Preparing for First Diverted Plasma Operation in the ST40 High-Field Spherical Tokamak

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Abstract

The ST40 tokamak [1], built and operated by Tokamak Energy, has recently been upgraded with upper and lower divertors to enable double null diverted operations with up to 1MA plasma current and 2MW neutral beam heating. ST40 is a high field spherical tokamak (ST), B_T=3T at R_0=0.4m with a goal to extend the high field spherical tokamak physics basis. Crucially, transport and confinement in high field, high temperature STs will be explored in support to the design of next step STs [2]. Extensive modelling activities have been undertaken to prepare for the exploitation of ST40. A range of plasma equilibrium in double-null configuration have been designed along with detailed scenario modelling, including 1.5D transport simulations and 2D SOL modelling. Gyrokinetic analysis has been performed to assess the level of expected turbulent transport. Building upon the NSTX pedestal database the pedestal width and height in the high performance ST40 scenarios have been predicted. MHD stability analysis and beta limit have been assessed. ST40 will be initially operated in hydrogen with up to 1.5 MW NBI (0.8MW at 55kV and 0.7MW at 25kV). The heating systems will be upgraded in view of the follow up campaign in deuterium, with 2MW, 55kV NBI and around 1.6MW 105/140GHz ECRH. Careful analysis of the power deposited in the divertor during high performance operation has also been carried out.

Scenario Modelling

The ST40 divertor configuration includes a vertical plate with Mo coated tiles and divertor poloidal field coils. This will be upgraded at the end of the present experimental campaign to include further divertor coils and a horizontal plate. Equilibrium in the present and upgraded configuration have been extensively studied with the FIESTA and FreeGS codes, examples are shown in Figure 1.

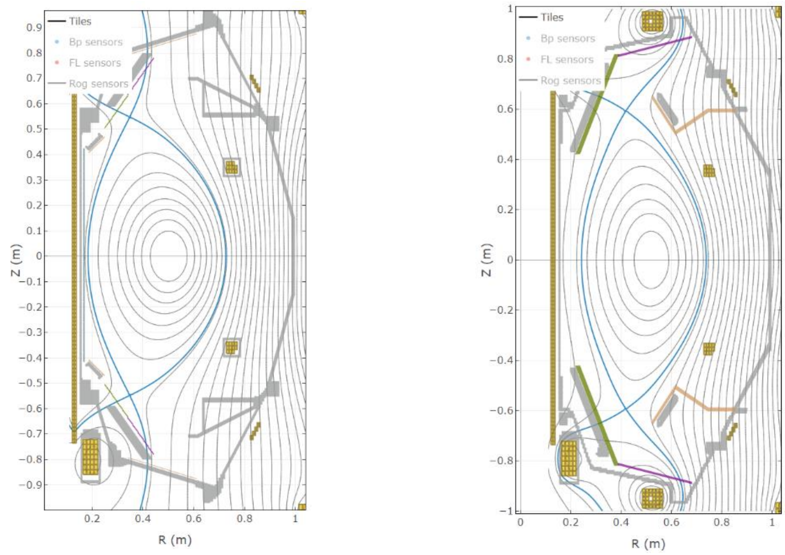

Figure 1: Equilibrium poloidal flux surfaces in present divertor configuration (left) and upgraded divertor configuration (right)

