Time-dependent modeling of coupled plasma-wall dynamics during transient heat load events

R.D. Smirnov[1], S.I. Krasheninnikov[1],
M.V. Umansky[2], I. Joseph[2], T.D. Rognlien[2], J. Guterl[3]

[1]*University of California San Diego, La Jolla CA, USA*
[2]*Lawrence Livermore National Laboratory, Livermore CA, USA*
[3]*Oak Ridge Associated Universities, Oak Ridge TN, USA*

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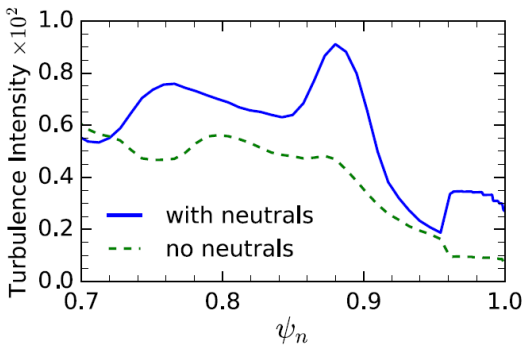
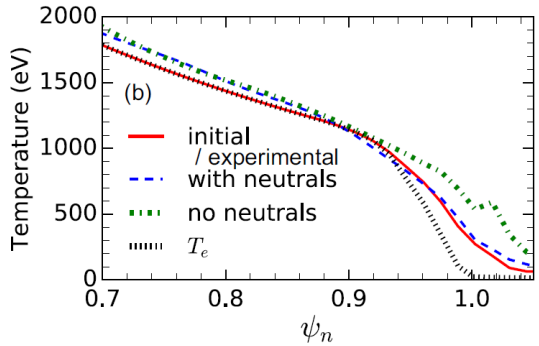
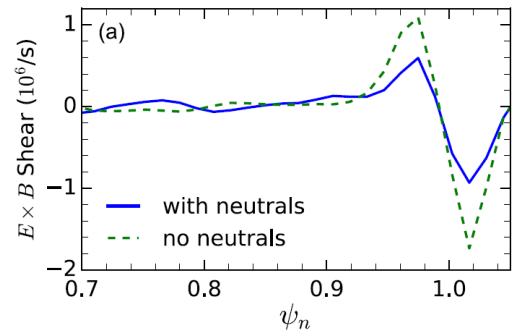
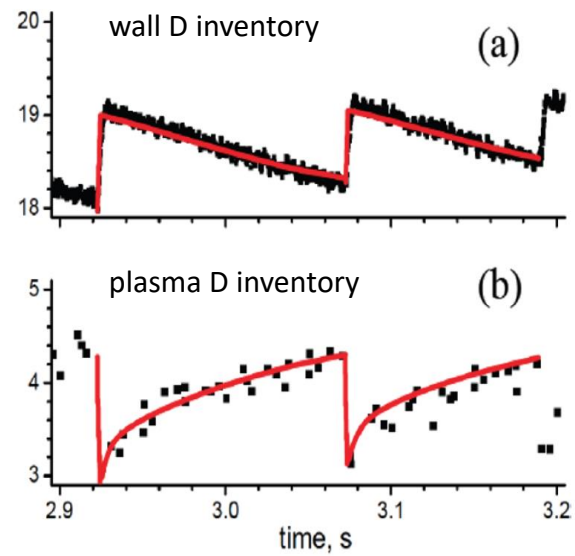
Introduction







- Wall plays important role in plasma stability, transport, and particle balance
  - XGC1 simulations show that neutrals enhance ITG turbulence through increase of T_i gradient and reduction of *E*×*B* shear[1]
  - 80% of pedestal particle loss in type-I ELMs is dynamically retained in wall material[2]



