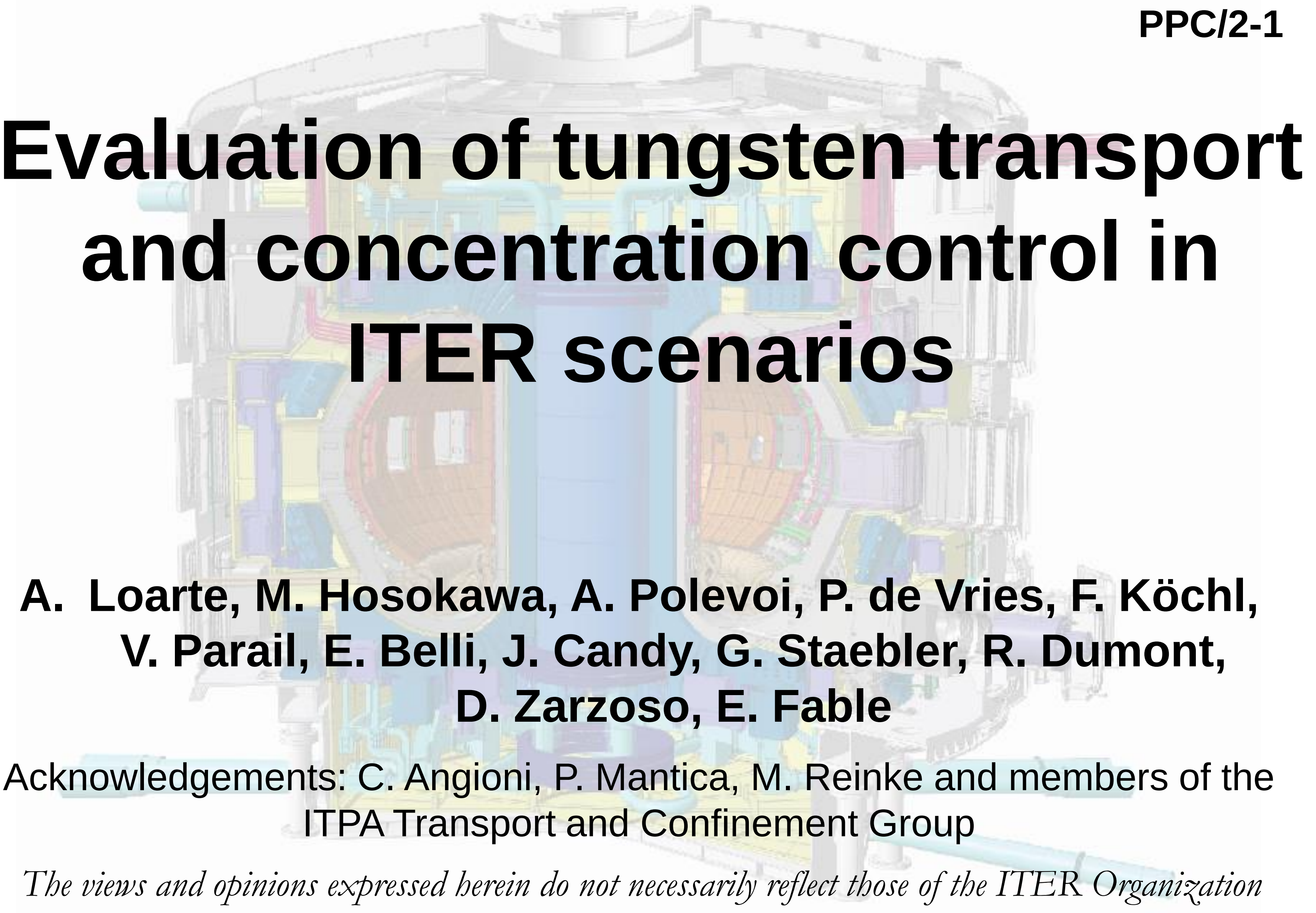


PPC/2-1

Evaluation of tungsten transport and concentration control in ITER scenarios

A. Loarte, M. Hosokawa, A. Polevoi, P. de Vries, F. Köchl, V. Parail, E. Belli, J. Candy, G. Staebler, R. Dumont, D. Zarzoso, E. Fable

Acknowledgements: C. Angioni, P. Mantica, M. Reinke and members of the ITPA Transport and Confinement Group

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization

Outline

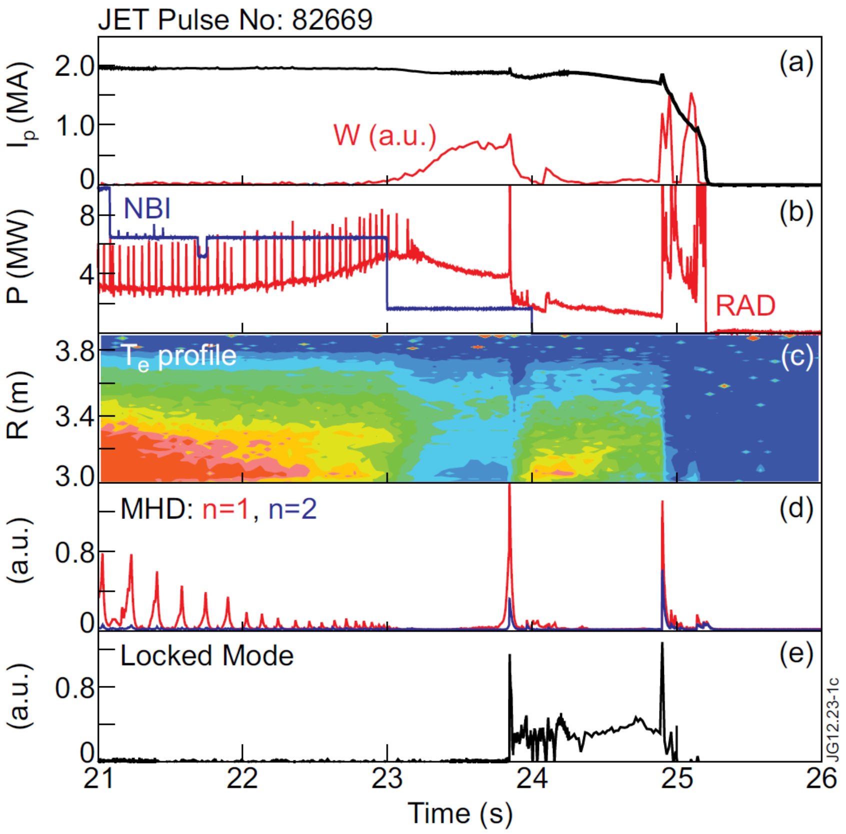
- Introduction : W transport and control in present experiments and ITER → objectives of study

- Simulations of core W transport in ITER
  - 15 MA/5.3T Q_{DT} ~ 10 plasmas
  - 7.5 MA/2.65T DT and DD plasmas
  - H-mode termination

- Conclusions

Introduction - I

- Control of W concentration in ITER scenarios (stationary phases and L-H/H-L confinement transients) is essential to achieve Q_{DT} = 10 goal and to maintain low plasma disruptivity
- Excessive W levels in core plasma leads to high radiation levels, loss of the H-mode and, eventually, to disruptions



P. de Vries PPCF 2012

Multi-machine analysis of termination scenarios EX/P6-41, P. de Vries

Introduction - II

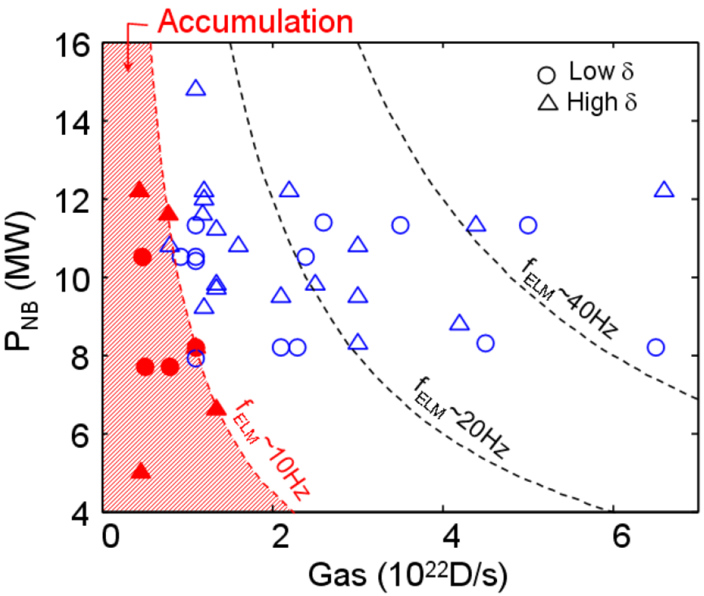
- Control of W in H-modes in present experiments and ITER:

