ITPA Divertor/SOL Topical Group report

Review meetings and results
High-priority research
Summary

BPO meeting, March 29, 2011

Presented by B. Lipschultz
On behalf of the SOL/divertor group
Div/SOL group meetings

14th meeting - Seoul Korea, October 18-21, 2010
- Joint meetings
  - Energetic particles and MHD (RE and disruptions)
  - MHD and Pedestal (ELMs)
  - Pedestal and Transport/confinement (fueling)
- Main chamber heat loads, high-Z melting….
- ≥50 participants

15th meeting – Helsinki, Finland, May 16-19
- Hosted by J. Likonen & T. Kurki-Suonio, Association Euratom-Tekes, VTT Processes
- SOL/divertor modelling, Surface modelling, Material transport….

16th meeting – likely near Juelich Germany, January, 2012
ITER R&D work plan

- DIV/SOL group research plan drafted to address ITER needs (Fall 2008)
- 5 task groups formed and DIV/SOL research plan revised (January - May, 2009)

1. Tritium retention and removal (leaders - R. Doerner, K. Schmidt)
2. Tungsten (leaders - A. Kallenbach, Y. Ueda)
3. Dust (leaders - N. Ashikawa, D. Rudakov)
4. Heat fluxes to plasma-facing surfaces (leaders - M. Lehnen, A. Leonard)
5. Material migration (leaders - V. Philipps, P. Stangeby)

- Significant overlap of tasks (e.g. material migration leads to T retention)
- First tasks finished and closed
- Every meeting we review their status to decide on new tasks and directions
ITPA joint DSOL experiments
**DSOL experiments** (4 closed + 4 running + 5 new)

**Fuel retention and removal**
- DSOL-8 ICRF Conditioning for hydrogen removal (N. Ashikawa) ➔ closed
- DSOL-12 Reactive gas wall cleaning (P. Stangeby)
- DSOL-13 Deuterium codeposition with carbon in gaps of PFCs (K. Krieger) ➔ closed
- DSOL-23 Efficiency of ICRF Conditioning (D. Douai) ➔ new
- DSOL-27 Mitigation of fuel accumulation and impurity deposition in the gaps of castellated structures (A. Litnovsky) ➔ new

**Dust**
- DSOL-21 Introduction of pre-characterized dust for dust transport studies (D. Rudakov)

**Transients**
- DSOL-20 Transient divertor reattachment (R. Pitts)
- DSOL-24 Disruption heat loads (E. Holman) ➔ new
**DSOL experiments** (4 closed + 4 running + 5 new)

**Material migration**
- DSOL-2 Injection to quantify chemical erosion (S. Brezinsek) ➞ closed
- DSOL-9 Tracer injection experiments to understand material migration (V. Philipps) ➞ closed
- DSOL-26 Marker experiments to study material migration (S. Brezinsek) ➞ new

**Tungsten**
- DSOL-25 Melt layer motion and disintegration, droplet propagation and resulting impact on plasma performance (J. Coenen) ➞ new

*+ Joint Modelling :*
- DSOL-22 Multi-code validation against experiment for improved detachment modelling (M. Wischmeier)
In what follows ....

• Summary of progress in the work plan in each task group, with some key results

  Significant progress since Task Groups established

  Moderate progress – in need of energising or re-orientation

• Note: 10 of original 33 tasks closed as a result of significant new results!
T-retention and removal work plan

1. Refine ITER prediction (MIT mini-meeting)
   - Report finished - CLOSED

2. Fuel retention machine database
   - E. Tsitrone (PSI 2010 paper) for C-dominated tokamaks

3. Ion cyclotron wall cleaning
   - Significant effort – papers by D. Douai, A. Lyssorvan PSI 2010 - CLOSED

4. Disruption flash heating
   - IO/FST/PWI contract with UCSD, data from JET, C-Mod, TS

5. Capability and risks of removing carbon
   - O-baking experiment On DIII-D – post deadline poster PSI 2010

6. Isotope exchange
   - Review previous work + JET experiments on H-He-H – T. Loarer PSI 2010

7. T removal by heating to 350°C
   - IPP/UCSD/ITER (DWO contract) – K. Sugiyama PSI 2010, J. Roth 10th Hydrogen workshop 2010 and IAEA 2010 - CLOSED

8. Retention in gaps
   - Reasonable progress – A. Litnovsky PSI 2010

9. Influence of mixed species on retention
   - IPP/UCSD/ITER (DWO contract) – K. Sugiyama PSI 2010, J. Roth 10th Hydrogen workshop 2010 and IAEA 2010 - CLOSED