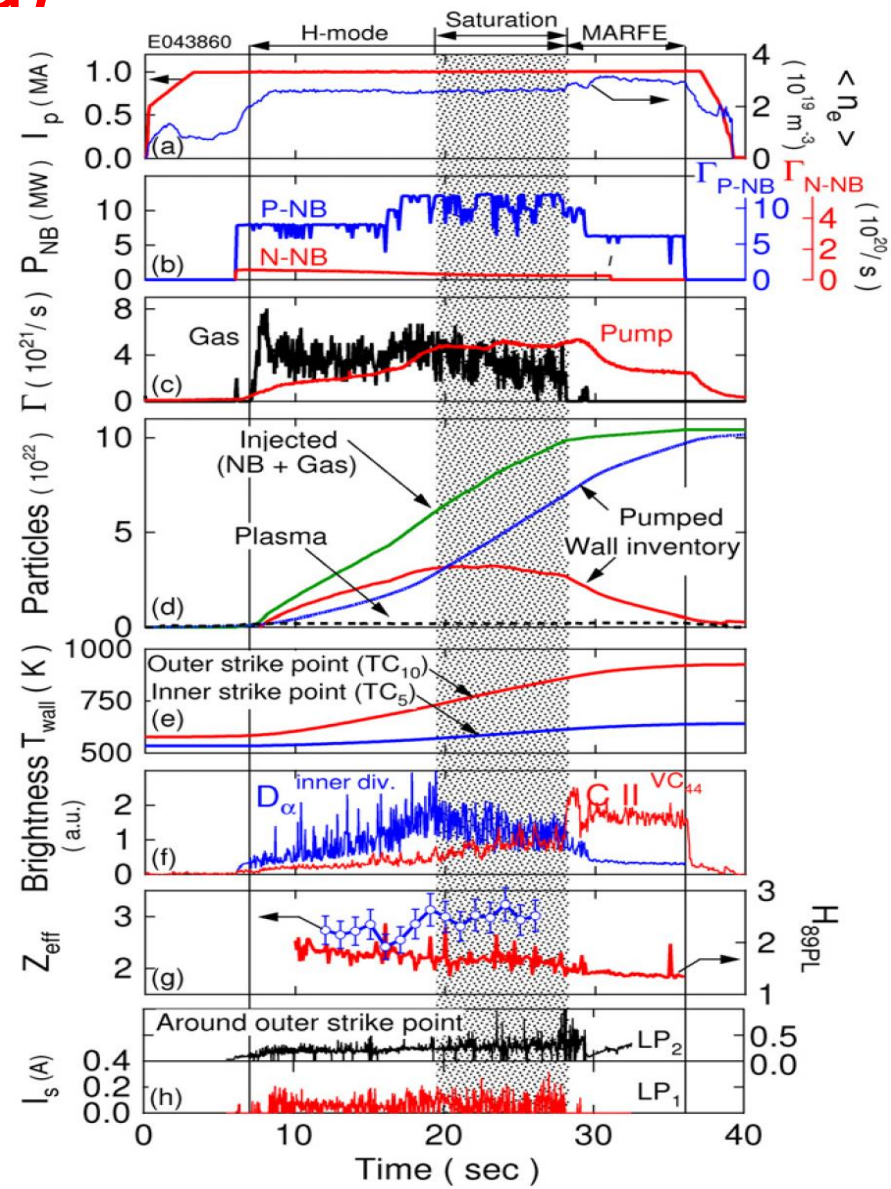
[1] D.P. Stotler *et al*. Nucl. Fusion **57** (2017) 086028
[2] A.Yu. Pigarov *et al. Phys. Plasmas* **21** (2014) 062514

Introduction (continued)

- wall saturation in JT60 repetitive long pulse discharges lead to MARFE, increased core density, and confinement degradation[3]

- Plasma transport simulations usually ignore wall state assuming constant recycling coefficient

- So far there were few attempts of self-consistent dynamic plasma-wall modeling



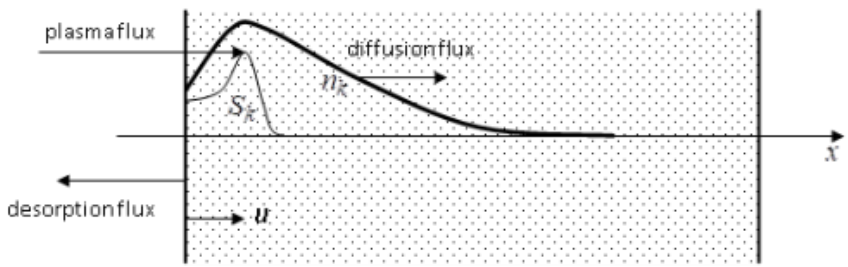
[3] T. Nakano *et al*. Nucl. Fusion **46** (2006) 626

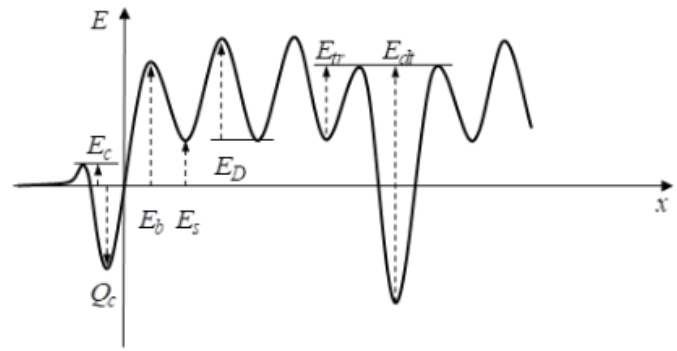
Outline

- UEDGE-FACE coupled model
- Steady-state plasma solutions
- Dynamic plasma-wall modeling
- Thermal desorption instability

FACE code

- Reaction-diffusion 1D code for multi-species transport in wall material[4]





- Bulk

$$\frac{\partial n_k}{\partial t} = \frac{\partial}{\partial x}\left(D_k \frac{\partial n_k}{\partial x} \right) + u \frac{\partial n_k}{\partial x} + S_k + R_k$$

$$S_k = S_{k0} + \sum_j \sigma_{kj} n_j \qquad R_k = \sum_j \nu_{kj} n_j + \sum_{j,i \le j} K_{kji} n_j n_i$$

- Surface

$$\frac{ds_k}{dt} = J_k^+ - J_k^- + S_k^s + R_k^s$$

$$J^+ = K_{sb} n_0 \exp\left[-\left(E_b - E_s \right)/T \right] + \Gamma_{ads}$$
$$J^- = K_{cb} s \exp\left[-\left(E_b - Q_c \right)/T \right] + K_r s^2 \exp\left[-2\left(E_c - Q_c \right)/T \right]$$