1. Control of W source by operating in high density/low temperature conditions at the divertor → control of W source

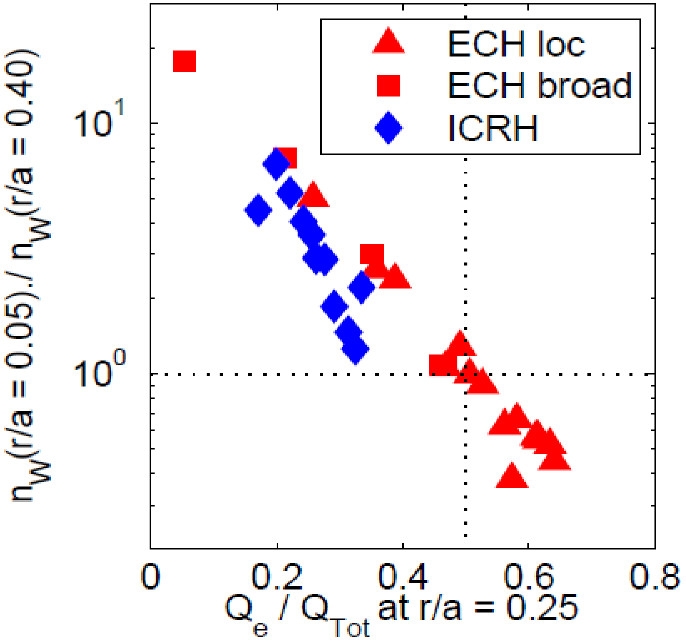
2. Control of W penetration through the edge plasma into the core plasma (Pedestal transport + ELM control) → control of $n_{W\text{-ped}}$

3. Control of core W transport → avoidance of core W accumulation (control of core ∇n vs. ∇T & core transport by central heating)

JET – J. Bucalossi – EPS 2012



ASDEX Upgrade – C. Angioni – TH/P2-6



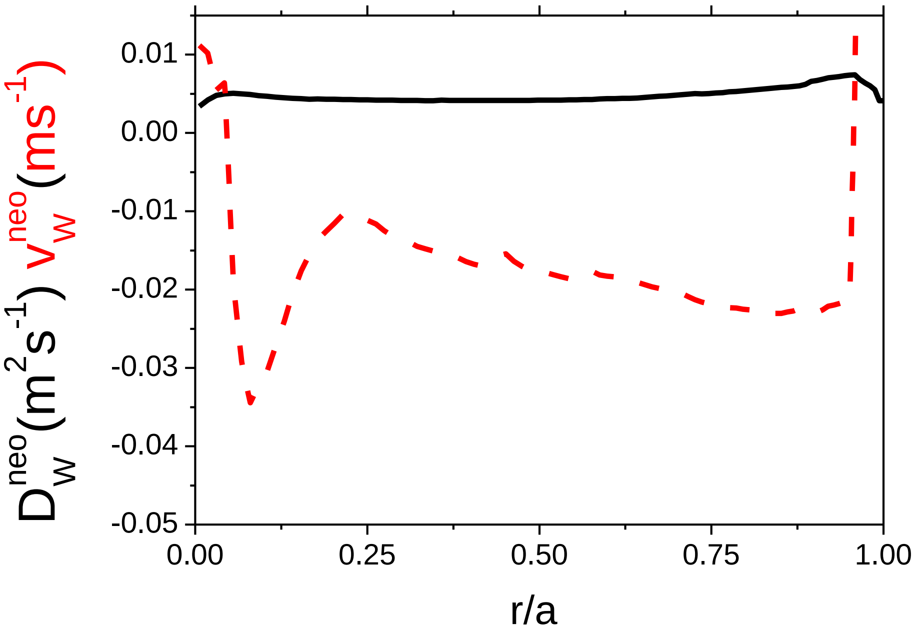
ITER studies for 1 & 2 presented at FEC-2012, FEC-2014 and FEC-2016 (EX/P6-44 – A. Polevoi)

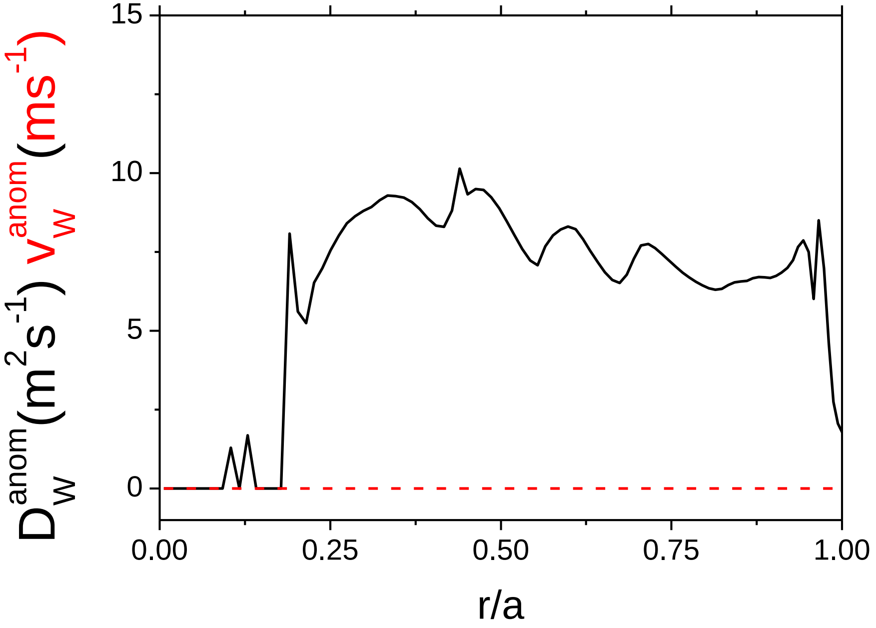
Modelling of Core W transport in ITER

- Objective → Model core W transport applying physics models used to describe present experiments :
  - Model W transport in ITER main plasma scenarios (steady-state and confinement transients H-L) → magnitude of possible W accumulation in ITER
  - Evaluate effects of physics effects known to affect core W transport in present experiments (toroidal rotation, fast particles ..)
  - Evaluate capabilities of ITER heating and fuelling systems for core W transport control and accumulation avoidance
- Simulations of core W transport carried out with ASTRA and JINTRAC with GLF23 model for anomalous transport (without sawteeth)
  - SOL and pedestal plasma conditions evaluated from SOLPS and EPED models
    - ✓ n_e,T_e,T_i n_W specified as boundary conditions with D_{ped},$\chi_{ped} \sim (P_{edge}/P_{L\text{-}H})$ in H-L transitions
    - ✓ Low n_W level to be able to model accumulation without plasma collapse
  - Core energy, particle + W transport : Anomalous + NCLASS transport
    - ✓ $D = D_{neo} + D_{anom}$ & $V = V_{neo} + V_{anom}$
    - ✓ $\chi = \chi_{neo} + \chi_{anom}$
    - ✓ Non self-consistent studies with NEO & TGLF of advanced physics effects

W transport in ITER Q = 10 Plasmas - I

- ITER Q =10 (33 MW NBI + 20 MW of RF)
  - ✓ Main plasma and W transport is anomalous except in very centre (r/a ≤ 0.2 m) where turbulent transport is ~ 0 → as seen in AUG/JET/C-MOD
  - ✓ Extent of region with low anomalous transport dependent on central shear



