EUROfusion

EU Core-Edge coupling effort

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and EUROfusion contributors

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- Motivation - Why need for integrated modelling?
- JET data analysis example 1:
  Analysis of JET type-I ELM cycles (C → ILW)
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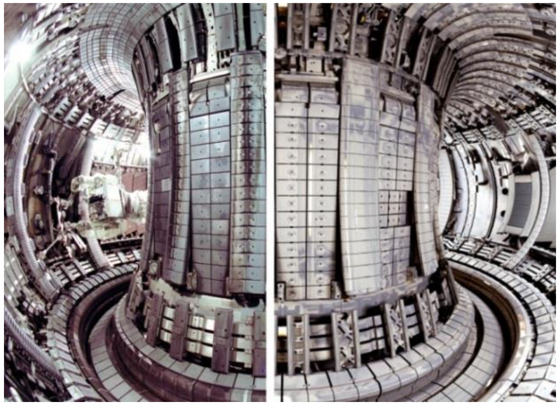
- JINTRAC Application: ITER scenario (detached divertor)
- ETS activity on integrated core-edge modelling (AUG)
- Conclusions

Motiviation: Need for integrated modelling

JET ITER-like wall (ILW) experiments: Be + W/W-coated CFC



Reduction of C: - strongly reduced D particle retention rate
- consequences for power exhaust: seeding

Material-migration: Be transport & deposition to remote areas
W-sputtering → core contamination

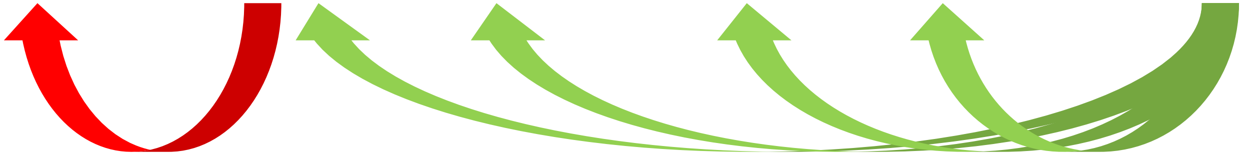
Recycling in JET-ILW vs JET-C:

JET-C: infinite reservoir of D particles stored in the surface layers

JET-ILW: implantation in near-surface → but fast dynamic outgassing of PFCs

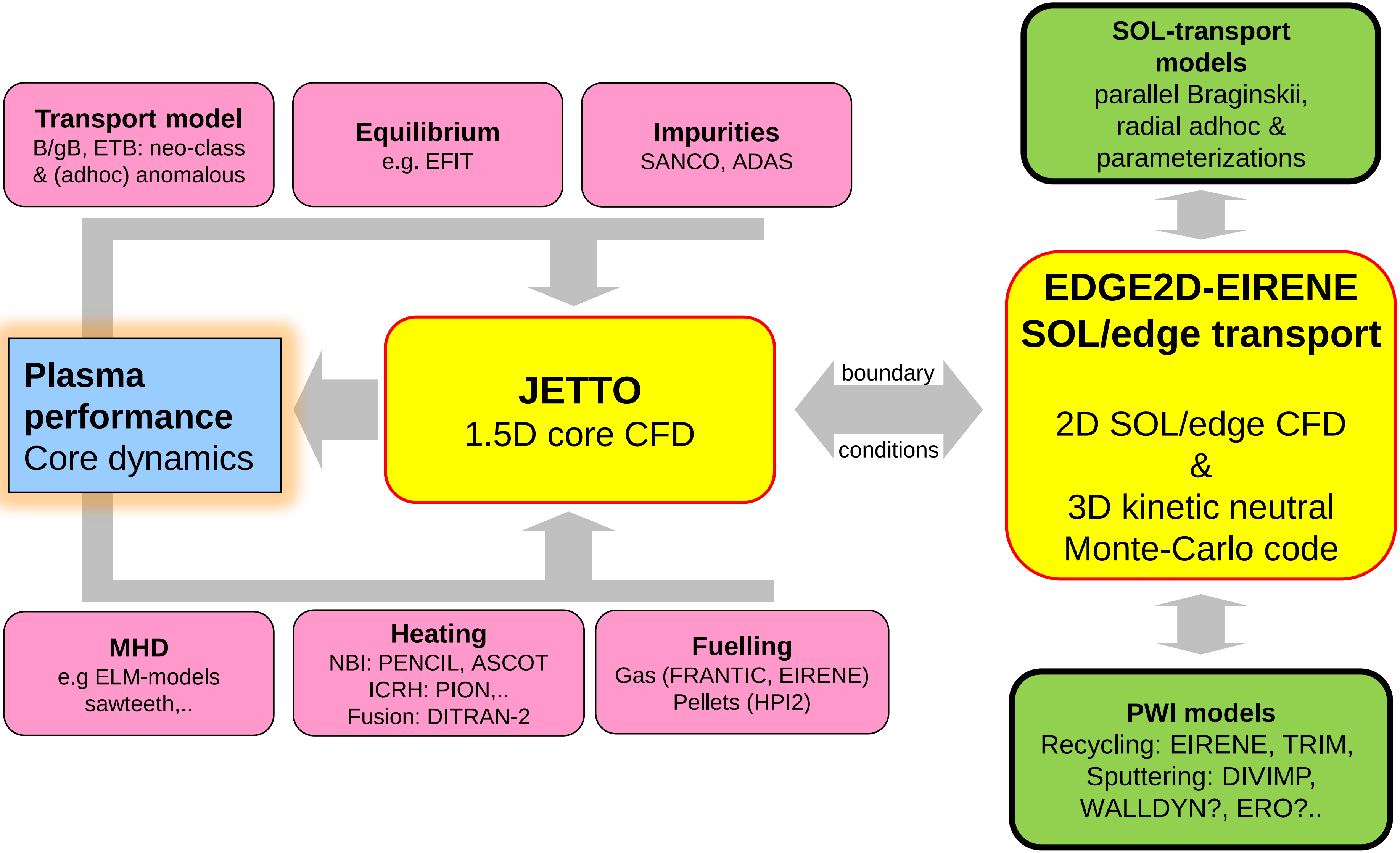
Plasma performance: Complex and stiff problem, e.g. plasma transport time-scales:

τ_{conf}	$\tau_{inter\text{-}ELM}$	τ_{SOL}	$\tau_{neutral}$	τ_{ELM}	τ_{PWI}	$\tau_{ion\text{-}gyro}$	τ_{eddy}
size, current/power, pedestal.conf.	$1/f_{ELM}$	$L_{\|\|}/c_s$	mfp/v	MHD	retention, sputtering, migration	kinetic	turbulence
1s	10-100ms	1ms	0.1-1 ms	0.1ms	0.1-10ms	<1μs	<1μs



averaged

JINTRAC integrated code suite



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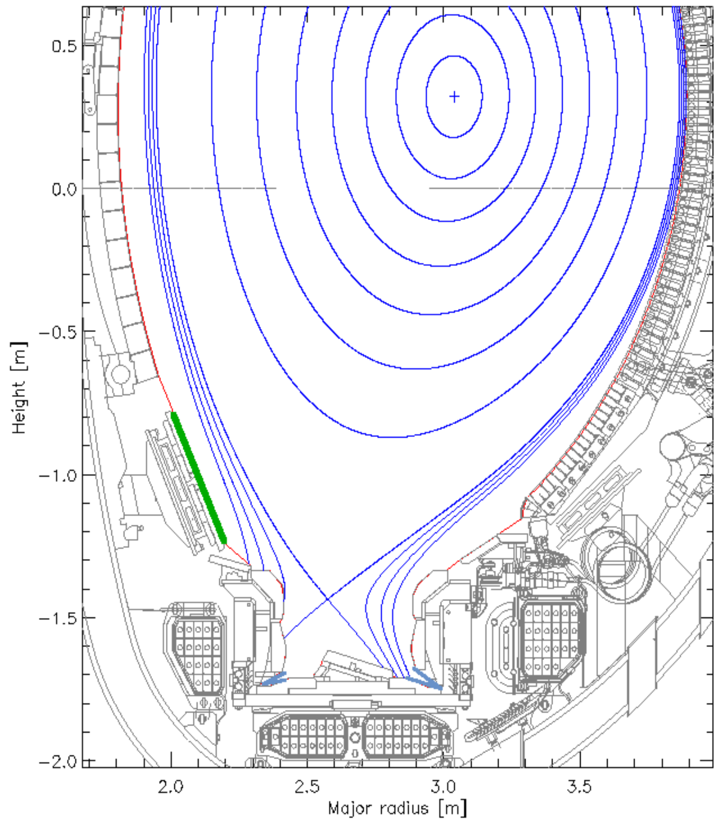
JINTRAC modeling of type-I ELMy H-mode C-reference JPN #73569



All-carbon reference discharge

I_p=2.2MA, B_t=2.0T, δ=0.2, P_{NBI}=13MW
$\nu_e{}^*{}_{ped}$=0.15,
f_{ELM}=15Hz, ΔW_{ELM} = 240kJ

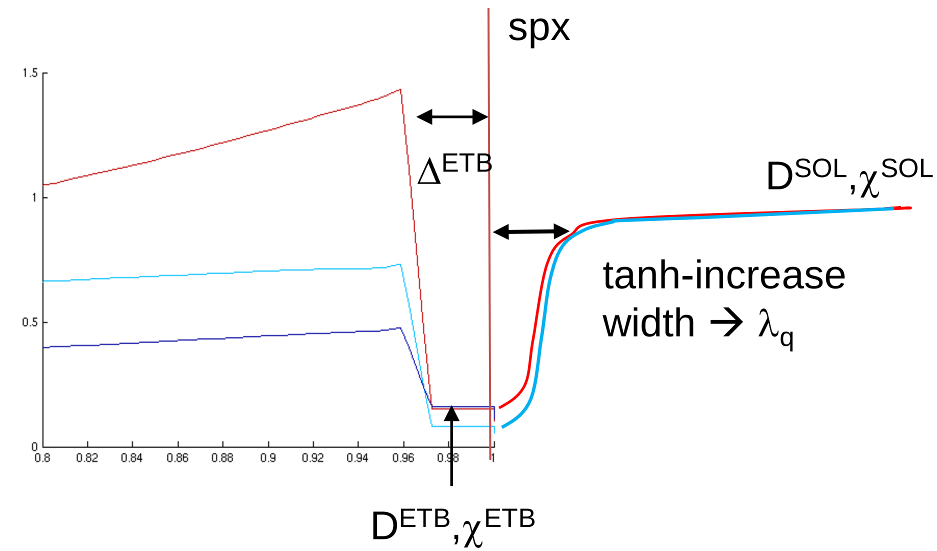
D+C JINTRAC simulation

- C chemical erosion (Roth model)
- C physical sputtering (Eckstein 1993)
- gas-flux scan, ELM-model scan

→ to match evolution of plasma profiles

Inter-ELM transport assumptions:

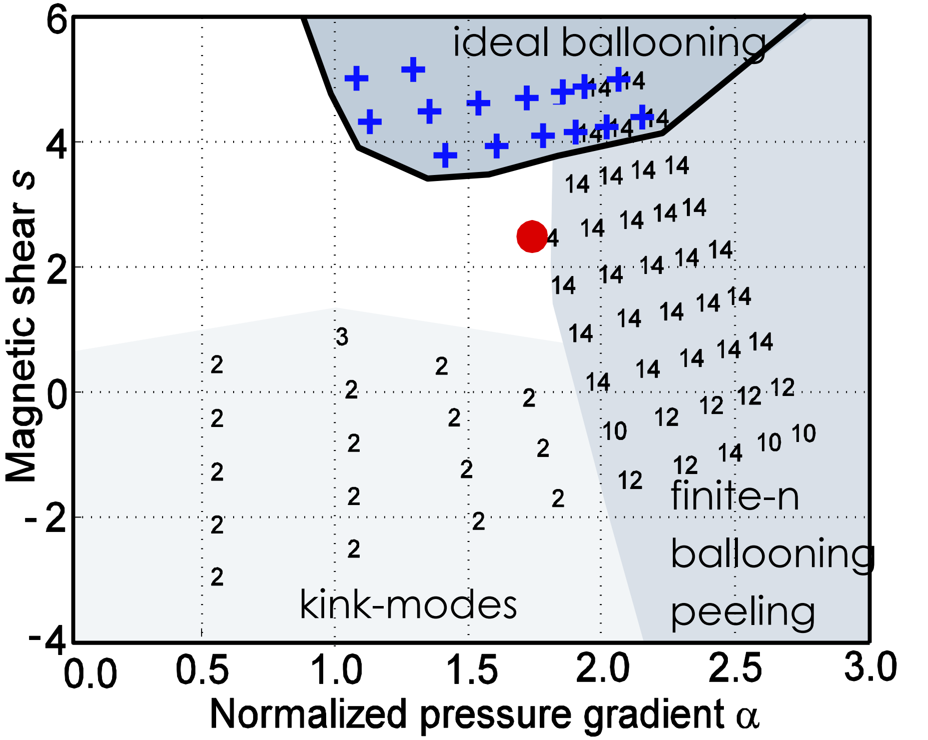
- deep core transport: Bohm/gyro-Bohm
- ETB transport: neo-class values + turbulent remnan
- near spx SOL transport: tanh increase to far-SOL
- far-SOL: Bohm-like values (~ 1m²/s)



JINTRAC Transport model: ELM-trigger

- A linear MHD-stability code (eg MISHKA) provides stability diagram for H-mode pedestals
- operational space constrained by means of magnetic shear s (current) and normalised pressure gradient α
- 1st stable regime: low-α limited by ideal-ballooning modes → type-III ELMs triggered
- 2nd stable regime: medium-s/high-α limited by medium-n ballooning modes → type-I ELMs triggered

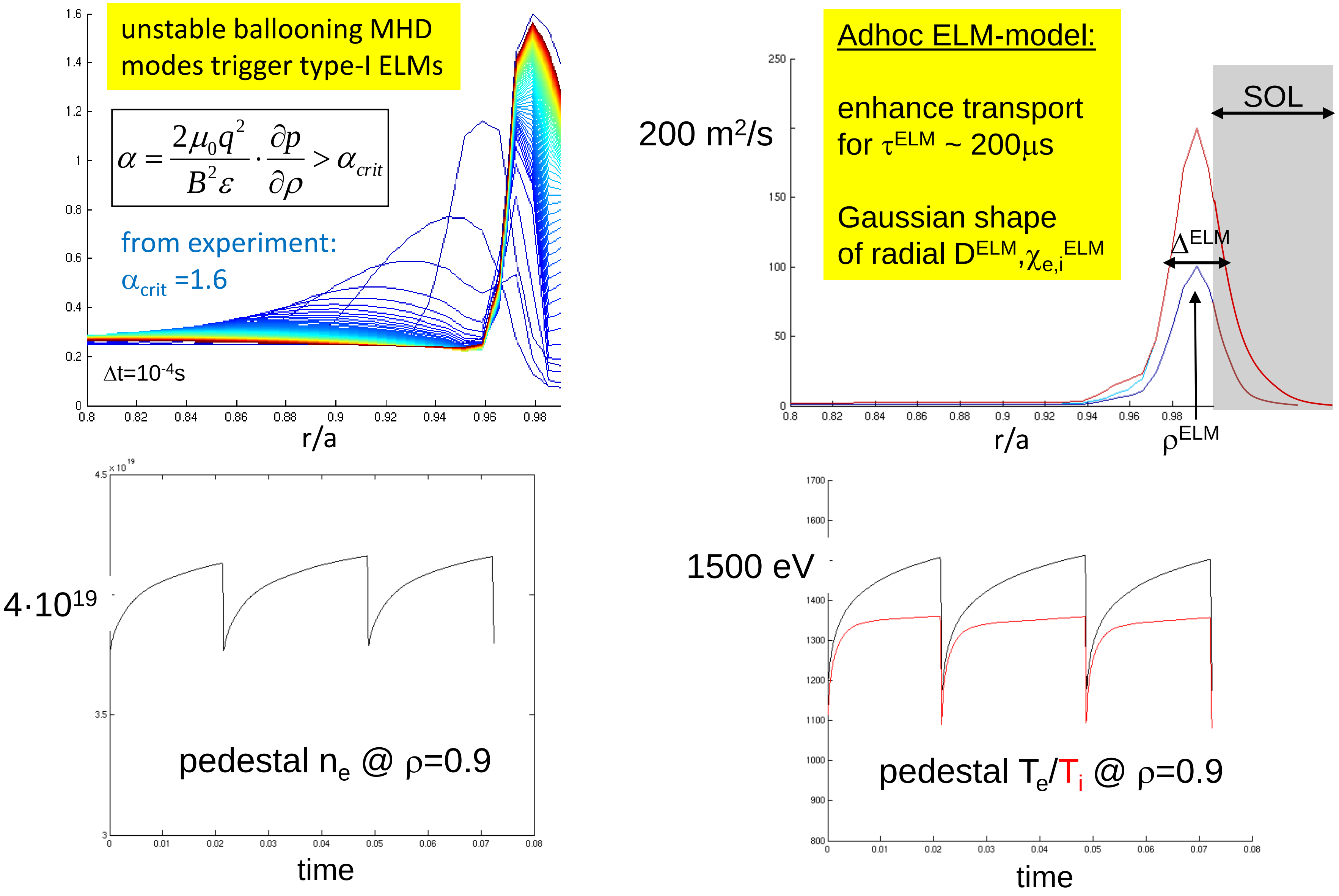
MISHKA, courtesy J.Lönnroth



here: ELM triggered, if a critical normalized pressure gradient is exceeded somewhere in the ETB:

