Dynamic Boundary Plasma–Wall modeling of ELMy H-mode

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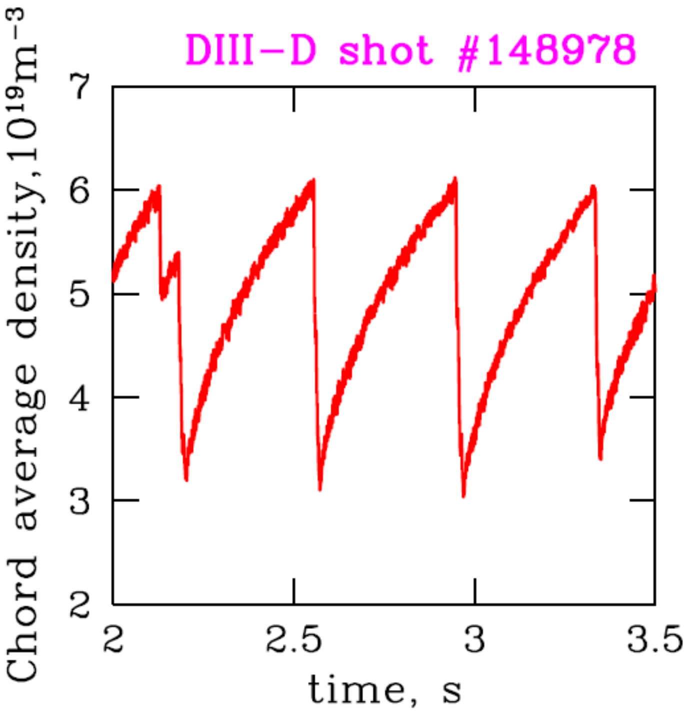
International Sherwood Fusion Theory Conference, San Diego, CA, 24-26 March 2014

Outline

- Motivation
- UEDGE-MB code for self-consistent modeling of boundary plasma transport and deuterium wall inventory including transient events
- Results of simulations of ELMy H-mode boundary plasmas
- Analysis of the roles of wall in the cases of frequent and infrequent ELMs
- Conclusions

Motivation



Giant type-I ELM events

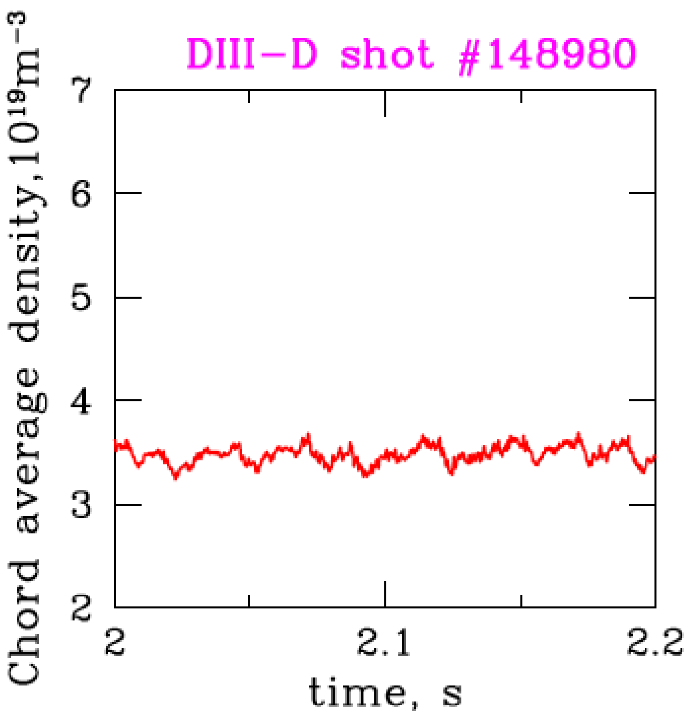
- Pedestal particle loss: ~3×10^{20} D
- Initial inventory in SOL+Divertors: ~3×10^{19} D
- After the ELM, pedestal inventory is recovering gradually during ~100-400 ms
- NBI fueling and pumping are small!
- No gas puff

Where are the particles expelled by ELM go to?

Where the particles are coming from to re-heal pedestal?

WALL? SOL+Divertors?

Motivation (cont.)



Small type-I ELM events

- Pedestal particle loss: ~4×10^{19} D
- Initial inventory in SOL+Divertors: ~2×10^{19} D
- After the ELM, pedestal inventory is recovering gradually during ~10-20 ms
- NBI fueling and pumping are small!
- No gas puff

Where are the particles expelled by ELM go to?

Where the particles are coming from to re-heal pedestal?

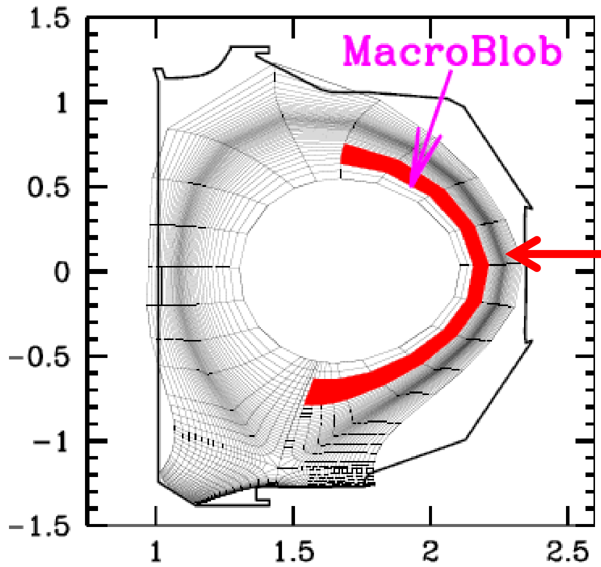
WALL? SOL+Divertors?