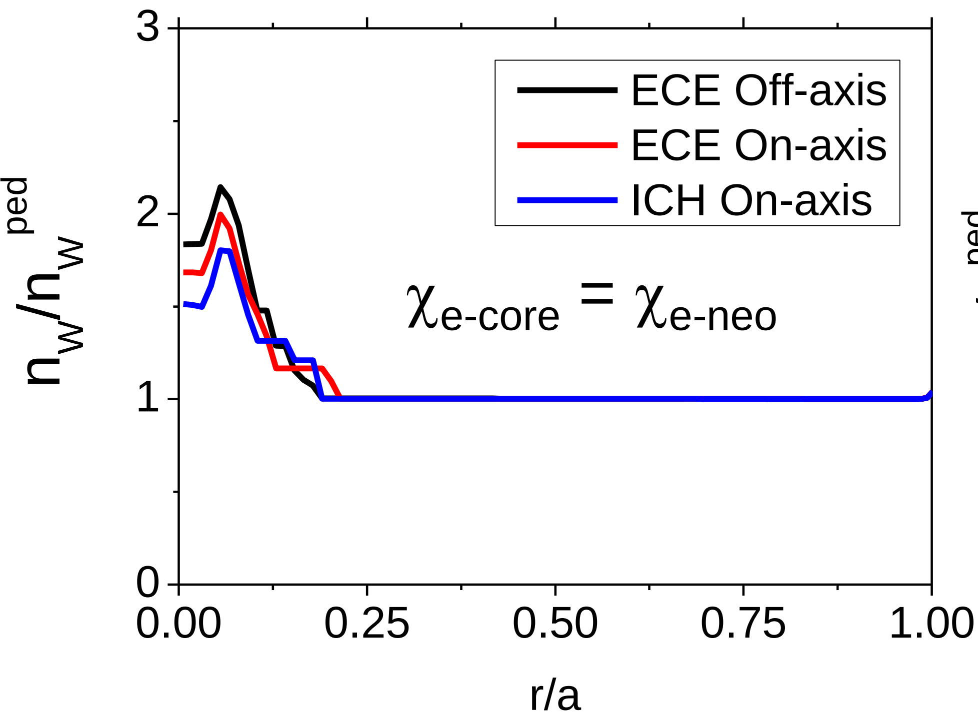


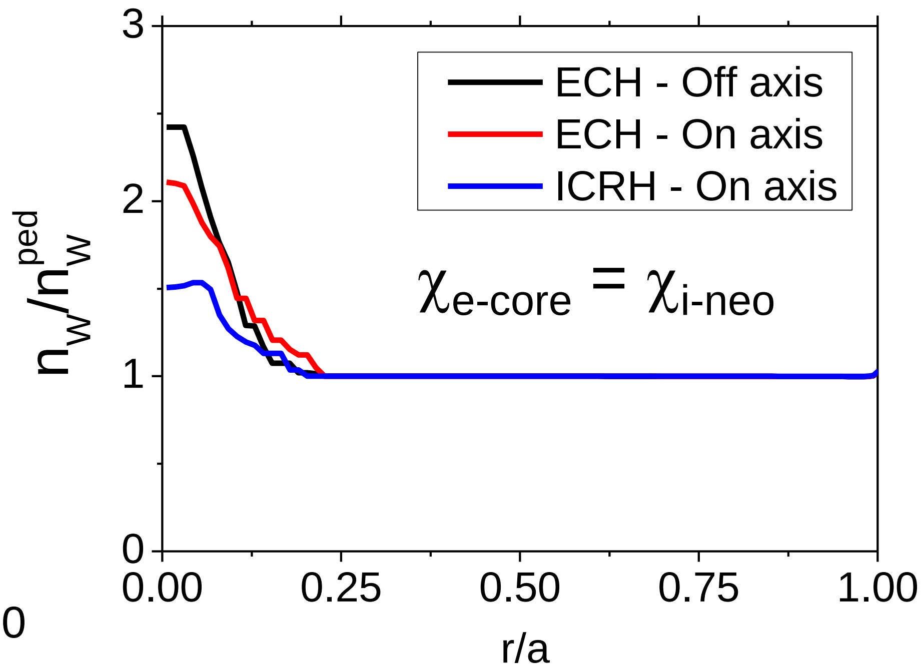
$$\frac{\nabla n_W}{n_W} \sim \frac{\nabla n_i}{n_i} - C\frac{\nabla T_i}{T_i} = \frac{v_W}{D_W}$$

- ✓ Large D_W^{anom} with v_W^{anom} ~ 0 → flat W density profiles except possibly in r/a ≤ 0.2 where neoclassical transport can be unfavourable

W transport in ITER Q = 10 Plasmas - II

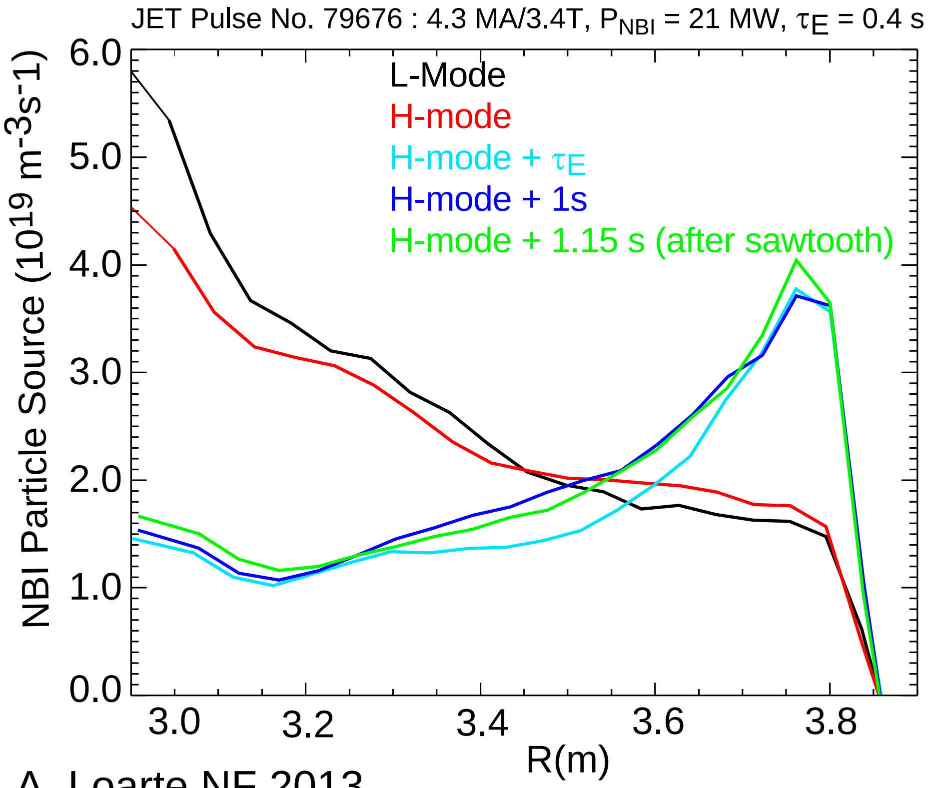
- Low core W peaking → very modest in ITER Q = 10 plasmas
- Degree of W peaking depends on heating scheme and assumptions on core transport



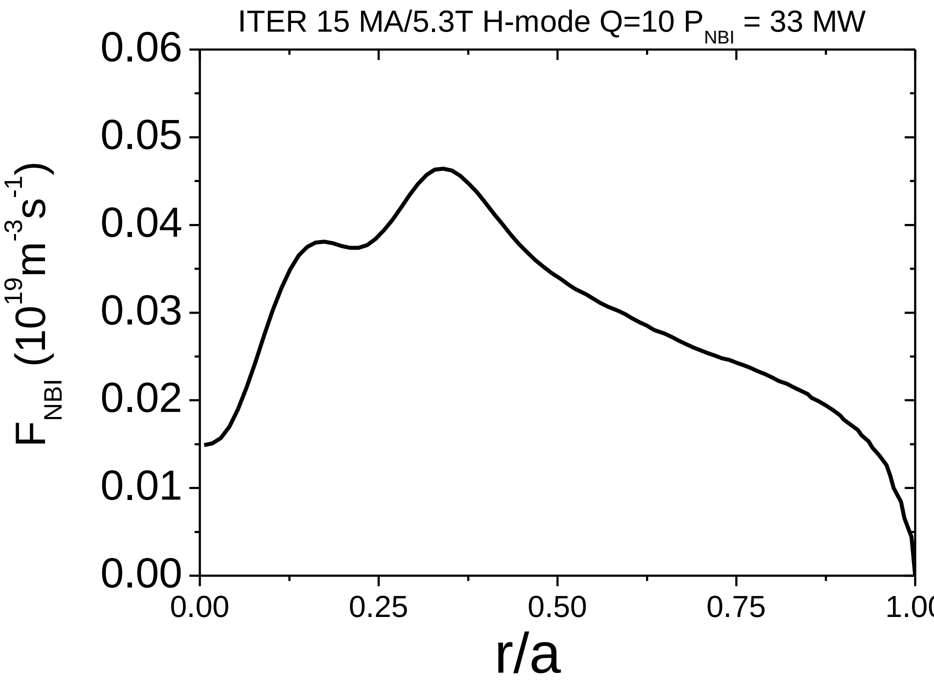


W transport in ITER Q = 10 Plasmas - III

- Low core W peaking due to low DT density gradients in the core → very low 1 MeV NBI particle source in ITER
- Core ∇n in ITER determined by transport physics <u>not</u> by NBI particle source