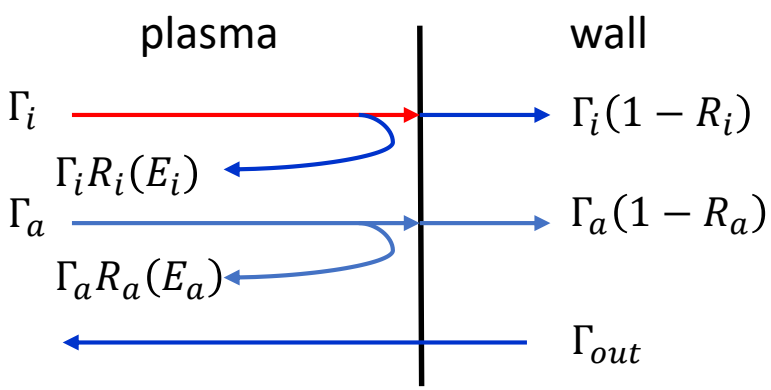
- Heat

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x} \right) + \rho c_p u \frac{\partial T}{\partial x} + S_T$$

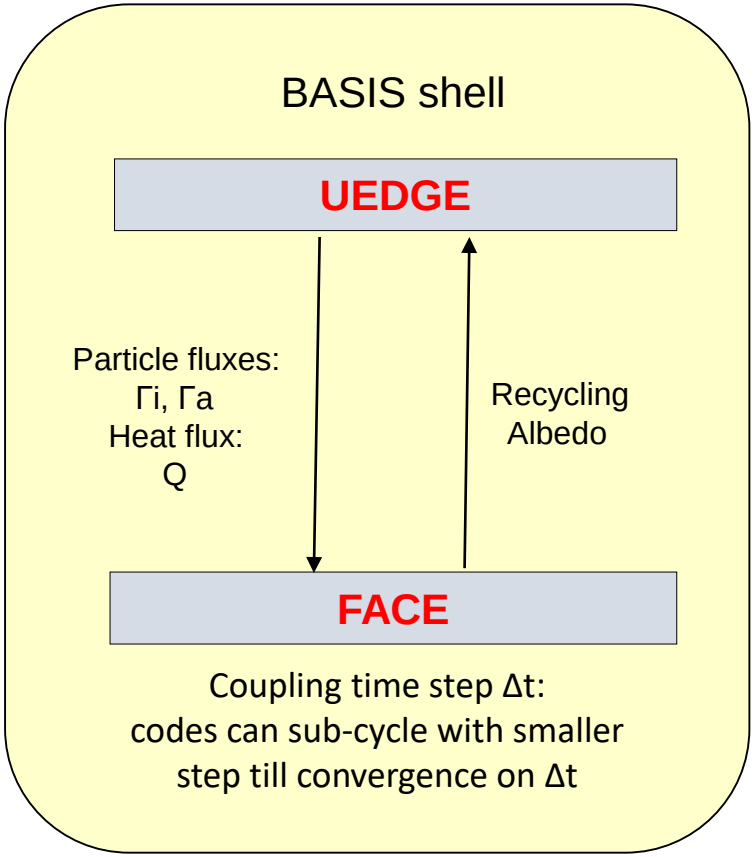
[4] R.D. Smirnov *et al*. Fusion Sci. Technol. **71** (2017) 75

UEDGE-FACE coupling

- Explicit coupling in fully time-dependent mode
- UEDGE and FACE use internally fully implicit solvers
- Conserving particles
- Both hydrogen ion and neutral fluxes to wall are considered

