Time Dependent Advanced Scenario Modelling on Present and Future Fusion Devices

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1. Introduction

The development of reactor-relevant plasma scenarios is one of the central challenges in the path toward fusion energy. Among the advanced tokamak (AT) regimes currently under investigation, the high poloidal beta (β_p) scenario stands out as a particularly promising candidate, combining high energy confinement $H_{98(y,2)}$ ~ 1.5 with operation at or above the Greenwald density limit [1]. Achieving such conditions represents a significant step toward the high-performance, steady-state operation envisioned for future reactors such as ITER, DEMO, and beyond.

The defining physical feature of the high β_p scenario is the formation of an internal transport barrier (ITB) at large normalized radius ($r/a \geq 0.5$). Unlike conventional ITBs located near the plasma core, this large-radius ITB is particularly attractive because it also associated to similar core temperatures. The ITB formation is closely linked to the current profile shaping during the scenario formation phase, which establishes a region of favorable (weak or reversed) magnetic shear that suppresses ion-scale turbulence, resulting in a reduced anomalous transport.

First demonstrated in JT-60U [2] and subsequently developed extensively in DIII-D, the high β_p scenario has now been tested in a growing number of devices, including EAST, ASDEX-U, JET, and more recently MAST-U. This broad experimental basis, spanning different machine sizes, aspect ratios, and heating configurations, provides a robust physics foundation. Nevertheless, many open questions remain regarding the precise conditions required for ITB access, the density evolution toward and beyond the Greenwald limit, and the long-term sustainment of the ITB during the flat-top phase.

In this work, we start addressing these questions through time-dependent integrated modelling, using the ASTRA–TGLF framework [3] applied to DIII-D discharges as a primary validation basis, and subsequently extending the lesson learned on DIII-D to support the design of a high β_p scenario for the DTT tokamak, currently under construction in Frascati, Italy.

2. Integrated Modelling Framework

The modelling presented here employs the ASTRA transport code coupled with the quasi-linear gyrokinetic model TGLF (Trapped Gyro-Landau Fluid), exploiting NCLASS and FACIT to compute the neoclassical related quantities [3]. This integrated framework allows the self-consistent, time-dependent evolution of plasma profiles, including in general, temperature, density, impurities, and current, from the current ramp-up phase through the flat-top, capturing the interplay between transport, heating, and current diffusion.

TGLF(SAT2) provides a computationally efficient yet physically accurate description of ion and electron-scale turbulent transport, including the effects of magnetic shear, pressure gradients, toroidal rotation, and electromagnetic stabilization. Its quasi-linear nature makes it suitable for the long time-scale simulations required to model the full discharge evolution, while retaining the key physics mechanisms identified by more expensive nonlinear gyrokinetic calculations.

Steady state and time dependent simulation of the DIII-D pulse 190904 have been performed to test the prediction capability of the framework and to identify the related modelling settings. The prediction of 5 channels i.e. electron temperature and density, ion temperature, light and heavy impurities, alongside with the self-consistent calculation of the plasma effective charge Z_{eff} and radiation P_{RAD} has been performed before extension to other devices.

3. Analysis of the 190904 DIII-D high β_p pulse

The selected DIII-D discharge features Ip/Bt=0.75MA/1.85T, with about 10 MW of auxiliary power from NBI in the steady state phase, associated to total P_{RAD} = 1.8MW. The DIII-D intrinsic light impurity is Carbon, while W has been selected has heavy impurity. Despite no W source are present in DIII-D, we consider that the transport properties of W and Mo (the DIII-D intrinsic heavy impurity) are reasonably similar to provide insight on the high-Z impurity behavior. Additionally, the study of W provides direct information for the future machines with full W wall, as DTT and ITER.

In this work we perform core transport analysis in the region ρ_t=[0; 0.9], while the pedestal is taken from the experimental data. All simulations are performed with the safety-factor profile fixed in time to the experimental kinetic EFIT reconstruction; consequently, no current diffusion equation is solved. This choice is motivated by the numerical instabilities encountered in the ASTRA fixed-boundary equilibrium solver when initializing the simulations with the high-q_{min}, weakly reversed q profile, characteristic of this scenario. Also the toroidal velocity is fixed at the experimental value and no momentum transport is performed.