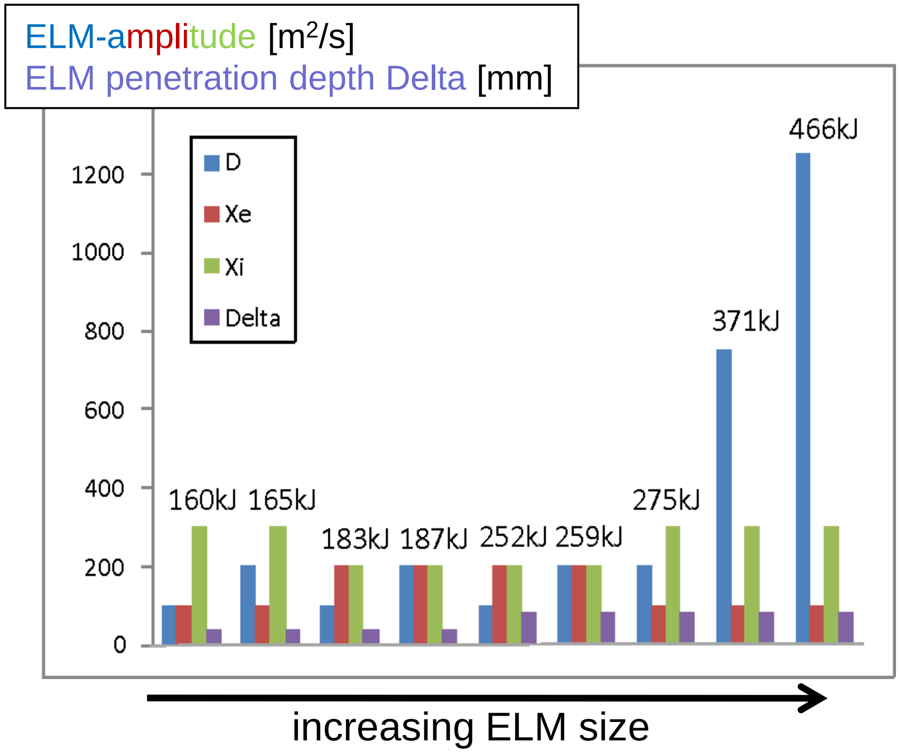
$$\alpha = \frac{2\mu_0 q^2}{B^2 \varepsilon} \cdot \frac{\partial p}{\partial \rho} > \alpha_{crit}$$

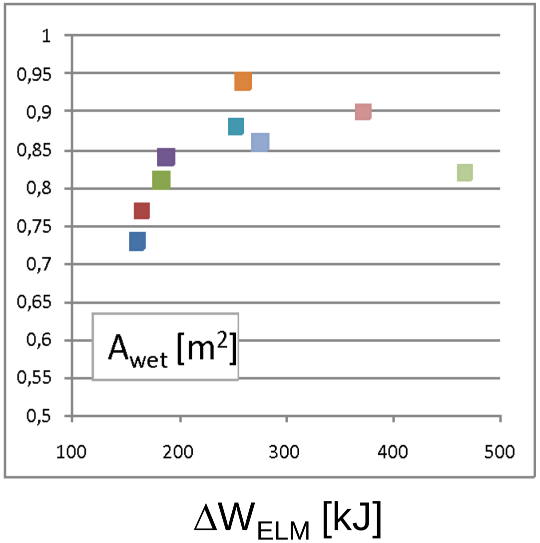
JINTRAC ELM-characteristics

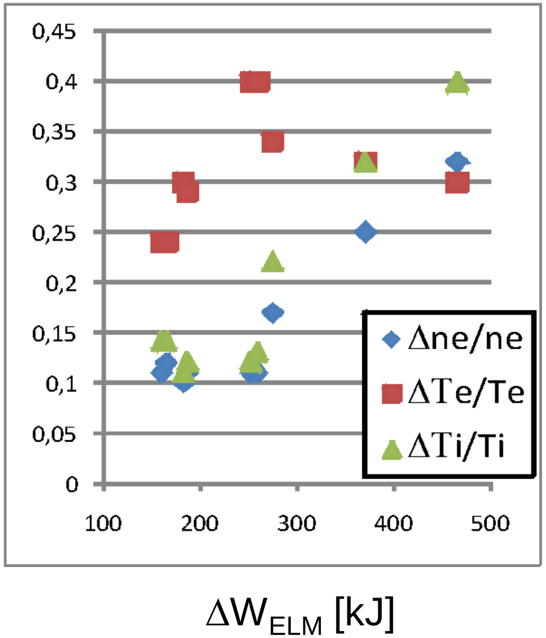


JINTRAC ELM characteristics studies

- ELM characteristics scan to vary ΔW_{ELM}



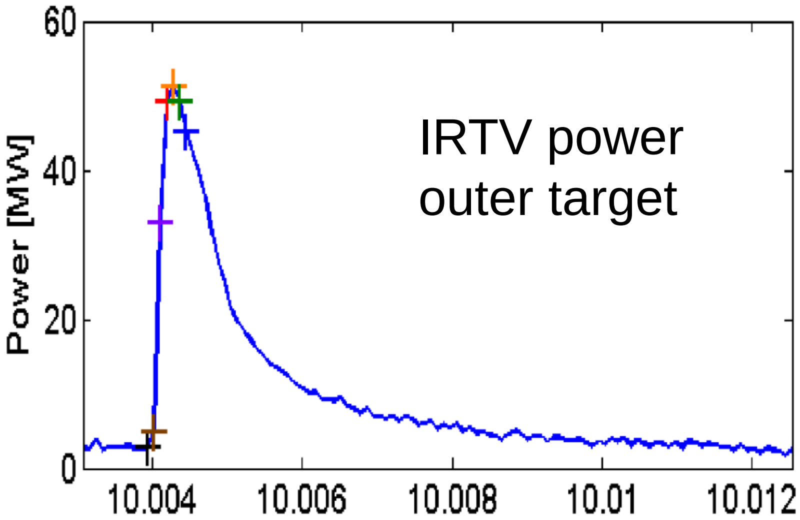


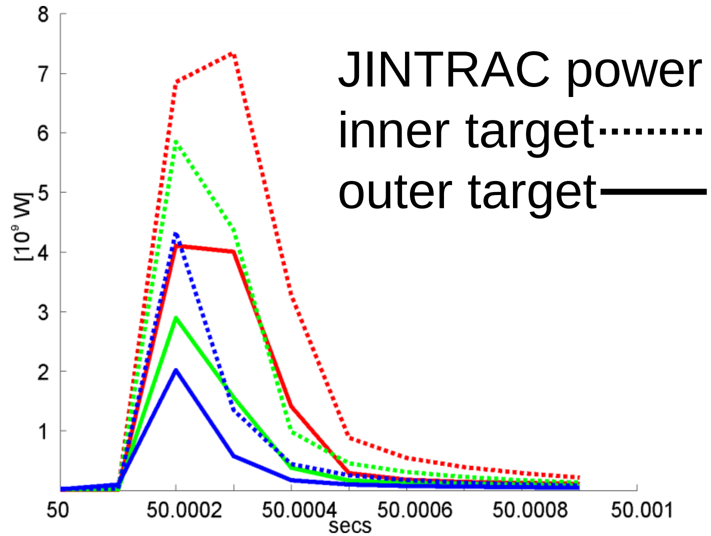


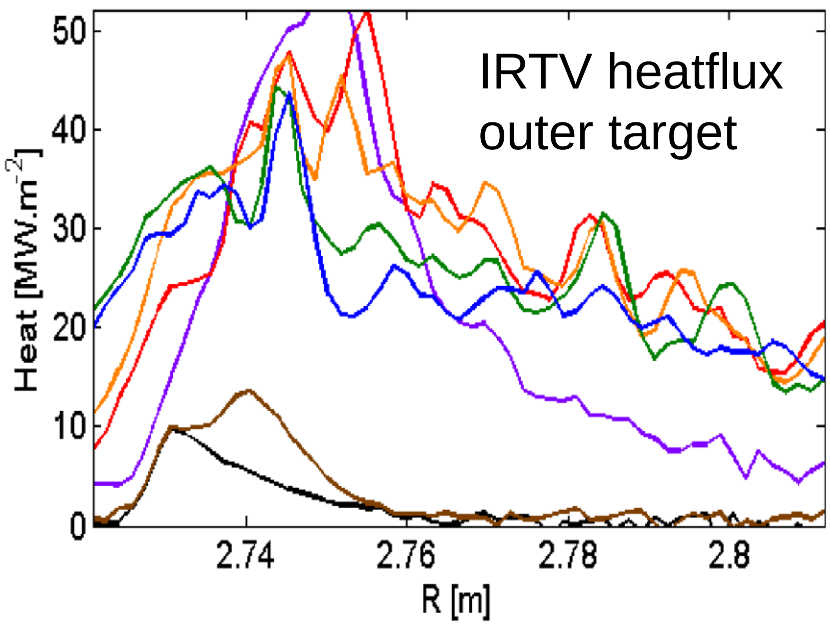
- assume same pre-ELM pedestal conditions for all cases
- with ΔW_{ELM} the ELM wetted area A_{wet} increases
- strong increase of ELM diffusive channel D^{ELM} saturates A_{wet}

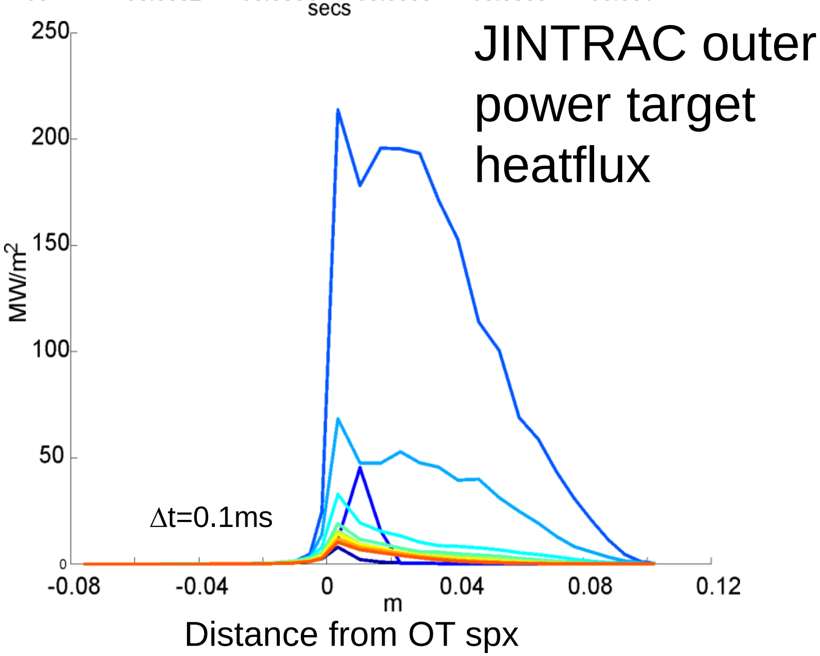
- with strong D^{ELM} the $\Delta n_e/n_e$, $\Delta T_i/T_i$ are increasing linearly
- at the same time: $\Delta T_e/T_e$ saturates as A_{wet}

Outer target heat load JPN 73569









Switching over to Be/W wall (ILW)

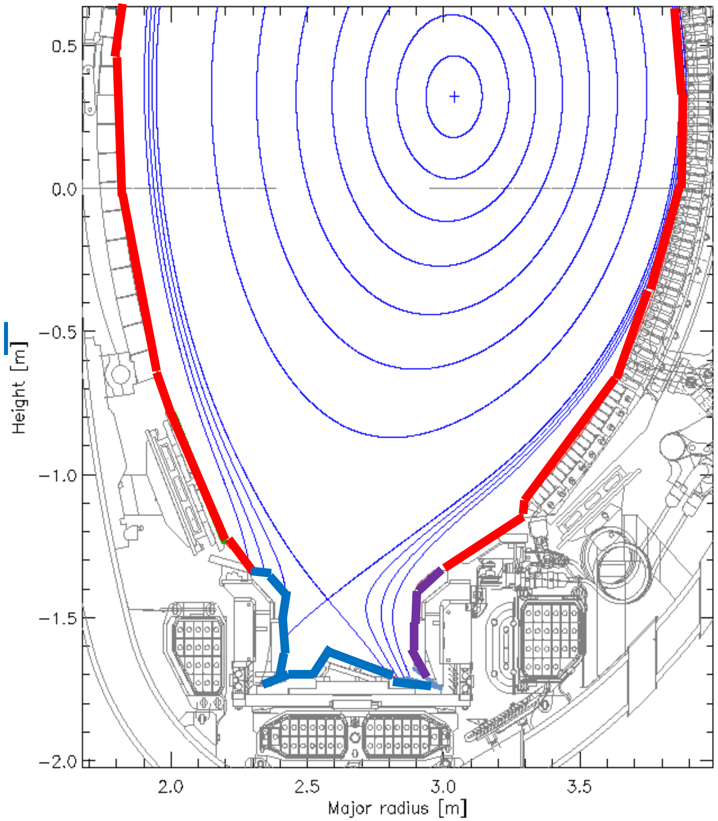
- main-chamber PFCs: beryllium, divertor: W-coated CFC or bulk-W

- other transport parameters as for the C-reference case (250kJ ELMs), i.e.:
  - geometry
  - inter- and intra-ELM transport model
  - SOL transport model
  - MHD critical pedestal pressure gradient
  - NBI power
  - gas-fuelling and pump-efficiency

- ILW: C-main radiator missing

Be has only low radiation potential, W radiates even less

→ add seeding (eg. Ne, N) to offset overall radiation level



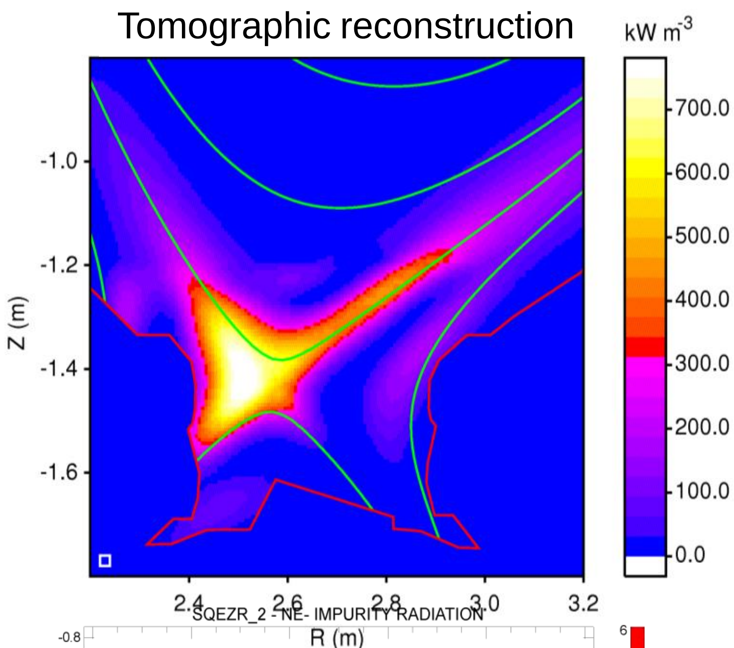
Impurity evolution in SOL and divertor → c_W

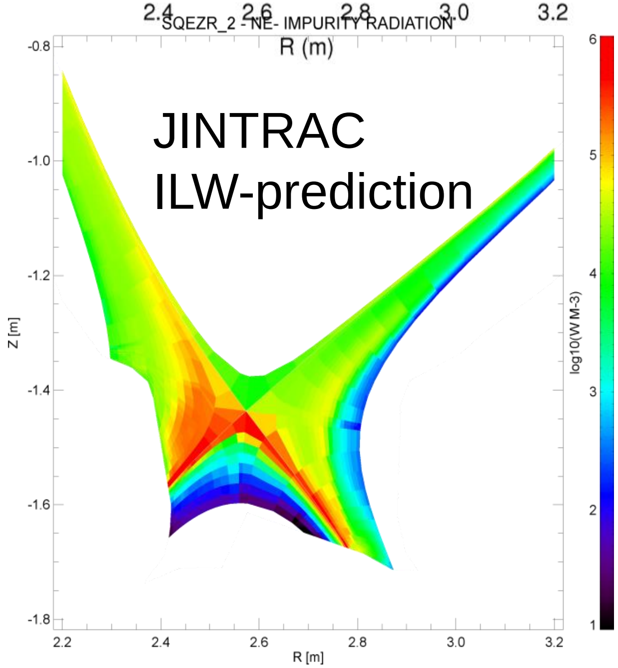
• W transport was (so far) neglected in JINTRAC analysis (OK: as W has only a minor role for SOL energy balance)

• from DIVIMP: W leakage fraction into core:
$f_{leak}=\Gamma_W^{core}/\Gamma_w^{gross\text{-}erosion} \sim 5\%$
(including prompt re-deposition: ~ 90%)

• f_{ELM} = 15Hz →
R.Dux et al., NF **51** 2011: $\tau_W=4\cdot10^2\cdot f_{ELM}^{-1.1}\,\tau_{SOL}^{1.1}\,D_{SOL}^{0.1}$
→ $\tau_W \sim 0.1$s

→ low average W concentration in core → $P_{rad,W} < 100$ kW





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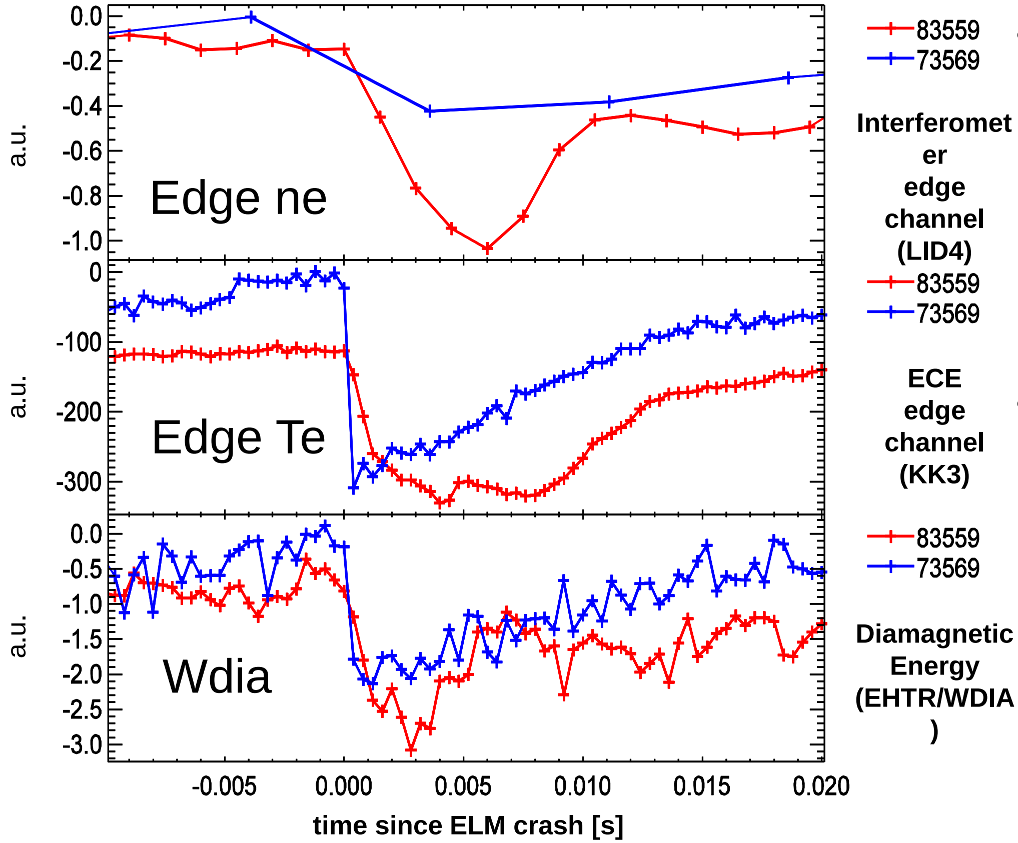
ELMs in JET-C vs. JET-ILW



- ELM cycle for JET-C (#73569):

  fast ELM crash time (<400 μs, below the time resolution of ECE and W_{DIA})

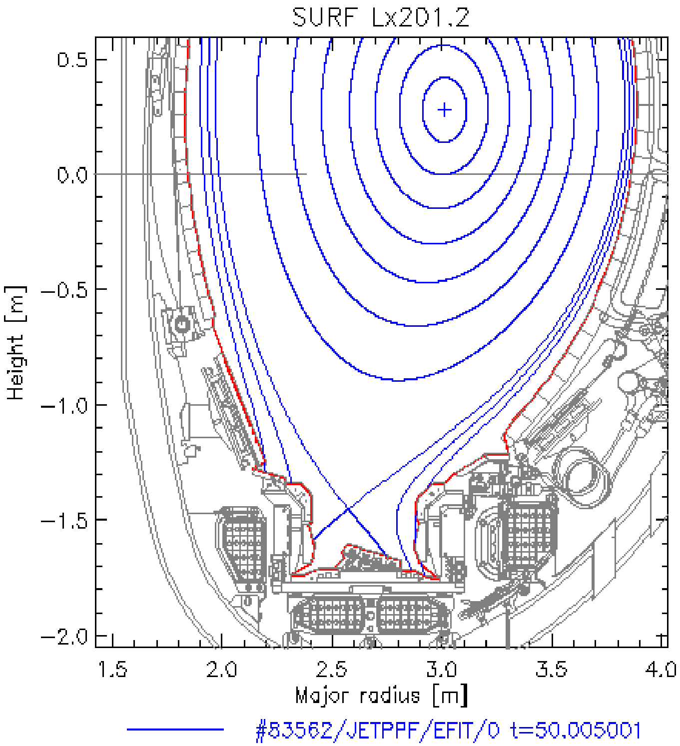
- JET-ILW (e.g. #83559, C30C):

  slower drop of the edge electron density and temperature after the ELM crash (order of ~few ms)

We need to answer the question: What is different in JET-ILW?

