

EU Core-Edge coupling effort

**S.Wiesen, I. Voitshekovitch, M. Romanelli, et al.
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 ($C \rightarrow ILW$)
- 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

Motiviation: Need for integrated modelling

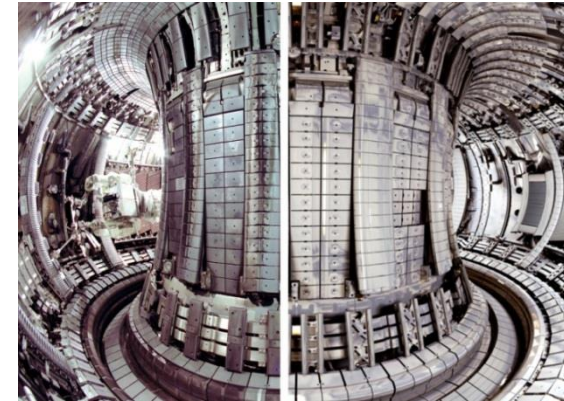


JET ITER-like wall (ILW) experiments: Be + W/W-coated CFC

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



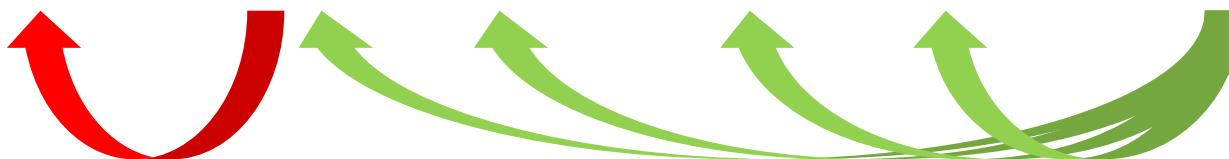
Recycling in JET-ILW vs JET-C:

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

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

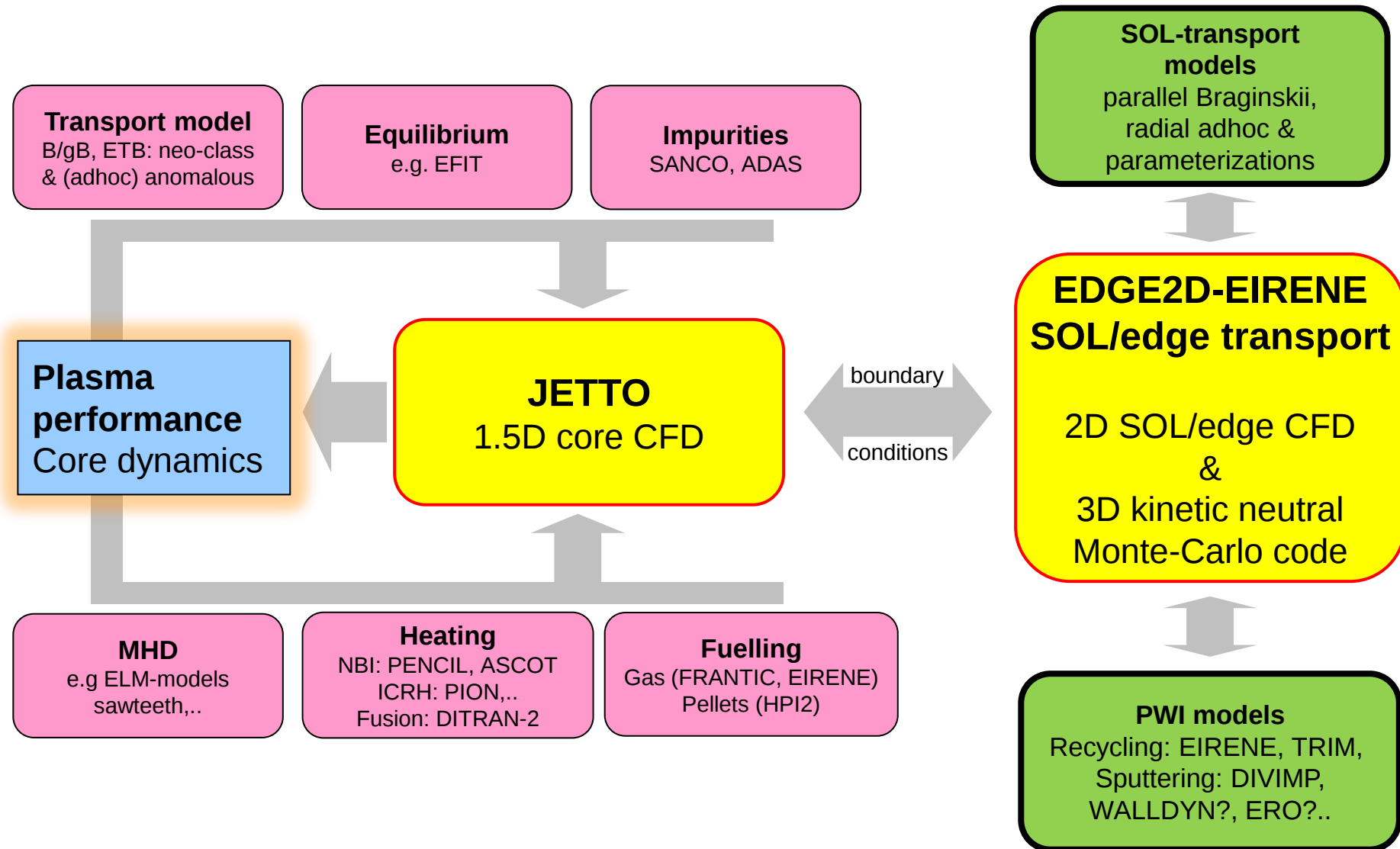
Plasma performance: Complex and stiff problem, e.g. plasma transport time-scales:

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



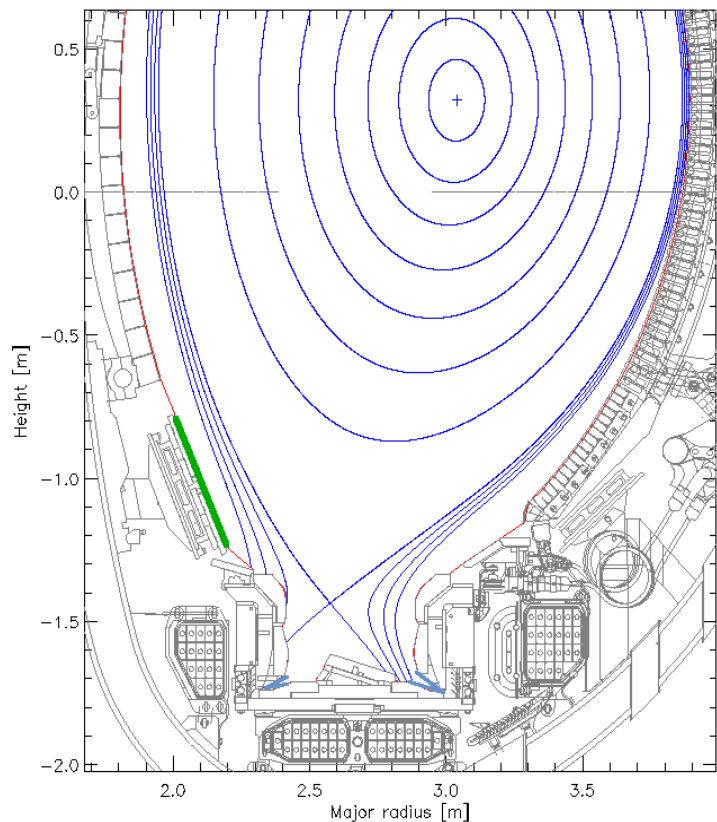
averaged

JINTRAC integrated code suite





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All-carbon reference discharge

$I_p=2.2\text{MA}$, $B_t=2.0\text{T}$, $\delta=0.2$, $P_{\text{NBI}}=13\text{MW}$

$v_{e^* \text{ ped}}=0.15$,

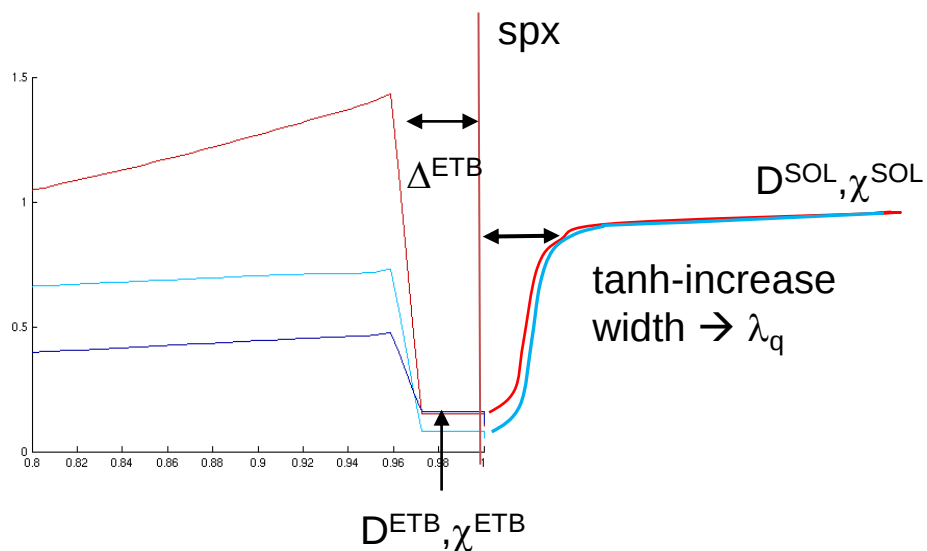
$f_{\text{ELM}}=15\text{Hz}$, $\Delta W_{\text{ELM}} = 240\text{kJ}$

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:

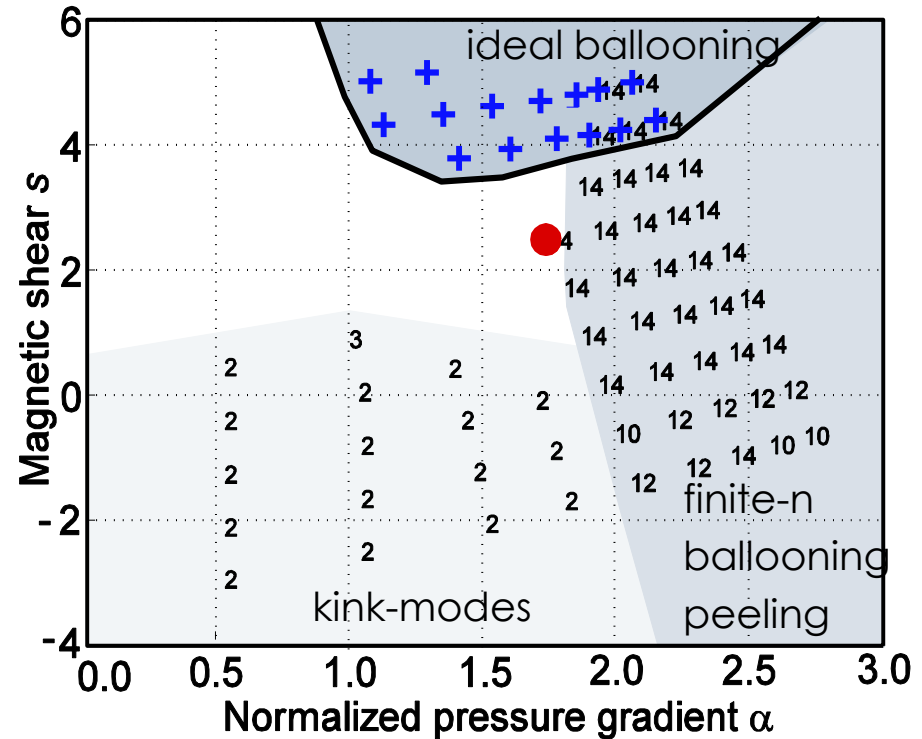
- deep core transport: Bohm/gyro-Bohm
- ETB transport: neo-class values + turbulent remnant
- near spx SOL transport: tanh increase to far-SOL
- far-SOL: Bohm-like values ($\sim 1\text{m}^2/\text{s}$)





- 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

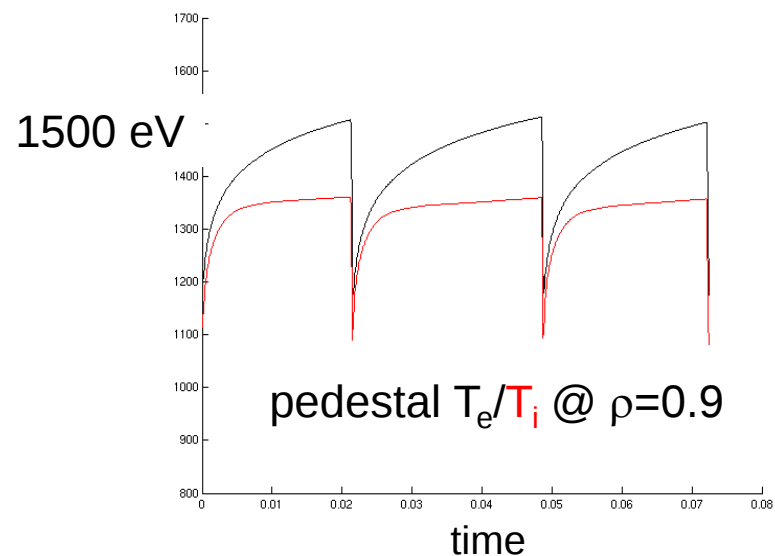
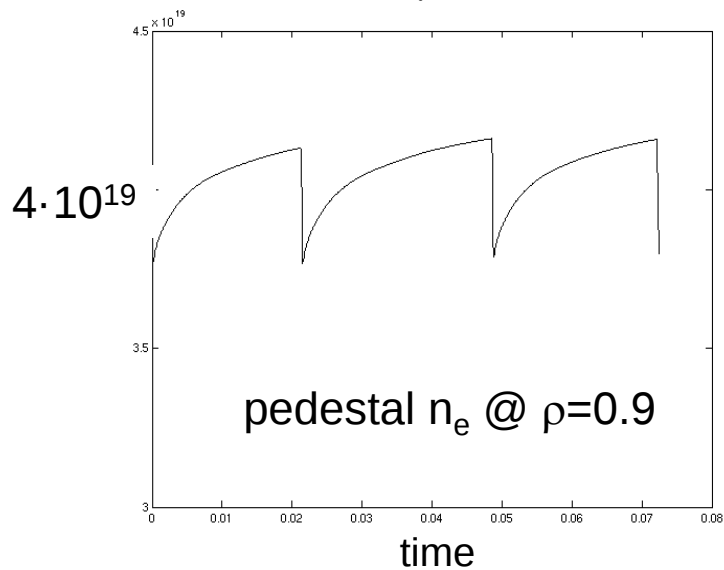
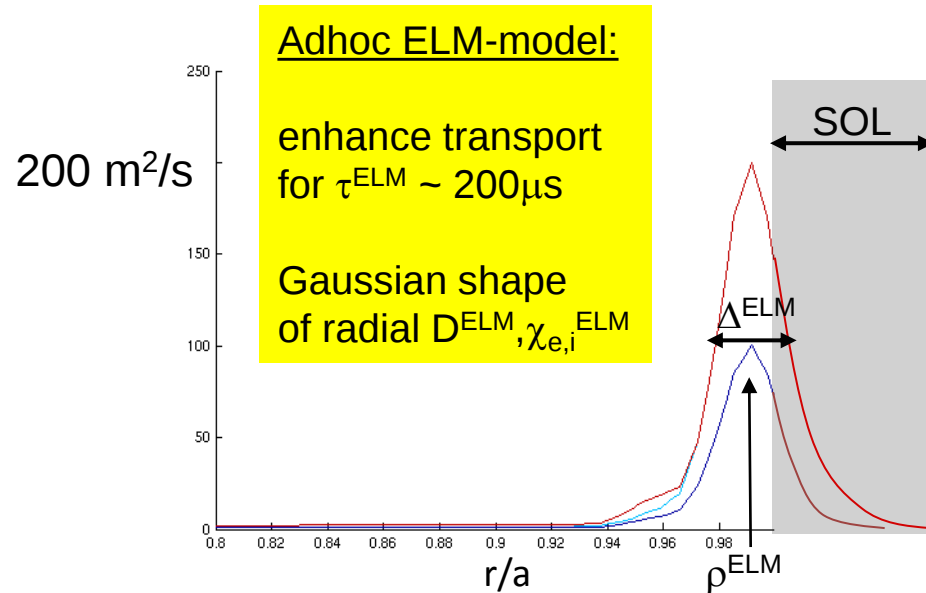
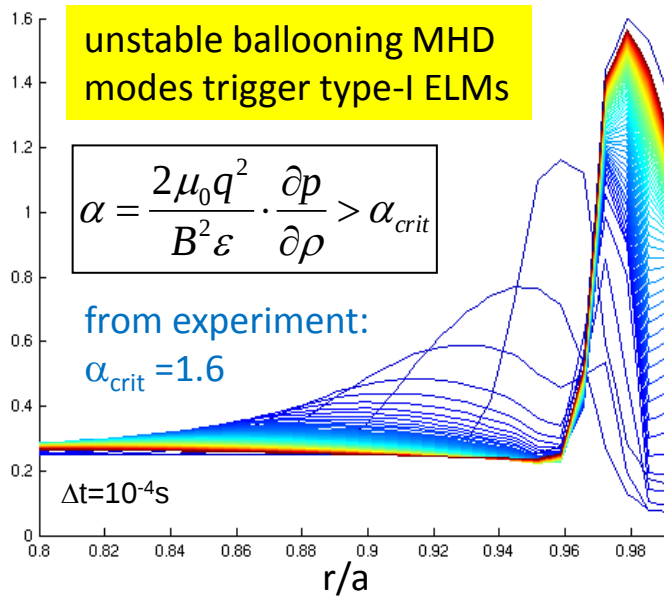
MISHKA, courtesy J.Lönnroth



