Predictive multi-channel flux-driven modelling to optimise ICRH tungsten control in JET

F. J. Casson, and EUROfusion JET contributors

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Acknowledgments

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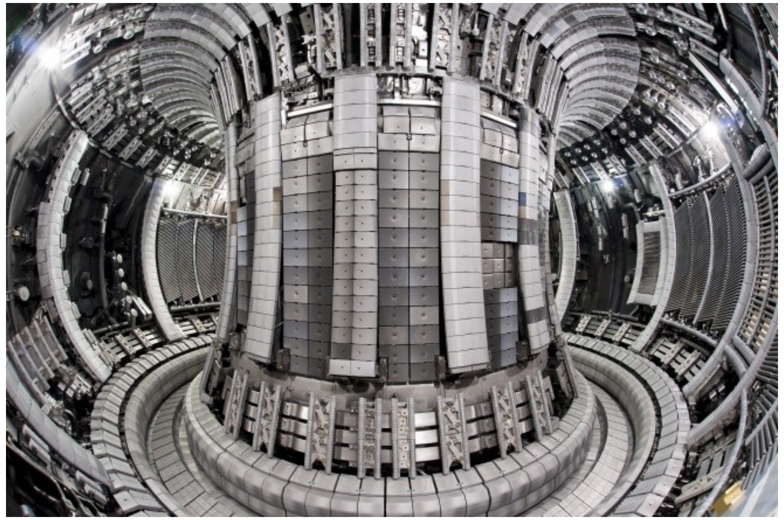
Motivation

- **Operation with JET ITER-like wall (ILW) requires management of tungsten impurities**



- **JET-ILW DT scenarios aim at steady high performance (15MW fusion for 5s)**

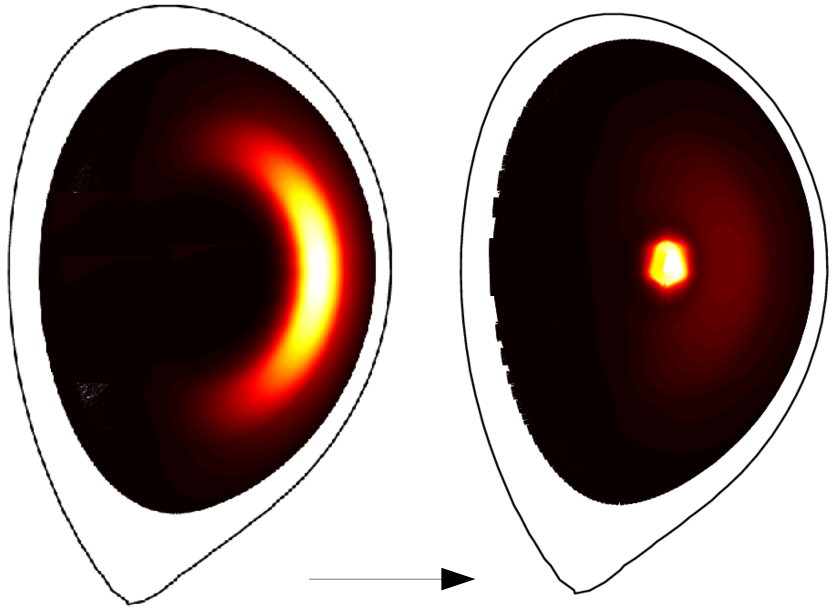
  (E. Joffrin, this conf.)

- **Scenario development must address 3 connected challenges**

  (L. Garzotti, this conf.)

  - **Maintain tolerable divertor heat loads**
  - **Control central W accumulation**
  - **Avoid performance limiting MHD**

- **Predictive modelling can help to guide scenario optimisation**



Outline

- Mechanisms of W accumulation
- Integrated predictive modelling
- Optimisation of heating
- Extrapolation to DT

Both neoclassical and turbulent transport are relevant for W

- **W transport has 4 components, focus on neoclassical convection and turbulent diffusion**

Logarithmic gradient in stationary state with no source

Complex, but benign

Threat: Drives accumulation

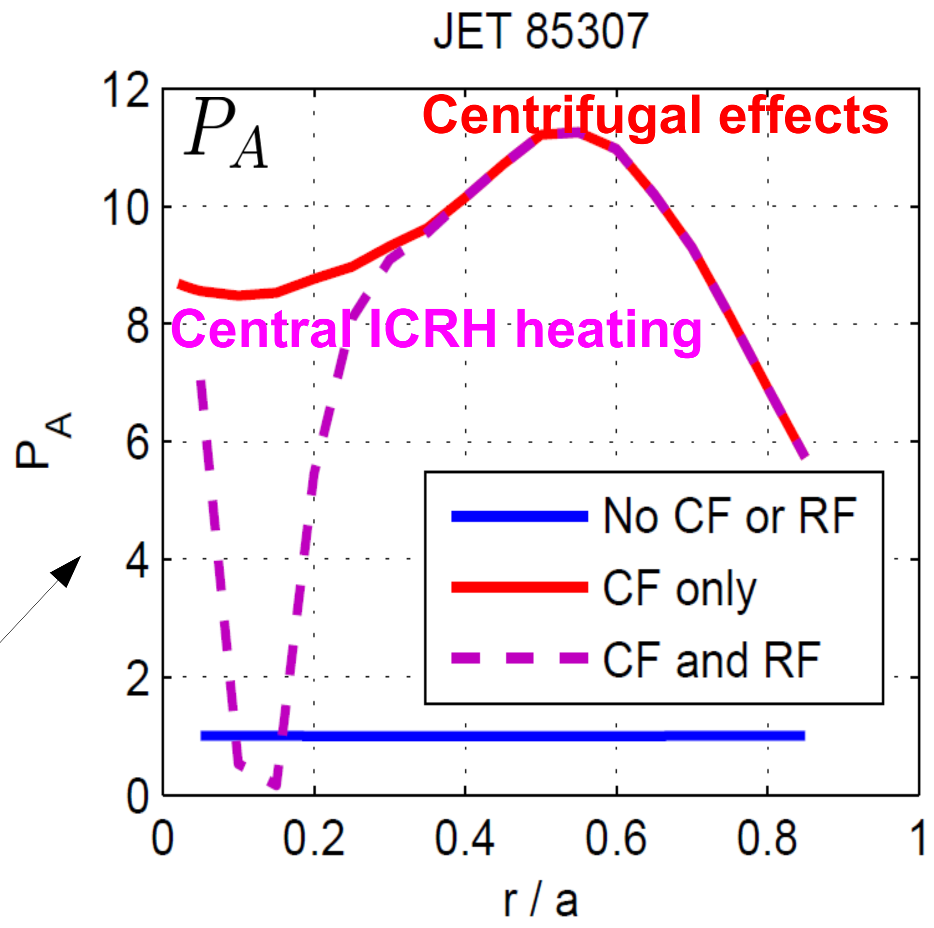
$$\frac{R}{L_{nZ}} = -\frac{RV_{Z\,\mathrm{trb}} + RV_{Z_{\mathrm{NC}}}}{D_{NZ\,\mathrm{trb}} + D_{NZ_{\mathrm{NC}}}}$$

Mitigation - large if turbulent transport

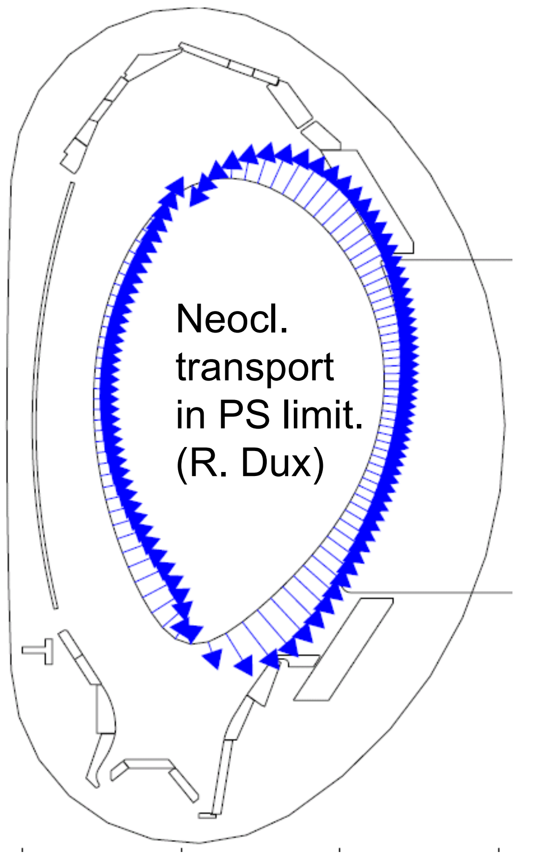
Small, ~ P_A, no Z dependence

$$V_{Z_{\mathrm{NC}}} \propto Z P_A \left(-\frac{R}{L_{n_i}} + \frac{1}{2}\frac{R}{L_{T_i}} \right)$$

Rotation -> Poloidal asymmetry
up to 20x increase in neocl. transport (JET)

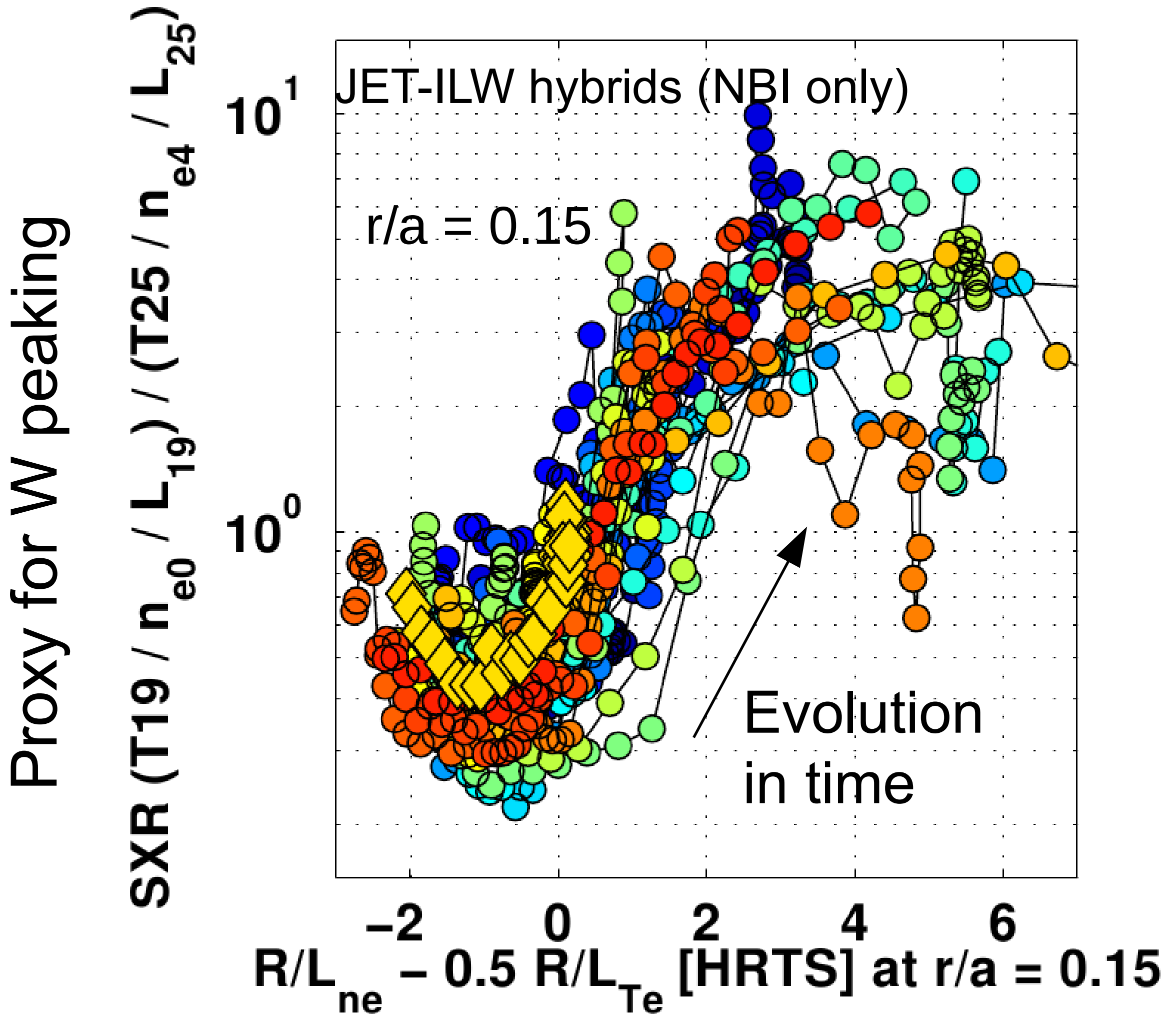


Casson PPCF 2015



Evolution of bulk density profile controls W accumulation timescale

- **Central W accumulation universal observation the Hybrid scenario (q_{95} ~ 4, β_N = 2 - 3)**
  - **Slow rise in density peaking leads to W accumulation**
- **JET Hybrid scenario more prone to W accumulation than Baseline (q_{95} ~ 3, β_N ~ 1.8):**
  - **Lower density stationary scenario**
  - **Density more peaked (central beam deposition)**
  - **Less sawteeth (central flushing)**
  - **Higher beta → NTMs**
  - **Larger Mach numbers (more poloidal asymmetry)**
- **Here we focus on the Hybrid scenario**