10. NEW - Comparison of ICWC with HF GDC and research into the role of various T removal processes (e.g. isotope exchange)
Recent highlights of T retention research

• O bake is very effective at T (and C) removal
  • The main problem at the moment is tritiated water which ITER has said it will not allow
  • Emphasis changing to T removal from high-Z without generating tritiated water.
• Recent US-EU study of hydrogenic retention in Be and Be compounds completed
  • T released from Be at lower temperatures than for C
  • Implantation in Be at higher temperatures can lower the retention significantly
    • But harder to remove – so roughly a wash
  • Impurities in the Be lead to a reduction in T removal at a given baking temperature
Tungsten work plan

1. Impurity production by ICRH
   - Awaiting new experiments on AUG, C-Mod – antenna design

2. Effect of divertor target damage on device operability
   - Related expts. On TEXTOR (J. Coenen PSI 2010) and AUG (K. Krieger).
   - C-Mod and AUG experiments. Negotiations underway between IO and JET (R. A. Pitts, ILW WG 11) to install “misaligned lamellas” in bulk W outer target

3. Tritium permeability and retention in neutron-damaged W
   - Significant progress – e.g. W. Wampler SNL \( \rightarrow \) not an issue for ITER - CLOSED

4. Investigation of surface morphology changes (W fuzz, cracking), blisters and material mixing
   - Good progress – V. Alimov (JAEA), J. Roth (IPP), R. Doerner (UCSD), Y. Ueda, D. Nishijima : Op. window for He+ formation of fuzz growth identified - CLOSED

5. ELM impurity sources vs. flushing
   - Good results from AUG (T. Putterich, PSI 2010) but driven more now by pedestal TG and new ITER Contract (A. Loarte) - CLOSED

6. Power load control by low-Z seeding
   - AUG/JET/C-Mod experiments - A. Kallenbach, G. Maddison, M. Reinke Div/SOL mtg + PSI 2010 – joint experiments proposed via IOS TG (IOS-1.2)

7. Edge modelling including W and Be/W
   - Some progress – DIVIMP & EDGE2D on JET, ITER, trace W in Eirene – M. Reinelt, S. Carpentier, J. D. Strachan PSI 2010

8. Mixed impacting ions species and H retention
   - Good progress – e.g. J. W. Davis (UofT), V. Alimov, J. Roth - CLOSED

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R&D type | Timescale  
--- | ---  
1 Model, design, report | Medium (1-2 yr)  
2 DSOL (new) | Short (1-2 yr)  
3 Lab. expts., report | Medium (2-4 yr)  
4 Lab. Tok. expts., report | Medium (2-4 yr)  
5 Tok. expts., report | Short (1-2 yr)  
6 Tok. expts. | Medium (2-4 yr)  
7 Code development | Medium (2-4 yr)  
8 Lab. expts., report | Short (1-2 yr)  

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Recent highlights of Tungsten research

- Retention increases with dpa damage
  - The main problem at the moment is tritiated water which ITER has said it will not allow
  - Threshold temperature for strong drop in retention between 300 and 400°C
- Tungsten melt layers
  - Movement of the melted W consistent with jxB forces
  - Thermionic currents dominate at high temperatures
  - Plasma pressure appears to be less important
- New experiments planned to study
  - Melt layer physics
  - Material properties of melt layers
  - Effect of repeated melts
Dust work plan

1. Characterization of dust production rates, conversion factor of erosion/damage to dust production
   - No real advance since 11th DivSOL TG session in Nagasaki – awaiting analysis of dust collected from JET wall changeout

2. Characterisation of ejection velocities, molten droplet size & morphology/size distributions of dust with high load
   - Awaiting further analysis of QSPA experiments and new high heat load exposures on Be targets to be obtained from IO contract ITER/C4T/10/115/RTS (laboratory studies of material damage). Possible later contribution from MAGNUM PSI ELM studies

3. Study the role of T-removal techniques in dust creation
   - No obvious progress

4. Cross-machine studies of dust injection
   - Good progress – energised by DSOL – deliberate/coordinated dust injection in DIII-D, MAST, TEXTOR, LHD, NSTX

5. Dust measurements and modeling
   - Reasonable progress but very difficult area – some advances in particle tracking (fast cameras, Mie scattering), detection (aerogel, electrostatic), modelling (DUSTT/UEDGE – R. Smirnov PSI 2010)