JET Pulse No. 79676 : 4.3 MA/3.4T, P_{NBI} = 21 MW, τ_E = 0.4 s

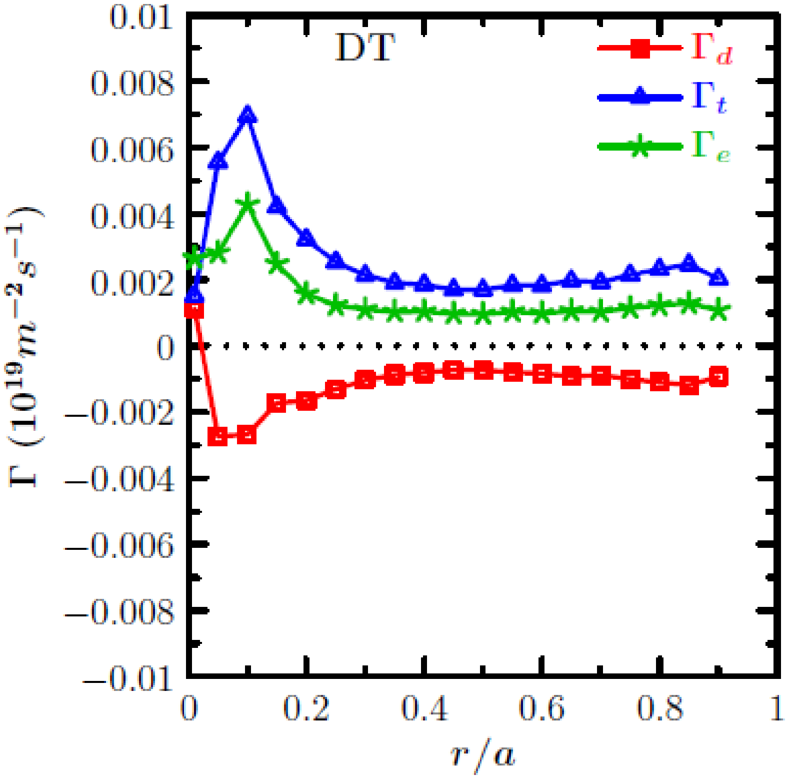
A. Loarte NF 2013


ITER 15 MA/5.3T H-mode Q=10 P_{NBI} = 33 MW

W transport in ITER Q = 10 Plasmas - IV

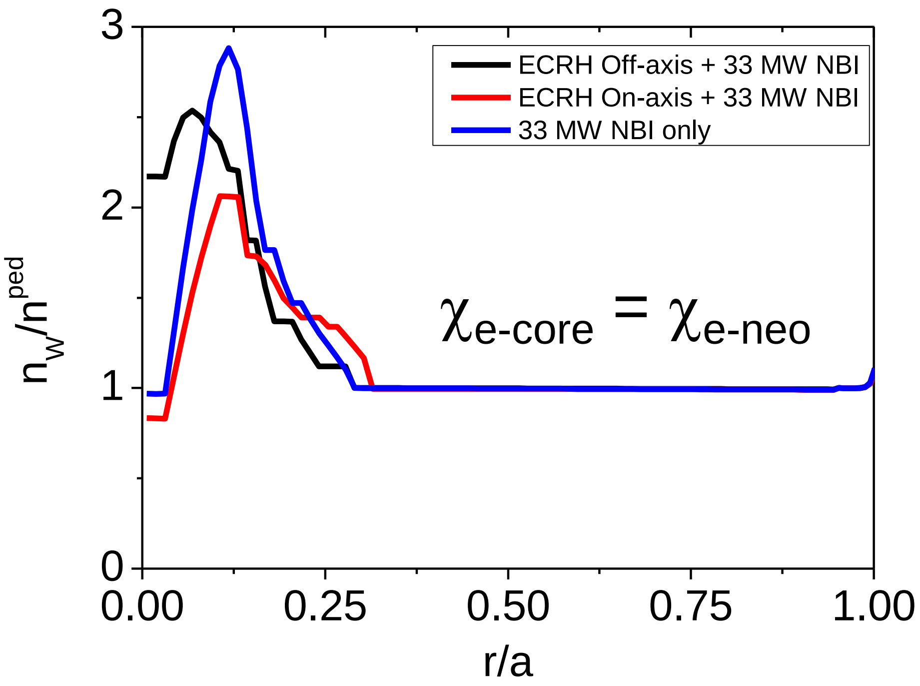
Neoclassical transport studies carried out to determine physics of core D and T transport in ITER

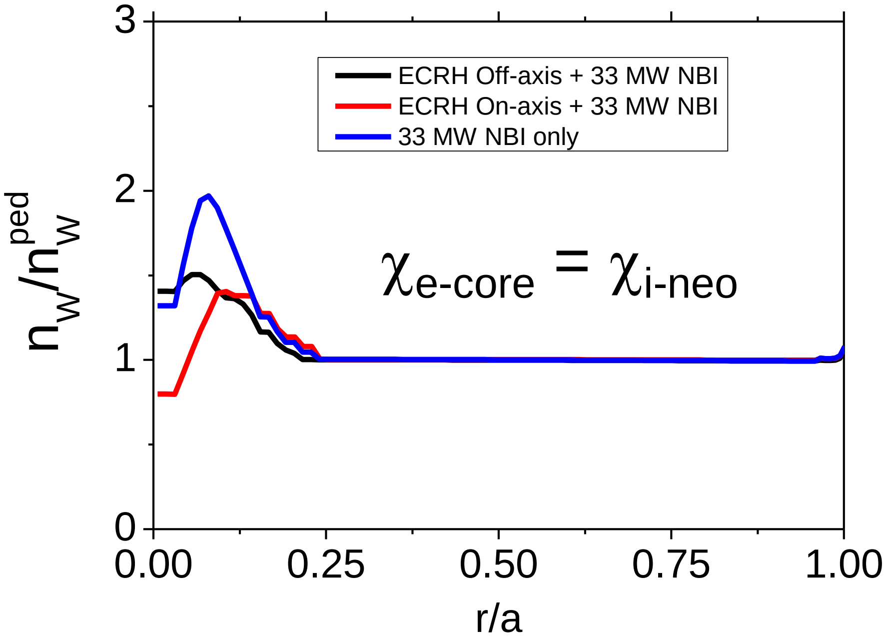
- Residual D + T core density peaking due to different ion masses
- Net Γ_D & Γ_T are determined by balance of outwards $D\nabla n$ and inwards nv (>> Γ_{NBI}) and have opposite directions



W transport in ITER 7.5 MA/2.65T Plasmas - I

- Similar findings for I_p = 7.5 MA/2.65T DT plasmas that for Q = 10
- Effects of additional heating schemes on W transport are stronger than for Q = 10 due to lack of P_α

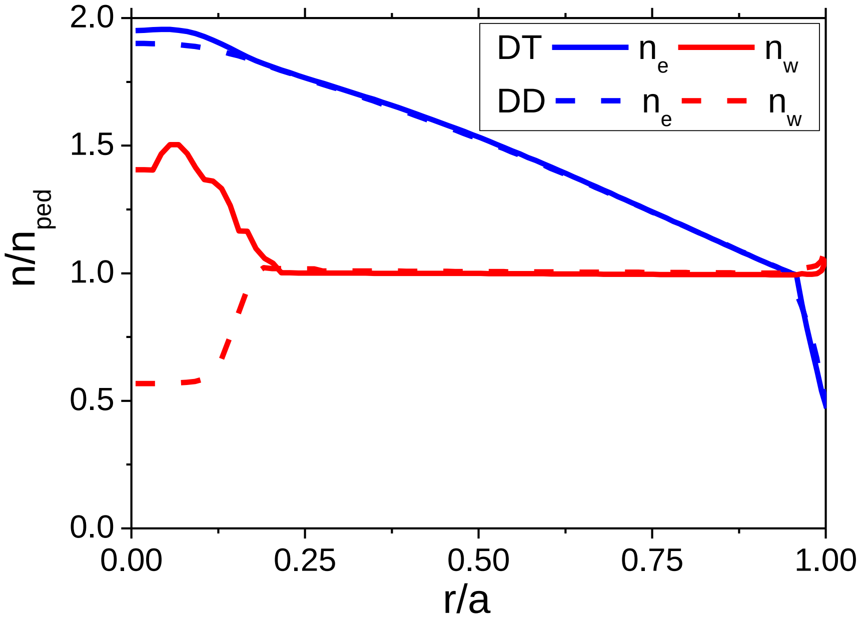


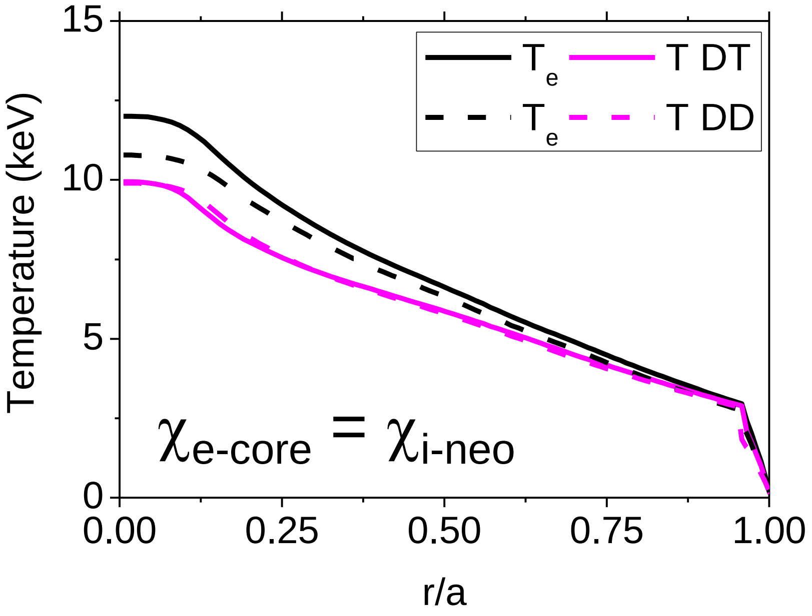


W transport in ITER 7.5 MA/2.65 T Plasmas - II

- Core W transport for I_p = 7.5 MA/2.65T DD plasmas is different that for DT due to lack of inwards neoclassical pinch in pure D plasmas
- No W accumulation expected for DD plasmas due to low NBI particle source and lack on inwards pinch on D

