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THEORY-BASED INTEGRATED MODELLING OF TUNGSTEN TRANSPORT: VALIDATION IN PRESENT-DAY TOKAMAKS AND PREDICTIONS FOR ITER

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Using state-of-the-art theoretical transport models in an integrated tokamak modelling workflow, this contribution shows that the physics of tungsten (W) transport in the core of a fusion reactor is in a markedly different regime as compared to present-day experiments, which has profound implications for the operation of the now fully-W-walled ITER fusion device. The workflow, based on the ASTRA transport code and the TGLF-SAT2 [1] quasi-linear turbulent transport and FACIT [2] neoclassical impurity transport models, has been validated against experimental data mostly in ASDEX Upgrade (AUG) [3,4] and also in JET. In particular, with this modelling approach, by condensing the recently developed theoretical knowledge on heavy impurity transport, for the first time quantitative predictions of the power requirements to avoid central W accumulation in present experiments have been achieved. This provides confidence on the physics understanding of high-Z impurity transport for extrapolation to future reactors. In ITER, the challenges introduced by W arise from global radiation losses that can hinder operation in H-mode, instead of local central accumulation as in present-day devices. The analysis reveals the interplay between the W content in the plasma, the applied auxiliary heating power, and the quality of the energy confinement, allowing us to determine the domain over which stable operation in H-mode at 15 MA can be expected and the ITER fusion performance targets can be achieved [4]. Furthermore, the access and sustainment of the H-mode at lower current as well as the plasma survival during the current ramp-up are analyzed at increasing W concentrations [5].

In present-day tokamaks, routine operation with neutral beam injection (NBI) also requires central wave heating to avoid core W accumulation and a subsequent local radiative collapse of the plasma center. The use of central electron and ion cyclotron resonance heating (ECRH, ICRH) to control high-Z impurity accumulation is a well-established technique across multiple fusion devices, whose physics basis is a simultaneous enhancement of the turbulent impurity diffusivity and a reduction of the neoclassical pinch, both leading to flatter impurity profiles. The ability to reproduce these effects is an important validation for an integrated modelling workflow that predicts impurity transport and radiation self-consistently. We demonstrate that the workflow presented in this contribution recovers essential physics of core W transport in the presence of central wave heating, quantitatively reproducing experimental observations [6] of AUG H-modes with constant NBI and power steps in ECRH and ICRH. Fig. 1 shows an example of the good agreement between simulation and measurements when the plasma temperature and density profiles, the W density and the radiation are self-consistently evolved.

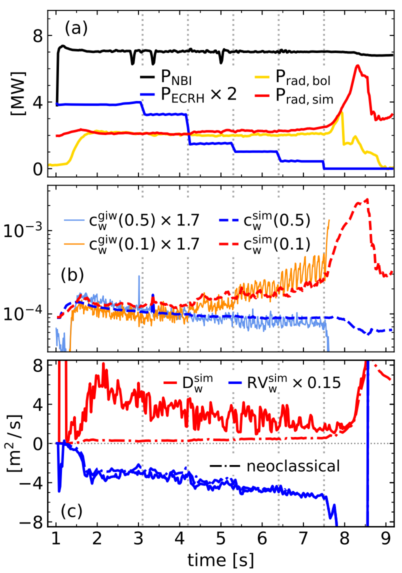

Fig. 1: Experimental and simulated time traces of AUG #32408 [4]. (a) Heating and radiated powers. (b) On- and off-axis W concentrations. (c) W diffusivity and convection.

The workflow is also validated against strongly seeded L-modes in AUG and JET. Full-radius simulations are performed, applying the transport models up to the separatrix. The impurity code STRAHL is coupled to ASTRA in order to calculate the distribution of impurity charge states and their radiation, accounting for non-coronal atomic physics that becomes relevant at the edge. An AUG discharge with high heating power and strong Ar seeding is modelled. This plasma features high confinement and no edge localized modes (ELMs) with an X-point radiator [7]. The coupled evolution of multiple transport channels leads to good agreement between the simulated and measured plasma and impurity profiles, the high radiated power fraction and the H-mode-like confinement. Furthermore, a set of high-power, 3.2 MA L-mode D plasmas in JET featuring a scan in Ne seeding [8] are modelled with the full-radius workflow. The impact of Ne content and radiation on the plasma profiles is investigated. For these AUG and JET seeded discharges, the transport of both the seeded species and W as well as the stabilizing effect of impurities on turbulence are analyzed.

Having validated the theory-based workflow, the attention is shifted to integrated modelling predictions of a variety of ITER plasmas. Multiple simulations span the range from the 15 MA baseline H-mode scenario in DT, to lower current electron-heated H-modes and L-modes in D (5 & 7.5 MA), to ECRH and Ohmic heated current ramp-ups in L-mode. Particular emphasis is placed on the transport and effects of tungsten, following the new ITER baseline and its replacement of Be for W as a first wall material.

