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

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JET

CCFE
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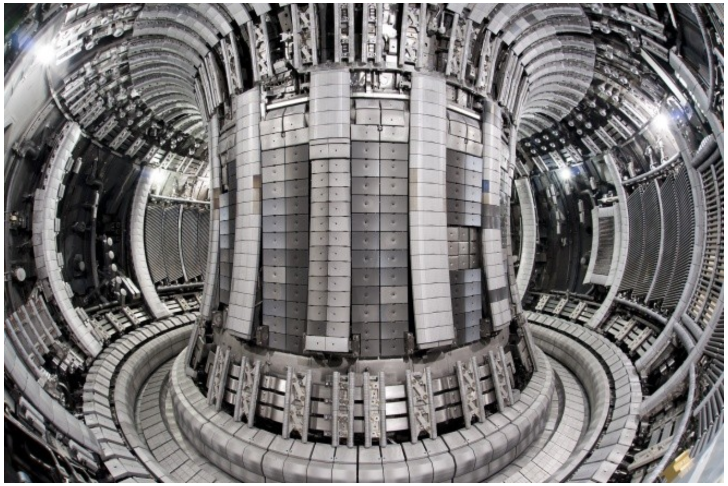
Motivation



- 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)

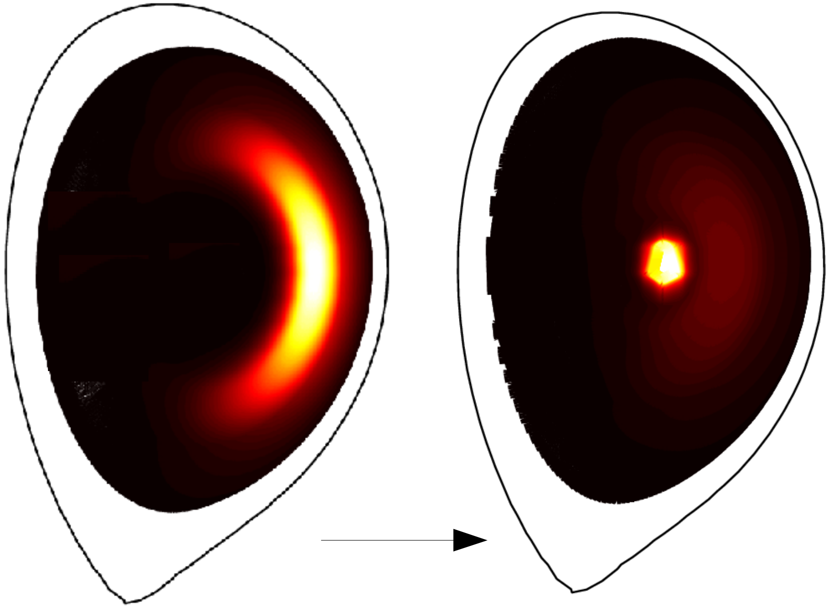
  (E. Joffrin, this conf.)

- 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



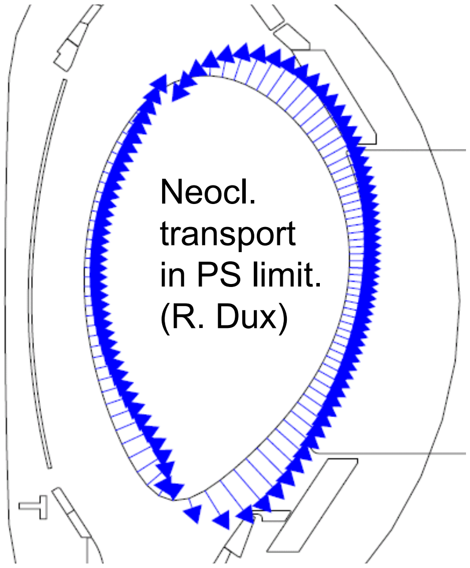
Localisation (LFS)   *Accumulation*

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, here focus on neoclassical convection and turbulent diffusion



Neocl. transport in PS limit. (R. Dux)

Logarithmic gradient in stationary state with no source

Complex, but benign

Threat: Drives accumulation

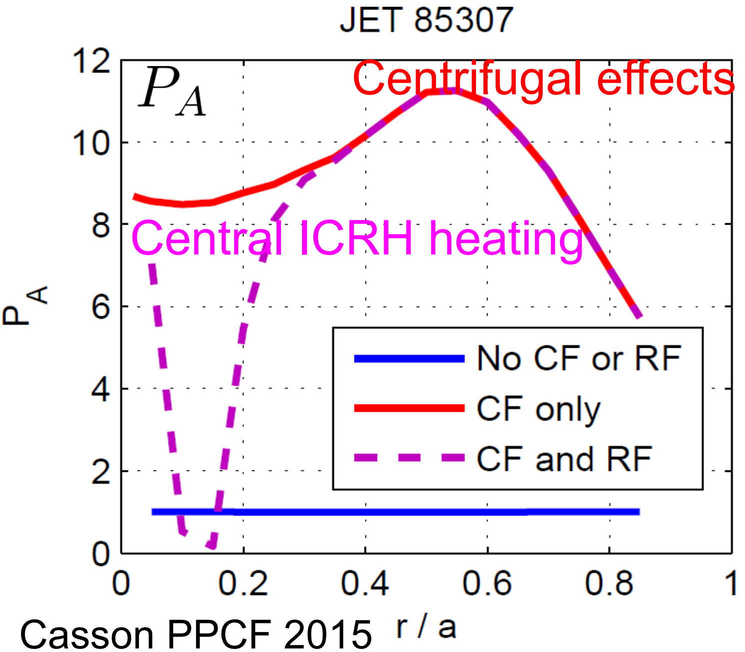
$$\frac{R}{L_{nZ}} = -\frac{RV_{Z\,\mathrm{trb}} + \boxed{RV_{Z_{\mathrm{NC}}}}}{\boxed{D_{NZ\,\mathrm{trb}}} + D_{NZ_{\mathrm{NC}}}}$$

Mitigation - large where turbulent transport

Small, ~ P_A, no Z dependence

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

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

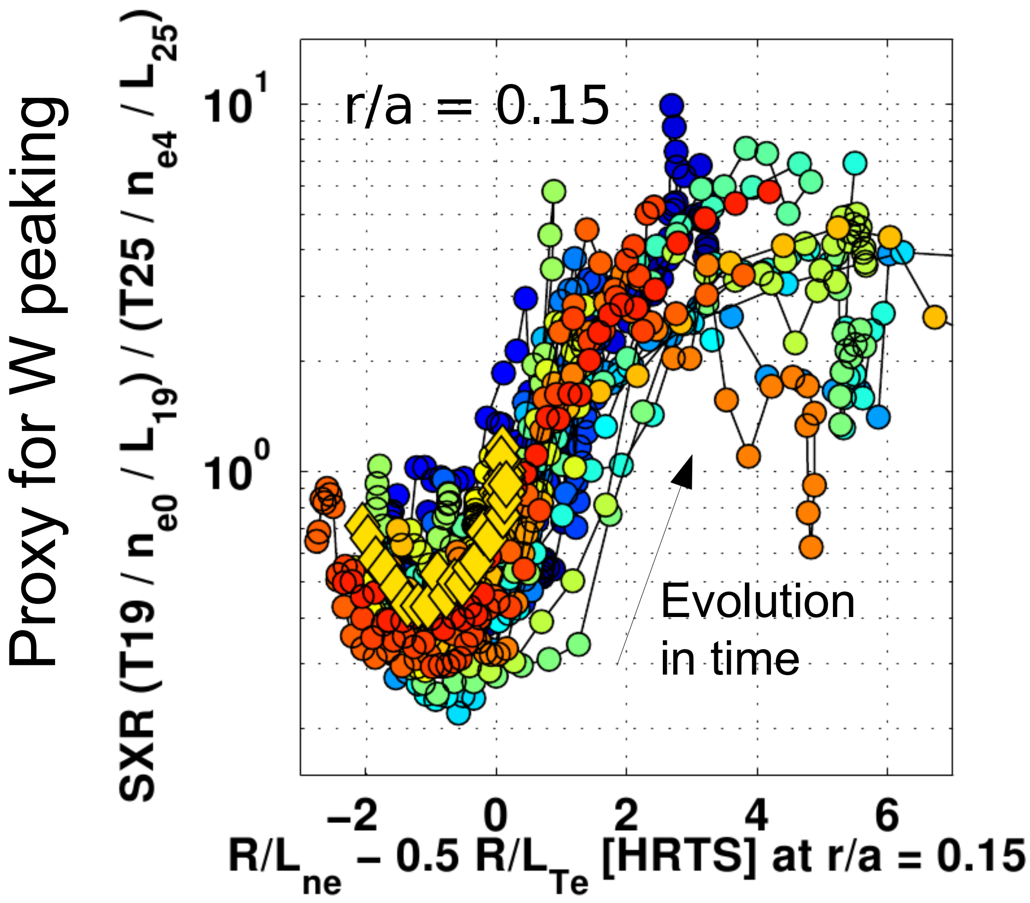


Casson PPCF 2015

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 eventually leads to W accumulation
- JET Hybrid scenario more prone than Baseline (q_{95} ~ 3, β_N ~ 1.8) to W accumulation:
  - 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

JET-ILW hybrids (NBI only)

