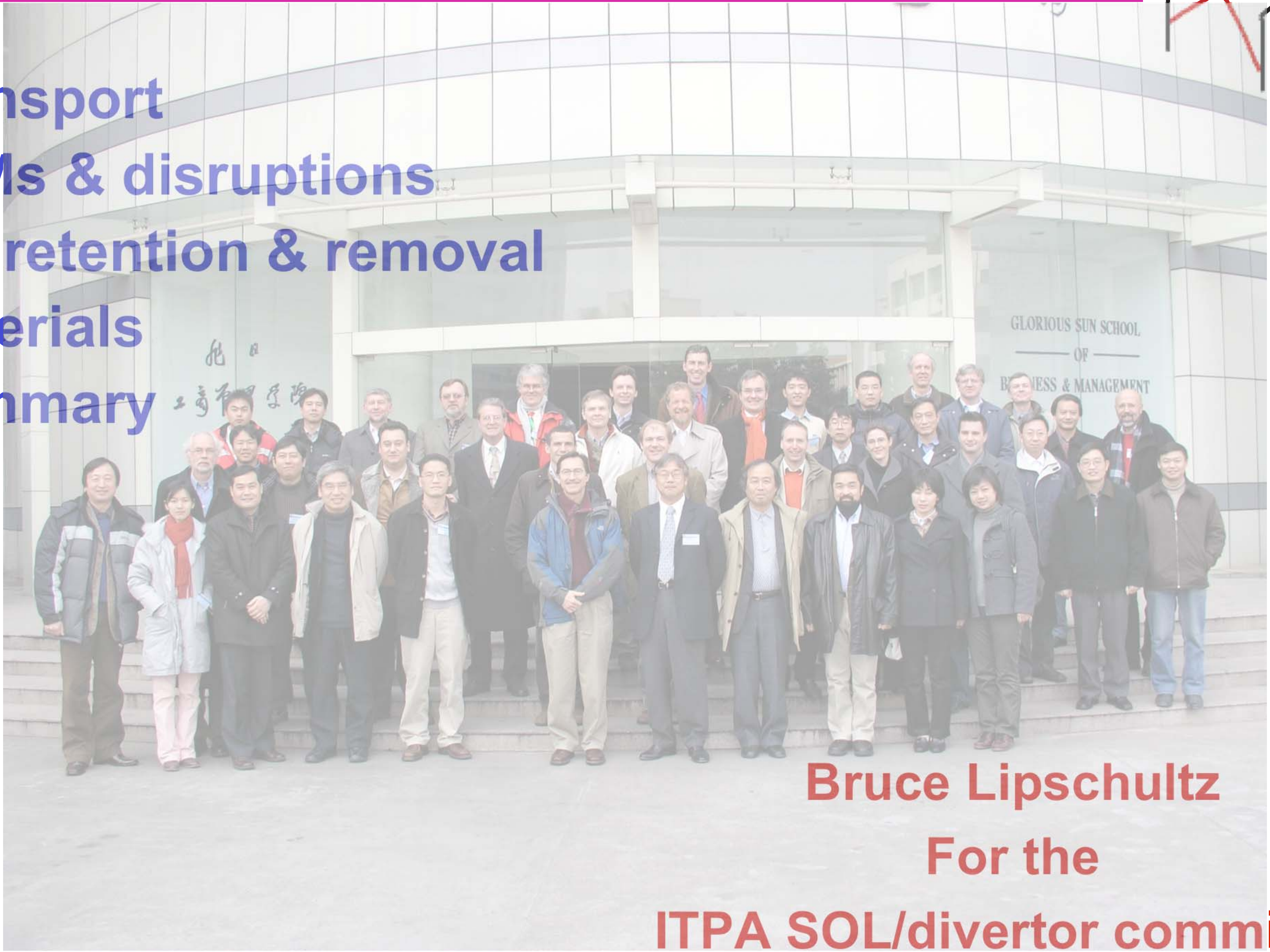
Plasma-surface interactions, SOL and divertor physics: Implications for ITER

ITPA SOL
& Divertor



Transport

ELMs & disruptions

D/T retention & removal

Materials

Summary

Bruce Lipschultz

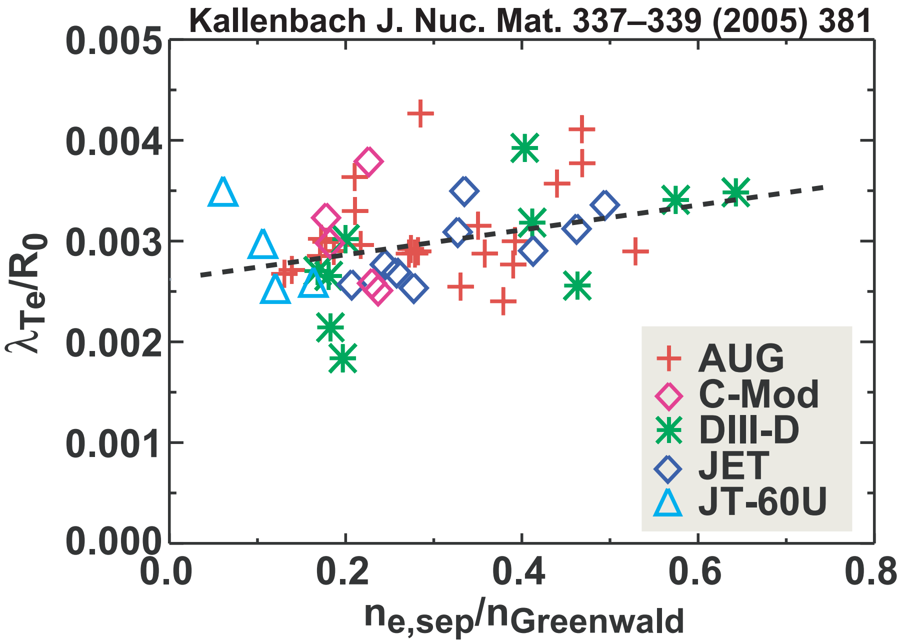
For the

ITPA SOL/divertor committee

It is a challenge to use our current experience to predict ITER performance

Current tokamaks	ITER
Operational experience primarily carbon Plasma Facing Components (PFCs)	Primarily Be with lesser amounts of carbon and tungsten
Surfaces coated with low-Z material (e.g. boronization)	No boronization planned (but Be may serve that purpose)
D/T retention ~ 3-30% of injected gas	T retention should be ~ 0.1% to maximize operational availability
Low ELM/disruption transient loadings	High transient heat loads - limits PFC lifetime

We are building a basic understanding of radial transport in the SOL



Kallenbach J. Nuc. Mat. 337–339 (2005) 381

- => ITER parallel power flow width similar (normalized to R) to current tokamaks.