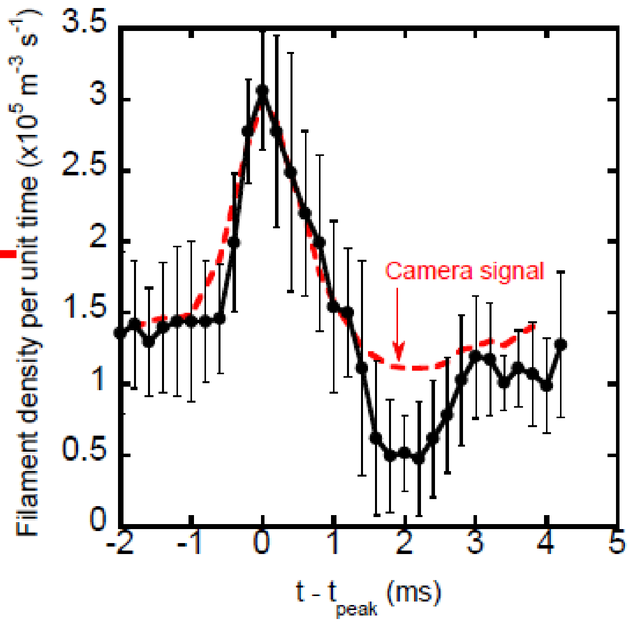
Motivation (cont.)

- As soon as we pointed on the wall in the cases considered above, the boundary plasma and deuterium wall inventories become strongly coupled and should be modeled self-consistently!
- So far, the ELMs were simulated with 2-D boundary plasma transport codes (UEDGE and SOLPS) as a sudden increase in plasma D_{perp} and χ_{perp} during an ELM with no contribution from wall effects
- However:
  - ELM transport is characterized by 3-D filamentary convective structures
  - The wall periodically “switches” from the net hydrogen deposition during the ELM to the net release between ELMs. Thus, the wall physics processes can be crucial in the pedestal recovery.
  - In a sequence of many ELMs, the pedestal plasma and hydrogen wall inventory simultaneously evolve to a dynamic equilibrium
- In what follows, we, for the first time, present results on self-consistent modeling of both plasma and wall dynamics in ELMy H-mode discharges

Modeling of ELMs with UEDGE-MB

The UEDGE-MB (Pigarov, 2011) version of UEDGE code incorporates the Macro-blob approach to simulate the non-diffusive filamentary transport

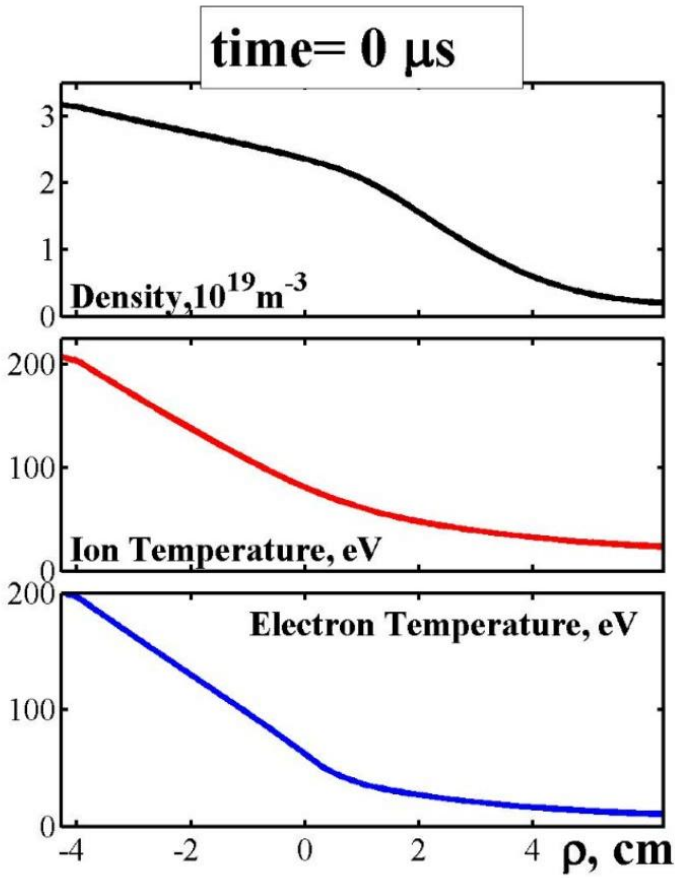




In Macro-blob approach, we pack numerous ELM filaments into the toroidally-symmetric continuous structure (Macro-blob) and advect it radially at a prescribed velocity

The density of filaments was measured on DIII-D with fast cameras. The number of filaments in ELM can be high ~300

Macro-blob dynamics



Movie on Macro-Blob motion

- Temporal evolution of plasma density, ion and electron temperature at outer mid-plane during macro-blob event
- Macro-blob propagates radially as a coherent structure and gradually decays due to the leakage of energy and particles to divertor targets
- Finally, Macro-blob interacts with the chamber wall

Wall model in UEDGE-MB

For each boundary cell of modeling domain, UEDGE-MB solves:

- 1-D heat conduction equation to find surface temperature $T_W^{cell}(t)$
- 0-D equation for deuterium wall inventory $N_D^{cell}(t)$

$$\frac{dN_D^{cell}}{dt} = \Gamma_{plasma}^{cell}(t)\left(1 - R(t)\right) - S_{th}(t) - S_{sd}(t)$$

where:

Recycling coefficient: $$R(t) = R_{ELM}\Upsilon(t) + R_{st}\left(1 - \Upsilon(t)\right)$$