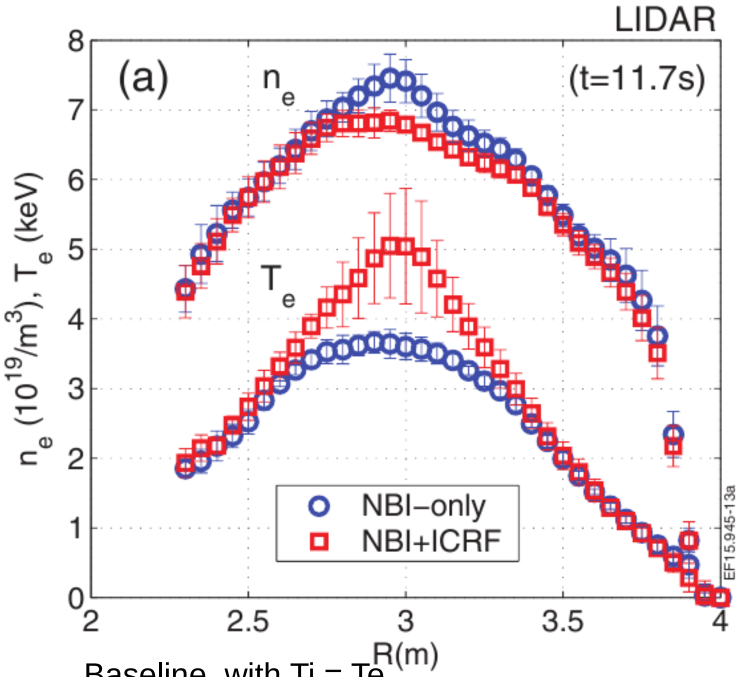


Proxy for neoclassical convection

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



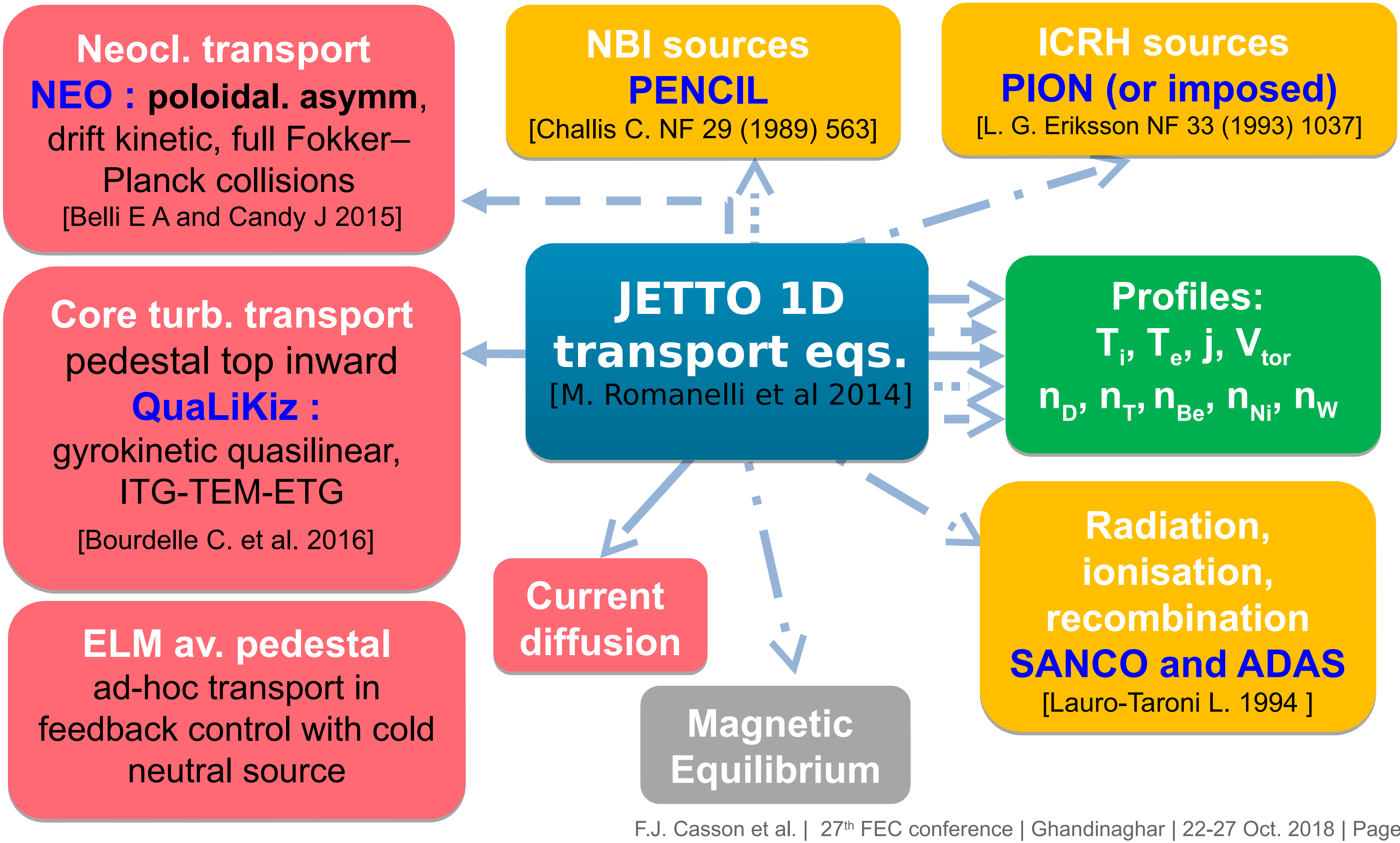
Baseline, with Ti = Te
E. Lerche Nucl. Fusion 56 (2016) 036022

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, first-principle transport models integrated in JINTRAC suite



Neocl. transport
NEO : poloidal. asymm, drift kinetic, full Fokker–Planck collisions
[Belli E A and Candy J 2015]

NBI sources
PENCIL
[Challis C. NF 29 (1989) 563]

ICRH sources
PION (or imposed)
[L. G. Eriksson NF 33 (1993) 1037]

Core turb. transport
pedestal top inward
QuaLiKiz :
gyrokinetic quasilinear, ITG-TEM-ETG
[Bourdelle C. et al. 2016]

JETTO 1D transport eqs.
[M. Romanelli et al 2014]

Profiles:
T_i, T_e, j, V_{tor}
n_D, n_T, n_{Be}, n_{Ni}, n_W

ELM av. pedestal
ad-hoc transport in feedback control with cold neutral source

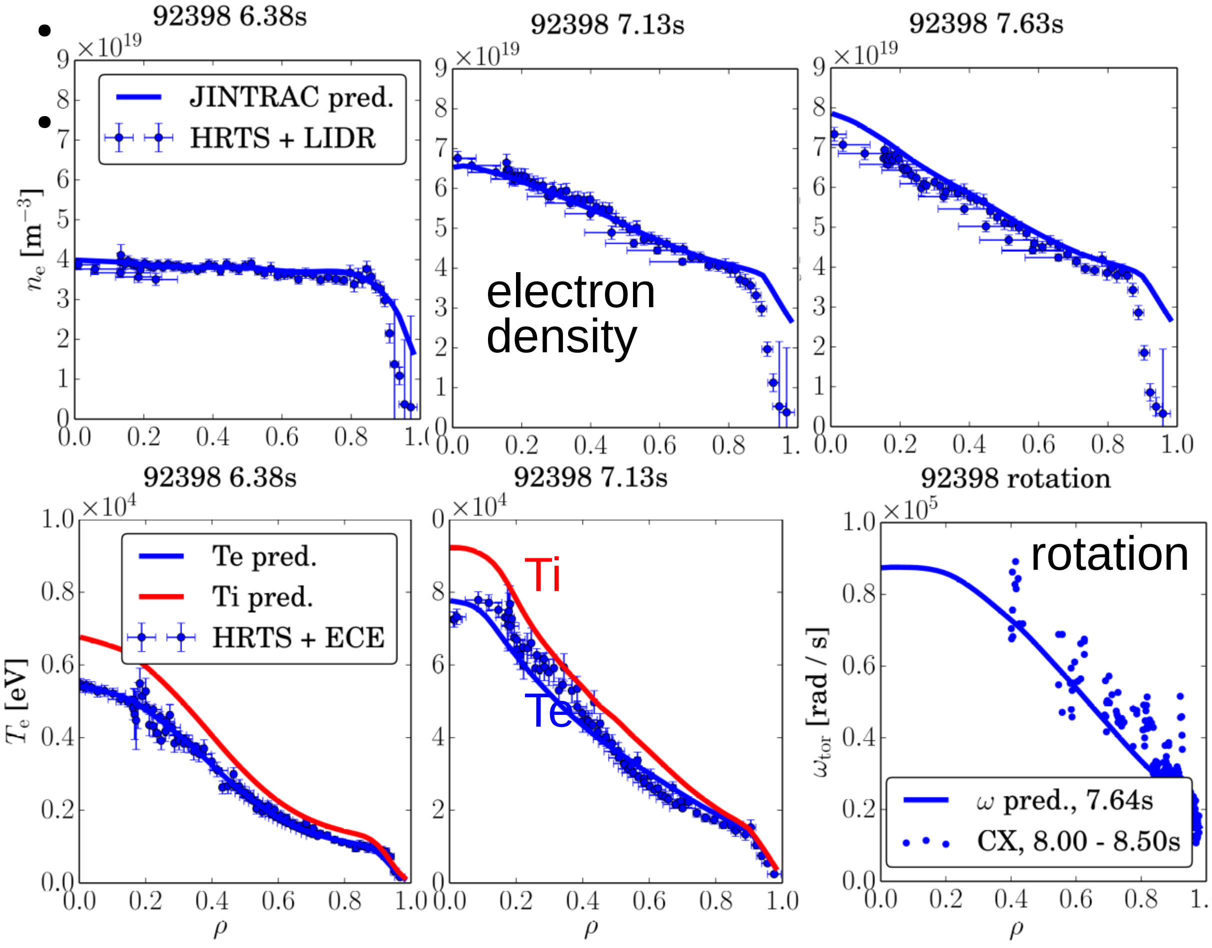
Current diffusion

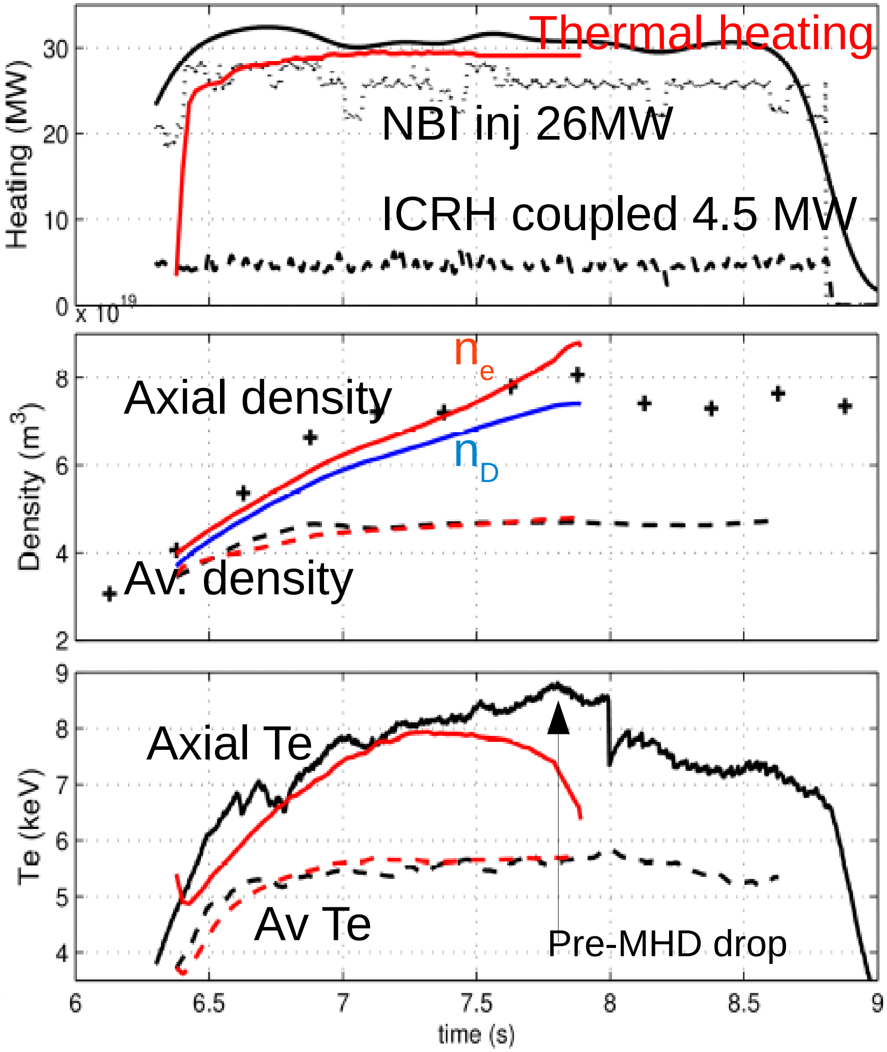
Magnetic Equilibrium

Radiation, ionisation, recombination
SANCO and ADAS
[Lauro-Taroni L. 1994]