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

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

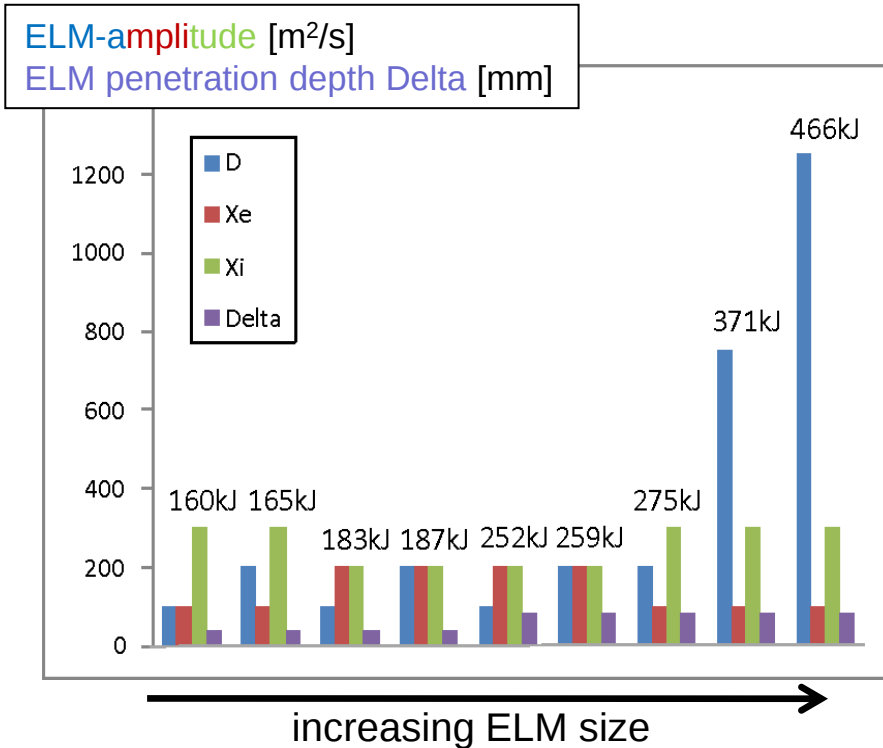
JINTRAC ELM-characteristics



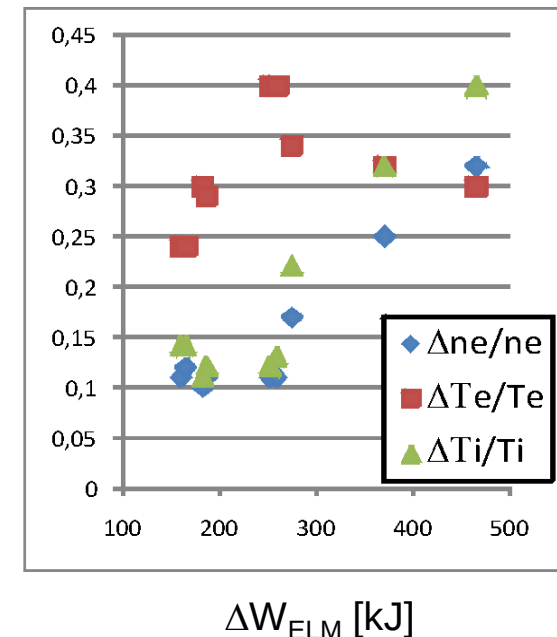
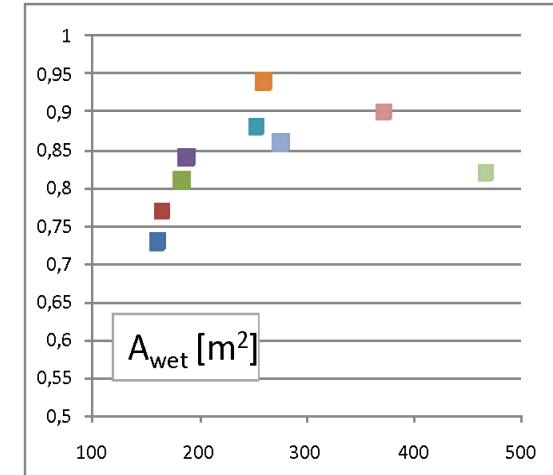
JINTRAC ELM characteristics studies



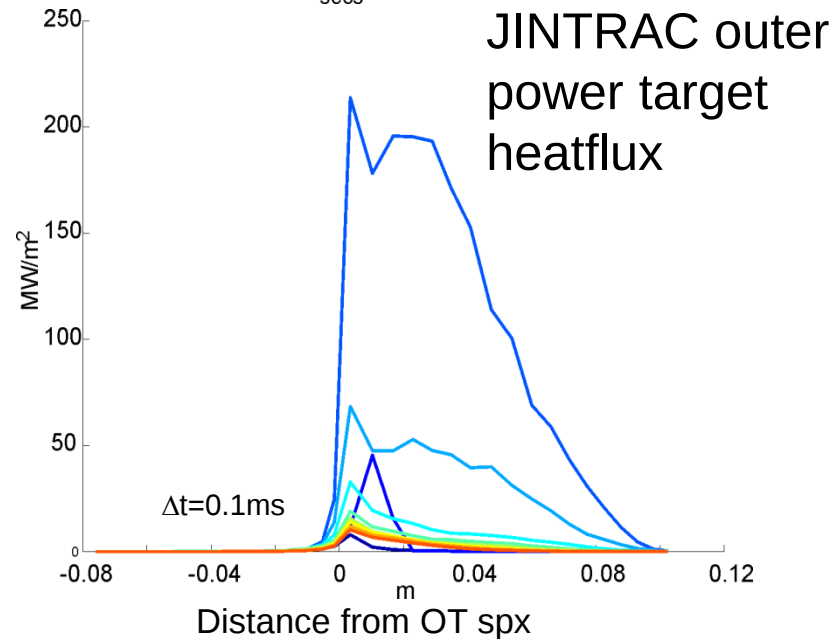
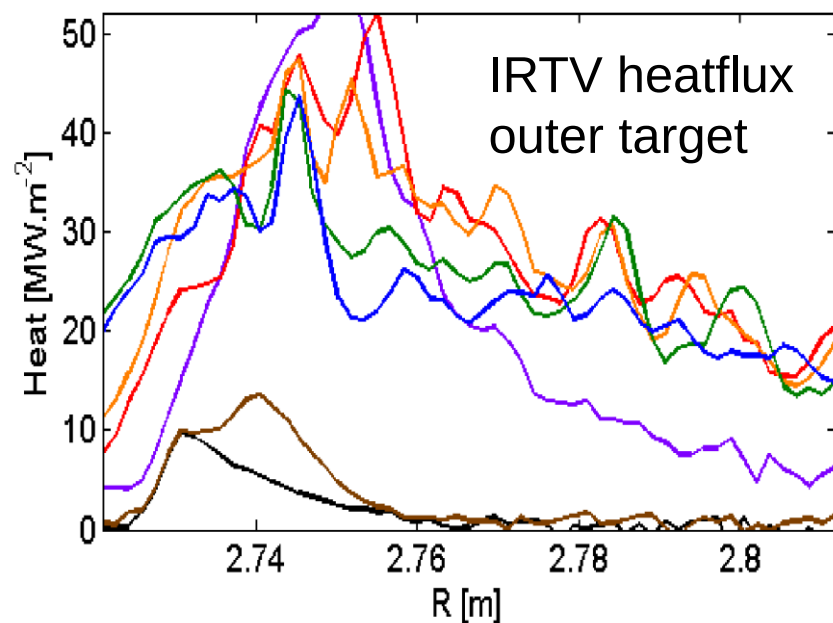
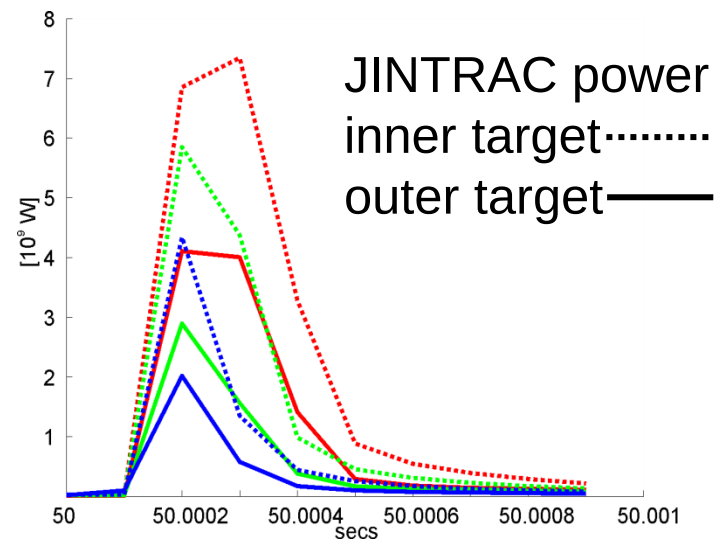
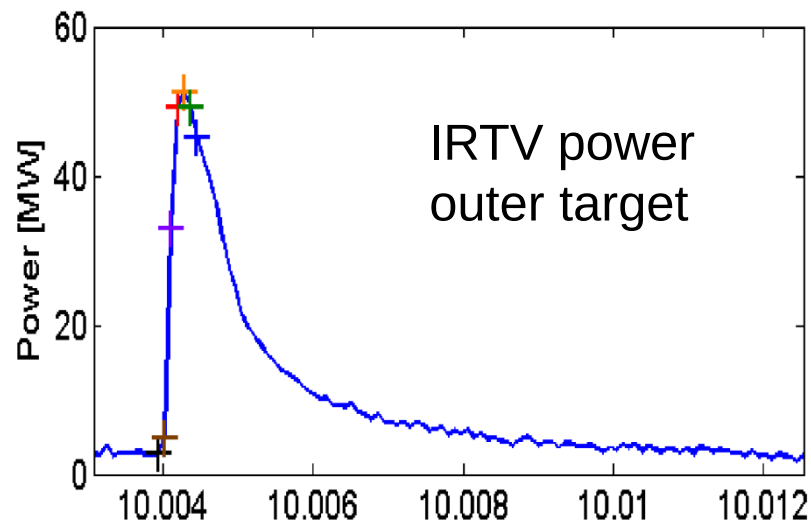
- ELM characteristics scan to vary ΔW_{ELM}



- 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)

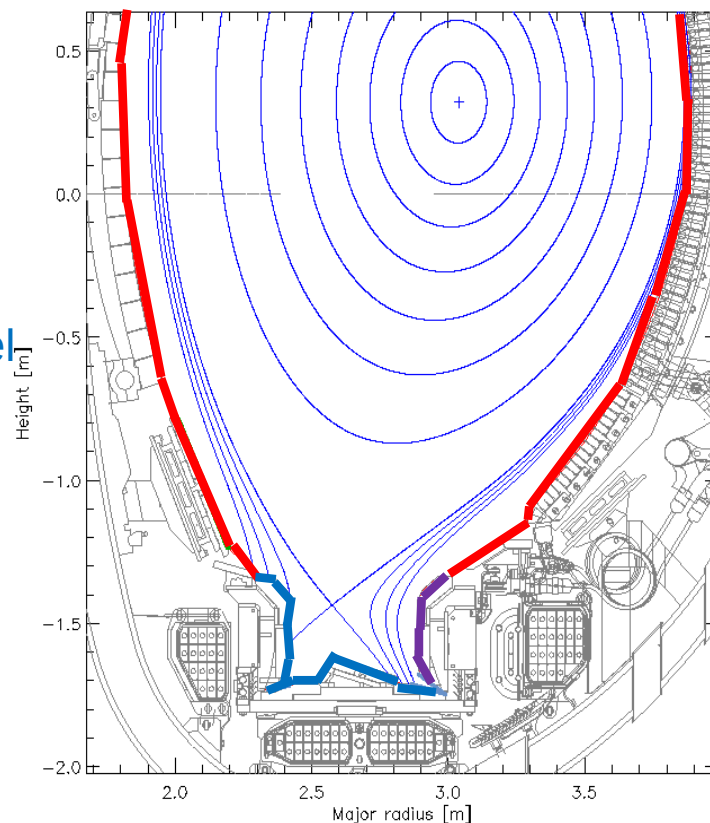


- main-chamber PFCs: beryllium, divertor: W-coated CFC or bulk-W
- other transport parameters as for the C-reference case (250kJ ELMs), i.e.:
 - geometry
 - inter- and intra-ELM transport model
 - SOL transport model
 - MHD critical pedestal pressure gradient
 - NBI power
 - gas-fuelling and pump-efficiency

- **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 $\rightarrow c_W$



- 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:

$$f_{\text{leak}} = \Gamma_W^{\text{core}} / \Gamma_W^{\text{gross-erosion}} \sim 5\%$$

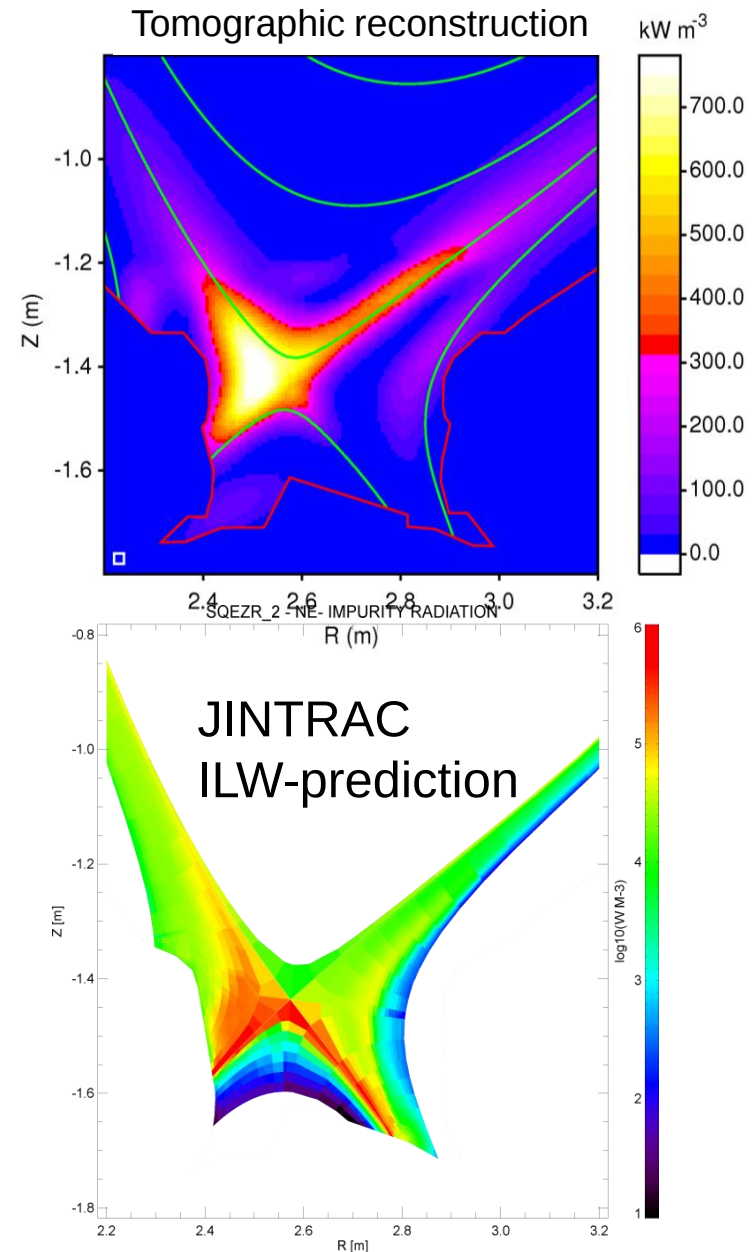
(including prompt re-deposition: $\sim 90\%$)

- $f_{\text{ELM}} = 15\text{Hz} \rightarrow$

$$\text{R.Dux et al., NF 51 2011: } \tau_W = 4 \cdot 10^2 \cdot f_{\text{ELM}}^{-1.1} \tau_{\text{SOL}}^{1.1} D_{\text{SOL}}^{0.1}$$

$$\rightarrow \tau_W \sim 0.1\text{s}$$

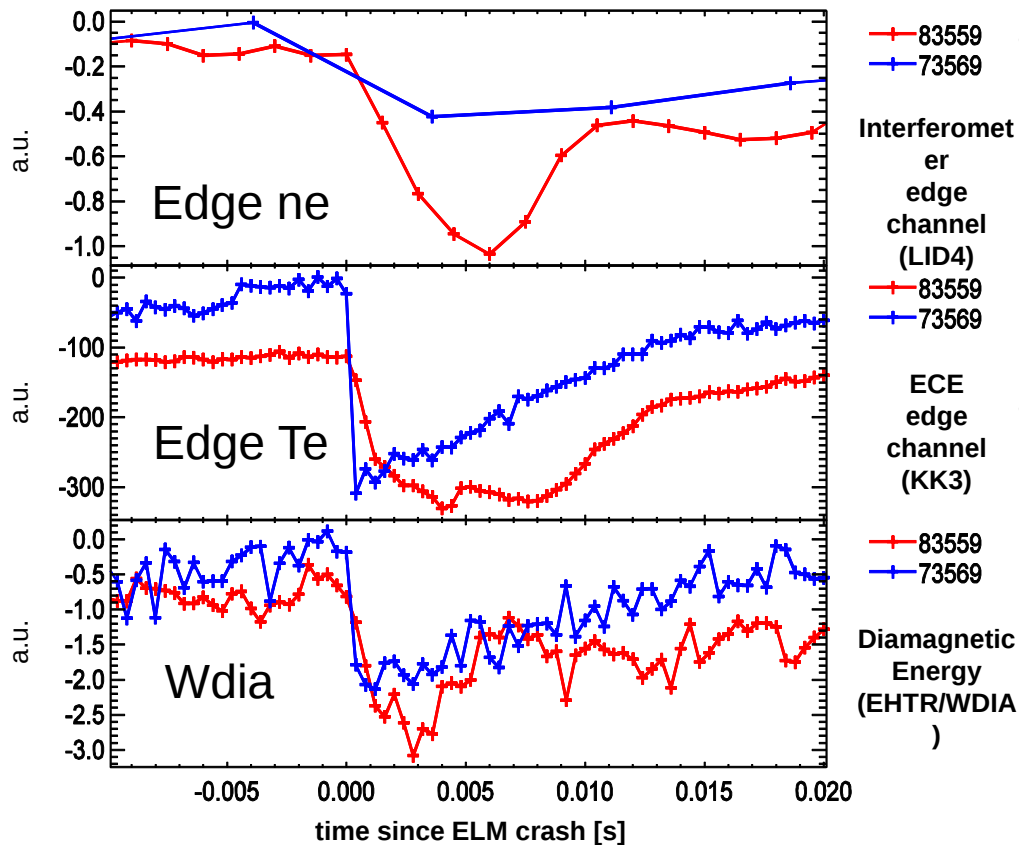
$\rightarrow$ low average W concentration in core $\rightarrow P_{\text{rad,W}} < 100 \text{ kW}$





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ELMs in JET-C vs. JET-ILW



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

fast ELM crash time
($<400 \mu\text{s}$, below the time resolution of ECE and W_{DIA})