Thermal desorption rate: $$S_{th} = \hat{S}_{th} F_{th}(T_W^{cell}(t))$$

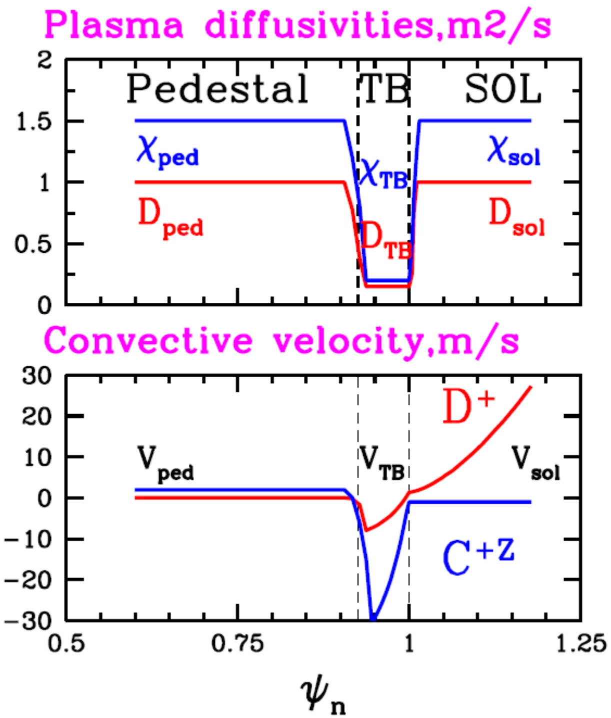
Stimulated desorption rate: $$S_{sd} = \hat{S}_{sd} F_{sd}(\Gamma_{plasma}^{cell}(t))\left(1 - Y(t)\right)$$

$\Upsilon(t) = 1$ when macro-blob interacts with a given boundary cell, otherwise =0

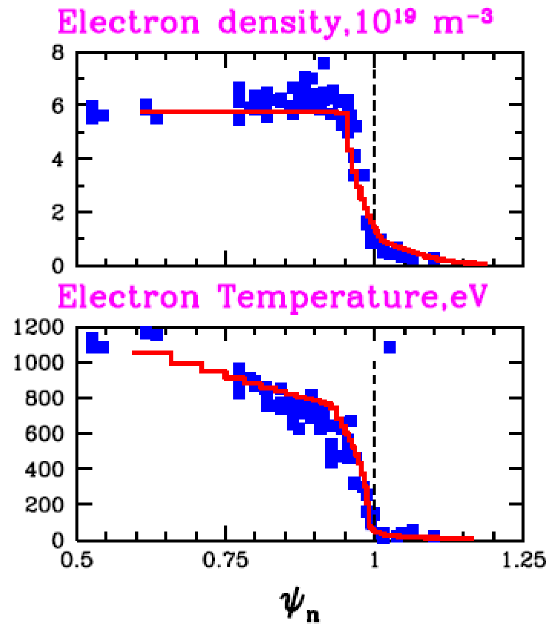
$\hat{S}_{th}$ $\hat{S}_{sd}$ are the sink strengths