Evolution of highest performance hybrid reproduced over ~10 τ_E

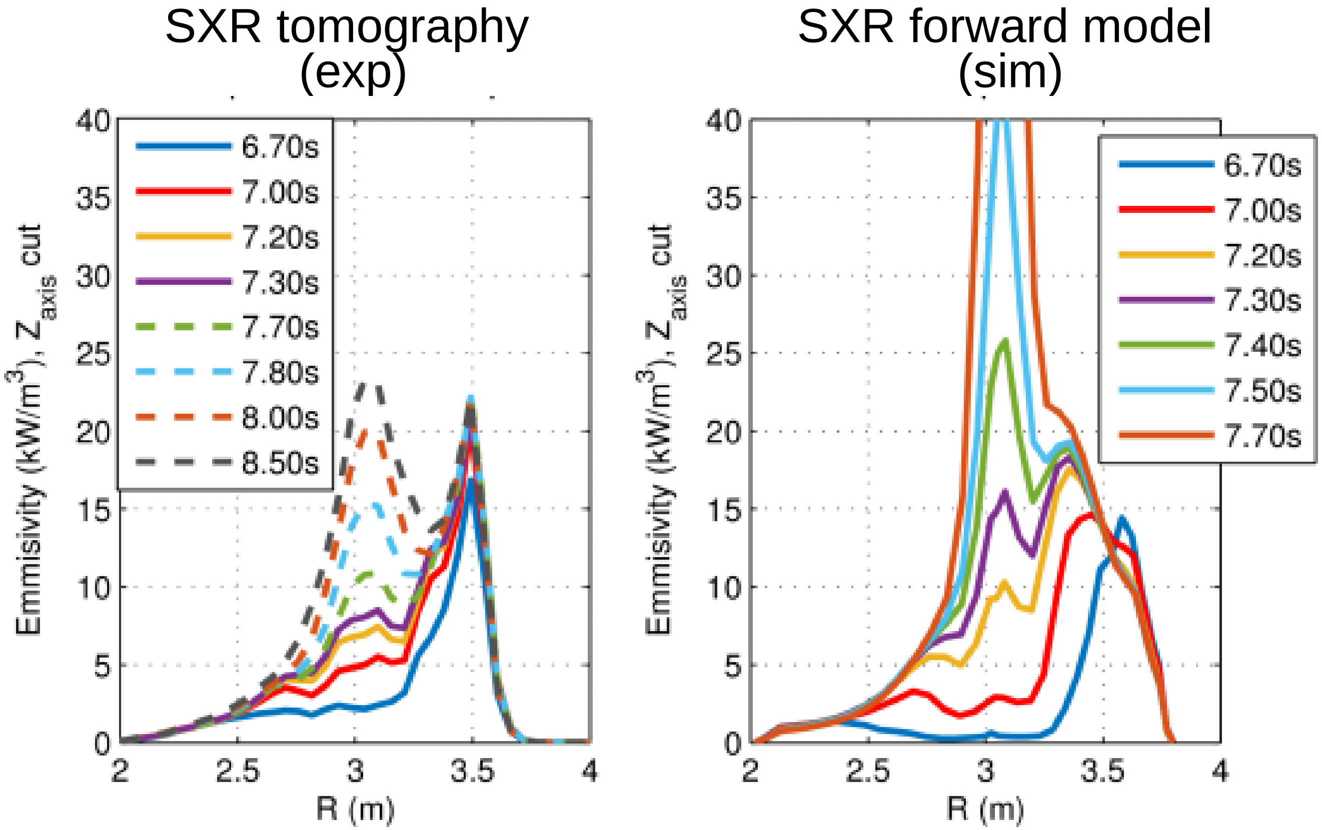
- Highest performance hybrid in JET-ILW Bt = 2.8T, Ip = 2.2 MA, H_{98} = 1.3, τ_E = 0.17s
  - Predicted from start of H-mode until W accumulation on axis
- **Timescale** of density rise correct; temp and rotation (first principles!) also well predicted
- Axial Te maximum after 1s → W radiation





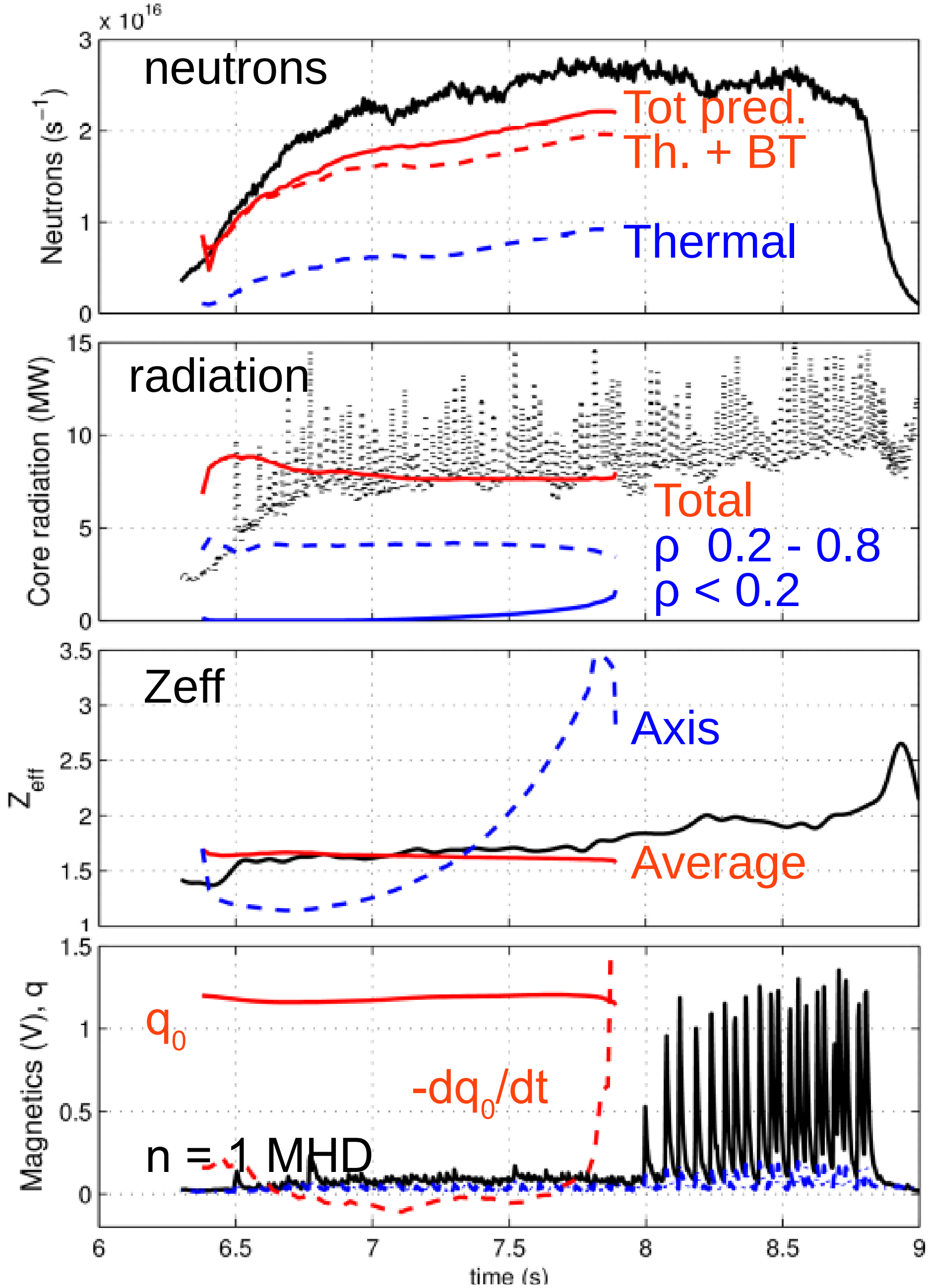
Simulation predicts correct timescale of W and Ni accumulation

- W on axis from 7.2s, in both simulation and expt.
  - W dominates total radiation, Ni dominates Zeff
- Accumulation process more controlled in experiment
  - Simulations *extremely* sensitive in accum. Phase
  - May suggest an missing transport process; no ad-hoc transport used



Simulation predicts correct timescale of W and Ni accumulation

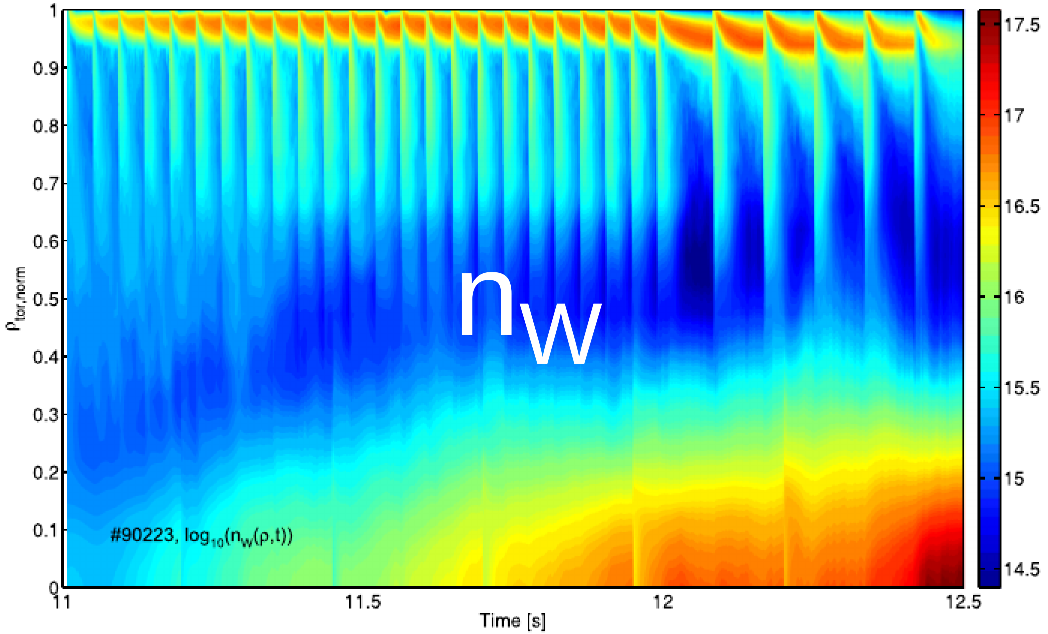
- 1,1 MHD arrives **after** accumulation begins
  - Triggered by W?
  - Temp collapse → loss of central bootstrap current
  - Limits performance but mitigates accumulation (not modelled)



Strengths and limitations of the presented modelling

- Core transport, equilibrium, and sources are self-consistent and 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

Elena de Luna, this conf
F Koechl PPCF 60 074008 (2018)