=> $Q_{||} \propto P/R^2$ NOT P/R

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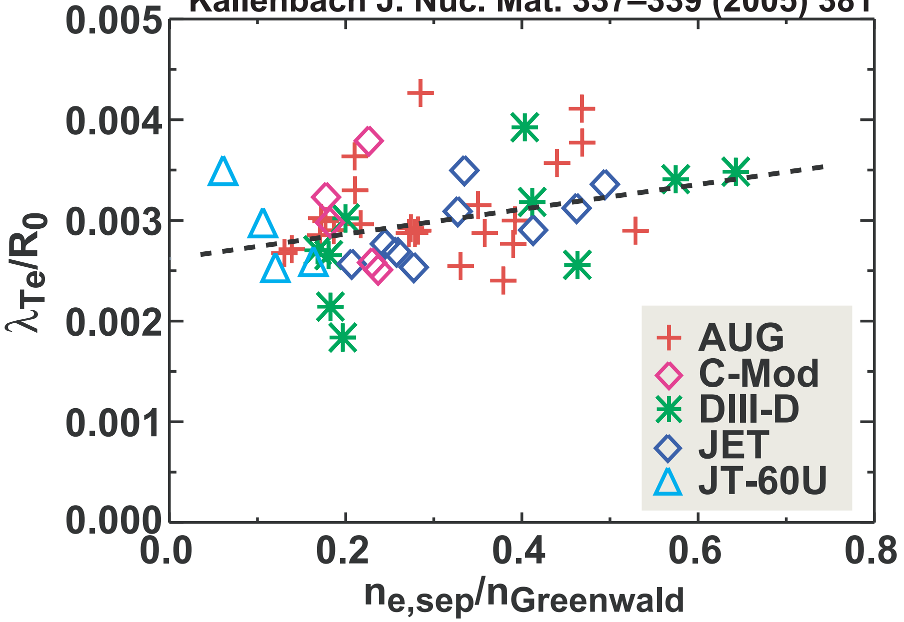

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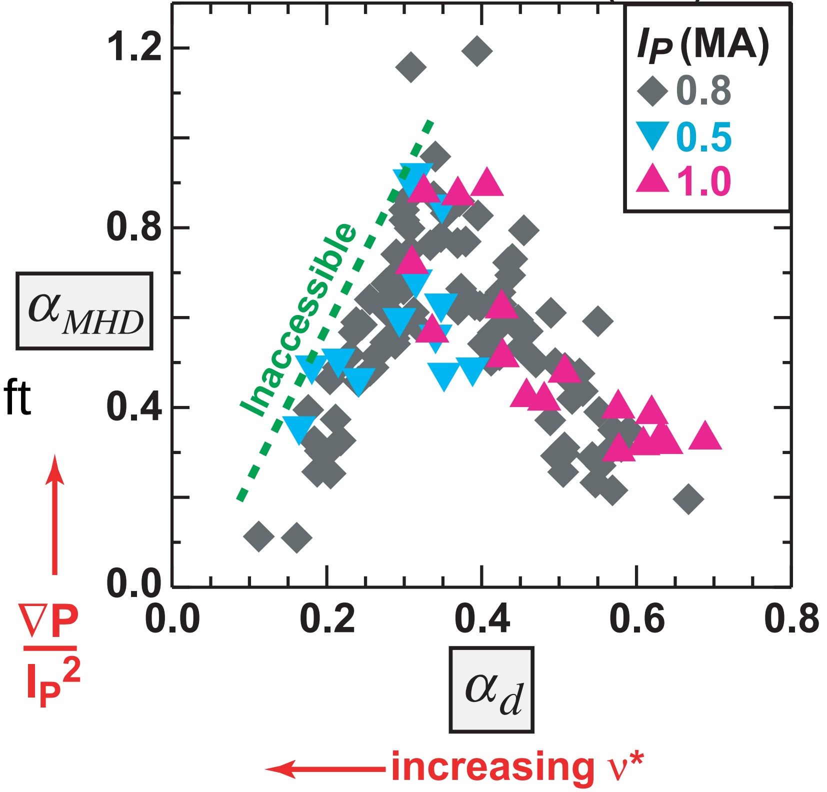
LaBombard, Nucl. Fusion 45 (2005) 1658



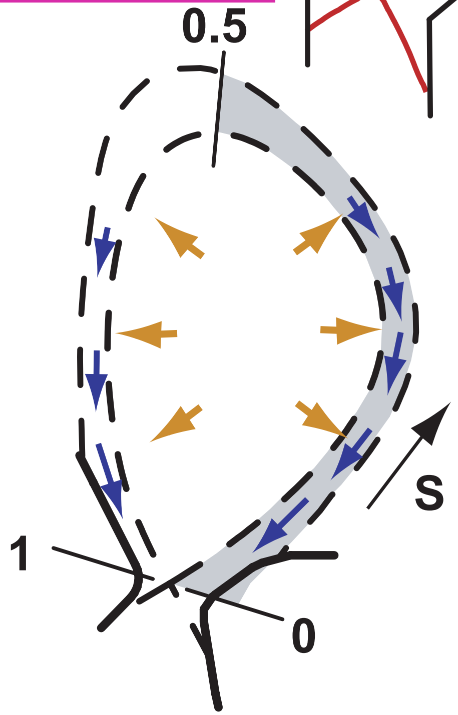
- Pressure gradients just outside the separatrix are well-organized by Electromagnetic Fluid Drift Turbulence parameters => direct connection between gradients and underlying turbulence.

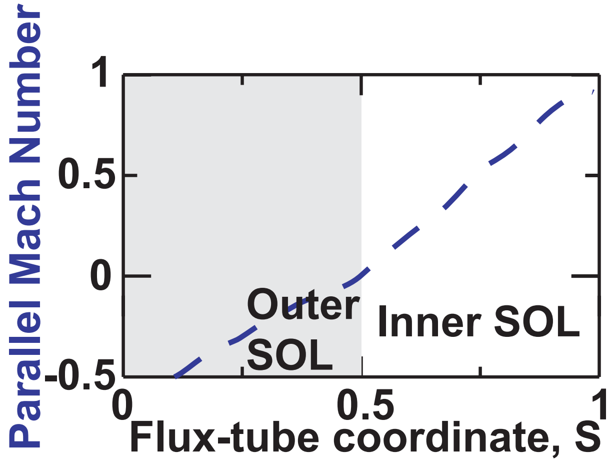
=> Potential to predict plasma profiles from first principles.

Much better understanding of flows in the edge

SOL flows are a controlling process in impurity transport as well as tritium co-deposition

- Standard models predict ~ stagnant flows in the SOL opposite the divertor

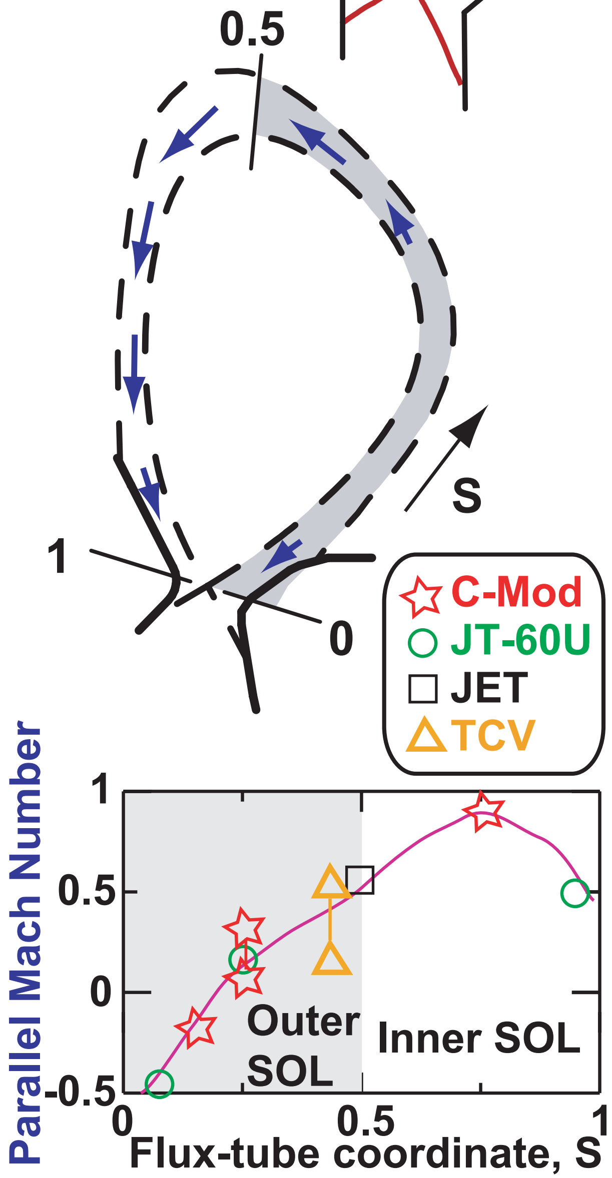




Much better understanding of flows in the edge

SOL flows are a controlling process in impurity transport as well as tritium co-deposition