Main fitting parameters of the model are R_{ELM} $\hat{S}_{sd}$ $\hat{S}_{th}$

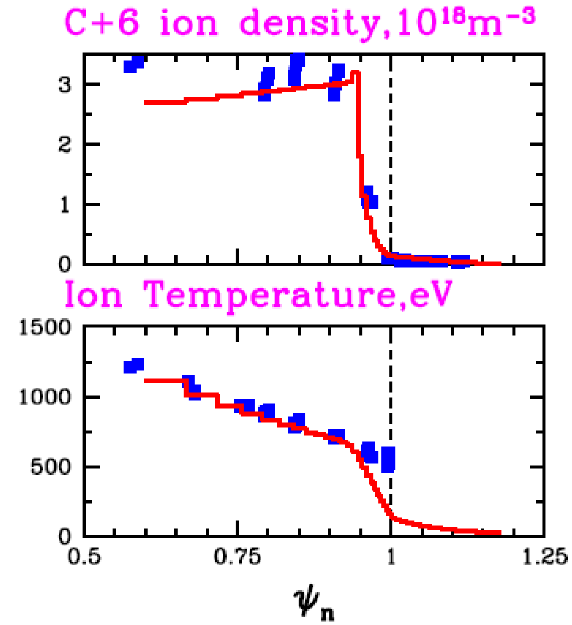
Transport coefficients



Thomson

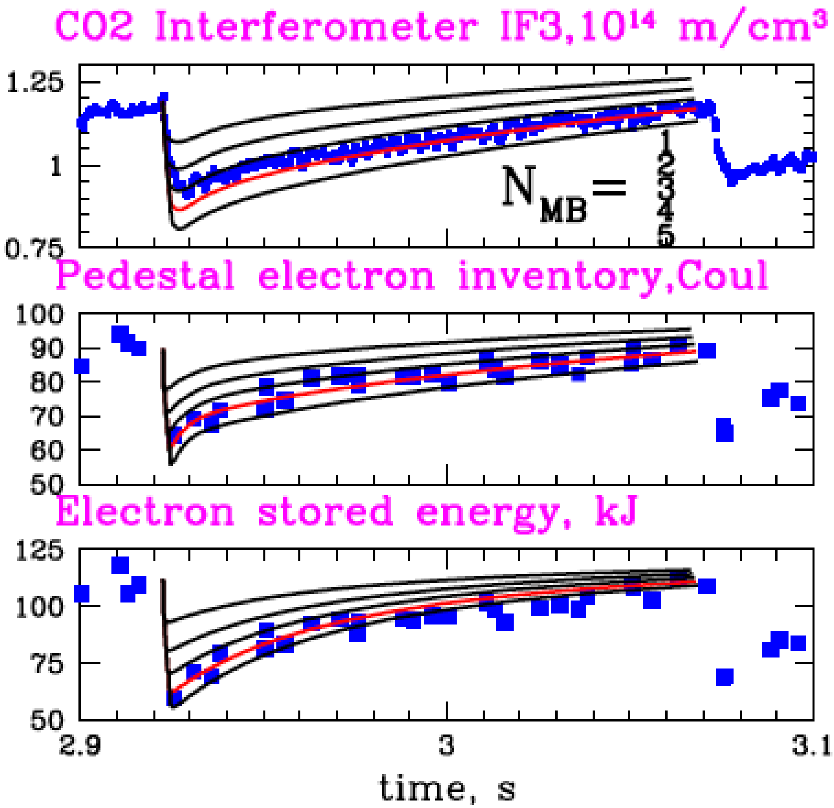


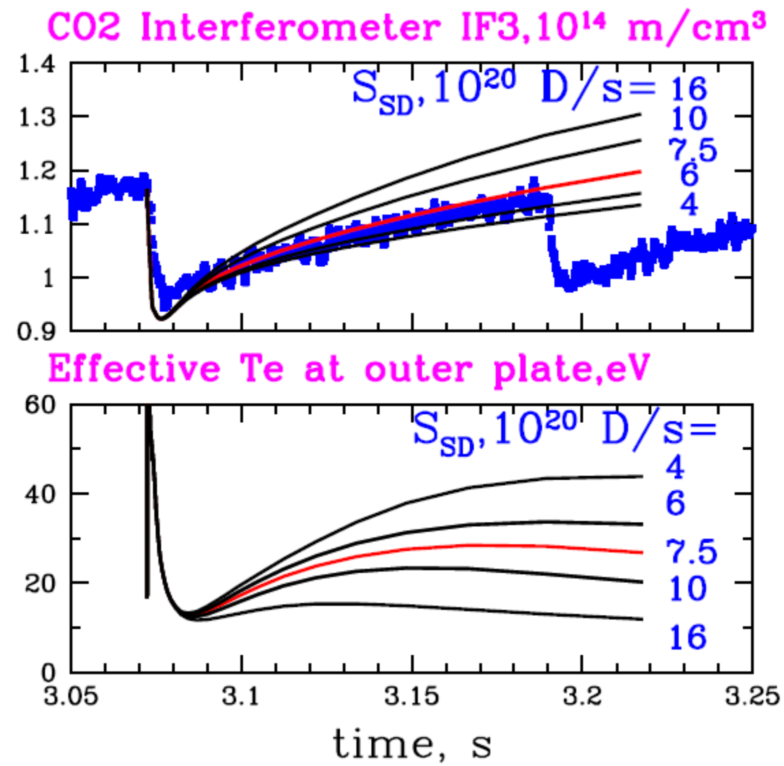
CER



- Radial profiles of anomalous D_{perp}, χ_{perp} and V_{perp} exhibit the transport barrier
- Profiles of transport coefficients are adjusted to match experimental plasma data over the sequence of ELMs
- During the ELMs, the values of local D_{perp}, χ_{perp} and V_{perp} change to the higher values following the Macro-blob movement