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<thead>
<tr>
<th>R&amp;D type</th>
<th>Timescale</th>
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<tr>
<td>Tok. expts. &amp; post-mortem studies</td>
<td>Medium (2-4 yr)</td>
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<tr>
<td>IO coordinated</td>
<td>Short (1-2 yr)</td>
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<tr>
<td>Lab. collaboration</td>
<td>Medium (2-4 yr)</td>
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<tr>
<td>DSOL-21</td>
<td>Short (1-2 yr)</td>
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<tr>
<td>Coordinated diag. development and code testing</td>
<td>Short (1-2 yr)</td>
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DSOL-21: Introduction of pre-characterized dust for dust transport studies in the divertor and SOL

- Devices involved: DIII-D, TEXTOR, MAST, NSTX, LHD, AUG

- In 2010 dust injection experiments have been performed at DIII-D and LHD
  - In DIII-D: graphite dust injected in the low field side SOL using reciprocating probe. Dust injection observed by a fast camera but no effect of the dust on the core plasma.
  - In LHD: spherical carbon dust 8 μm in diameter injected into divertor plasma and observed by a fast camera. Most dust particles moved nearly unidirectionally at speeds up to 40 m/s. Reflections of dust particles from wall collisions observed.

- Progress has been made on modeling of the reconstructed 3D dust trajectories from NSTX (with DUSTT code) and from MAST (with DTOKS code). Good overall agreement is obtained between the experimental and simulated data.

- Results from 2009 dust injection in TEXTOR have been analyzed. As confirmed by a number of diagnostics, dust injection resulted in a significant increase of the edge impurity content but had no effect on the core plasma.

- Future plans
  - Dust injection experiments are proposed on AUG, DIII-D, LHD, NSTX, TEXTOR, T-10
  - 3D dust trajectory reconstruction will be implemented at AUG and possibly TEXTOR

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Heat fluxes to PFCs work plan

1. ELM characteristics
   - Aim was cross-machine comparisons of ELM statistics for natural variability of ELM and divertor fluxes (controlled and uncontrolled ELMs). No real progress. Renew or extend DSOL-1?

2. Disruption heat loads
   - Good progress in some areas, less in others. Radiation asymmetries and some plasma loads during mitigated and natural disruptions E. Hollmann, A. Huber, M. Reinke PSI 2010. RE loads poorly characterised. Modelling lagging behind → stimulate with new IO contract, collaboration with MHD TG?

3. Transient detachment control
   - Good initial session at DivSOL Amsterdam – work slowed since → stimulation required (R. A. Pitts)

4. Far-SOL heat and particle fluxes
   - Slow progress. Some secondary divertor heat loads (DIII-D, TCV) but analysis incomplete. No advance with DSOL-15

5. Divertor and SOL ELM and inter-ELM heat fluxes
   - Good recent progress. Exciting results from JET, US ReNeW data to be integrated with ITPA effort - CLOSED

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**R&D type** | **Timescale**
--- | ---
1. Tok. expts., collab. PEP? | Medium (2-4 yr)
2. Tok. expts., model development | Short (1-2 yr)
3. DSOL-20 | Medium (2-4 yr)
4. Tok expts., DSOL-15 | Medium (2-4 yr)
5. Tok. expts., database + PEP collab. + US ReNeW | Short (1-2 yr)
6. New DivSOL task force | Medium (2-4 yr)
7. IO coordinated | Short (1-2 yr)

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Heat fluxes to PFCs work plan

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6. Modelling detachment
   - DivSOL task force established (Amsterdam TG meeting). Good initial progress but then slowed. Manpower promised now that PSI 2010 out of the way

7. Rampup/rampdown heat loads
   - Excellent response to IO ROF request to DIII-D – fairly complete experimental study and report to 13th DivSOL TG meeting and then at PSI 2010 (D. Rudakov). Experiments also performed on TS. Awaiting new JET experiments and TS report once analysis complete.

NEW: Machine size scaling of ELM footprint width
   - both mitigated and non-mitigated ELMs
Recent highlights of Heat loads research

- Toroidal and poloidal asymmetries occur during mitigated disruptions
  - Toroidal asymmetries persist longer into thermal quench
  - Experiments planned with toroidally spaced injectors
- ELM-wetted area increases with ELM energy
  - A factor of 5 increase in wetted area over ITER assumption ($A_{ELM}/A_{inter-ELM} = 1$)

- ELM heat load time dependence assumed for ITER needs to be revised
- Mitigated ELMs do not significantly change ELM wetted area
1. Cross machine comparisons of main wall erosion and local re-erosion and co-deposition
   - Built mostly around low-Z marker injection (e.g. $^{13}$CH$_4$). DIII-D data just in. Analysis of last JET injection awaited.
2. Development of local models taking into account surface shaping and attempting to predict the observed deposition patterns for both steady (diverted operation) and limiter start-up/ramp down phases
   - Mostly an IO coordinated effort → centered around EAST moveable limiter experiments and LIM/DIVIMP modelling work (S. Carpentier). Dedicated EAST migration tile to be installed by end 2010
3. Characterise outer and inner divertor erosion as well as the movement of impurities from main chamber to divertor and from divertor to divertor
   - C-Mod W migration analyzed (Barnard, PSI2010).
Recent Material migration results