7.5 MA/2.65T P_{NBI} = 33 MW P_{ECRH} = 20 MW (off-axis)

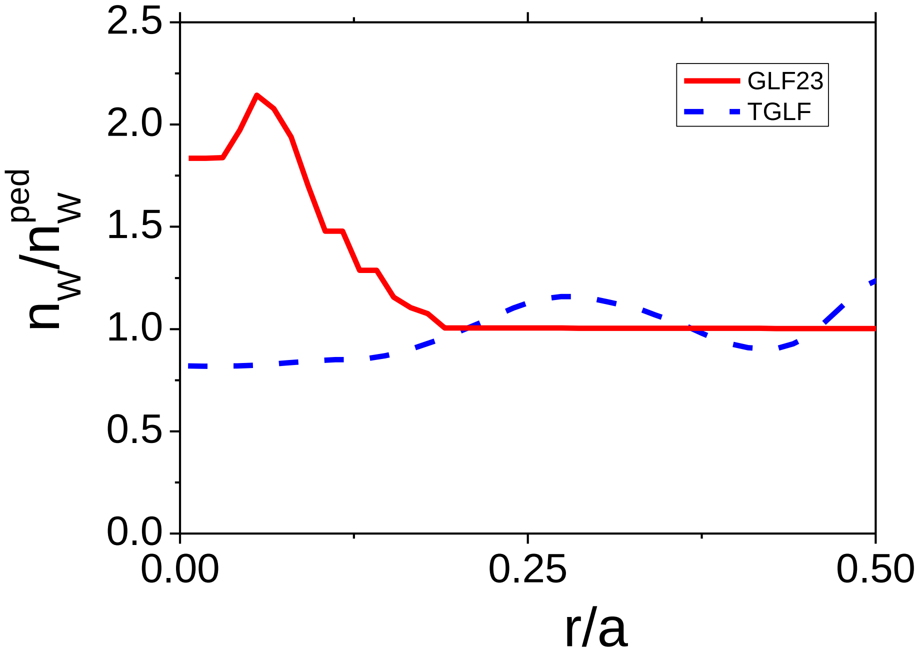


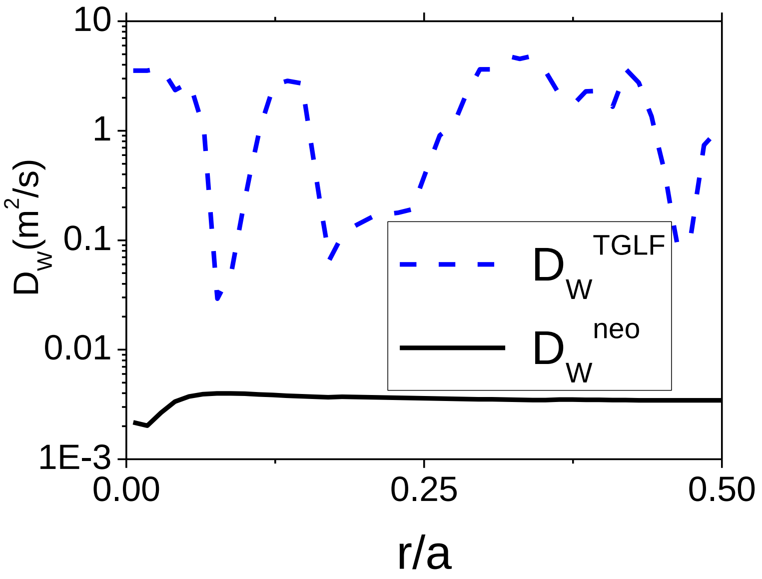


Studies for He H-mode plasmas in non-active phase in progress

Additional physics effects – Anomalous Transport

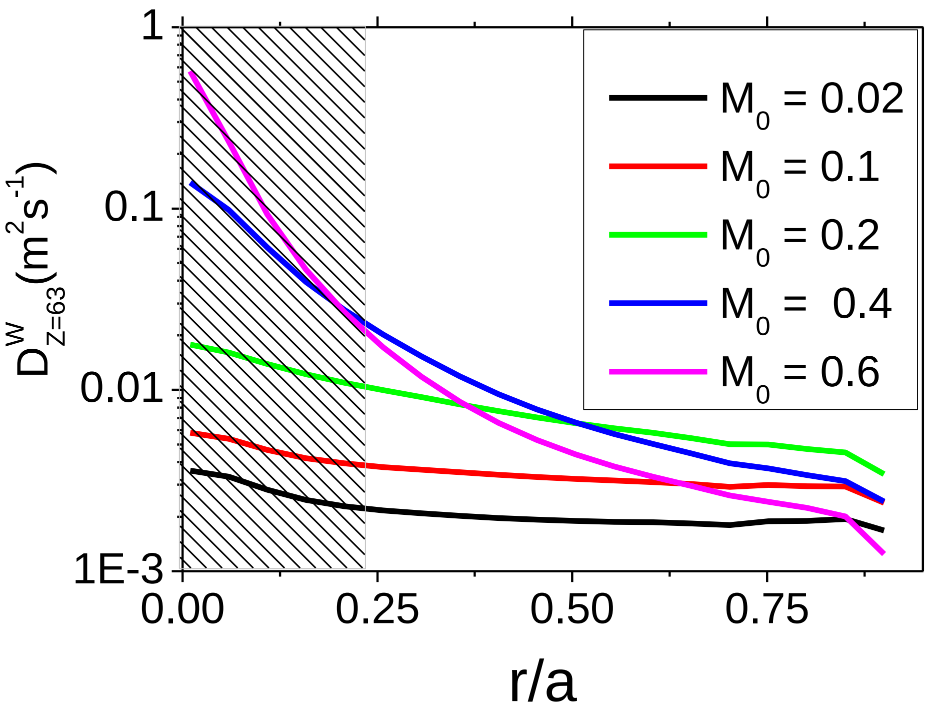
- Inclusion of more sophisticated models of anomalous transport removes residual W peaking obtained with GLF23
- TGLF including saturation for multi-scale turbulence leads to flattish W profiles where GLF23 predicts a small residual core peaking

