Exploring Divertor Tokamak Test (DTT) operation space and plasma scenarios through time-dependent 0.5D integrated modelling

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The new super-conducting Divertor Tokamak Test facility ("DTT", R = 2.19 m, a = 0.7 m, $B_T \leq 6$ T, $I_p \leq 5.5$ MA) [1], [2] is currently under construction in Frascati (Italy). DTT is designed to investigate innovative solutions to the power exhaust problem in support of ITER operations and DEMO design. This goal will be achieved through the flexibility of DTT in terms of divertor configurations. DTT is characterized by reactor-relevant dimensionless plasma parameters, with the goal of reaching a normalized power crossing the separatrix of $P_{sep}/R \sim 15$ MW/m. DTT will be finally equipped (~ 6 - 7 years after the first plasma) to provide high power density to the plasma with a mix of auxiliary heating and current drive – H&CD systems (up to a total of 45 MW) [1], [3], currently designed to be:

- 170 GHz Electron Cyclotron Resonance Heating (ECRH) system, $P_{ECRH} \sim 28.8$ MW
- 510 keV, negative-ion based Neutral Beam Injection (NBI) system, $P_{NBI} \sim 10$ MW
- 80-90 MHz Ion Cyclotron Resonance Heating (ICRH) system, $P_{ICRH} \sim 6$ MW.

In the present contribution we illustrate the modelling environment and first results regarding the accessibility of the target reference plasma (baseline H-mode, Single Null – SN – divertor, full H&CD power) and its time evolution through simplified time-dependent modelling. To this purpose, METIS [4] 0.5D simplified transport code is used here to simulate the entire

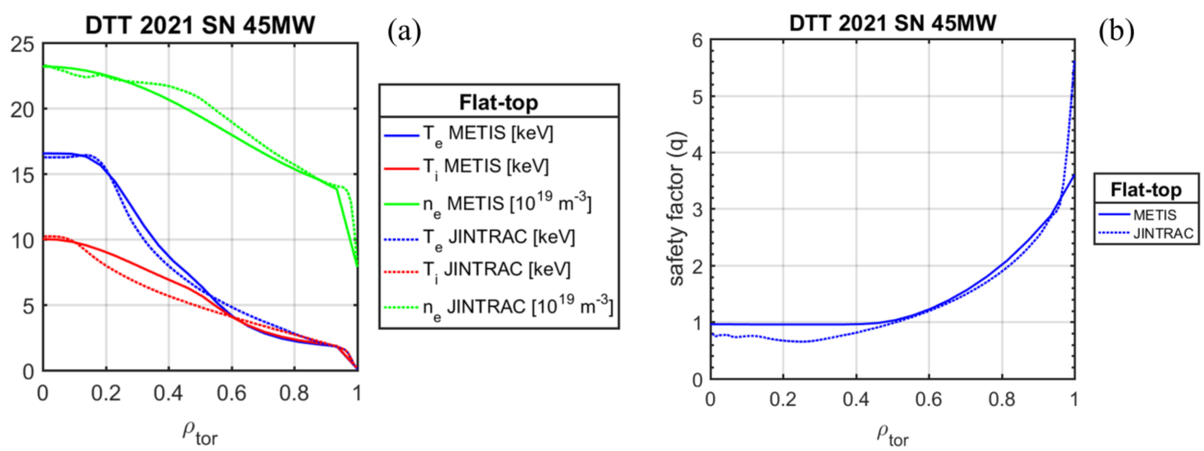

Figure 1: Flat-top plasma kinetic (a) and safety factor (b) profiles: METIS results compared to JINTRAC modelling [5], [6].

plasma discharge, in order to design the time evolution of plasma parameters during transient phases, in particular ramp-up. Future work will include the study of ramp-down phase and plasma scenarios different from the reference plasma, e.g. at reduced H&CD power or with different divertor configurations or different plasma confinement regimes. The METIS reference flat-top simulation is validated towards JINTRAC 1.5D, first principle, transport modelling [5], [6], while plasma boundaries are provided by free boundary CREATE-NL solver [7]. Flat-top kinetic profiles and safety factor are shown in fig. 1. The profiles and values reported in this paper have to be considered as current values, which may slightly change in future.