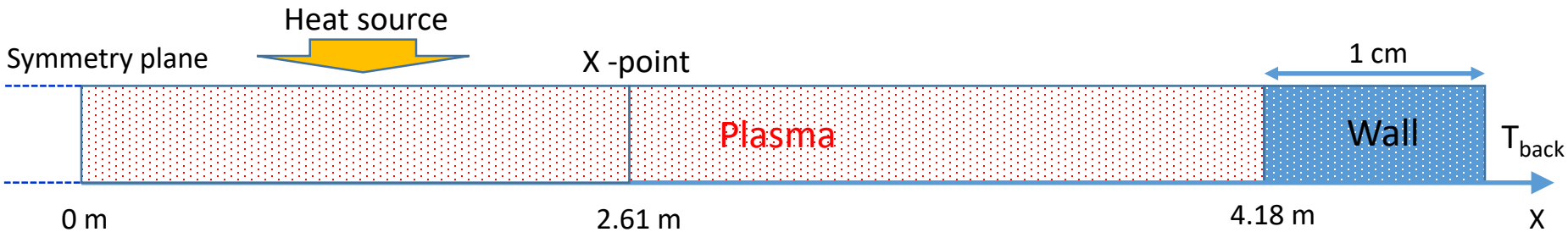


$$\Gamma_{imp} = \Gamma_i(1-Ri)+\Gamma_a(1-Ra)$$



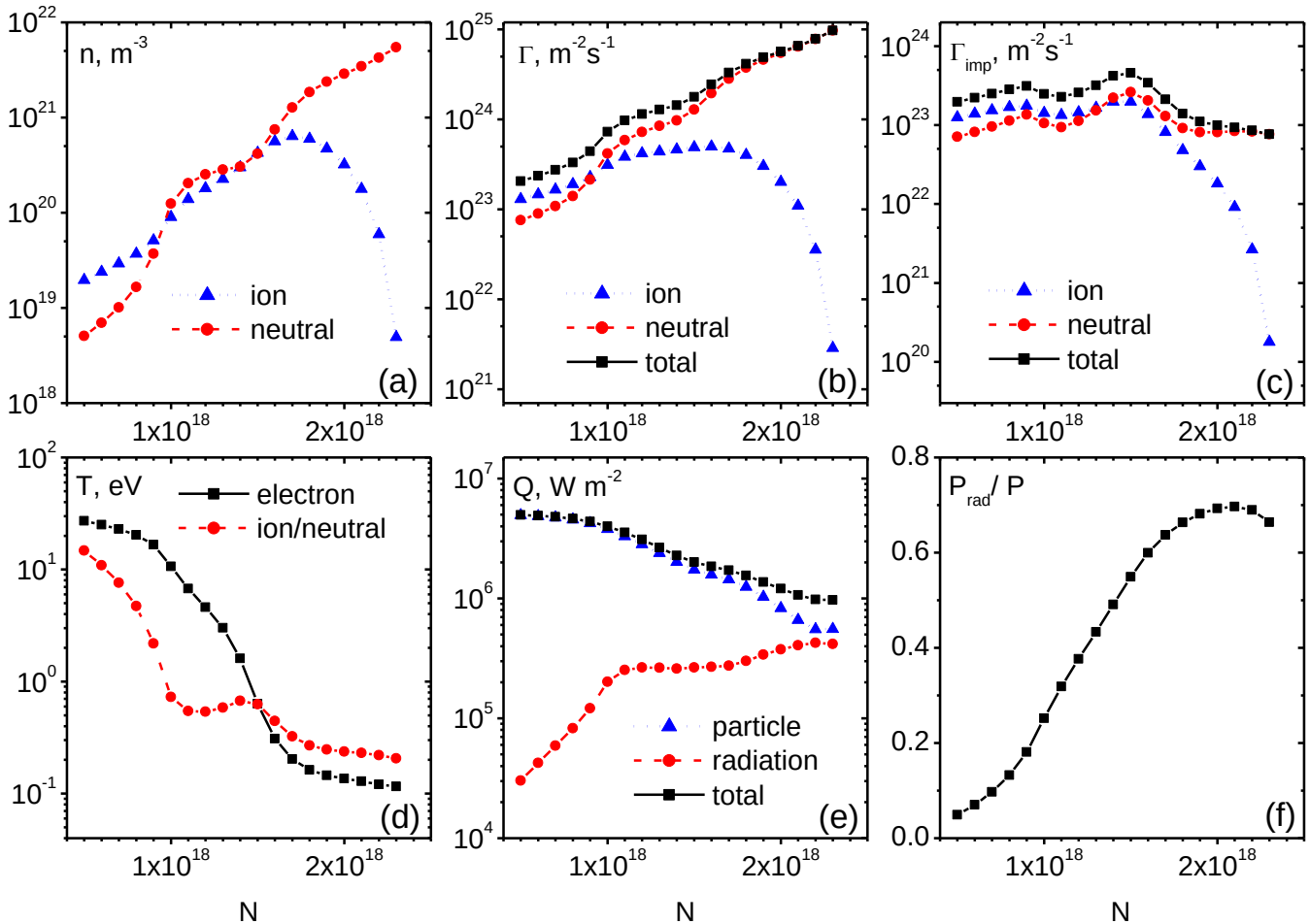
$$\text{Recycling} = (1-Ri)\Gamma_{out}/\Gamma_{imp}+R_i$$
$$\text{Albedo} = (1-Ra)\Gamma_{out}/\Gamma_{imp}+R_a$$