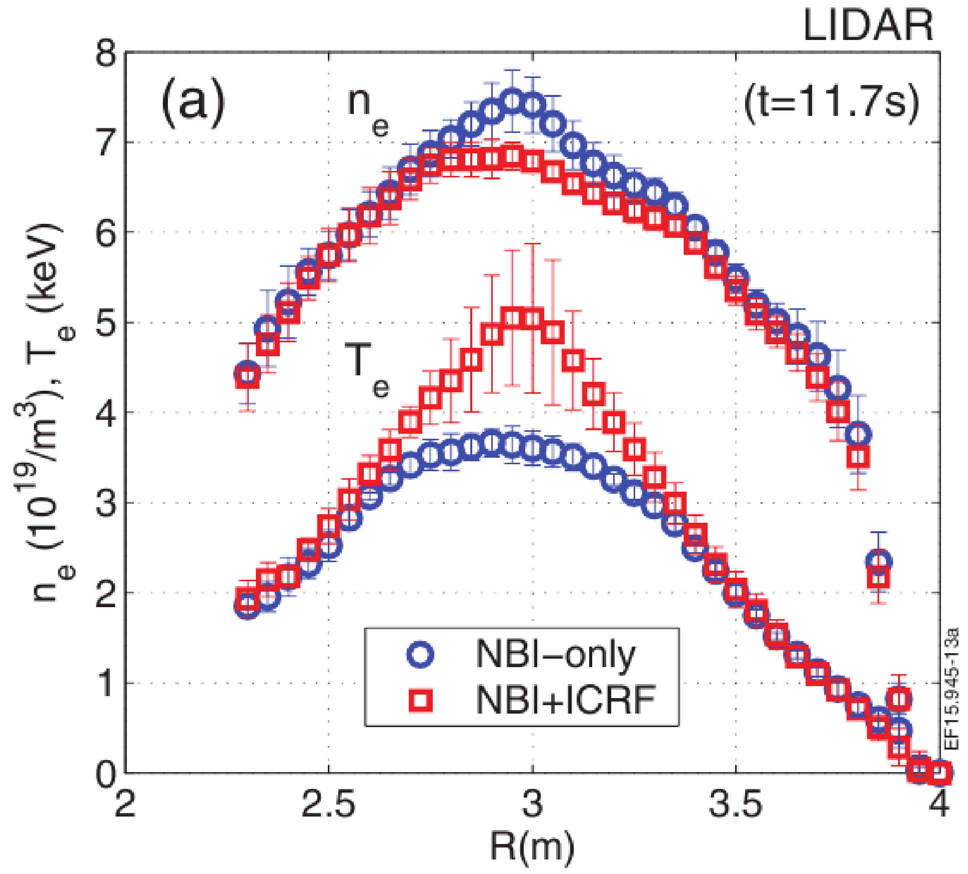


Proxy for neoclassical convection

Angioni NF 2014

ICRH can mitigate W accumulation in several ways

- **Central ICRH has multiple beneficial effects**
  - Drives central turbulence
    - **Decreases main ion density peaking and rotation**
    - **Increases W diffusion**
  - Increased temperature peaking and neoclassical screening
  - Fast ions act on neoclassical W transport
    - **Anisotropy of minority reduces poloidal asymmetry of W**
    - **Additional temperature screening**
- **The various effects present a complex optimisation**
  - Requires integrated flux-driven modelling
  - Requires high fidelity ICRH modelling



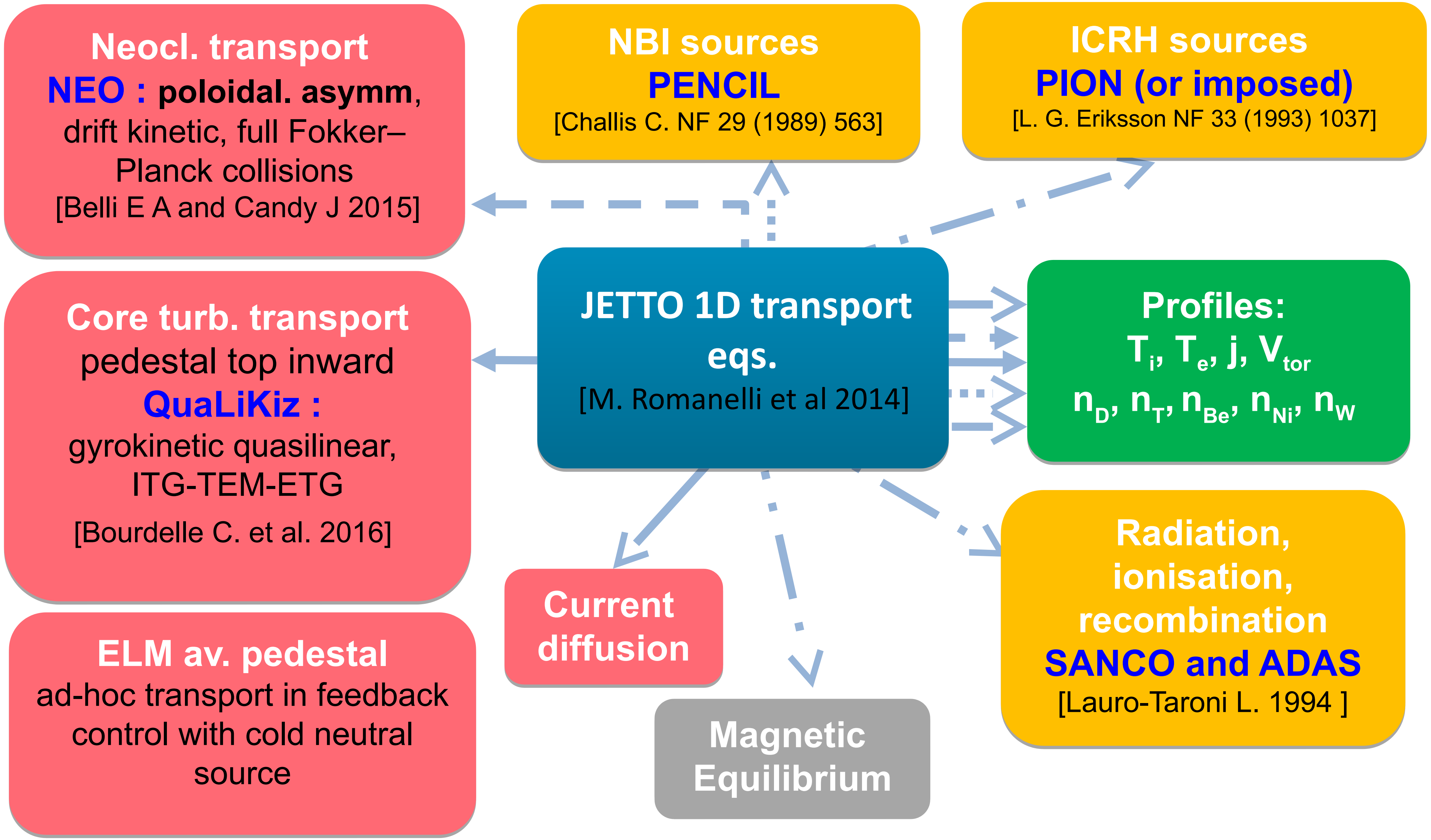
Baseline, with Ti = Te
E. Lerche Nucl. Fusion 56 (2016) 036022

Outline

- Mechanisms of W transport
- **Integrated predictive modelling**
- Optimisation of heating
- Extrapolation to DT

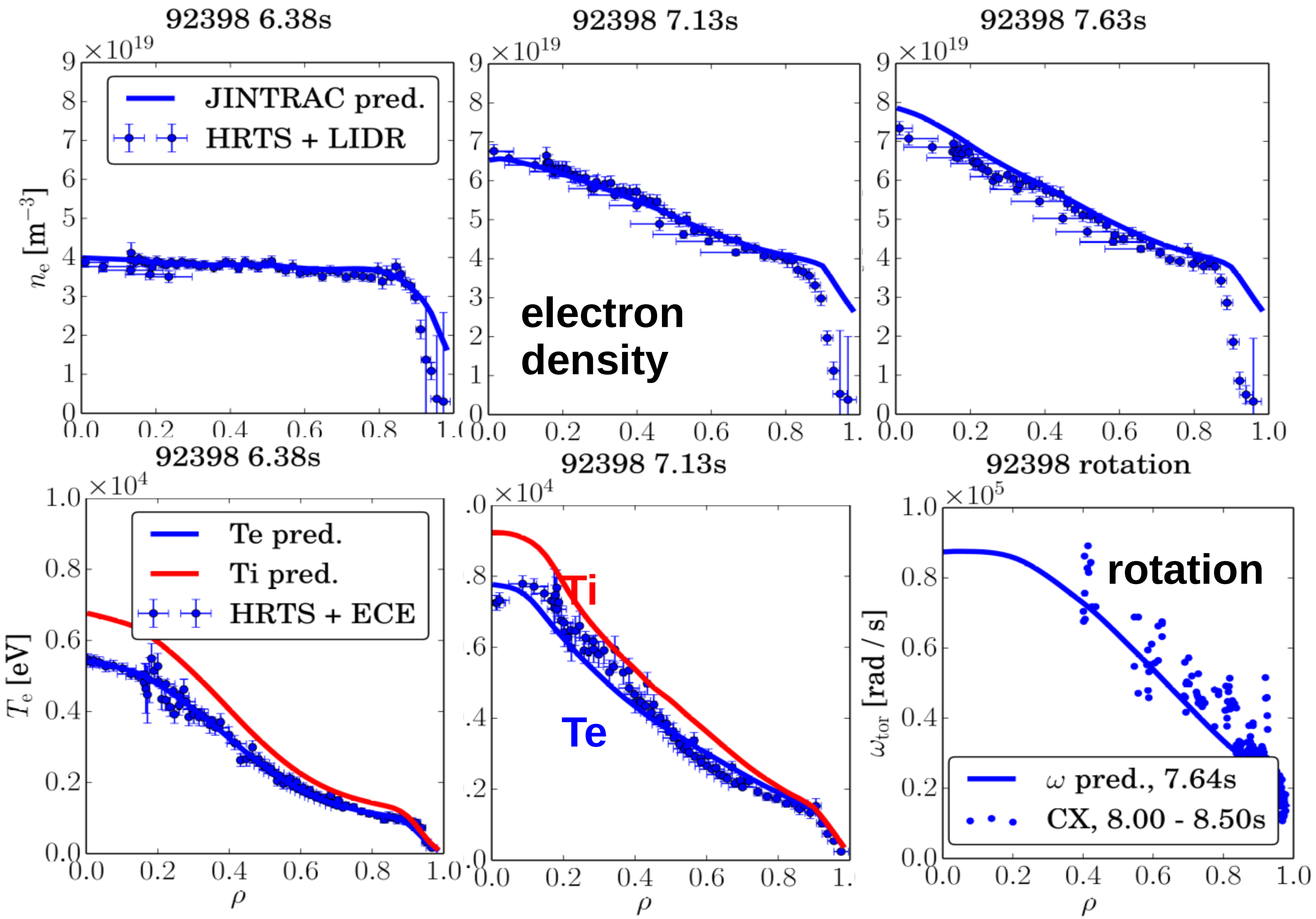
Integrate first principle models to predict 9 channels self-consistently

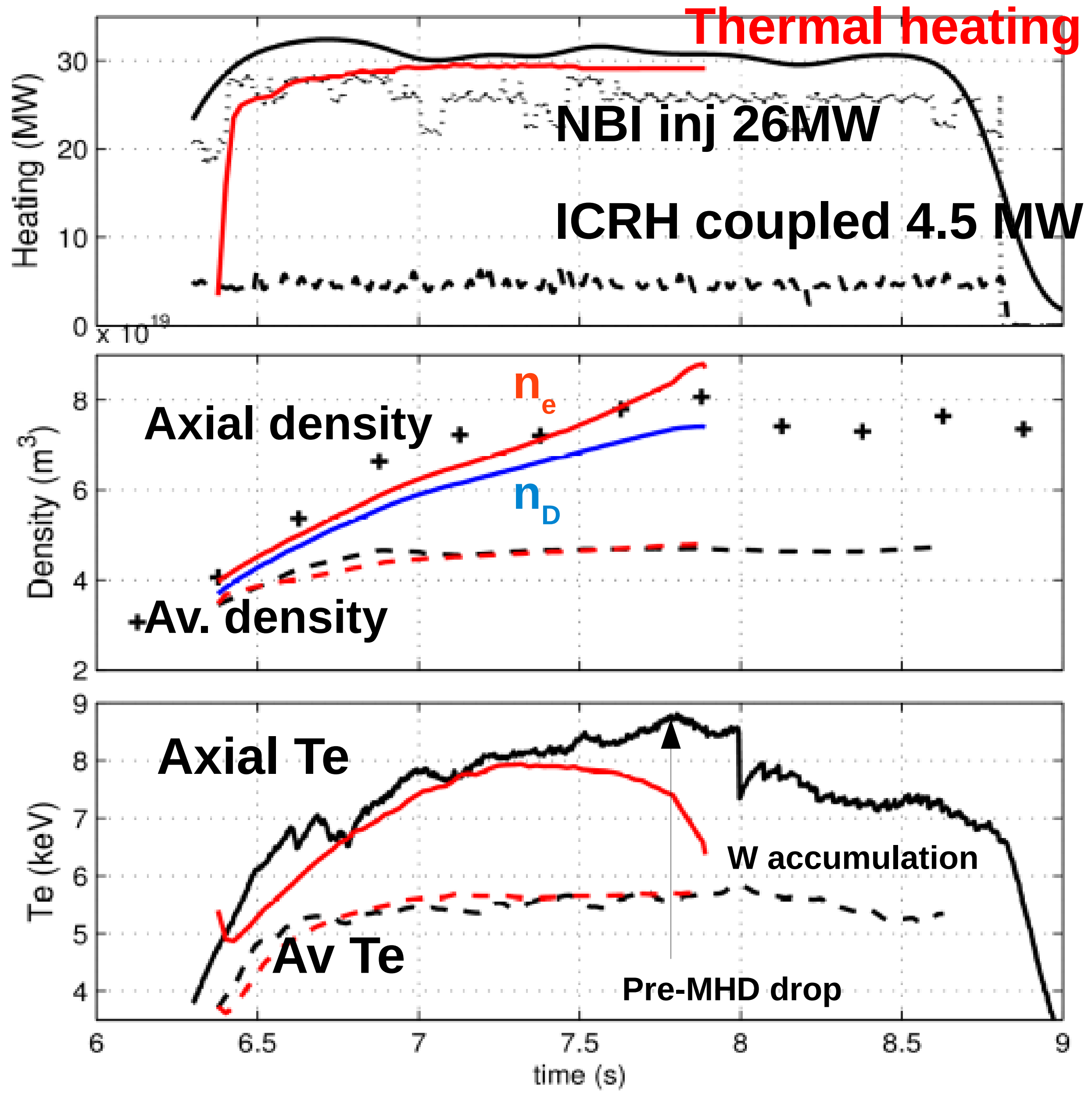
- **To enable this work, transport models NEO and QuaLiKiz integrated in JINTRAC suite**
- **All channels <u>including rotation</u> predicted from first principles**
- **Quasi-linear models enable flux driven multi-channel interactions:**
  - **L1: Ti, Te**
  - **L2: Ti, Te, ne**
  - **L3: Ti, Te, ne, Vtor**
  - **L4: Ti, Te, multi-ion, Vtor**



Evolution of highest performance hybrid reproduced over ~10 τ_E

- **Hybrid JET-ILW Bt = 2.8T, Ip = 2.2 MA, H_{98} = 1.3, τ_E = 0.17s**
  - **Predicted from start of H-mode until W accumulation on axis**
- **Correct timescale of density rise; all bulk channels well predicted**