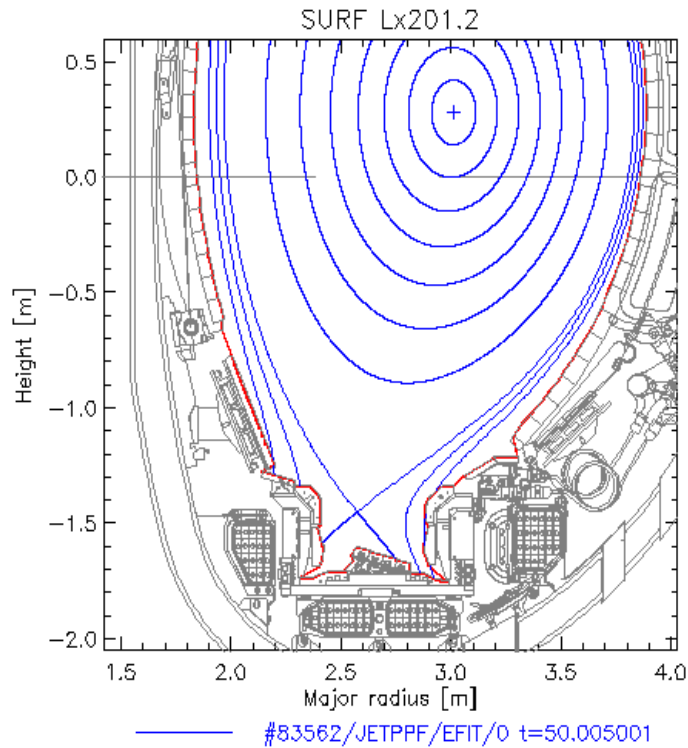
- JET-ILW (e.g. #83559, C30C):

slower drop of the edge electron density and temperature after the ELM crash (order of $\sim$ 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

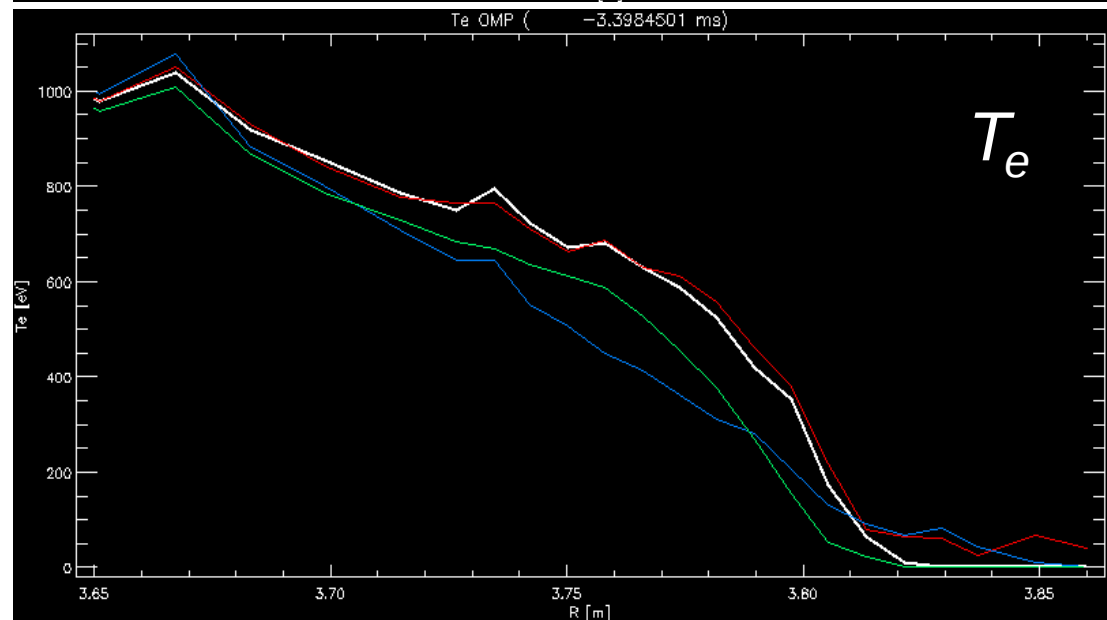
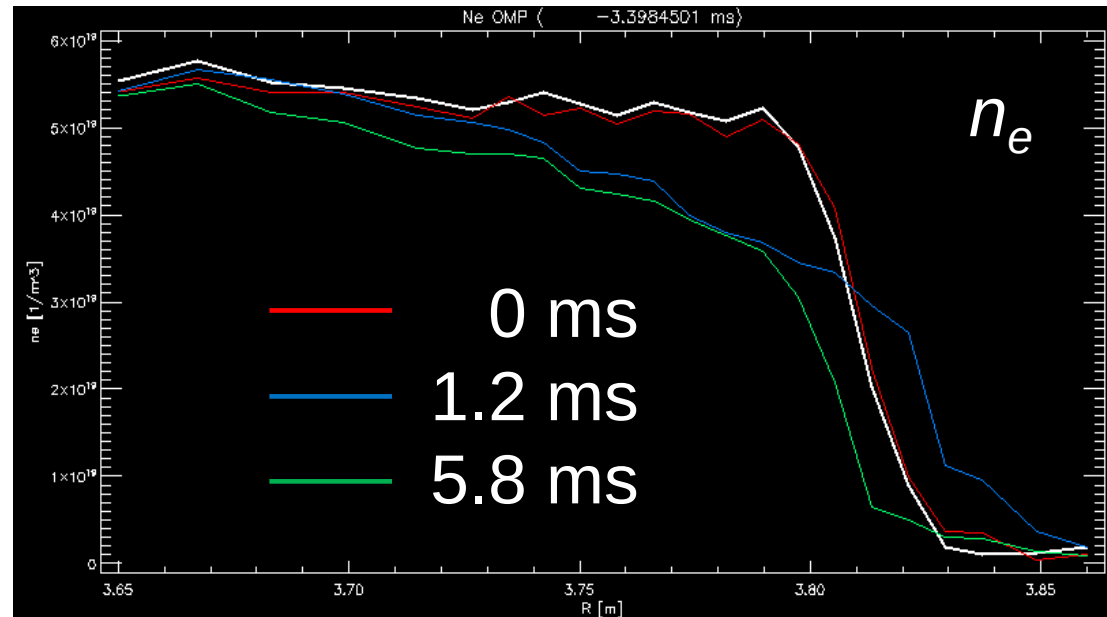
$I_p/B_t = 2.0\text{MA}/2.0\text{T}$, low- δ , $P_{\text{NBI}} = 12\text{MW}$

$f_{\text{ELM}} = 30\text{Hz}$, $\Delta W = 160\text{KJ}$, 6sec flat-top

S. Brezinsek et al, NF 2013

D.Harting, PSI 2014

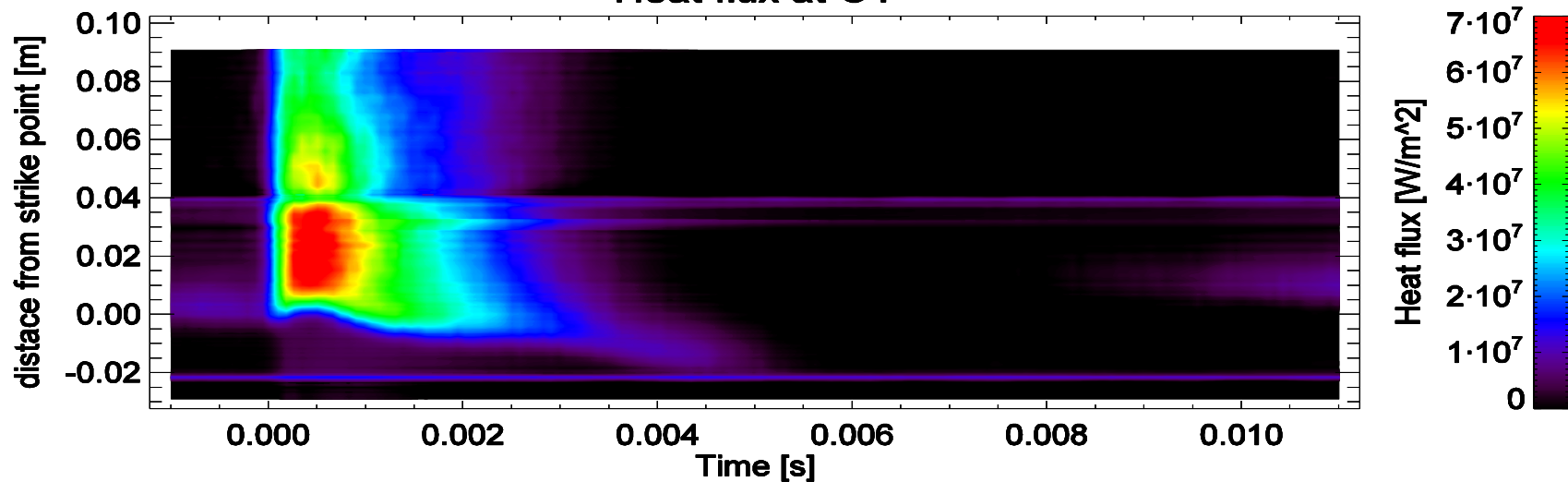
(Statistical analysis for HRTS
of 53 similar discharges)



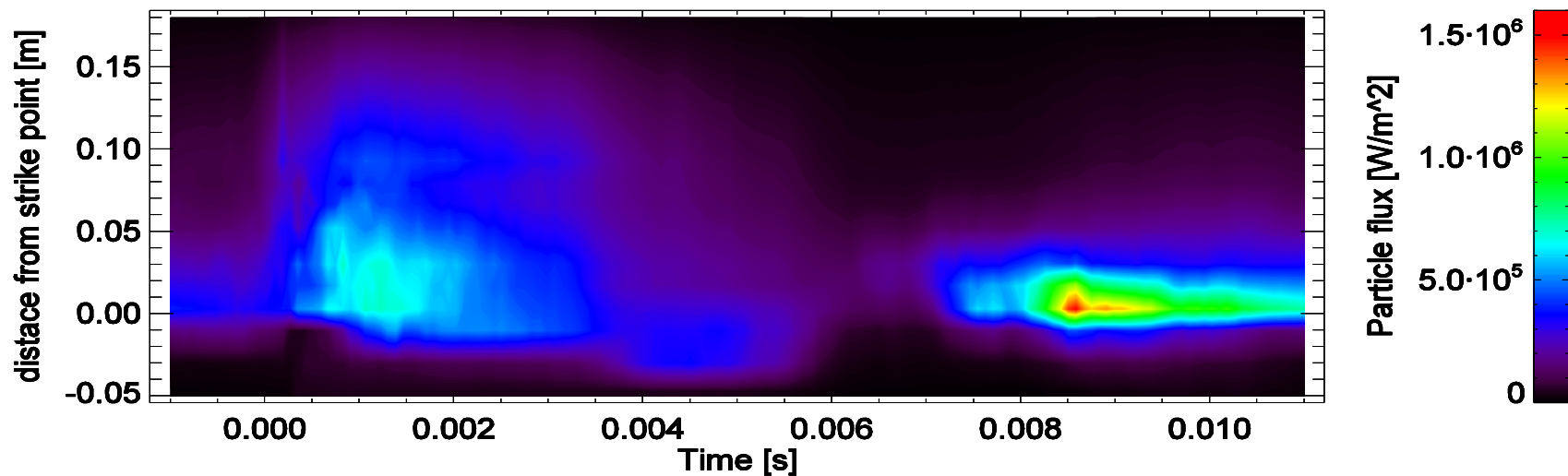
Outer Target Heat and Particle Flux JPN 83562



Heat flux at OT



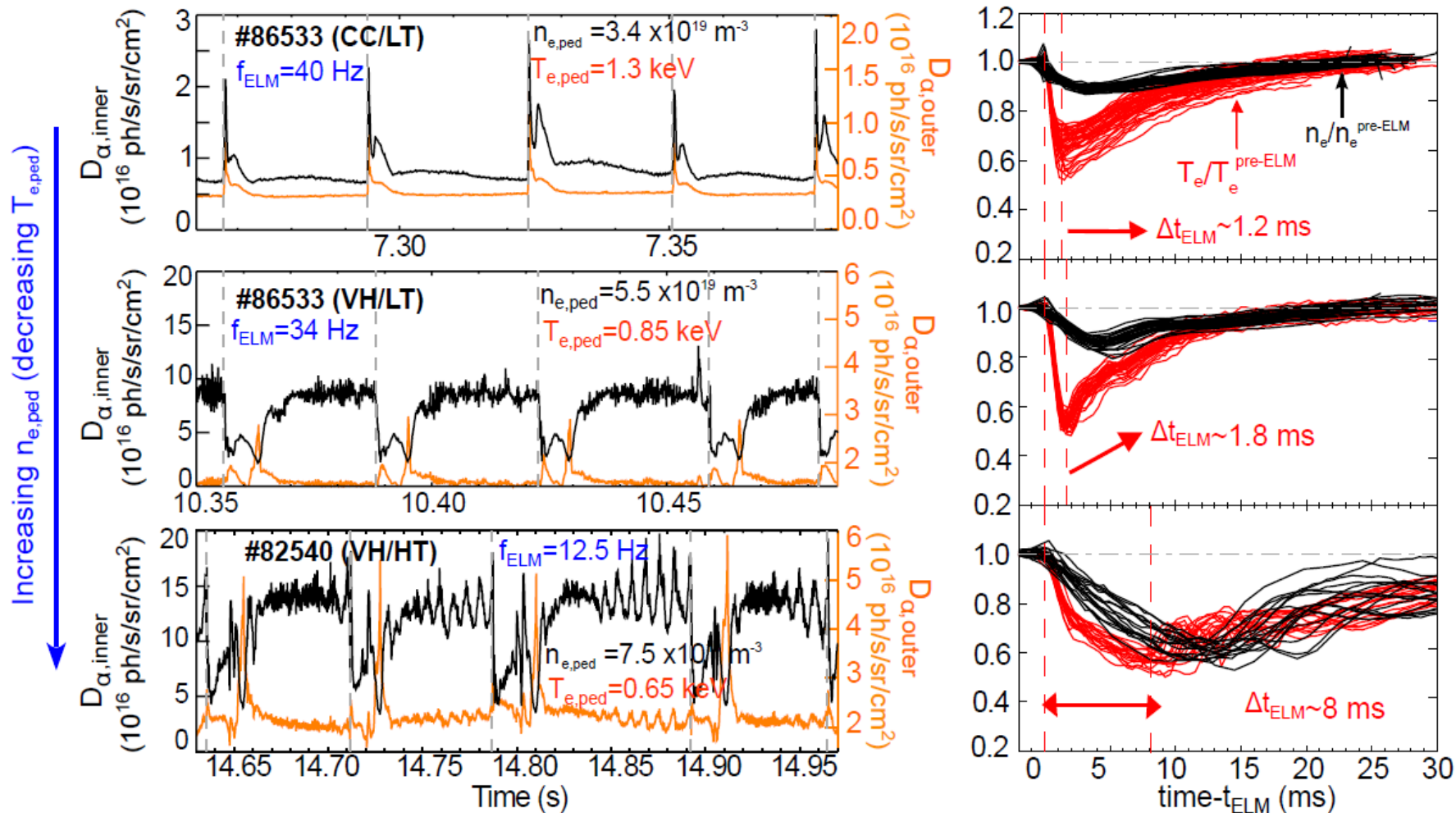
Saturation current at OT



JET-ILW: configuration scan $\rightarrow$ recycling scan



E. de la Luna IAEA2014

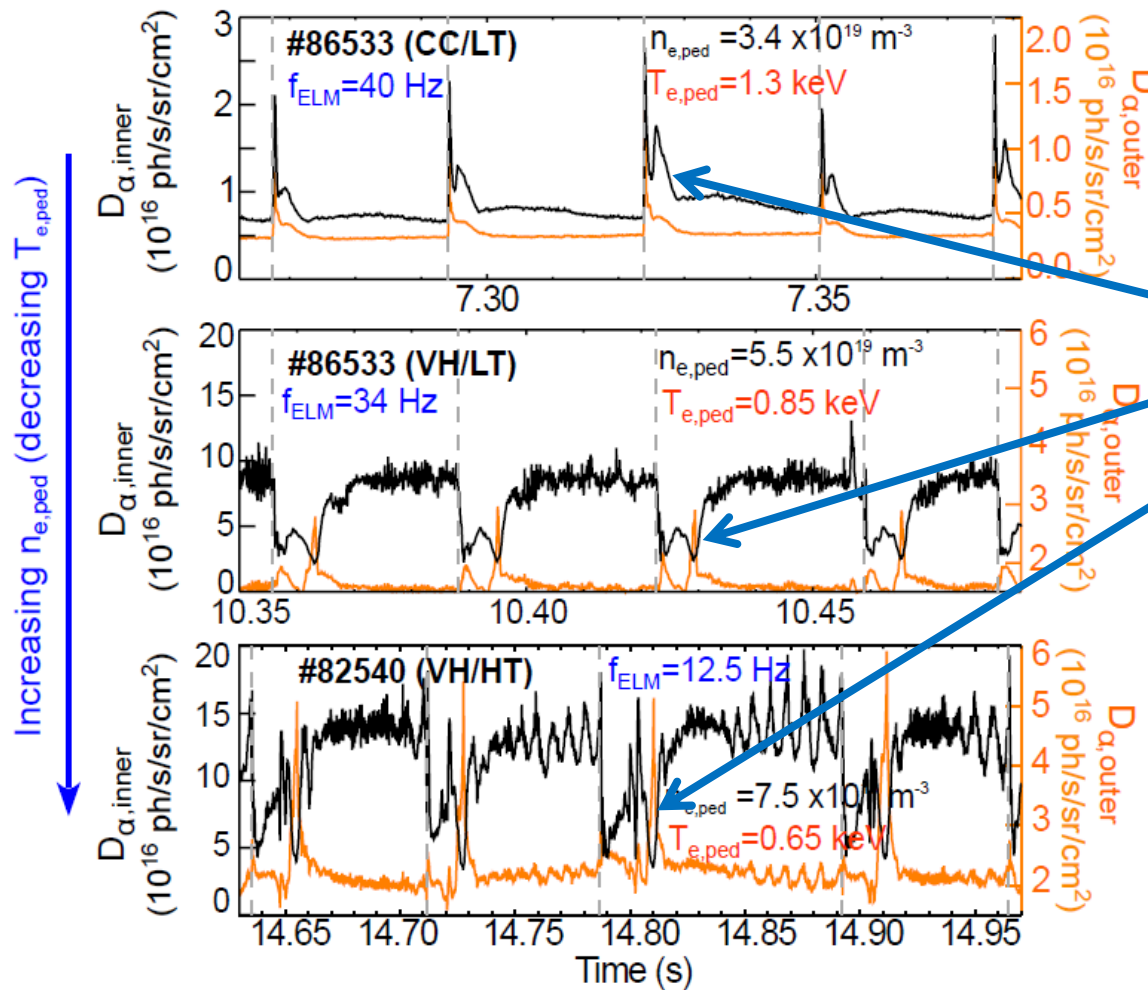


$\rightarrow$ Depending on the level of recycling:
 delay of pedestal build-up after ELM-crash