Model parameters



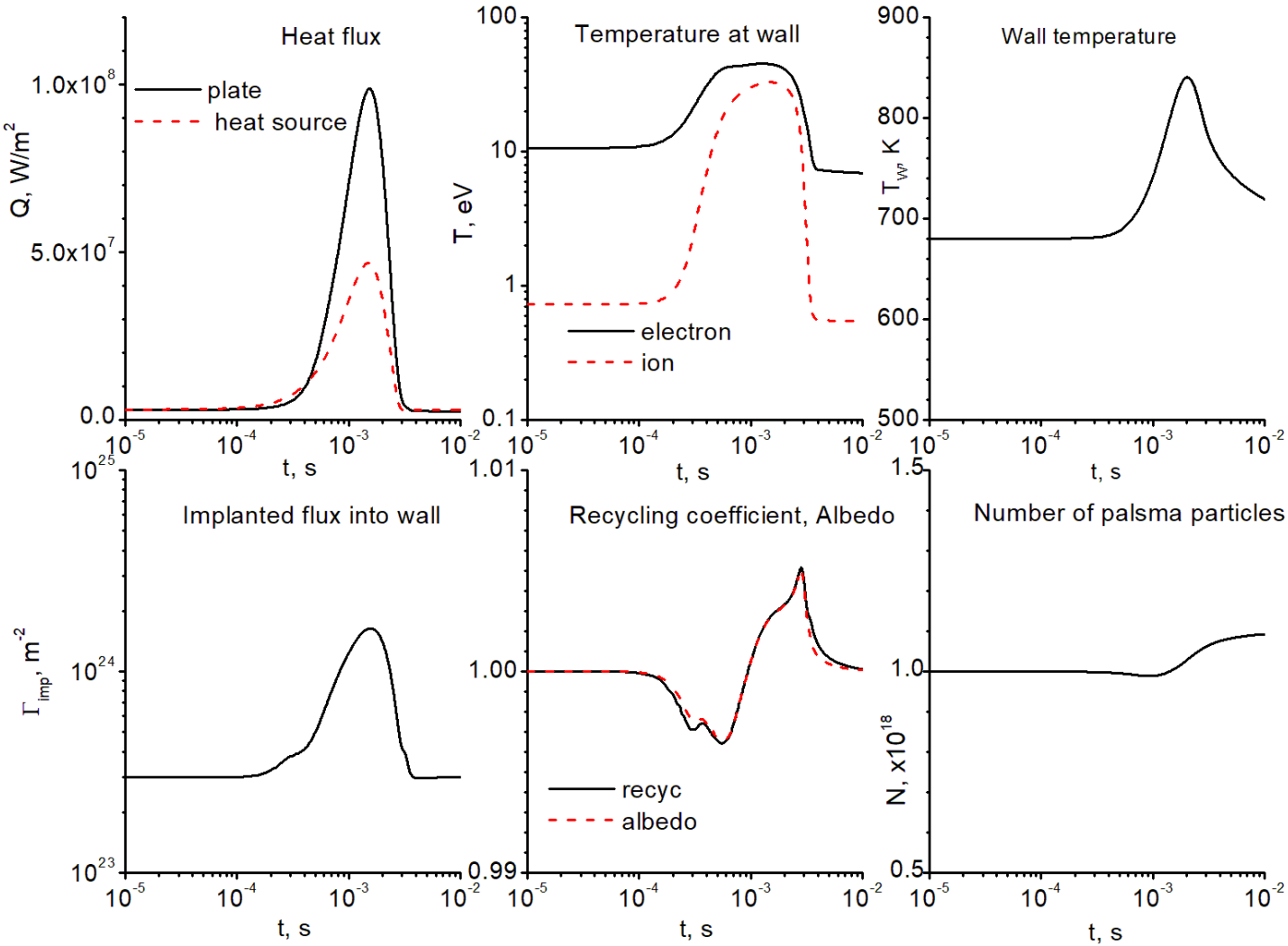
- Using simplified 1D model
- X - poloidal direction in a magnetic flux tube
- Total number of hydrogen particles is conserved "closed box"
- Nitrogen impurity with increasing toward the wall fixed fraction density (5% at wall, ~0.1% at X-point)
- Steady-state upstream heating source 2.3 MW/m^3
- ELM pulse x15 peak heating power; τ =3 ms duration; ~$\sin^2(\pi t/\tau)$ time profile
- Tungsten wall with single kind of H trap (E_{dt}=0.9eV, 0.1 at.%); T_{back}=500K
- Heat transmission coefficients $\gamma_i = 3.5, \gamma_a = 2.0$; barrier $E_{imp} = 2\ eV$
- Steady state initial conditions for both plasma and wall

Plasma steady state



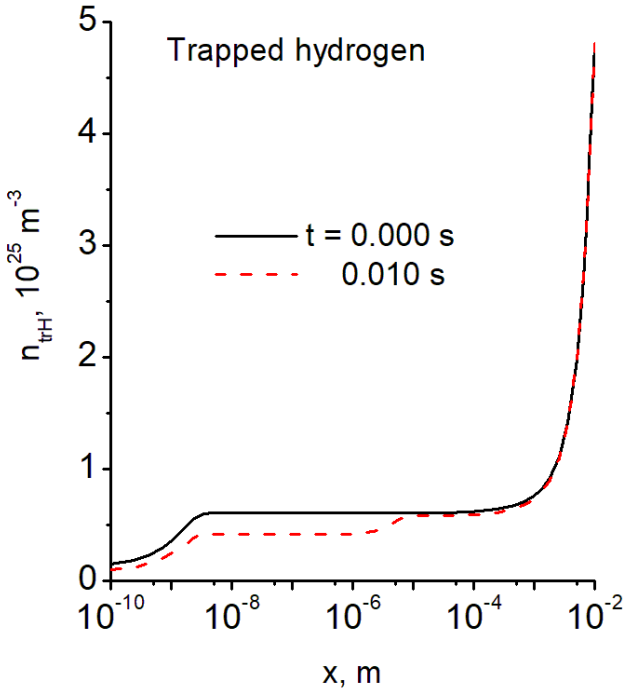
- Steady state depends only on number of particles in plasma N (Recyc, Albd = 1)
- $N<10^{18}$ - attached; $10^{18}<N<1.6\times10^{18}$ – transition; $N>1.6\times10^{18}$ – detached
- Neutral flux monotonically increases, significant neutral heat transport
- Implanted particle flux drops in detached regime

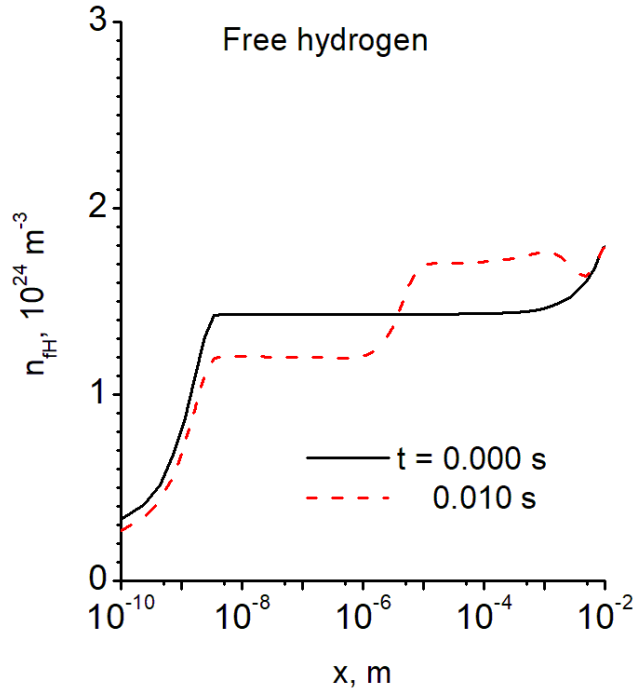
ELM-like pulse (attached, N=1.0x10^{18})