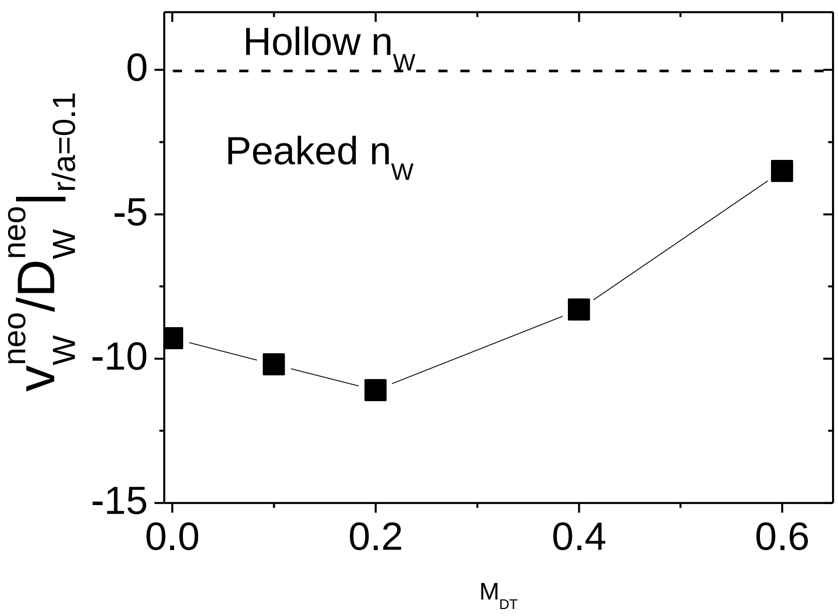




Rotation effects on W neoclassical transport

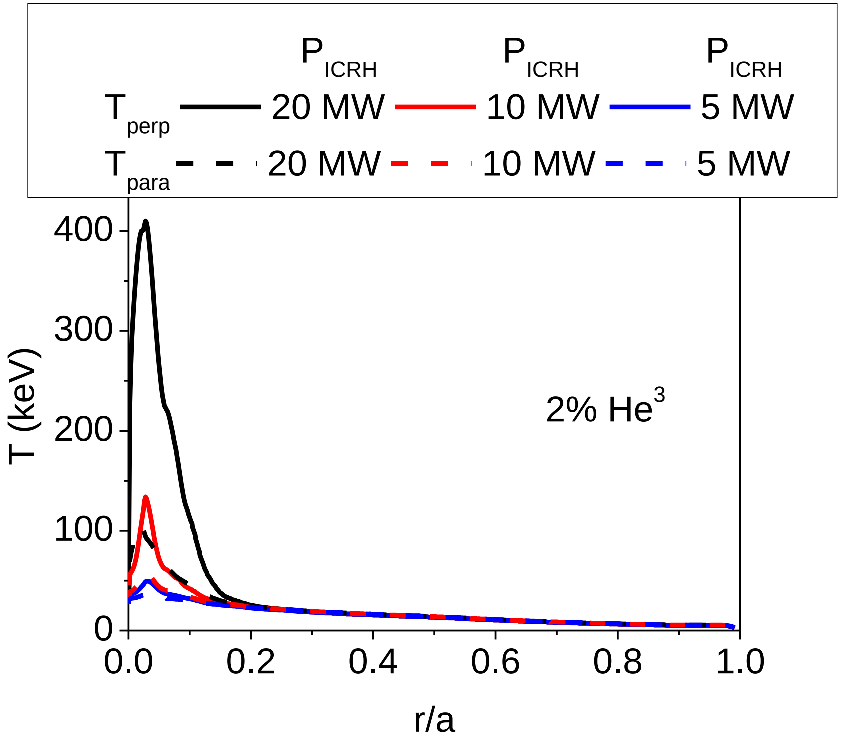
- M_{DT} < 0.1 for Q = 10 ITER plasmas based on NBI source torque → centrifugal effects on neoclassical W transport are small
- Rotation effects on W transport modelled (not-self consistently) with NEO → Similar findings as in Angioni NF 2014, PoP 2015 → D_W increases with M_{DT} and V_W/D_W becomes less negative at high M_{DT}

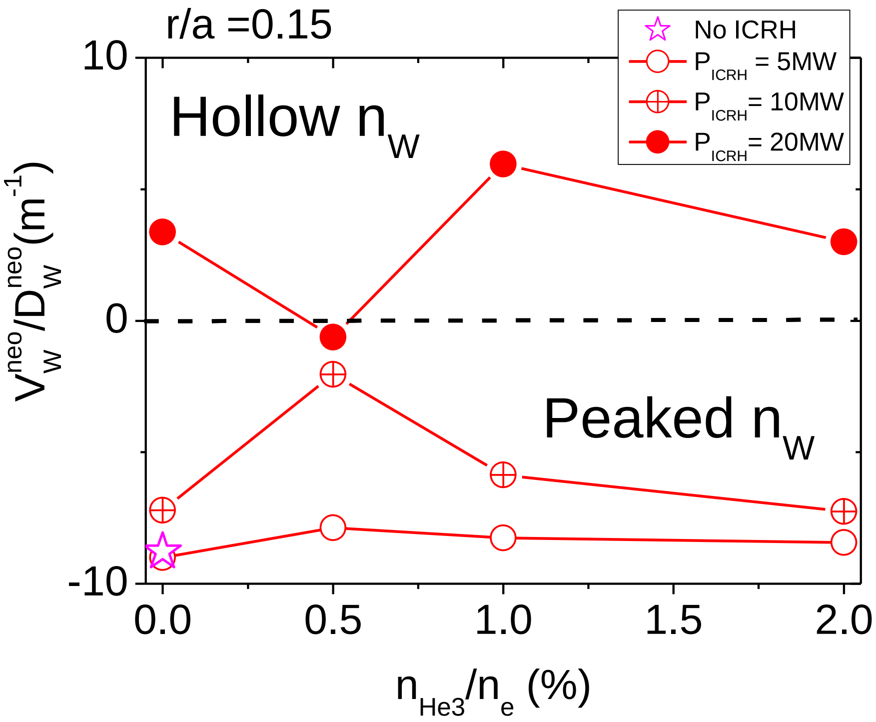




Effects of fast particles on W neoclassical transport

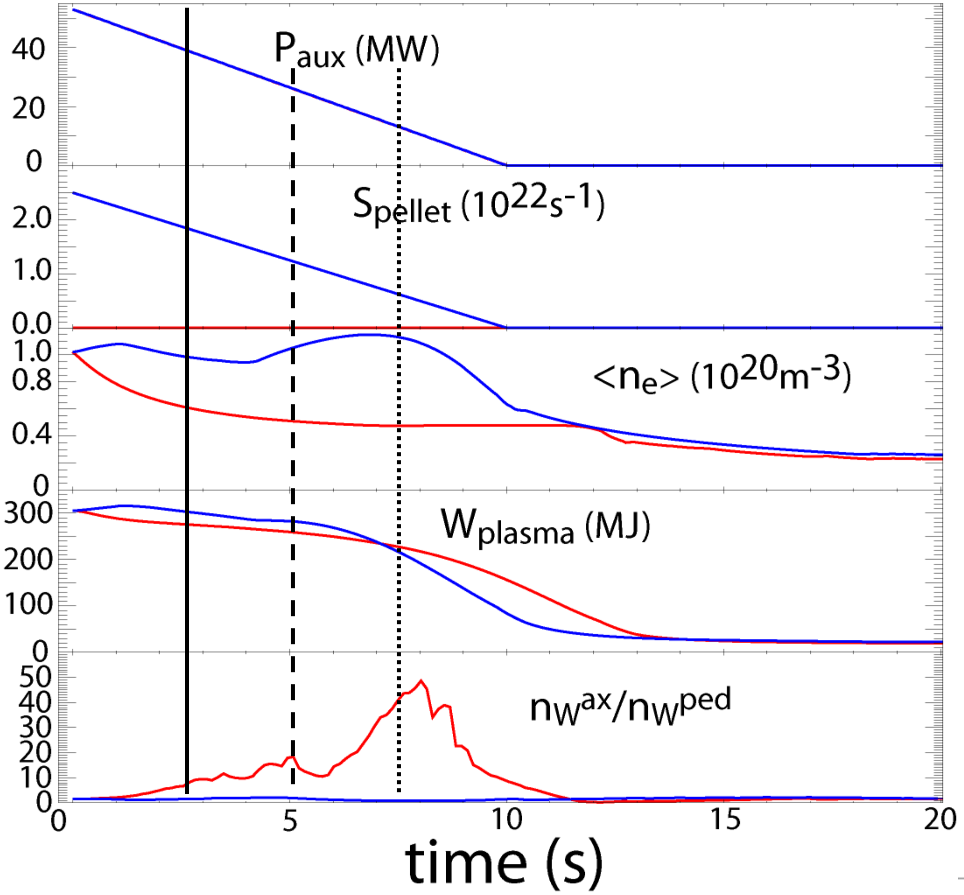
- Fast particle effects can affect W neoclassical transport
  - ✓ NBI ions/α particles: 1- 3.5 MeV have relatively flat n + T profiles → no effects
  - ✓ He^3 and fast-T with ICRH→ strong effects but radially dependent on He^3-W collisionality and grad-T_{He3}/grad T_{fast-T} → similar to JET and AUG results with H-minority (Casson PPCF 2015, TH/P2-6 Angioni)