JET-ILW: configuration scan $\rightarrow$ recycling scan

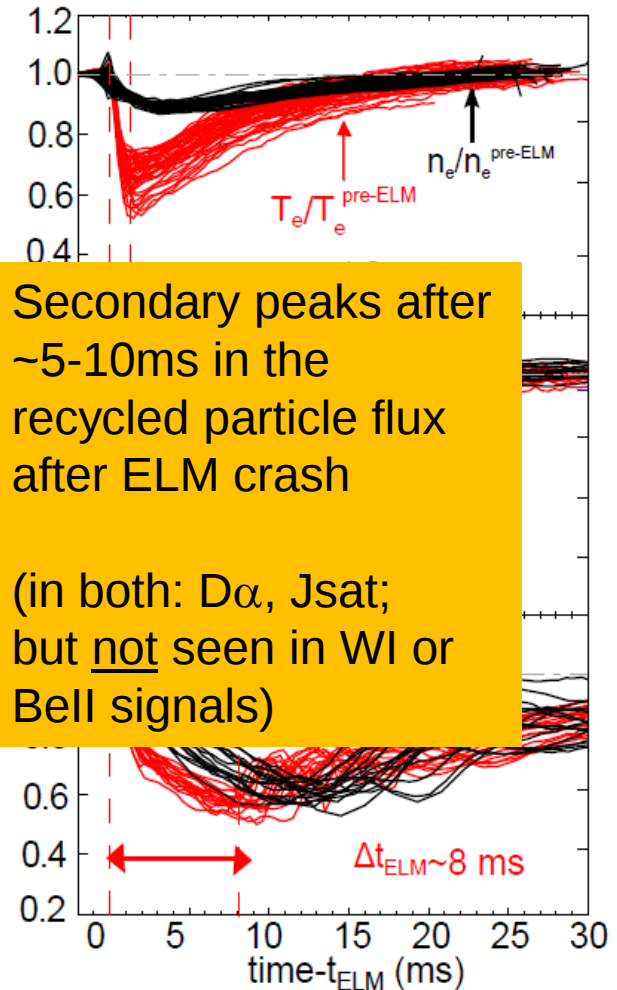


E. de la Luna IAEA2014



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

(in both: $D\alpha$, J_{sat} ;
 but not seen in WI or
 Bell signals)

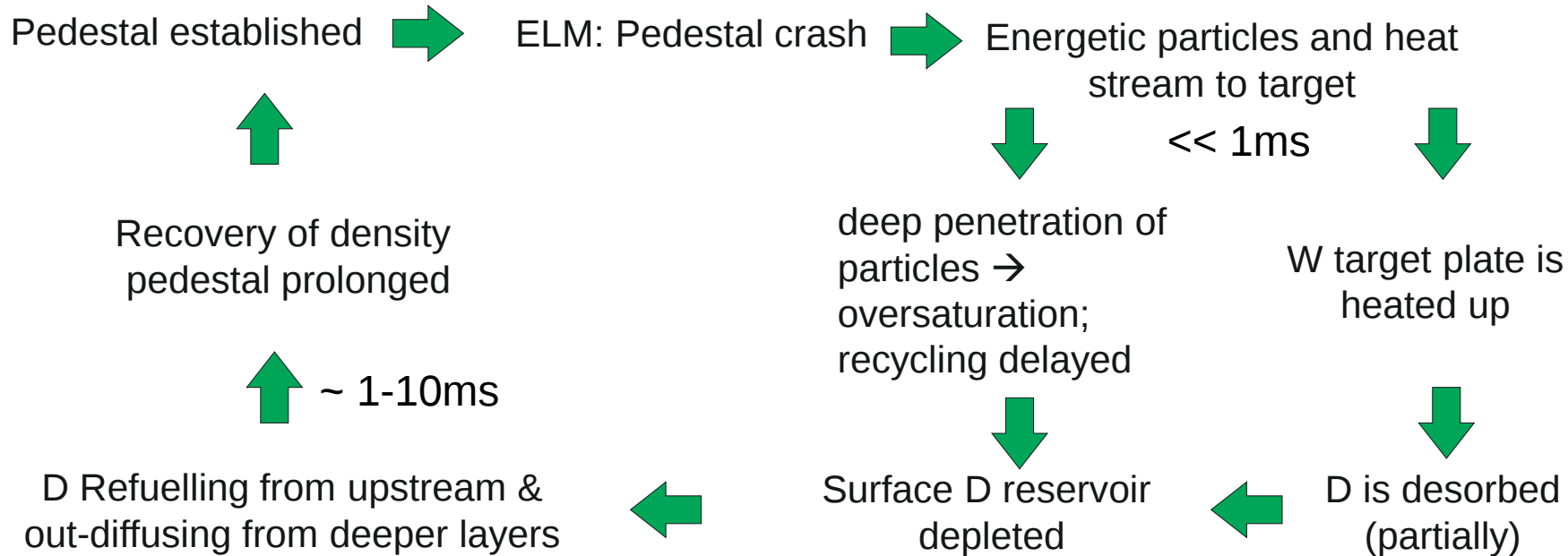


$\rightarrow$ Depending on the level of recycling:
 delay of pedestal build-up after ELM-crash

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



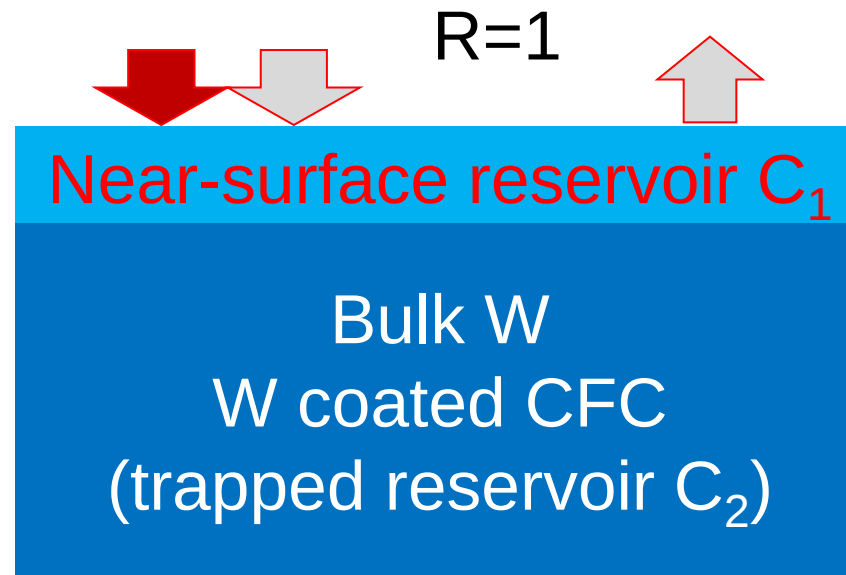
- Fast D-desorption ($\ll 1\text{ms}$) in the order of 10^{20} particles after ELM impact (near surface)
- Local sources (gas injection/re-absorption of neutrals) cannot provide in a few ms the necessary amount of D to refill

- Effective „Refill-time“ determined by the amount of outgassed D (finite) and the flux to target ($\sim 10^{23} \text{ D/m}^2\text{s}$, depends on plasma)
→ varies between $\sim 1\text{-}10\text{ms}$ (in C: no sign.delay)

Modified Recycling model (1/4)



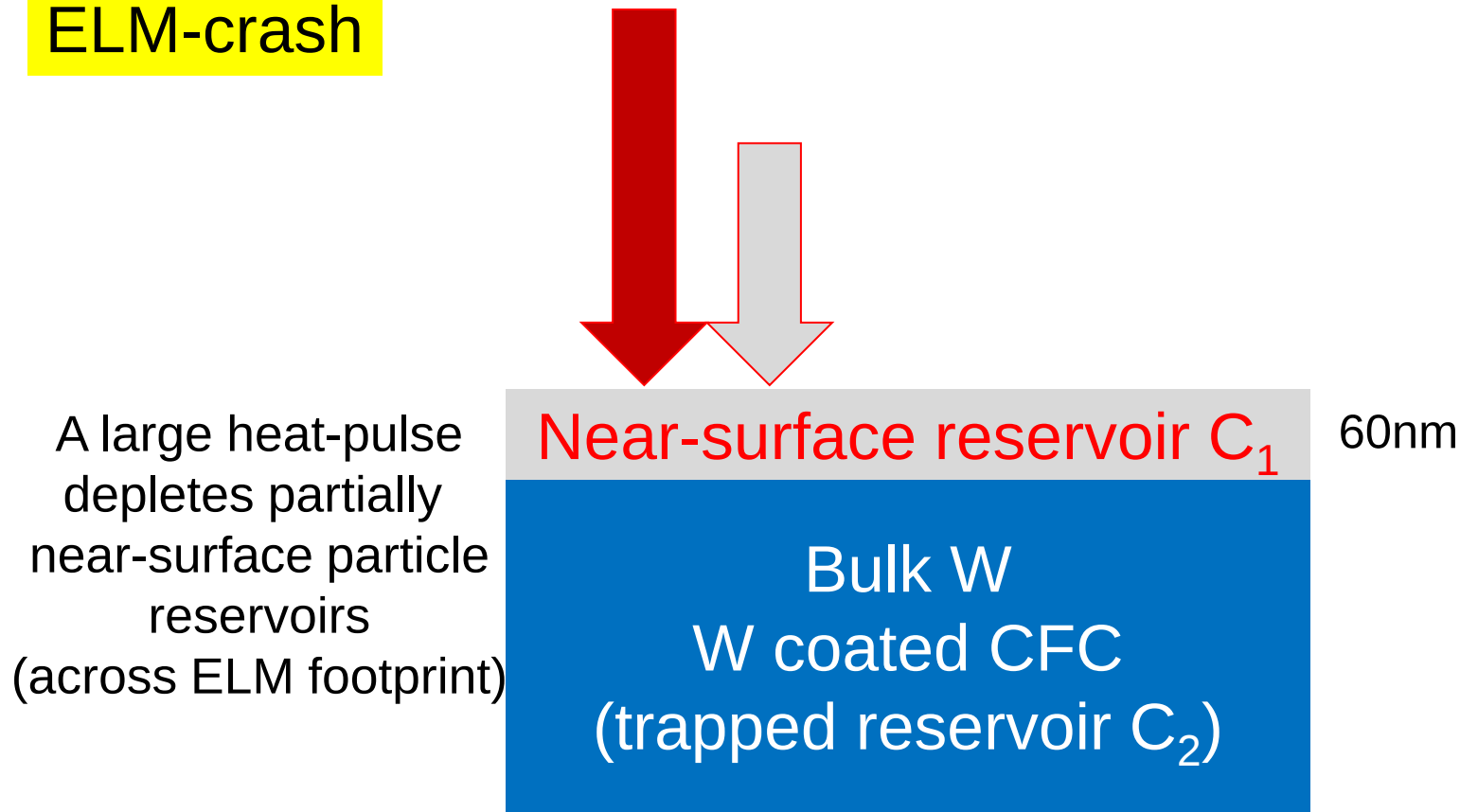
Inter-ELM
(i.e. pre-ELM)



Modified Recycling model (2/4)



ELM-crash



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

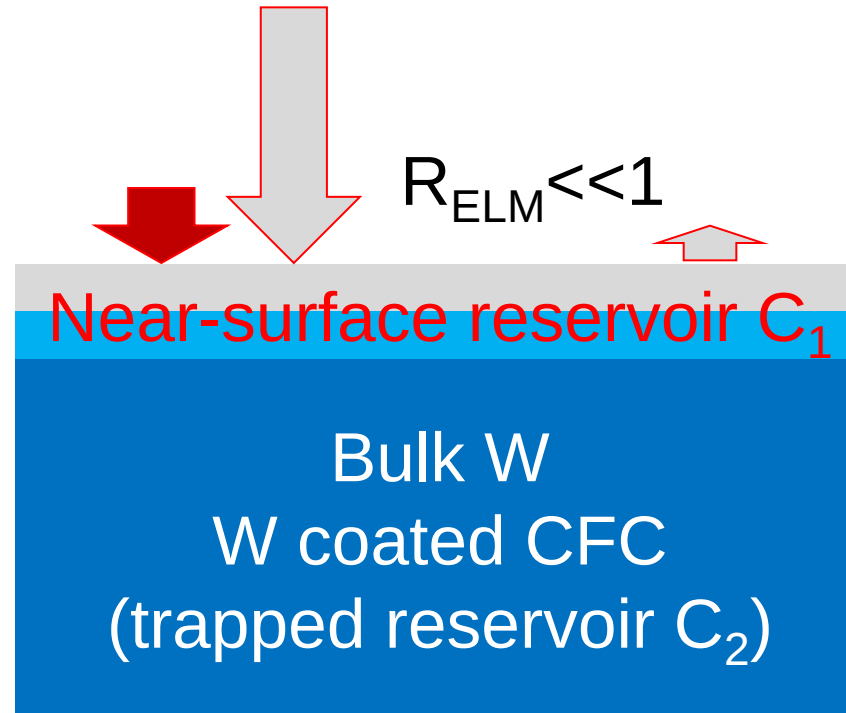
Modified Recycling model (3/4)



Shortly after
ELM <1ms:

Recycling strongly
reduced:

refilling
 C_1 reservoir

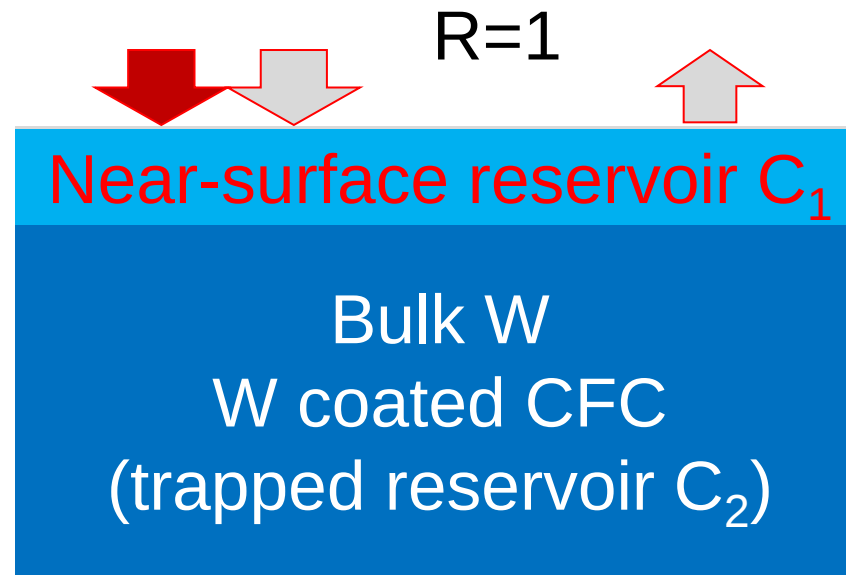


Modified Recycling model (4/4)



Few ms after
ELM crash:

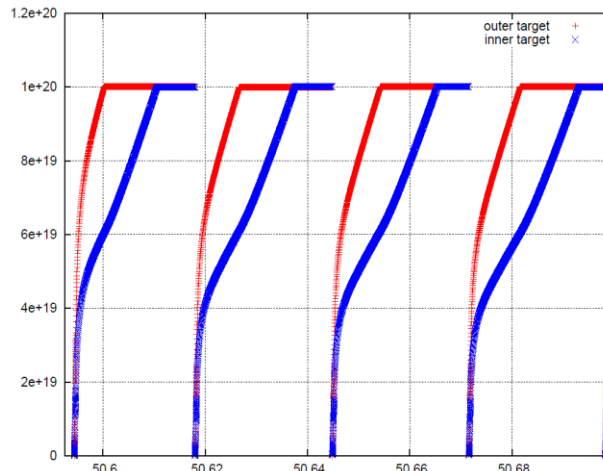
C_1 replenished:
remaining ELM
driven particle
flux
recycled



Result: Impact on pedestal refuelling

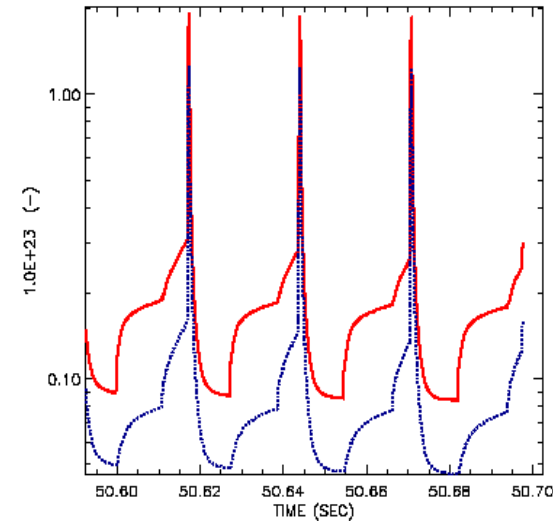


Near surface reservoirs

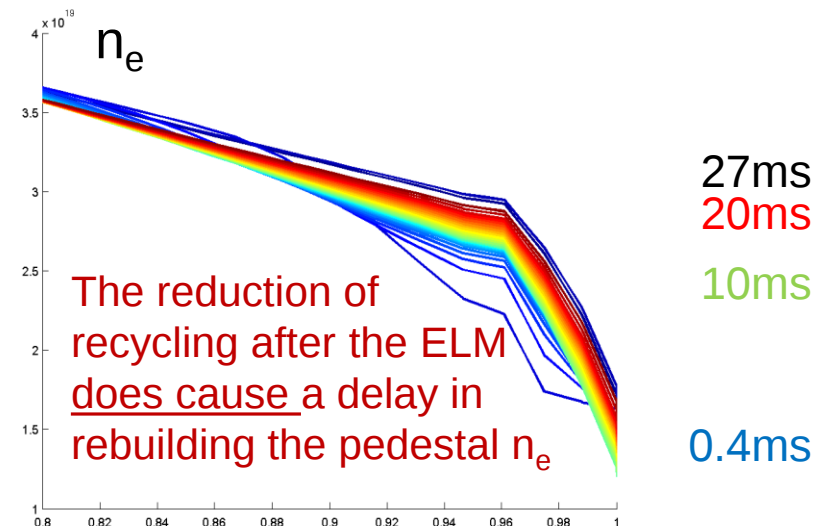
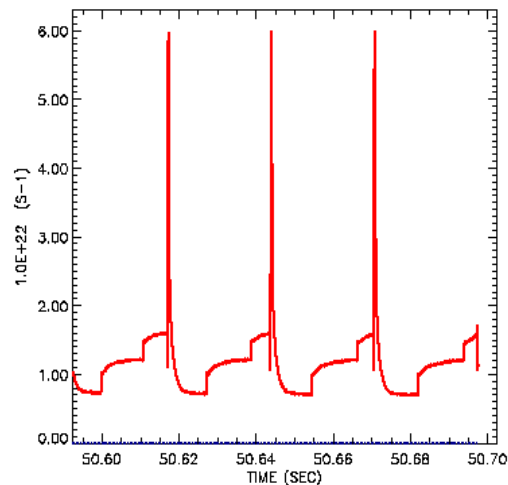