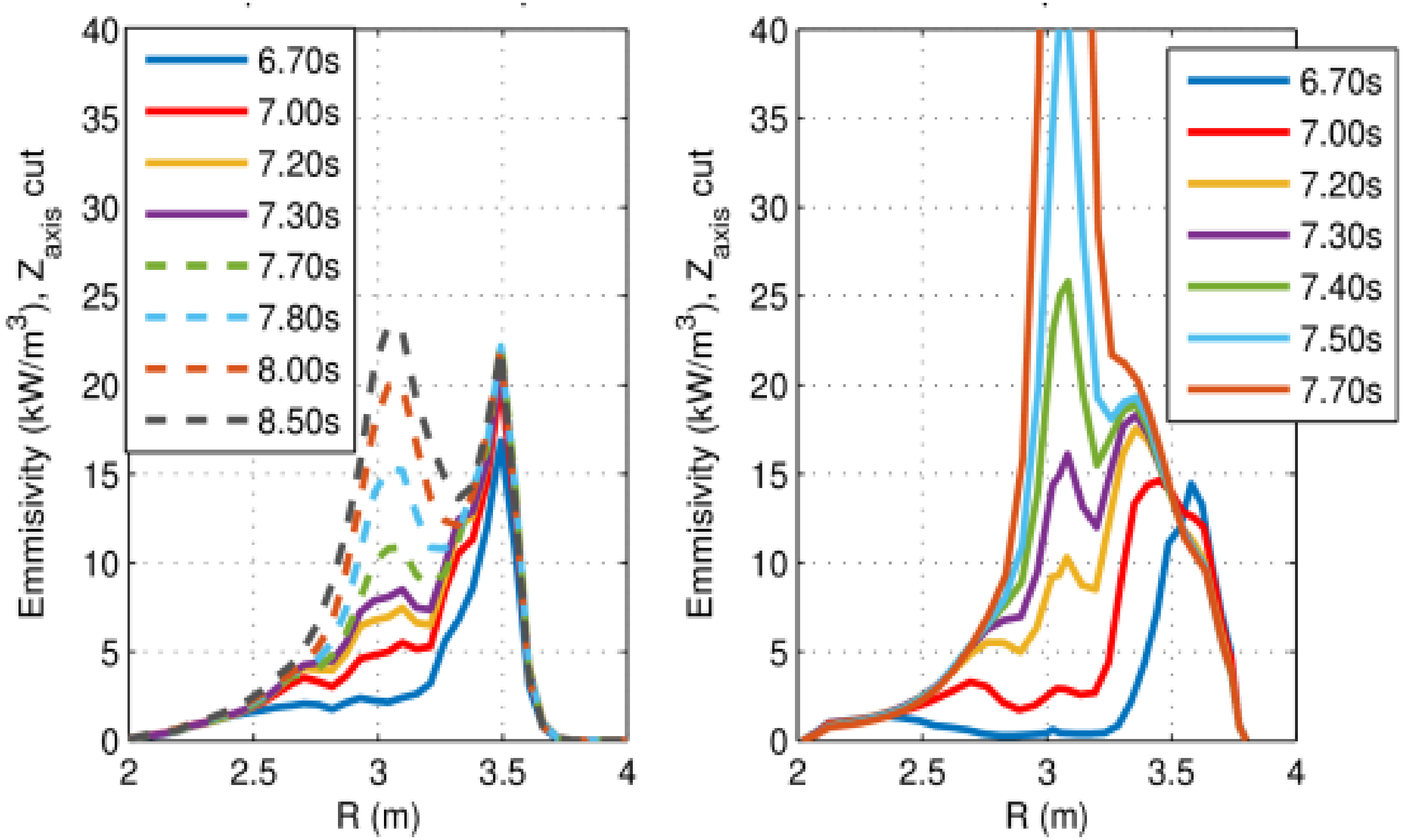


Simulation predicts correct timescale of W and Ni accumulation

- **W on axis from 7.2s, in both simulation and expt.**
  - **W dominates total radiation, Ni dominates Zeff**
- **Accumulation process less extreme in experiment**
  - **Simulations *extremely* sensitive in accum. phase**
  - **May suggest an missing transport process**
  - **No ad-hoc transport used**

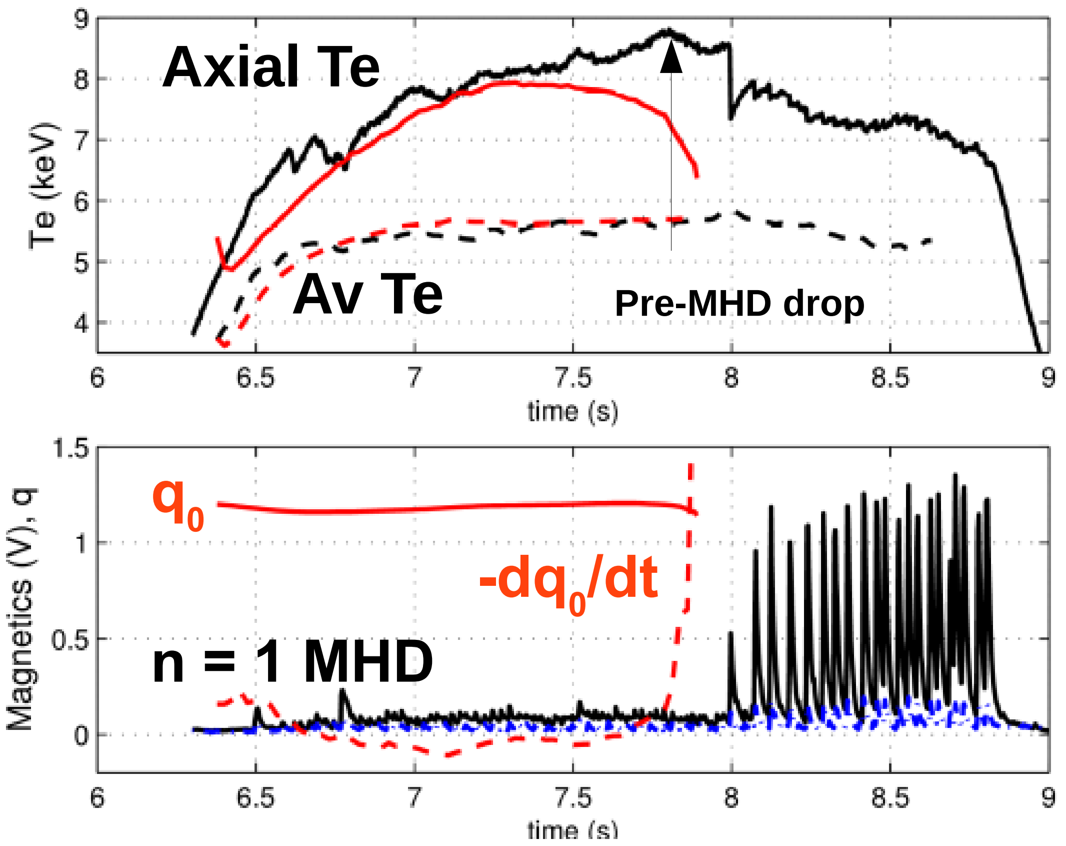
SXR tomography (exp)

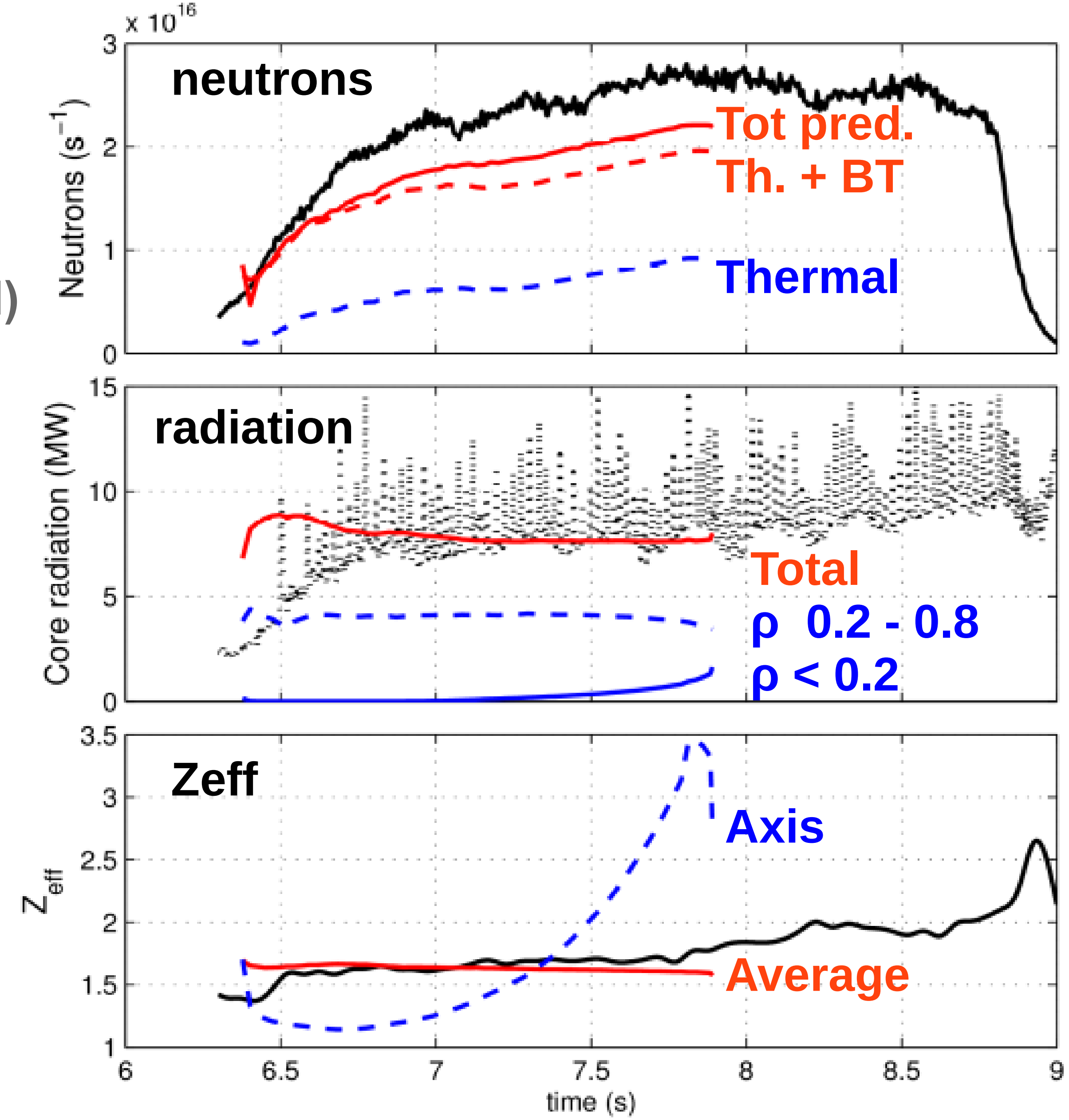
SXR forward model (sim)



Simulation predicts correct timescale of W and Ni accumulation

- **1,1 MHD arrives after accumulation begins**
  - Triggered by W?
  - Temp collapse → loss of central bootstrap curr.
  - Limits performance but mitigates accumulation (not modelled)





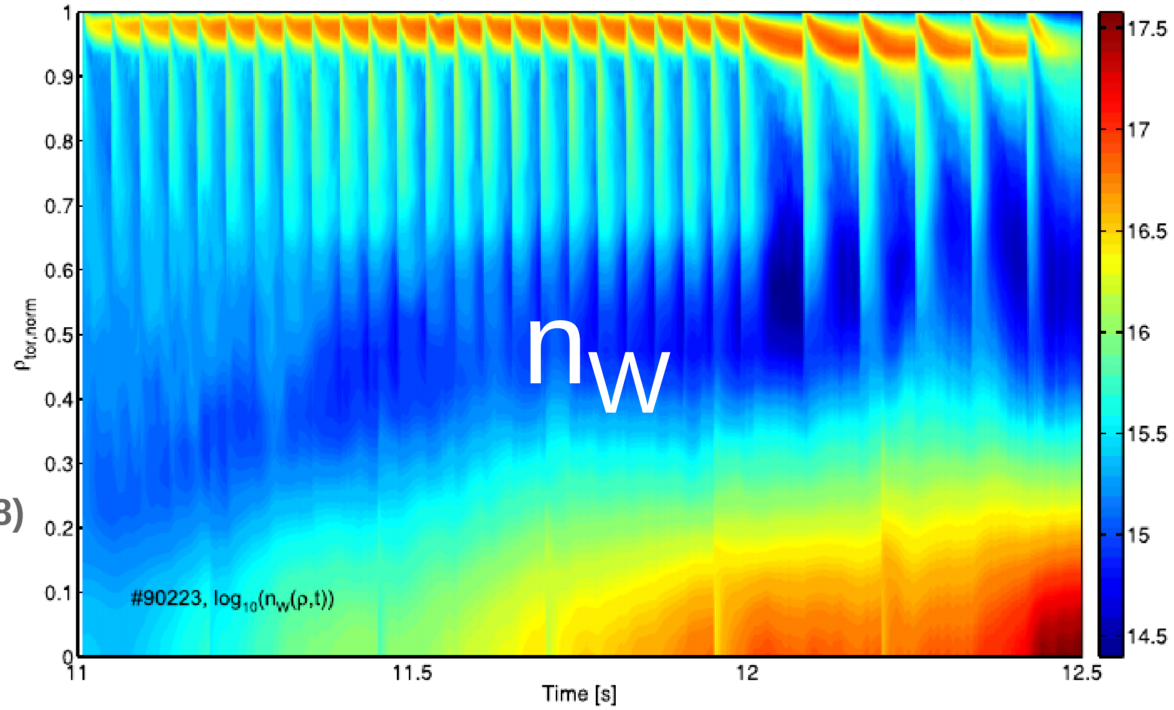
Strengths and limitations of the presented modelling

- **Core transport, equilibrium, and sources are self-consistent & first-principle based**
  - Excellent predictive power
  - Explores non-linear, multi-channel interactions
- **Pedestal sources and transport are matched to experiment**
  - Little predictive power
  - ELM cycle not modelled
- **Core MHD is not modelled**
  - Not present in early phase of hybrid pulses, but significant later

- **SOL not modelled, W sources not computed**
  - Necessary to control both source and transport
  - In flat top, W flushing and pedestal convection are in balance if ELM freq. constant (RTC)
  - Total W content constant in simulation and experiment

Complementary modelling for ramp down integrates SOL W sputtering, ELM cycle, and sawteeth

E de la Luna, this conf.;
F Koechl PPCF 60 074008 (2018)