Impact of sawtooth activity on flat-top dynamics

In JINTRAC reference simulation, sawtooth (ST) instability is not taken into account and the q profile is free to relax to a slightly reversed profile with off-axis q_{min} = 0.65. The present METIS simulation assumes instead an infinite ST frequency approximation by imposing a clamping of the safety factor profile at q = 0.95 (see fig. 1(b)). The time dependent effect of ST instability is being preliminarily investigated in METIS by a simplified representation of Porcelli's model [8]. The model can reproduce the variation of the ST period and amplitude as function of the critical shear for sawtooth triggering and the slope of q inside the mixing radius, as seen in experiments (e.g. [9]). The first results being obtained, however, have to be considered only indicative, since other effects should be taken into account for a more robust estimate of the ST dynamics, such as the role played in DTT by the energetic particles from NBI and ICRH or the control by ECRH system.

First exploration of plasma time-dependent evolution

The investigation of the time evolution of the reference SN plasma scenario has started with the ramp-up phase. In this phase, crucial points in terms of plasma controllability and evolution are the X-point formation (foreseen between 9 - 14 s after the start of the discharge),

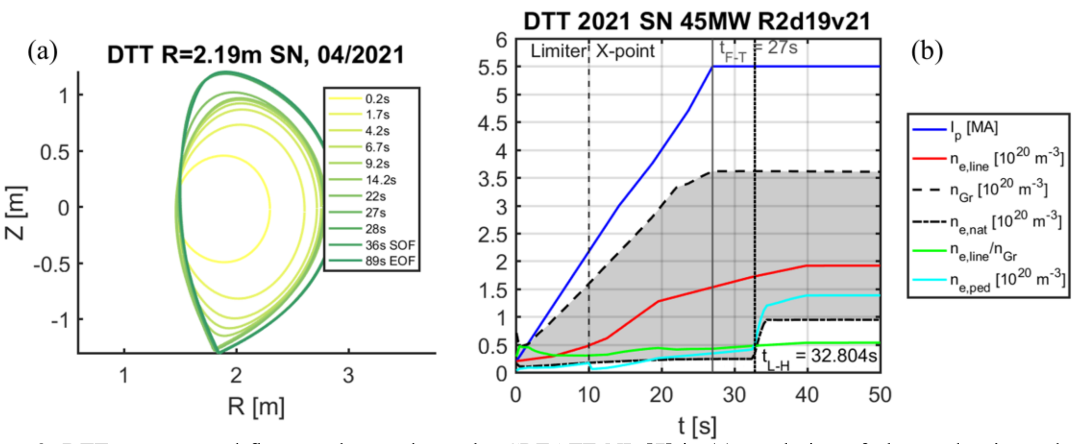

Figure 2: DTT ramp-up and flat-top plasma shapes by CREATE-NL [7] in (a), evolution of plasma density and current during the ramp-up phase in (b).

the current ramp-rate set to ~ 200 kA/s (flat-top I_p reached at t = 27 s with a linear current increase) and the L-H transition foreseen in the I_p flat-top, but before t = 36 s, when the stationary phase begins (“Start of Flat-top” – SOF). The stationary phase should last until t = 84 - 89 s (“End of Flat-top” – EOF); afterwards the ramp-down phase will start with a current ramp-rate in the range of 250 – 750 kA/s.