Outer target
Inner target

Ion flux to targets



Neutral flux across spx



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

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

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

- The delayed secondary peak in $D\alpha/J_{\text{sat}}$ not reproduced yet:
 - In the simple model we did not credit for the ELM induced energetic particles ($E_{\text{kin}} \sim T_{\text{ped}} \sim 1000\text{eV}$) which penetrate much deeper into the W-PFC, leading to multi-trapped particles → oversaturated solute → delayed out-diffusion

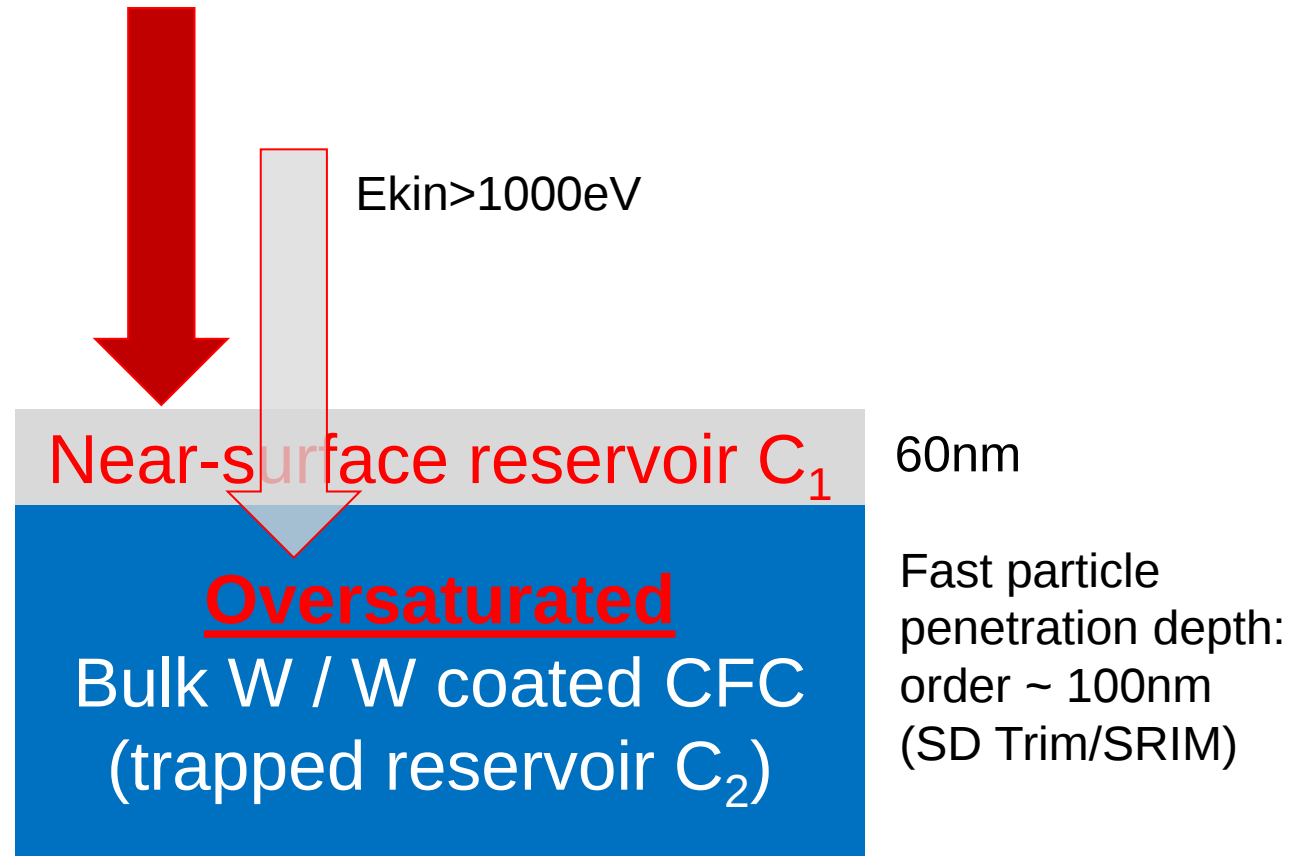
→ a secondary deep layer reservoir C_2 available (with delayed diffusive outgassing)

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



ELM-crash

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

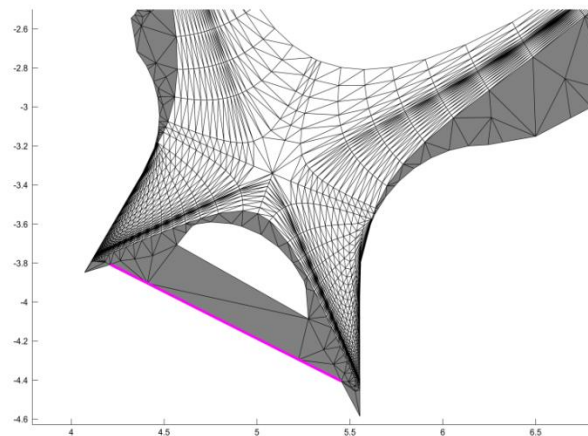
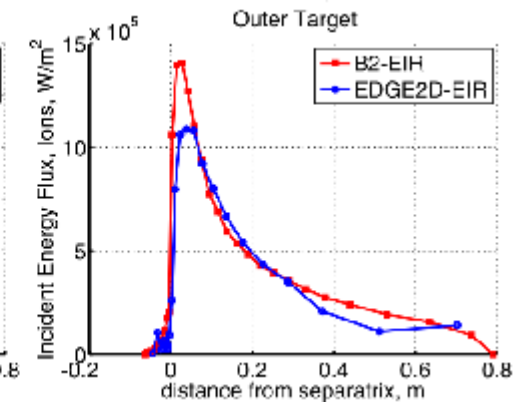
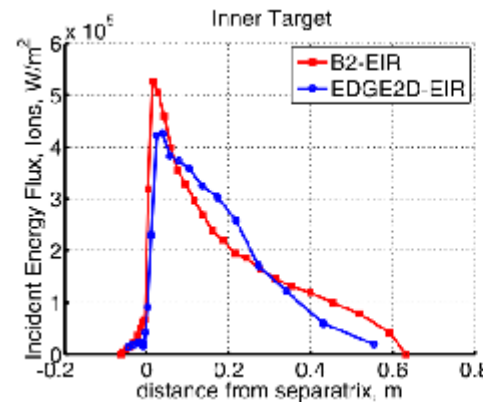
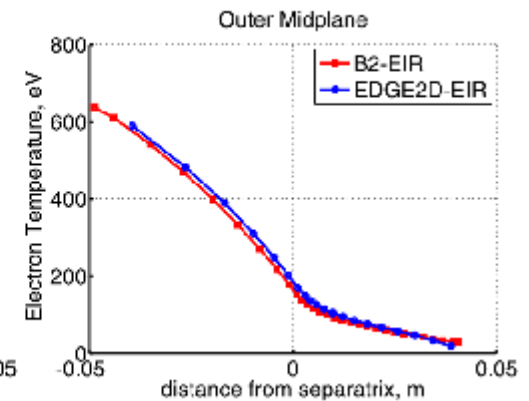
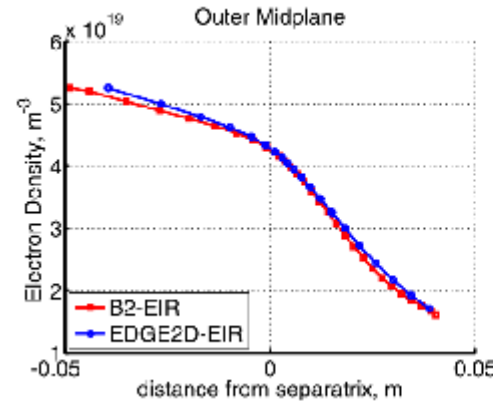
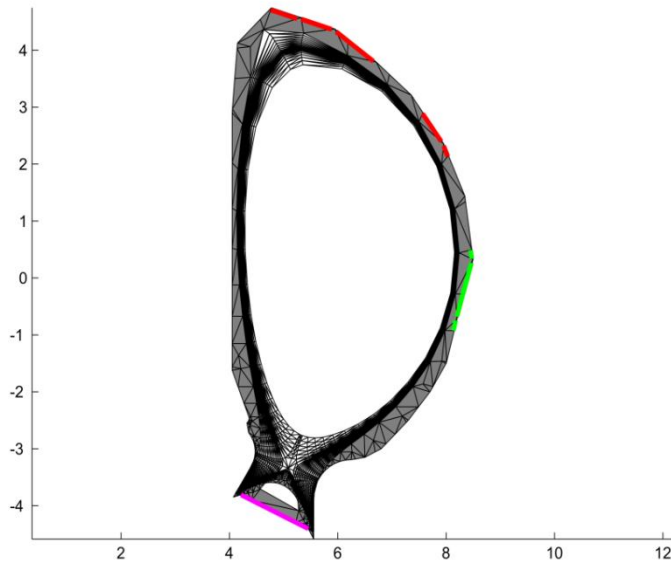


after-ELM C_1 reservoir balance: plasma flux and D out-diffusion of deep layers



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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): $\Gamma_{\text{core}} = 2e21..1e23 \text{ s}^{-1}$
 top D2 gas flux: $\Gamma_{\text{gas}} = 1.4e23 \text{ s}^{-1}$ fixed (factor 3 higher as in SOLPS)
 omp Neon gas flux: $\Gamma_{\text{Ne}} = 1e19..8e19 \text{ s}^{-1}$
- particle sinks:
 pumping surface below divertor dome:
 albedo = 0.94 $\rightarrow L = A (1-\text{albedo}) 36.38 (T_{D2}/4) \sim 790 \text{ m}^3/\text{s}$
- heat sources: $P_{\text{edge}} = 80 \text{ MW}$ (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 $v=300\text{m/s}$
- 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: $\alpha_{\text{crit}} = 1.7$
- fusion product: DITRAN-2
- NBI aux power: 33MW PENCIL, $P_{\text{rad}}^{\text{core}}=43\text{MW}$ fixed ($Z_{\text{eff}}=1.7$ flat)
- EDGE2D-EIRENE transport model: as before, $\Gamma_{\text{gas}}=1.4e23\text{s}^{-1}$ fixed, **$P_{\text{rad}}^{\text{SOL}}=60\text{MW}$ fixed (impurity transport neglected)**

Pedestal/core profiles (minimum, before pellet)



$$\begin{aligned} n_{e, \text{ped}} &= 1.05e20 \text{ m}^{-3} \\ n_{e, \text{ped}} &= 0.88e20 \text{ m}^{-3} \\ n_{e, \text{ped}} &= 0.70e20 \text{ m}^{-3} \end{aligned}$$

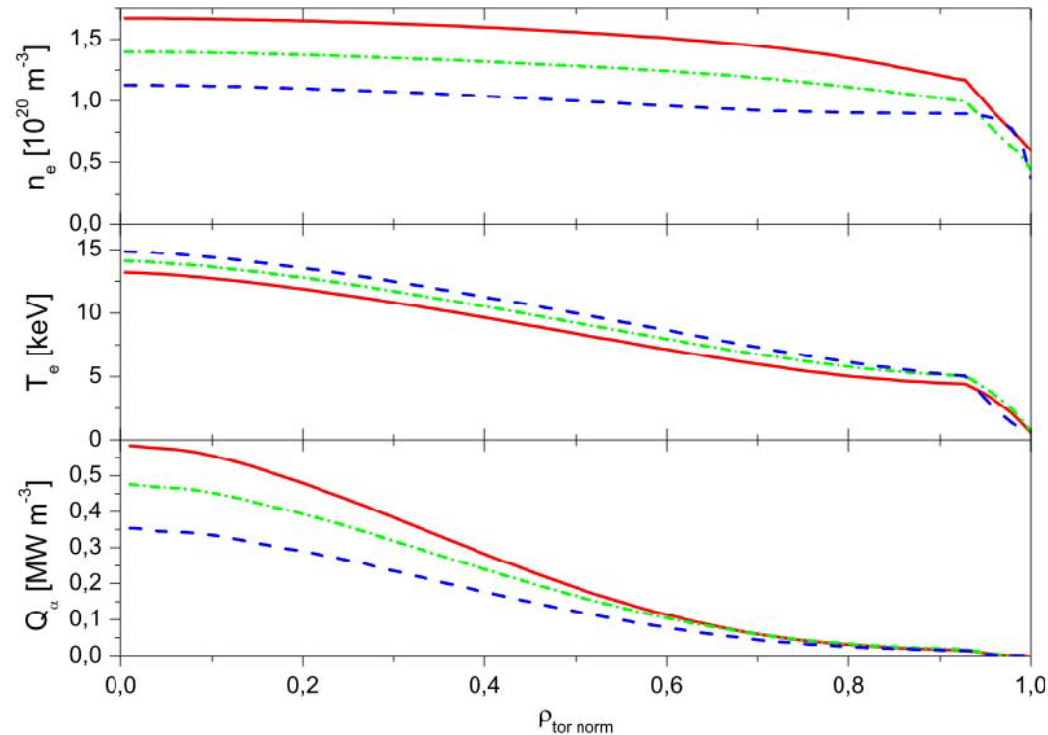


Figure 9 From top to bottom: electron density, electron temperature and α power deposition at the time $t = 339.3$ s for the simulations shown in Fig. 7.

Time-transients

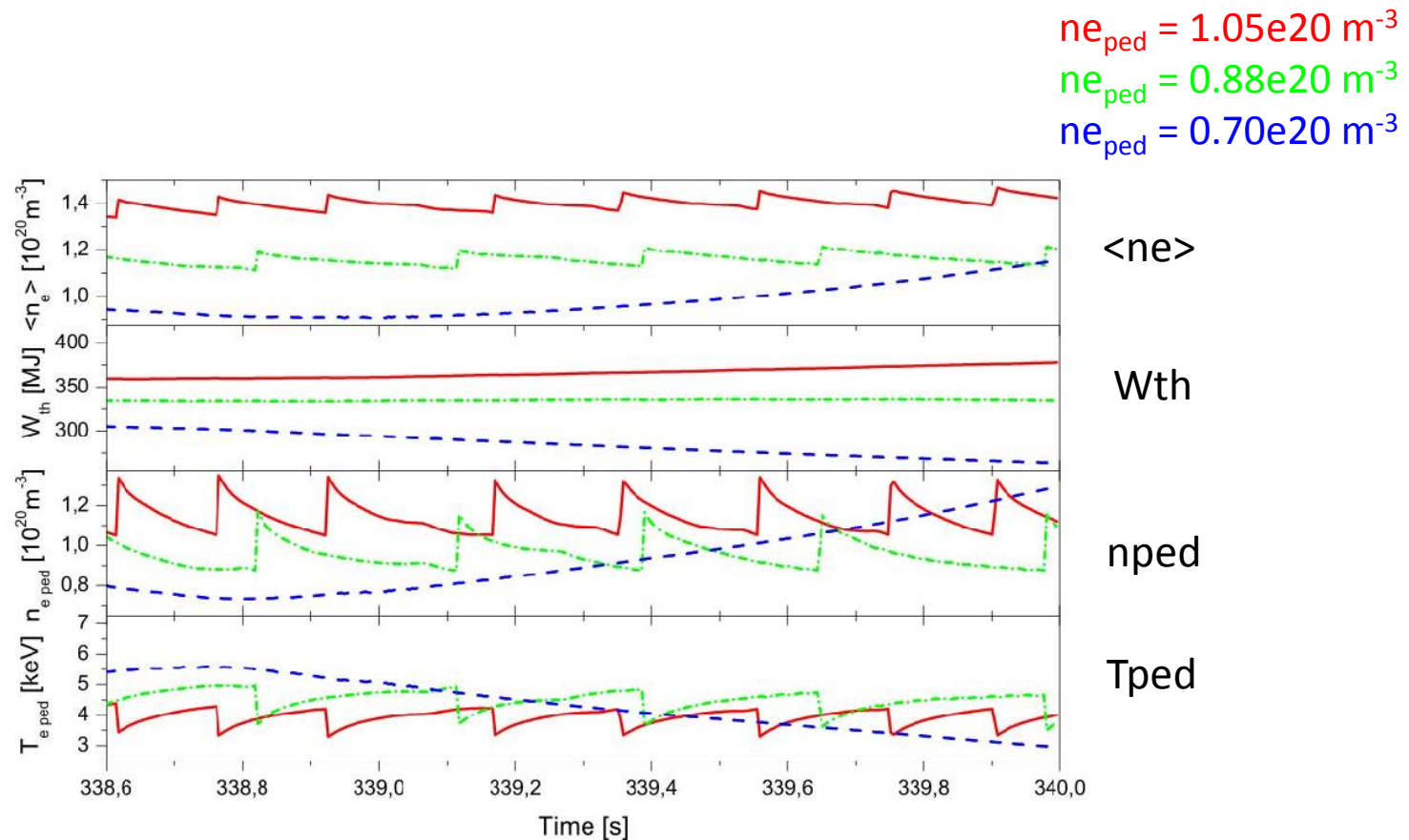


Figure 7 From top to bottom: average electron density, thermal energy content, electron density on top of the pedestal, electron temperature on top of the pedestal, for simulations of an ITER ELMy H-mode scenario ($t = 338.6\text{--}340$ s) with pellet feedback maintaining a minimum density level of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

Transient confinement



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

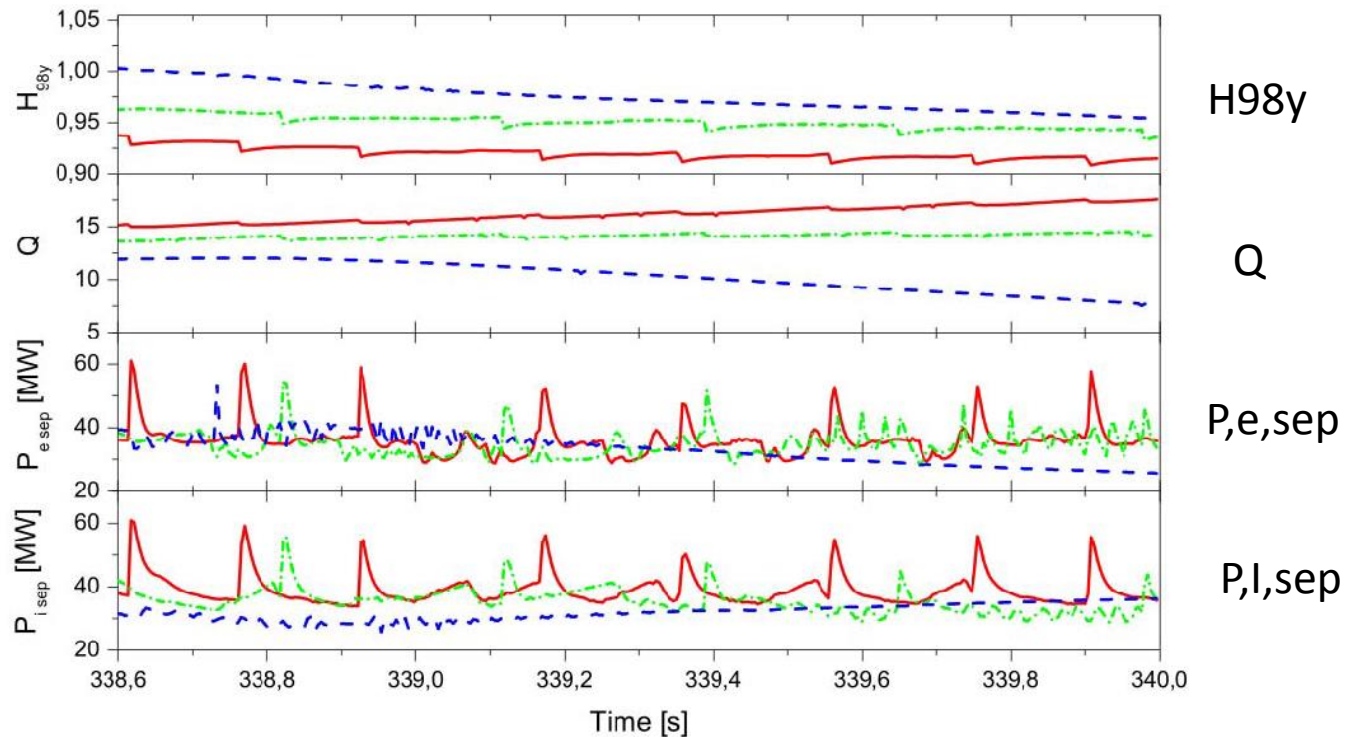


Figure 8 From top to bottom: H_{98y} , fusion Q , electron and ion power crossing the separatrix for the same simulations as shown in Fig. 7.

