Exploring operational scenarios of DTT through core-edge integrated modelling

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The DTT tokamak

TABLE 1: DTT MAIN DESIGN PARAMETERS	
major radius R (m)	2.19
minor radius a (m)	0.70
Volume (m^3)	35
Gas	Deuterium
Plasma current (MA)	5.5
Vacuum $B_{toroidal}$ at R=2.19 m	5.85
Electron density $\overline{n_e}$ (10^{20} m^3)	1.5
Auxiliary power P_{tot} (MW)	45
P_{ECRH} (MW)	29
P_{ICRH} (MW)	6
P_{NBI} (MW)	10

Table 1 DTT main design parameters

One of the major challenges in the realization of fusion energy is the management of the heat and particle loads, which are generated by high-performance plasmas. The Divertor Tokamak Test (DTT) facility, which is currently under construction in Frascati, will be dedicated to developing credible solutions for heat and particle exhaust. The facility assesses the compatibility of exhaust solutions with reactor-relevant core performance in a core-edge integrated approach. It will also contribute to studying topics such as transport, MHD, energetic particle physics, heating and current drive. A complete research plan was issued in May 2024 [1]. Table 1 summarizes the main design parameters of DTT. In addition, a key quantity P_{sep}/R for DTT is 15 WM/m, very similar to those of ITER (14 WM/m) and DEMO (19WM/m). That means DTT would have divertor power flux similar to that of ITER and DEMO, making DTT results valuable in supporting ITER operation and DEMO design.

Integrated modelling of DTT scenarios

The design phase of DTT has been supported by intensive scenario modelling, facilitating the optimization of auxiliary heating, informing diagnostic development, and providing inputs for MHD stability analysis, neutron-yield estimates, fast-particle loss studies and fueling strategies [1]. And that has also been the starting point of the elaboration of the DTT Research Plan. Utilizing the JINTRAC code and the ASTRA code, the modelling covers all phases of the plasma discharges: current ramp-up, flat-top and ramp-down, using state-of-art physics-based transport models, i.e., TGLF-SAT2, NCLASS and FACIT for turbulent and neoclassical transport, GRAY for ECH, PION for ICH, PENCIL or RABBIT for NBI, EUROped for pedestal. In this modelling [2,3], electron temperature T_e, ion temperature T_i, electron density n_e, impurity density and current density J are predicted. Equilibrium is evolved self-consistently. The geometric configurations used are single null (SN) with positive triangularity (PT) and SN with negative triangularity (NT). The modelling with X divertor configuration (XD) is in progress.