- Existing C13 migration dataset indicated that ALL of main chamber erosion is transferred to divertor where it plays a central role in T co-deposition.
- Suspicion that this is not true is confirmed by recent $^{13}$CH$_4$ injections near second x-point
  - Modelling also reproduces the deposition pattern (U. Toronto)
  - => The ITER upper divertor will have a significant Be source and lead to main chamber T co-deposition

- New tungsten migration experiments (C-Mod & AUG) follow expectations for migration
  - Down the outer divertor to the PFZ section
  - Across PFZ form outer to inner divertor
- Discussions underway for new high-Z migration experiments.

DSOL-9 has been successful and will be extended in the future including metallic tracers (new DSOL 26)

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IEA/ITPA work status: 7 continue +1 new proposal

<table>
<thead>
<tr>
<th>DSOL-2</th>
<th>Chemical erosion under ITER-like divertor conditions (semi-detached) (Brezinsek) - spokesperson changed</th>
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<tr>
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<td>Proposal: TEXTOR, JET, AUG, JT-60U, DIII-D</td>
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<td>DSOL-8</td>
<td>ICRF Conditioning for hydrogen removal (Ashikawa) Proposal: LHD, HT-7, EAST, AUG, TEXTOR</td>
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<td>DSOL-9</td>
<td>Tracer injection experiments to understand material migration(Philipps)</td>
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<td>Proposal: JET, DIII-D, TEXTOR, ASDEX-Upgrade</td>
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<td>DSOL-12</td>
<td>Reactive gas wall cleaning (Stangeby) Proposal: TEXTOR, HT-7, EAST, DIII-D</td>
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<td>DSOL-13</td>
<td>Deuterium codeposition with carbon in gaps of plasma facing components (Krieger)</td>
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<td>Proposal: data from AUG, TEXTOR, MAST, DIII-D, ToreSupra, C-MOD</td>
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<td>DSOL-14</td>
<td>Multi-code, multi-machine edge modelling and code benchmarking (Coster) Closed</td>
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<td>DSOL-15</td>
<td>Inter-machine comparison of blob characteristics (Terry) Closed</td>
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<td>DSOL-16</td>
<td>Determination of the poloidal fueling profile (Groth) Closed</td>
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<td>DSOL-17</td>
<td>Cross-machine Comparisons of Pulse−by−Pulse Deposition (Skinner) Closed</td>
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<td>DSOL-20</td>
<td>Transient divertor reattachment (Pitts) DIII-D, ASDEX-Upgrade</td>
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<td>Introduction of pre-characterized dust for dust transport studies in divertor and SOL (Rudakov) Proposal: DIII-D, TEXTOR, MAST, NSTX</td>
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<tr>
<td>NEW</td>
<td>DSOL-22: Multi-code validation against experiment for improved detachment modelling (M. Wischmeier) Proposal: AUG, JET, JT-60U, IO</td>
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NOTE - DSOL-22 is a test case proposed to the CC in the last year. It is ramping up and, as more detailed work is done, will need further support for travel as well as general time in support of the project.
A very busy year for SOL/Divertor group

- ITER R&D research up and running
- Stronger ties with IO as well as IO leadership have been a boost
- D/T retention
  - Effect of implantation temperature on T retention
  - Ion cyclotron discharge conditioning characterised
  - Neutron damage effects on T retention defined
- Disruption power asymmetries (mitigated and un-mitigated)
- ELM wetted area larger than assumed. Timescales for power deposition better defined
- Edge modelling codes comparison to experimental measurements of detachment has led to new coordinated effort
- Material migration studies of both carbon and tungsten brought new understanding
- Dust diagnostics improved and modelling playing a larger role in defining experiments
Reactive wall gas cleaning being tested at multiple machines

- Labs involved: DIII-D, Garching, Juelich, Madrid, Pilot-PSI, Toronto
- Thermal O_2, plasma-activated O, N_2, NH_3
- Thick deposits can be removed about as quickly as thin ones.
- Contamination (metal) is usually not important.
- Plasma-activated O is more effective than O_2-baking.
- N_2-baking at ~300°C as effective as O_2-baking at ~300°C.
- Plasma operation can be recovered quickly.
- Proposed: effectiveness of N and its compounds; dust removal by O_2-baking.