Dynamic Operational Space



$$\begin{aligned} n_{e,ped} &= 1.05e20 \text{ m}^{-3} \\ n_{e,ped} &= 0.88e20 \text{ m}^{-3} \\ n_{e,ped} &= 0.70e20 \text{ m}^{-3} \end{aligned}$$

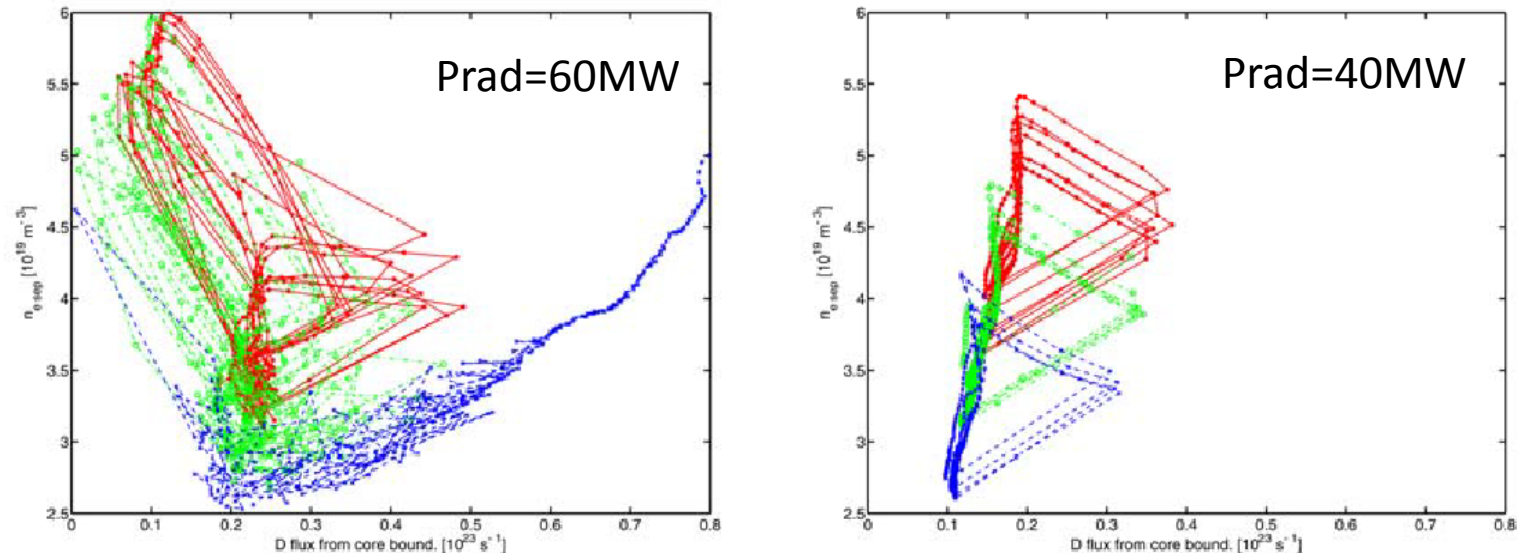


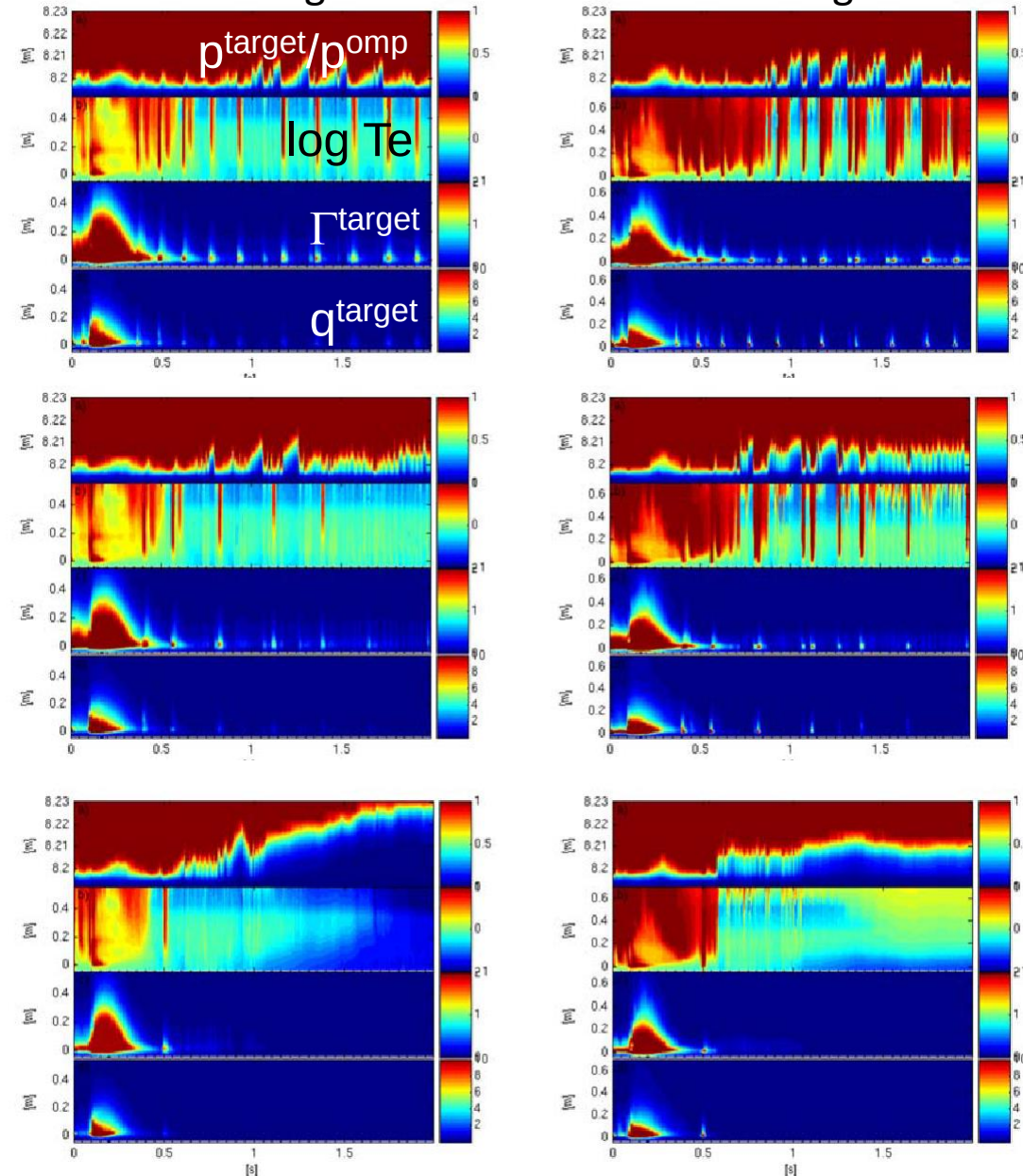
Figure 14 Electron densities at the separatrix as a function of the deuteron flux at the separatrix, for simulations of an ITER ELMy H-mode scenario ($t = 338.6\text{-}340$ s) with a minimum electron density level of 1.05 (solid/red), 0.875 (dash-dotted/green), and $0.7 \cdot 10^{20} \text{ m}^{-3}$ (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 $E \times B$ drift taken into account).

Target/divertor conditions



HFS target

LFS target



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

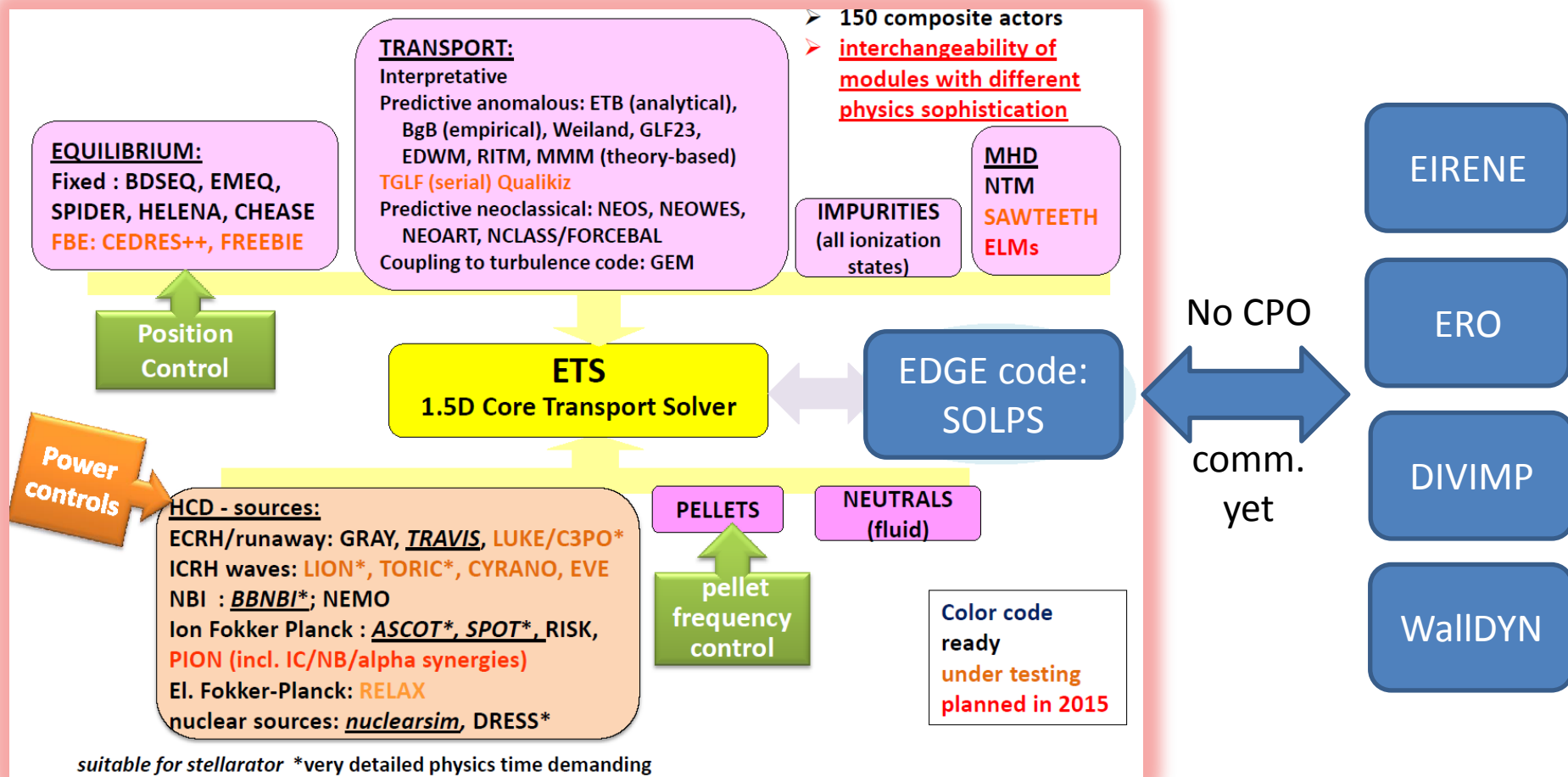
- Medium density:
the inner target stays detached whilst the outer target reattaches at pellet ablation time
→ a preferred scenario

- Low density:
both targets are completely detached
→ very difficult to control



- Motivation - Why need for integrated modelling?
- JET data analysis example 1:
Analysis of JET type-I ELM cycles ($C \rightarrow ILW$)
- 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

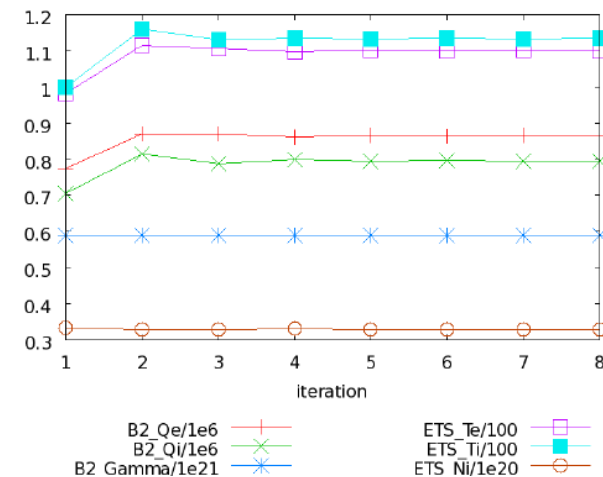
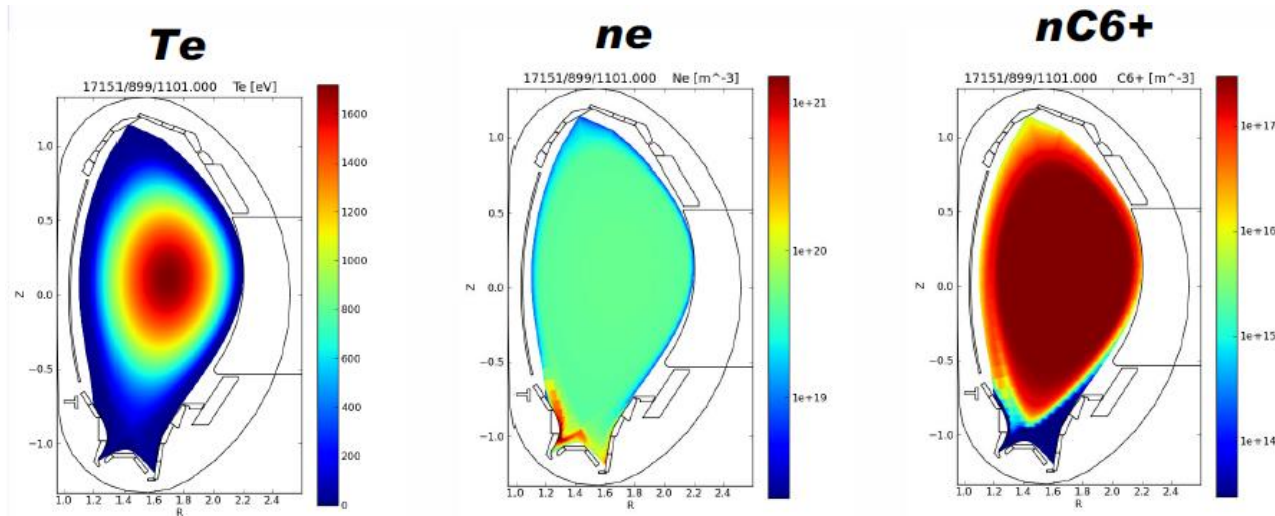
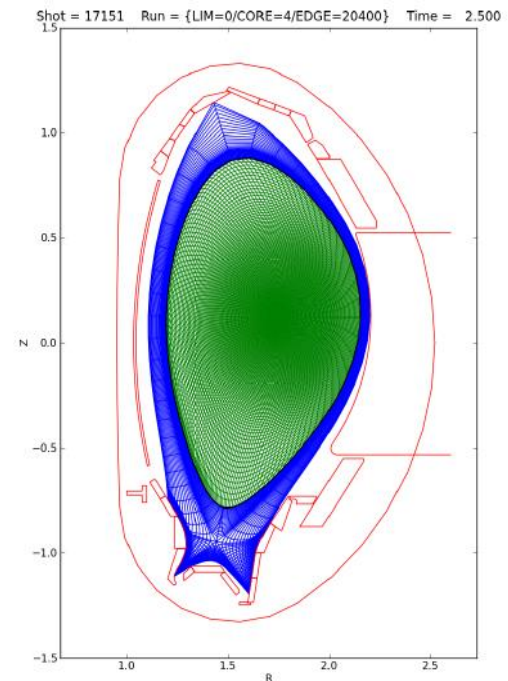