- Standard models can't match measured flows
- New inner wall probe measurements provide clues:
  - Pressure drop from from low- to high-field SOL
  - M~1 flows at high field side*



[*] LaBombard, Phys Plasmas 12 (2005)

Much better understanding of flows in the edge

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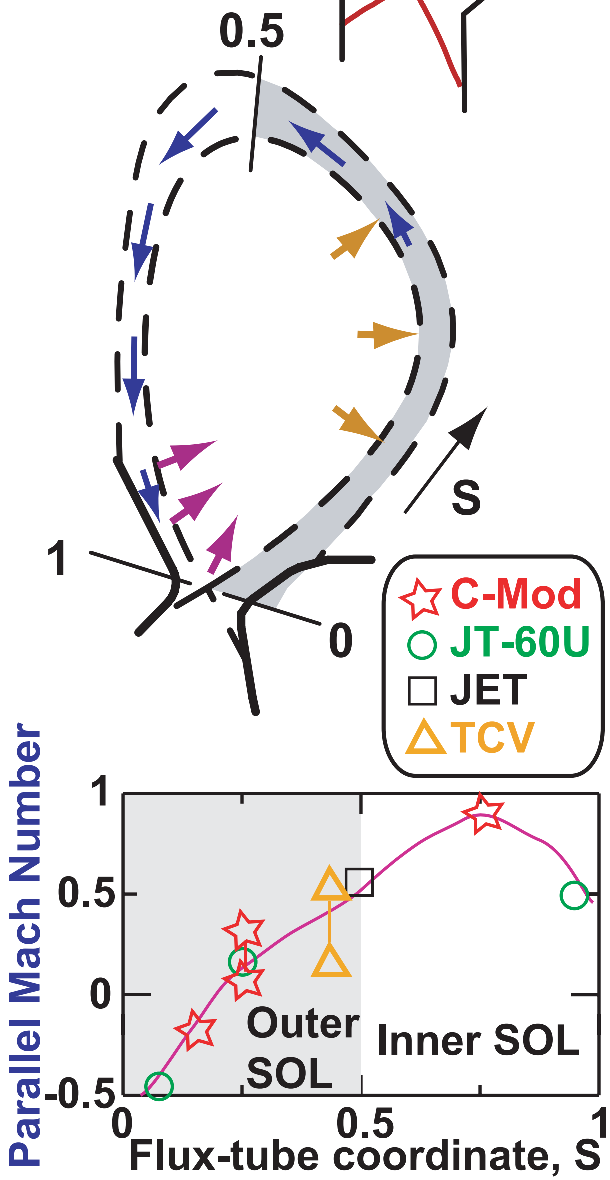
SOL flows are a controlling process in impurity transport as well as tritium co-deposition

- Standard models can't match measured flows
- New inner wall probe measurements provide clues:
  - Pressure drop from from **low- to high-field SOL**
  - **Pressure imbalance => driving parallel flows**
  - Pressure imbalance driven by low-field side ballooning transport out of core, across separatrix*
- Evidence of transport-driven flows setting toroidal rotation boundary condition for confined plasma



Allows better understanding of impurity migration and T retention

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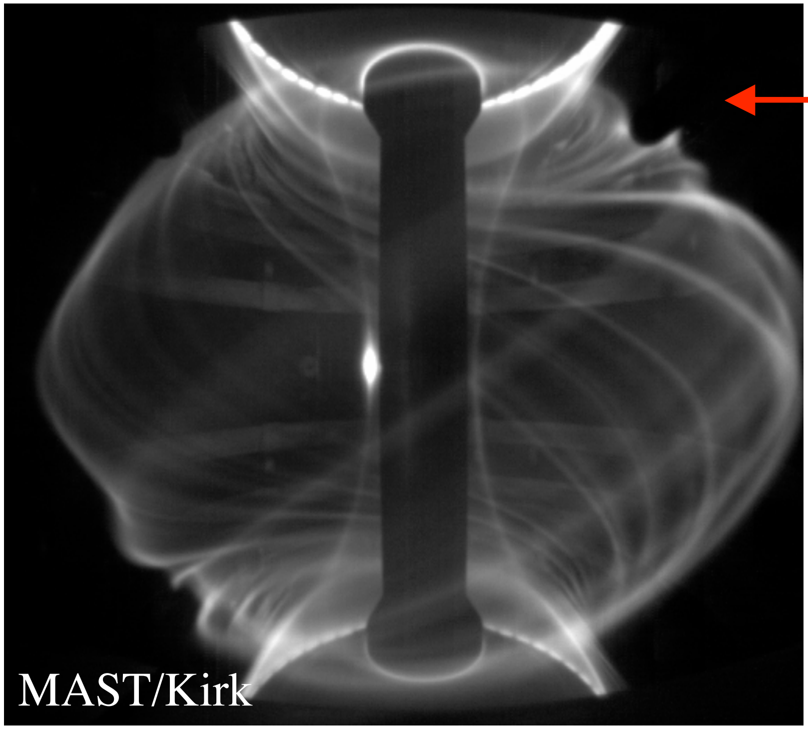
* Gunn, EX/P4-9, LaBombard, Phys Plasmas 12 (2005)

ELM filaments travel far through the SOL to the wall

Type I ELMs reduce ITER divertor and main chamber PFC lifetime[†]



- Filamentary nature of ELMs (n ~ 7-15) rotating toroidally and poloidally*

[†]Loarte, IT/P1-14, Boedo, EX/P4-2, *Kirk , EX/9-1

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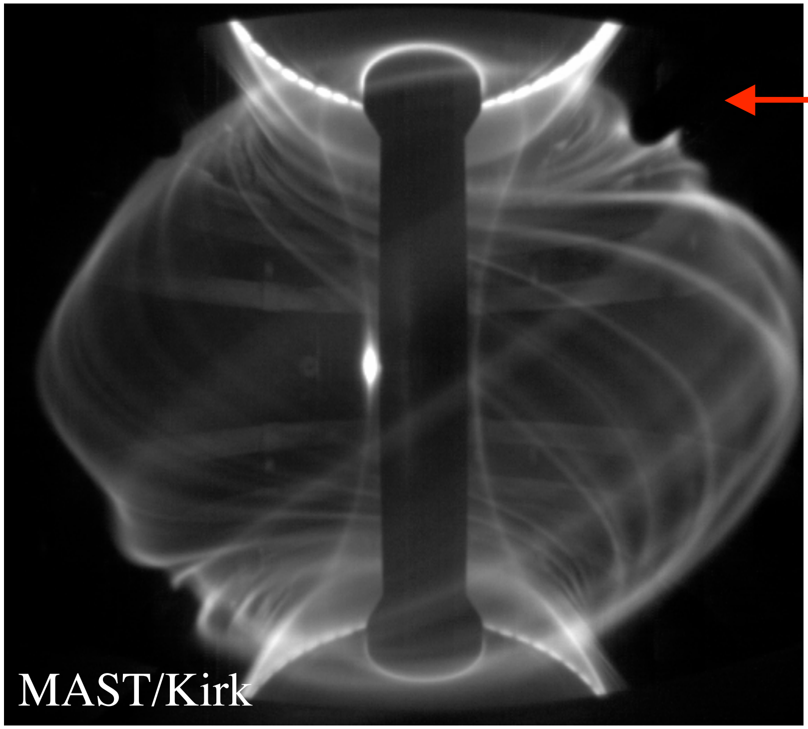