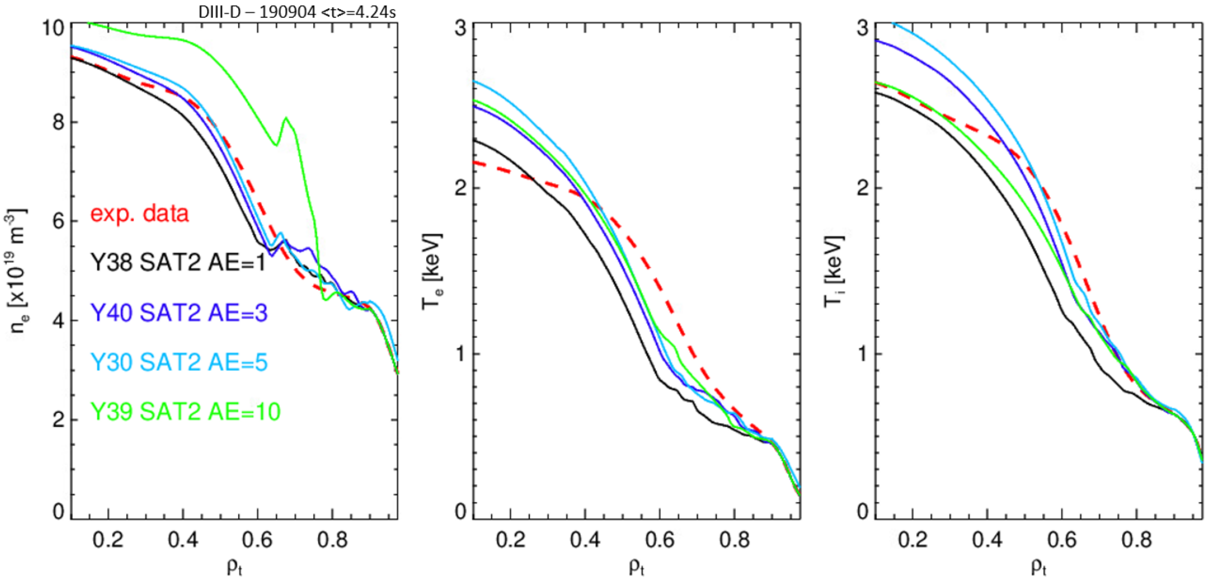

Figure 1 predicted profiles of the steady state ITBs for different levels of ExB stabilization (AE=ALPHA_E parameter I TGLF settings). The experimental profiles are also shown for comparison.

3.1 Steady-state DIII-D analysis

The DIII-D high β_p plasma features ITBs at large radius which stay steady during the current flattop. For the pulse 190904 we select the time window [4.08; 4.5] s where a fully developed barrier is present on the main plasma quantities, located in the region ρ_t=[0.5;0.8]. The results of the predictive analysis shows that the ASTRA-TGLF(SAT2) framework with standard settings is able to sustain a steady barrier which turns out to be in good agreement with the n_e data, while a weaker barrier for the temperatures is obtained. Figure 1 reports the comparison between the experimental fits (dashed red line) and the predicted profiles (solid black lines). In the same figure also the results of simulation with artificially increased ExB stabilization is reported: the parameter ALPHA_E (AE) in TGLF is scanned in the range

[1,3,5,10], showing that the values for optimal agreement are AE= 3, 5, while AE=10 overshoots the density gradient and consequently suppresses the temperatures.

A quasi-linear analysis of the flux spectra computed by TGLF shows that the AE=3 choice is in agreement with the experimental data, still retaining a residual turbulent transport, while AE=5 full suppress the turbulence. The analysis also confirms that the primary driver of ITB formation is the suppression of ion-scale turbulence, predominantly ITG (Ion Temperature Gradient) modes. TGLF calculations show a how the reduction in the linear growth rates of ITG modes in the barrier region, consistent with nonlinear gyrokinetic studies, allows the pressure gradient to steepen, further reinforcing the stabilization through the Shafranov shift and the associated magnetic geometry effects.