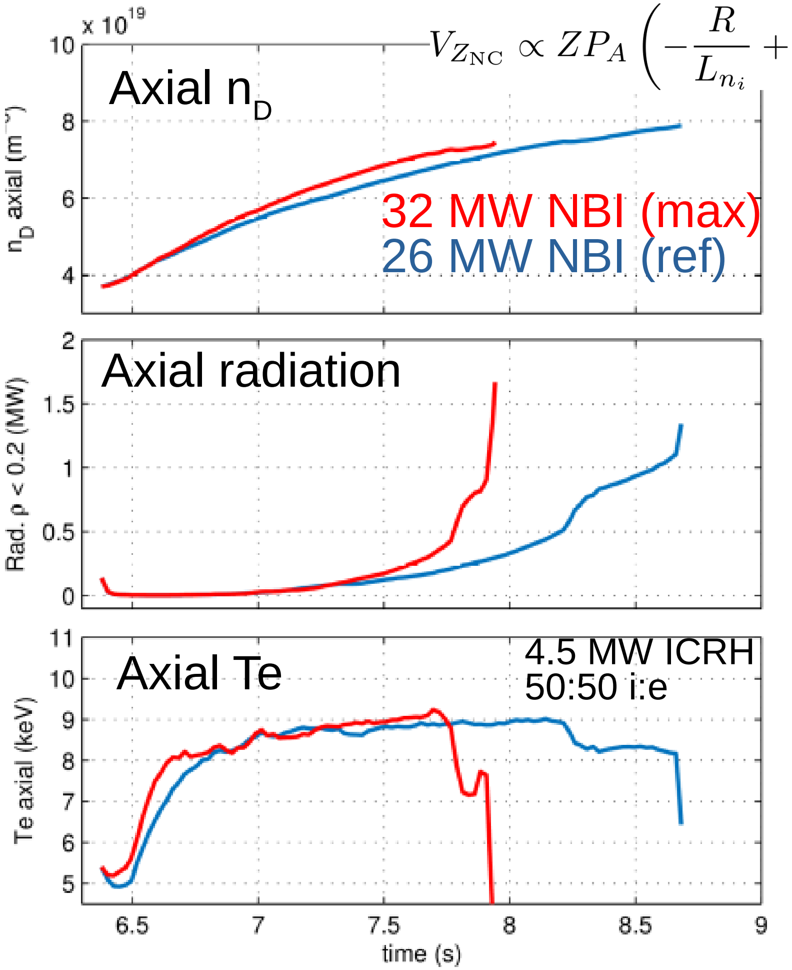
Outline

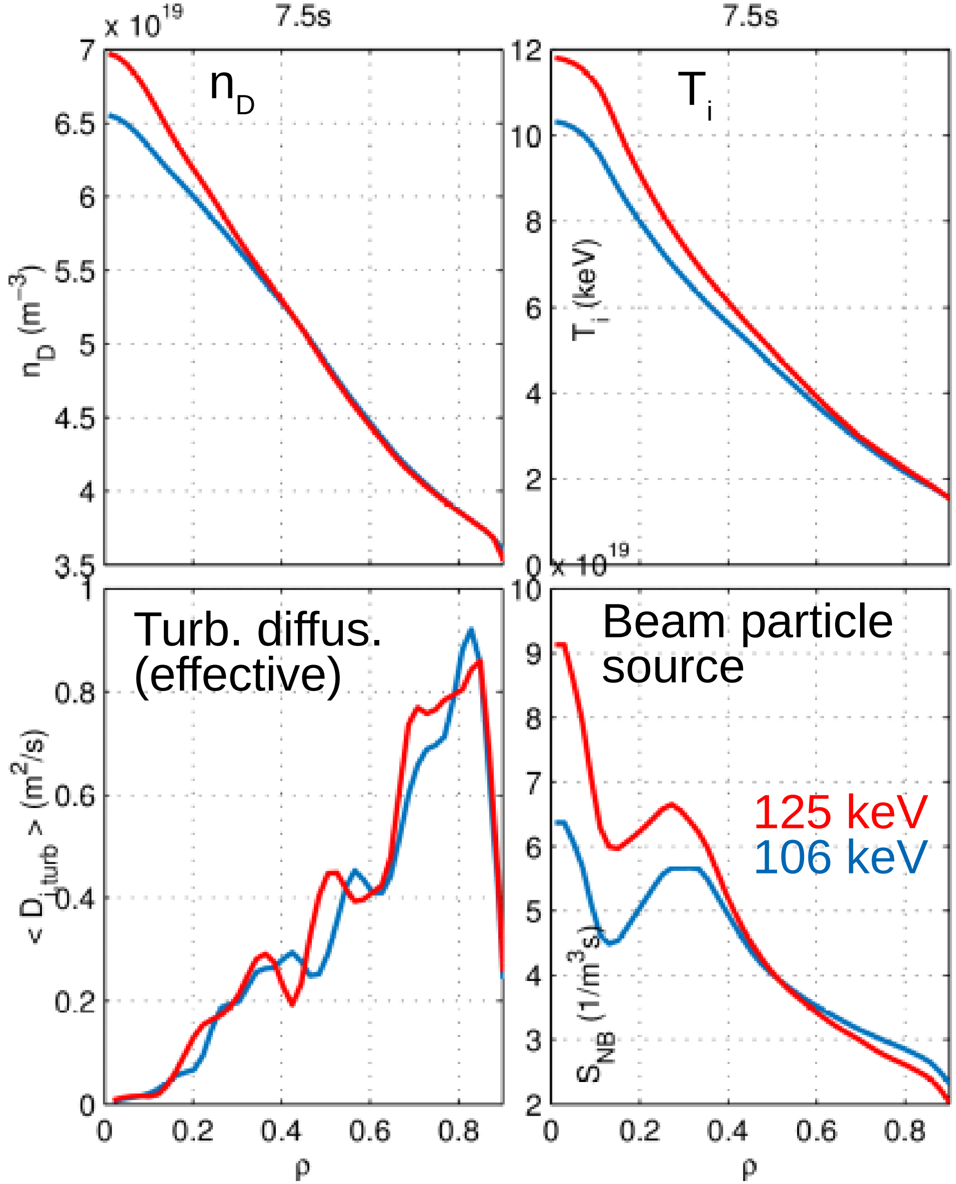
- Mechanisms of W transport
- Integrated predictive modelling
- **Optimisation of heating**
- Extrapolation to DT

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

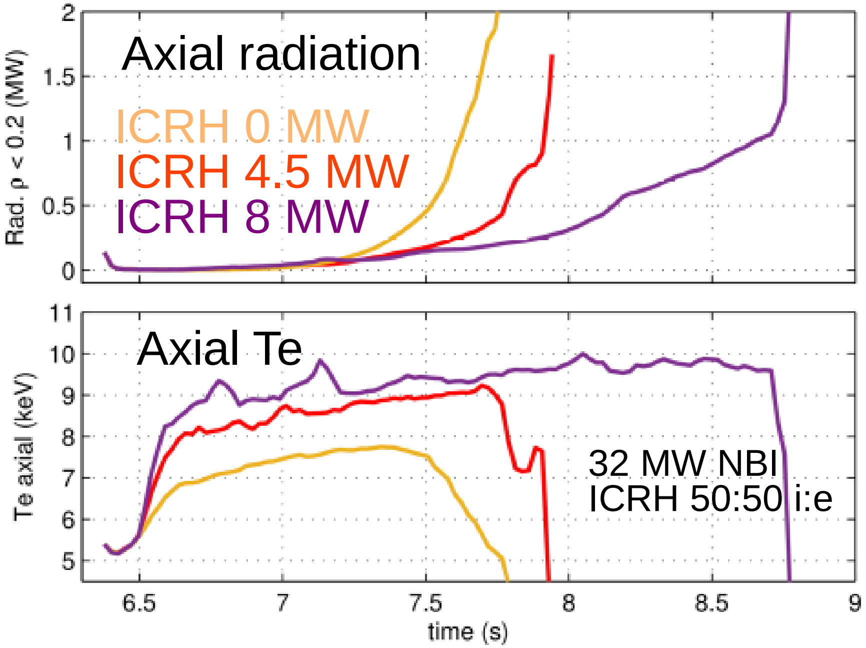
$$V_{Z_{\mathrm{NC}}} \propto ZP_A\left(-\frac{R}{L_{n_i}}+\frac{1}{2}\frac{R}{L_{T_i}}\right)$$

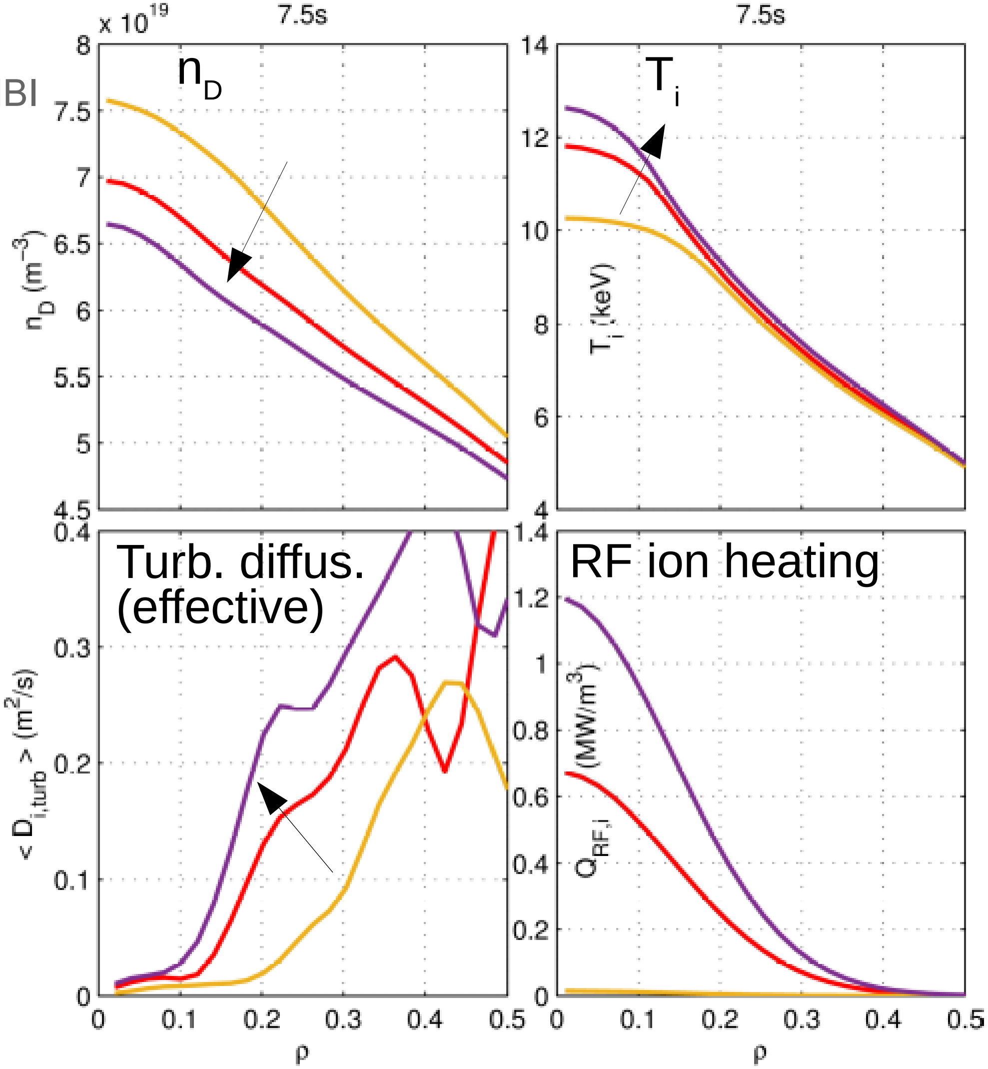




ICRH heating delays W accumulation, as observed

- 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
  - Predictions consistent with JET observations
  - 4MW increase in ICRH compensates 6MW increase in NBI