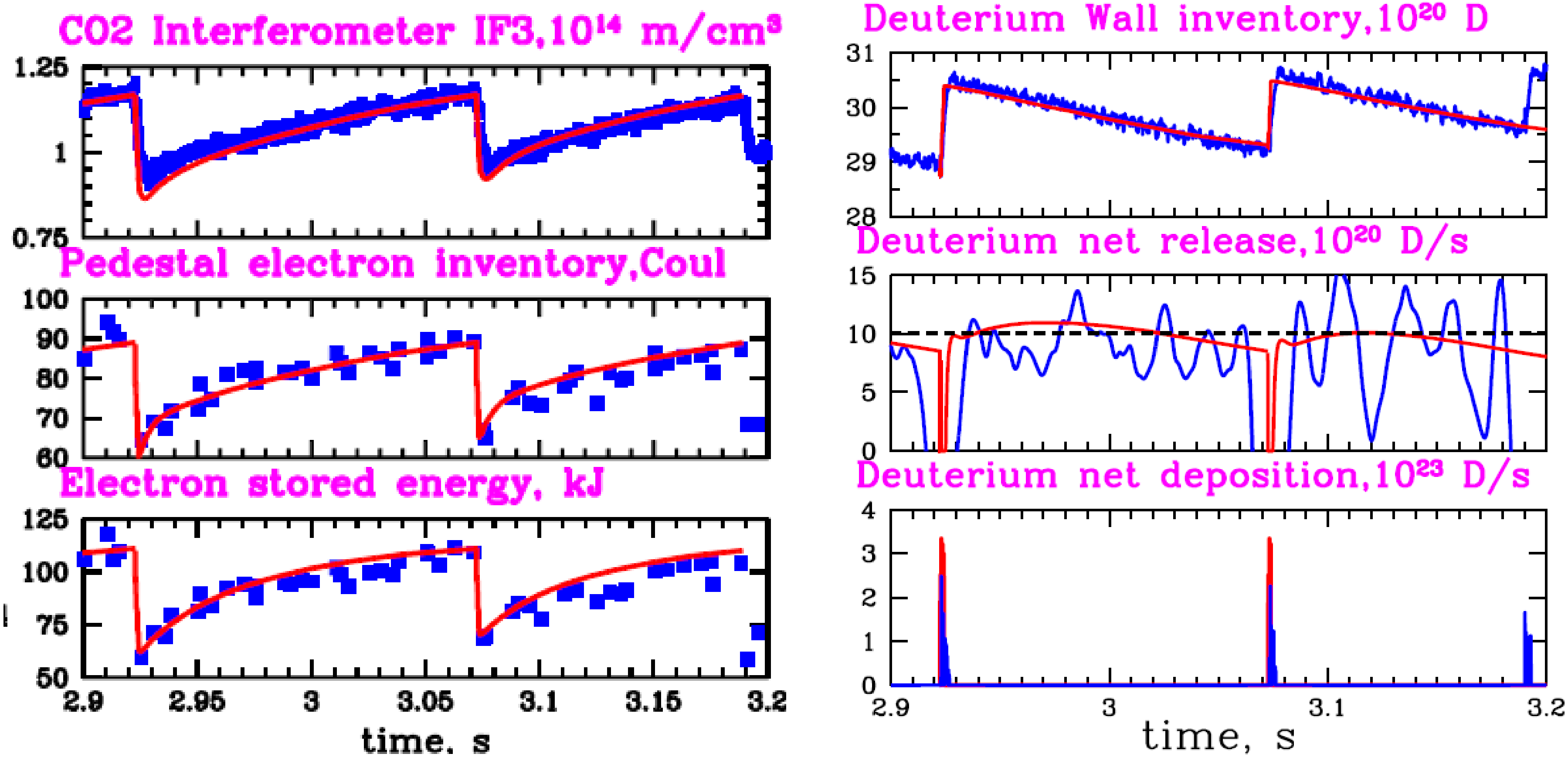
Matching experimental data





- We find the number of Macro-blobs in our ELM modeling by matching pedestal particle and energy losses in ELM
- We determine the wall parameters in our model by matching pedestal recovery dynamics

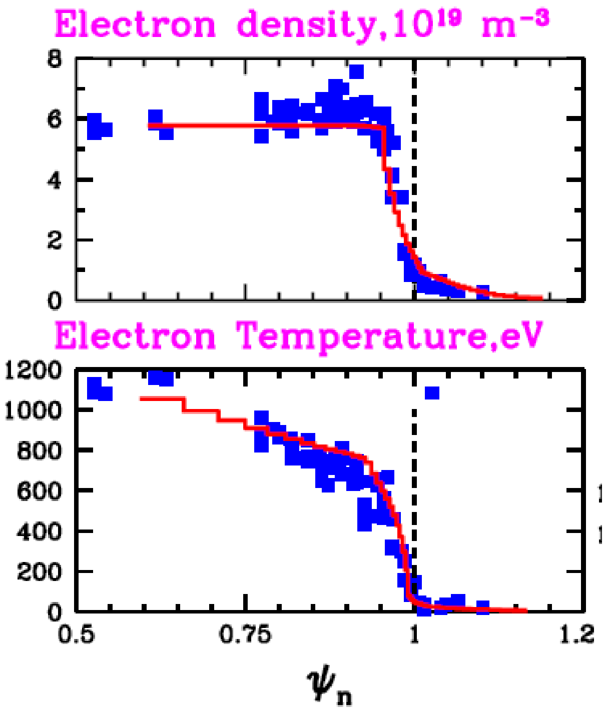
Matching experimental data (cont.)



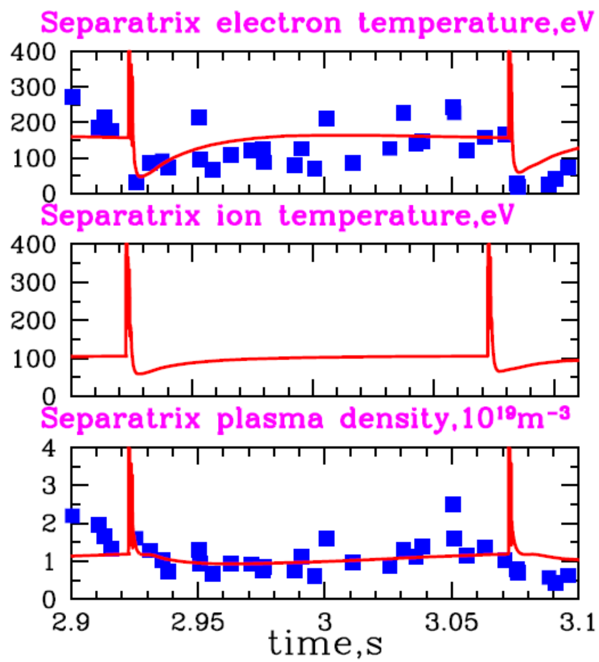
- As a result, we are able to obtain a good agreement with experimental data on a few “real” consecutive ELMs in both plasma parameter and particle inventory variations

Matching experimental data (cont.)