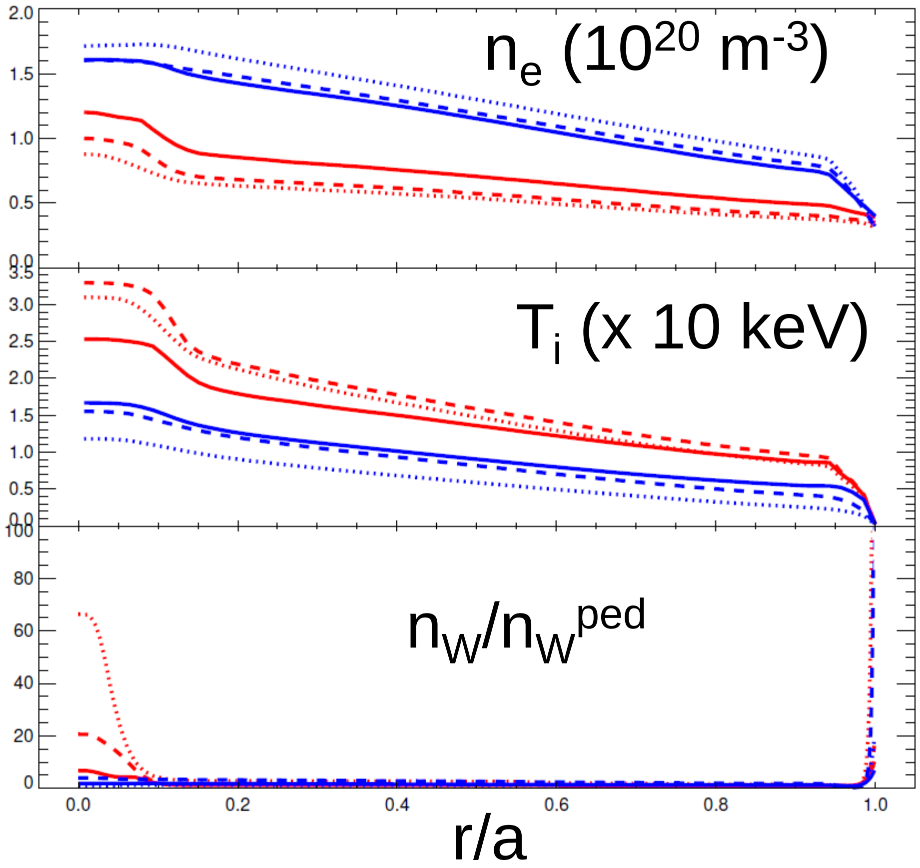




Modelling of core W transport in H-mode terminations - I

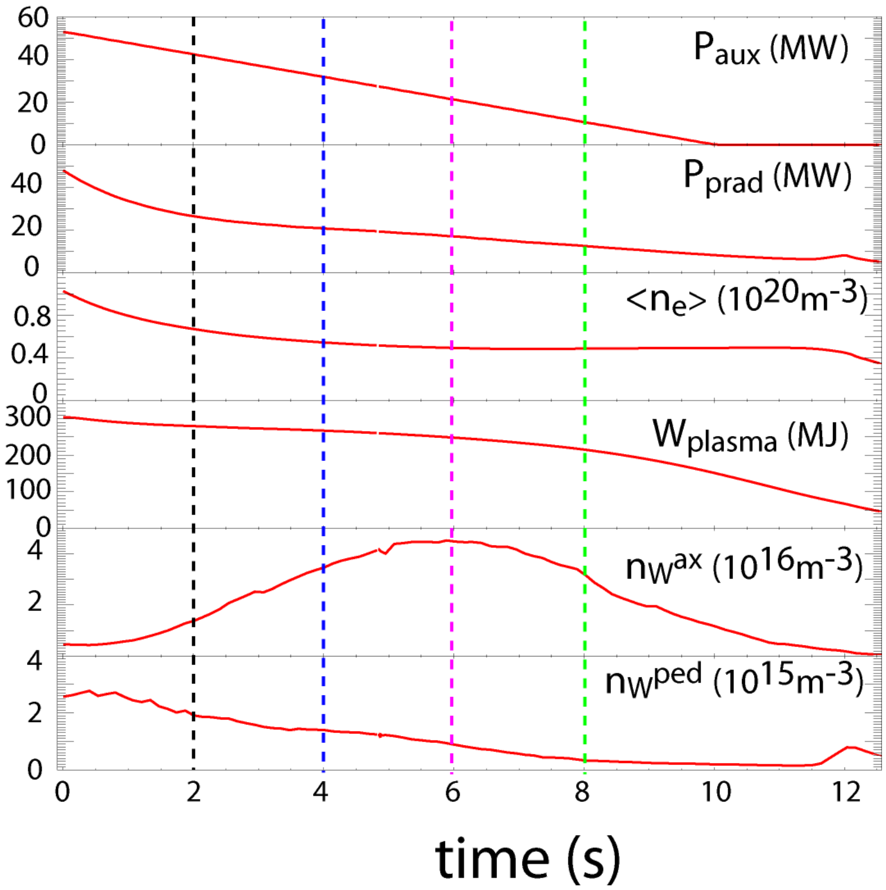
- ITER Q = 10 H-mode termination should be controlled to keep dW/dt as low as possible (radial position and divertor power load control) → keep H-mode as long as possible
- Optimization of P_{aux} + S_{pellet} ramps (+ gas fuelling) to avoid W accumulation

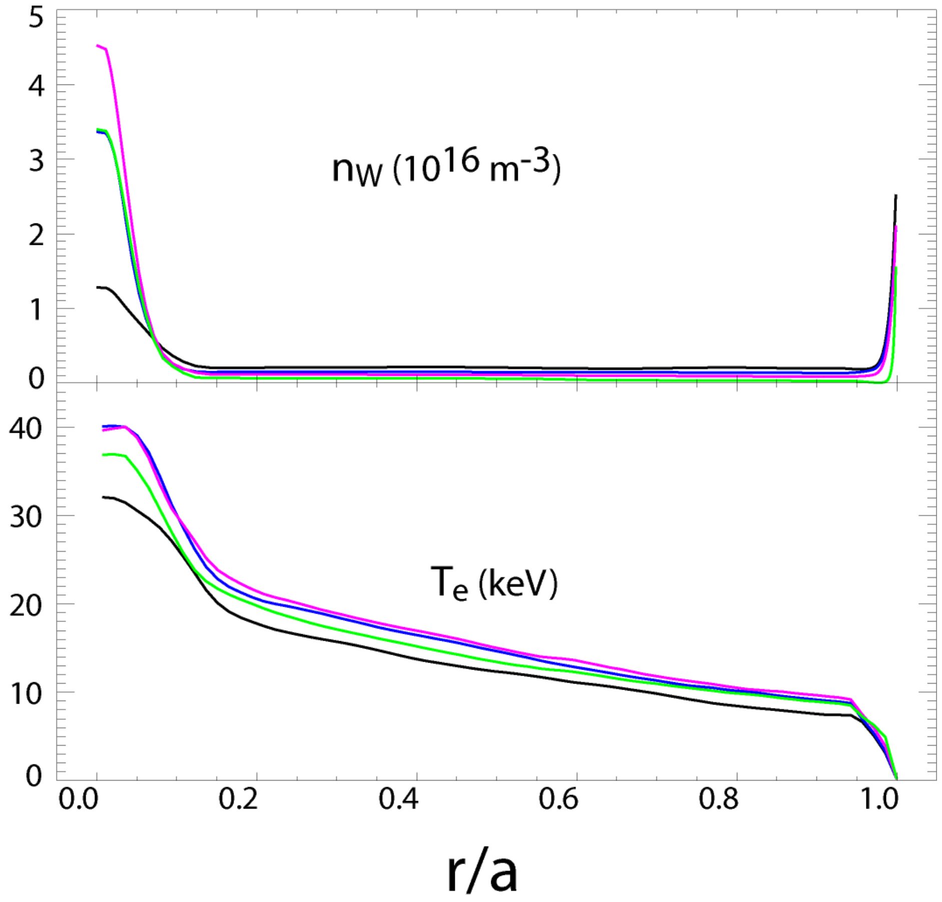




Modelling of core W transport in H-mode terminations - II

- Radiative collapse of central plasma not reproduced in ITER Q = 10 terminations with W accumulation with realistic values of $n_W^{ped}/n_{ped} \sim 10^{-5}$
  - High core T_e in Q=10 termination leads to low W radiation even with $n_W/n_e \sim$ few 10^{-4} in the central plasma