In the core of a reactor like ITER, the much higher temperatures lead to a much lower collisionality compared to the core of present day devices. This, in addition to the lower expected toroidal rotation and lack of a central particle source, leads to a strong reduction of neoclassical high-Z impurity transport. The core W convection is dominated by turbulence, in contrast to the mostly neoclassical W convection which is responsible for problematic central W peaking in present tokamaks. Turbulent transport does not produce any mechanism of strong inward convection of impurities, yielding W density profiles with a similar shape as that of the main plasma density. Consistently, flat W concentration profiles have been obtained in ASTRA simulations of ITER plasmas using TGLF-SAT2 and FACIT. The reduction of the magnitude of neoclassical transport with respect to turbulent transport going to reactor conditions is predicted by these theory-based transport models, and it can be ordered by a simple physical parameter, as shown in Fig. 2.

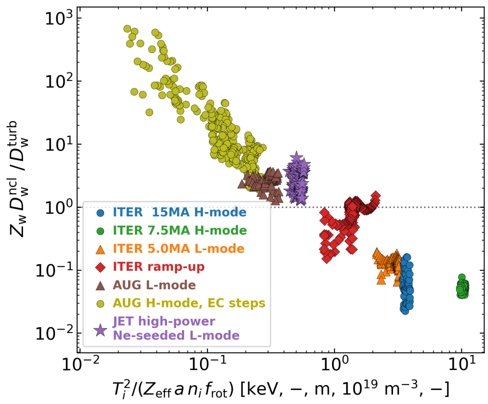

Fig. 2: Reduction of magnitude of core neoclassical W convection with respect to turbulent diffusion, going from plasma parameters in present-day devices to reactors.

The self-consistent evolution of the plasma and of the impurities allows us to determine the operational space of ITER in view of its full-W walls. Global radiative losses can hinder the access and sustainment of the H-mode and the survival of the plasma during the ramp-up phase. Wave heating can serve as an actuator to control the effects of W radiation, by allowing the plasma to tolerate a higher W concentration while remaining in H-mode, instead of by flattening the central W density, as in present devices. However, a higher auxiliary heating leads to a decrease of the fusion power multiplication factor Q_{fus}, due to the limited increase of both the pedestal pressure and the central temperatures with increasing power.

The interplay between the edge W concentration, the required power at the separatrix for H-mode sustainment, the pedestal top pressure and the performance in Q_{fus} is shown in Fig. 3 for a scan in ECRH power for the ITER 15 MA baseline with 30 MW of NBI. The increased confinement associated with a pedestal pressure at the peeling-ballooning (PB) boundary, compared to a reduced pressure mimicking ELM-free operation, leads to a limiting W concentration more than twice higher (5×10^{-5} vs 2×10^{-5}), due to the stronger alpha heating. With a PB-limited pedestal, the models and assumptions of this work lead to a comfortable achievement of ITER's $Q_{\mathrm{fus}} = 10$ objective at 20 MW of ECRH + 30 MW of NBI, even with a fairly high W concentration in the plasma.

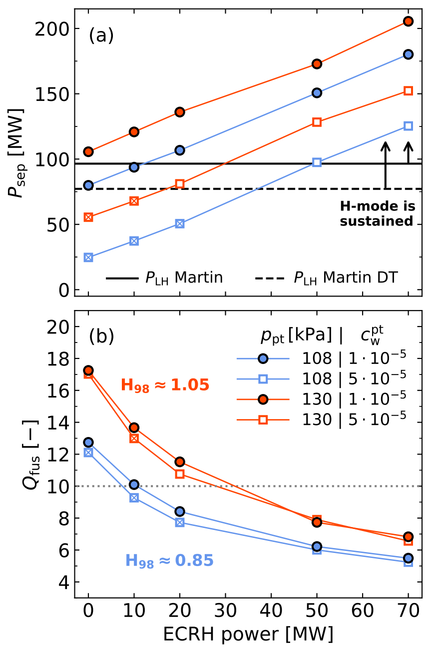

Fig. 3: ECRH scan of the ITER 15 MA baseline at two different pedestal top pressures and W concentrations [5]. (a) Power crossing the separatrix. (b) Fusion power multiplication factor.

Simulations in L-mode and H-mode are performed at lower currents in electron-heated D plasmas to assess the maximum W concentrations that allow access and sustainment of H-mode operation, as well as dynamical simulations of the ramp-up, from the limiter to the diverted phase, finding maximum tolerable W concentrations to avoid a radiative collapse of the plasma.

This contribution demonstrates new theory-based predictive capabilities which have been validated against experimental data and allow for an improved understanding of ITER plasmas.

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