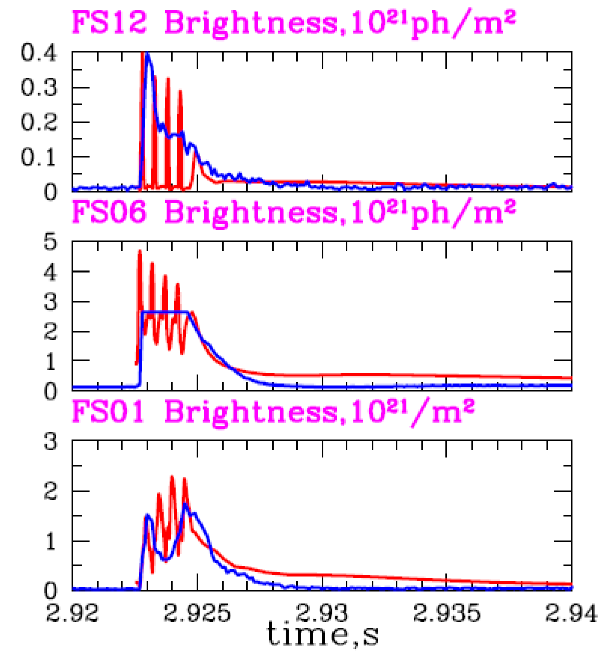
Pedestal



SOL

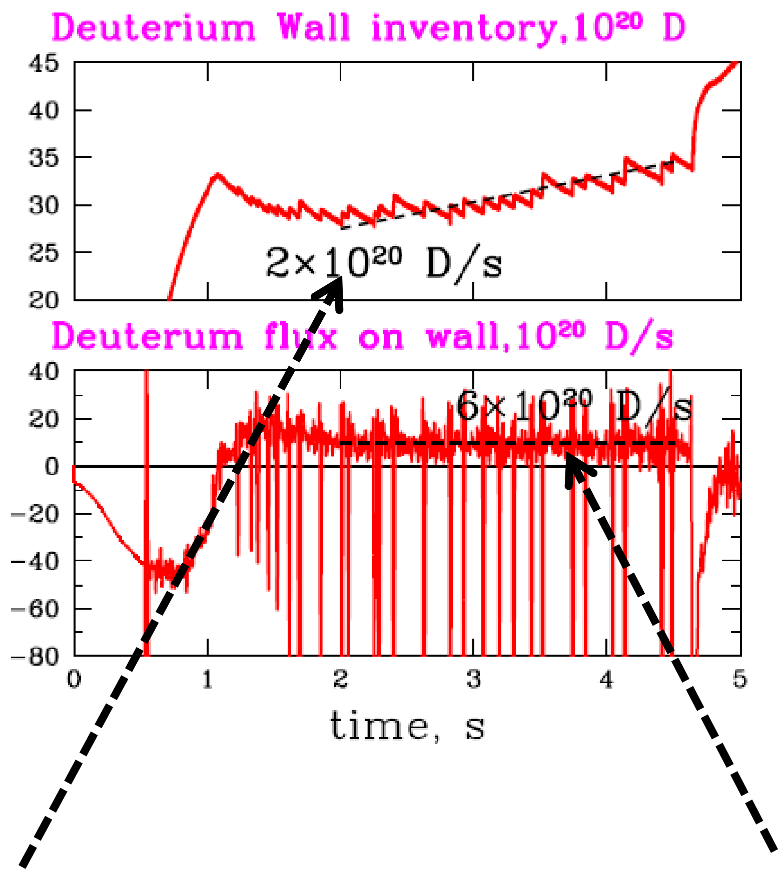


Divertors



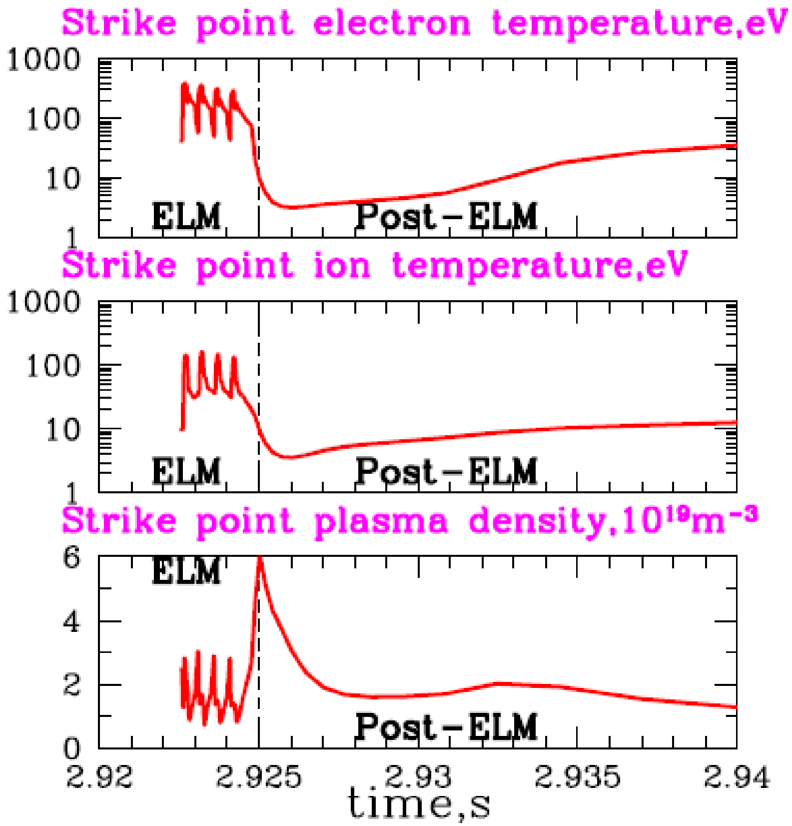
- In UEDGE-MB modeling, we use experimental data on plasma parameters in the pedestal, SOL, and divertors

Matching experimental data (cont.)



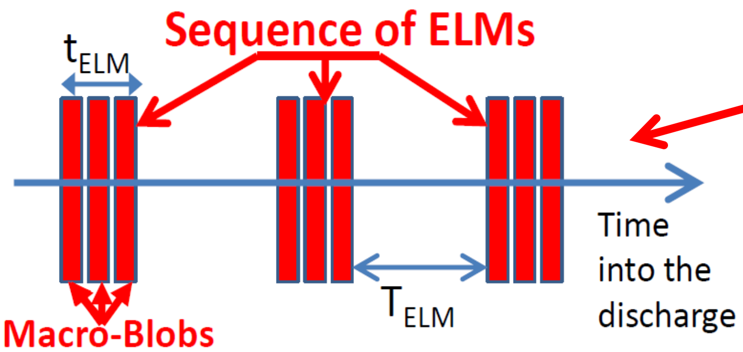
- We also matching experimental data of a long term evolution of particle inventory in both plasma and wall, e.g., the average rate of deuterium wall pumping, net rate of wall outgassing between ELMs and net rate of particle deposition during ELMs.