- Plasma mostly recovers after the heat pulse

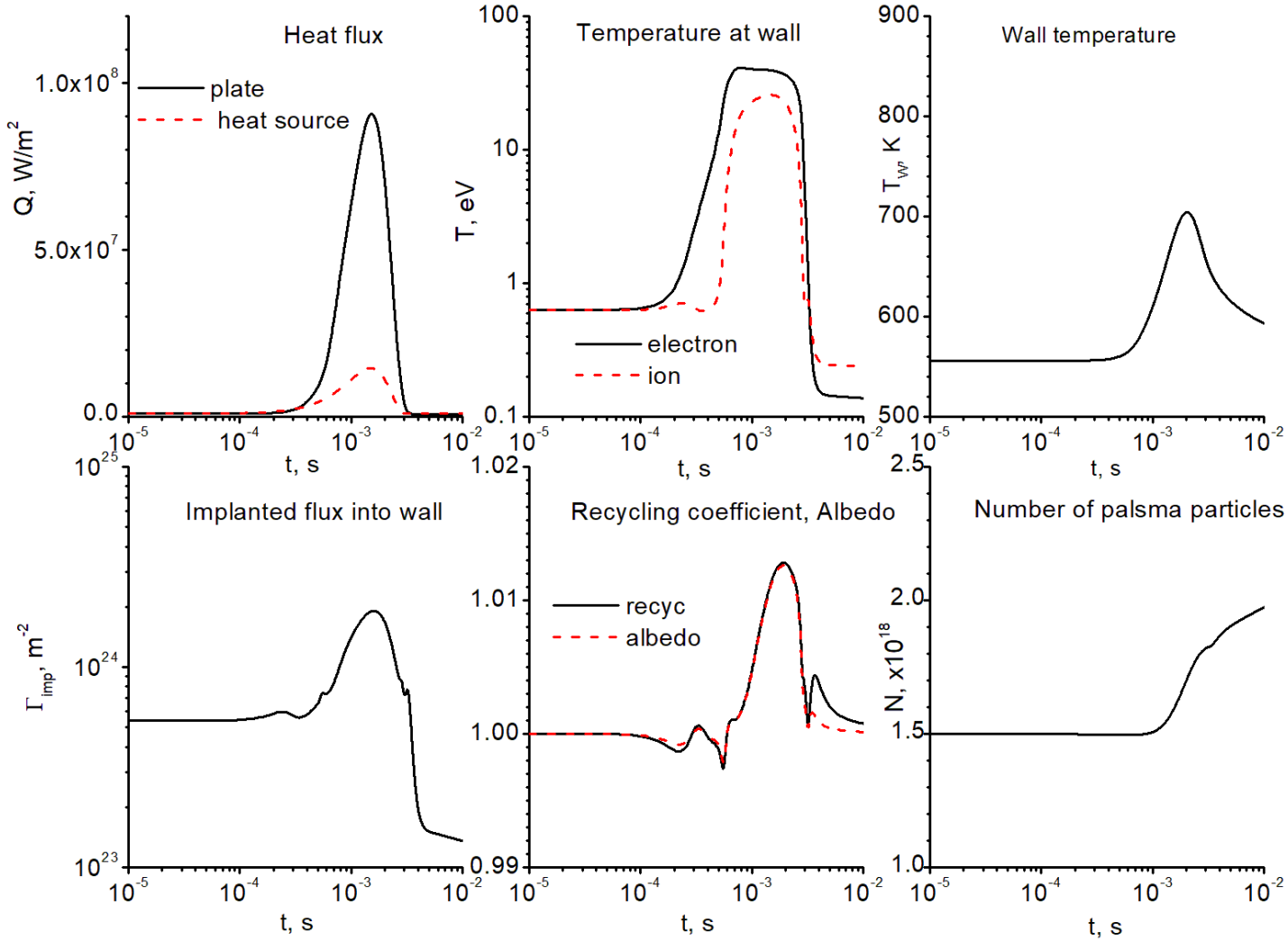
Wall profiles (attached, N=1.0x10^{18})