Core/Pedestal transport? MHD? SOL-transport? Recycling?....

JINTRAC modelling of type-I ELMy H-mode



Unseeded JET-ILW C30C discharge

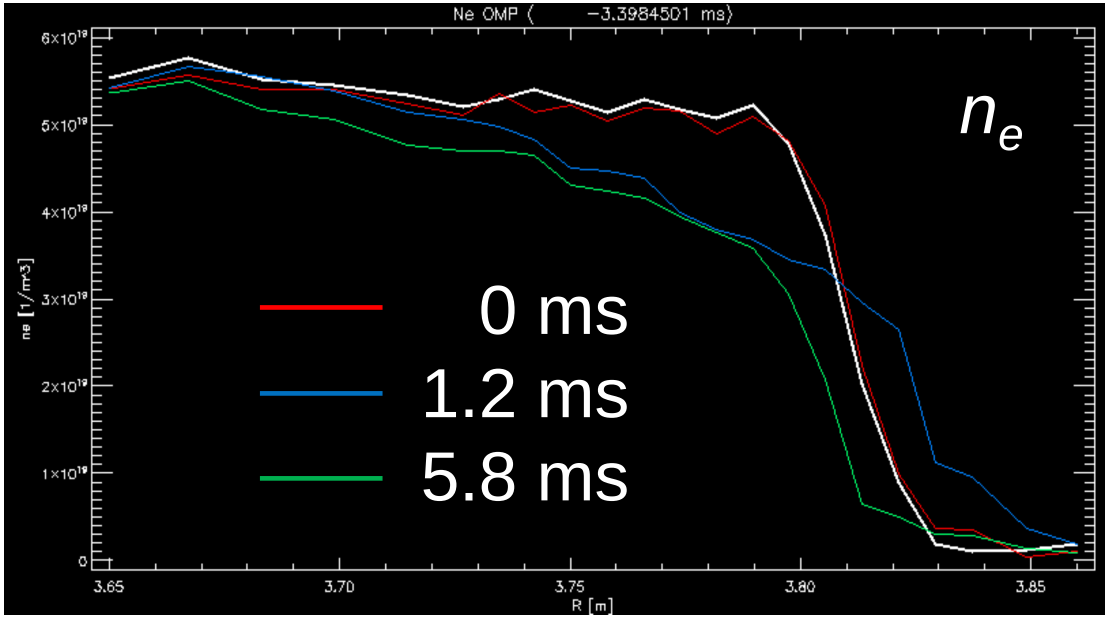
I_p/B_t=2.0MA/2.0T, low-δ, P_{NBI}=12MW

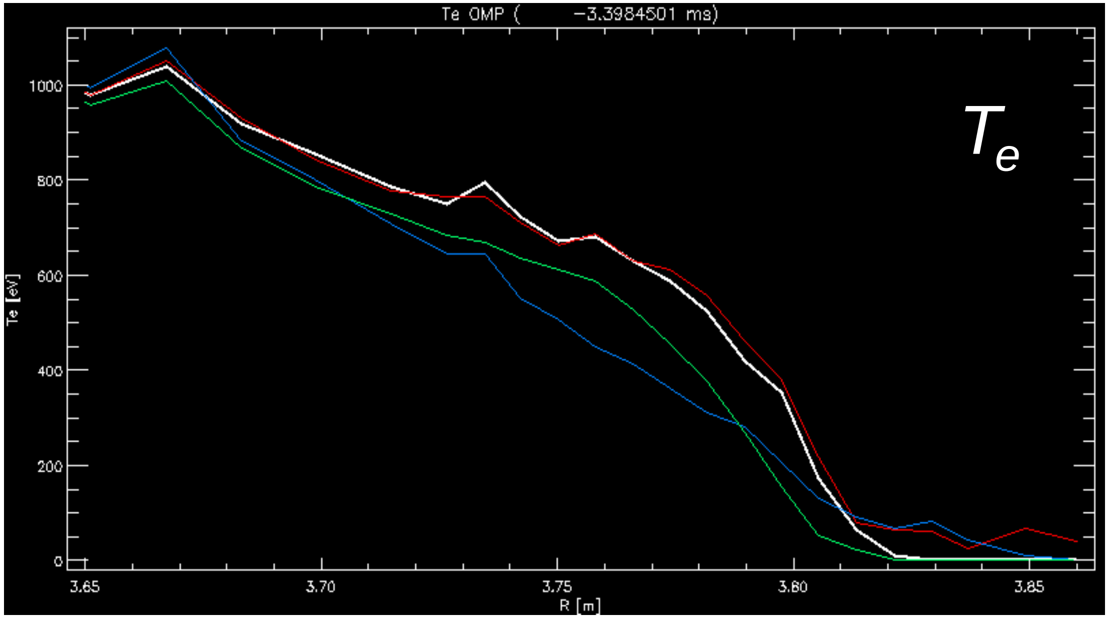
f_{ELM}=30Hz, ΔW=160KJ, 6sec flat-top

S. Brezinsek et al, NF 2013

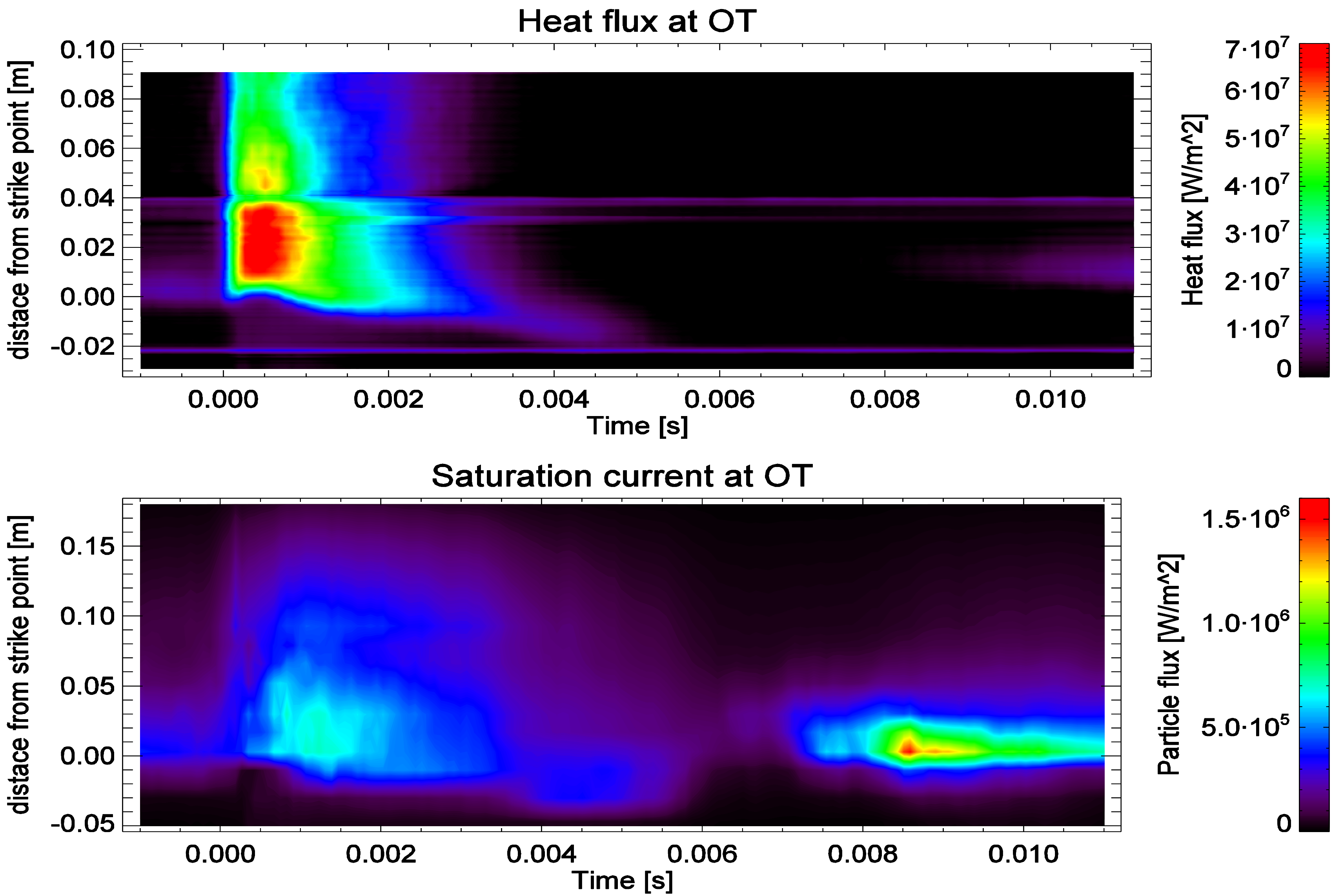
D.Harting, PSI 2014

(Statistical analysis for HRTS of 53 similar discharges)





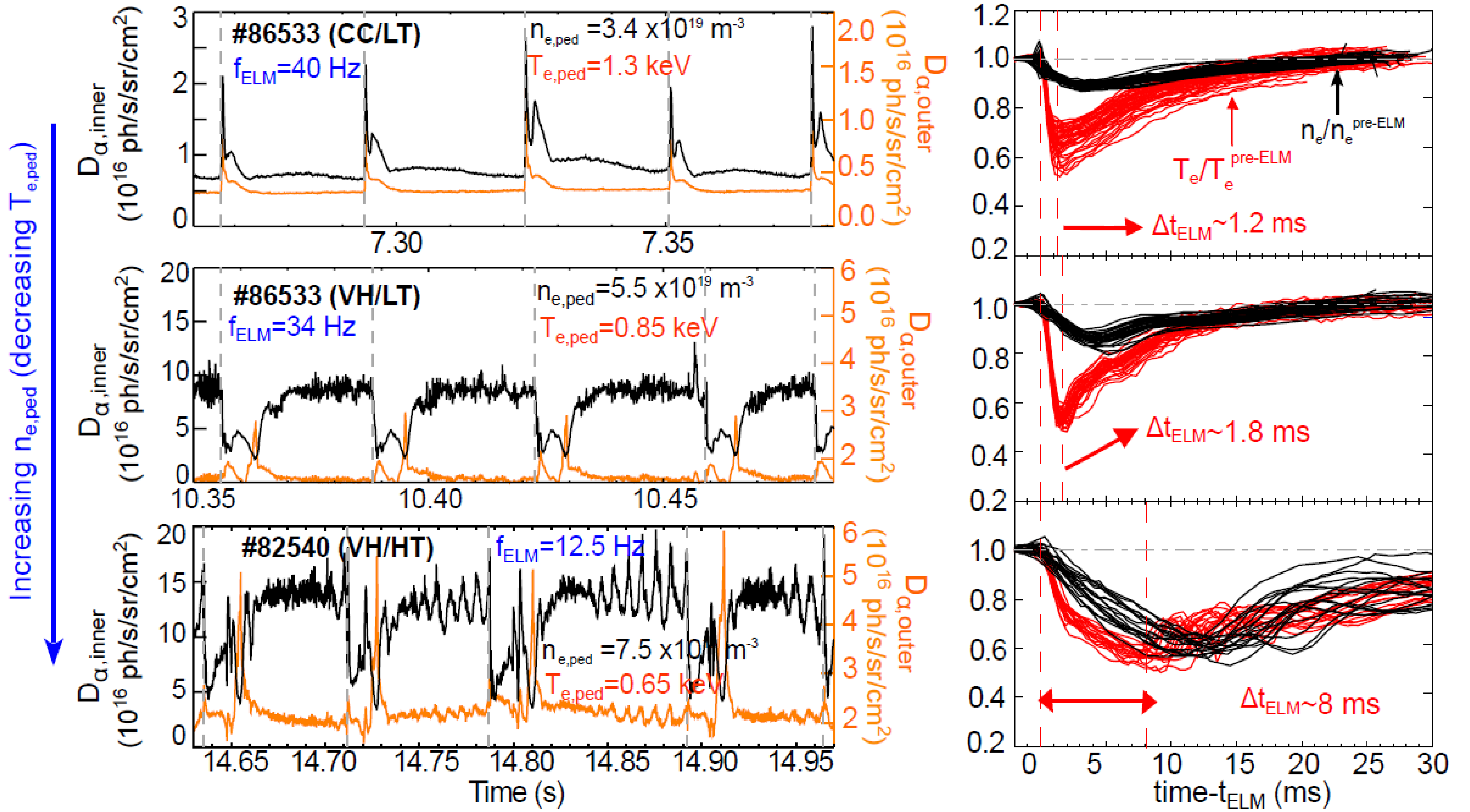
Outer Target Heat and Particle Flux JPN 83562



D.Harting PSI2014

JET-ILW: configuration scan → recycling scan

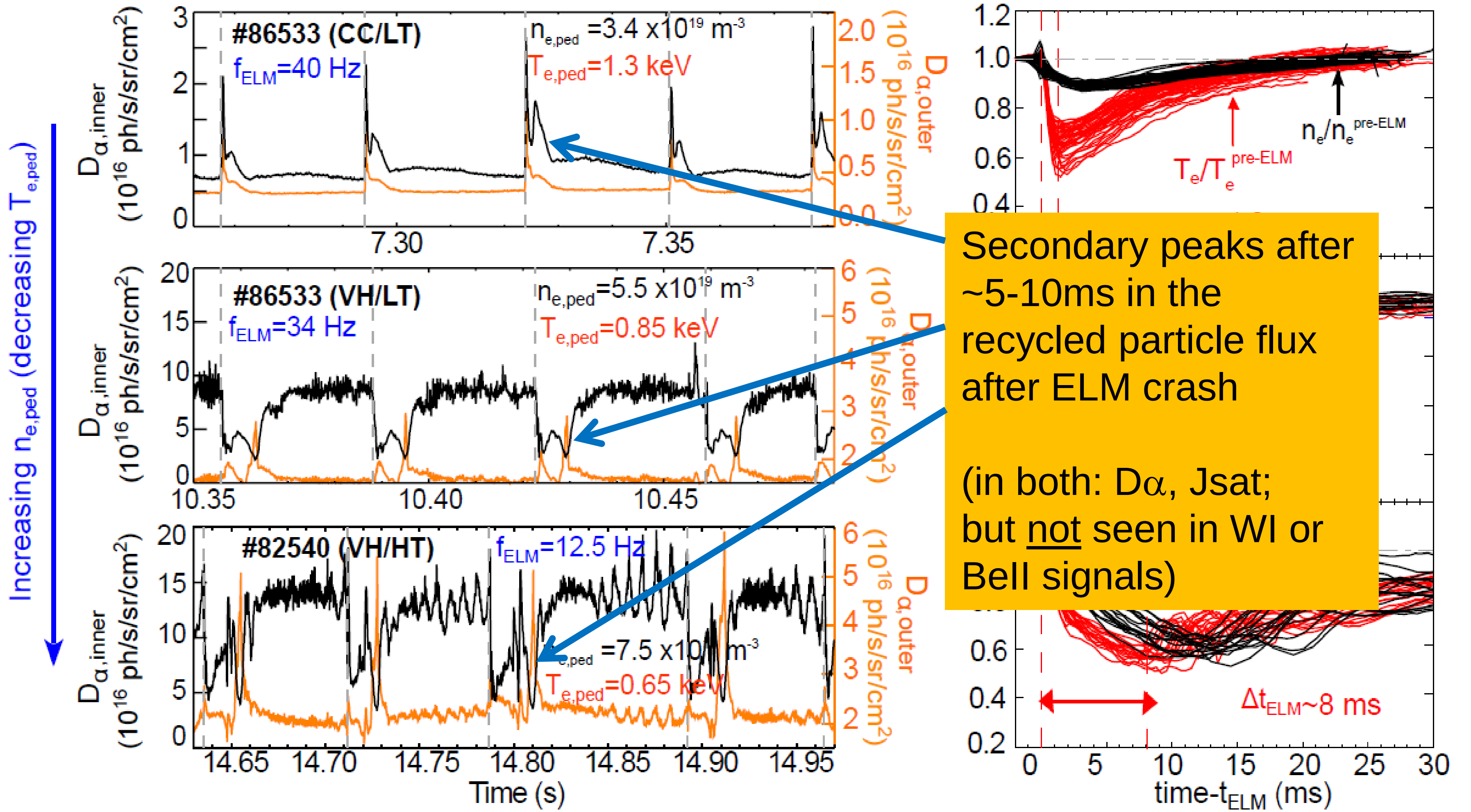
E. de la Luna IAEA2014



→ Depending on the level of recycling:
delay of pedestal build-up after ELM-crash