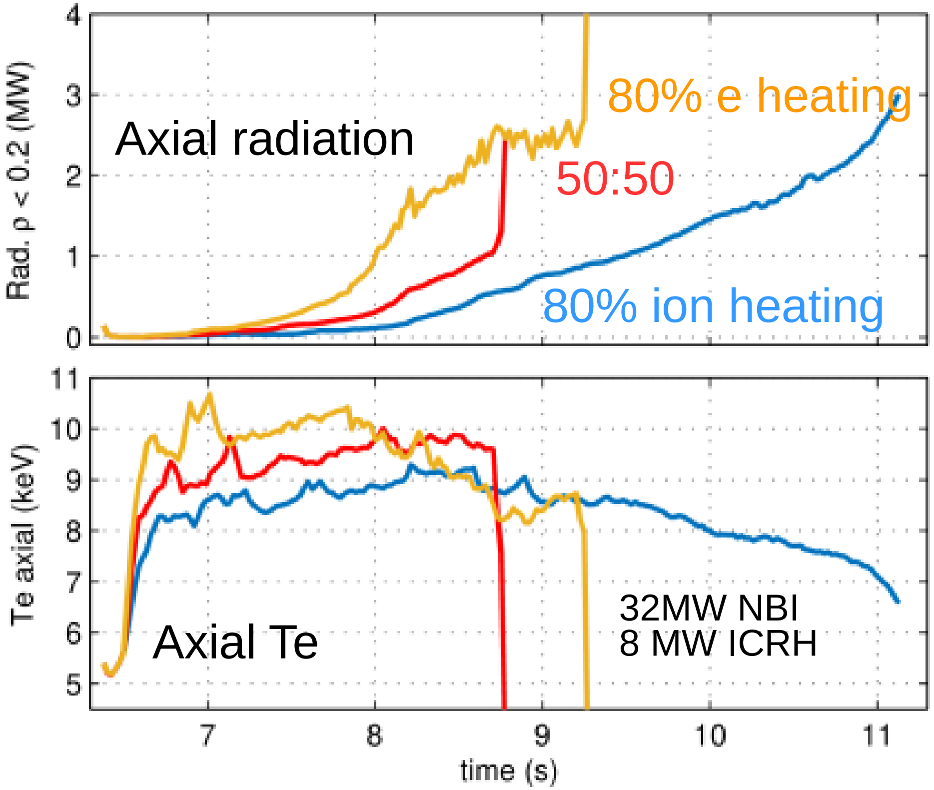


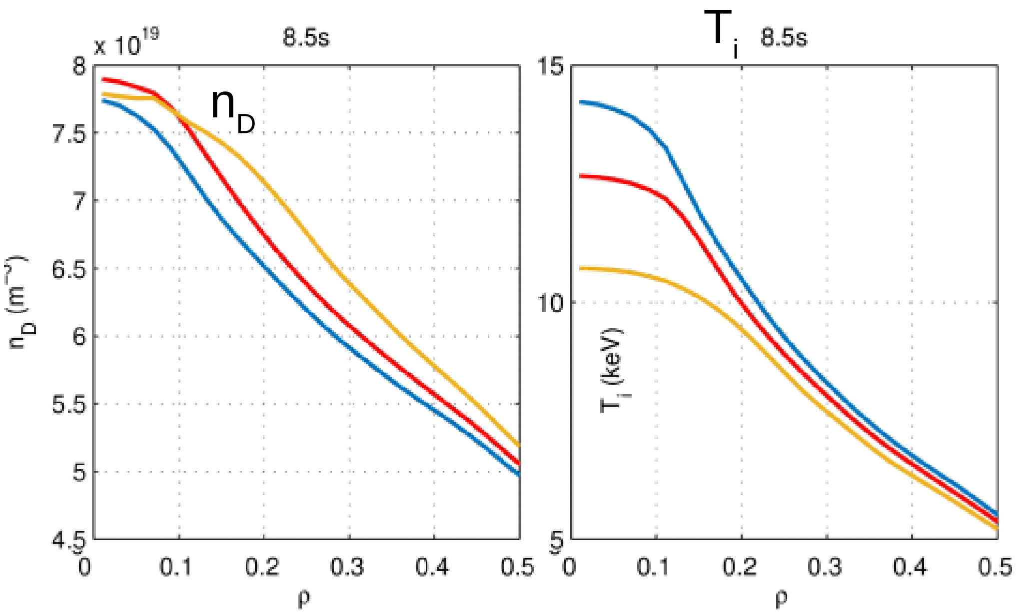


Ion heating schemes *predicted* as most effective on W

Prediction, not yet tested

- 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)

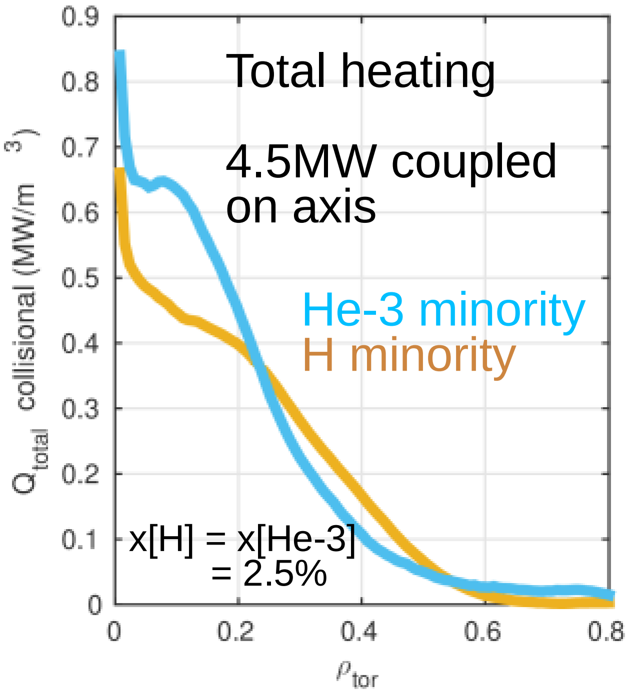




High fidelity ICRH modelling supports He-3 minority scheme

- 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

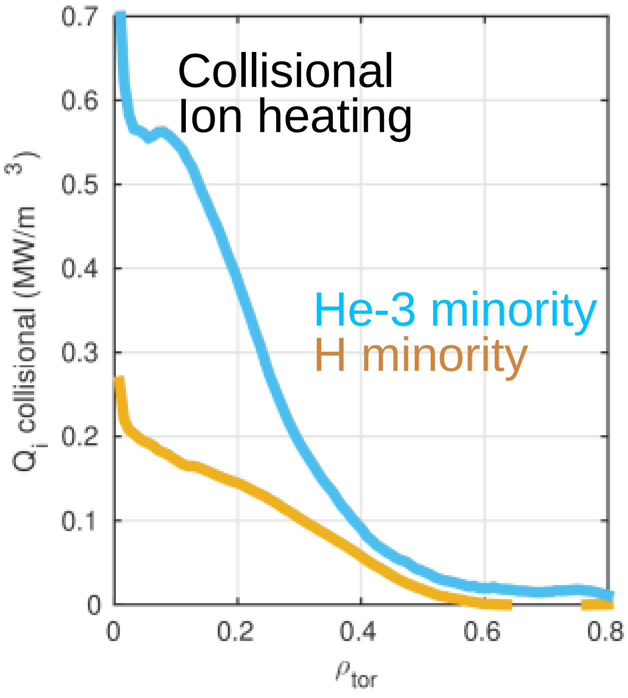
    (Y.O. Kazakov, this conf.)
- Power density and W control maximised when resonance within 10cm of axis



Total heating

4.5MW coupled on axis

x[H] = x[He-3] = 2.5%



Collisional Ion heating

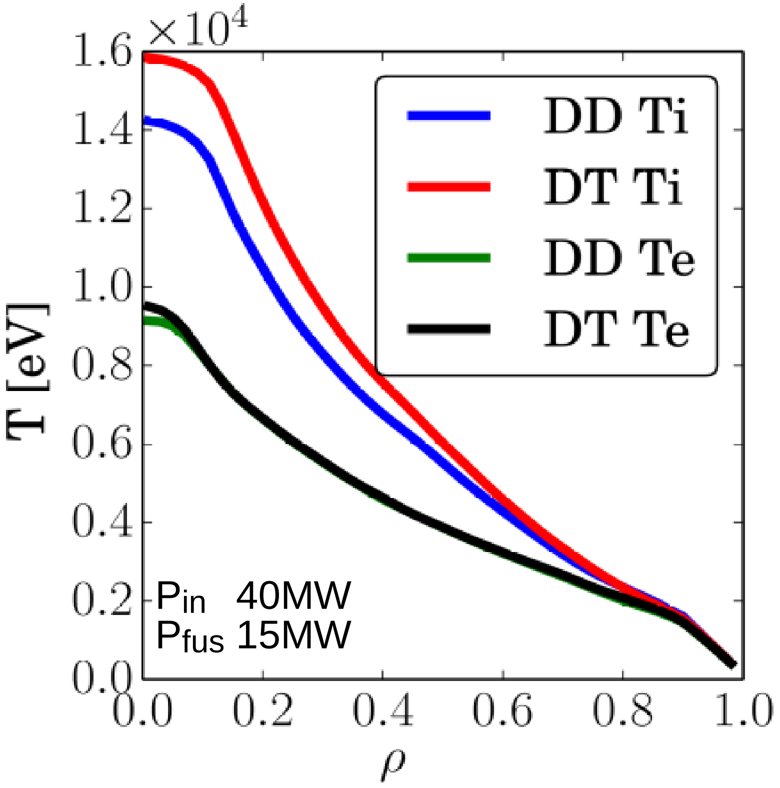
Outline

- 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.)
  - Specific to high power discharges with Ti > Te
  - Relies on ETG scales, need to verify with nonlinear
- Caveat: Understanding of isotope scaling is incomplete

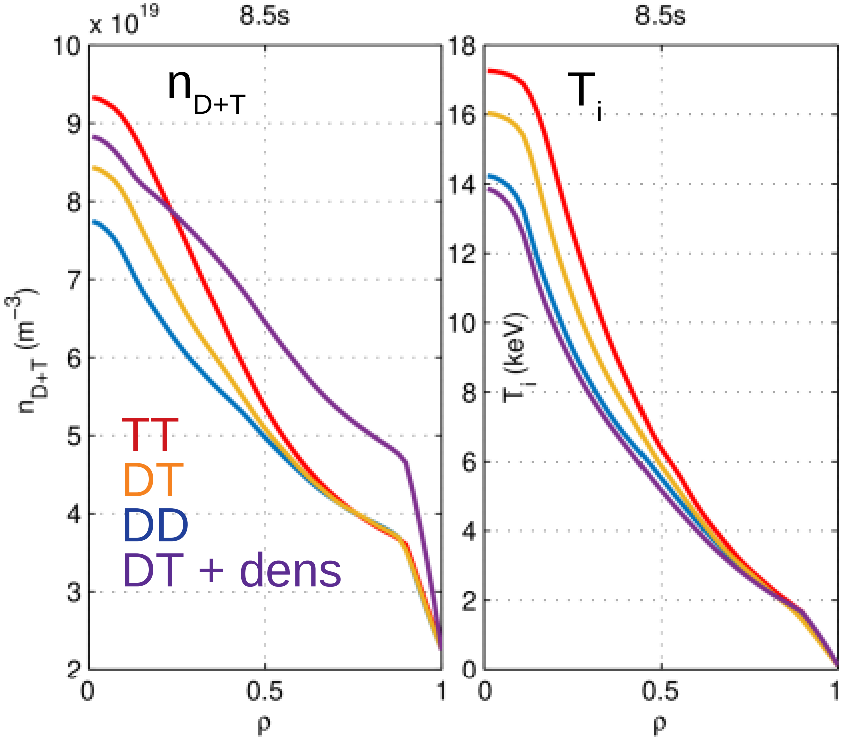
(H Weisen, this conf.)

