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

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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
  - Maintain tolerable divertor heat loads (L. Garzotti, this conf.)
  - 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, focus on neoclassical convection and turbulent diffusion

Logarithmic gradient in stationary state with no source

\[
\frac{R}{L_{nZ}} = \frac{RV_{Z_{trb}} + RV_{Z_{NC}}}{D_{NZ_{trb}} + D_{NZ_{NC}}}
\]

Mitigation - large if turbulent transport

Complex, but benign

Threat: Drives accumulation

Small, \( \sim P_A \), no Z dependence

Rotation \( \rightarrow \) Poloidal asymmetry up to 20x increase in neocl. transport (JET)

\[
V_{Z_{NC}} \propto ZP_A \left( -\frac{R}{L_{ni}} + \frac{1}{2} \frac{R}{L_{Ti}} \right)
\]

Central ICRH heating

JET 85307

Centrifugal effects

Casson PPCF 2015

Both neoclassical and turbulent transport are relevant for W
Evolution of bulk density profile controls W accumulation timescale

- Central W accumulation universal observation the Hybrid scenario ($q_{95} \sim 4, \quad \beta_N = 2 - 3$)
  - Slow rise in density peaking leads to W accumulation
- JET Hybrid scenario more prone to W accumulation than Baseline ($q_{95} \sim 3, \quad \beta_N \sim 1.8$):
  - Lower density stationary scenario
  - Density more peaked (central beam deposition)
  - Less sawteeth (central flushing)
  - Higher beta $\rightarrow$ NTMs
  - Larger Mach numbers (more poloidal asymmetry)

- Here we focus on the Hybrid scenario

Proxy for W peaking

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
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 including rotation predicted from first principles
- Quasi-linear models enable flux driven multi-channel interactions:
  - L1: Ti, Te
  - L2: Ti, Te, ne
  - L3: Ti, Te, ne, V\text{tor}
  - L4: Ti, Te, multi-ion, V\text{tor}

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

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

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

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

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

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

**Profiles:**
- \( T_\text{i}, T_\text{e}, j, V_\text{tor} \)
- \( n_D, n_\text{T}, n_\text{Be}, n_\text{Ni}, n_\text{W} \)

**Current diffusion**

**Magnetic Equilibrium**

**Radiation, ionisation, recombination**
- SANCO and ADAS
  - [Lauro-Taroni L. 1994]
Evolution of highest performance hybrid reproduced over ~10 $\tau_E$

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

- Thermal heating
  - NBI inj 26MW
  - ICRH coupled 4.5 MW
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 $Z_{eff}$

- **Accumulation process less extreme 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 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
- 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 $\nabla n_D$
    (T. Tala, this conf., Garzotti, Valovic NF 2006/7)
  - For $V_W$, increased $\nabla n_D$ dominates increased $\nabla T_i$

\[ V_{ZNC} \propto ZPA \left( \frac{R}{L_{ni}} + \frac{1}{2} \frac{R}{L_{T_i}} \right) \]
ICRH heating delays W accumulation, consistent with JET observations

- ICRH helps in neoclassical dominated core, both increasing $\nabla T_i$ and decreasing $\nabla n_D$
  - 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

\begin{itemize}
  \item ICRH helps in neoclassical dominated core, both increasing $\nabla T_i$ and decreasing $\nabla n_D$
  \item Increased turbulent diffusion reduces central density peaking
  \item Localised axial ICRH most effective in increasing temp. screening
  \item 4MW increase in ICRH compensates 6MW increase in NBI
\end{itemize}
Ion heating schemes *predicted* as most effective on W

- Ion heating both increases $\nabla T_i$ and decreases $\nabla n_0$

- Specific to JET hybrid scenario: $T_i > T_e$, and dominant neoclassical convection (large Mach no $\sim 0.7$)
  - Where $T_i \sim T_e$ 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) (J.P. Graves, this conf)
  - 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 $W \rightarrow$ 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
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.)
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
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http://www.qualikiz.com
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

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 $\beta_{\text{thermal}}/\beta_{\text{total}}$
Validation of global evolution
Electron heating preferred in ITER
better for W turbulent transport (outward convection)


C. Angioni et al 2017
Nucl. Fusion 57 022009
Poloidal asymmetries with anisotropy

- ICRH heats minorities anisotropically, LFS localisation of minority

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

- Anisotropy requires coupled Wave-Fokker-Planck simulation.

- Anisotropy increases with power density

\[ \Gamma_{T_i} = \frac{n_D R}{T_D^{1/2} L_D} - \frac{n_H R}{T_H^{1/2} L_H} \]

TORIC-SSFPQL, R. Bilato

ICRH has no influence on Vnc in off-axis case

Experimentally validated:
JET: L. C. Ingesson PPCF 2000 ??
CMOD: M. Reinke PPCF 2012
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 \( \sim 10 \tau_E \)
  - 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 \( \frac{T_i}{T_e} \) and ITG stabilisation
  - Inclusion of ETG scales pins \( T_e \); 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)