JET-ILW: configuration scan → recycling scan

E. de la Luna IAEA2014



Secondary peaks after ~5-10ms in the recycled particle flux after ELM crash

(in both: Dα, Jsat; but not seen in WI or Bell signals)

→ Depending on the level of recycling: delay of pedestal build-up after ELM-crash

Hypothesis: Impact on ELM cycle by change of W-PFCs recycling

1. Each ELM footprint acts as a mini-desorption and depletes partially the D reservoir
2. The W PFCs act for a couple of milliseconds as large deuterium pump

Pedestal established → ELM: Pedestal crash → Energetic particles and heat stream to target

<< 1ms

deep penetration of particles → oversaturation; recycling delayed

W target plate is heated up

Surface D reservoir depleted

D is desorbed (partially)

D Refuelling from upstream & out-diffusing from deeper layers

~ 1-10ms

Recovery of density pedestal prolonged

- Fast D-desorption (<< 1ms) in the order of 10^{20} particles after ELM impact (near surface)
- Local sources (gas injection/re-absorption of neutrals) cannot provide in a few ms the necessary amount of D to refill

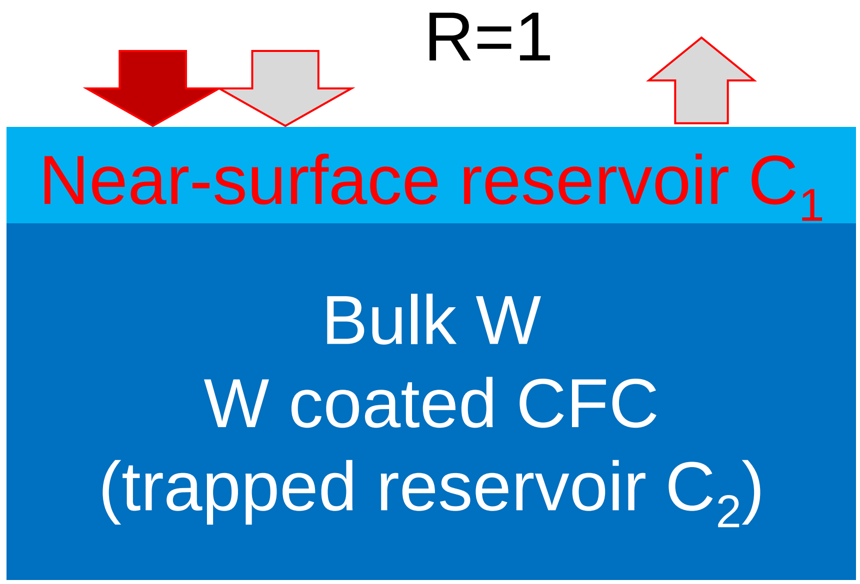
- Effective „Refill-time“ determined by the amount of outgassed D (finite) and the flux to target (~ 10^{23} D/m^2s, depends on plasma)

  → varies between ~ 1-10ms (in C: no sign.delay)

cf. Brezinsek, Wiesen et al PSI2014

Modified Recycling model (1/4)

Inter-ELM
(i.e. pre-ELM)

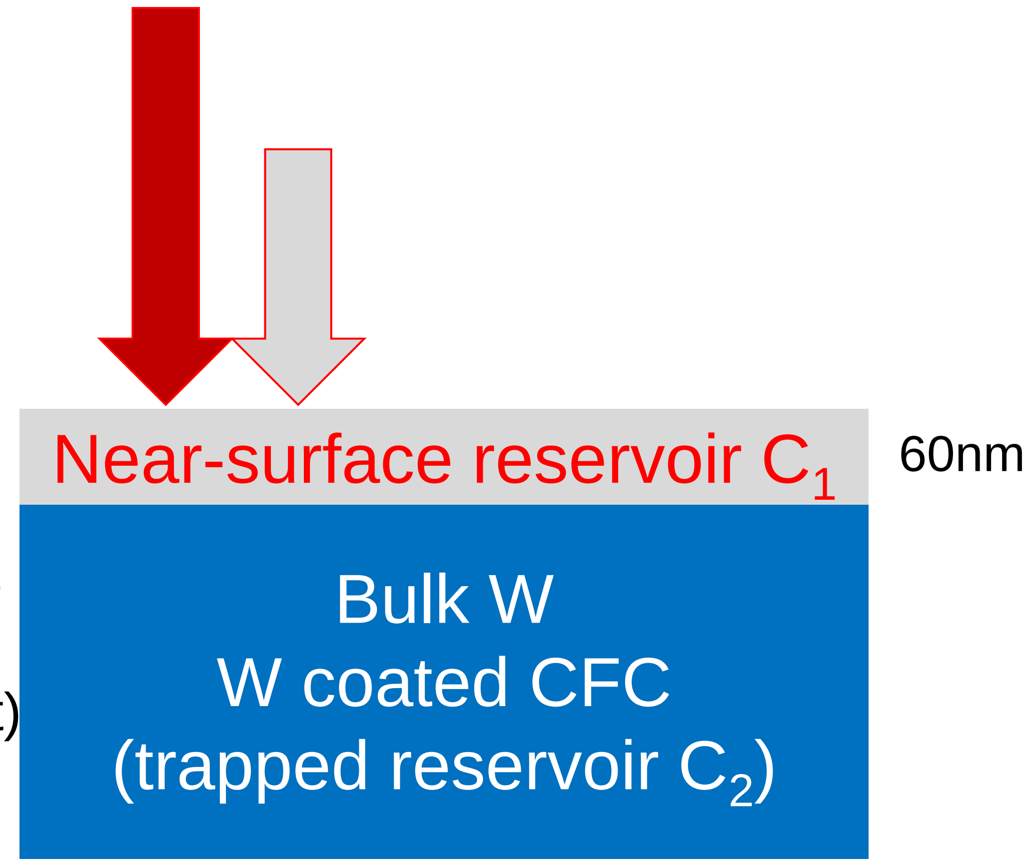


Wiesen 2014

Modified Recycling model (2/4)

ELM-crash

A large heat-pulse depletes partially near-surface particle reservoirs (across ELM footprint)



C_1 reservoir depletion estimate: ~10^{20} (assuming $A_{ELM\text{-}wet}$ ~ $1m^2$)
(JET: 10^{20} ~ particle content in pedestal region)

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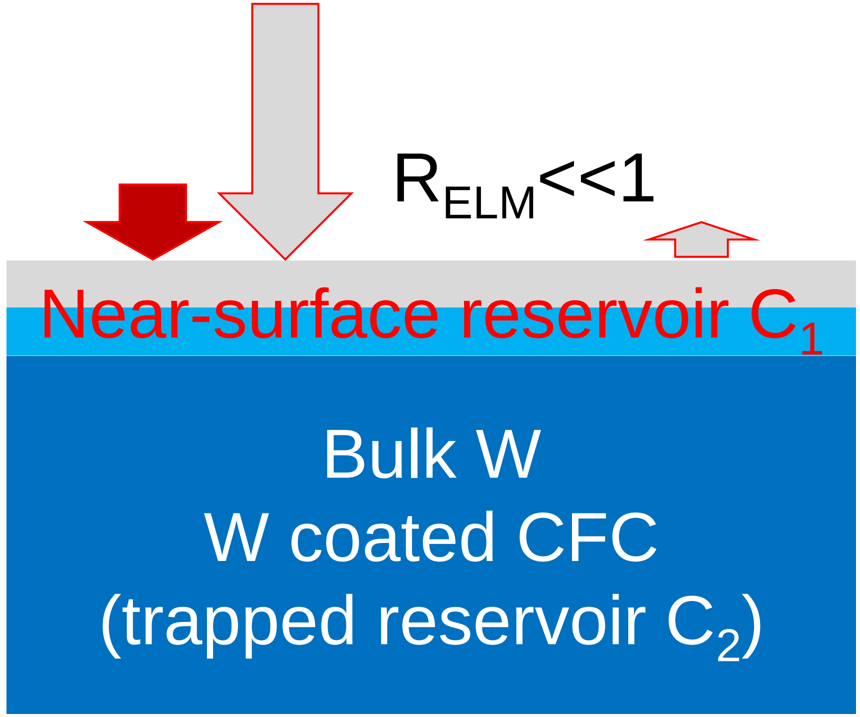
Modified Recycling model (3/4)

Shortly after ELM <1ms:



Recycling strongly reduced:

refilling C_1 reservoir

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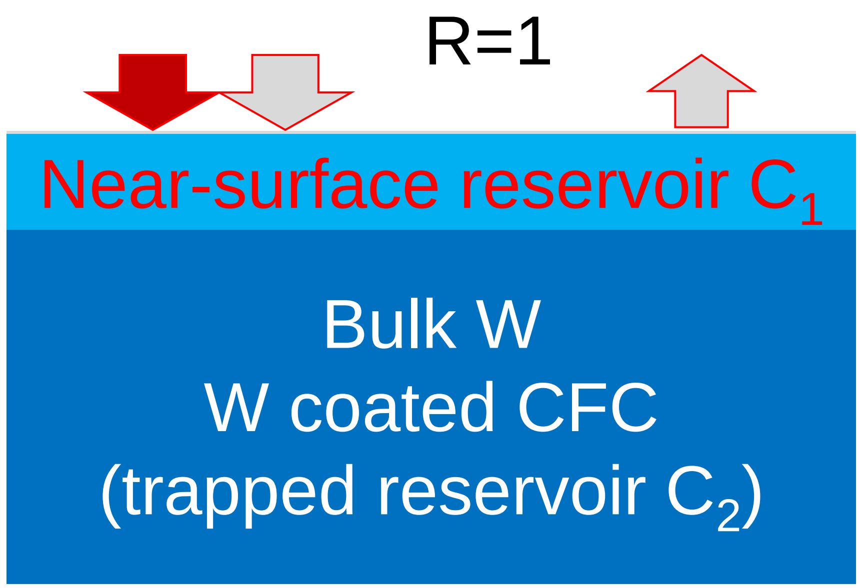
Modified Recycling model (4/4)

Few ms after ELM crash:

C_1 replenished: remaining ELM driven particle flux recycled



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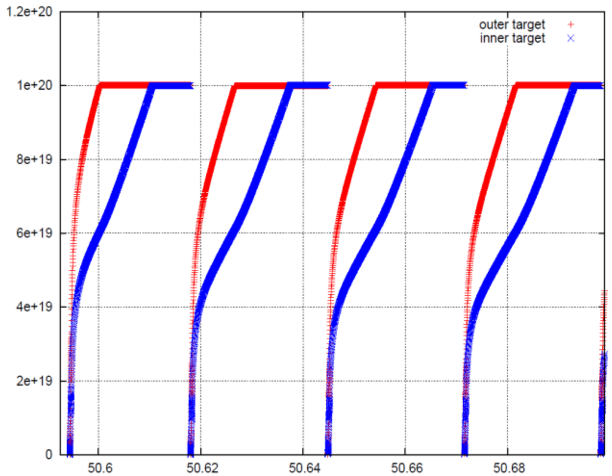
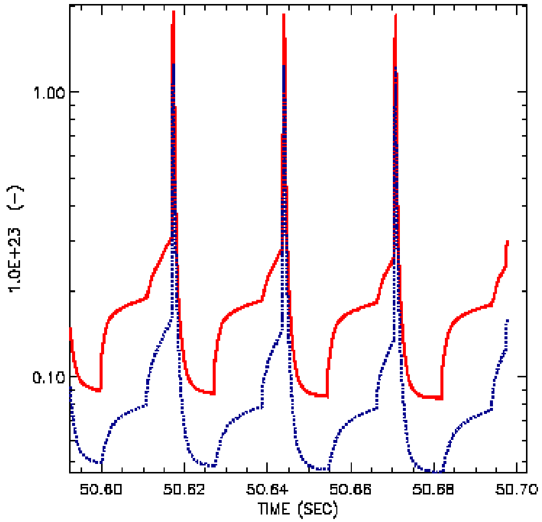
Result: Impact on pedestal refuelling

Near surface reservoirs

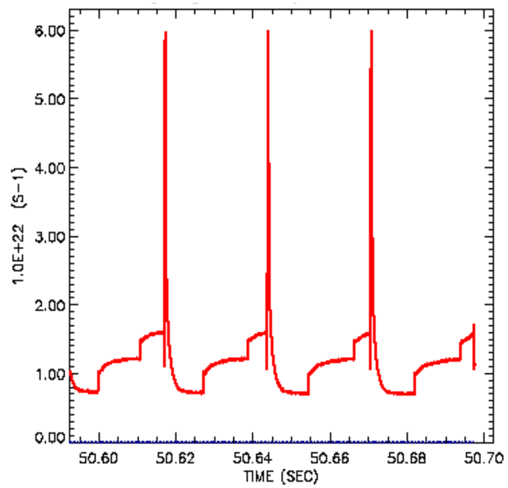


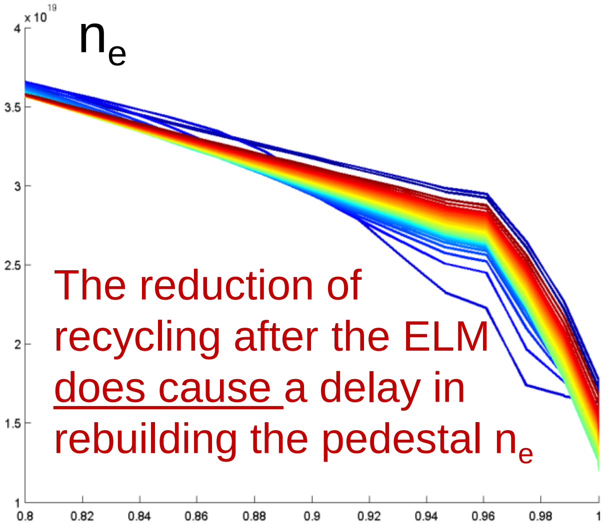
Outer target
Inner target

Ion flux to targets



Neutral flux across spx





27ms
20ms
10ms
0.4ms

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Towards model improvements

- Replenishing of the surface layer reservoirs: assuming a reduced target recycling coefficient R_{ELM}, which is arbitrary at the moment (yet R_{ELM} is a *big knob*)

  It was shown (K.Schmid; et al) that the recycling coefficient after the ELM shows a strong T-dependence

  → a combined model for heat-conduction in the PFC and thermal desorption of particles is needed → R (near surface reservoir C_1)

R_{ELM}	Reservoir	f_{ELM}
1.0	-	60Hz
0.5	1e20	36Hz
0.3	1e20	50Hz
0.3	2e20	25Hz
0.2	2e20	20Hz

- The delayed secondary peak in Dα/Jsat not reproduced yet:

  \- In the simple model we did not credit for the ELM induced energetic particles (Ekin ~ Tped ~ 1000eV) which penetrate much deeper into the W-PFC, leading to multi-trapped particles→ oversaturated solute → delayed out-diffusion

  → a secondary deep layer reservoir C_2 available (with delayed diffusive outgassing)

→ Ongoing collaboration, 1D diffusive model K. Schmid (AUG) D. Matveev (FZJ)

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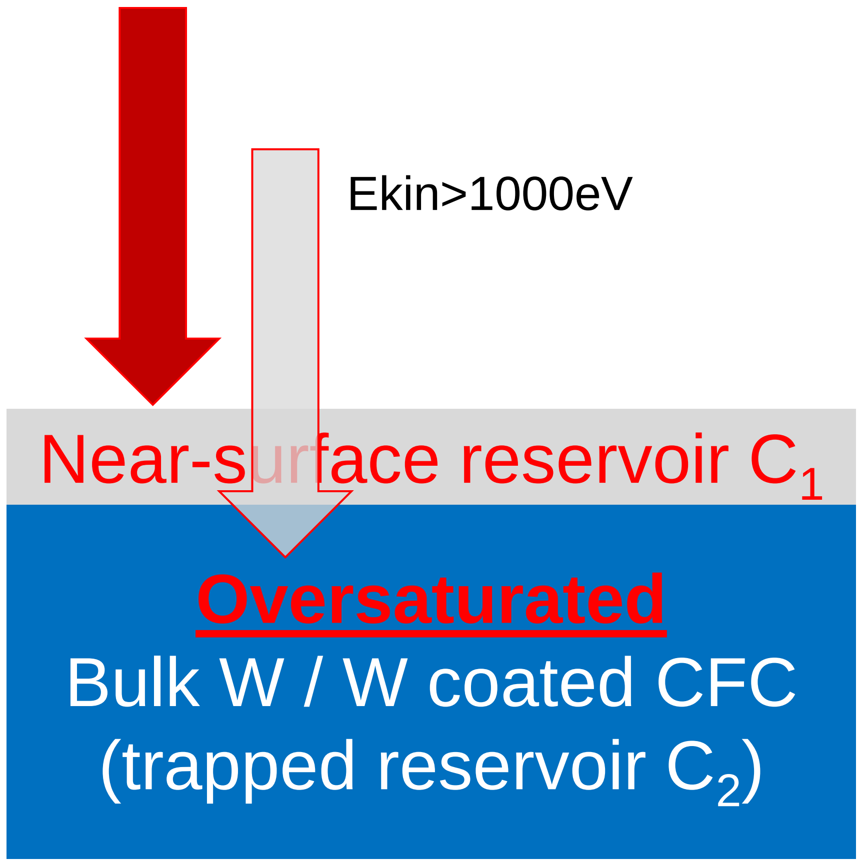
Furtherly revised recycling model: deep penetration of hot particles

ELM-crash



60nm

Kato et al. 2014:
multi-traps in deep layers possible
(6 or more D in W)
also: neutron dmg!