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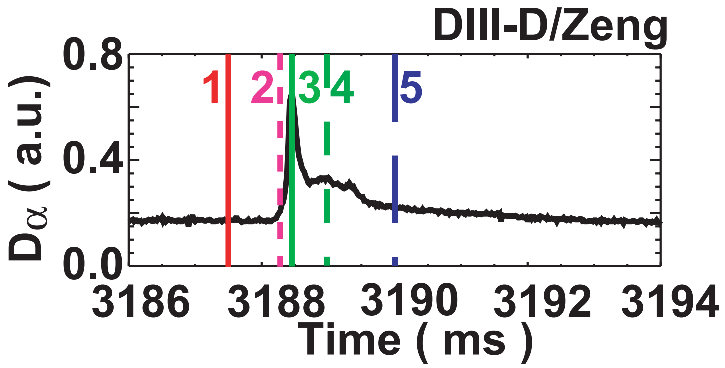
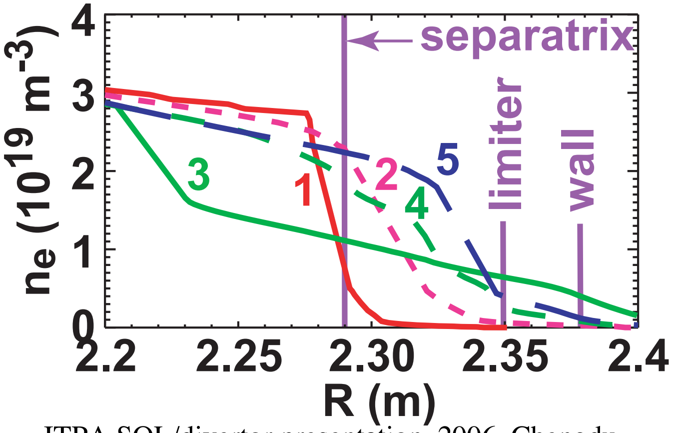


- ELMs travel far into the SOL having a substantial effect on the density and temperature at the limiter



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†Loarte, IT/P1-14, Boedo, EX/P4-2, *Kirk , EX/9-1

Type 1 ELM filaments lead to variable heat loads on first wall surfaces

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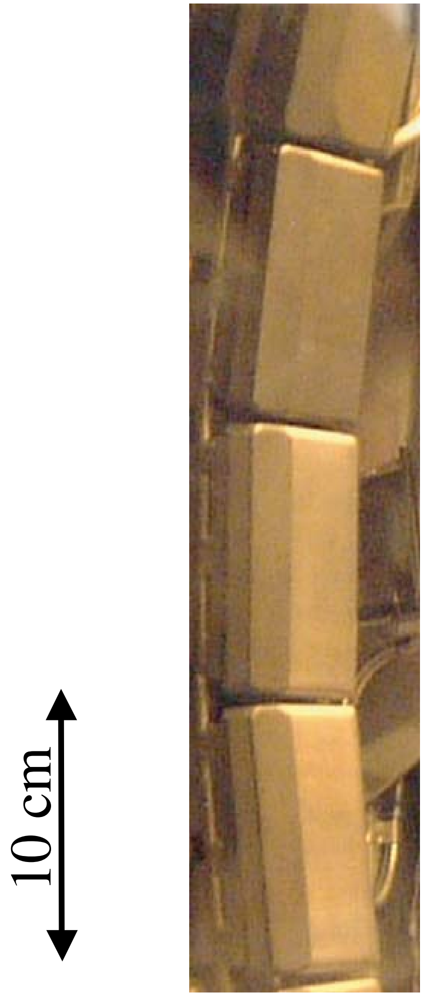
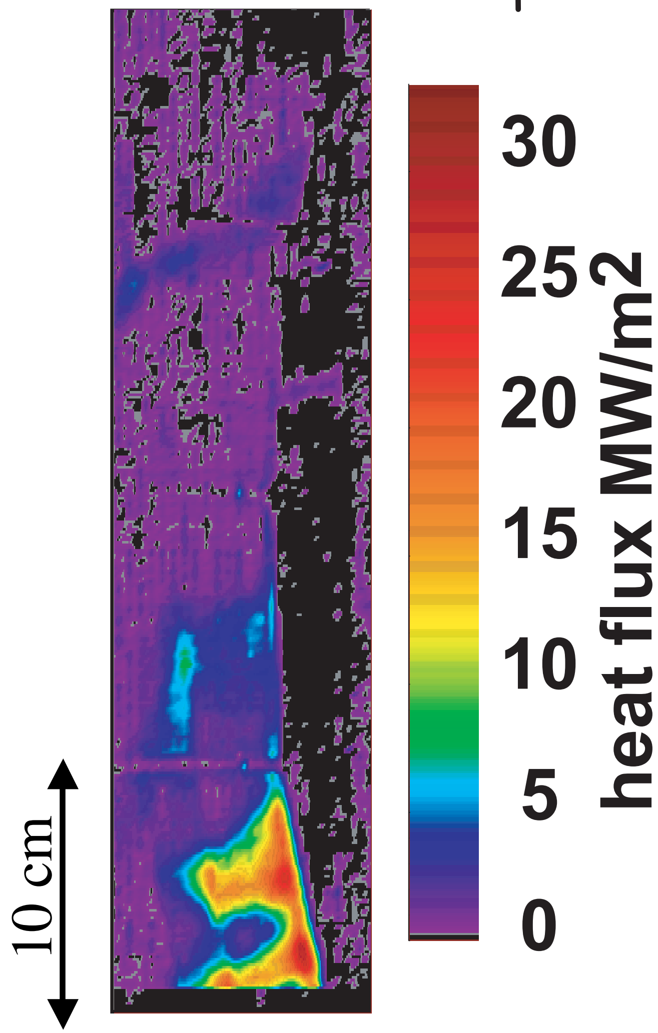
- Visible image of ASDEX-Upgrade limiter*