Post-ELM plasma



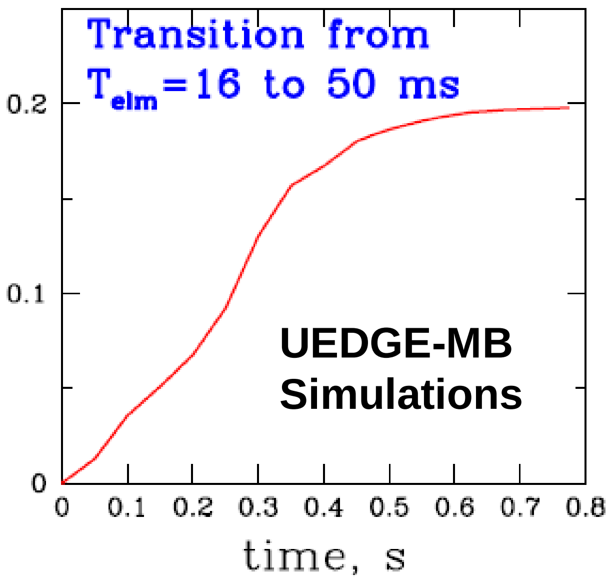
- In Giant type-I ELMs, not all particles expelled from the pedestal are deposited into the wall.
- Just after an ELM, some amount of particles are coupled to the SOL and divertors, that results in formation of relatively cold and dense Post-ELM plasma.
- This plasma evolves on ~20 ms time scale, which is set up by the Transport Barrier properties and feeds the pedestal by particles.

Dynamic equilibrium for plasma/wall with ELMs

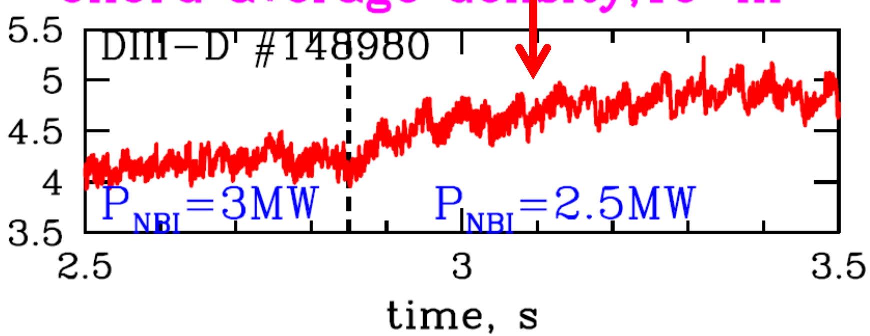


- We model a periodic sequence of identical ELMs
- As a result, after some transient time, both plasma and wall parameters, averaged over the ELM cycle, reach a dynamic equilibrium and practically do not vary
- Characteristic time-scale of reaching dynamic equilibrium is about a second, which is in agreement with experimental data

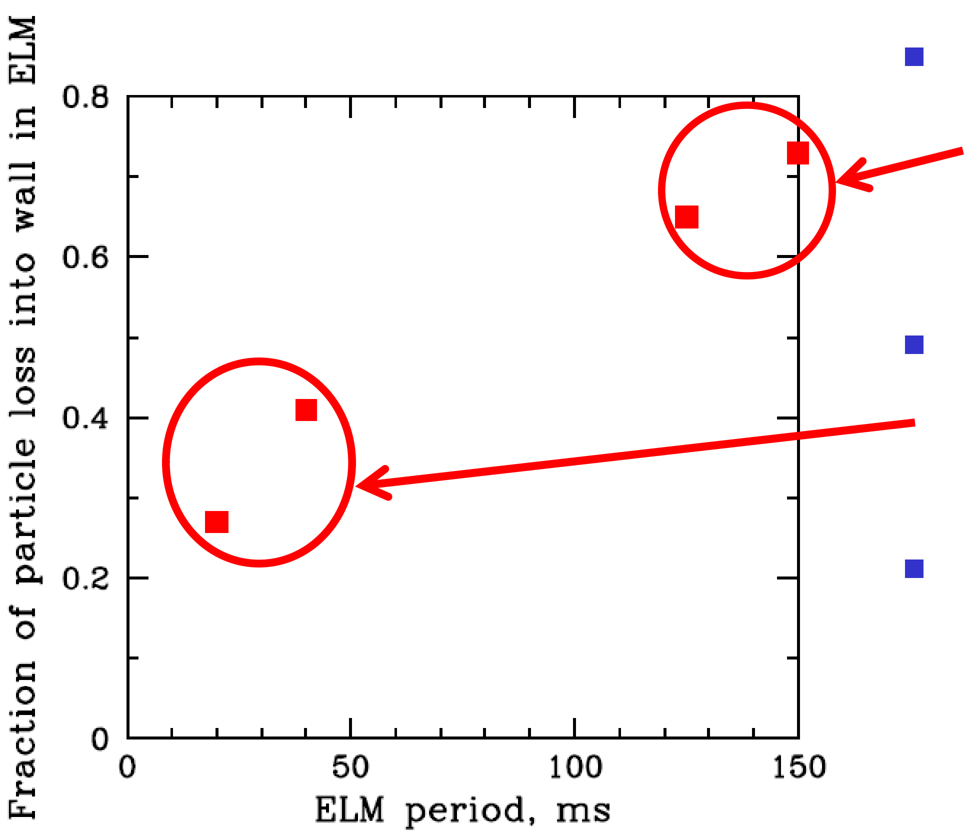
Variation of D pedestal inventory with respect to initial inventory



Chord average density, $10^{19}m^{-3}$



Particle losses into wall during the ELM



- Our simulations show:
- Pedestal particles are mainly (up to 80%) “pumped out” by the wall in the case of infrequent ELMs (t_{elm}>100 ms)
- Frequent ELMs (t_{elm}<30 ms) retain more particles after the ELM in the SOL and divertors
- This difference is because of the fact that the SOL and divertors can only accommodate a limited number of particles, otherwise divertor plasma becomes deeply detached

