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First-principle based multi-channel integrated modelling in support to the design of the Divertor Tokamak Test Facility

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ABSTRACT

First results of the integrated modelling of DTT scenarios (R=2.14 m / a=0.65 m) using first-principle quasi-linear transport models are presented, in support to the design of the device and to the definition of the DTT scientific work-programme. In the full power scenario, central temperatures of ~20 keV for electrons and ~10 keV for ions with central densities ~2.5 1020 m-3 are predicted in fair agreement by the two models used. Gyrokinetic simulations have been used to validate the models in the DTT range of parameters. As a result of this work, the heating mix was defined, the size of device was increased to R=2.19 m/a=0.70 m, and reference profiles for diagnostic design, estimates of neutron yields and fast particle losses have become available.

INTRODUCTION

- Studying the **controlled power and particle exhaust from a fusion reactor** is a main research topic in the European Fusion Roadmap [1].
- Developing an alternative exhaust strategy, which is crucial to mitigate the risk, is the main task of the new D-shaped superconducting tokamak **DTT** (**Divertor Tokamak Test facility**)[2], with the first plasma planned for 2026.

AIM OF THE STUDY

Performing **integrated modelling** of the foreseen operational scenarios using first principle based transport models and state-of-art modules for heating, fuelling and magnetic equilibrium is of key importance for the optimisation of the various aspects of the DTT. It is required to:

- support the definition of the heating mix,
- support the design of the neutron shields,
- support the assessment of fast particle losses,
- support the design of diagnostic systems,
- help the elaboration of a DTT scientific work-programme.

INTEGRATED MODELLING SET-UP

SCENARIOS

The integrated modelling of various DTT scenarios with **Single Null** (SN) configuration in **H-mode** has been performed. Particularly, the **Full Power** (FP) scenario **steady-state** predictions are crucial for the DTT design.

SIMULATIONS

The simulations predict steady-state radial profiles of electron and ion temperature, density, current density, rotation, power depositions, and impurity densities in the region $\rho_{tor} < 0.94$. The pedestal was calculated using the EPED1 model. Integrated runs have been primarily done using the **JINTRAC**[3] suite of codes and in some cases using the **ASTRA**[4] transport solver with a mixed ASTRA–JINTRAC approach.

TURBULENT TRANSPORT

Inside the top of the pedestal, the turbulent heat and particle transport is calculated by the **Trapped-Gyro-Landau-Fluid (TGLF)** [5] or **QuaLiKiz (QLK)**[6] quasi-linear transport models. The two most recent versions of TGLF have been used: **TGLF SAT1-geo**, released in November 2019, and **TGLF SAT2**, released in January 2021. In runs with QLK, two versions have also been employed: the new **standard QLK** release and an **“ad hoc” QLK** version, specifically developed for DTT to match gyrokinetic predictions in TEM dominant conditions.

Table 1: DTT Parameters
$B_{tor} \leq 6$ T
$I_{pl} \leq 5.5$ MA
$t_{pulse} \leq 100$ s
R = 2.14 m
a = 0.65 m
$P_{sep}/R \approx 15$ MW/m

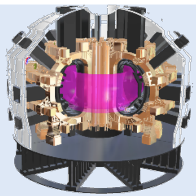

Figure 1: DTT device.
Drawing reproduced from [2].

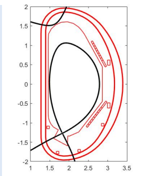

Figure 2: Plasma shape of the SN DTT scenario.

HEATING SYSTEMS

Following simulations of several alternatives (some listed in Table 2) , the OPTION D has been chosen as **reference heating mix for full power scenarios.**

- The choice of higher NNBI energy (together with maximum allowed injection angle) was driven by the need of minimizing fast particle losses and allowing resonant excitation of Alfvenic waves.
- The choice of higher ICRH power was driven by the need of central ion heating and fast ions, to alleviate the $T_e > T_i$ tendency due to high ECH power.