The upgraded divertor will allow to sustain the heat loads during higher plasma current (up to 2MA), steady state operation (up to 1s of current flat top). Plasma scenarios in the two configurations have been modelled using an integrated workflow including equilibrium, transport, MHD stability, Gyrokinetic analysis, 2D SOL/divertor codes. H-mode operation has been assumed and pedestal characteristics have been projected from observation in MAST, NSTX and JET. In particular, the NSTX scaling of the pedestal width described in [3] has been adopted. The top of the pedestal density has been optimized to mitigate central penetration of the NBI leading to peaked / potentially MHD unstable pressure profiles. Top of the pedestal temperatures ranging from 1 keV (for Ip=1MA) to 3 keV (Ip=2MA) have been found to be consistent with pedestal peeling ballooning stability limit. The pedestal width ranges between 0.09 and 0.11 $\Delta\psi$. For the transport modelling we have used the ASTRA code with fixed boundary condition at the top of the pedestal and BgB model [4] for the core. The choice of the transport model, that proved to reproduce START and MAST discharges, is dictated by the lack of validated first principles models for STs. The complete model adopted in the simulation is as follow: $\chi_e=\chi_{eNC}+\chi_{eBgB}$; $\chi_i=\chi_{iNC}+0.4\chi_{iBgB}$; $D=D_{NC}+\chi_{eBgB}$; $\chi_\phi=5\chi_i$; It is found that χ_ϕ larger than χ_i is needed to prevent high rotation frequencies to appear in the simulations. NBI power deposition is calculated in ASTRA with NUBEAM and verified with ASCOT5 standalone. The resulting profiles are shown in Figure 2 for the Ip=1MA, P_{NBI}=1.5MW and Figure 3 for the Ip=2MA, P_{NBI}=2.0MW cases.

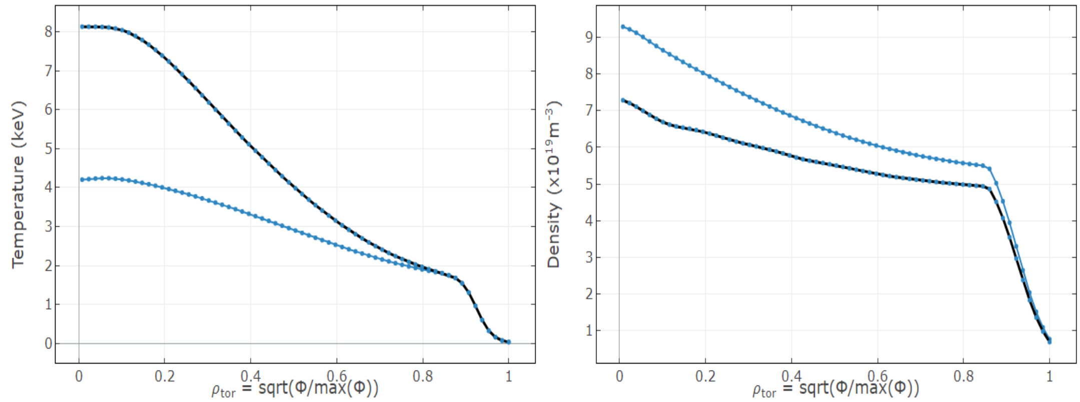

Figure 2: Steady state ion (dark blue) and electron (light blue) temperature (left) and density (right) profiles for the 1MA, 2.6T, 1.5MW plasma, present divertor configuration. P_{NBI}, H, 0.8MW, 55kV and 0.7MW, 25 kV.

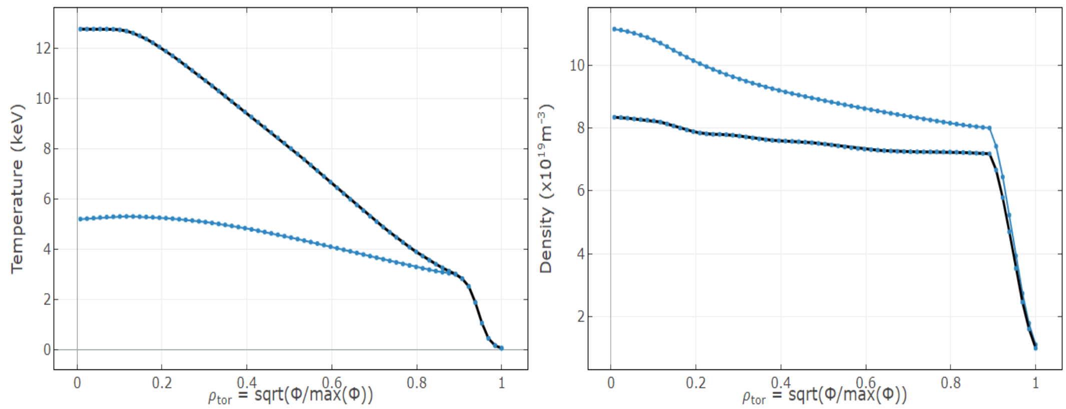

Figure 3: Steady state ion (dark blue) and electron (light blue) temperature (left) and density (right) profiles for the 2MA, 2.4T, 2.0MW plasma, upgraded divertor configuration. P_{NBI}, D, ~2MW, 55kV