Outline

- Mechanisms of W transport
- Integrated predictive modelling
- **Optimisation of heating**
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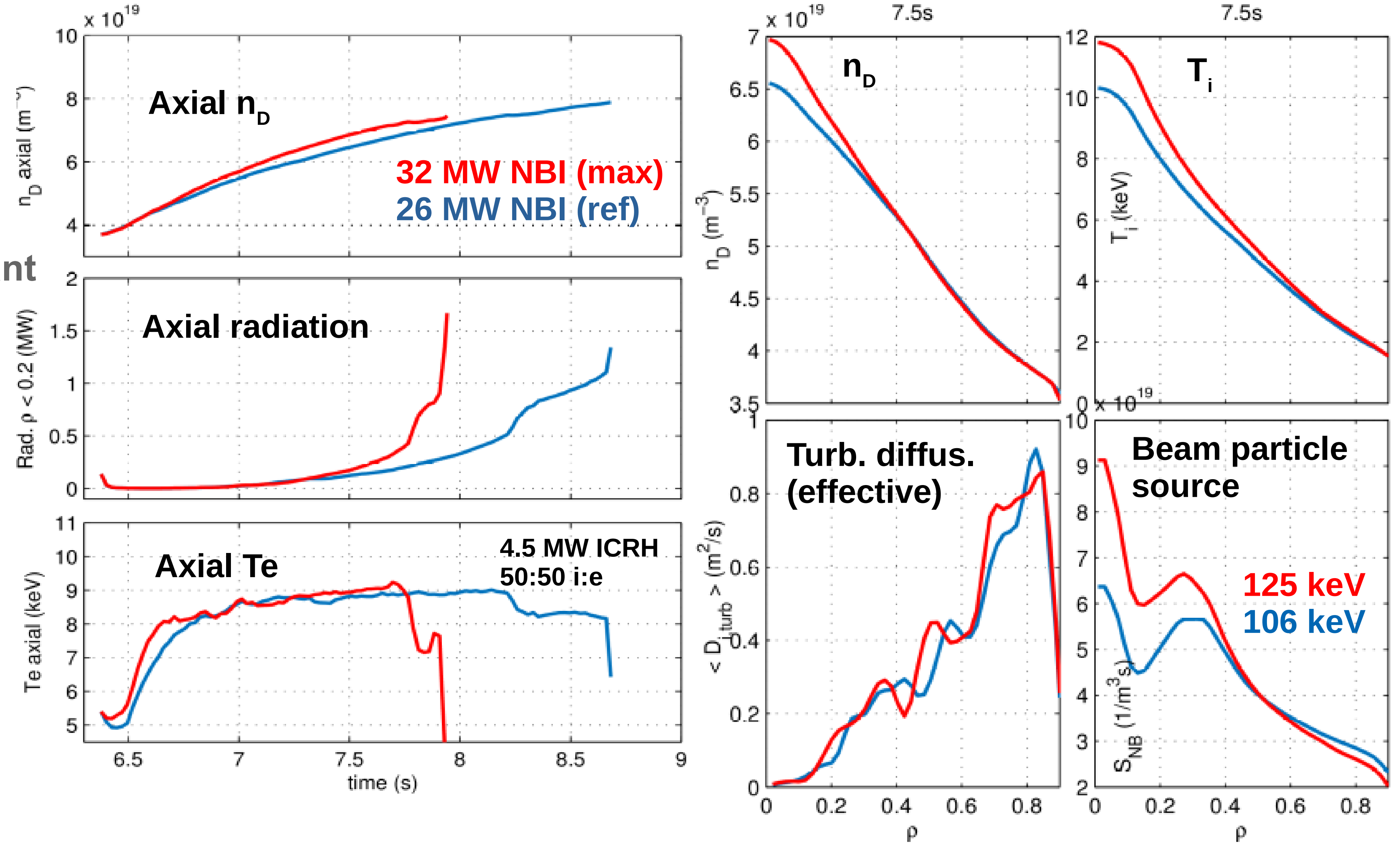
Increased NBI power will accelerate W accumulation

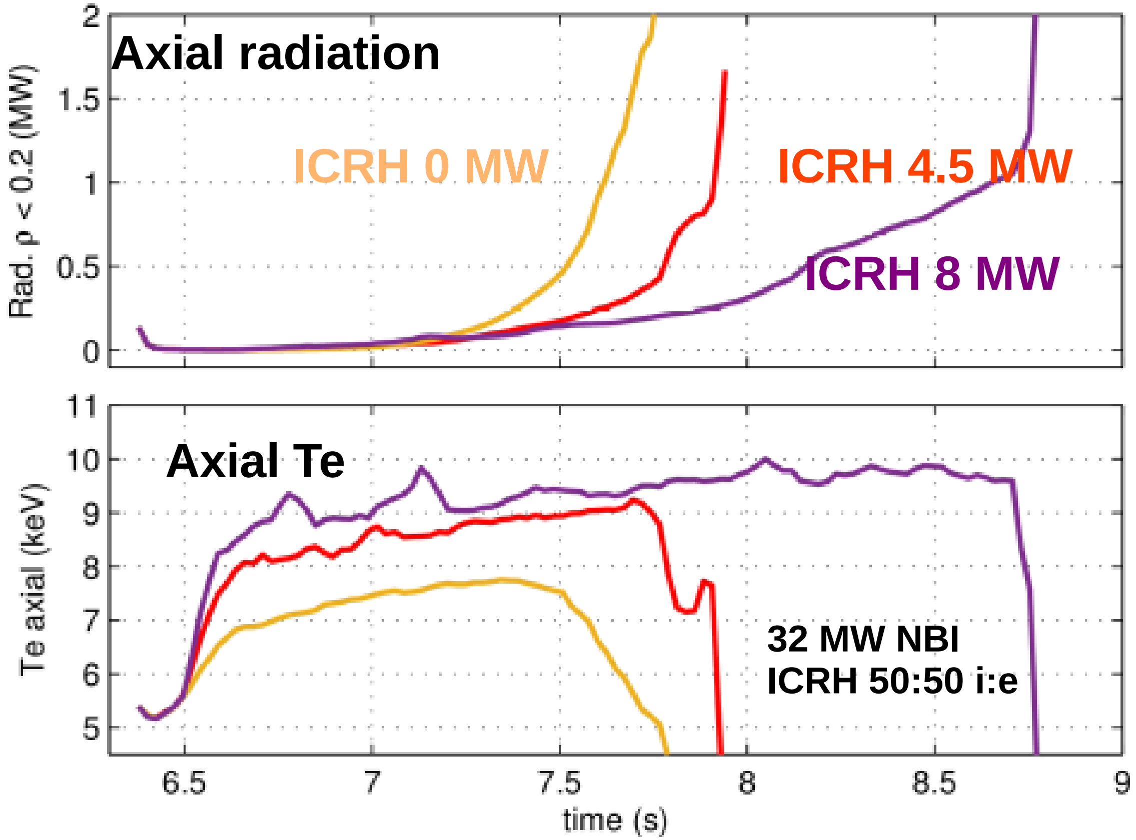
- **Beam energies will be increased to reach maximum power**
  - **More central power, particle, and torque deposition**
  - **NBI particle source is significant in increasing central ∇n_D**
    (T. Tala, this conf., Garzotti, Valovic NF 2006/7)
  - **For V_W, increased ∇n_D dominates increased ∇Ti**

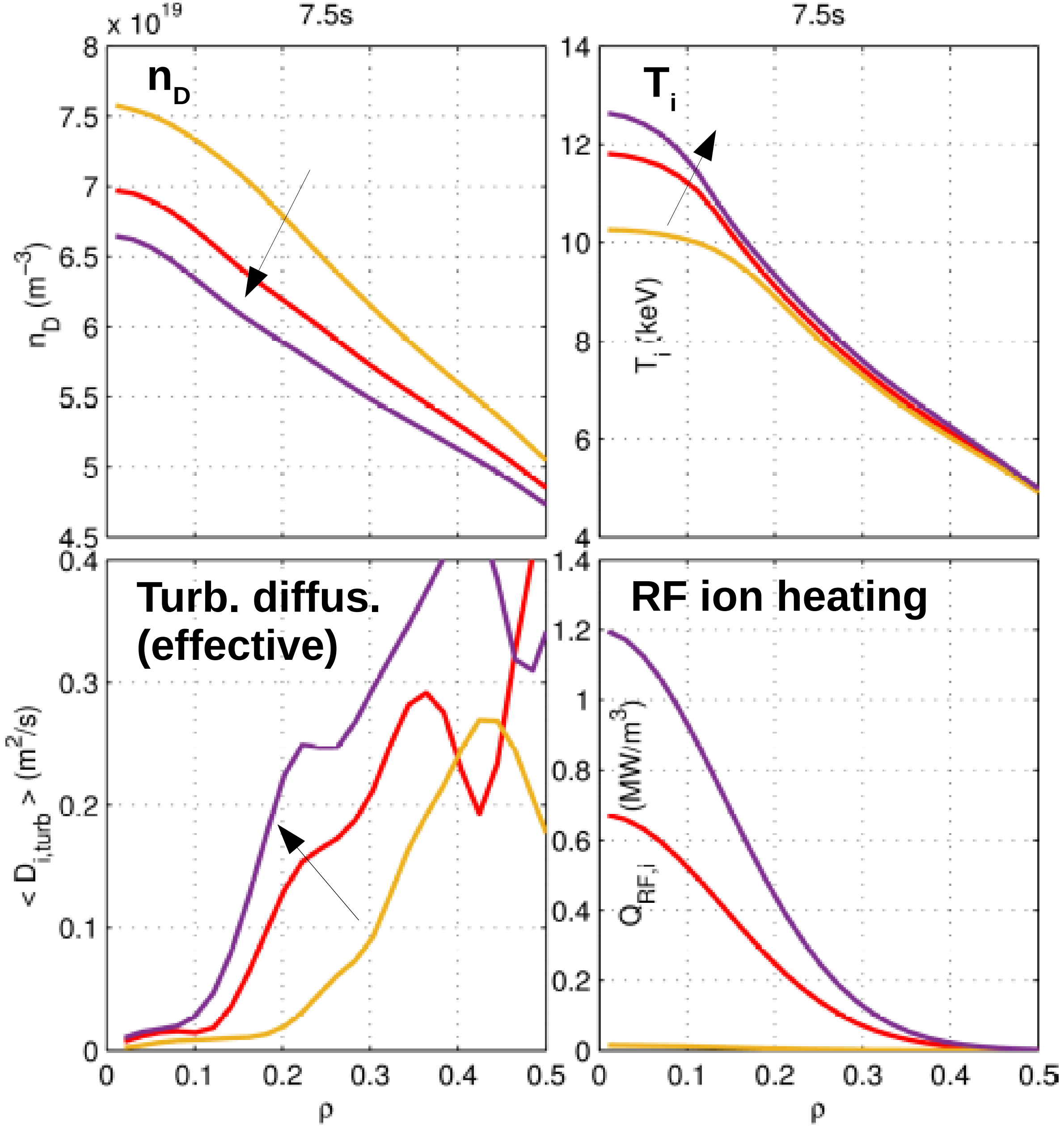
$$V_{Z_{NC}} \propto Z P_A \left(-\frac{R}{L_{n_i}} + \frac{1}{2}\frac{R}{L_{T_i}}\right)$$



ICRH heating delays W accumulation, consistent with JET observations

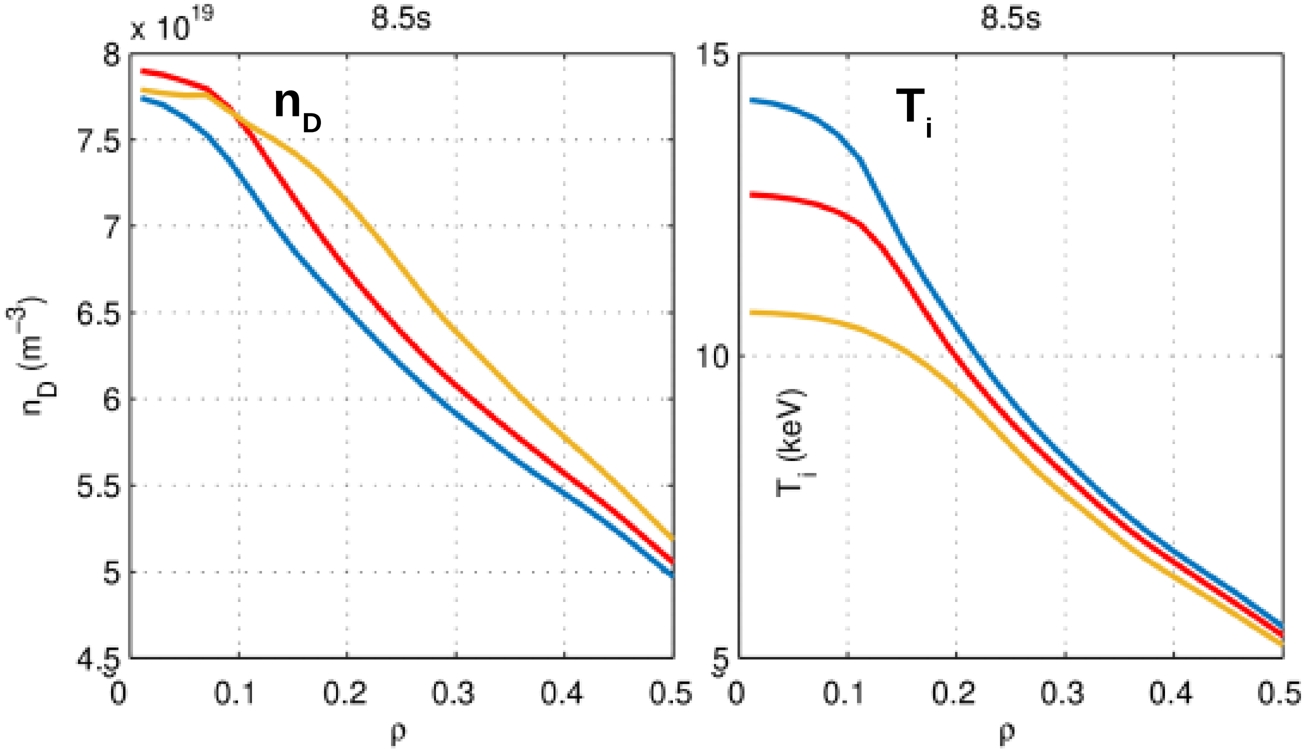
- **ICRH helps in neoclassical dominated core, both increasing ∇T_i and decreasing ∇n_D**
  - Increased turbulent diffusion reduces central density peaking
  - Localised axial ICRH most effective in increasing temp. screening
  - 4MW increase in ICRH compensates 6MW increase in NBI