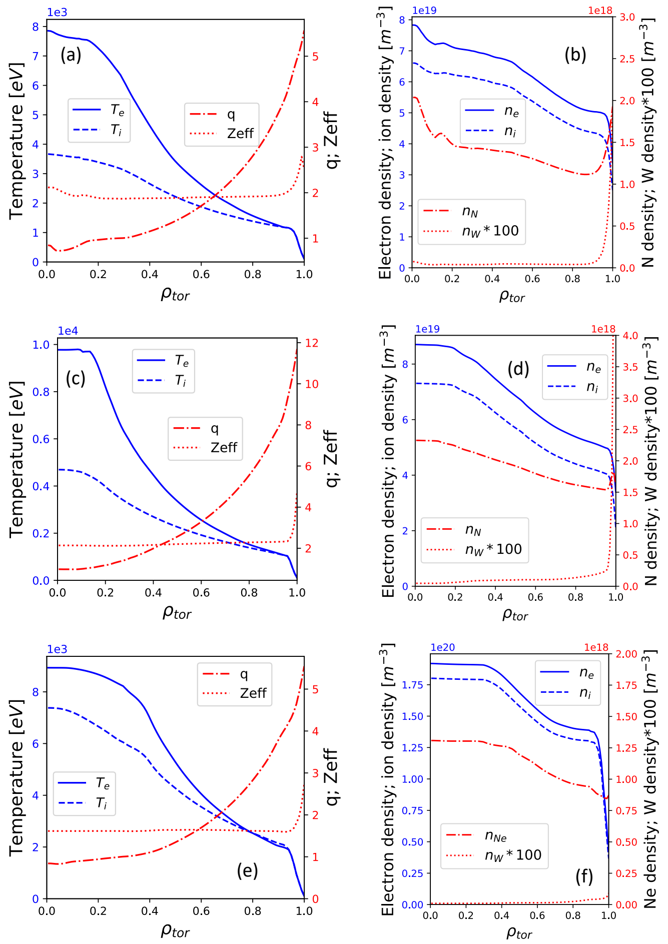

Figure 1 Temeperature, q, Z_{eff} and density profiles for scenario A, A^* and C

Full power scenario

Scenario E H-mode baseline with SN is a reference scenario with full power (total auxiliary heating power $P_{heating} \approx 45$ MW), full field ($B_T = 5.85$T) and full current ($|\ I_p\ | = 5.5$MA). The plasma boundaries used in the simulations are calculated by the CREATE-NL code. In this scenario, off-axis ECH is used in ramp-up and ramp-down to control internal inductance l_i and limit CS flux consumption, so that the flat-top can be sustained for 30-40s. In the flattop, ECH is designed to be radially broad to avoid TEM-dominant behavior and density drop. The impurity species are neon (Ne) and tungsten (W) in the ramp-up and argon (Ar) and W in the flattop. Prediction shows that impurity W is not accumulating. Large sawteeth are an open issue for this scenario, thus motivating the development of a hybrid scenario.

Early operational scenarios

Scenario A, A^* and C that are in the operational phase 1 have been modelled. The scenarios are all H-mode baseline with SN. Scenario A is with 7.2 MW of ECRH and 3T of toroidal magnetic field. The plasma current is 2 MA. Impurities nitrogen (N) and W are predicted. The new scenario A* has been designed due to the earlier availability of the ICRH heating. The scenario is an upgrade of scenario A in terms of full toroidal field, 6T and 1.5MW of additional ICRH power. Scenario C is with larger plasma current (4MA) and full toroidal field (6T). It is with 14.4 MW of ECRH and 4.75 MW of ICRH. Impurities neon (Ne) and W are predicted. The flat-top of those scenarios has been simulated with JINTRAC. All of them are in H-mode with SN. A continuous sawtooth model has been applied to those scenarios. The simulations of those scenarios have been stored in a structured IMAS-based scenario database, which has been tested on the ITER SDCC cluster using the SimDB tool. Such a database will support future DTT scenario development, experimental planning and physics study.

Hybrid scenario

Based on scenario E H-mode baseline with SN, a hybrid scenario has been developed using ASTRA and METIS [4]. The plasma current is 3.8 MA, the toroidal field is 5.85 T and total auxiliary heating power is about 45 MW. The current ramp-up and the flattop are simulated. ECRH is the only auxiliary heating in the ramp-up. Several tests were carried out to investigate the impact of the current overshoot strategy and the optimal deposition of ECRH for tailoring the q profile. That indicated the heating of ECH should be as soon as possible, together with early formation of the X-point (1.5s). The study also proved that the current overshoot is not helpful. In the flattop, a q profile with a broad q~1 region is maintained for ~8s. JINTRAC-GRAY simulation is ongoing to test the used ECCD and the control of q profile.

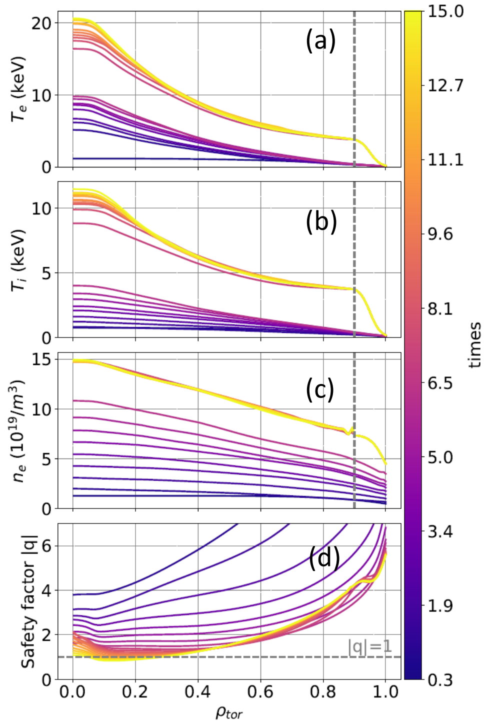

Figure 2 Time evolution of (a) electron temperature, (b) ion temperature, (c) electron density and (d) safety factor of the hybrid scenario.