Fast particle penetration depth:
order ~ 100nm
(SD Trim/SRIM)

after-ELM C_1 reservoir balance: plasma flux <u>and</u> D out-diffusion of deep layers

Wiesen 2014

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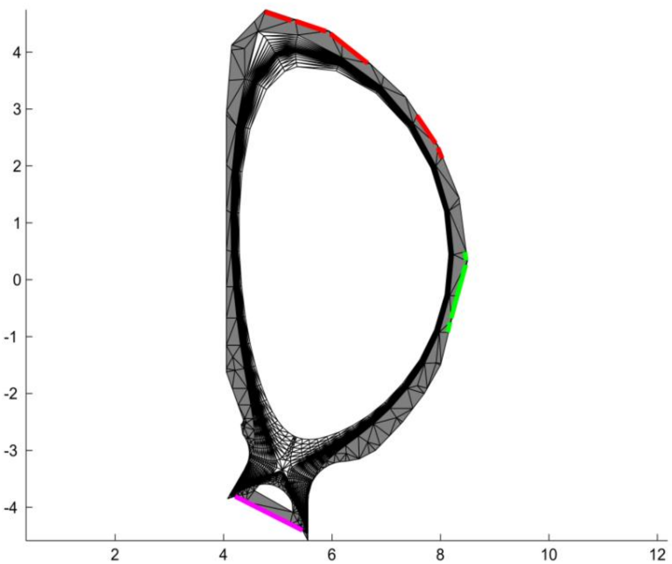
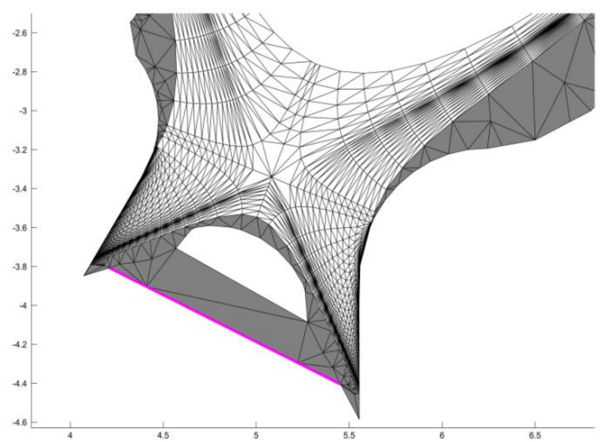
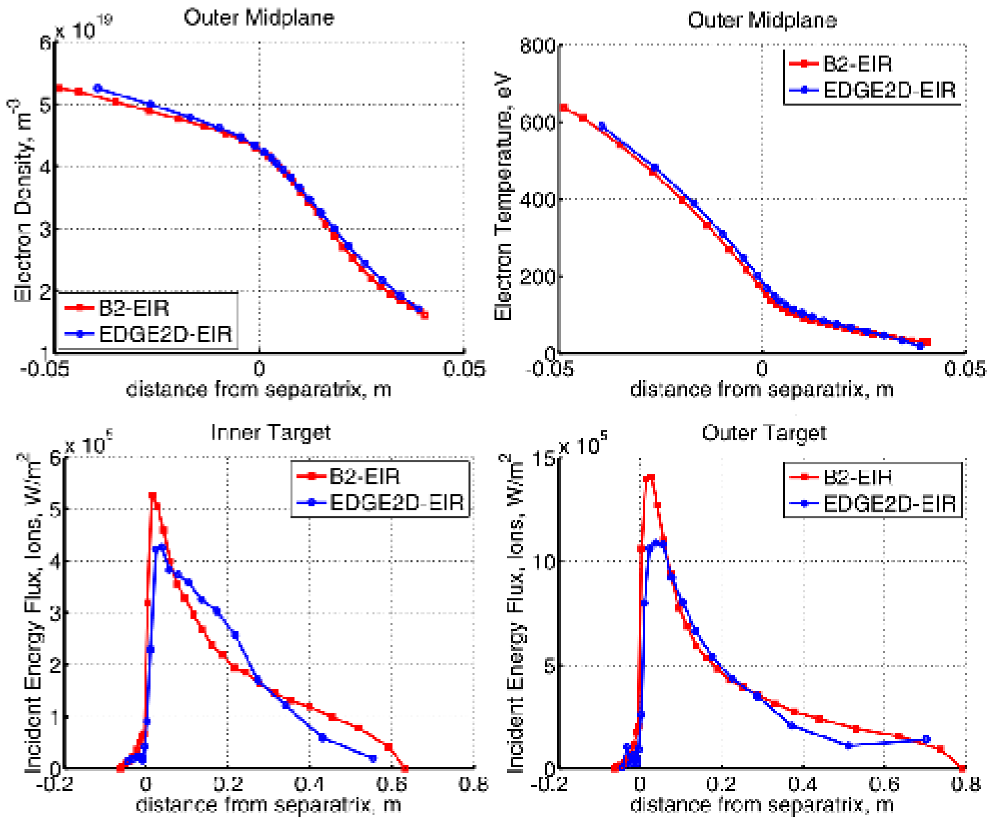
Comparison EDGE2D-EIRENE vs SOLPS







- 2D simulation domain extends into edge (6cm@OMP)
- parallel transport classical, flux limited for electrons
- radial transport model: adhoc anomalous

- particle sources: core (const pellets): Γ_{core} =2e21..1e23 s^{-1}
  top D2 gas flux: Γ_{gas} = 1.4e23 s^{-1} fixed (factor 3 higher as in SOLPS)
  omp Neon gas flux: Γ_{Ne} = 1e19..8e19 s^{-1}
- particle sinks:
  pumping surface below divertor dome:
  albedo = 0.94 → L = A (1-albedo) 36.38 (T_{D2}/4) ~ 790 m^3/s

- heat sources: P_{edge}=80MW (1:2 ratio ions/els)

Kotov, Wiesen 2010

Transient modelling of ITER baseline density evolution

• transient pellet ablation model HPI2
→ provides time-dependent source profiles for given pellet injection configuration

• pellets from high-field side, 6e21 atoms per pellet 50/50 D/T at v=300m/s
• assume plasmoid drift: 100%, 50%
• pellet trigger thresholds: minimum top pedestal density: 1.05, 0.88, 0.70 [$10^{20}m^{-3}$]

• JETTO transport model: B/gB, sawteeth, cont. ELM model: α_{crit} = 1.7
• fusion product: DITRAN-2
• NBI aux power: 33MW PENCIL, P_{rad}^{core}=43MW fixed (Z_{eff}=1.7 flat)

• EDGE2D-EIRENE transport model: as before, Γ_{gas}=1.4e23s^{-1} fixed,
P_{rad}^{SOL}=60MW fixed (impurity transport neglected)

Pedestal/core profiles (minimum, before pellet)

ne_{ped} = 1.05e20 m^{-3}
ne_{ped} = 0.88e20 m^{-3}
ne_{ped} = 0.70e20 m^{-3}

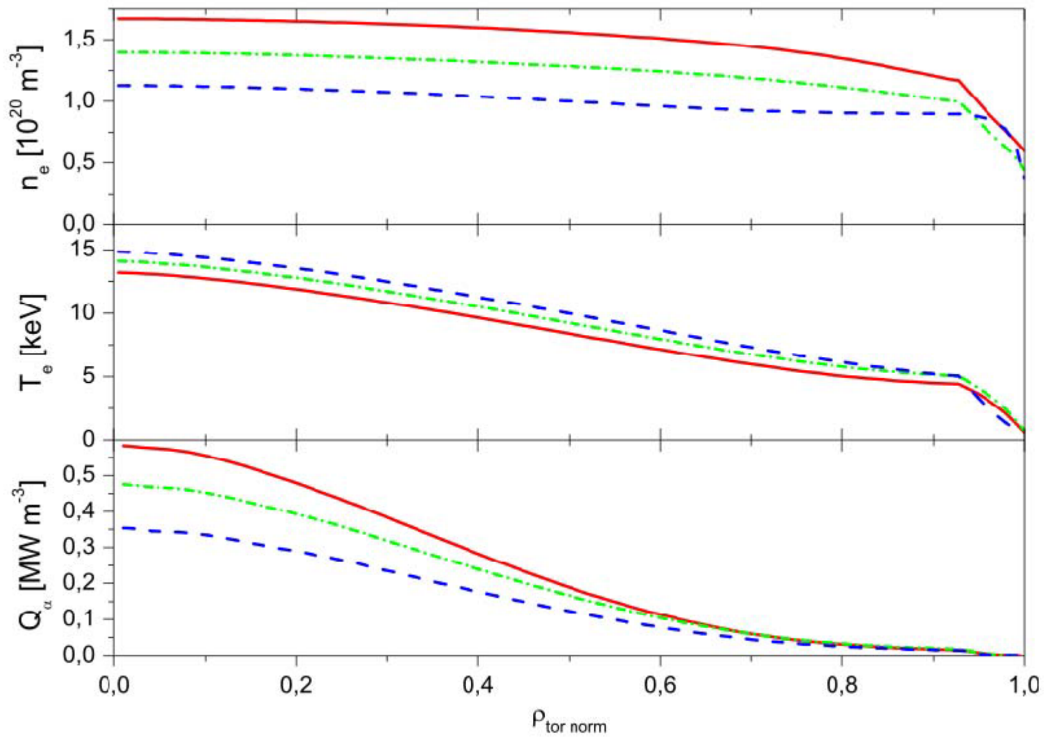


Figure 9 From top to bottom: electron density, electron temperature and α power deposition at the time t = 339.3 s for the simulations shown in Fig. 7.

Koechl, Wiesen 2011-14

Time-transients

ne_{ped} = 1.05e20 m^{-3}
ne_{ped} = 0.88e20 m^{-3}
ne_{ped} = 0.70e20 m^{-3}

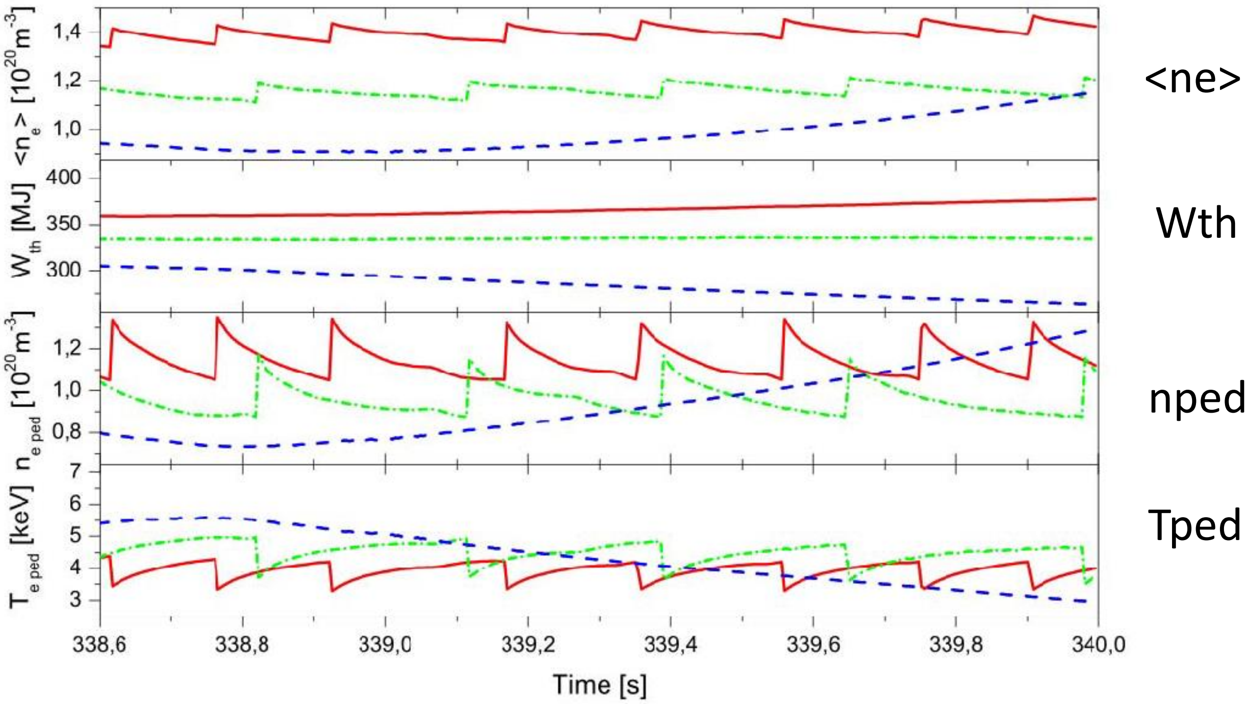


Figure 7 From top to bottom: average electron density, thermal energy content, electron density on top of the pedestal, electron temperature on top of the pedestal, for simulations of an ITER ELMy H-mode scenario (t = 338.6-340 s) with pellet feedback maintaining a minimum density level of 1.05 (solid/red), 0.875 (dash-dotted/green), and $0.7{\cdot}10^{20}$ m^{-3} (dashed/blue) on top of the pedestal (with 50% of the predicted E×B drift taken into account and 60 MW of radiated power in the SOL).

Koechl, Wiesen 2011-14

Transient confinement

ne_{ped} = 1.05e20 m^{-3}
ne_{ped} = 0.88e20 m^{-3}
ne_{ped} = 0.70e20 m^{-3}

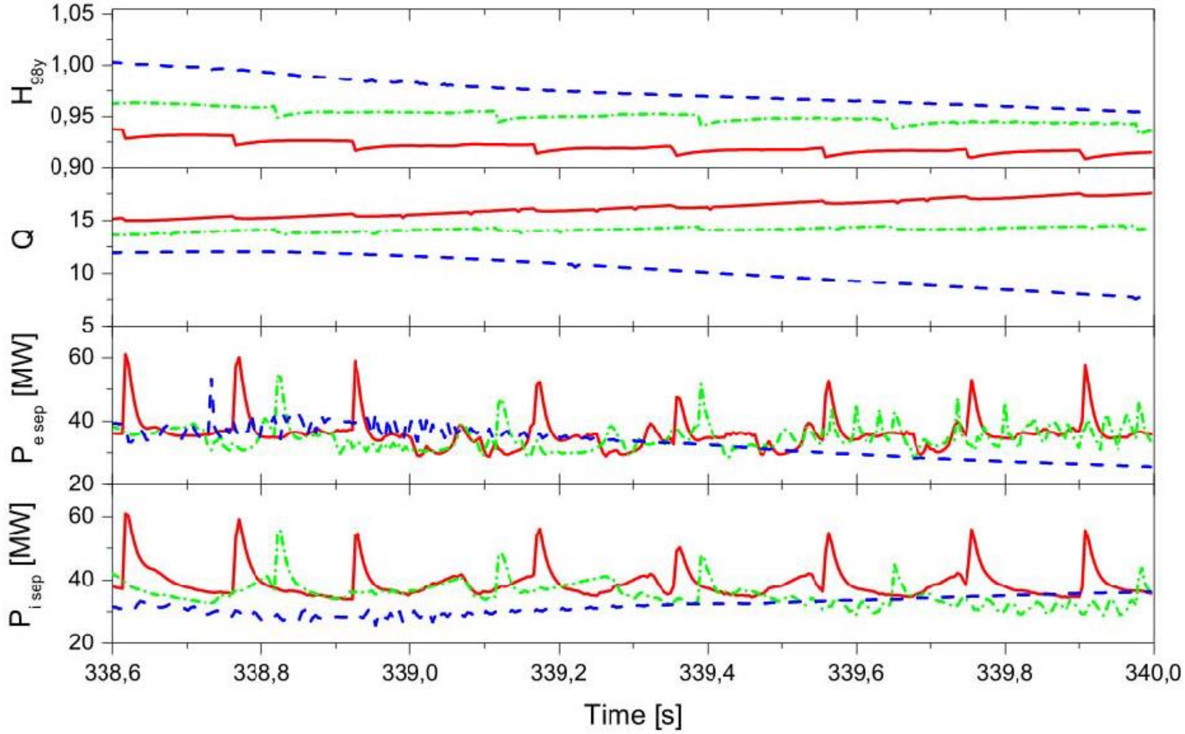


Figure 8 From top to bottom: H_{98y}, fusion Q, electron and ion power crossing the separatrix for the same simulations as shown in Fig. 7.