*Herrmann et al J. Nucl. Mater. 337-339 (2005) 697

Type 1 ELM filaments lead to local hot spots on limiters

- Individual ELM filaments lead to hot spots on limiter surface*



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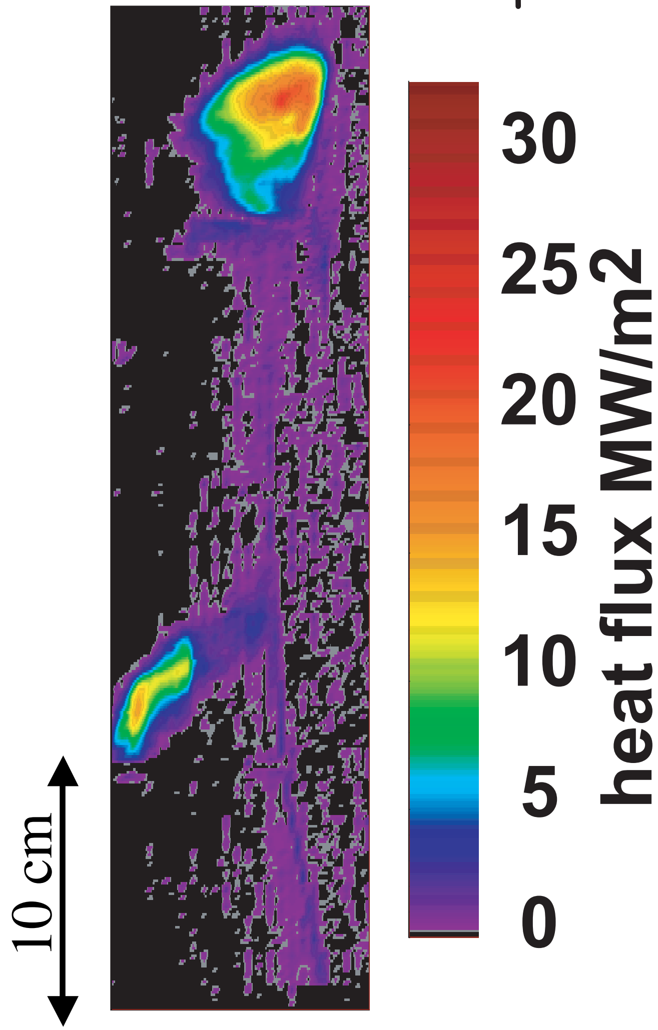

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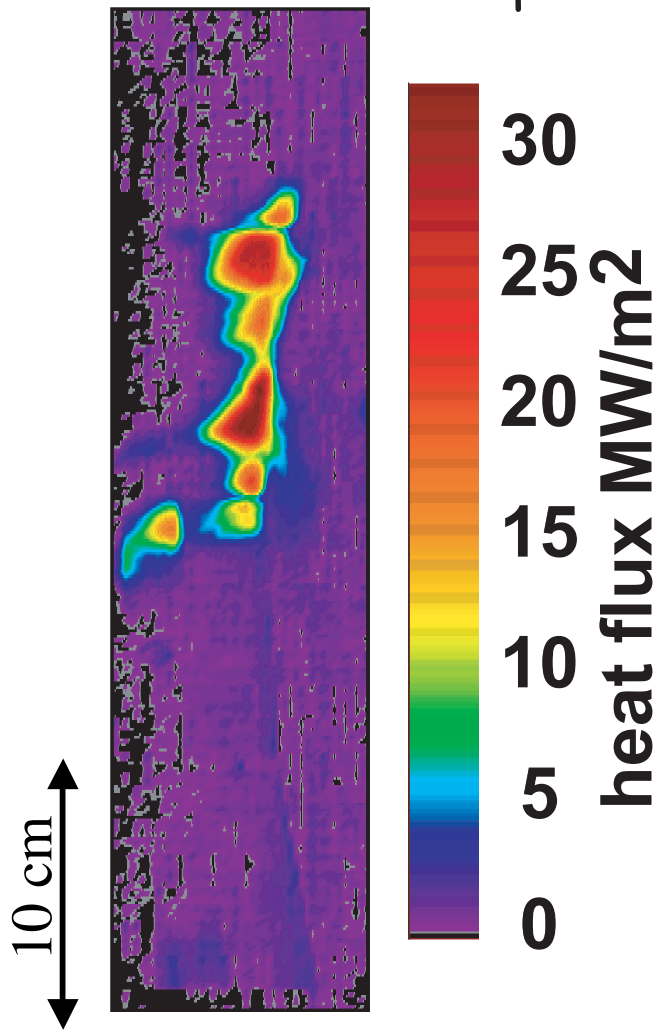
Type 1 ELM filaments lead to local hot spots on limiters

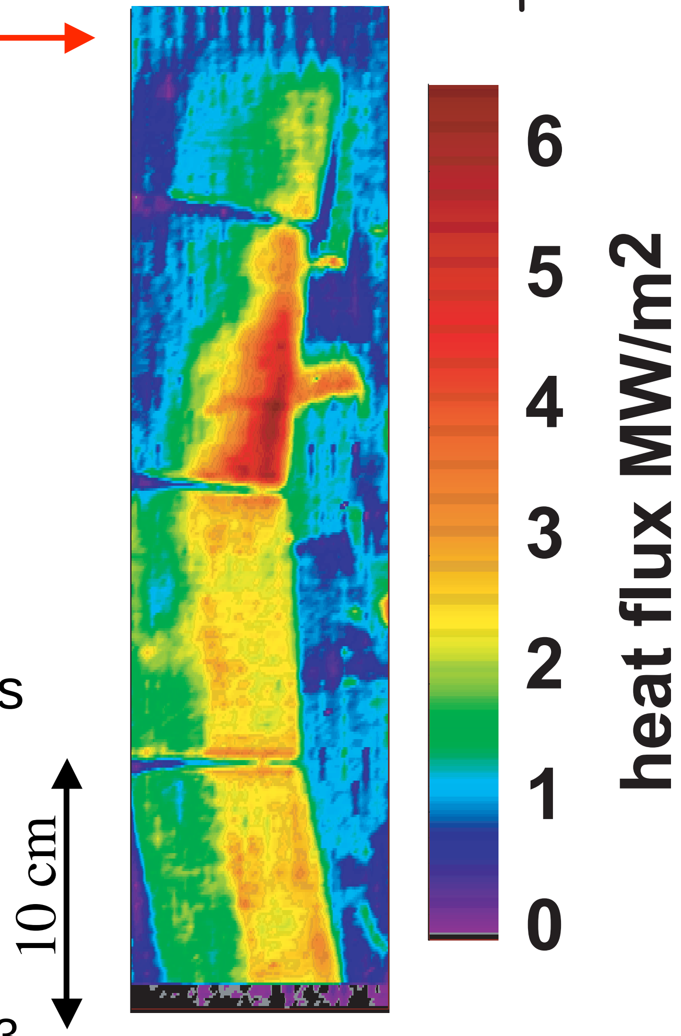
- The instantaneous heat load is high*.



*Herrmann et al J. Nucl. Mater. 337-339 (2005) 697

Heat loads are less localized when averaged over ELMs

- When averaged over ELMs the heat load is more uniform*



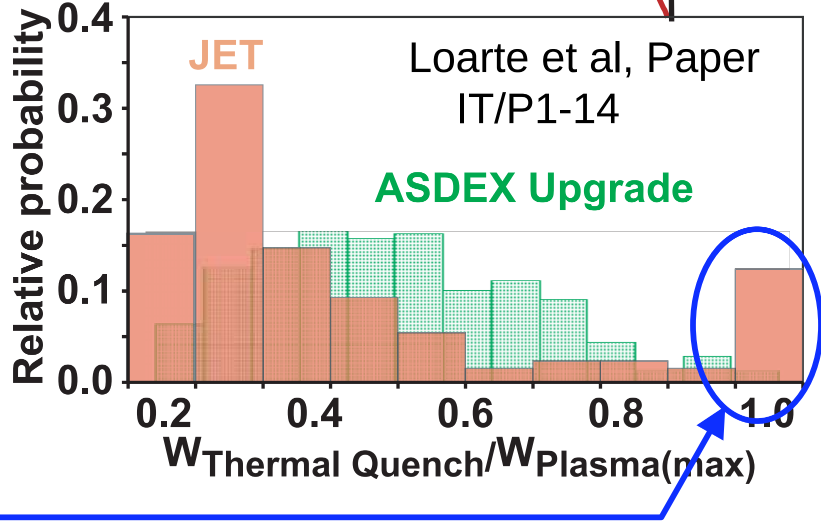
- ELMs need to be small enough such that the divertor survives ($\Delta W_{ELM}/\Delta W_{PED} < 5\%$) - then main chamber surfaces should be ok too**.
- But, a few strong ELMs can reduce the tile resistance to thermal shock
- The community is pursuing small ELM regimes as well as ELM mitigation***.