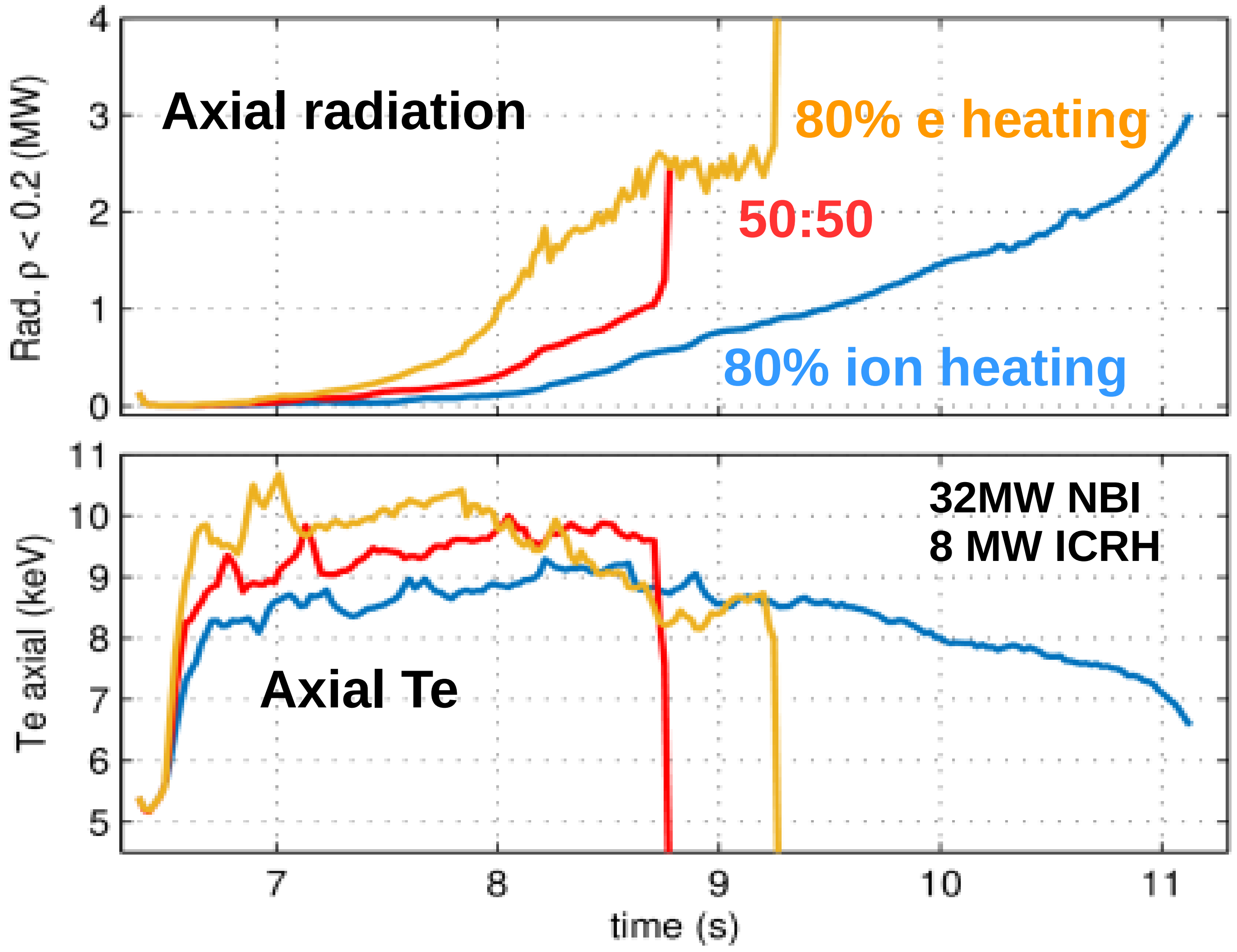


Ion heating schemes *predicted* as most effective on W

- **Ion heating both increases ∇T_i and decreases ∇n_D**
- **Specific to JET hybrid scenario:**
  Ti > Te, and dominant neoclassical convection
  (large Mach no ~ 0.7)
  - Where Ti ~ Te coupled, or turbulence dominates, electron heating more effective (AUG and ITER)



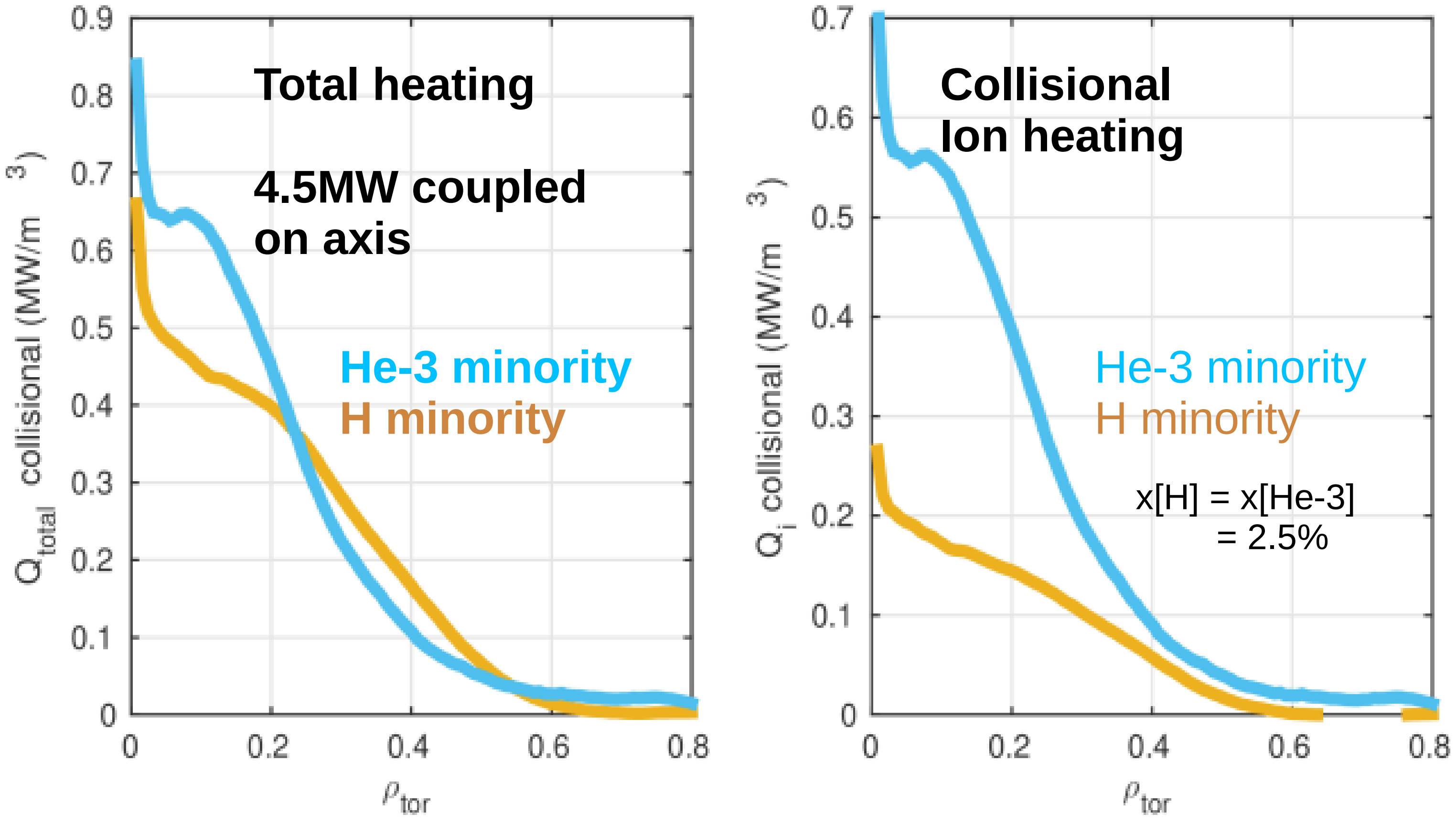
Prediction, not yet tested



High fidelity ICRH modelling supports He-3 minority scheme

- **Support the integrated modelling with standalone state-of-the-art ICRH modelling (SCENIC)**
  - **Full wave solver, second harmonic absorption**
  - **Monte Carlo fast ions and Fokker-Planck**
  - **Self-consistent equilibrium with fast ion anisotropy**
  - **Finite orbit widths reduce impact of anisotropy on W → negligible in high NBI JET**
- **He-3 minority scheme preferentially heats ions**
  - **Narrower power deposition due to narrower orbits, higher power density on axis**
  - **Best for neoclassical W screening**
  - **Similar expected for 3-ion scheme**
    (Y.O. Kazakov, this conf.)
- **Power density and W control maximised when resonance within 10cm of axis**

(J.P. Graves, this conf)



Outline

- Mechanisms of W transport
- Integrated predictive modelling
- Optimisation of heating
- **Extrapolation to DT**

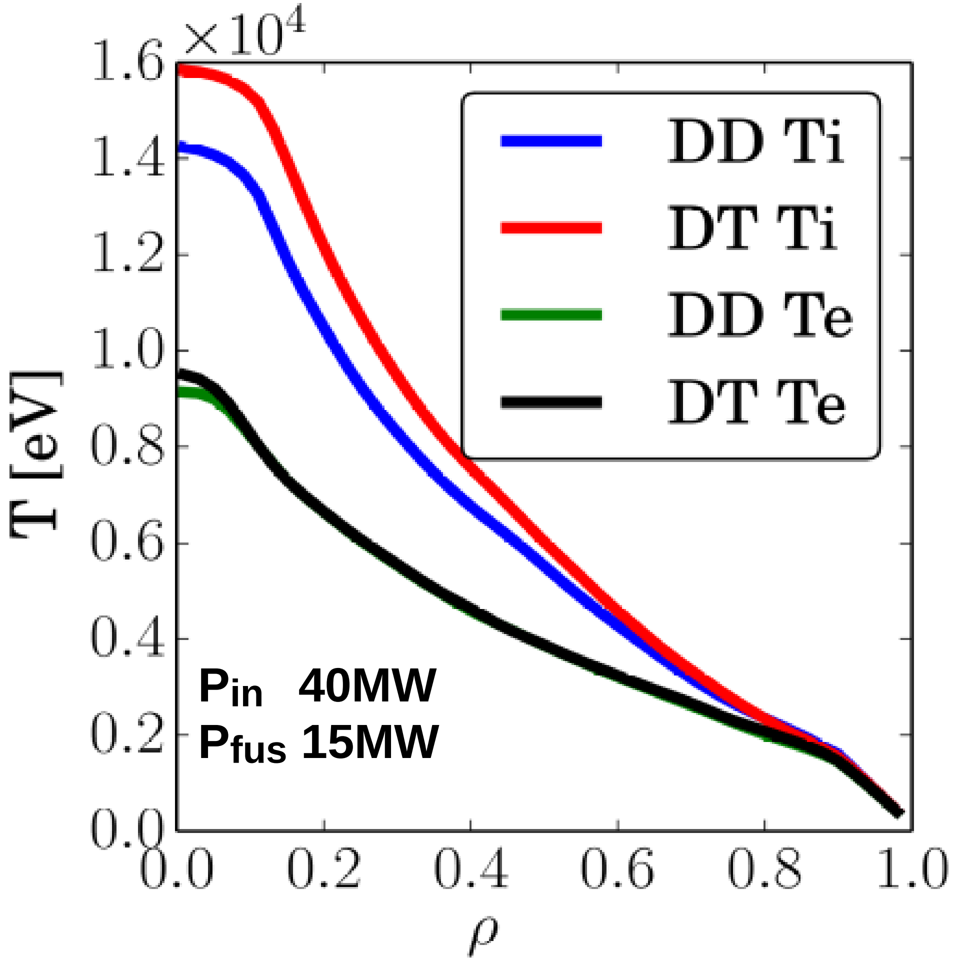
Tritium plasmas have better confinement….

- **Extrapolations to TT and DT plasmas find positive isotope scaling of core confinement**
  - Inclusion of ETG scales pins Te
  - i-e collisional energy exchange reduces with mass
  - Increased Ti / Te and ITG stabilisation

- **Similar scaling to other DT extrapolations** (J Garcia, this conf.)
  - This mechanism specific to high power discharges with Ti > Te
  - Relies on ETG scales, need to verify with nonlinear

- **Caveat: Understanding of isotope scaling is incomplete**

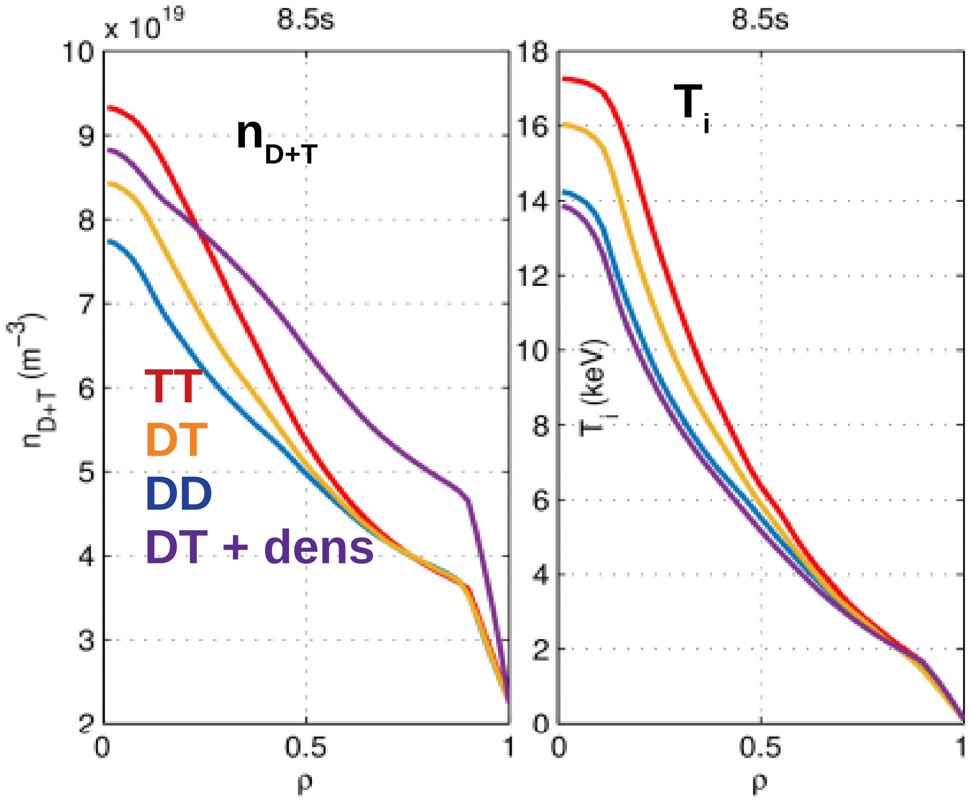
(H Weisen, this conf.)