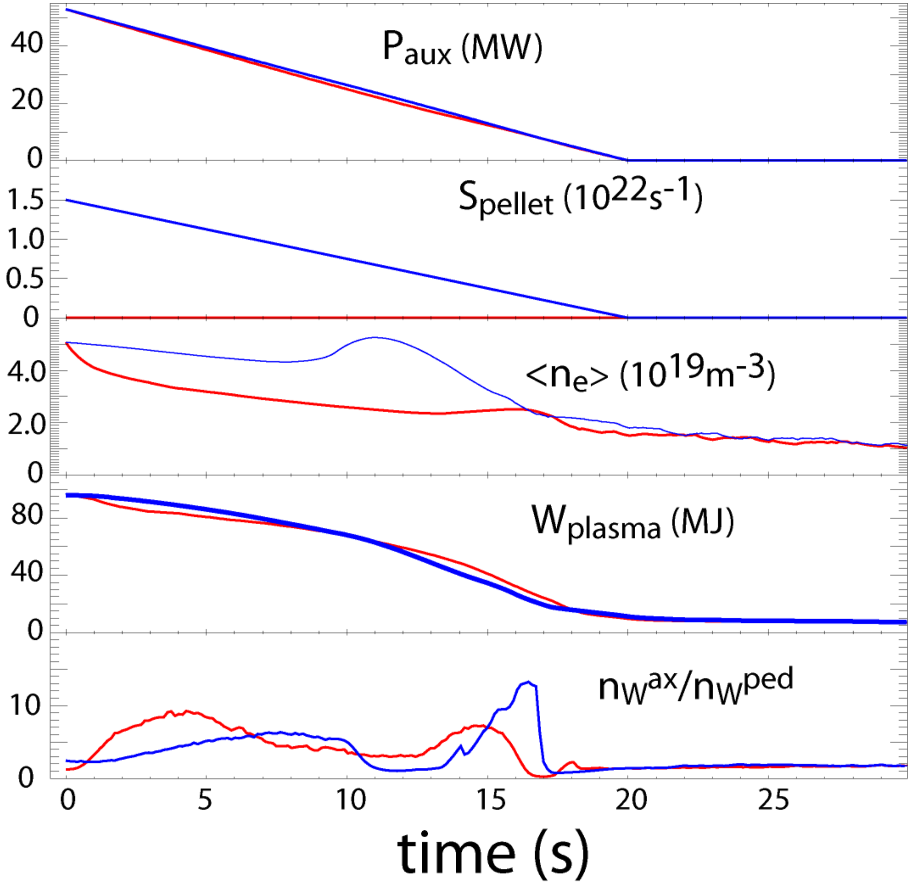




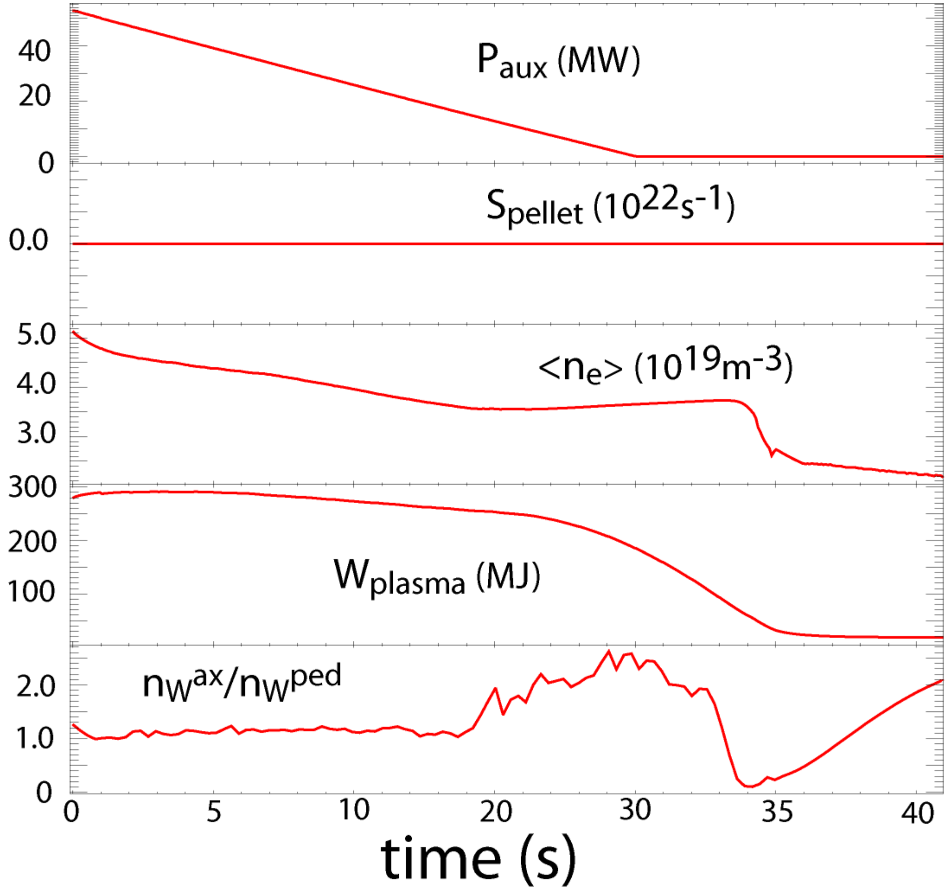
Modelling of core W transport in H-mode terminations - III

- ➢ Optimization is dependent on H-mode plasma conditions
  - ✓ Slow pellet fuelling ramp not always improves termination (7.5 MA/2.65T)
  - ✓ Lower Q = 5 15 MA/5.3T plasmas are more robust to W accumulation

7.5 MA/2.65T



15 MA/5.3T Q = 5



Conclusions

- Modelling of core W transport shows favourable conditions that prevent strong core W accumulation in stationary ITER Q = 10 plasmas
  - Low core source from 1 MeV NBI → weak ∇n_{DT} determined by transport
- Core W transport in 7.5MA/2.65T DT plasmas similar to Q = 10
  - For DD plasmas core ∇n_{DD} → hollow W profiles
- W accumulation in H-mode transients (H-L transitions) can take place in ITER → optimization of heating and fuelling ramp-down required
  - Optimum fuelling/heating depends on H-mode conditions
- Quantitative features on ITER simulations depend Plasma transport (thermal and main ion and impurities) in core region (low anomalous transport)
  - ITER core neoclassical transport is very low ($D_{DT}^{neo} \sim 10^{-2}\ m^2s^{-1}$ and $D_W^{neo} \sim 10^{-3}\ m^2s^{-1}$) → residual turbulence can dominate W transport (no accumulation)

Further development of transport physics basis in central plasma region + experimental validation is required to refine predictions for ITER

"Low energy" NBI plays major role in W accumulation in present experiments → high core particle source, high toroidal rotation, dominant ion heating

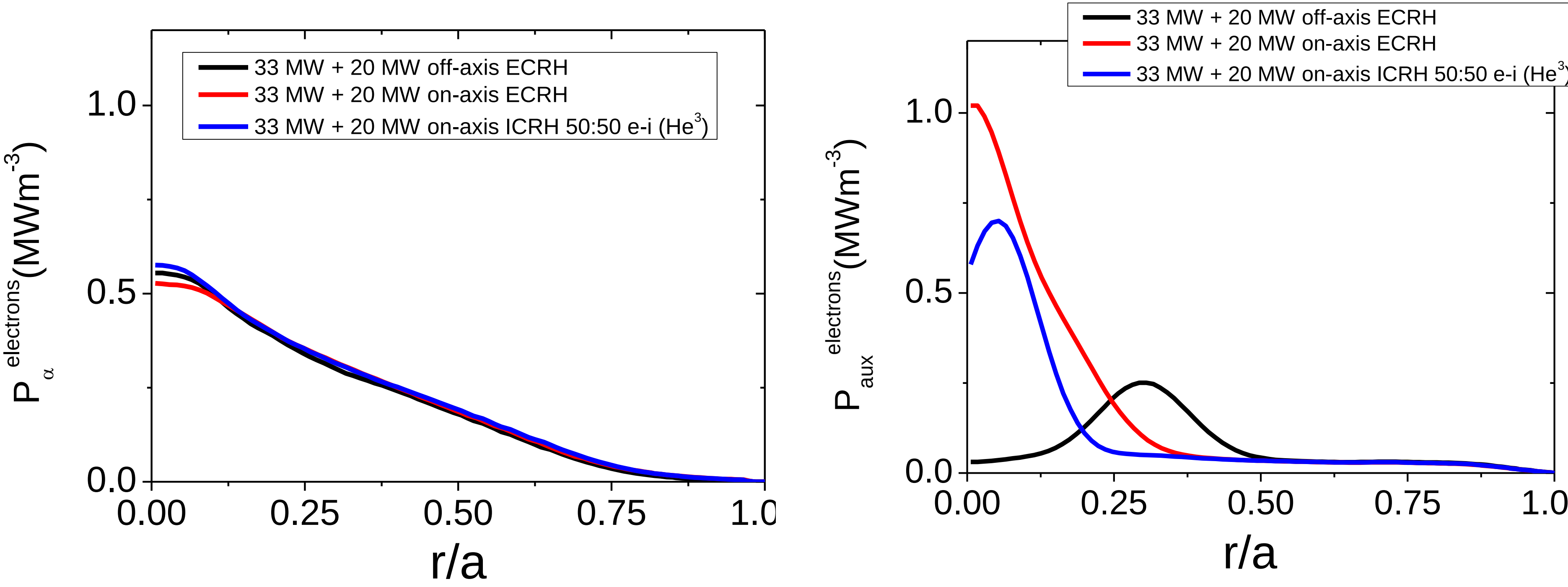
JET – F. Köchl EX/P6-14 , ASDEX Upgrade – C. Angioni TH/P2-6, C-Mod – M. Reinke EX/P3-3

Reserve Material

W transport in ITER Q = 10 Plasmas - IIIr

- Even if P_α /P_{aux} ~ 2 for Q =10 ITER H&CD schemes can modify core plasma parameters → q_{aux} >> q_α in central part for RF heating schemes

Electron power deposition profiles



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