Heating option	NBI energy/ power	ECH Power (MW)	ICH Power (MW)	τ_E (SAT1-geo)	H98Y	β_{pol} $therm/tot$	$\frac{\text{Wfast}}{\text{Wth}}$	$\frac{Te0}{Ti0}$	DD neutrons
A	400 keV 15 MW	32	4	0.26 s	0.89	0.57 / 0.61	6.7%	1.92	1.28e17 s^{-1}
B	400 keV 7.5 MW	40	4	0.26 s	0.91	0.59 / 0.61	3.7%	2.04	0.83e17 s^{-1}
D	500 keV 10 MW	33.6	8	0.27 s	0.95	0.54 / 0.57	6.0%	1.91	1.31e17 s^{-1}

Table 2: simulated plasma performance for different options of heating mix

PLASMA PROFILES FOR FULL POWER SCENARIO

Radial profiles predicted for the reference full power scenario option D are shown in Figure 3. The 4 models agree reasonably outside ρ_{tor} =0.4, whilst QLK features much flatter density inside ρ_{tor} =0.4, which is the region of very high ECH power density. According to gyrokinetic simulations, TGLF is more reliable in this TEM dominated region.

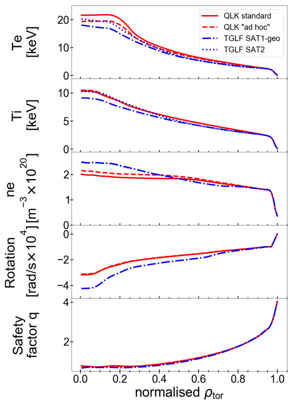

Figure 3: Radial profiles of the reference Full Power SN scenario.

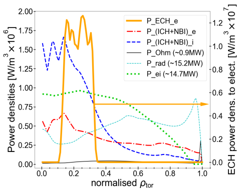

Figure 4: Radial profiles of power densities.

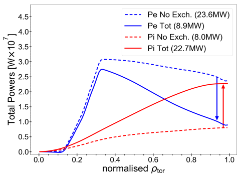

Figure 5: Radial profiles of electron and ion power.

- T_e significantly larger than T_i.
- n_e profiles rather peaked
- NBI: 60% P_e 40% P_i
- ICH: 20% P_e 80% P_i
- Large collisional exchange
- To have a reference q_{95} value >3, the DTT size has been increased to **R=2.19m** and **a=0.70m**.
- Neutron rate is compatible with present design of neutron shields.

GYROKINETIC SIMULATIONS

- To identify the most reliable prediction inside ρ_{tor} =0.4, linear and nonlinear gyrokinetic simulations have been performed at ρ_{tor} =0.32, using the local flux tube version of the GENE code [7] and the parameters of the SAT1geo simulation.
- Linear analysis shows that at this radius the dominant mode is the Trapped Electron Mode (TEM).
- At zero particle flux GENE predicts a sizeable density peaking R/L_n~1.8, closer to TGLF. The very flat QLK n_e profile is not validated.

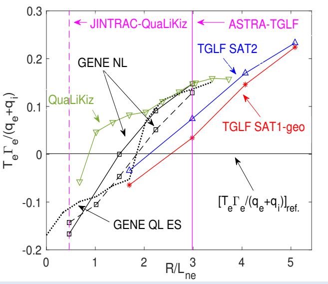

Figure 6: Particle to heat flux ratio vs R/L_n from GENE, TGLF, QLK.

CONCLUSIONS

- Integrated steady-state simulations of DTT scenarios are now available to support DTT design and the development of a scientific work-programme..
- TGLF and QLK give similar predictions in the region ρ_{tor} >0.4, whilst in the inner TEM dominated region TGLF has to be retained as more reliable, according to gyro-kinetic simulations.
- The machine size has been increased and the heating mix has been defined.

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