**Loarte et al, Paper IT/P1-14, ***Moyer et al, Paper EX/9-3

*Pitts et al, Paper EX/3-1, Herrmann et al J. Nucl. Mater. 337-339 (2005) 697

Disruption statistics reveal details of energy balance during a disruption

- A significant fraction of the stored energy is often lost before the thermal quench
  - Energy lost through L-H transitions…..
- => specify fewer ITER high power disruptions for ITER reference scenario
- Advanced scenario (ITB and high-β) disruptions are the most dangerous: All the stored energy comes out rapidly



Loarte et al, Paper IT/P1-14

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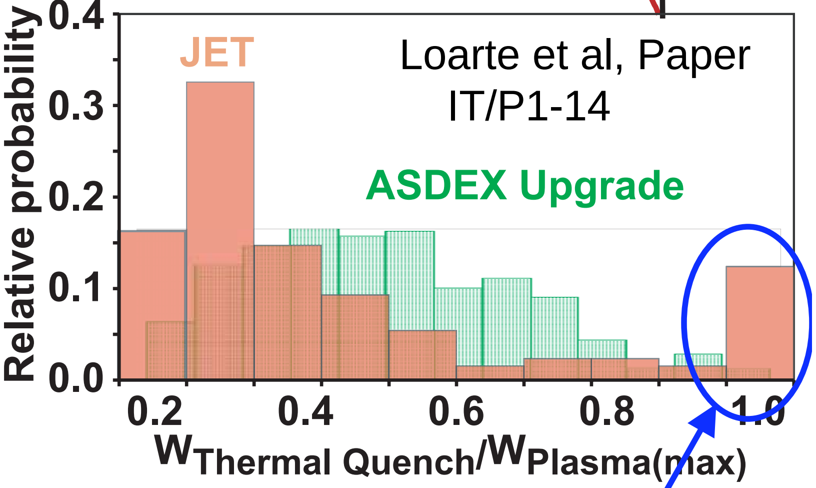

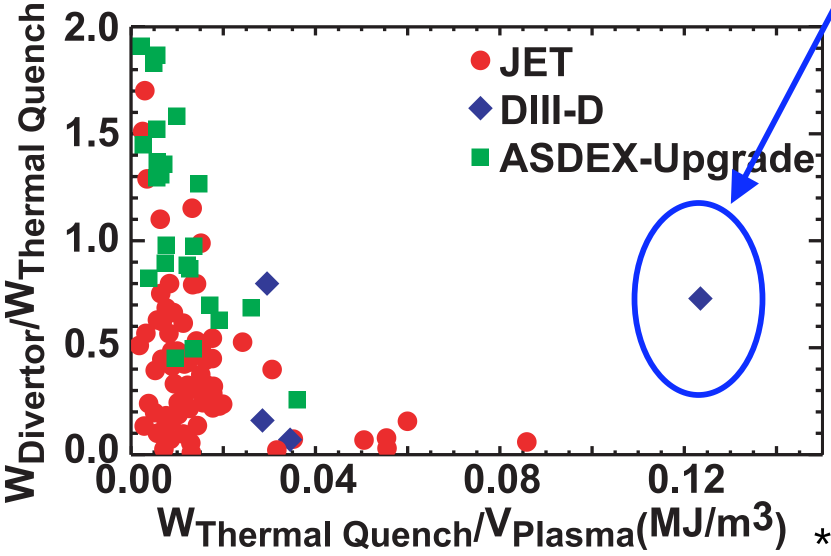

- The divertor receives less of the disruption energy as the stored energy increases
- Surfaces outside the divertor become more of a concern
- Disruption mitigation is being pursued with success*

*Granetz, EX/4-3, Pautasso, EX/P8-7, Izzo, TH/P3-15

Tritium retention is a central emphasis of SOL/divertor work

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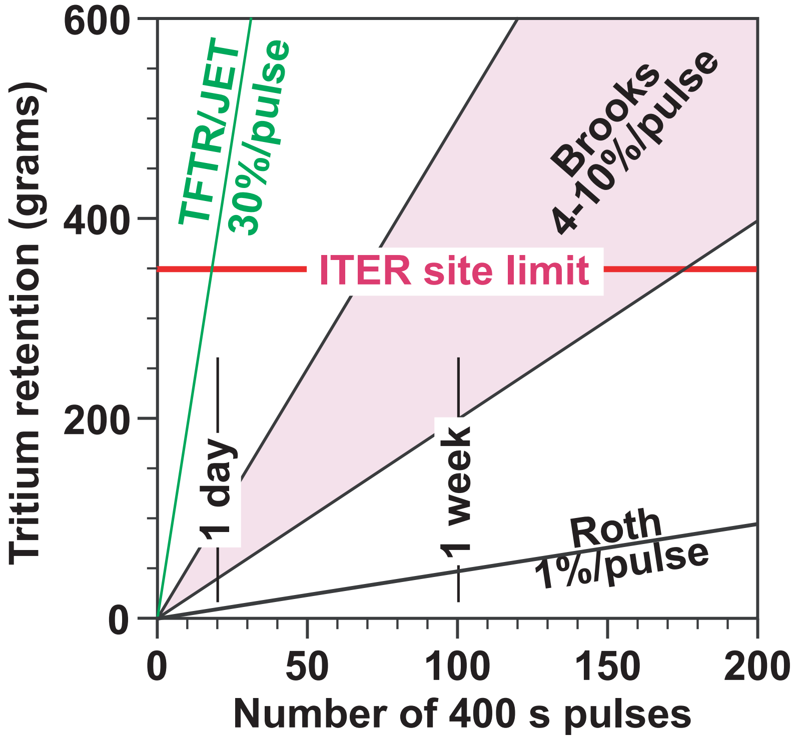
- Estimates of T retention in ITER are uncertain
  - All-carbon PFC tokamaks have D retention per discharge ~3-50% of that injected
    - ITER retention of 0.1% needed for continuous operation
  - ITER will have much less carbon, replaced with Be and tungsten (W).
  - Be does co-deposit with tritium but releases it at a lower temperature than C
  - Be will not migrate to remote cooled locations as easily as carbon => less likely to accumulate thick co-deposited layers
  - Predicted to lead to lower T retention than current tokamaks

=>Modelling estimates give a range of 1-3 weeks operation before T site limit reached



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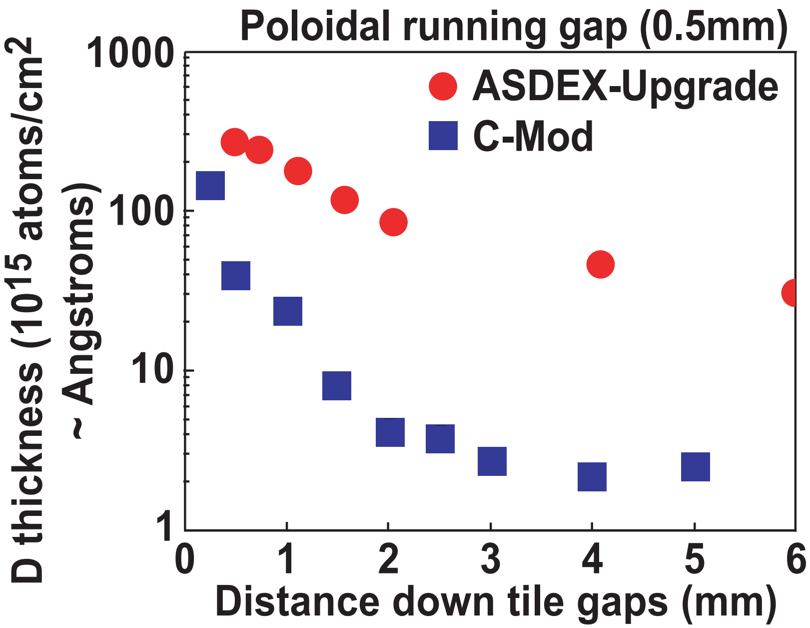
T retention on tile sides could be more important in ITER