Advanced scenario

An advanced scenario has been developed based on scenario B using ASTRA [5]. The plasma current is 0.95 MA, the toroidal field is 3 T and total auxiliary power is about 20 MW (16 MW ECRH and 4 MW ICRH). The q profile is the same as a DIII-D high-β_N

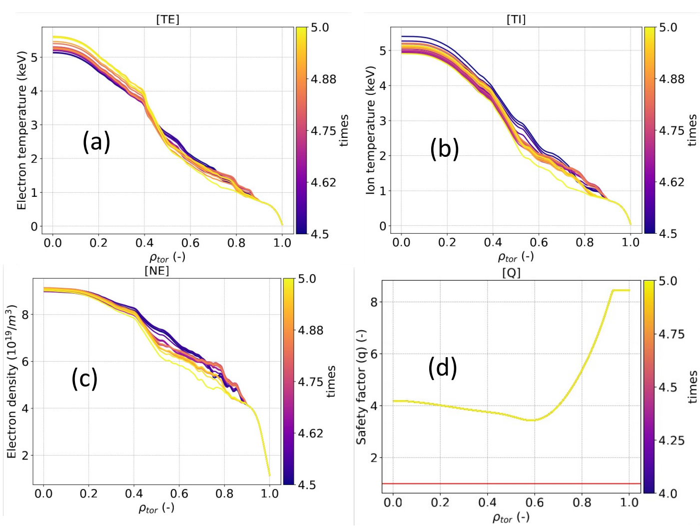

Figure 3 Time evolution of (a) electron temperature, (b) ion temperature, (c) electron density and (d) safety factor of the advanced scenario.

plasma with ITB and is set interpretive. In the simulation of the flattop, the pedestal temperature and density are set to be 700 eV and 4.2×10^{19} m^{-3} and impurity neon (Ne) and tungsten (W) are predicted. Using TGLF-SAT2 as the turbulence transport model, an ITB is formed at ρ_{tor}=0.55. The formation of the ITB starts with the formation of the density ITB and then the temperature ITB forms. The Greenwald density fraction reaches 1.1. JINTRAC-GRAY simulations are ongoing to test if such q profile can be realized in DTT and maitained in time.

Negative triangularity scenario

Negative triangularity (NT) plasmas show advantages in demonstrating H-mode-like performance without pedestals, thus suppressing edge localized modes (ELMs). DTT scenarios with NT geometry have been planned and are under study [6]. Referring to TCV and AUG plasmas, two NT shapes were designed for DTT, with lower and higher |δ|. Both shapes prevent access to 2nd stability and H-mode. By modelling up to the separatrix, we find that the pedestal loss of confinement is not recovered, but central pressure is ~15% lower than the PT H-mode. Thus, the NT scenario is a valuable ELM-free high-performance scenario to be explored on DTT.

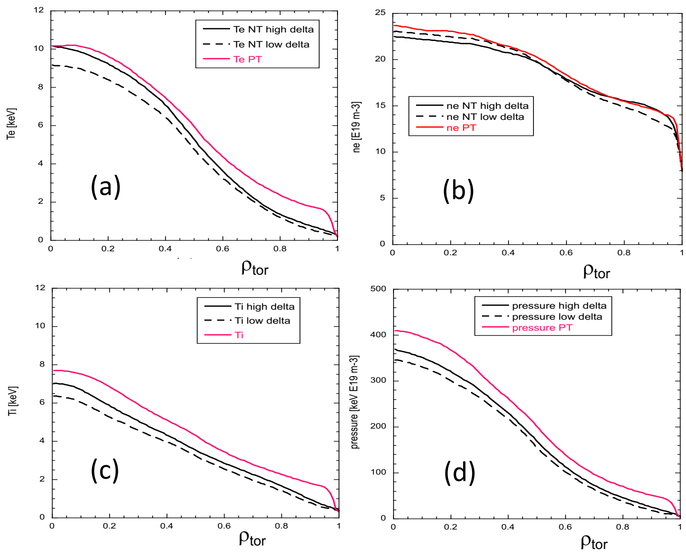

Figure 2 Predicted (a) electron temperature, (b) ion temperature, (c) electron density and (d) pressure of the negative triangularity plasmas with high (solid black line) and low (dashed line) |δ| and a positive triangularity conterpart (solid red line).

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