ETS-SOLPS coupling scheme



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

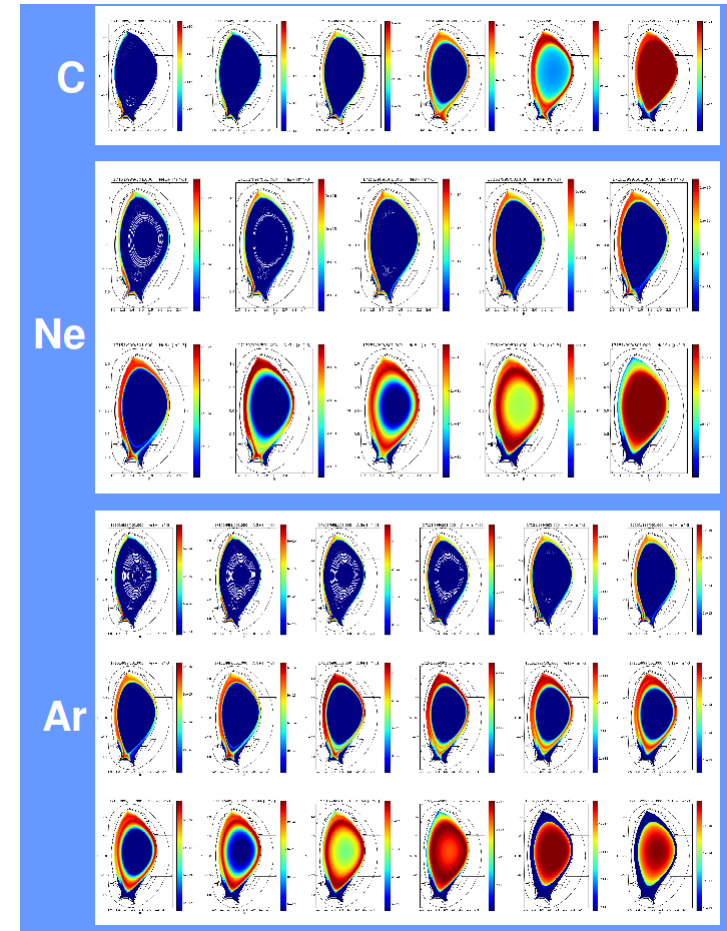
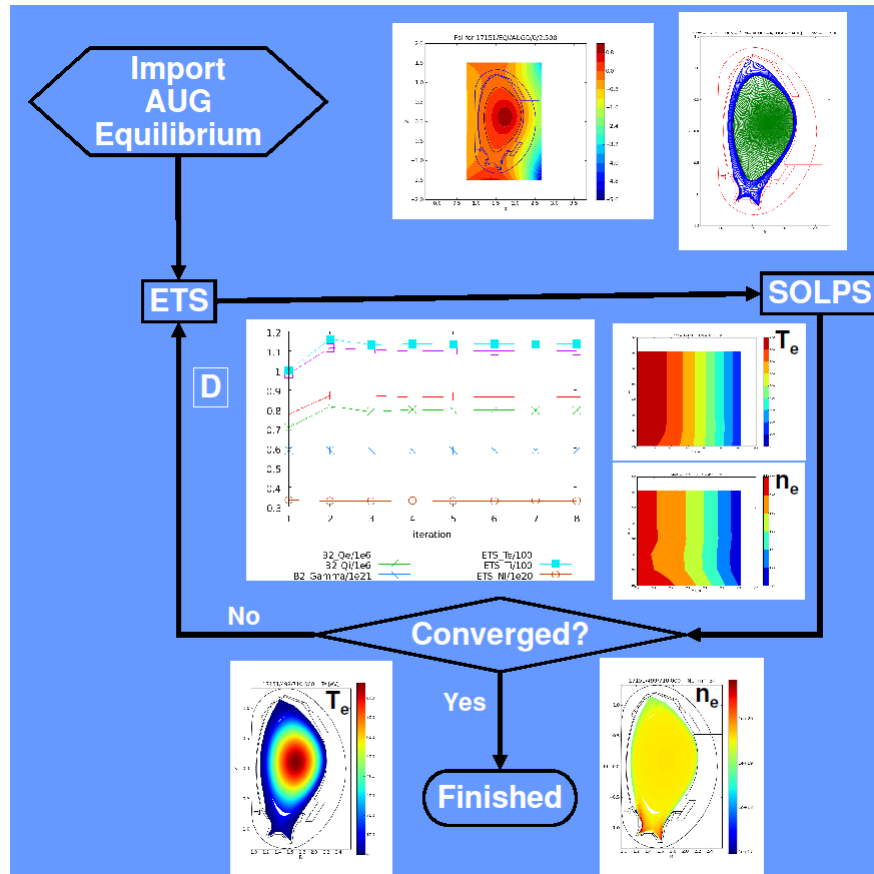
- Fluxes: ETS→SOLPS, boundary SOLPS→ ETS. Converged after few iterations
- CLISTE equilibrium for AUG shot → HELENA for core equilibrium, CARRE for edge geometry
- Main species (D, He) and impurity (C, Ar, Ne) are simulated
- Neutrals – SOLPS only simulations (zero-flux boundary conditions)



ETS-SOLPS coupling scheme



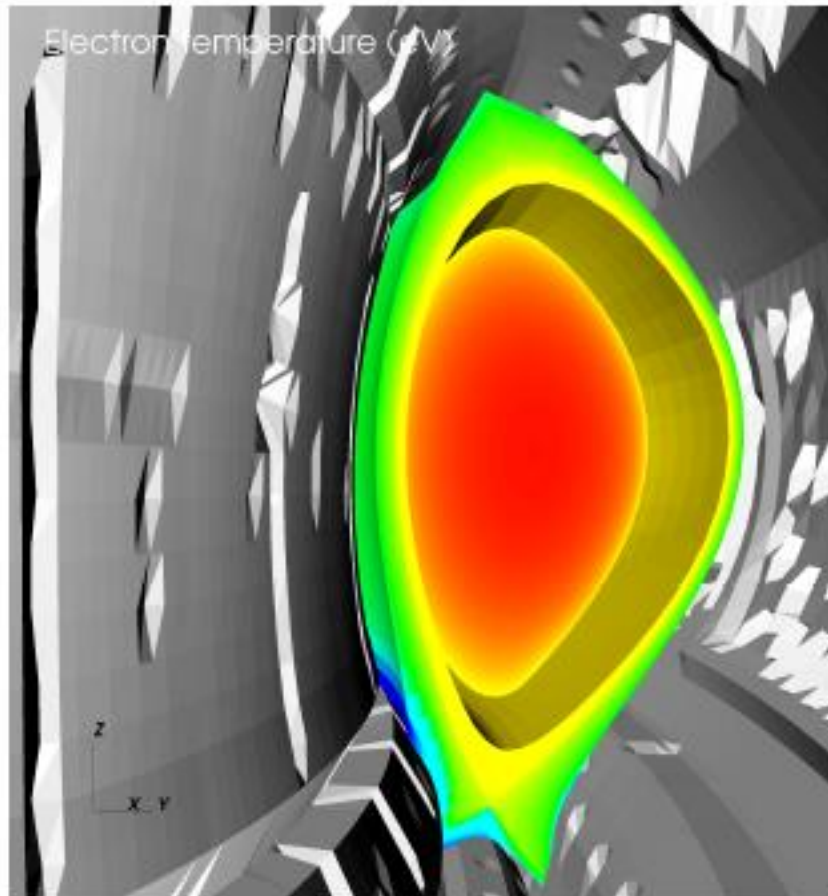
D.P. Coster, H.-J. Klingshirn, et al EPS 2012



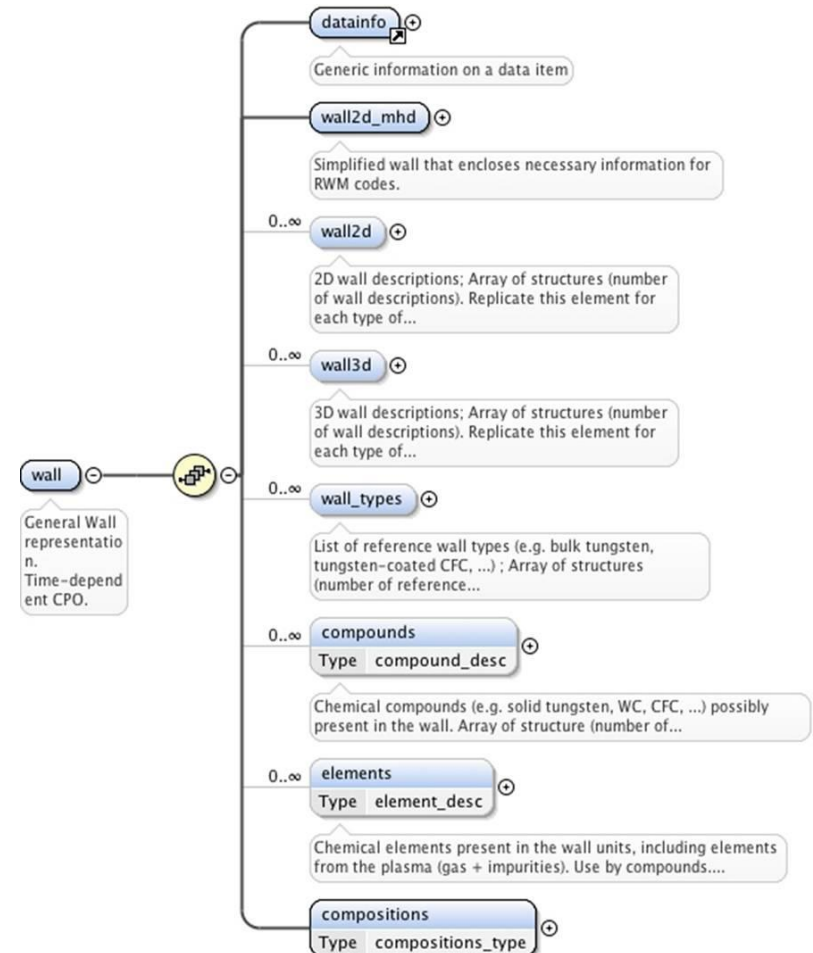
SOLPS-ETS visualization



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



Courtesy of **R. Coelho**



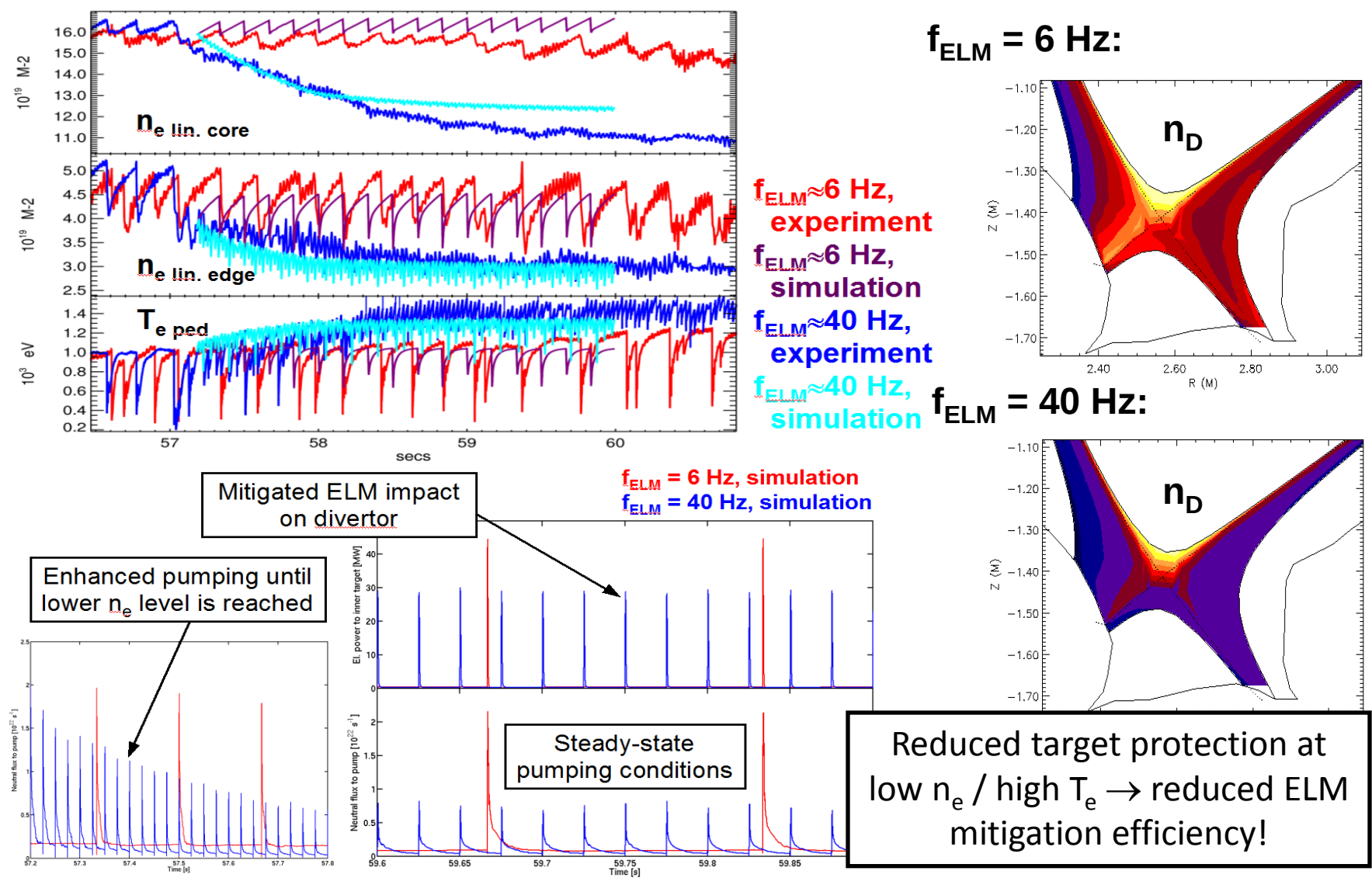


- The JINTRAC integrated model is extensively used for combined core-pedestal-SOL-PWI modelling tasks
 - JET type-I ELMy H-mode discharges
 - transition JET-C $\rightarrow$ JET-ILW
 - effect of PMI on recycling and pedestal performance
- JINTRAC is a tool which can be used to predict ITER scenarios
 - 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)
 - JINTRAC 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:



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):

$\tau_{\parallel}$, $L_{\parallel}$, p^{ped} , T^{ped} and ion mass (ie. sound speed c_s^{ped})
 $\rightarrow$ normalised quantities $q_{\max}^{\text{norm}}$, $\varepsilon^{\text{norm}}$

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

- IRTV JPN 73569 ($\Delta W_{\text{ELM}} \sim 250\text{kJ}$)

$$q_{\max}^{\text{norm}} \sim 0.2 \quad \varepsilon^{\text{norm}} \sim 0.35$$

- kinetic 1D PIC:

(Tskhakaya et al., JNM2009, JPN 62221, $\Delta W_{\text{ELM}} = 400\text{kJ}$)

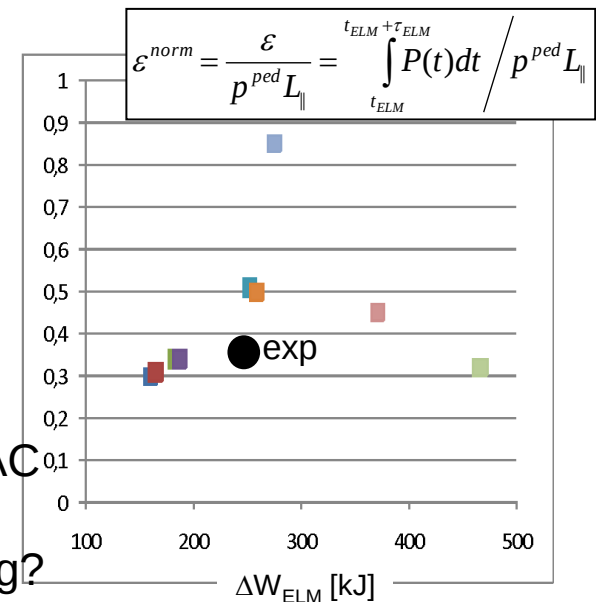
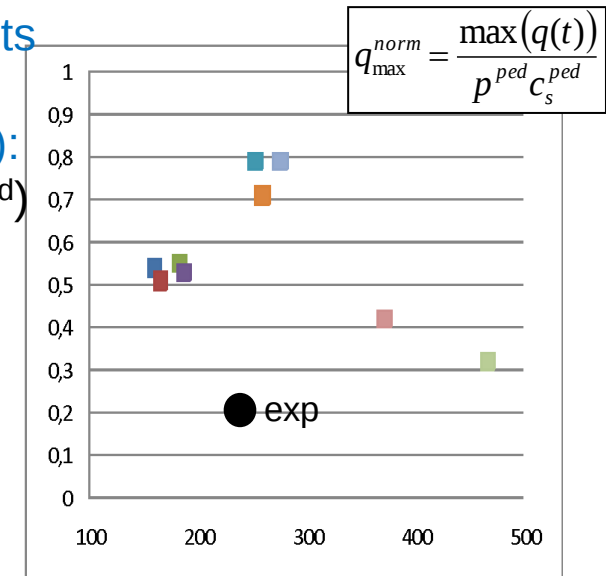
$$q_{\max}^{\text{norm}} \sim 0.56 \quad \varepsilon^{\text{norm}} \sim 0.6$$

- JINTRAC values are in the same range

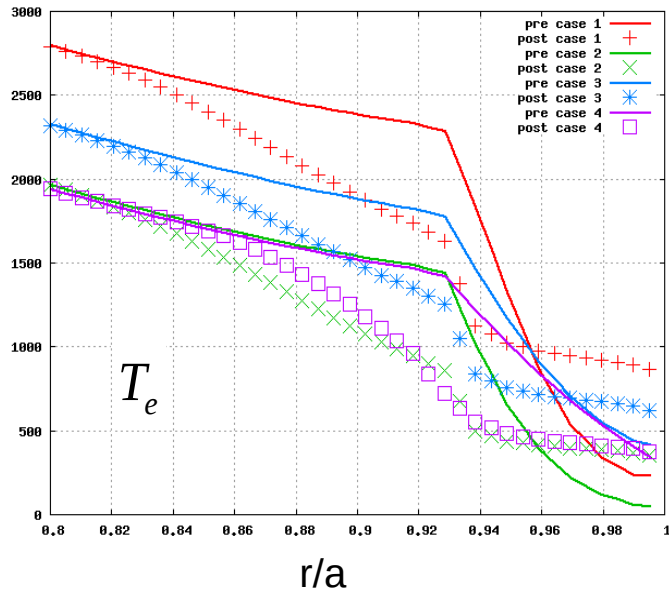
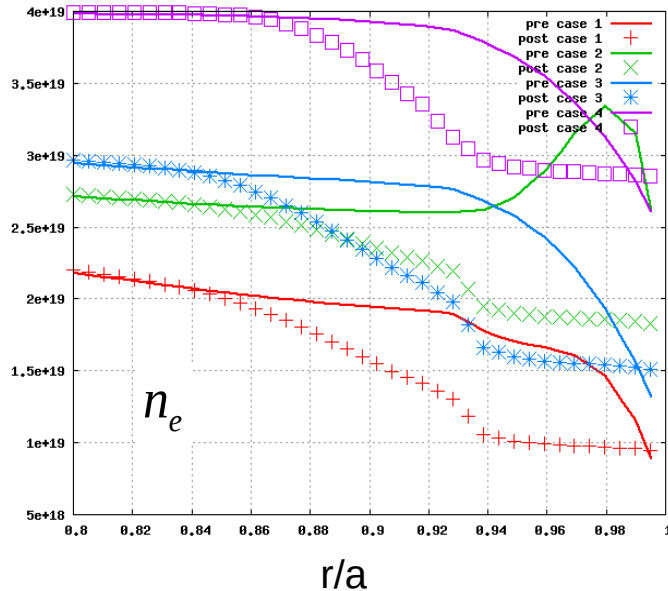
- strong dependence on ELM diffusive channel to

$\rightarrow$ lower values of $q_{\max}^{\text{norm}}$, $\varepsilon^{\text{norm}}$ w/ D^{ELM} observed in JINTRAC

$\rightarrow$ 2D effect? Stronger spreading of heat by divertor recycling?