The sensitivity of the results on the radiation and toroidal velocity v_{TOR} profiles have been studied: the P_{RAD} profile only mildly affects the prediction, with a slightly stronger effect on T_e. Three approaches were used: (i) self-consistent radiation and impurity transport modelling, (ii) bolometric inversion, and (iii) spectroscopy-based impurity content combined with a radiation model. The self-consistent approach yields results intermediate between the two experimental estimates. Regarding the v_{TOR} dependence, simulations with v_{TOR}=0 have been performed: the results show that removing the v_{TOR} modifies both the magnitude and the radiale electric field E_r profile, while the E_r well is preserved in the ITB region. The E_r well, which is responsible for turbulence suppression through E×B shear, is therefore sustained by the pressure gradient and poloidal velocity contributions. These results indicate that the scenario is not critically dependent on external torque injection, which is encouraging for its extrapolation to low-rotation devices such as ITER and DTT.

3.2 Time-dependent analysis of the DIII-D barrier formation and evolution

The time interval between 3.30 s and 3.65 s was selected for the time-dependent analysis because, during this phase, the density ITB is already fully established, whereas the temperature ITBs, although present, exhibit a stationary foot and an oscillating top. The choice of initializing the simulations with a pre-existing density ITB is motivated by the fact that the modelling was not able to trigger the formation of the density barrier from a non-ITB density profile. In contrast, as discussed in the following sections, the formation of the electron and ion temperature ITBs is successfully reproduced. During the selected time interval, the oscillatory behavior of the temperature ITBs is temporally correlated with variations of the magnetic shear at the top of the barrier ($\rho_t \approx 0.55$). The temporal evolution of the temperature ITBs is shown in Fig. 2. The black solid lines represent the simulated T_e and T_i values at two radial locations, ρ_t=0.5 and 0.8, while the red dashed lines correspond to the experimental measurements at the same locations. Starting from temperature profiles without ITBs at t=3.30 s, the simulations successfully reproduce the formation of the temperature barriers, reaching the experimental values at t=3.47 s. Then, following the increase in the mid-radius magnetic shear already mentioned, the barrier weakens, although the simulated reduction is larger than that observed experimentally. These results demonstrate the capability of the model to reproduce the formation of the temperature ITBs, provided

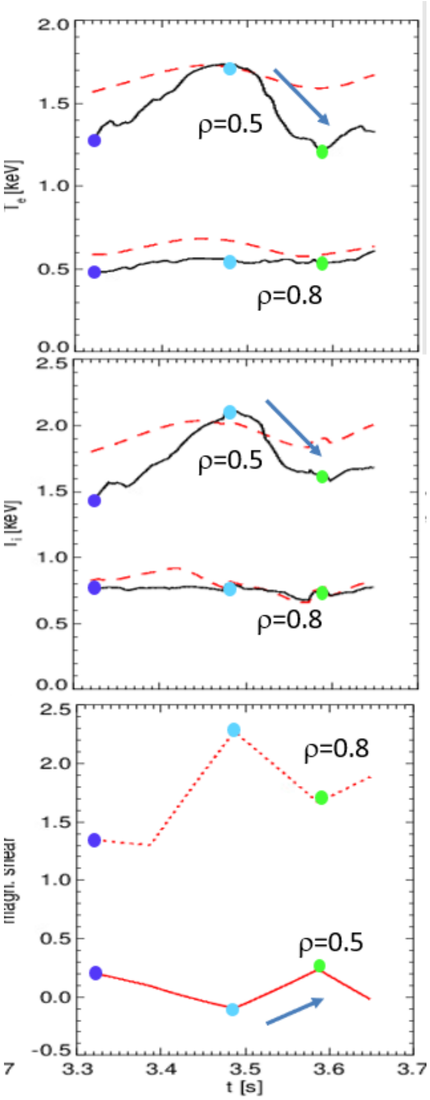

Figure 2 time-traces of the modelled (solid black) and experimental (red dashed) temperatures evolution at 2 radial locations. The magnetic shear at the same location is also shown.

that the density ITB is already established, and to capture the barrier dynamics associated with changes in the magnetic shear.