- 20% of the **total** D retention is on the sides of tiles
  - Co-deposition with C ions and molecules
- ITER design increases the ratio of tile side to front surface areas over current carbon PFC tokamaks

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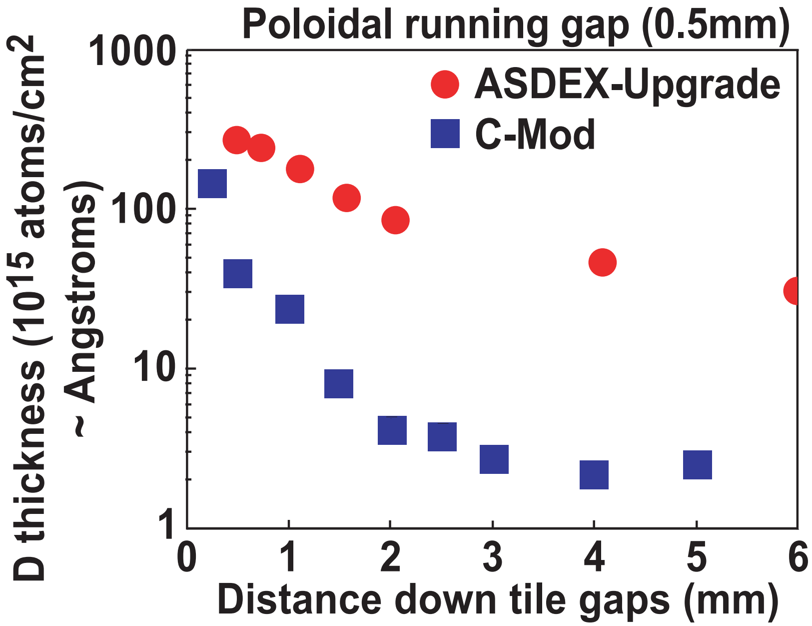

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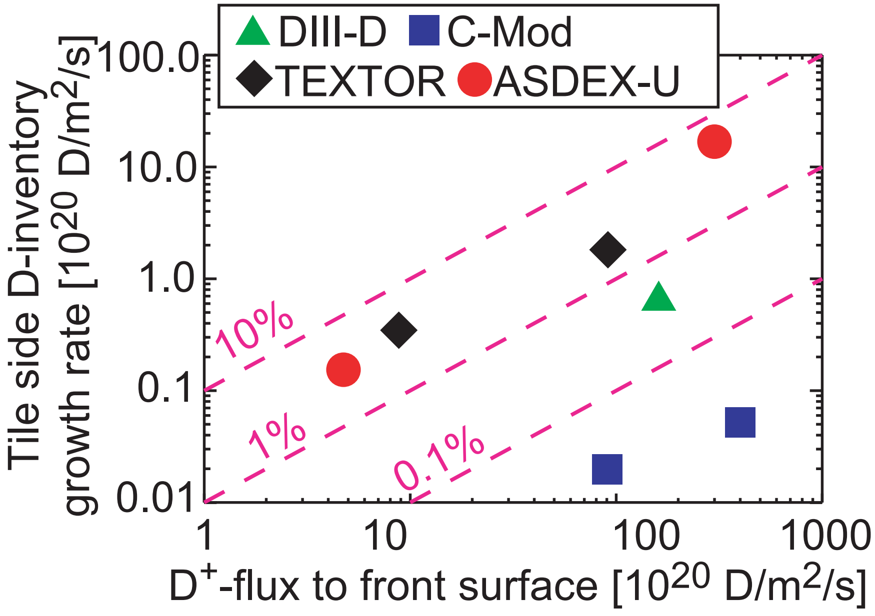
- Cross-tokamak studies indicate tile side D retention
  - proportional to surface ion fluence
  - Lowest in fully high-Z tokamak
  - Reduced by elevated tile temperatures
- More difficult to remove



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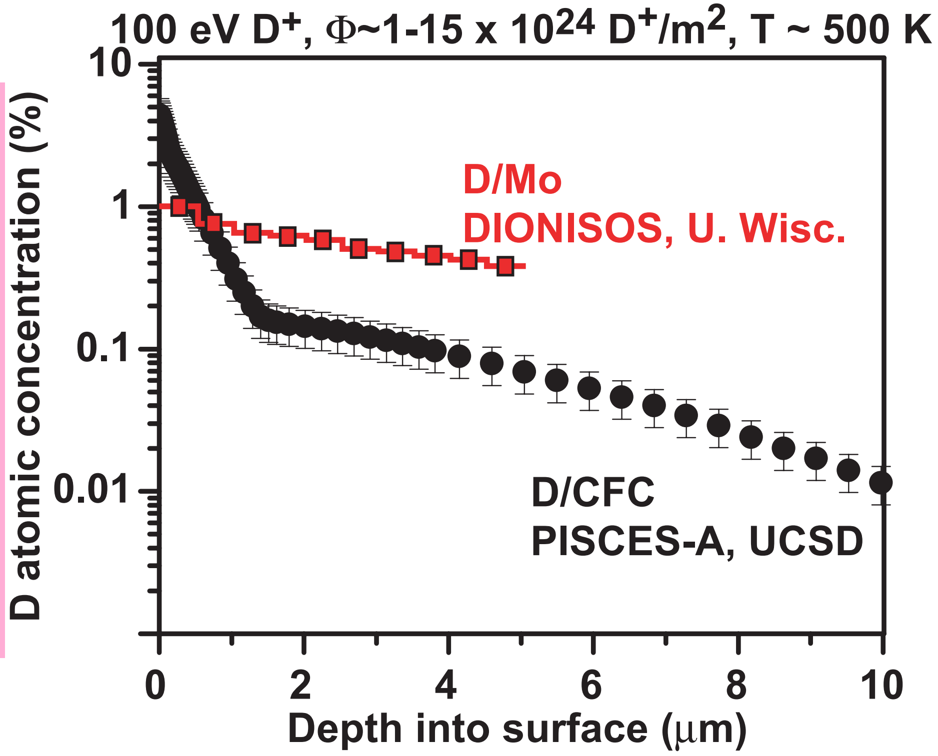
Studies have revealed another process besides co-deposition that leads to T retention

- A number of tokamaks have reported that co-deposition on tile surfaces cannot explain the level of D retention measured (e.g. Tore Supra*, C-Mod**, JT-60U)
- New laboratory studies have found that D can be stored deep below surface
  - True for carbon AND molybdenum

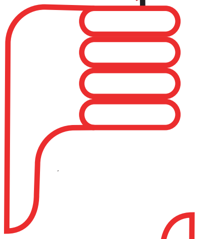
- Deep retention in tiles will add to ITER T retention levels
  - Potentially dominate over co-deposition in high flux regions
  - Potentially more difficult to remove through surface T removal techniques
  - Exploring for Be, W as well