Excursion: inter-ELM ETB transport model



- From neo-classical theory with $v_{e \text{ ped}}^* = 0.15$:

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

- 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: $D = \chi_i = 0.03 \text{ m}^2/\text{s}$, $\chi_e = 0.03 \text{ m}^2/\text{s}$, $\Gamma_p = 0.5 \cdot 10^{22} \text{ 1/s}$, 90Hz

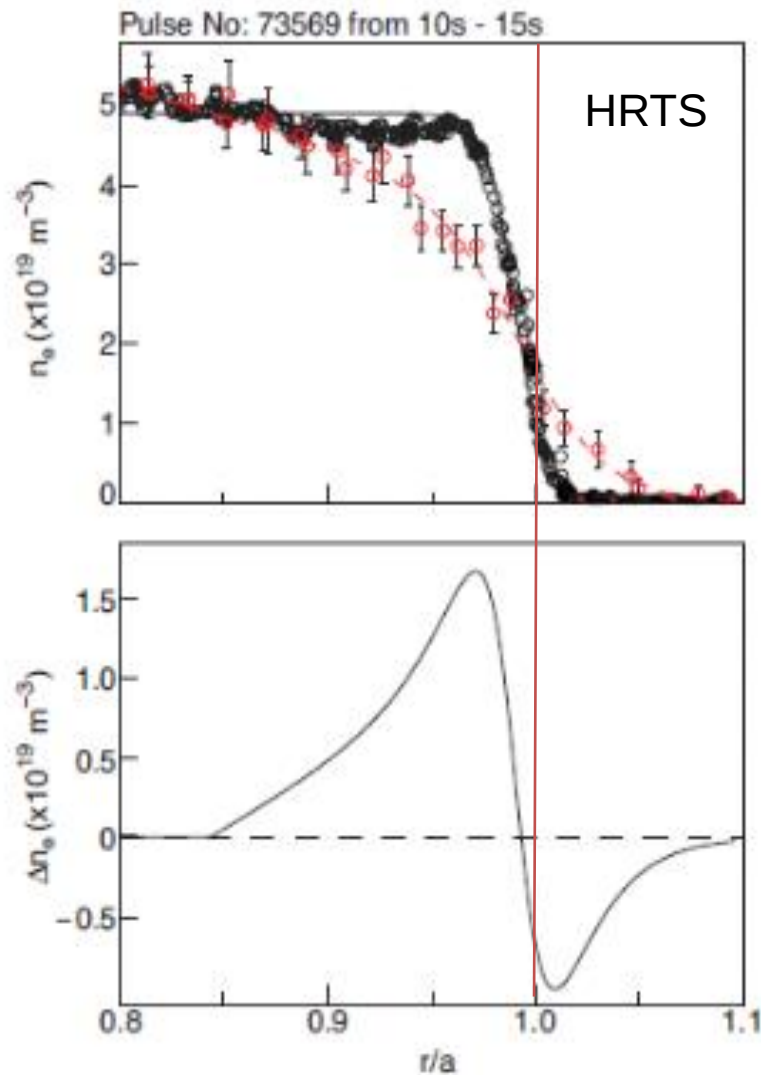
Case 2: $D = \chi_i = 0.03 \text{ m}^2/\text{s}$, $\chi_e = 0.03 \text{ m}^2/\text{s}$, $\Gamma_p = 1.5 \cdot 10^{22} \text{ 1/s}$, 96Hz

Case 3: $D = \chi_i = 0.10 \text{ m}^2/\text{s}$, $\chi_e = 0.05 \text{ m}^2/\text{s}$, $\Gamma_p = 1.5 \cdot 10^{22} \text{ 1/s}$, 47Hz

Case 4: $D = \chi_i = 0.15 \text{ m}^2/\text{s}$, $\chi_e = 0.08 \text{ m}^2/\text{s}$, $\Gamma_p = 3.0 \cdot 10^{22} \text{ 1/s}$, 16Hz

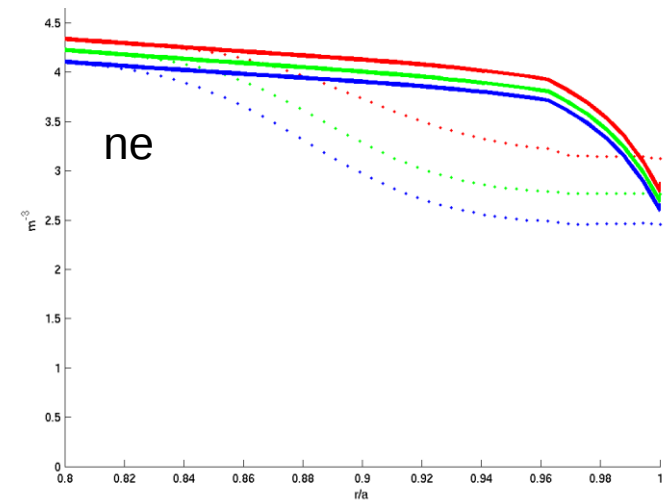
fixed $\alpha_{\text{crit}} = 1.6$

Upstream density JPN 73569

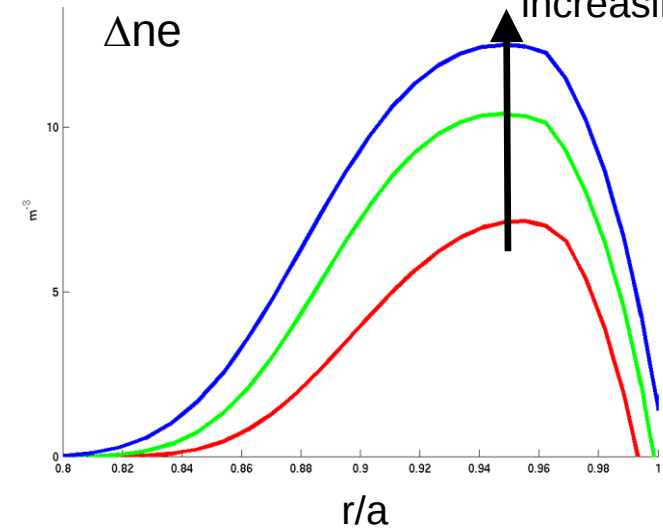


courtesy: M.Beurskens et al. IAEA 2008

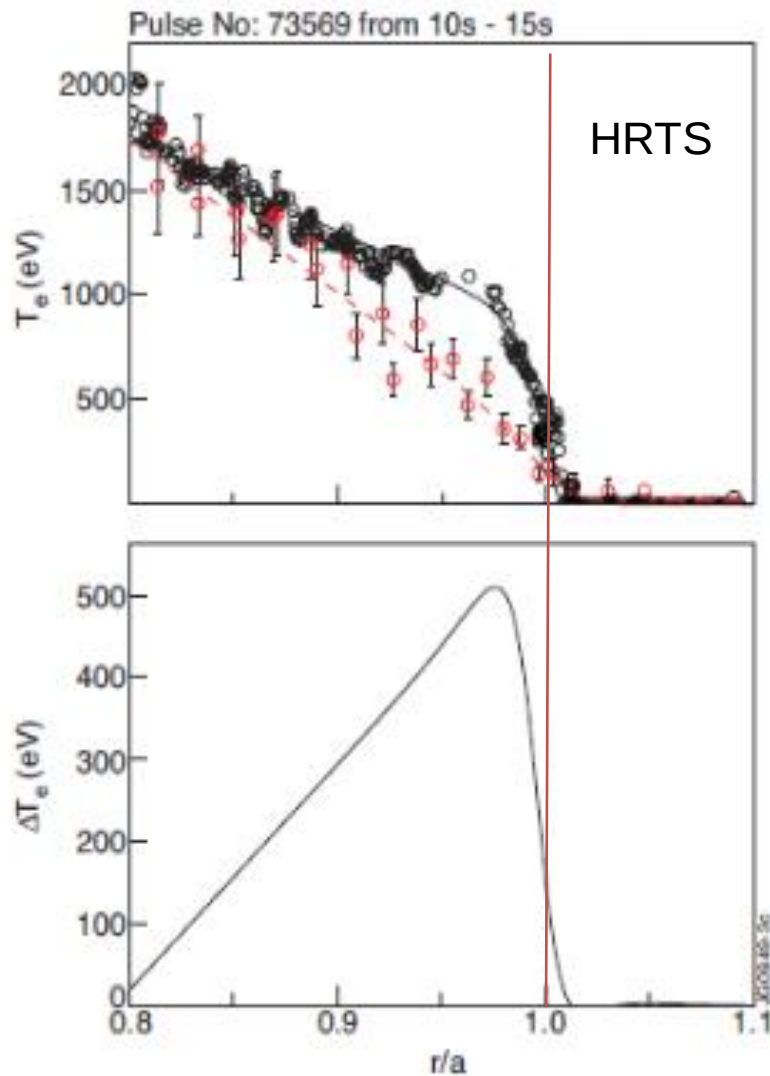
$5 \cdot 10^{19}$ 10^{19} JINTRAC



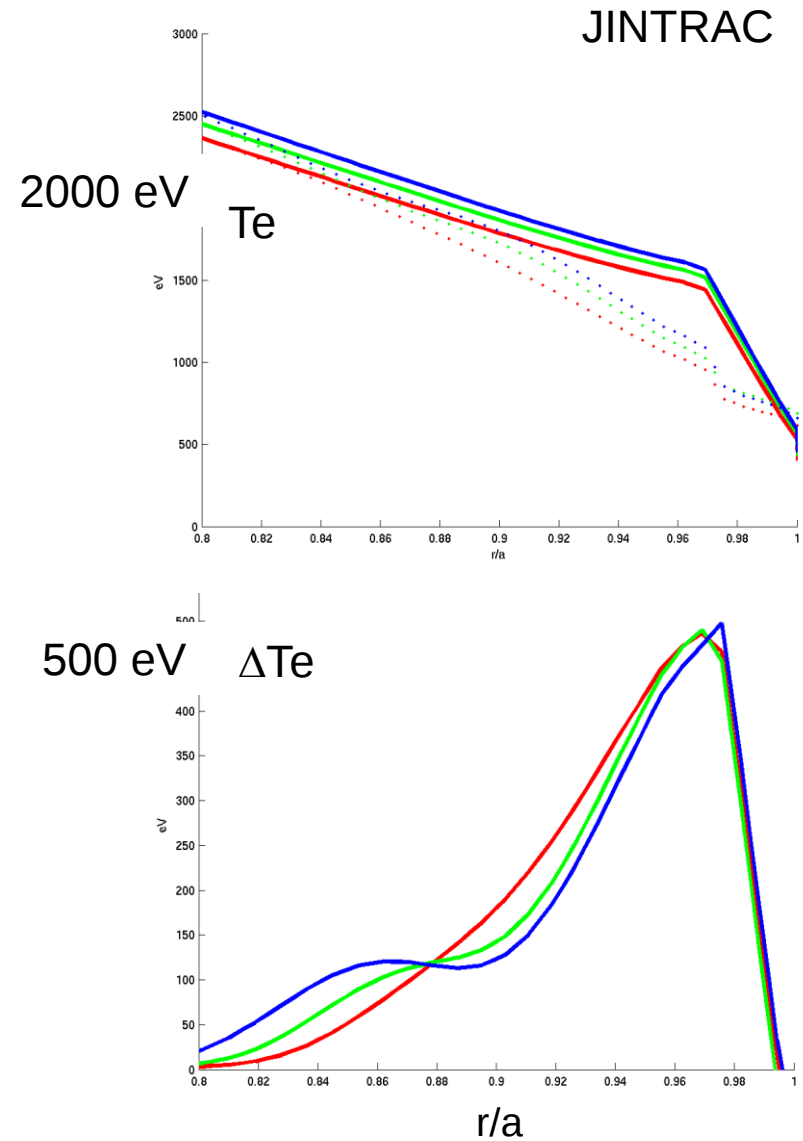
$1.5 \cdot 10^{19}$ 10^{19} Δn_e increasing D^{ELM}



Upstream temperature JPN 73569



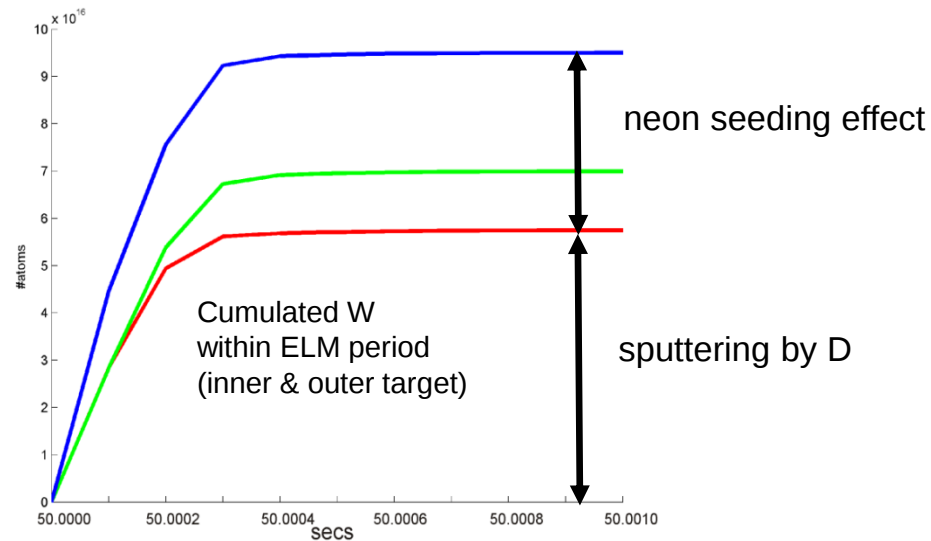
courtesy: M.Beurskens et al. IAEA 2008



Estimate of W erosion fluxes



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

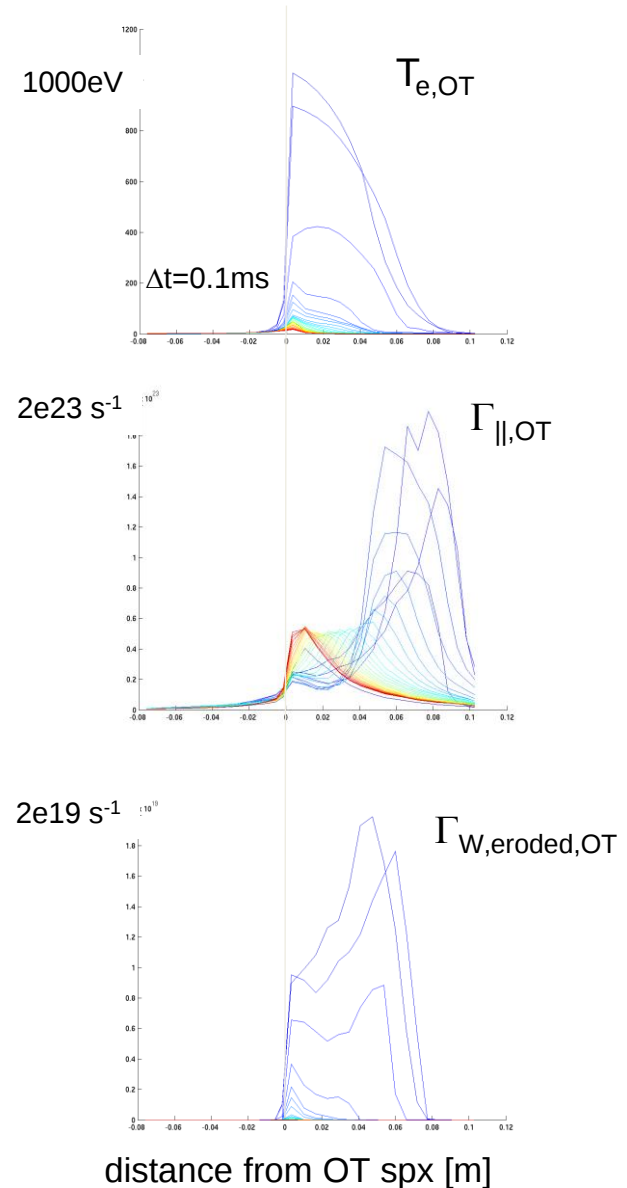


- assume:

- $E_{\text{ion}} = 4.5 T_e$ (plasma sheath)
- $\Gamma_{\text{ion,perp}} = \sin(1\text{deg}) \Gamma_{\parallel}$
- $\Gamma_{W,\text{eroded}} = (Y_{D \rightarrow W} + c_{\text{Be}} Y_{\text{Be} \rightarrow W} + c_{\text{Ne}} Y_{\text{Ne} \rightarrow W}) \Gamma_{\text{ion,perp}}$

- cumulation over 1 ELM period:

- $N_{W,\text{eroded}} = 5 \cdot 10 \cdot 10^{16}$ or more W atoms/ELM
(crude estimate: no prompt re-deposition, no self-sputtering)





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 $\alpha_{\text{crit}} = 1.7$
- $P_{\text{aux}} = 33 \text{ MW}$, P_{fusion} : DITRAN-2 $\rightarrow$ target $P_{\text{fus}} \sim 500 \text{ MW}$ ($Q \sim 10$)
- $Z_{\text{eff}} = 1.7$ ($P_{\text{rad}} = 43 \text{ MW}$ fixed)
- cont.pellet model: fixed gaussian source profile in time
- $S_{\text{pellet}} = 1.5 \text{e}22 \text{ s}^{-1}$, $\Delta_{\text{pellet}} = 0.1$, $\rho_{\text{pellet}} = 0.9$ (case A), 0.8 (case B) (plasmoid drift)
- in far-SOL: fixed transport: $D = 0.3 \text{ m}^2/\text{s}$, $\chi_i = \chi_e = 1.0 \text{ m}^2/\text{s}$
- in near-SOL: ETB transport prolonged into SOL (0.5 cm @ omp)
- DT-flux coming from plasma core (JETTO) combined into single D-flux into SOL: $\Gamma_{\text{D}}^{\text{EDGE2D}} = \Gamma_{\text{D}}^{\text{JETTO}} + \Gamma_{\text{T}}^{\text{JETTO}}$
- neutral recycling flux $\Gamma_{\text{D}0}$ from SOL split up 50/50 $\Gamma_{\text{D}0}/\Gamma_{\text{T}0}$ when entering core