METIS takes as input the evolution of the plasma current, the toroidal magnetic field and the plasma shapes (fig. 2(a)) calculated by CREATE-NL assuming a set of internal inductance – li(3) and normalized poloidal plasma pressure – β_p values which can be controlled by the DTT magnetic field coils (fig. 3(b)). The goal of the ongoing activity is to reach an optimal ramp-up trajectory with a convergence between CREATE-NL electro-magnetic plasma scenarios (coil currents and controllable plasma shapes with related (li(3), β_p) values) and transport simulations (current density profiles, plasma pressure), through iteration between the codes. We present here the first step of this process, i.e. a possible plasma evolution generated acting on the plasma density waveform, H&CD input power and timings and ECRH deposition (on/off – axis). In fig. 2(b) we show the evolution of the plasma density, which is constrained to reach $f_G \sim 0.5$ in the stationary phase, staying above the natural density at values of $f_G >$ 0.25 during the whole ramp-up phase. Plasma density influences the required power to access H-mode, which has been estimated in METIS through ITPA 2008 scaling [10]. In the present work, the maximum density is reached after the plasma current flat-top, in order to access the H-mode at full current but at lower auxiliary power (ideally, only ECRH in the present trajectory). The L-H transition, happening when the power leaving the plasma (P_{loss}) overcomes the threshold power, and the auxiliary heating (power and timings) are shown in fig. 3(a). DTT H&CD systems are being designed to be capable of increasing the injected power by steps. In METIS the power ramp is approximated by a continuous line (fig. 3(a)). Ramp-up auxiliary power has been set in the present work with the aim of keeping li(3)

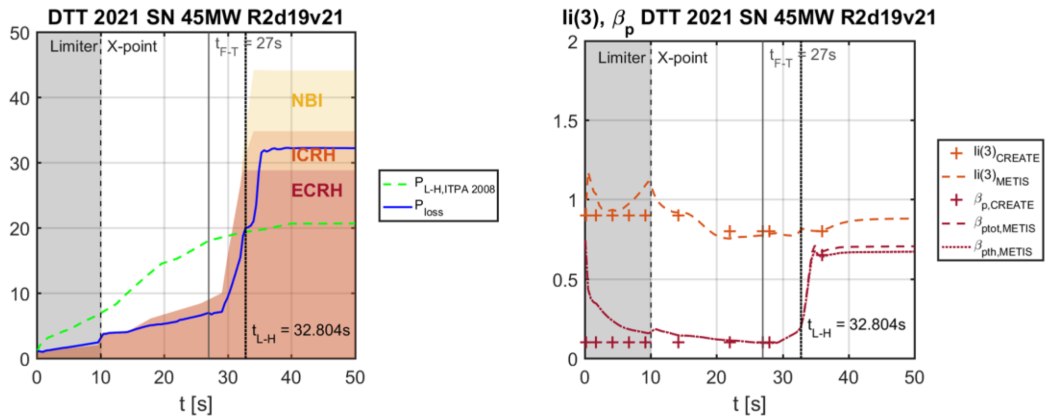

Figure 3: Ramp-up evolution of H&CD power and L-H transition timing in (a), internal inductance li(3) and normalized poloidal plasma pressure β_p in (b).

and β_p close to CREATE-NL controllable values (fig. 3(b)), and to maintain the plasma in L-mode until the maximum plasma current is reached. With the present H&CD settings, a controllable trajectory has been obtained, at least for the whole plasma diverted phase, with a perfect matching also during the L-H transition. The limiter phase and the increase of li(3) at limiter – X-point transition will be further investigated. One of critical points in the ramp-up evolution is to counteract the natural tendency of current density peaking, achieved in the present work by off-axis ECRH deposition (ρ_{tor} ~ 0.65 - 0.8). Thanks to the consequent resistive effect, li(3) values can be maintained close to CREATE-NL values. DTT ECRH system is indeed capable of moving the deposition in the plasma during the discharge, although the actual radial accessibility has not been defined yet. ECCD appears to be almost negligible during the ramp-up phase due to the T_e/n_e dependence of its efficiency. If off-axis heating or CD could be obtained also by the other two systems (ICRH, NBI), they could be useful in the ramp-up phase, too. Anyway, high energy NBI could be likely switched-on only in the last part of the ramp-up at larger plasma density values, due to the risk of harmful shine-through losses. The increase of auxiliary power to full capability by the three systems in the flat-top phase will be further studied to check the compatibility with divertor protection by detachment conditions obtained thanks to impurity seeding. In the present trajectory we increased the power to maximum values in ~ 5 s with a linear ramp (fig 3(a)). The ramp-up plasma evolution is critical also for the central solenoid flux consumption: to extend the discharge duration, the internal inductance and plasma resistivity are the crucial knobs.

Acknowledgment

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