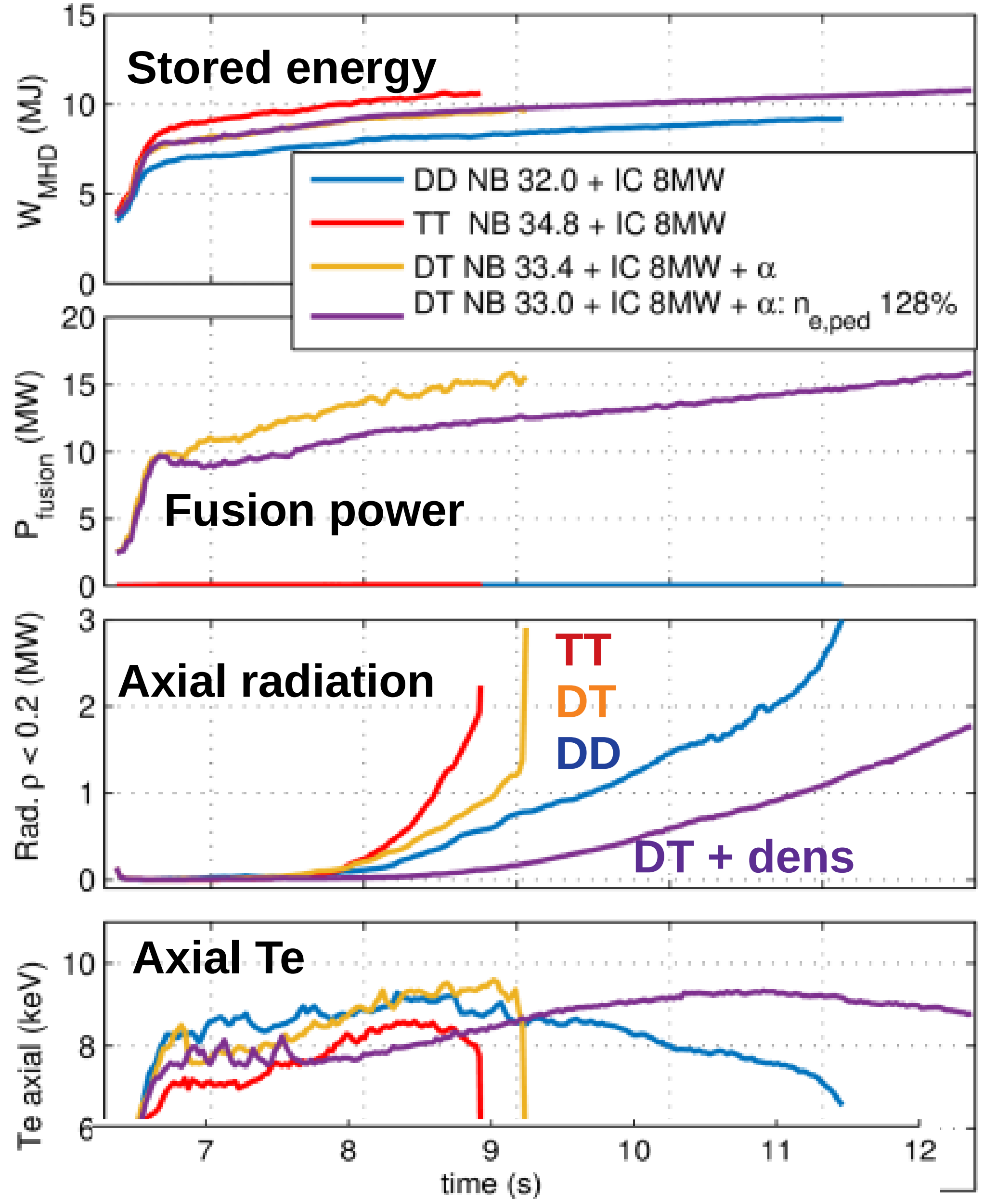


Conservative pedestal assumptions (no scaling with power or isotope)

…. but earlier W accumulation

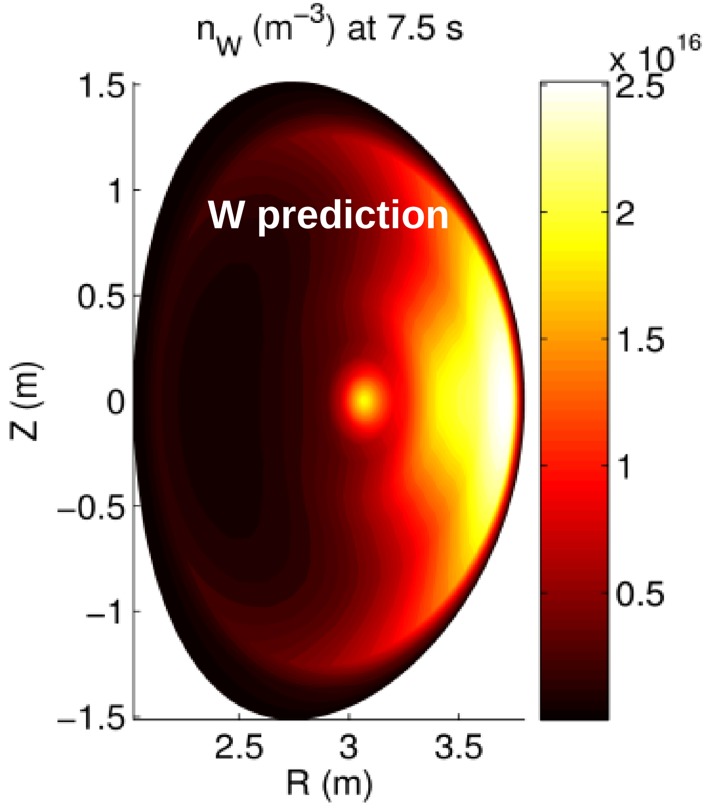
- **Improved confinement in DT also gives larger density peaking, and earlier W accumulation**
  - Mitigate with increased density (less central NBI particle deposition, less density peaking)
  - Some cost in performance
  - Requires optimisation / integration of
    - Increased triangularity
    - Increased plasma current
    - Pedestal isotope scaling
    - Re-optimised q profile to keep MHD free





Conclusions

- **First-principle models integrated into a powerful multi-channel predictive tool for core plasma**
  - Able to analyse complex nonlinear plasma evolution over several confinement times
  - Use to predict first and optimise scenarios - an exciting era for integrated modelling
- **Guides scenario development to optimise W control in JET hybrid:**
  - Reproduces observed W accumulation
  - He-3 ICRH scheme predicted to be more effective for W control
    - **Specific to strongly rotating JET plasmas, with Ti > Te, where neoclassical convection dominates W transport**
  - Positive isotope scaling of confinement from ion-electron energy exchange
    - **This mechanism specific to plasmas with Ti > Te**
  - Earlier W accumulation predicted in DT plasmas
    - **Mitigated by increased plasma density, at some cost in performance**



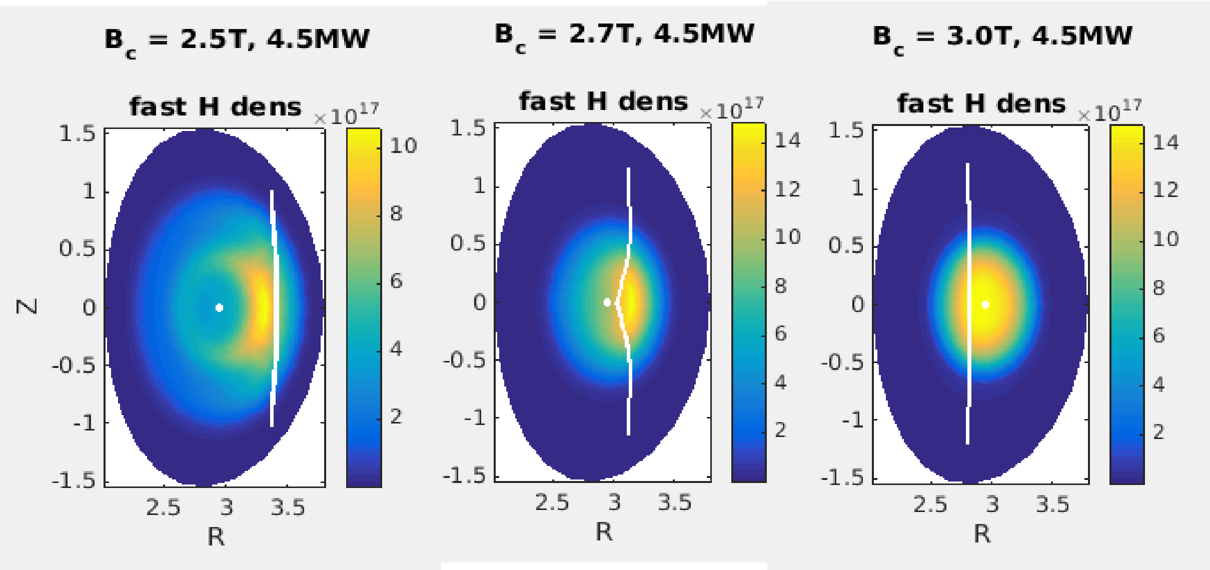
References

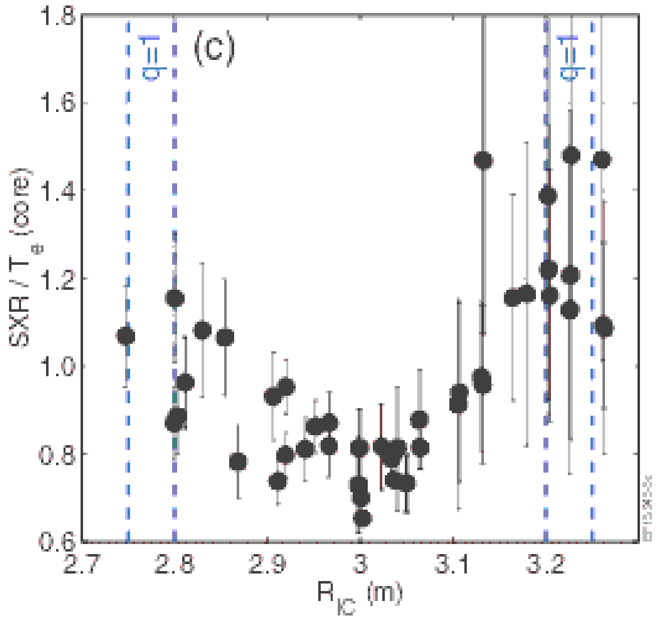
- Angioni, C. et al. Tungsten transport in JET H-mode plasmas in hybrid scenario... NF 54, 83028 (2014);
- Angioni, C. et al. The impact of poloidal asymmetries on tungsten transport in JET... PoP 22, 55902 (2015);
- Romanelli, M. & Ottaviani, M., Effects of density asymmetries on heavy impurity transport... PPCF 40, 1767 (1998);
- Breton, S. et al. First principle integrated modeling of multi-channel transport including Tungsten in JET. NF 58, 96003 (2018);
- Casson, F. J. et al., '...heavy impurity transport and ... modelling of tungsten in JET and AUG', PPCF, 57 (2015),14031;
- Angioni, C. & Helander, P., Neoclassical transport of heavy impurities with poloidally asymmetric density. PPCF 56, 124001 (2014);
- Belli, E. A. and Candy, J., a) PPCF, 50 (2008), 95010 ; b) PPCF, 51, (2009) 75018; c) PPCF, 54 (2012), 15015;
- Bourdelle, C. et al., Core turbulent transport in tokamak plasmas… with QuaLiKiz, PPCF, 58 (2016), 14036;
- Citrin, J. et al., Tractable flux-driven temperature, density, and rotation with... QuaLiKiz, PPCF, 59, 124005 (2017);
- http://www.qualikiz.com
- Cenacchi, G. and Taroni, A., JETTO: A Free-Boundary Plasma Transport Code, Internal report JET-IR(88)03, (1988);
- Romanelli, M. et al., JINTRAC: A system of codes for Integrated Simulation..., Plasma and Fusion res, 9 (2014), 3403023;
- Lerche, E. et al. Optimization of ICRH for core impurity control in JET-ILW. NF 56, 36022 (2016);
- Eester, D. V. et al. H majority inverted radio frequency heating scheme expts in JET-ILW. EPJ Web Conf. 157, 3061 (2017);
- Angioni, C. et al. A comparison of the impact of central ECRH and central ICRH on W behaviour in AUG. NF 57, 56015 (2017);
- Goniche, M. et al. ICRH for W control in ... JET scenarios. PPCF 59, 55001 (2017);
- M. Jucker et al. , 'Integrated modeling for ICRH in toroidal systems', CPC., 182 (2011), 912;
- W. A. Cooper et al., Anisotropic pressure bi-Maxwellian distribution.., NF, 46 (2006);
- M. Sertoli et al, Effects of ICRH resonance on ... W density..., EPS 2018 O4.103;
- Schneider, P. A. et al. Explaining the isotope effect with collisional electron-ion energy exchange. NF 57, 66003 (2017);
- Garcia, J. et al. Challenges in extrapolation from DD to DT... PPCF 59, 14023 (2017)

Supplementary material

High fidelity ICRH modelling supports near axial resonance

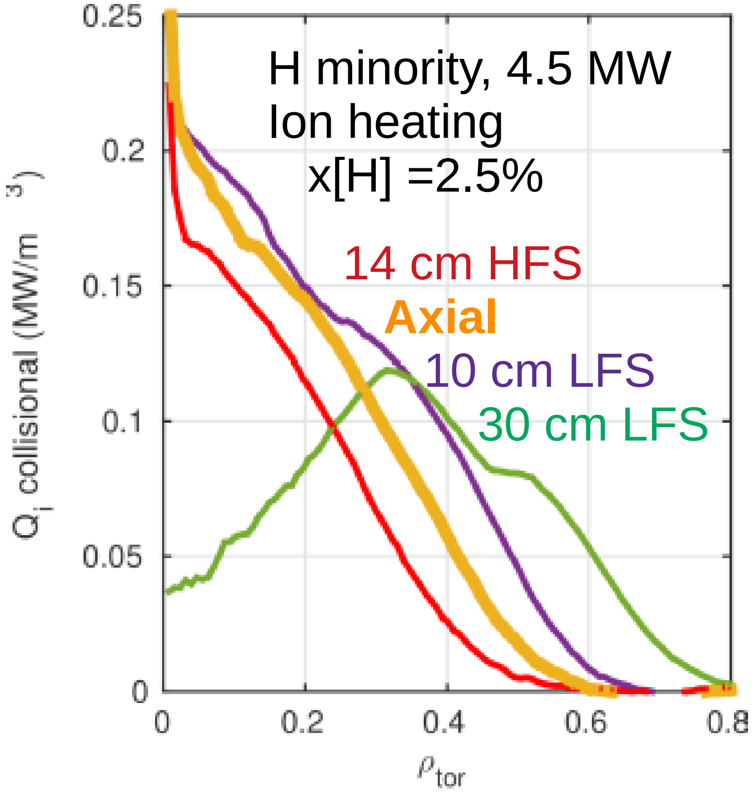
- Fine resonance scan modelled
  - Power density maximal when resonance within 10cm of axis
  - Insensitive within +/-10cm, due to orbit power spreading
- Anisotropic pressure is relevant only for LFS heating, but has negligible impact on W asymmetry (in high NBI JET)
  - Effect reduced compared to previous works, by finite orbit effects
  - Cannot overcome dominant rotation effect, even more negligible in He-3
  - Fast ion temperature screening also negligible due to orbit power spreadir