• O bake is very effective at T (and C) removal
• The main problem at the moment is tritiated water which ITER has said it will not allow
• Emphasis changing to T removal from high-Z and to techniques that do not lead to tritiated water.
Implantation of T into Be at higher temperatures changes the amount retained and affects T removal

- We are working towards the capability to predict the level of T retention in the many Be and mixed-Be surfaces
- Implantation in Be at higher temperature can lower the retention significantly
  - Stronger effect for divertor than main chamber
Implantation of T into Be at higher temperatures changes the amount retained and affects T removal

- We are working towards the capability to predict the level of T retention in the many Be and mixed-Be surfaces
- Implantation in Be at higher temperature can lower the retention significantly
  - Stronger effect for divertor than main chamber

- On the other hand the T that is retained is harder to remove through baking
  - Even a small increase in implantation temperature (e.g. 150°C) strongly decreases the amount that can be recovered at 350°C (divertor)

K. Sugiyama, San Diego Div/SOL, PSI 2010
Small amounts of impurities in Be also raise the temperatures required for T removal.

- Impurities in the Be lead to a reduction in T removal at a given baking temperature.
  - Significant effect to keep track of.

Room temperature implantation
DSOL-24: Disruption heat loads (new)

- Improve our understanding of power balance during disruptions (including VDEs and rapid shutdowns).

  - What sets the SOL broadening during the thermal quench?
  - What sets TQ duration?
  - How much energy can be dissipated in the vessel structure?
  - How large are conducted heat loads during the current quench?
  - Can we predict net impurity sputtering during thermal quench?

- Minimum plan: cross-machine comparison of IR images during hot VDE (worst case heat load scenario)

  - Where possible, get data from other disruptions (current limit, beta limit, etc) and rapid shutdowns (massive gas injection).

- Participating machines: ASDEX-U (G. Pautasso), C-MOD (B. Lipschultz), DIII-D (E. Hollmann), JET (G. Arnoux), MAST (A. Thornton), NSTX (A. McLean), TEXTOR (M. Lehnen), and Tore-Supra (J. Bucalossi).

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ELM-wetted area decreases with increasing ELM energy

- Up to a factor of 5 increase in wetted area over ITER assumption ($A_{\text{ELM}}/A_{\text{inter-ELM}} = 1$)
  - Can be considered as providing more confidence in protecting tiles from damage
  - Further studies are needed to understand scaling with machine size
- New ELM data from JET show that the ELM heat load time dependence assumed for ITER needs to be revised

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Mitigated ELMs do not significantly change heat load profiles

- Similar trends in ELM wetted area increase with $W_{\text{ELM}}$ observed for RMP ELMs
  - Inter-ELM scalings different
- The primary effect of mitigation (RMP or ‘kick’s) is to increase the ELM frequency and lower pedestal density
  - Efforts to regain density loss lead to poorer confinement than non-mitigated case

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<thead>
<tr>
<th></th>
<th>No RMP</th>
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<td></td>
<td>no gas</td>
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<td>inter-ELM</td>
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Poroidal asymmetries of first-wall heat loads in disruptions reduced by mitigation

- Poroidal asymmetry introduced by gas valve is small after start of puff — true for DIII-D and AUG as well
- Need peaking factor of time-integrated heat load

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Toroidal peaking factor more of a concern than poloidal peaking of radiation during MGI disruption mitigation

- Toroidal asymmetry also peaks during gas injection but extends through thermal quench period
  - Essentially 1 in current quench
- Integral over entire disruption yields a toroidal radiation asymmetry of order 2
  - Be wall melting a concern
- More experiments needed
  - Multiple valves
  - Variations in pressure

C-Mod

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Recent limiter startup experiments confirm ITER assumptions for SOL power widths

- Dedicated experiments (DIII-D, TS) to check ITER assumptions for expected power widths during main wall limiter start-up/ramp-down
- Within scatter, ITER assumptions confirmed across wide range of operating conditions on DIII-D for limiter plasmas
- TS data analysis awaited
Tungsten migration studies indicate most eroded tungsten stays in the divertor

- Toroidally continuous source of tungsten from lamella tiles in outer divertor
Tungsten migration studies indicate most eroded tungsten stays in the divertor

- Toroidally continuous source of tungsten from lamella tiles in outer divertor
- Migration of W
  - down the outer divertor (expected)
  - across to ‘dome’ area as sputtered atoms
  - across to inner divertor (flowing through SOL or private flux region)
  - No measurable W in core plasma from sputtering source
- Further analysis and experiments needed

DSOL-9 has been successful and will be extended in the future including metallic tracers (new DSOL 26)