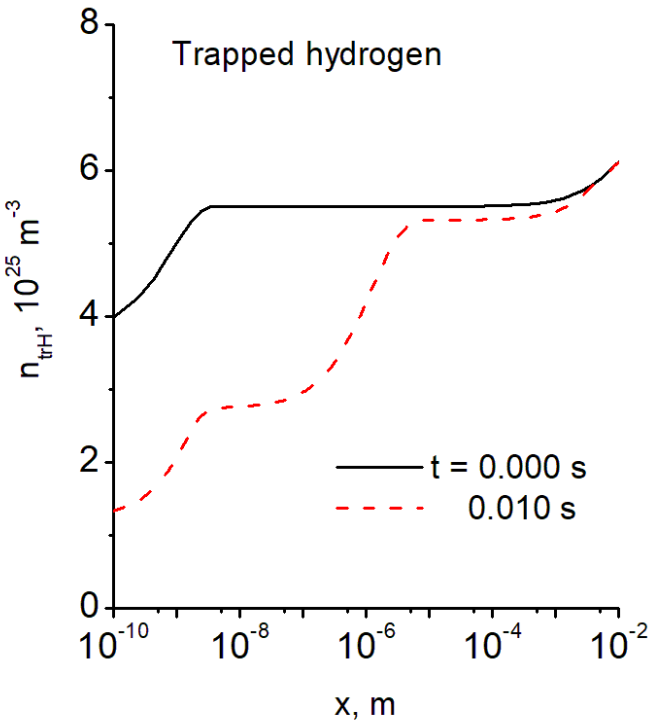
- Hydrogen is released from traps and outgassed down to ~1 micron
- Dissolved hydrogen density increases deep in the bulk

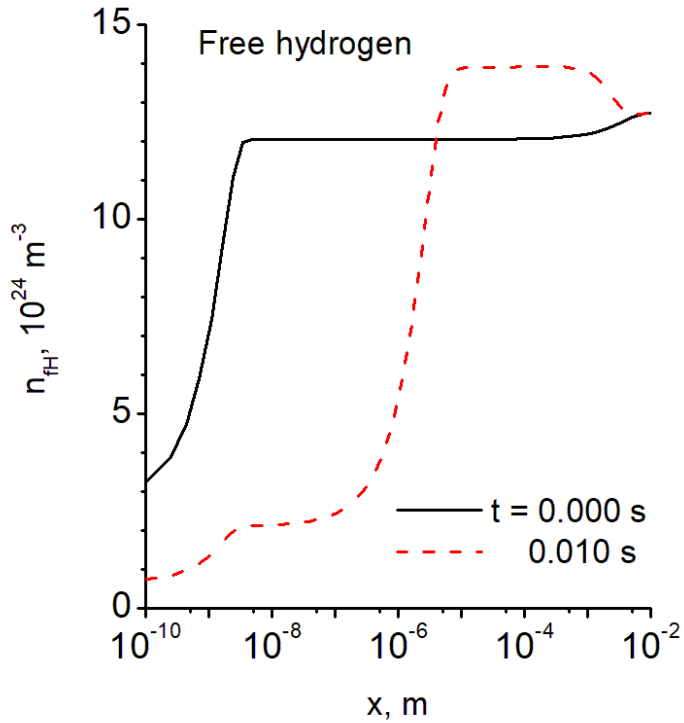
ELM-like pulse (semi-detached, N=1.5x10^{18})



- ELM induces deep plasma detachment in divertor

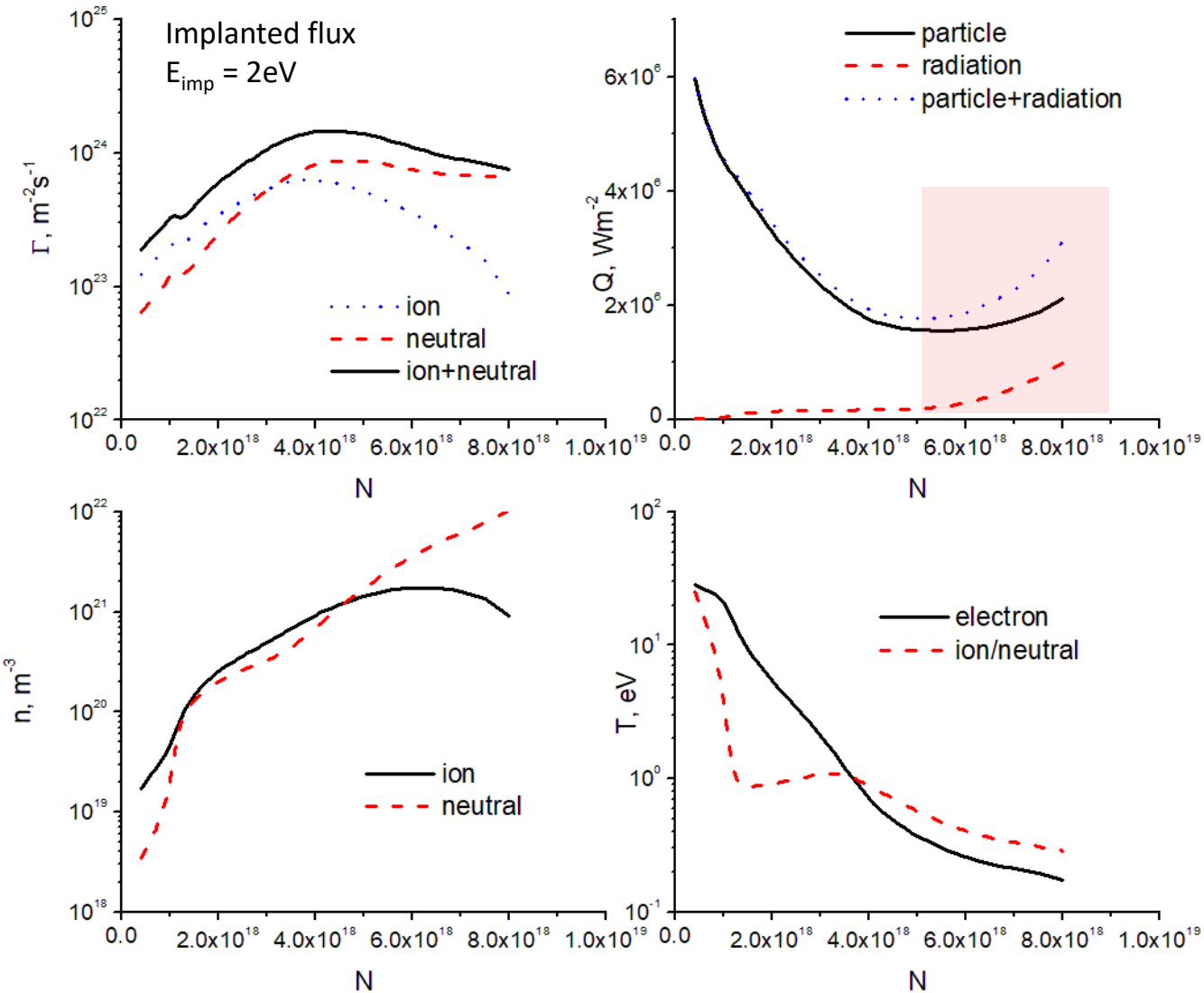
Wall profiles (semi-detached, N=1.5x10^{18})





