Modelling of Hybrid Scenario: from present-day experiments toward ITER

The 'hybrid' scenario is an attractive operating scenario for ITER since it combines long plasma duration with the reliability of the reference H-mode regime. We review the recent European modelling effort carried out within the ITER Scenario Modelling (ISM) working group (ISM-WG) organized within the EFDA Task Force on Integrated Tokamak Modelling (ITM-TF) [1, 2]:

(i) understanding the underlying physics of the hybrid regime in ASDEX-Upgade and JET
(ii) extrapolating them toward ITER

Integrated modeling of ASDEX-Upgade and JET hybrid scenario

JET and ASDEX-Upgade database

- More than fourteen JET and two ASDEX-Upgade hybrid scenarios performed under different experimental conditions have been simulated in an interpretative and predictive way
- By optimising the current density profile $H_{\text{Phys}}(\rho)$ up to 1.4.
- JET: q-profile modification via the ‘current-overshoot’ method [2, 3].
- ASDEX-Upgade: q-profile modification by varying the NBI timing, with the later heating case resulting in a broader q-profile [4].

Current diffusion interpretative analysis

- neo-classical prediction for the resistivity and bootstrap current interpretative analysis
- same modelling assumption with CRONOS [5] for JET & ASDEX-Upgade
- JET: dynamics is reasonably well reproduced
- ASDEX-Upgade: q-profile is clamped to the $q_{\alpha}=1$ surface

Self-consistent modelling of hybrid scenario (current, thermal, particle, and rotation): ExB shear influence on transport [8,9]

- Validation of the GLF23 transport models in the self-consistent four-field: density, temperatures, and momentum + first application of the TGLF model
- GLF23: good agreement with measured density by reducing $\alpha_T$ by factor 2 – Te & Ti well predicted
- ASTRa [7] simulations of toroidal rotation using the GLF23 [8,9]:
  - GLF23 momentum transport over-prediction of toroidal rotation
  - A better agreement with measured toroidal velocity when applying the fraction of the GLF23 computed thermal ion diffusivity for momentum transport.
  - The Prandtl number is $P_T=0.3$ and $P_T=0.5$ in low and high triangularity discharges

Modelling of hybrid termination

- Simulation (density, $T_e$ and $T_i$ evolution) of termination of JET hybrid scenarios including the H-L transition + Ip and Bo ramp down phase
- The transition from hybrid performance with type I ELMs to type III reproduced with the Bohm-gyroBohm model and continuous ELM model by reducing the ballooning stability limit and L-H threshold power by 40%.
- transition from type II H-mode to ohmic plasma with the reduction of power below the L-H threshold by switching from the H-mode to L-mode Bohm-gyroBohm model

Results of combined heat and particle transport GLF23 simulations for JET (top) and AUG (bottom) with and without ELM simulation effect (left column) q-profile (center column) T_e profiles (right column) $\alpha_T$ profiles (top) JET 79628, bottom q-profile inputs from both 79628 and 79635. (bottom) AUG 20995, comparing q-profile inputs from both 20995 and 20993.

| Machine | $\alpha_T$ | $T_e$ (keV) | $T_i$ (keV) | $
u_{\text{F}}$ transport modeling (MJ) |Heat & particle transport modeling (MJ) | with ELM | with ELM |
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<td>1.97</td>
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<td>2.82</td>
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<td>1.61</td>
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<tr>
<td>AUG 20995</td>
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<td>2.32</td>
<td>3.87</td>
<td>1.65</td>
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$\alpha_T$ and $T_e$ profiles. (top) JET 77922: (left) NBI power, D$_{\text{E}}$ profiles. (right) measured (High Resolution Thomson Scattering) and simulated $n_e$ profiles. (middle) q-profile influence on transport [6].

Self-consistent current, temperature, and density ASTRa simulations including the H-L transition + Ip and Bo ramp down phase.

Modelling of hybrid scenario (current, thermal, particle and rotation): ExB shear influence on transport [8,9].

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Predictive integrated modeling of ITER hybrid scenario  

(see also Parail V. et al this conference)

ITER hybrid operational domain from 0-D modeling
- simulations performed with the 0.5-D code METIS [10]
- fast calculation in order to scan the operational domain
- double constraint \( q_e > 1 \) for 1000s and \( Q_{DT} \)
- \( I_p = 12MA \) at \( B_T = 5.3T \) (top 3.3), with the ITER baseline heating mix 20MW ICRH, 33MW NBI, 20MW ECD and with a line averaged density fixed to \( n_e \gg 7.5 \times 10^{13} \) \( \left( n_e/\omega_{ce} > 0.8 \right) \) during the burn phase
- sensitivity study are the density peaking factor with \( f_{\text{pea}} \geq 1.2, 1.4 \) and \( H_{\text{npea}} \geq 1.1, 1.2, 1.4 \)
- METIS calculations indicate that high confinement and peaked density profiles are required to increase the bootstrap current at level above a certain value \( (f_{\text{pea}} > 3MA) \) or \( f_{\text{pea}} > 30\% \) to sustain the q-profiles above unity

Current profile optimization during current ramp-up phase [11,12,13]
- \( q \) profile with \( q_e > 1 \) at the end of the current ramp up phase with the ITER heating systems
- The flexibility of the heating system open the route to an active control of the q-profile
- Optimum between resistive flux consumption Eijiama coefficient, \( C_{\text{Ejima}} \) and optimizing the \( q \) profile \( F_q(q) \)

Assumptions for reference case:
- Simulations start 1.5s after breakdown, when \( I_p = 0.5MA \).
- Current flat top (12MA) at 80 s with an expanding elongated shape, starting on the Low Field Side (X-point at 15s \( I_p = 5.5MA \)).
- The parabolic density profile with \( n_e/\omega_{ce} = 1.3 \) and \( n_e > 2.5 \times 10^{13} \)
- A flat \( Z_{\text{eff}} \) profile, decreasing in time from 5 to 1.7
- An L-mode edge with applied power (after 50s) below the L-H power threshold (~25MW).

Pedestal prediction with first principle predictive model EPED [14,15]
- EPED is a first-principle model for predicting the H-mode pedestal height and width two constraints:
  - (1) onset of non-local peeling–ballooning modes at low to intermediate mode number
  - (2) onset of nearly local kinetic ballooning modes at high mode number

Consistent core and pedestal integrated modeling
- CRONOS simulation: GLF32 (core) with EPED constrains
- Prescribed density profile scan at fixed
- \( n_e = 8.8 \times 10^{13} \) and \( n_e = 1.25, 1.5 \)
- consistent core & edge simulations \( n_e/\omega_{ce} \) at \( n_e = \text{cst} \)
- Edge confinement \( \uparrow \)
- Core confinement \( \uparrow \)

Model-based Magnetic and Kinetic real time Control [17-19]
- An integrated model-based plasma control strategy, ARTAEMIS [21,22] applied to ITER hybrid regime for the control of the poloidal flux profile and \( P_{\text{pea}} \)
- The control actuators are NBI, ECRH, ICRH and LHCD systems, and the plasma surface loop voltage.
- The nonlinear plasma response to the actuators is modeled with METIS. A two-time-scale model identified from open-loop simulations.
- Closed-loop control simulations were performed by inserting the METIS code at the output of the two-time-scale ARTAEMIS controller. Various target profiles for the poloidal flux have been obtained simultaneously with various target levels of fusion power. This shows that current profile control can be combined with burn control, sharing a common set of actuators.

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