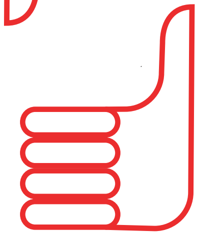
*Loarer, EX/3-6. **Whyte, EX/P4-29

Mixed materials in ITER are a mixed blessing

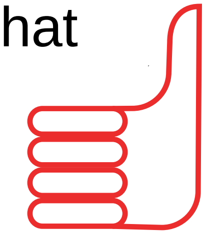
- A number of alloys form
  - Beryllides (e.g. Be_2W) lowers tungsten melting temperature
  - Carbides can increase T retention (WC)
  - Alloys could form barriers to the out-diffusion of T



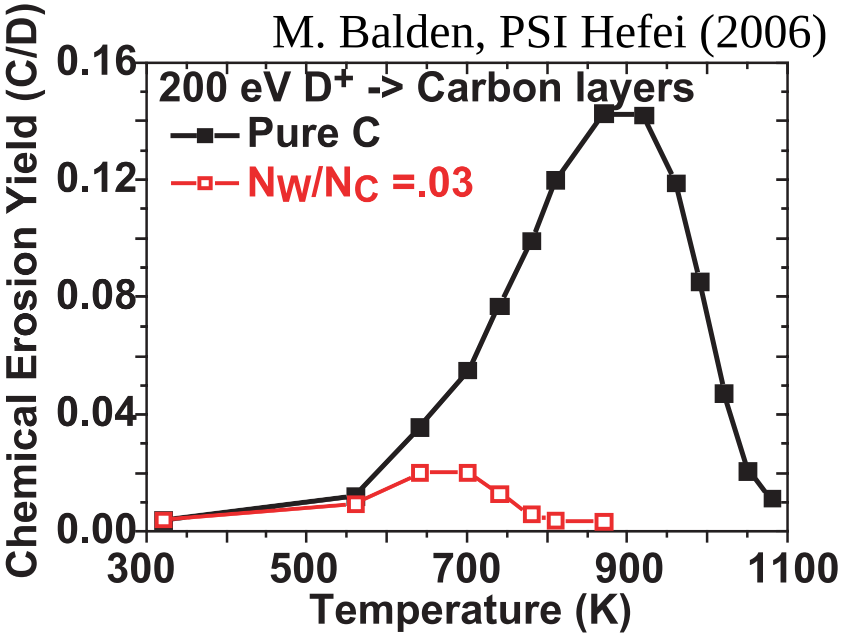
- Be or W on carbon surfaces reduces carbon chemical sputtering



- Carbon tiles could even be doped with metals before installation such that the chemical erosion is reduced



M. Balden, PSI Hefei (2006)



Tritium removal techniques are being developed

- Tritium removal techniques include
  - Heating the surface to increase T diffusion (e.g. laser, disruptions)
  - Chemical removal of carbon & T (Oxygen exposure, discharge cleaning…)
  - Ablation of the carbon - freeing the T (e.g. flash-lamps, lasers)

- All techniques must
  - Remove T from wherever it is stored (tile front, sides, bulk)
  - Be compatible with ITER toroidal field
  - Not cause dust
  - Be able to remove T from mixed material surfaces such as
    - Be, W, C, BeC, WC, Be_2W
  - Not cause problems for subsequent operation
    - Impurities or damage to vessel

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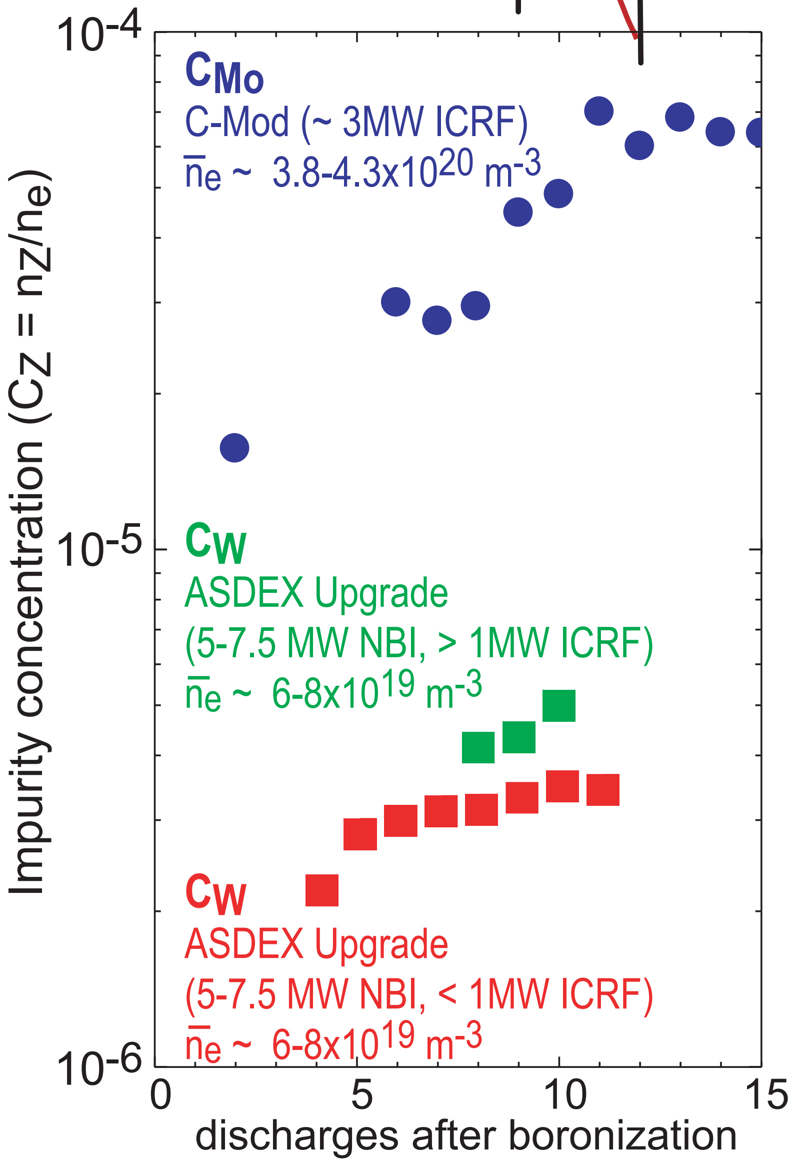
ITER not ready to go to fully high-Z

ITER operation with high-Z PFCs is a goal in support of DEMO

- Tokamaks with primarily high-Z PFCs
  - ASDEX-Upgrade (85% W-coated carbon)
  - C-Mod (100% solid Mo tiles)
- Core high-Z content rises quickly after boronization* →
- ICRF erodes B layer (and Mo/W underneath) more quickly than NBI or Ohmic heating
- Erosion localized to small fraction of PFCs

- Questions remain
  - Core high-Z concentration (and radiation)
  - Boronization needed?
  - Melting



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*Dux et al, EX/3-3, Marmar et al, EX/3-4

Better understanding but uncertainties are still a concern

- We are making progress towards first-principles prediction of transport
  - Much better capability of predicting parallel transport (and impurity transport)
  - Connection of radial transport to underlying turbulence
- Tritium retention rate estimated to be lower than before but still uncertain
  - Combined Be/W/C reduces T retention over pure carbon
  - A number of T removal techniques are being explored with success
- Transient loading on PFC surfaces is very complicated
  - Much of the stored energy can be lost before disruption thermal quench
  - The loading of first-wall surfaces by ELMs and disruptions is uncertain
- Material characteristics and their interactions strongly affect ITER operation
  - A variety of alloys are created whose behavior is difficult to include in predictions
  - High-Z operational experience for ITER is being developed

The Interaction with the first-wall is central to the success of ITER

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We cannot afford to ignore problems

Nor can we say: ‘the sky is falling’