4. Design of a High βp Scenario for DTT

The Divertor Tokamak Test (DTT) facility, currently under construction at ENEA Frascati, represents a major new European fusion device designed to address plasma-exhaust and divertor physics at reactor-relevant power loads [4]. With a major radius of R = 2.19 m, magnetic field B_t = 5.85 T, and plasma current up to 5.5 MA, DTT will operate in a parameter regime intermediate between present devices and ITER. In its early phase, with limited I_p/B_t = 1.5MA/3.0T and large current drive capabilities (mainly ECCD), it represents an ideal testbed for advanced scenario development.

Applying the physical understanding gained from DIII-D, we use the ASTRA–TGLF framework to design a high-β_p scenario for DTT. In this simulation, the evolution of the current density is not computed, and an interpretive q-profile, based on the DIII-D steady-state solution, is imposed. Independent JINTRAC analysis have been performed to identify the EC settings compatible with the desired q profile. Since no info on the pedestal are available (Europed computation are ongoing), we first assess the sensitivity of the results to the pedestal-top temperature values. Imposing T_e and T_i at the pedestal top in the range [200–500] eV leads to an unphysical density buildup at the core boundary (ρ_t=0.9), resulting in a very high core density (exceeding the target f_{GW}=1.1) and a correspondingly cold plasma core, with $T_e(0)\approx 2T_i(0)\approx 4$ keV. Additionally, although the simulation is initialized with a density ITB established at ρ_t=0.8, this structure is rapidly eroded, and no ITBs are sustained in the converged solution. Increasing the pedestal-top temperatures to 700 eV, the initial density ITB remains stable and temperature ITBs develop at ρ_t=0.8. This is a preliminary but encouraging result, demonstrating the feasibility of a high-β_p scenario in DTT, with parameters in the range $H_{98(y,2)}\sim 1.7$ and $\beta_p \sim 2.4$. The spontaneous formation of electron density, electron temperature and ion temperature ITBs is also observed, as shown in fig. 3. Indeed, starting from relaxed profiles with no ITBs, a positive feedback loop is established: reduced magnetic shear at ρ_t=0.55 lowers turbulence, which enhances profile gradients and leads to the formation of an E_r well. This further suppresses turbulence, ultimately resulting in a self-sustained ITB.

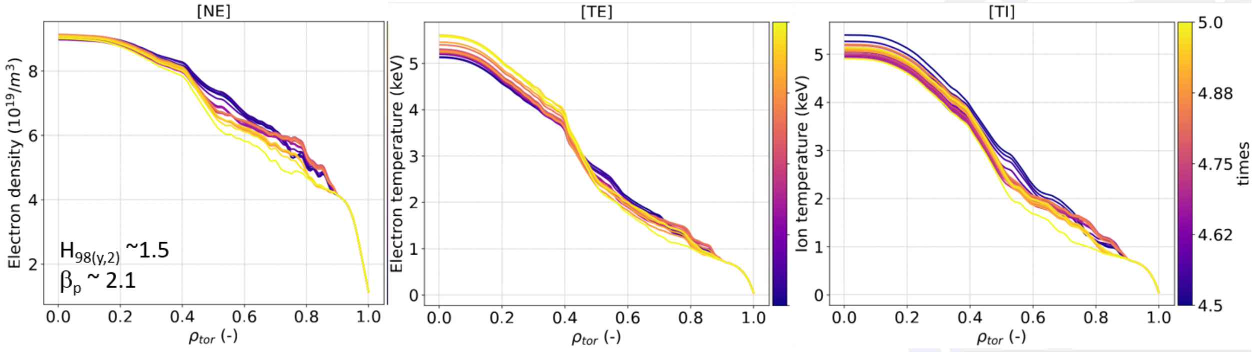

Figure 3 radial profiles evolution of the DTT high β_p plasma. The temperatures ITBs spontaneously build up fat the q_{min} location, provided sufficiently high pedestal top temperatures.

Acknowledgements

Work supported by US DOE under DE-FC02-04ER54698, and carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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