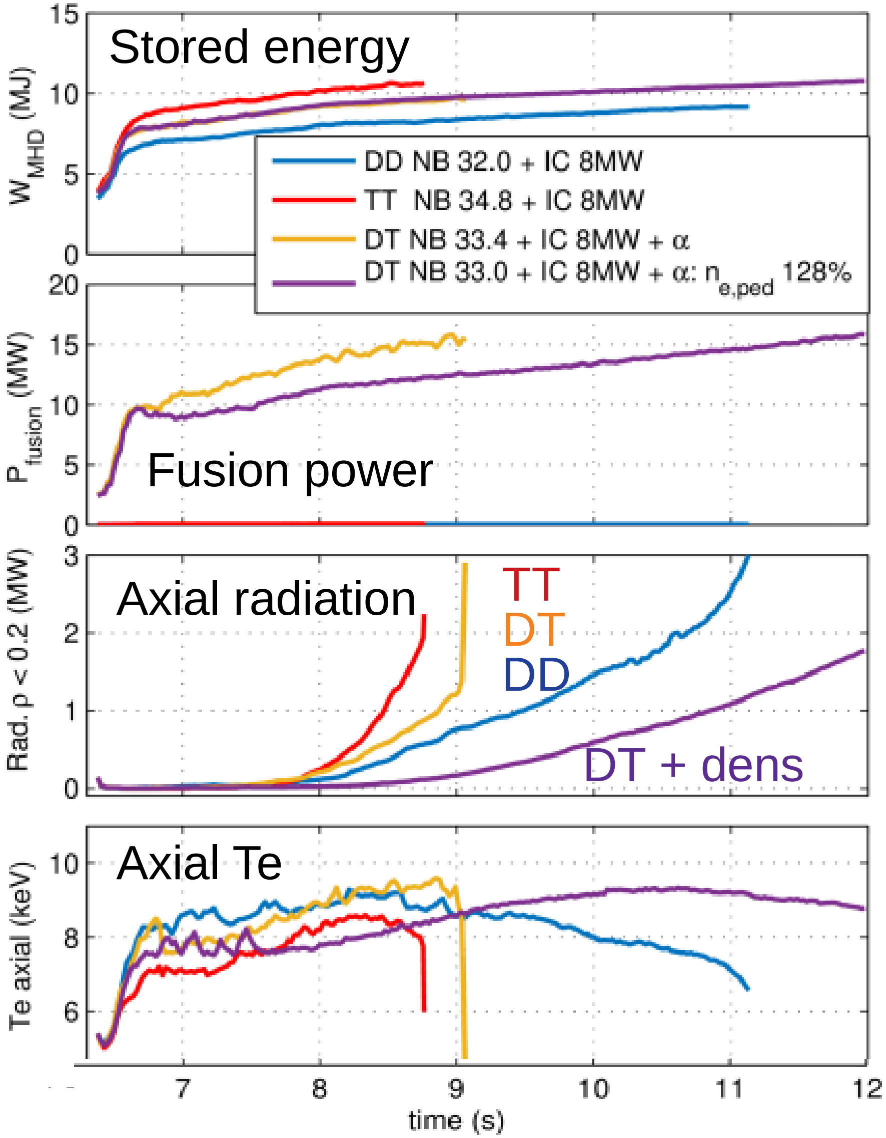


Conservative pedestal assumptions (no scaling with power or isotope)

…. but earlier W accumulation

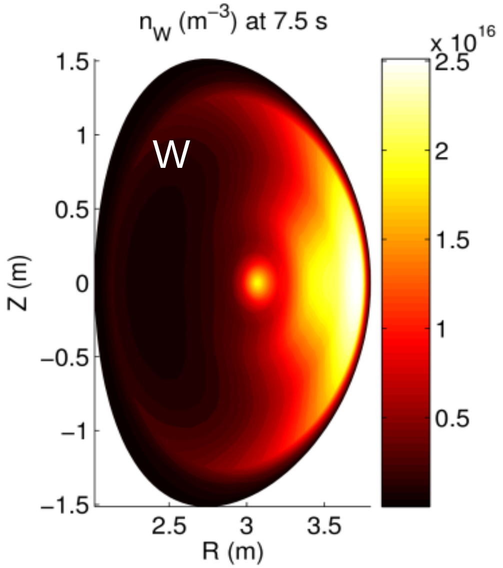
- Improved confinement in DT also gives larger density peaking, and earlier W accumulation
  - Mitigate with increased density
    (less central NBI particle deposition, less density peaking)
  - Some cost in performance
  - Requires optimisation / integration of
    - Increased triangularity
    - Increased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





Conclusions

- First-principle models integrated into a powerful multi-channel predictive tool for core plasma
  - An exciting era for integrated modelling
- Reproduces observed W accumulation after several confinement times
- Guides scenario development to optimise W control in JET hybrid:
  - 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



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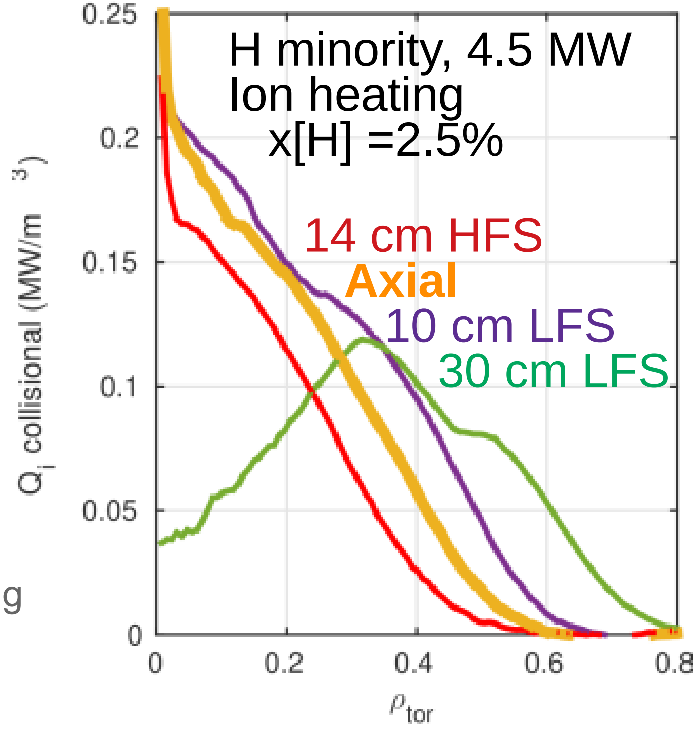
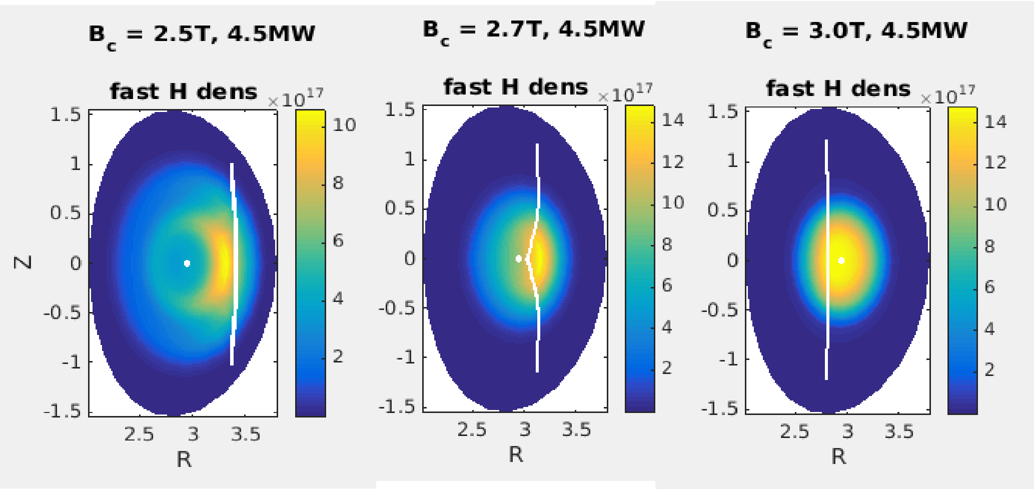
Supplementary material

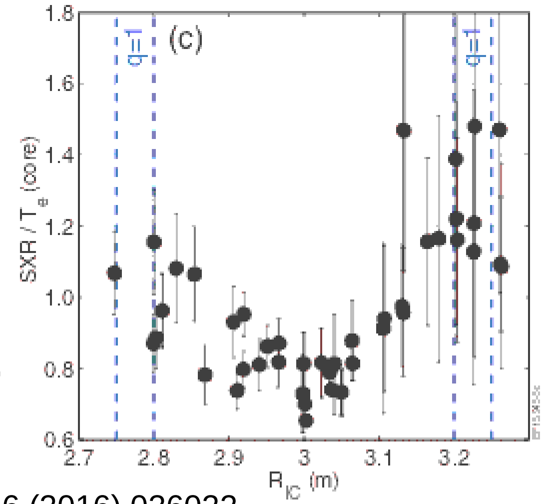
High fidelity ICRH modelling supports near axial resonance