Koechl, Wiesen 2011-14

Dynamic Operational Space

ne_{ped} = 1.05e20 m^{-3}
ne_{ped} = 0.88e20 m^{-3}
ne_{ped} = 0.70e20 m^{-3}

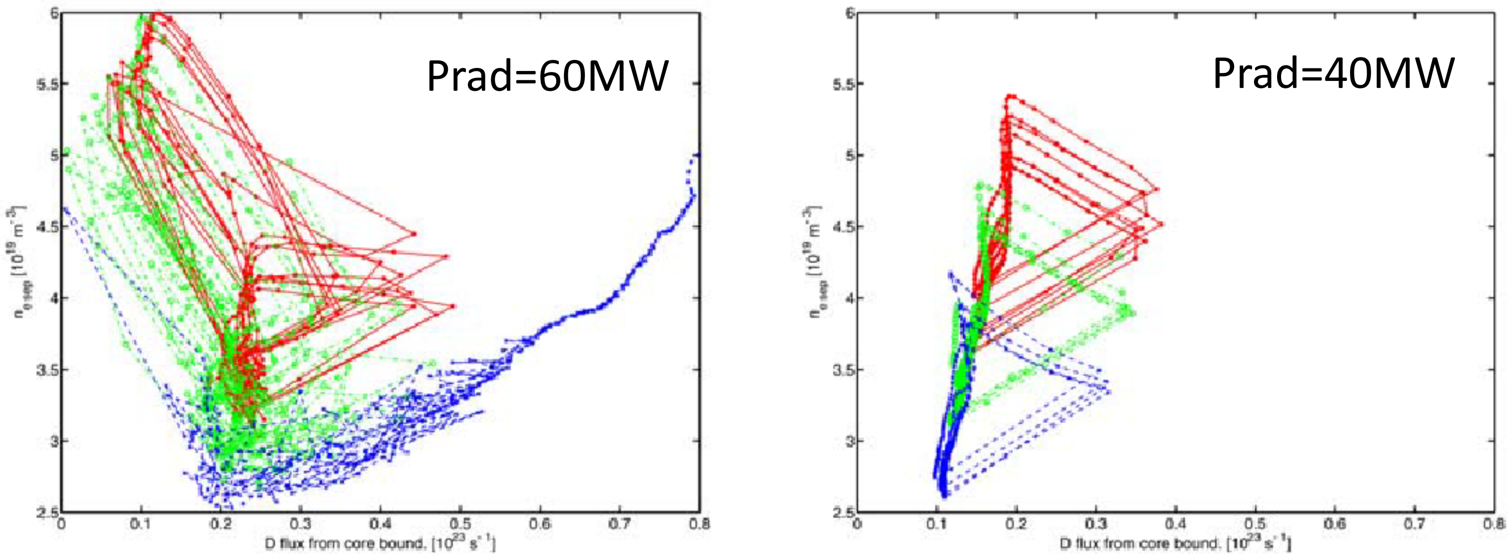
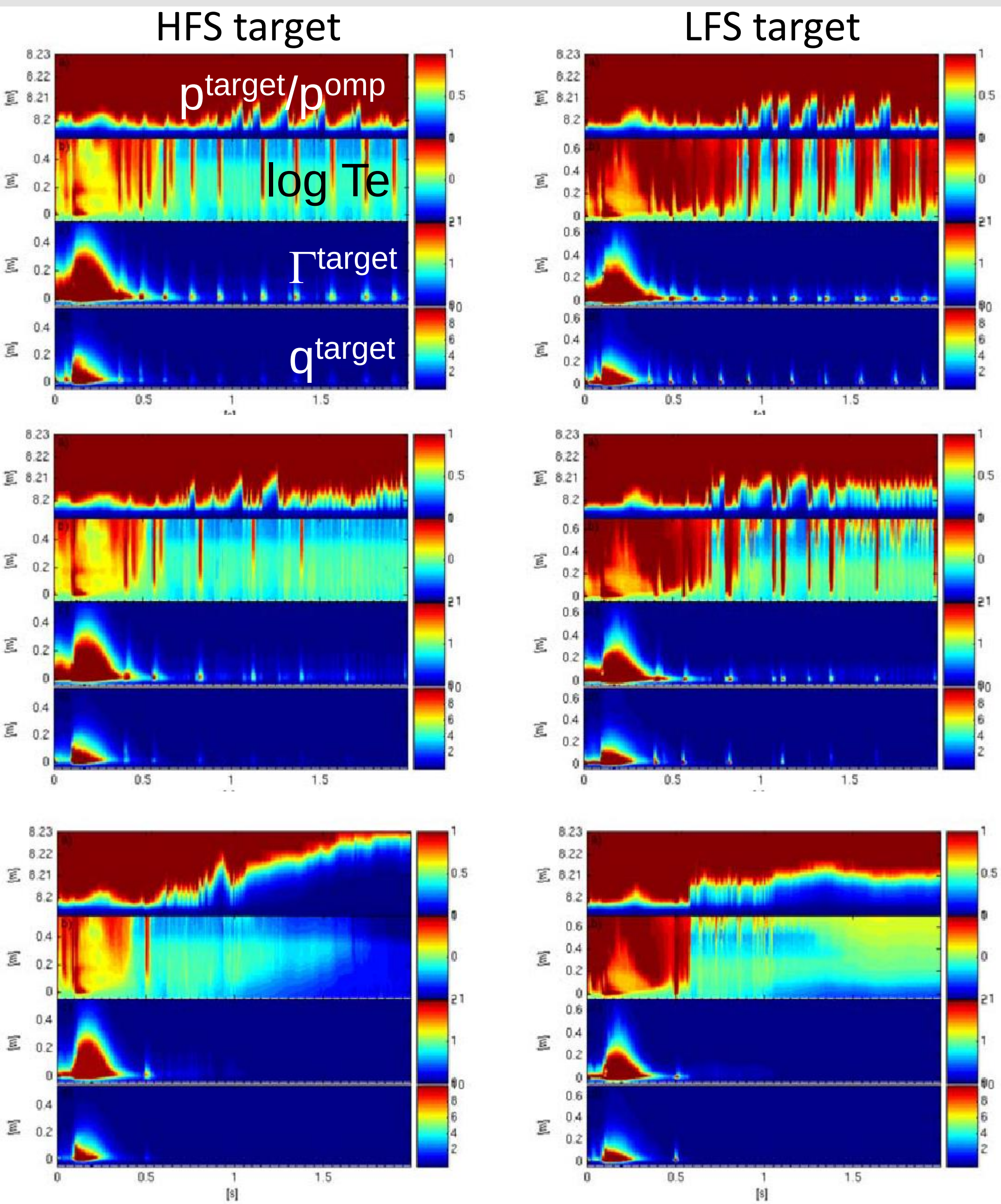


Figure 14 Electron densities at the separatrix as a function of the deuteron flux at the separatrix, for simulations of an ITER ELMy H-mode scenario (t = 338.6-340 s) with a minimum electron density level of 1.05 (solid/red), 0.875 (dash-dotted/green), and $0.7 \cdot 10^{20}$ m^{-3} (dashed/blue) on top of the pedestal and 60 MW (left) or 40 MW (right) of radiated power in the SOL (with 50% of the predicted E×B drift taken into account).

Koechl, Wiesen 2011-14

Target/divertor conditions



- <u>High density:</u>
both targets re-attach when pellet ablation peaks since PSOL increases significantly due to high fusion product in high-density

- <u>Medium density:</u>
the inner target stays detached whilst the outer target reattaches at pellet ablation time
→ a preferred scenario

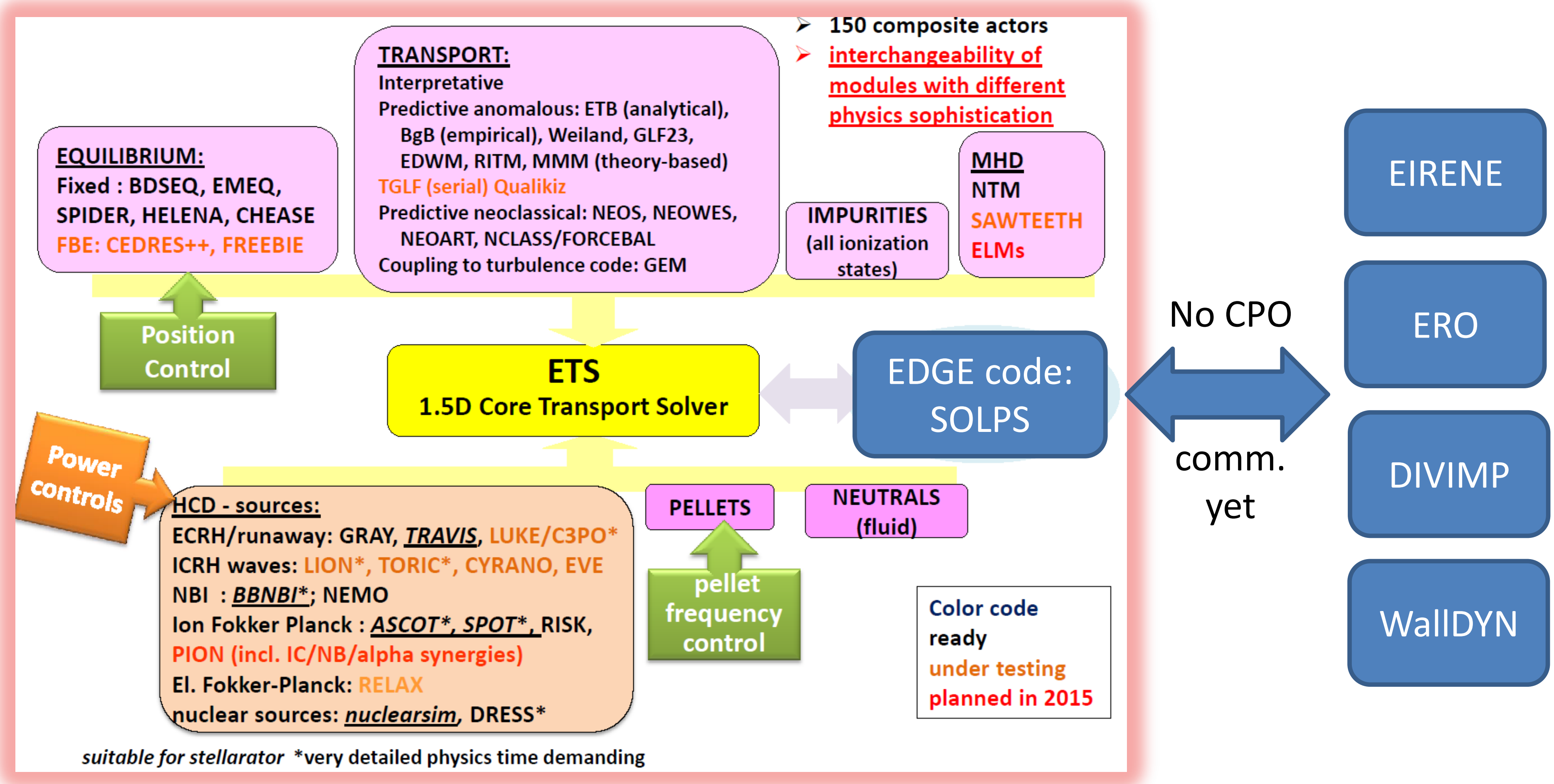
- <u>Low density:</u>
both targets are completely detached
→ very difficult to control

Koechl, Wiesen 2011-14

Contents

- Motivation - Why need for integrated modelling?
- JET data analysis example 1:
  Analysis of JET type-I ELM cycles (C → ILW)
- JET data analysis example 2:
  Effect of divertor PWI on edge plasma fuelling (ELMs)
- JINTRAC Application: ITER scenario (detached divertor)
- ETS activity on integrated core-edge modelling (AUG)
- Conclusions

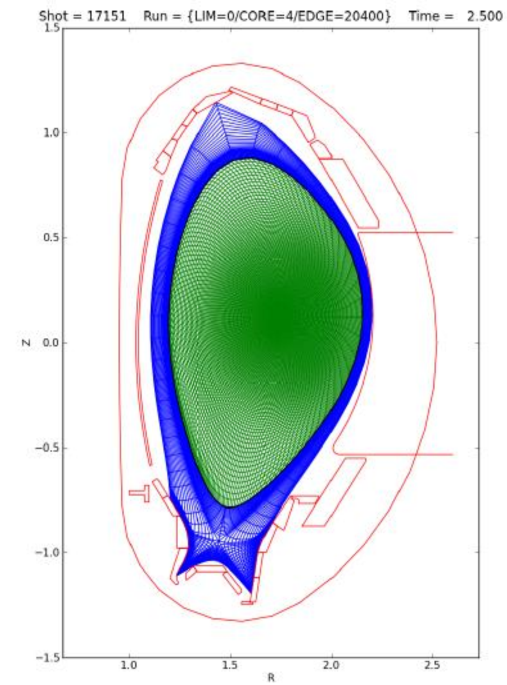
Status core-edge coupling of ETS framework

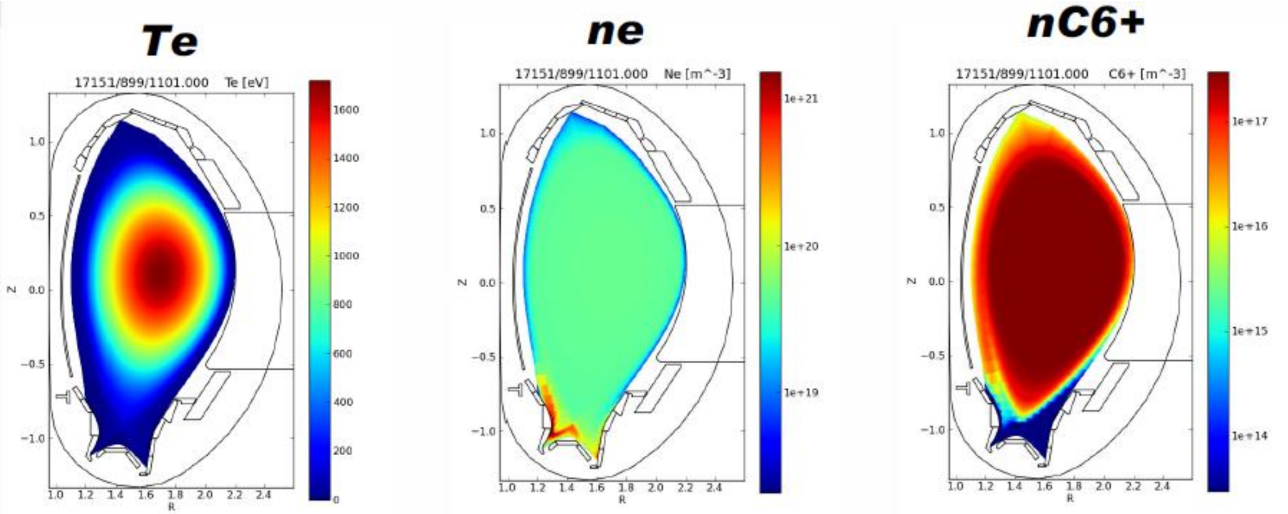


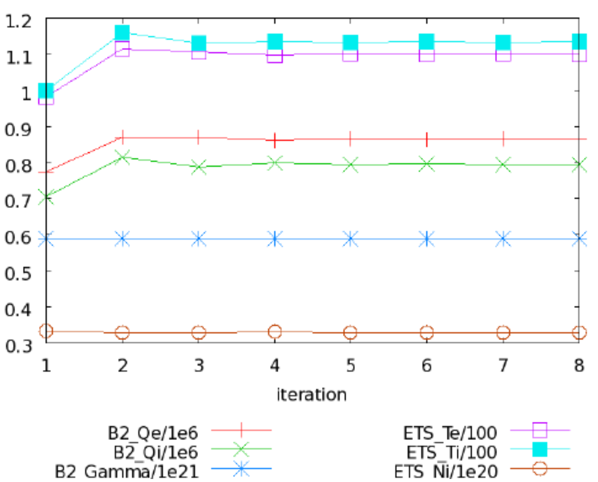
ETS-SOLPS coupling scheme

D.P. Coster, H.-J. Klingshirn, et al EPS 2012

- Fluxes: ETS→SOLPS, boundary SOLPS→ ETS. Converged after few iterations
- CLISTE equilibrium for AUG shot → HELENA for core equilibrium, CARRE for edge geometry
- Main species (D, He) and impurity (C, Ar, Ne) are simulated
- Neutrals – SOLPS only simulations (zero-flux boundary conditions)