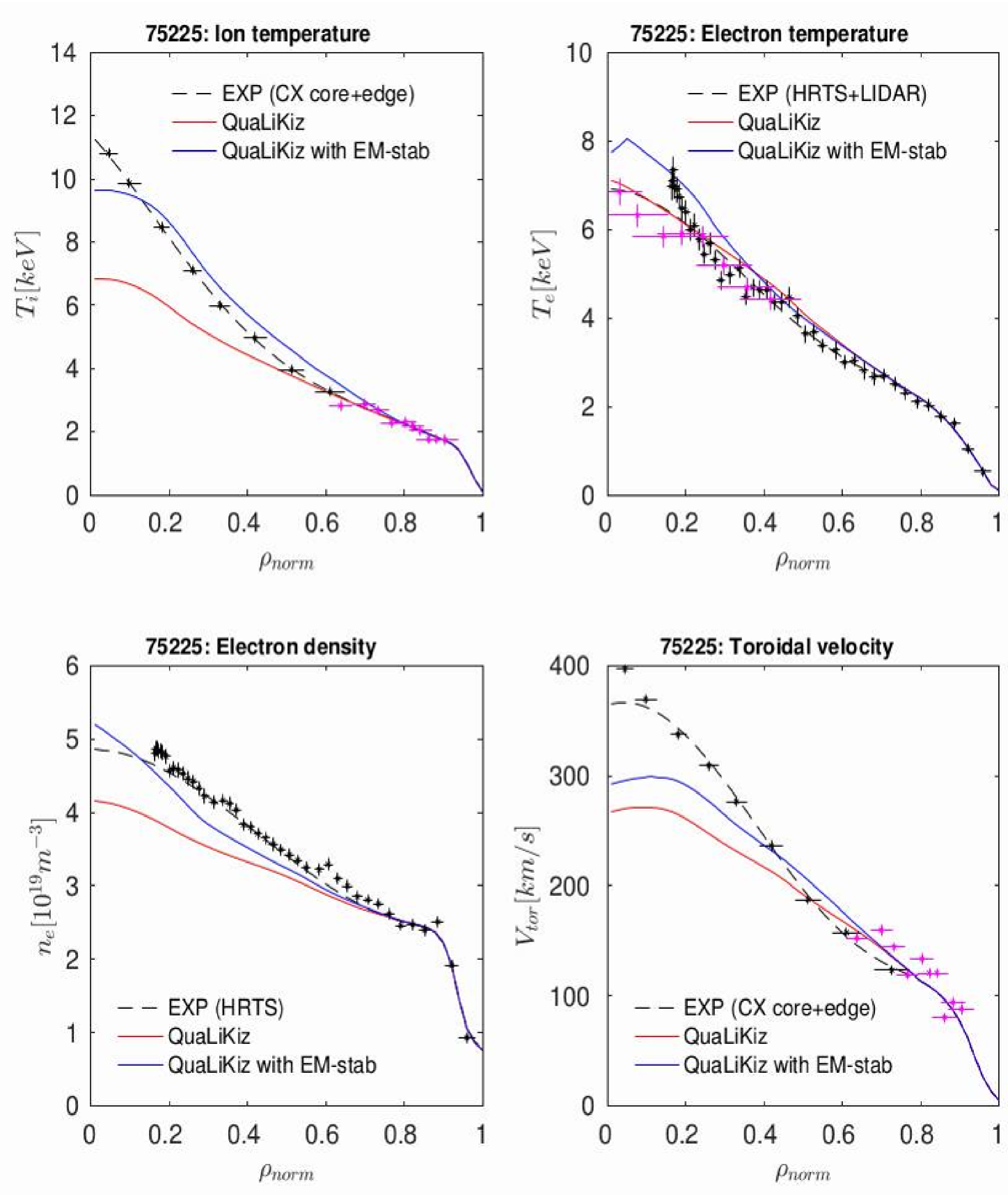


Consistent with observations

E. Lerche Nucl. Fusion 56 (2016) 036022



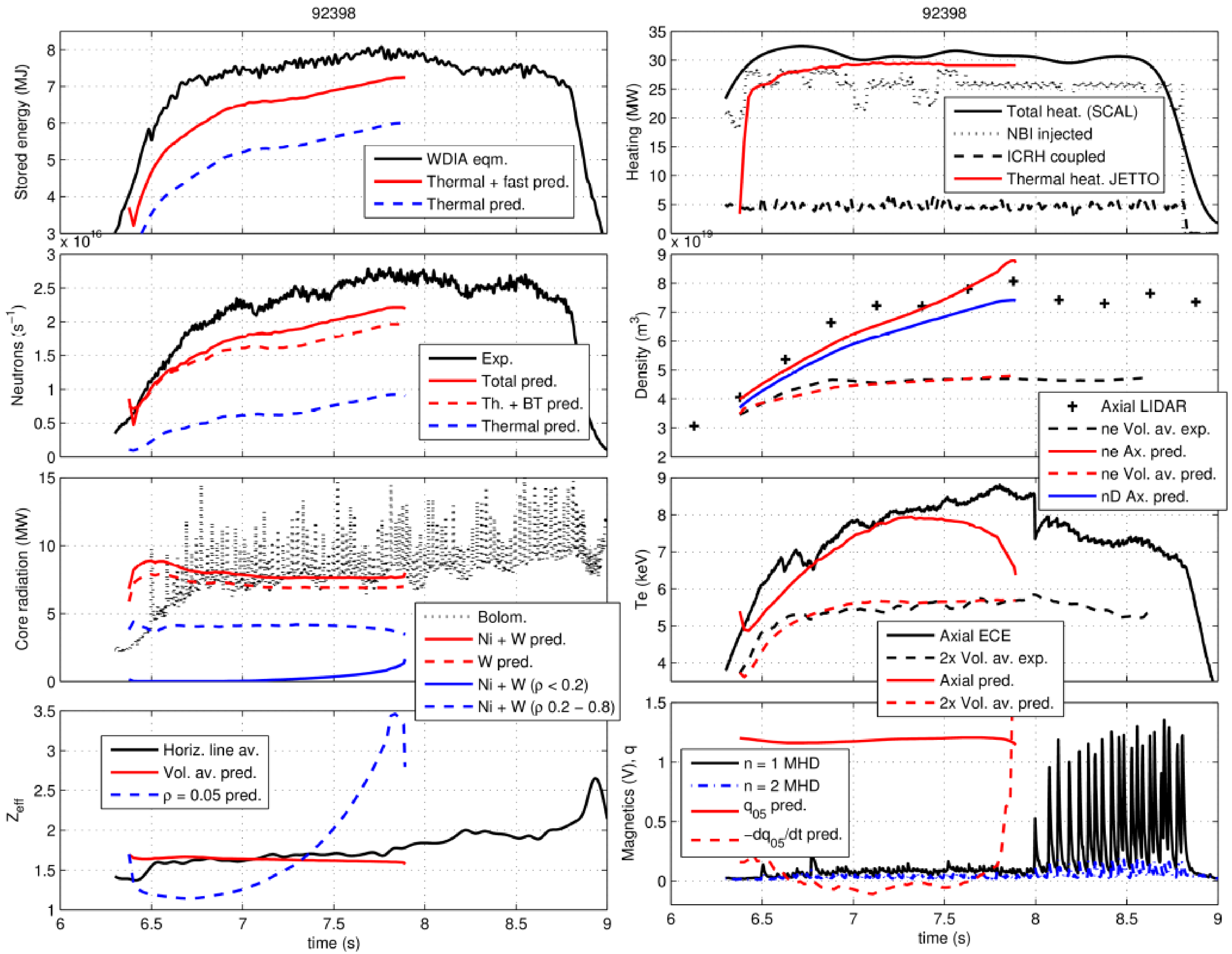
4-channel validation in JET-C hybrid (with core Ti measurement)



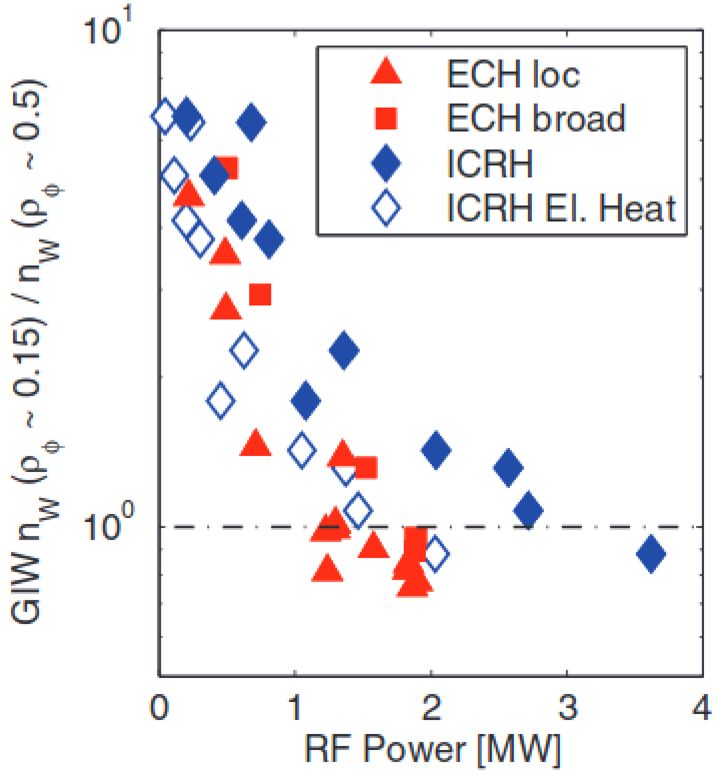
Ad hoc model to emulate electromagnetic stabilisation of ITG turbulence (not present in QuaLiKiZ)

R/LTi inputs decreased by $\beta_{thermal}/\beta_{total}$

Validation of global evolution

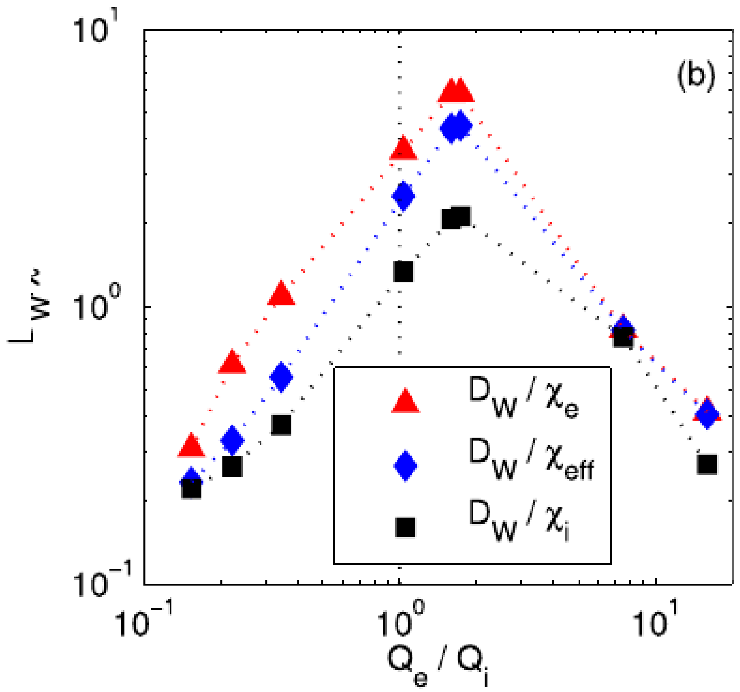


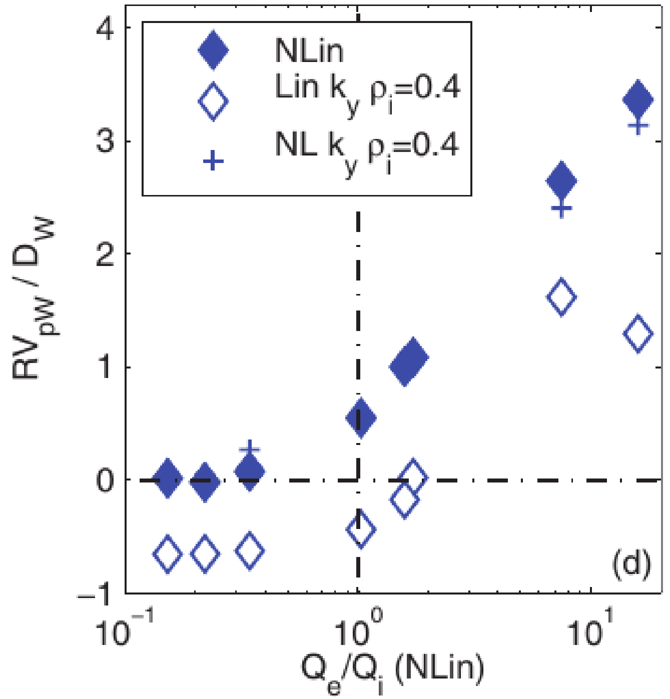
Electron heating preferred in ITER better for W turbulent transport (outward convection)



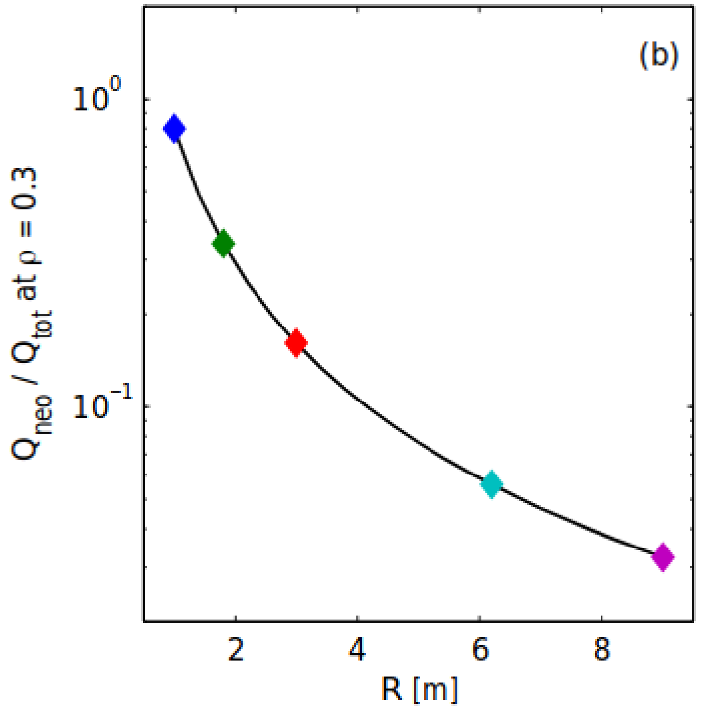
C. Angioni et al 2017
Nucl. Fusion 57 056015