- 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 spreading





Consistent with observations ->



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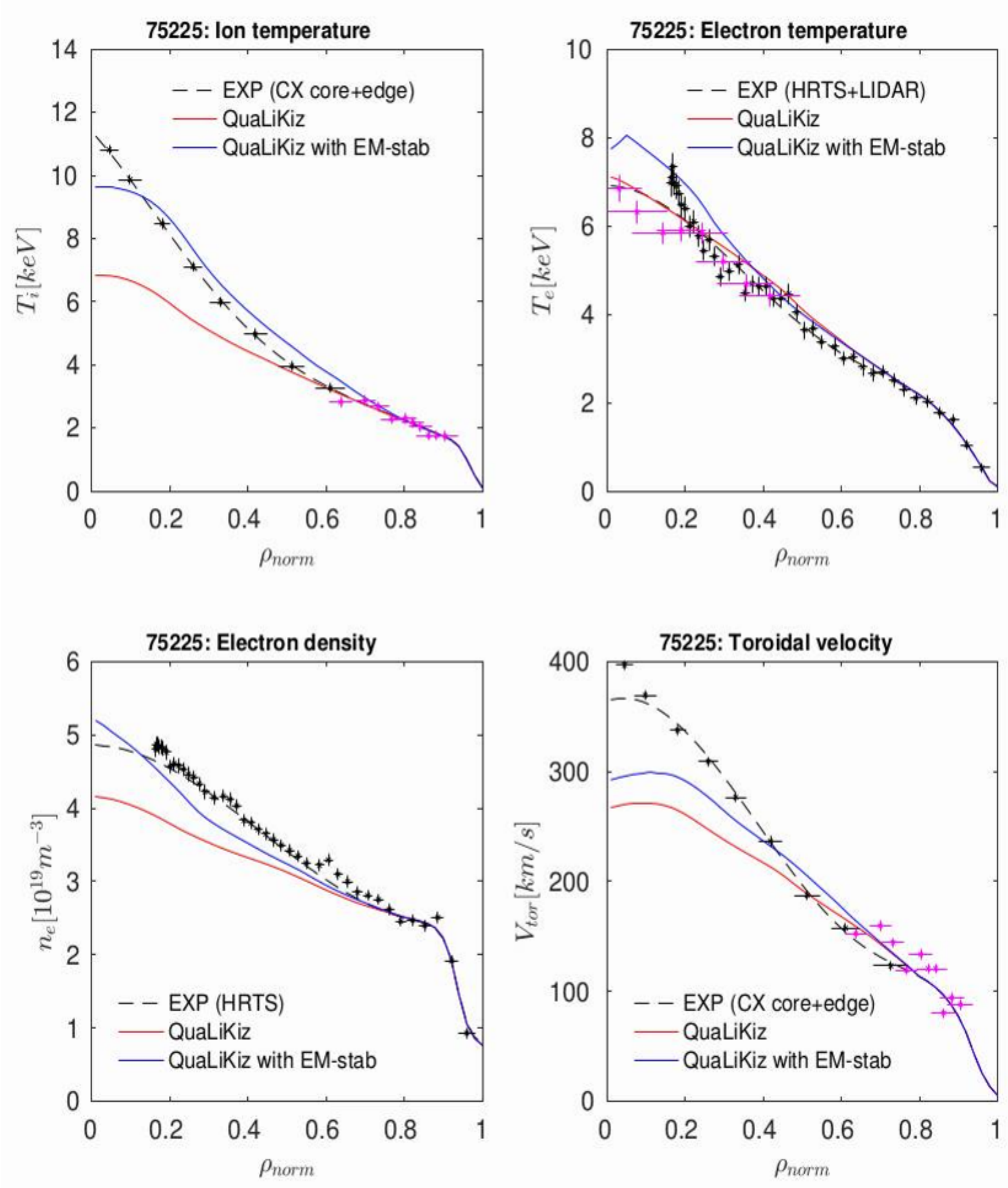
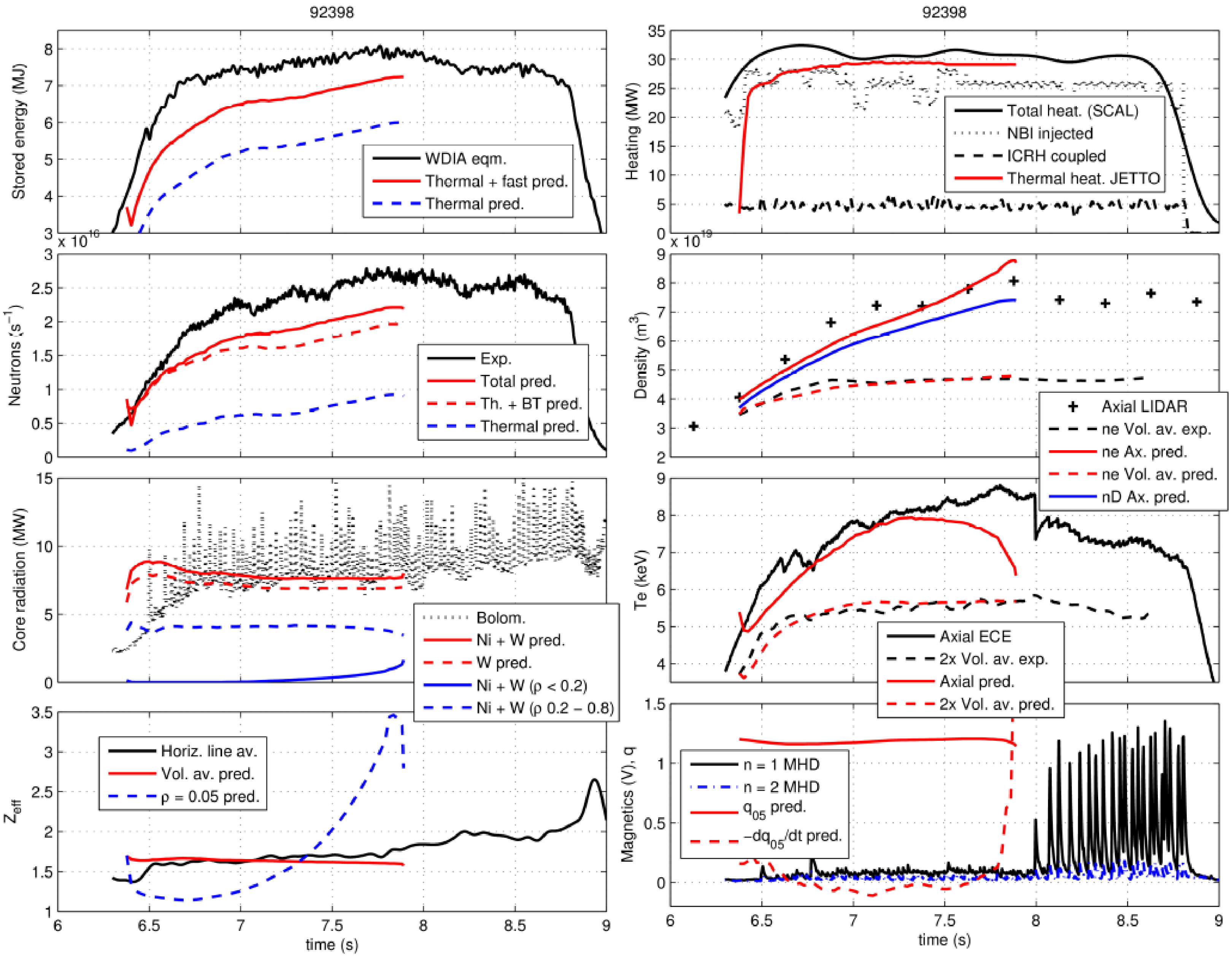
4-channel validation in JET-C hybrid (with core Ti measurement)



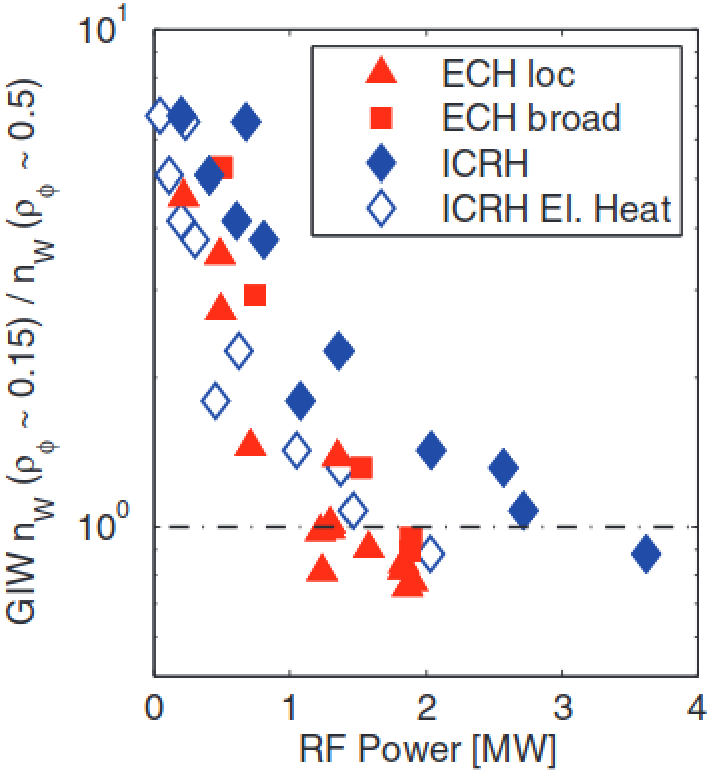
Ad hoc model to emulate electromagnetic stabilisation of ITG turbulence (not present in QuaLiKiZ)

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

Validation of global evolution

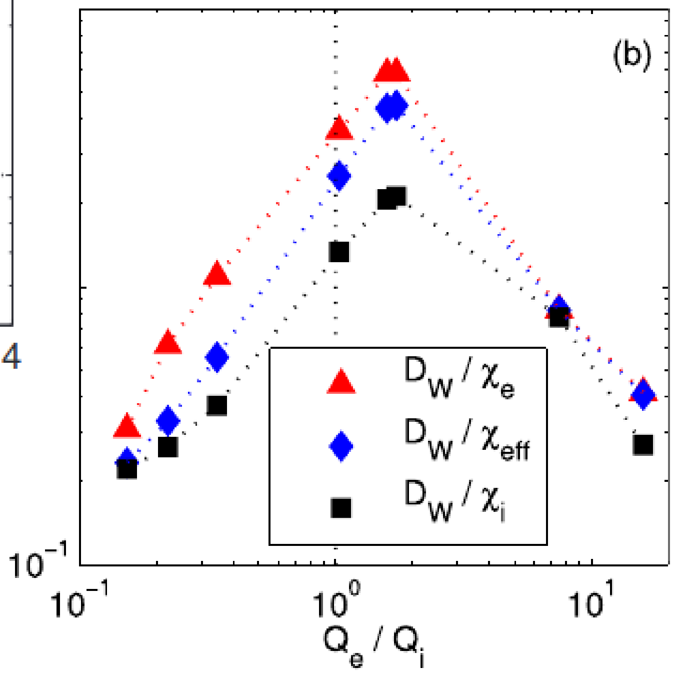


Electron heating preferred in ITER better for W turbulent transport (outward convection)

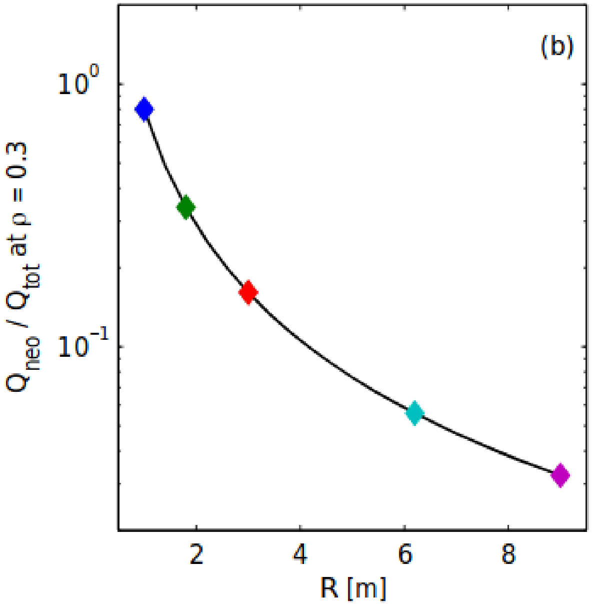


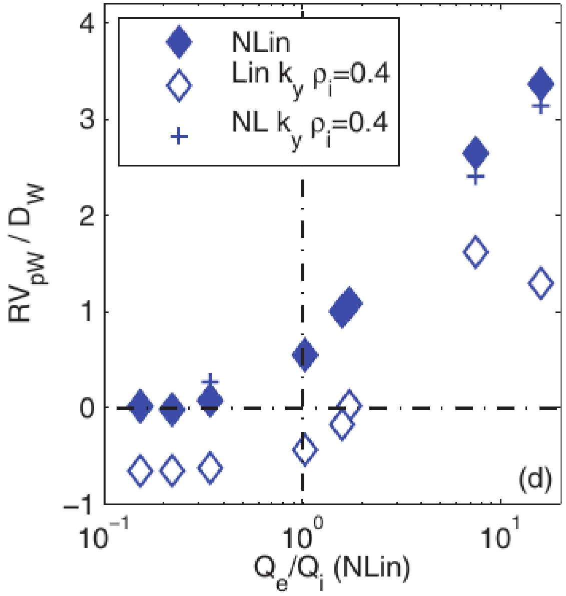
C. Angioni *et al* 2017 *Nucl. Fusion* **57** 056015

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

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

HFS localisation of heavy impurities

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

- Anisotropy requires coupled Wave-Fokker-Planck simulation.