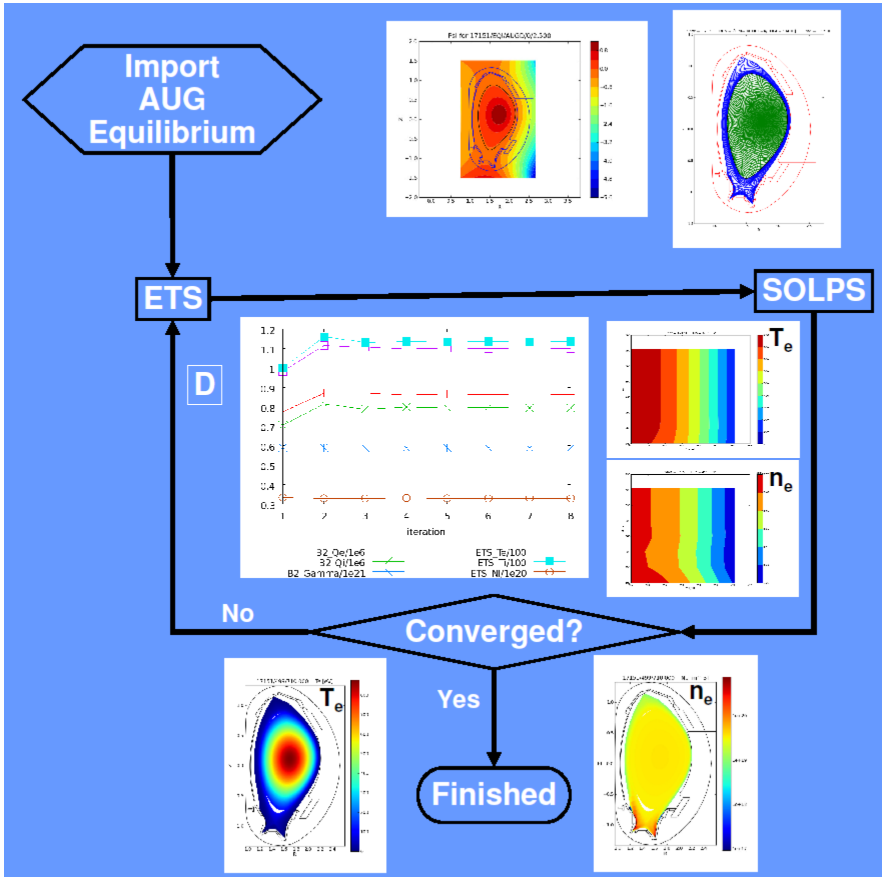


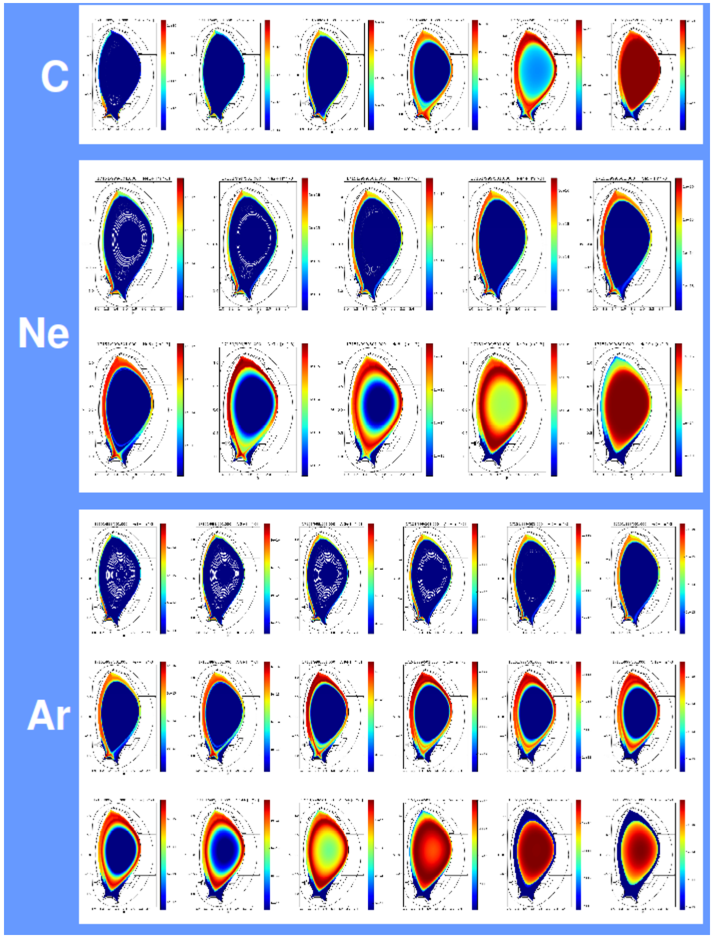




ETS-SOLPS coupling scheme

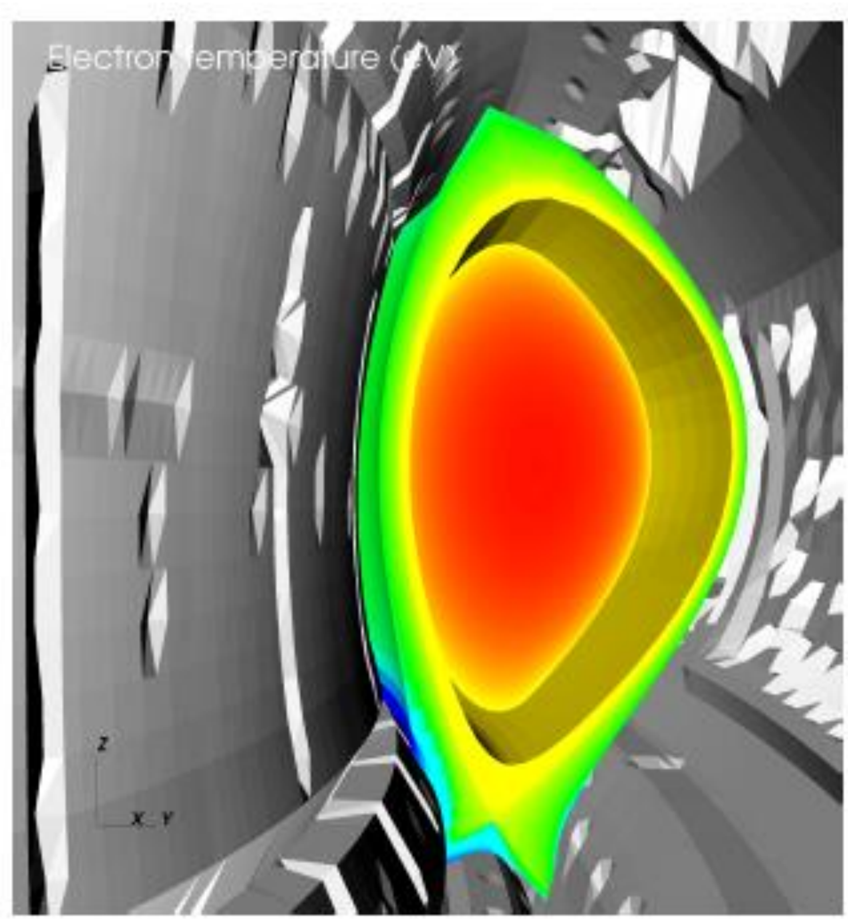
D.P. Coster, H.-J. Klingshirn, et al EPS 2012

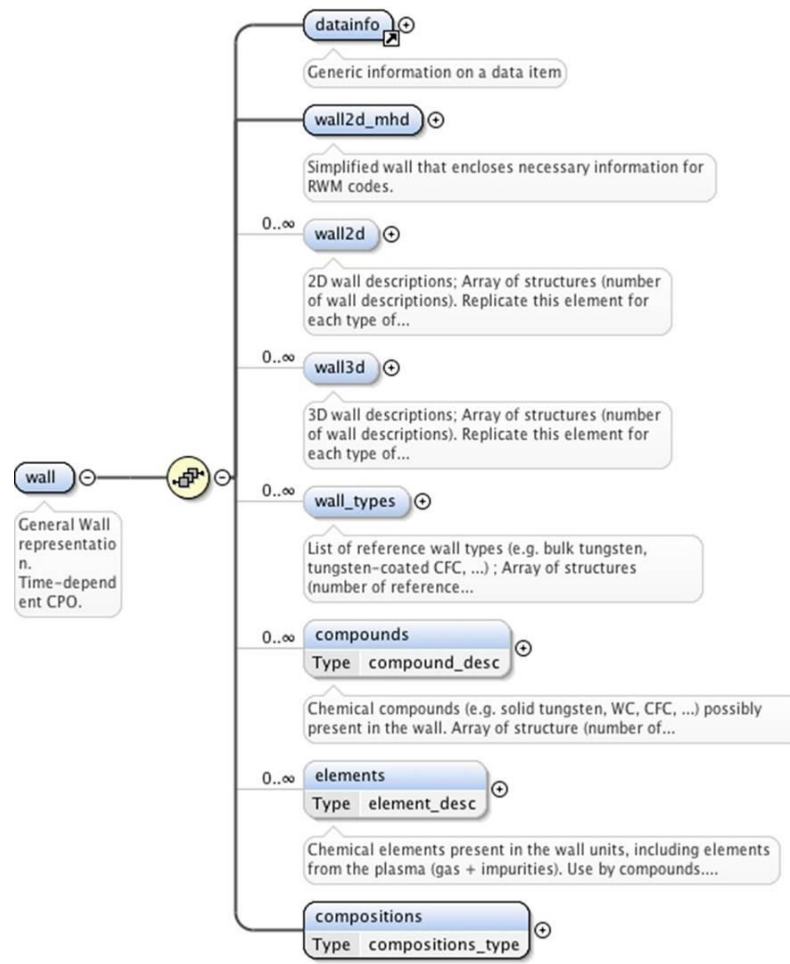




SOLPS-ETS visualization

Graphic created using **VISIT** and the **Wall CPO** (ASDEX)





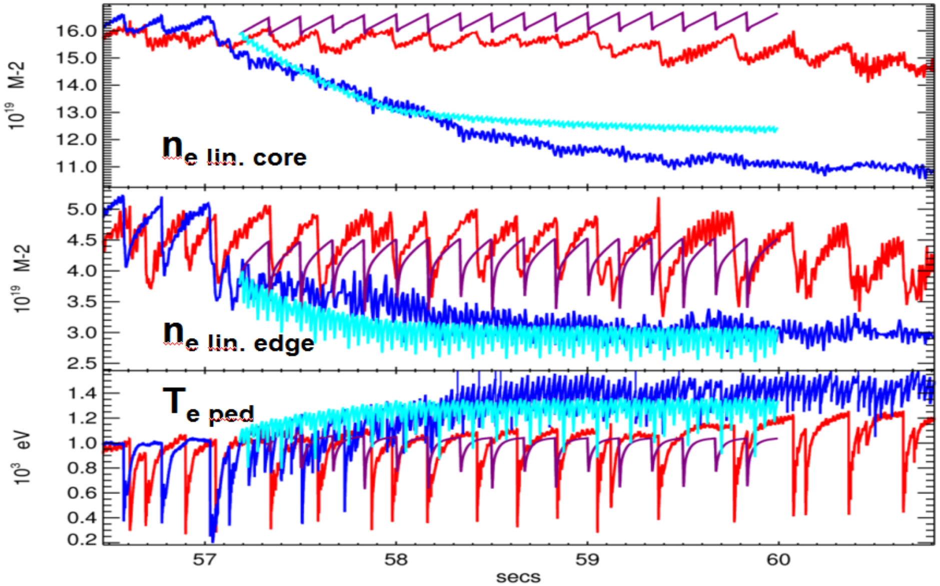
Courtesy of ***R. Coelho***

Conclusions

- The JINTRAC integrated model is extensively used for combined core-pedestal-SOL-PWI modelling tasks
  - JET type-I ELMy H-mode discharges
  - transition JET-C → JET-ILW
  - effect of PMI on recycling and pedestal performance
- JINTRAC is a tool which can be used to predict ITER scenarios
  - complex fuelling cycle: pellets, gas, pumping, rad. divertor, divertor detachment
- ETS-SOLPS coupling
  - interpretative modeling (AUG results)
  - ITER predictions under way (multi-component plasma w/ ELMS), D.Coster et al (F4E task)
- Other applications (not mentioned in this talk)
  - JINTRAC modelling of ELM triggering (e.g. kicks, pellets) (Koskela, et al)
  - JITNRAC L-H / H-L transition (V. Parail, et al)
  - JINTRAC coupling of NBI or ICRH heat deposition: coupled ASCOT (Koskela)
  - JINTRAC/SOLPS JT60SA predictions: core transport, rad. divertor (Garzotti, Wiesen)
  - DEMO needs (comparison SOLPS/EDGE2D w/ COREDIV model under way, link to systems codes… (R. Wenninger, et al)

backup

Density depletion in ELM mitigated regime:



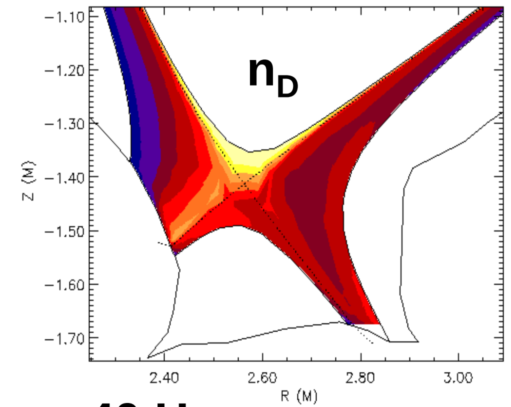
f_{ELM}≈6 Hz, experiment

f_{ELM}≈6 Hz, simulation

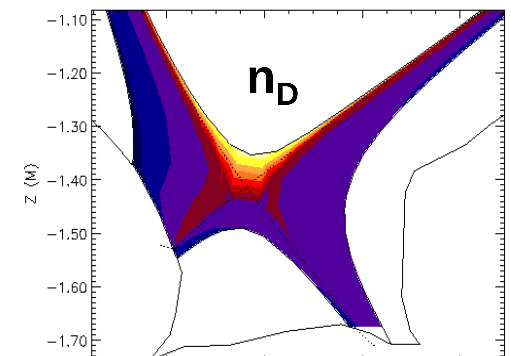
f_{ELM}≈40 Hz, experiment

f_{ELM}≈40 Hz, simulation

f_{ELM} = 6 Hz:

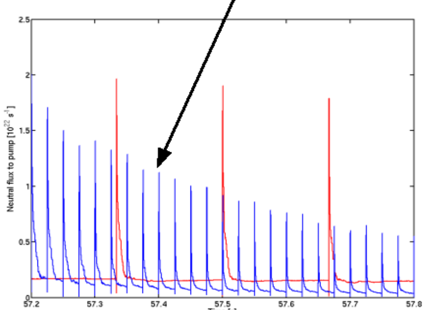


f_{ELM} = 40 Hz:



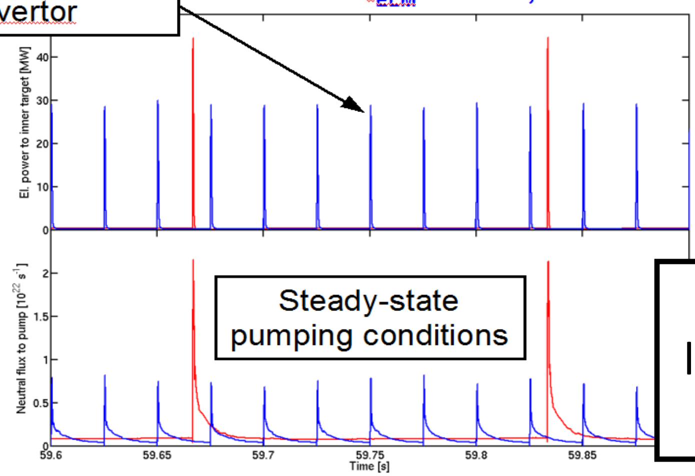
Mitigated ELM impact on divertor

Enhanced pumping until lower n_e level is reached



f_{ELM} = 6 Hz, simulation

f_{ELM} = 40 Hz, simulation



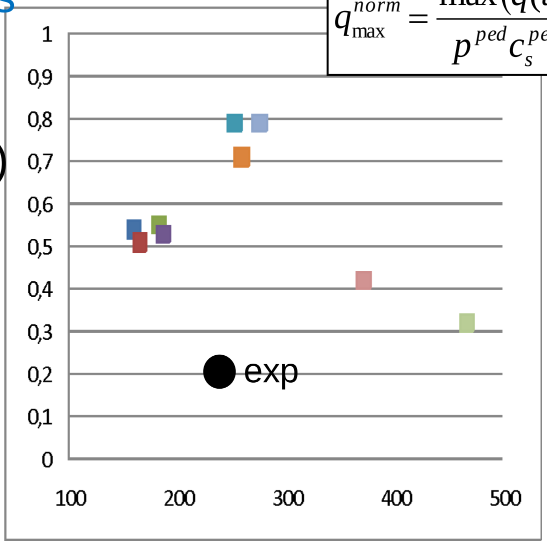
Steady-state pumping conditions

Reduced target protection at low n_e / high T_e → reduced ELM mitigation efficiency!

JINTRAC ELM characteristics studies

- The free streaming approximation of ELM filaments suggests that maximum of heatflux q_{max} and energy density ε arriving at the target depend solely on (cf. Fundamenski, PPCF2006):
  $\tau_{||}$, $L_{||}$, p^{ped}, T^{ped} and ion mass (ie. sound speed c_s^{ped})
  → normalised quantities q_{max}^{norm}, ε^{norm}

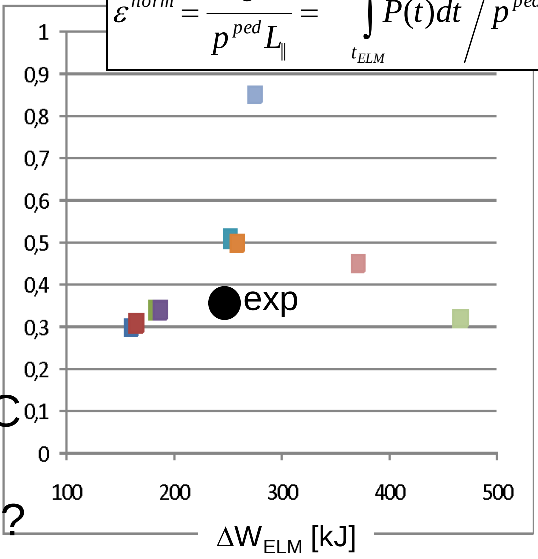
$$q_{\max}^{norm} = \frac{\max(q(t))}{p^{ped} c_s^{ped}}$$



- It was shown that the free-streaming approx. succesfully describe the power load distribution on inner/outer divertor target for JET and AUG (cf. T.Eich et al, JNM2009)

- IRTV JPN 73569 (ΔW_{ELM} ~250kJ)
  q_{max}^{norm} ~ 0.2 ε^{norm} ~ 0.35
- kinetic 1D PIC:
  (Tskhakaya et al., JNM2009, JPN 62221, ΔW_{ELM} =400kJ)
  q_{max}^{norm} ~ 0.56 ε^{norm} ~ 0.6

$$\varepsilon^{norm} = \frac{\varepsilon}{p^{ped} L_{\|}} = \int_{t_{ELM}}^{t_{ELM}+\tau_{ELM}} P(t)dt \Big/ p^{ped} L_{\|}$$

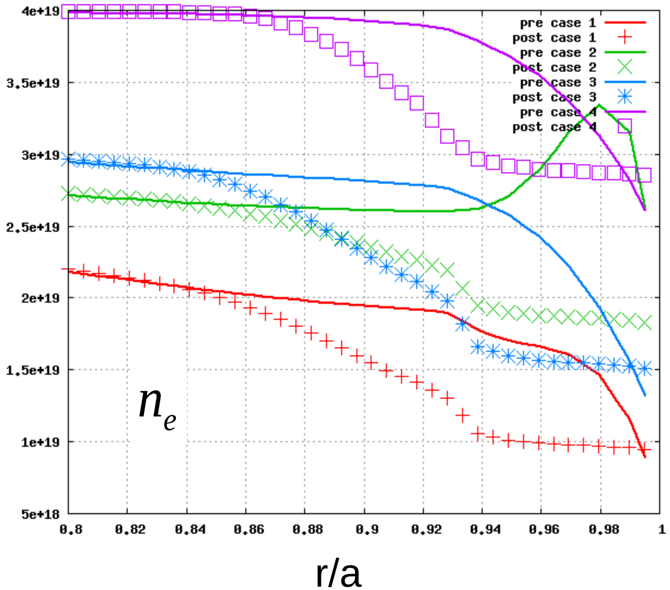


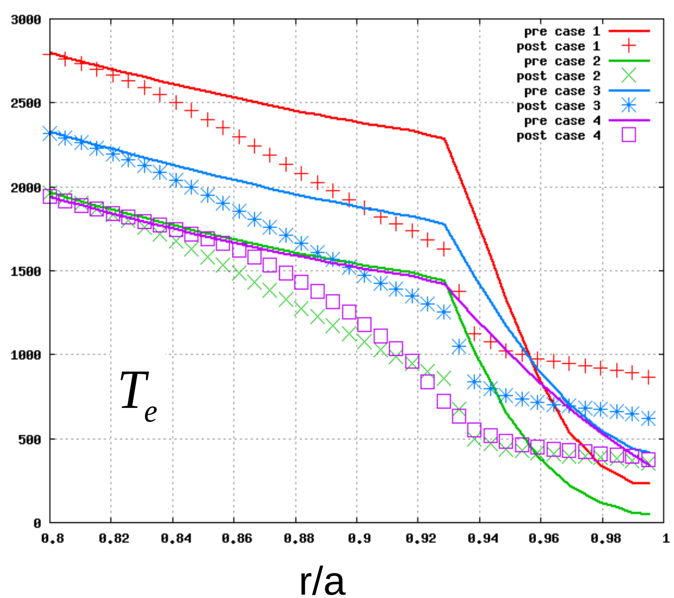
- JINTRAC values are in the same range

- strong dependence on ELM diffusive channel to
→ lower values of q_{max}^{norm}, ε^{norm} w/ D^{ELM} observed in JINTRAC

→ 2D effect? Stronger spreading of heat by divertor recycling?