ELM particle losses and edge/wall inventories

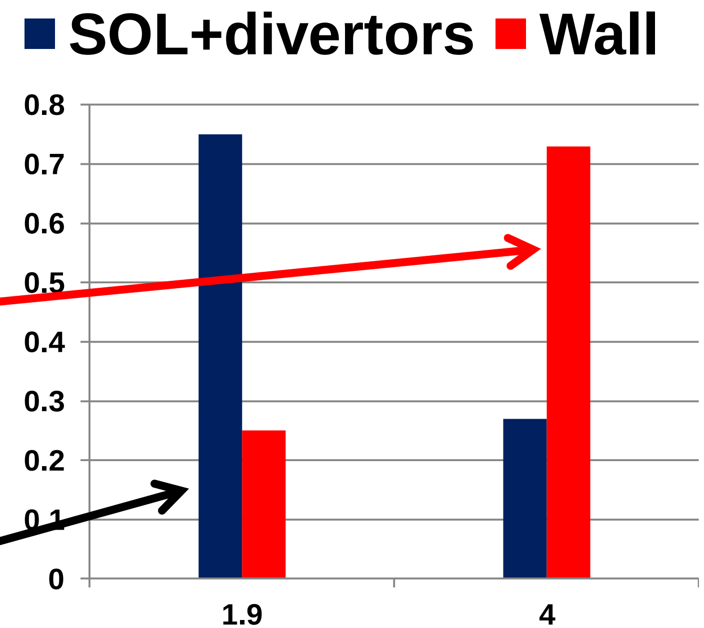
As a figure of merit we introduce parameter $\eta = N_{pedloss}/N_{soldiv}$

$N_{pedloss}$ is the pedestal particle loss during an ELM

N_{soldiv} is the hydrogen inventory in the SOL+divertors before ELM

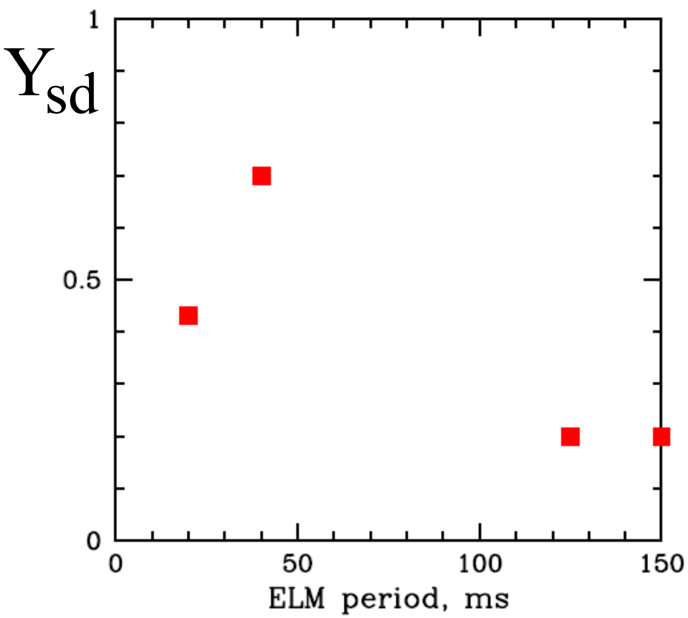
- After dynamic equilibriums in a sequence of ELMs are reached, we find:
- Giant ELMs: large $\eta \geq 4$
  - Pedestal recovery is determined by the physics of wall
- Small ELMs: small $\eta \leq 2$
  - Pedestal recovery is determined by the physics of SOL, e.g. by the leakage of neutrals from the divertors, anomalous inward pinch, etc

Retained after the ELM in:



$\eta = N_{pedloss}/N_{soldiv}$

Yield of stimulated desorption



- There are two groups of processes for hydrogen release from the wall
  - Thermal desorption and
  - ion-stimulated desorption
- Binding energies for hydrogen in graphite are high ~1 eV, so thermal process are slow as the surface temperature measured and simulated between ELMs is typically below 300C.
- Define the stimulated desorption yield is $Y_{sd} = S_{sd} / \Gamma_{plasma}$

$Y_{sd} \sim 0.2 - 0.7\%$ in DIII-D

Conclusions

- We simulate ELMy H-mode discharges in D-IIID with UEDGE-MB code, which is capable of self-consistent modeling of both ELMy plasma transport and wall processes
- We are able to match the temporal evolution of large amount of experimental data on both short (~ 100 μs, during the ELM), medium (~10 ms, during the ELM cycle) and long (~ second) time scales
- We find that in infrequent giant ELMs the particles expelled from the pedestal during the ELM are dynamically retained in the wall
  - Pedestal recovery in this case is determined by the wall physics, which is sensitive to wall material
    - This might explain different particle inventory dynamics in ILW JET ELMy discharges
- For frequent small ELMs, large fraction of particles expelled from the pedestal transiently reside in the SOL and divertors
  - Pedestal recovery in this case is determined by the SOL physics

Conclusions (Cont.)

- The difference between wall absorption of particles expelled from pedestal in large and small ELMs is due to the difference in the particles impinging the wall
- In the ELMy H-mode, the wall, in average, is pumping out deuterium at the rate of 20-50% of the fueling rate.
- In a sequence of ELMs, the wall is periodically shifting from the net “pumping” (during an ELM) to the net “desorption” (between ELMs)
  - This effect is more pronounced in the case of infrequent giant ELMs
- The average wall desorption rate between ELMs in DIII-D is high ~10^{21} D/s which is much larger than NBI fueling or pumping rates
- For graphite wall tokamaks, the hydrogen desorption from the wall between ELMs is due to ion-stimulated desorption with an yield of about 0.5%
- For further advancements in self-consistent plasma-wall simulations, more sophisticated wall models are needed

Acknowledgements

This work was supported by the
USDoE Grant # DE-FG02-04ER54739
at UCSD

Thank you