)
$r_{div} - r_{peak}$ (m)