- Anisotropy increases with power density

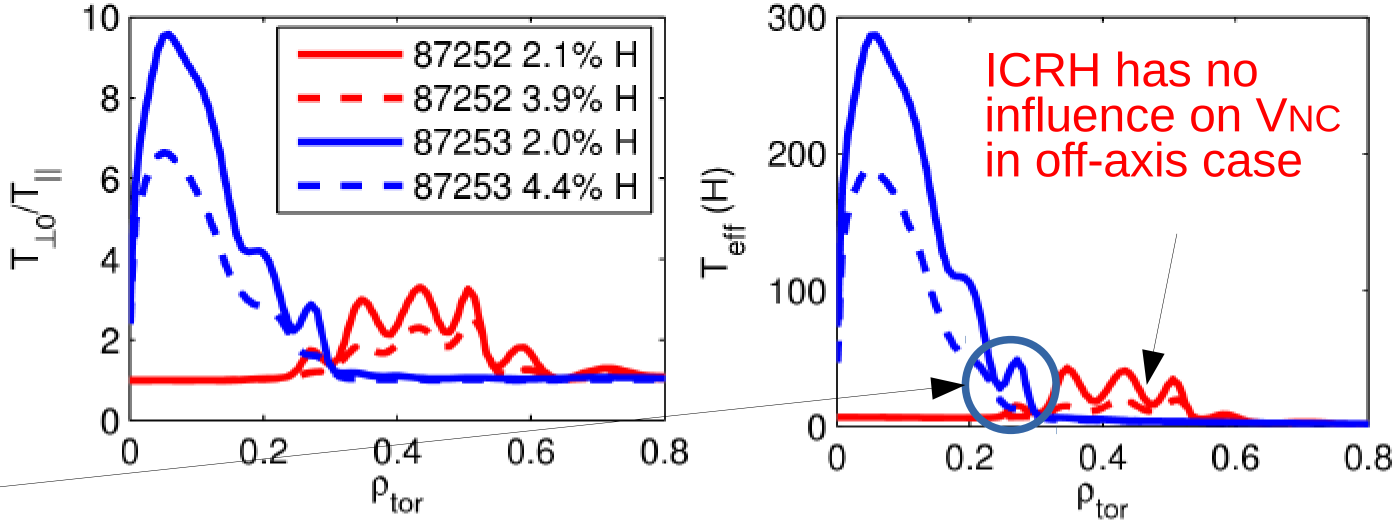
Temperature screening scales as

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

TORIC-SSFPQL, R. Bilato

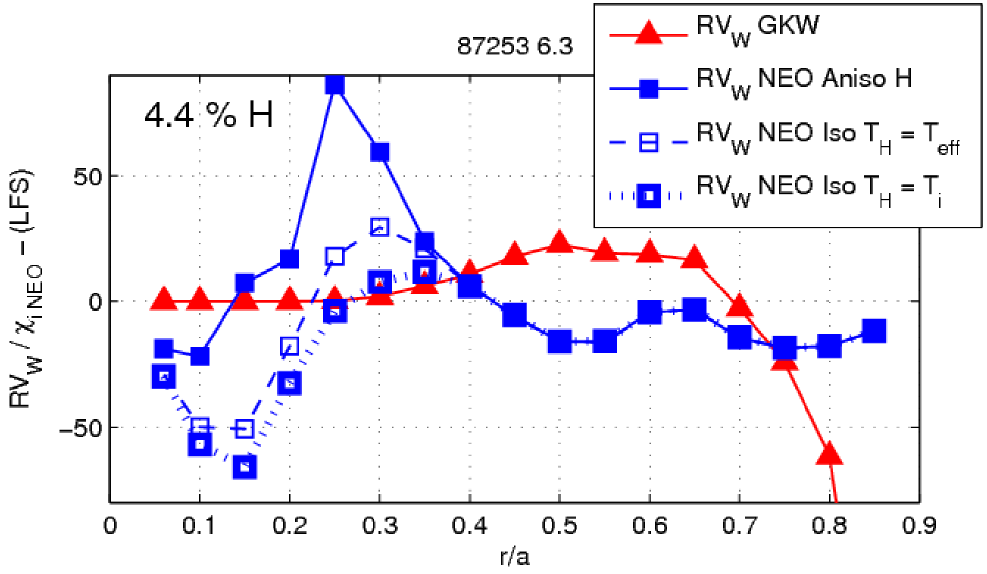
H anisotropy

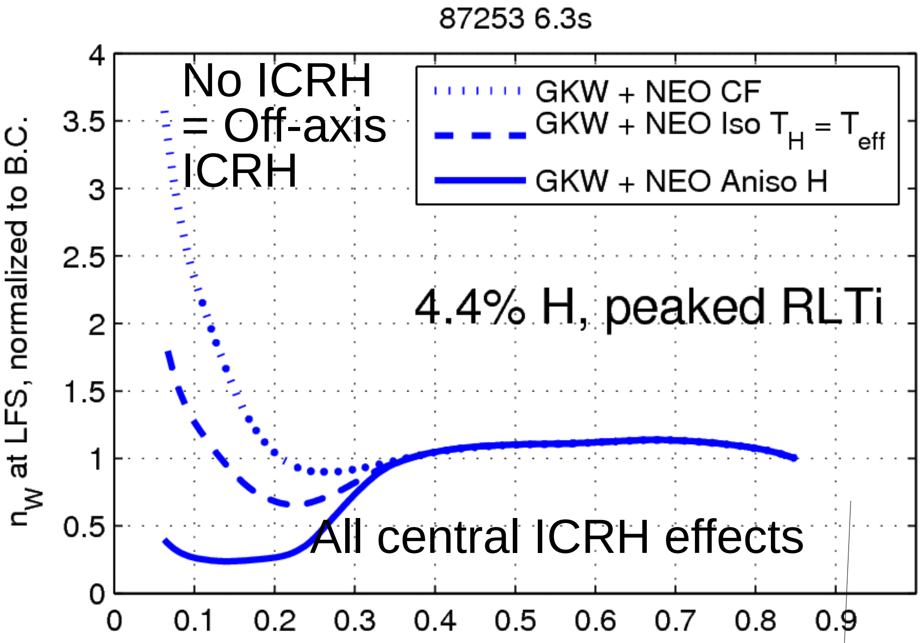
H temp. → screening

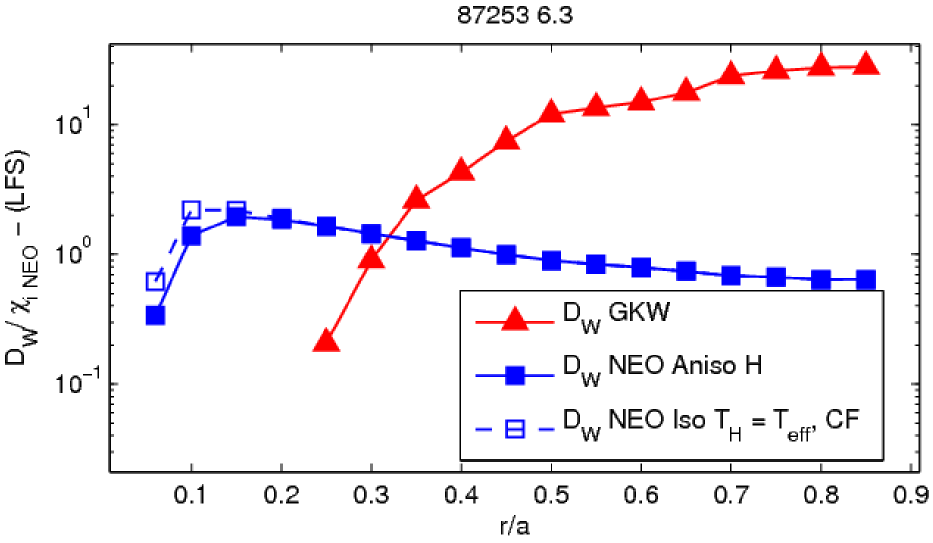


ICRH has no influence on V_{NC} in off-axis case

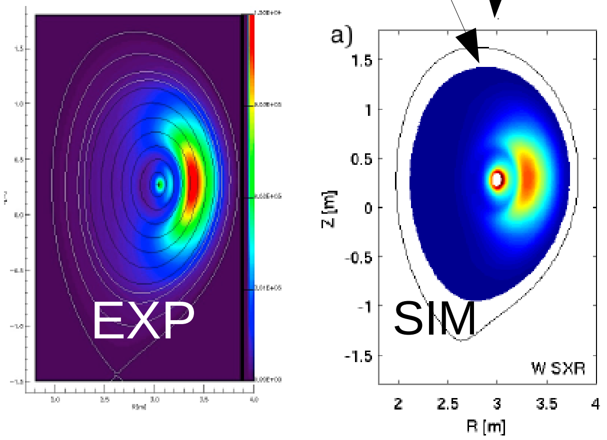
Influence of H minority at 4.4% (No FOW effects)







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



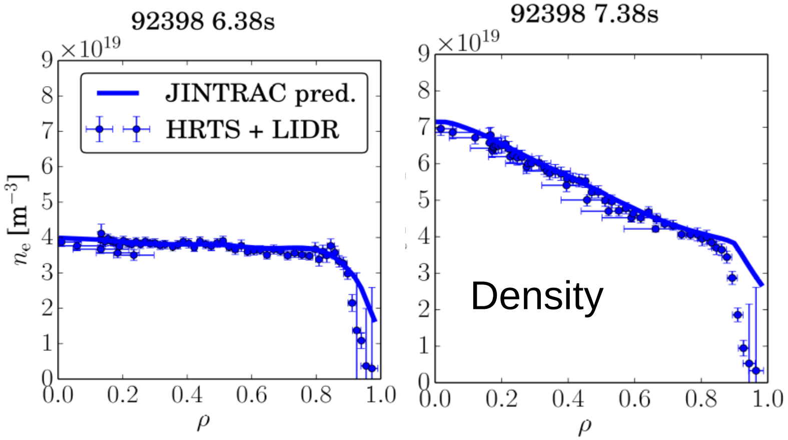
Mantica EPS 2015;
Casson PPCF 2015

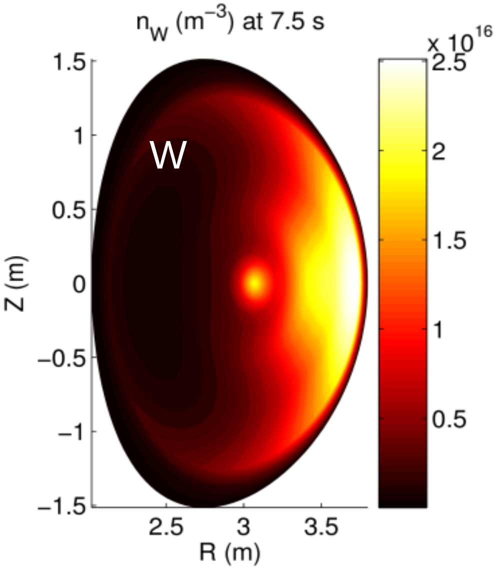
Predictive multi-channel modelling to optimise W control in JET

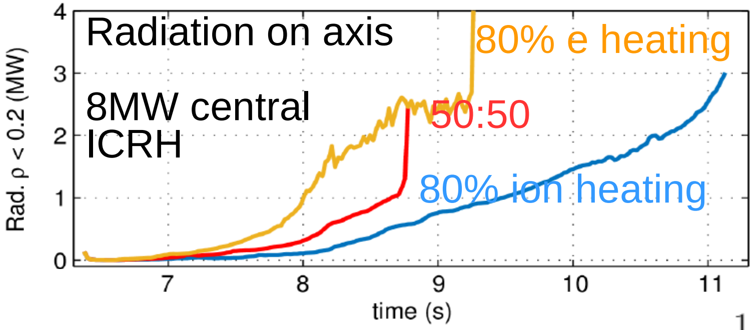
- 8 channels modelled predictively with first-principle models:

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

  - 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 *in JET hybrid conditions*

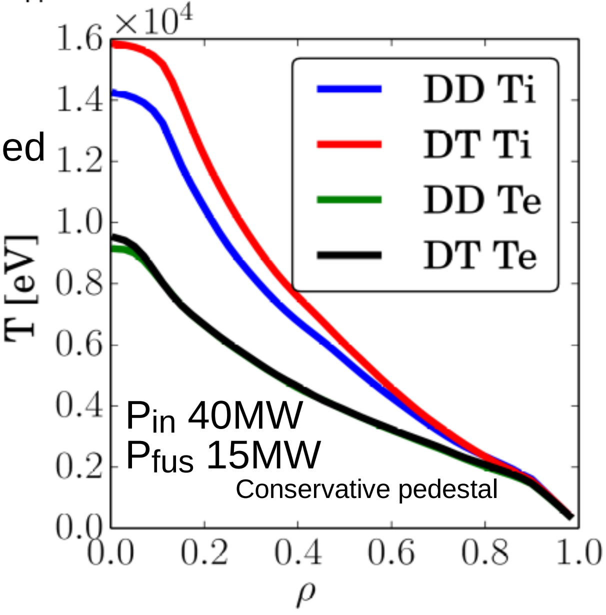






(increased temperature screening)

- 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)



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