- Higher initial trapped hydrogen concentration due to lower initial Twall
- Significantly more trapped hydrogen is released during ELM

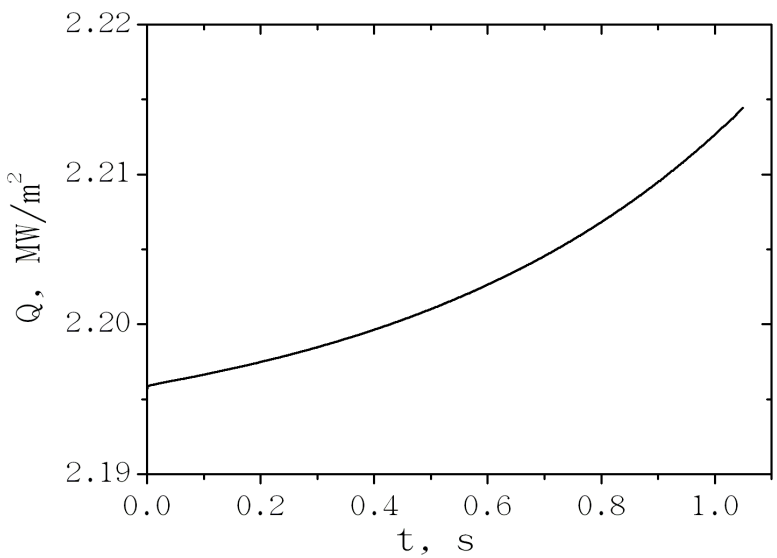
Steady state without impurities



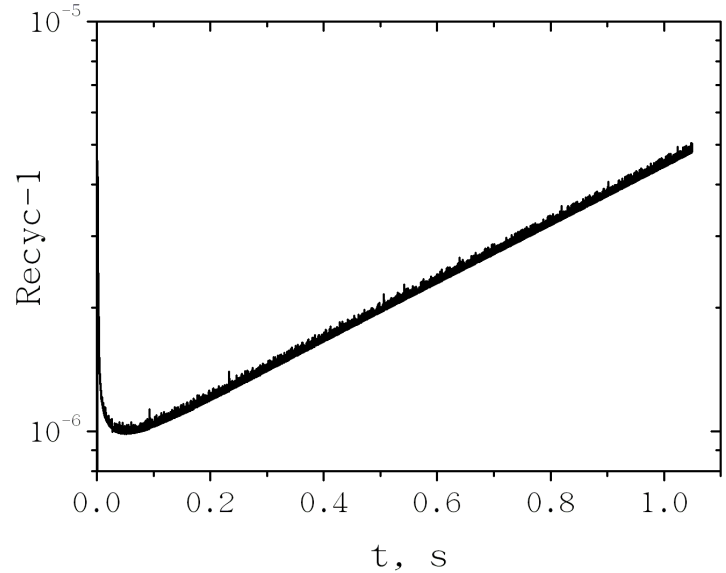
- Heat flux increase in detached regime due to neutral transport and radiation contributions
- This can lead to thermal desorption instability

Thermal desorption instability

Heat flux



Recycling



- Evolution of perturbed plasma-wall steady state is simulated
- Simulations confirm thermal desorption instability
- Instability growth is very slow ~1 s^{-1}

Summary

- UEDGE and FACE codes are coupled in time dependent mode
- Steady state and dynamic plasma-wall simulations are performed
- Simulations show significant role of neutral heat flux in detached divertor
- ELMs can trigger transition to deep detachment by releasing hydrogen from wall
- When impurity radiation losses are small, total heat flux to wall can increase in detachment leading to thermal desorption instability
- Dynamic simulations confirm the instability, growth rate is low ~1 s^{-1}

- Future work
  - Investigate plasma-wall dynamics for series of ELMs
  - Include ELM particle source
  - More realistic 2D coupling
  - Explore plasma-wall instabilities

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