C. Angioni, Physics of Plasmas 22, 102501 (2015)





C. Angioni et al 2017
Nucl. Fusion 57 022009



Poloidal asymmetries with anisotropy

- ICRH heats minorities anisotropically, LFS localisation of minority

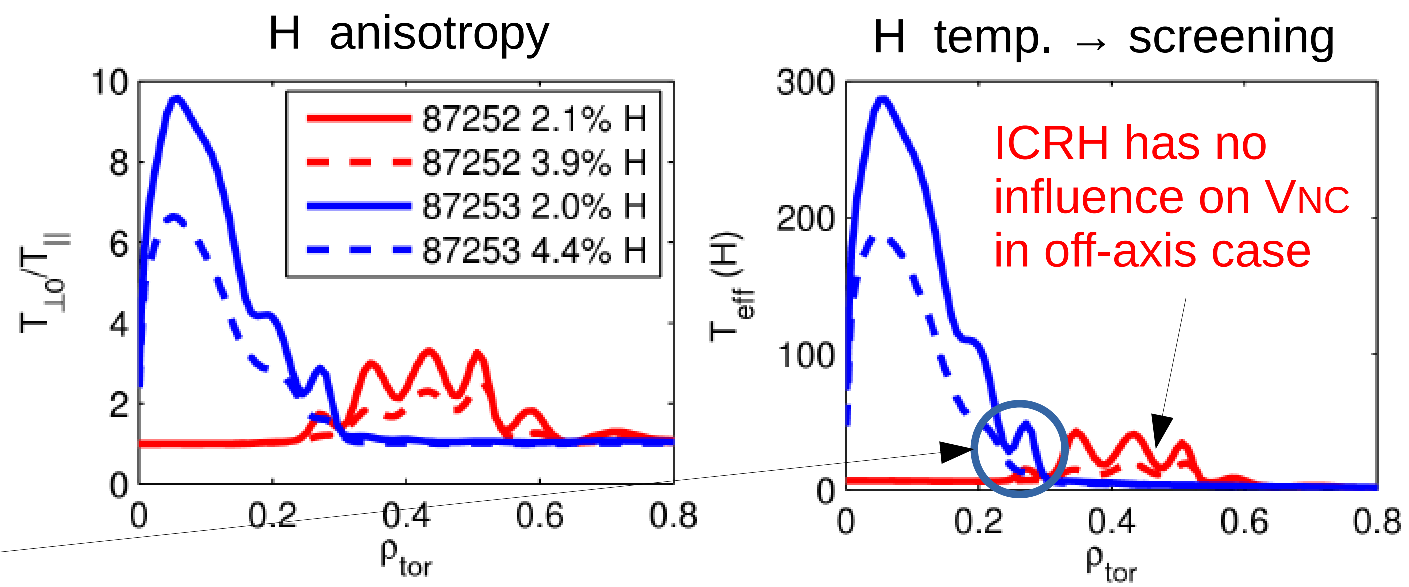
$$\nabla_{\parallel} p_{\parallel} - \frac{p_{\parallel} - p_{\perp}}{B} \nabla_{\parallel} B + n_m Z_m e \nabla_{\parallel} \Phi - n_m m_m \Omega^2 R \nabla R = 0$$

- Anisotropy requires coupled Wave-Fokker-Planck simulation.

Experimentally validated:
JET: L. C. Ingesson PPCF 2000 ??
CMOD: M. Reinke PPCF 2012

- Anisotropy increases with power density

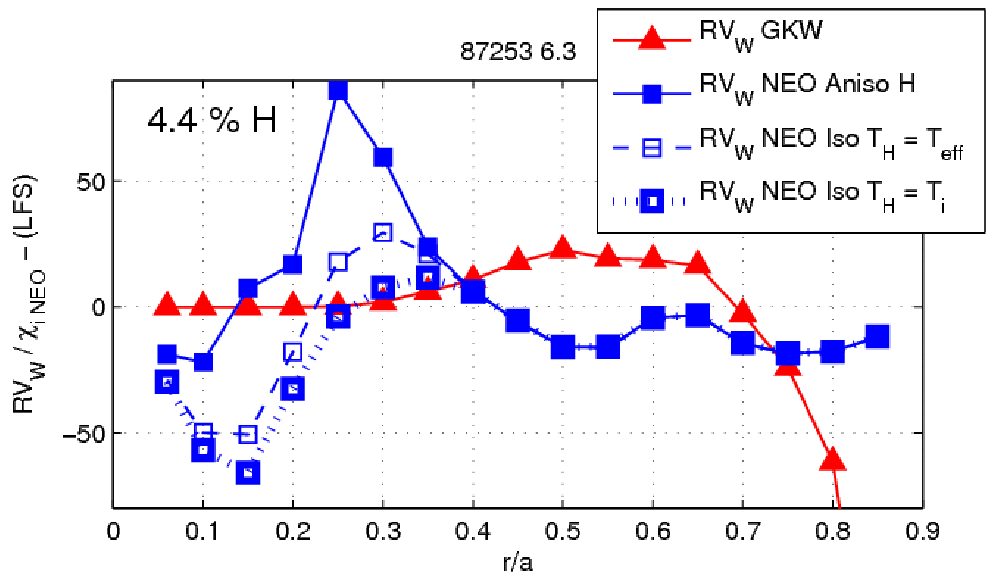
TORIC-SSFPQL, R. Bilato

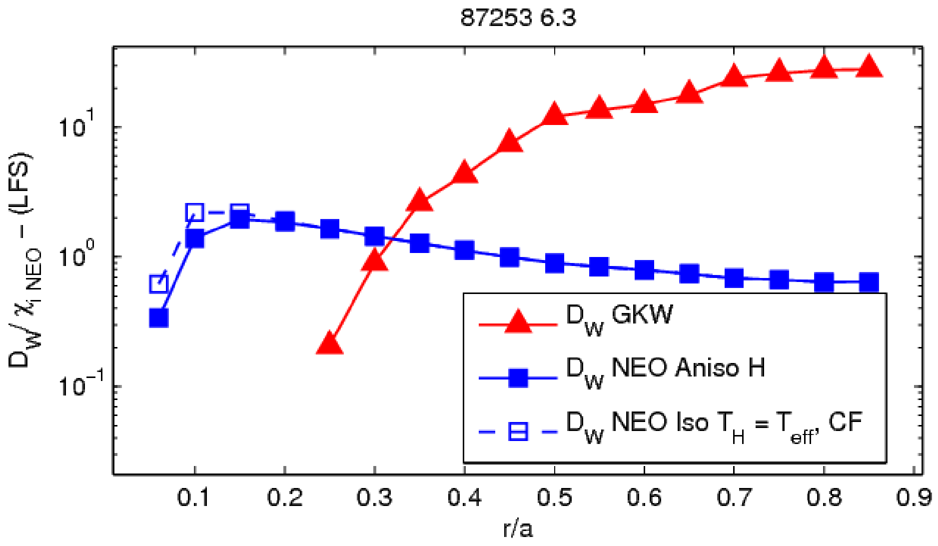


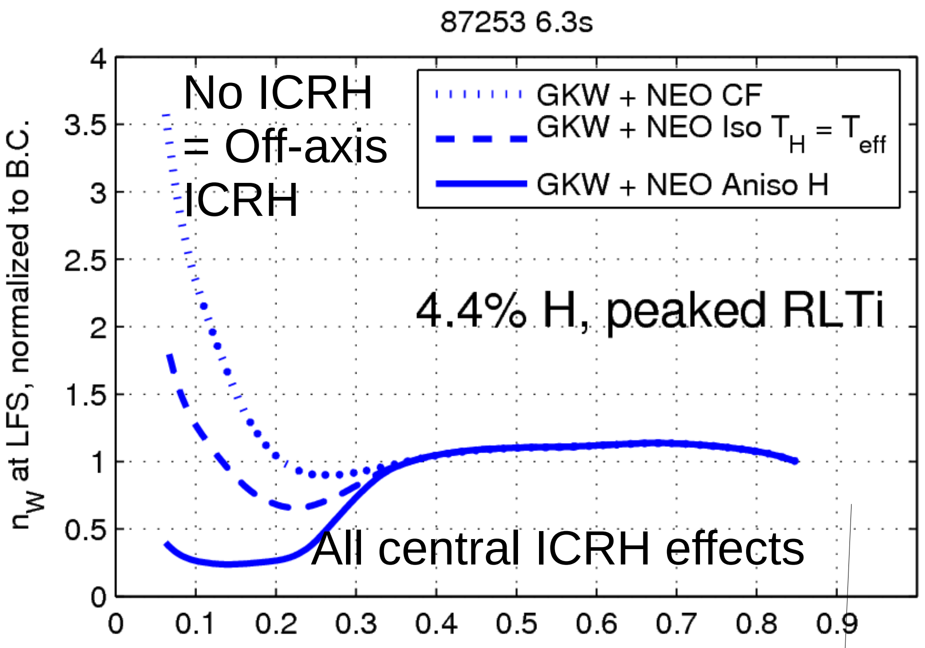
Temperature screening scales as

$$\Gamma_{T_i} \equiv -\frac{n_D}{T_D^{1/2}} \frac{R}{L_{T_D}} - \frac{n_H}{T_H^{1/2}} \frac{R}{L_{T_H}}$$

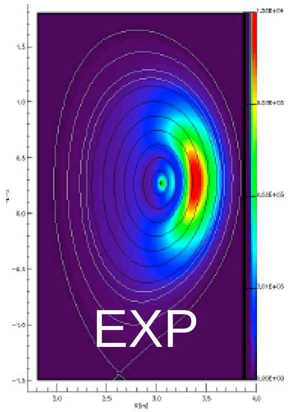
Influence of H minority at 4.4% (No FOW effects)

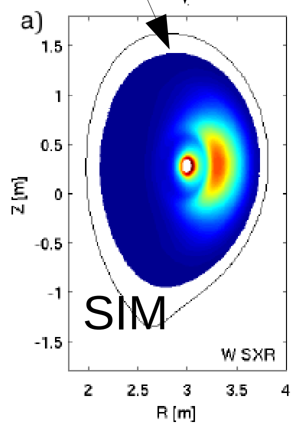






- Needed v. peaked Ti for this result –
  hollow SXR means *very* hollow nW





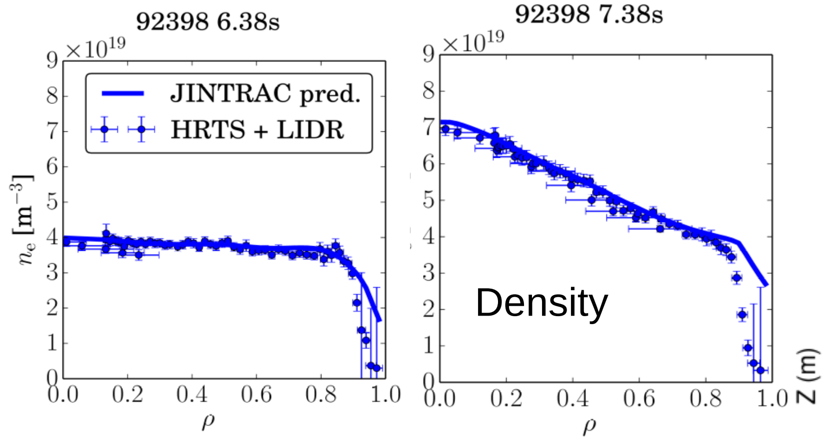
Mantica EPS 2015;
Casson PPCF 2015

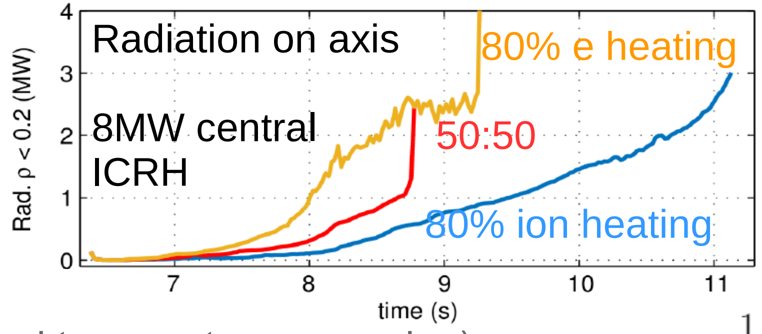
Predictive multi-channel modelling to optimise W control in JET

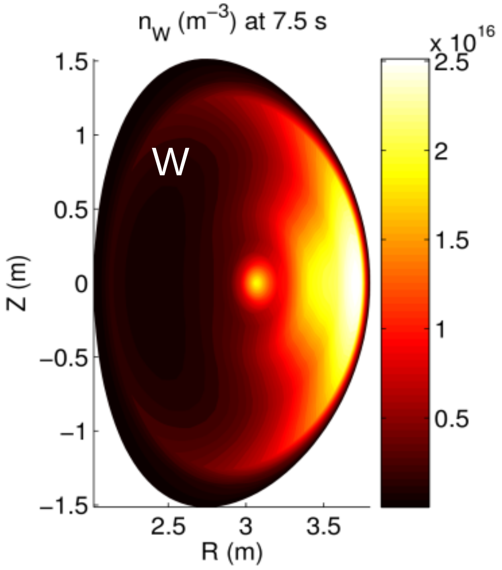
- 8 channels modelled predictively with first-principle models:

$$T_i, T_e, j, n_D, n_{Be}, n_{Ni}, n_W, \omega$$

  - Reproduces evolution including radiative collapse after ~10 τ_E
  - Includes poloidal asymmetry enhancement of neoclassical W transport (20x)
  - Used to optimise ICRH for W control: He-3 predicted more effective than H minority (increased temperature screening)
    in JET hybrid conditions







- Extrapolations to DT find positive isotope scaling of confinement due to increased Ti / Te and ITG stabilisation
  - Inclusion of ETG scales pins Te; ion-electron collisional energy exchange decreases with isotope mass
  - Improved confinement in DT also gives larger density peaking and earlier W accumulation
  - Mitigate with increased density (less central NBI particle deposition)