Excursion: inter-ELM ETB transport model





- From neo-classical theory with $\nu_e{}^*{}_{ped}$=0.15:

$$\chi_e^{neo} = D^{neo} \approx 0.004 \frac{m^2}{s} \qquad \chi_i^{neo} \approx 0.24 \frac{m^2}{s}$$

- Assuming these pure neo-classical values leads to unreasonable high pedestals in the model, i.e. the effective inter-ELM ETB transport is strongly underestimated

→ manual revision of ETB inter-ELM transport to higher values than predicted by neo-classical transport to incorporate residual levels of turbulence for electron heat conduction and mass diffusion

Case 1: $D=\chi_i$=0.03 m²/s, χ_e=0.03 m²/s, Γ_p = 0.5 10^{22} 1/s, 90Hz

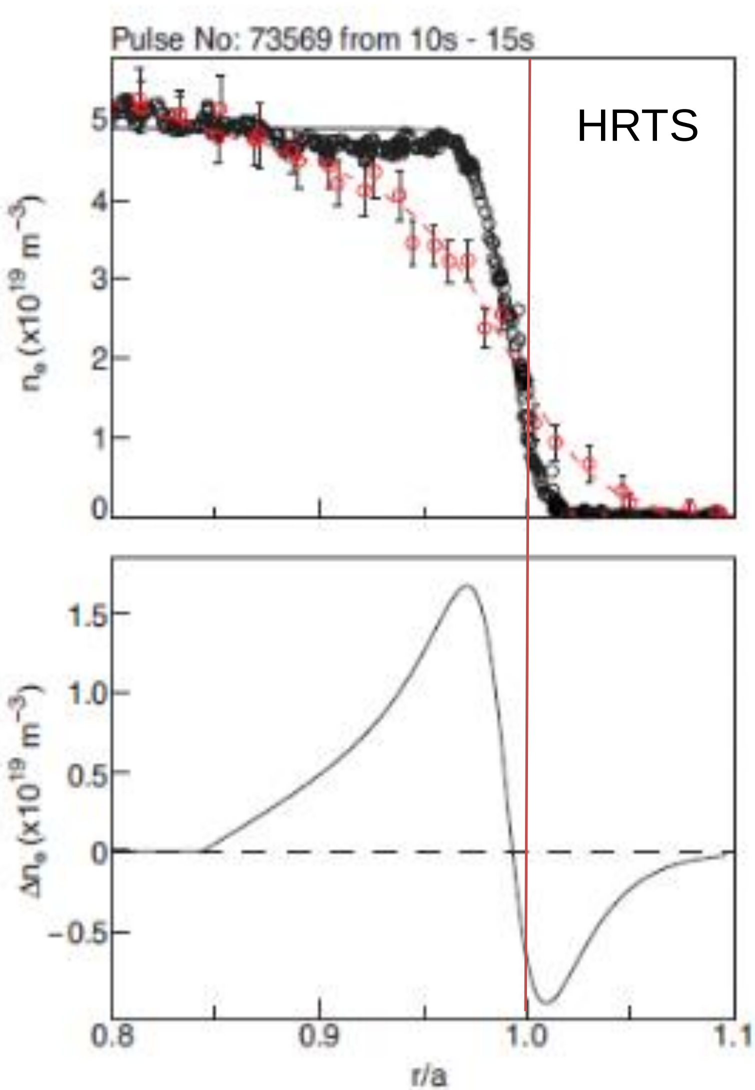
Case 2: $D=\chi_i$=0.03 m²/s, χ_e=0.03 m²/s, Γ_p = 1.5 10^{22} 1/s, 96Hz

Case 3: $D=\chi_i$=0.10 m²/s, χ_e=0.05 m²/s, Γ_p = 1.5 10^{22} 1/s, 47Hz

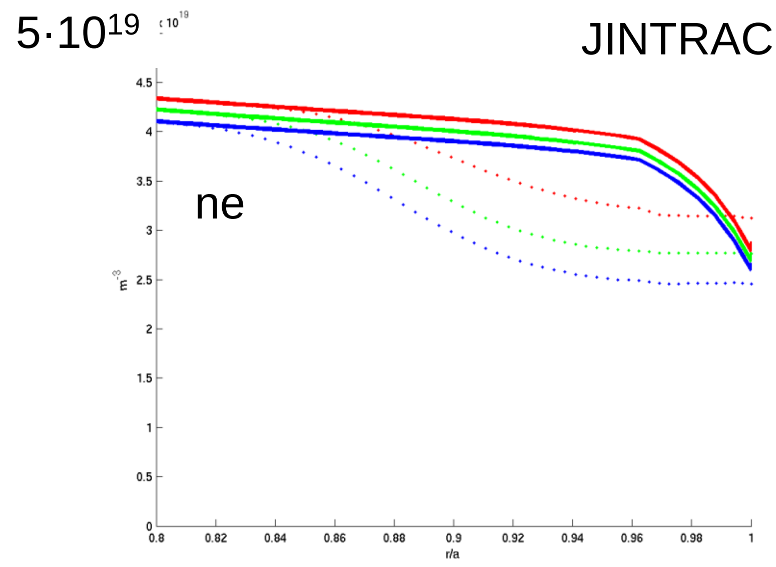
Case 4: $D=\chi_i$=0.15 m²/s, χ_e=0.08 m²/s, Γ_p = 3.0 10^{22} 1/s, 16Hz

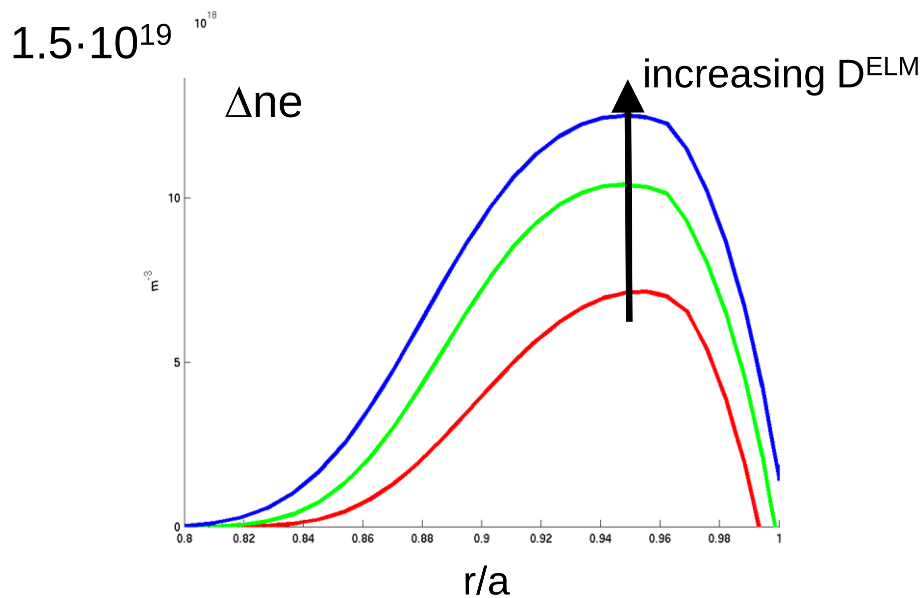
fixed α_{crit} =1.6

Upstream density JPN 73569

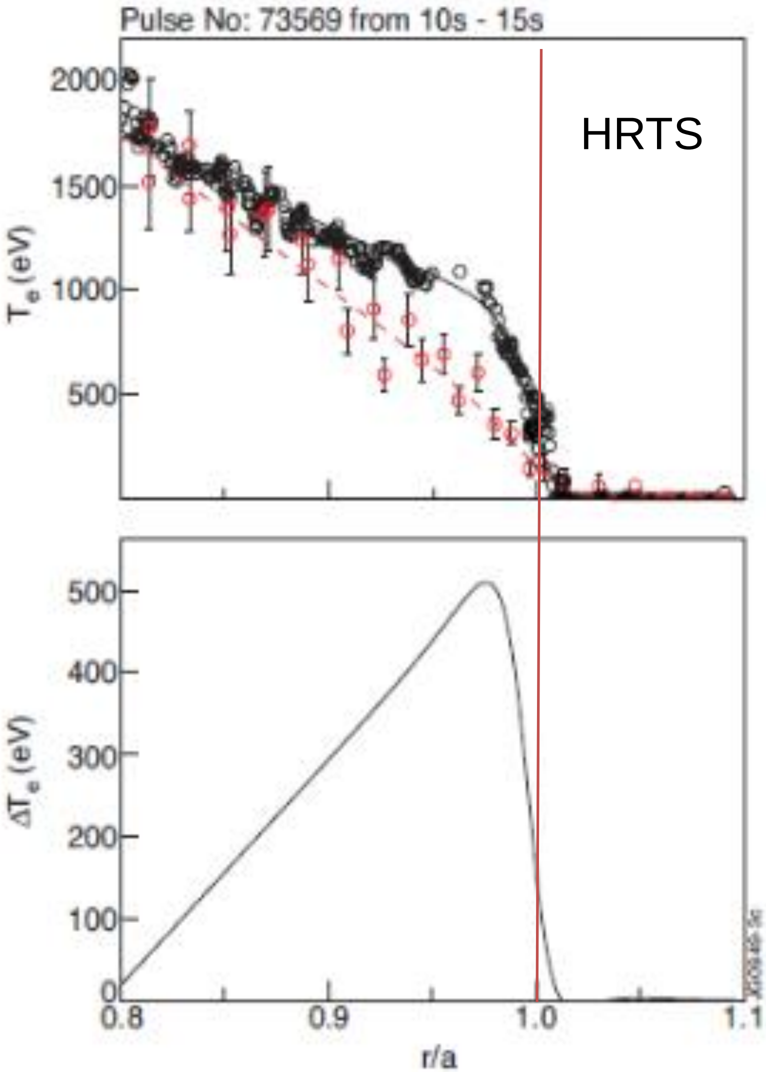


courtesy: M.Beurskens et al. IAEA 2008

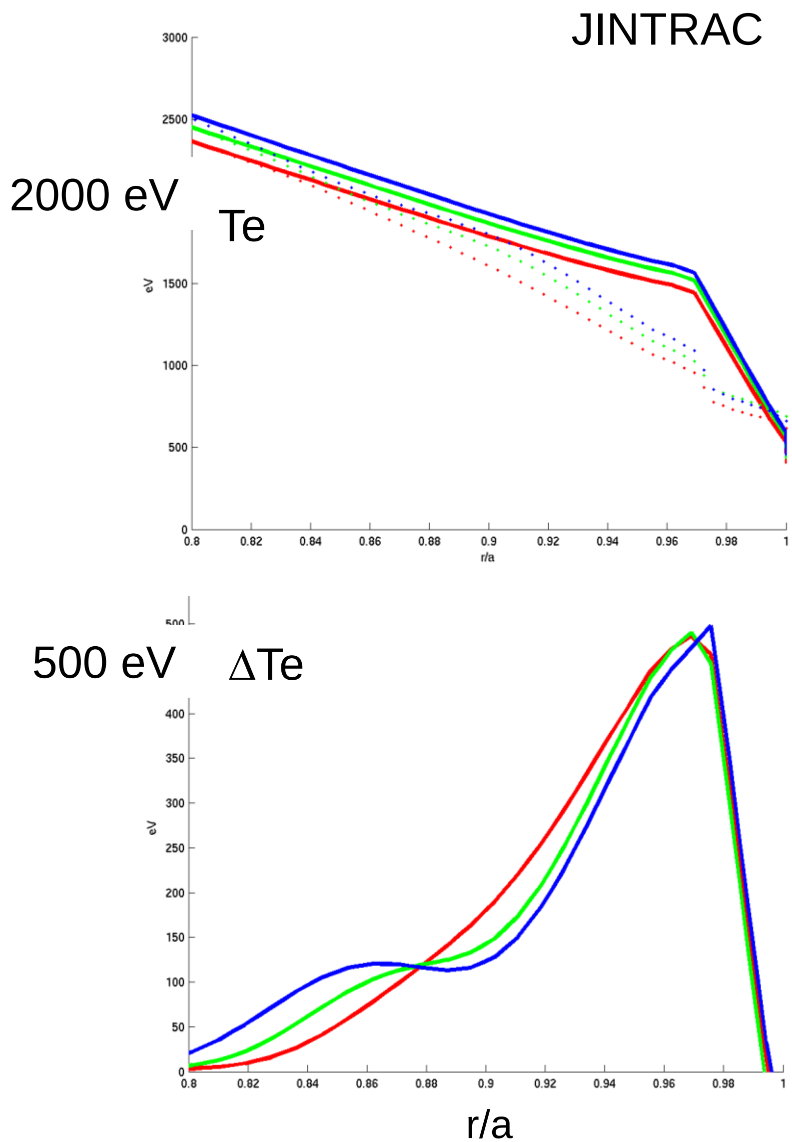




Upstream temperature JPN 73569

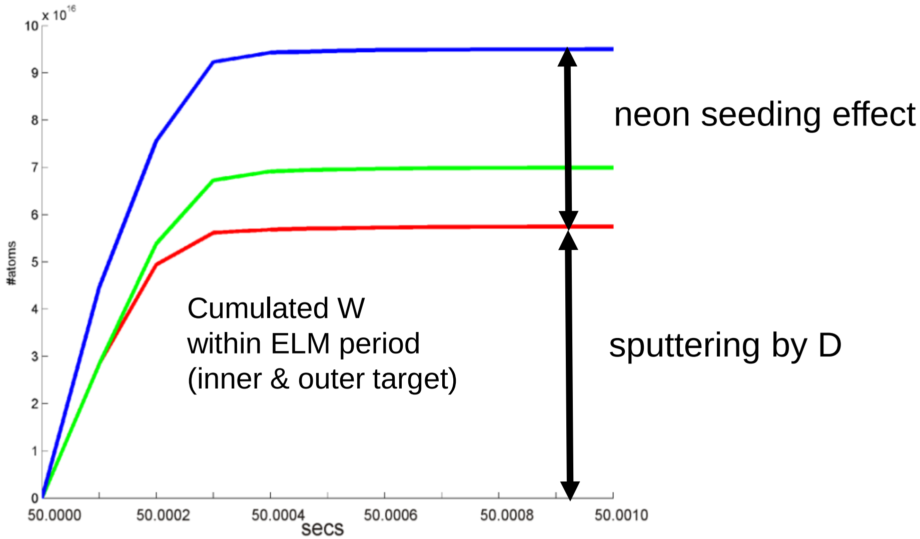


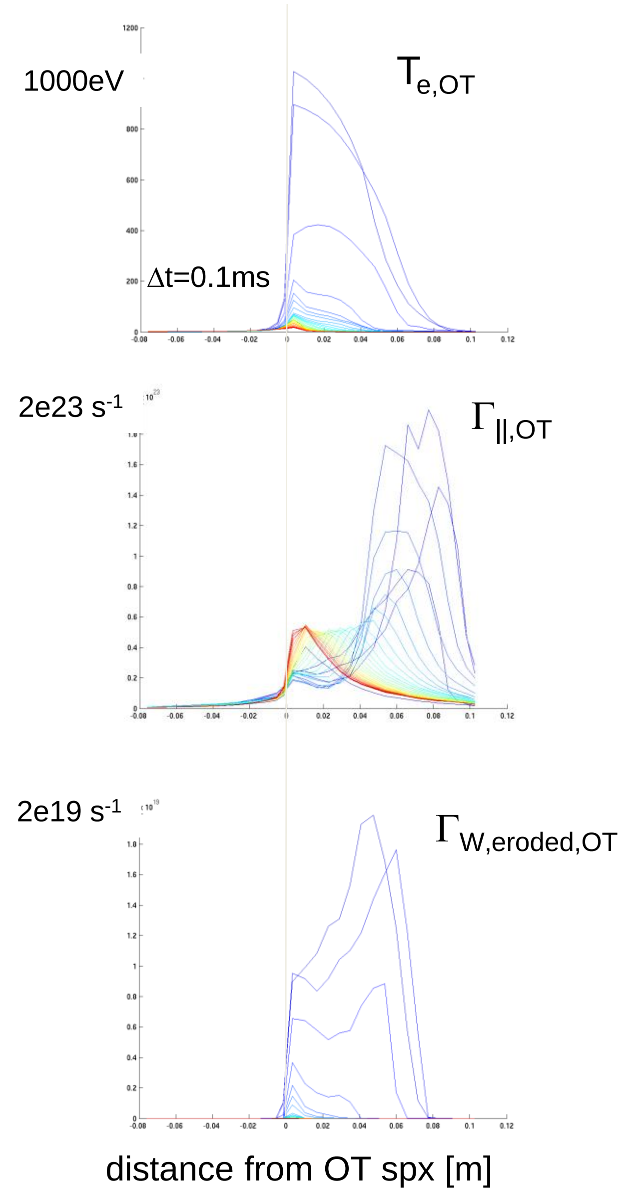
courtesy: M.Beurskens et al. IAEA 2008



Estimate of W erosion fluxes

calculate W influx from targets due D, Ne and Be-impact
from Eckstein formula for physical sputt. yield (1993)





- <u>assume:</u>

- $E_{ion} = 4.5\ T_e$ (plasma sheath)
- $\Gamma_{ion,perp} = \sin(1\text{deg})\ \Gamma_{||}$

→ $\Gamma_{W,eroded} = (Y_{D\to W} + c_{Be} Y_{Be\to W} + c_{Ne} Y_{Ne\to W})\ \Gamma_{ion,perp}$

- cumulation over 1 ELM period:

→ $N_W^{eroded} =$ 5-10·10^{16} or more W atoms/ELM

(crude estimate: no prompt re-deposition, no self-sputtering)

JINTRAC steady-state simulations for ITER baseline scenario

Starting point: steady pellet fuelling (as before, ie. no transients)

- modified Bohm/gyroBohm transport in core
- in the edge: cont. ELM-model, critical pressure gradient α_{crit} = 1.7

- P_{aux} = 33 MW, P_{fusion}: DITRAN-2 → target P_{fus} ~ 500 MW (Q ~ 10)
- Z_{eff}=1.7 (P_{rad} = 43MW fixed)

- cont.pellet model: fixed gaussian source profile in time
- S_{pellet} = 1.5e22 s^{-1}, Δ_{pellet}=0.1, ρ_{pellet}= 0.9 (case A), 0.8 (case B) (plasmoid drift)

- in far-SOL: fixed transport: D=0.3 m^2/s, $\chi_i=\chi_e$=1.0m^2/s
- in near-SOL: ETB transport prolonged into SOL (0.5cm @ omp)

- DT-flux coming from plasma core (JETTO) combined into single D-flux into SOL: $\Gamma_D^{EDGE2D} = \Gamma_D^{JETTO}+\Gamma_T^{JETTO}$

- neutral recycling flux Γ_{D0} from SOL split up 50/50 Γ_{D0}/Γ_{T0} when entering core