The combined central NBI deposition and hot core, lead to a safety factor below one on the magnetic axis. MHD stability analysis with KINX and MISHKA has been carried out for both the pedestal and the core; a sawtooth model has been included in the ASTRA simulation. KINX analysis shows that the growth rate of the vertical instability for these elongated plasmas is below 200 s^{-1}, well within the range of the ST40 Plasma Control System (PCS). Gyrokinetic analysis of the two scenarios has been carried out with GS2 and GENE. The profiles are found broadly stable and mild ITG modes have been identified in the gradient region (ρ_{tor}=0.5) leading to estimated mixing length transport coefficients of the order of 0.3m^2/s, in agreement with the BgB model. Extensive gyrokinetic simulations are ongoing to verify the BgB assumption. The effect of additional 0.8 -1.6 MW of ECRH heating has been investigated with the GENRAY and CQL3D codes. It is found that central deposition leads to peaked electron temperatures up to 60% higher than those in Figure 2, 3. Sustainability of divertor heat loads is crucial for longer pulse operation and have been analyzed with the SOLPS code. The power deposition profiles at the outer divertor target for the 2MA scenario is shown in Figure 4. Condition for detachment has been investigated and found to occur at separatrix densities above 2.5 10^{19} m^{-3}. Neutral fueling and divertor pumping capability have been investigated. Finally, assessment of the induced currents and forces on the vessel component in the event of VDEs has been studied with MAXFEA / ANSYS. It has been found that forces are well below those allowed for safe operation.

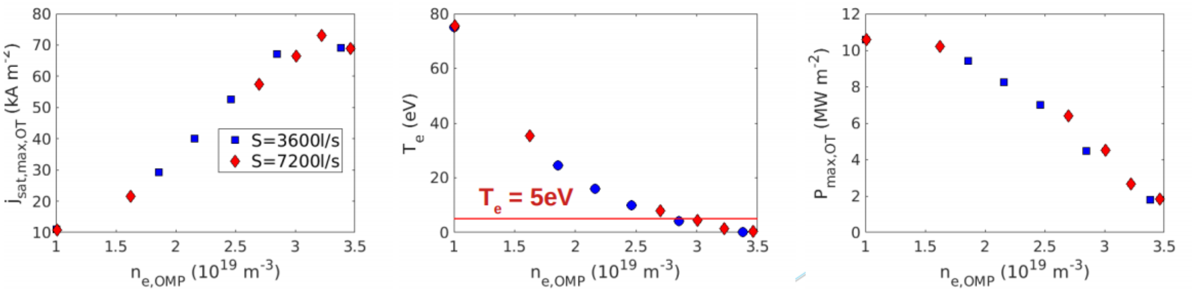

Figure 4: Left to right: saturation current, maximum Te and power at the outer divertor target for increasing values of the separatrix density in the 2MA,2.4T scenario.

Conclusion

Integrated modelling of ST40 1MA / 2MA scenarios has been carried out in preparation of DND operations. Within the assumptions of the models, it has been found that stable, steady state ion temperatures above 8keV can be achieved and sustained in 1MA, 2.6T, 1MW plasmas; ion temperatures of above 10 keV at densities of the order of 1.2 $x10^{20}$ m^{-3} can be achieved and sustained in 2MA, 2.4T, 1.5MW double null diverted plasmas. The addition of 0.8 – 1.6 MW of ECRH will allow to achieve electron temperatures above 5keV. Confinement times of 70 / 100ms (H_{98}=2.4 / 1.9; H_{NSTX-E}=0.9 / 1.1) [2, 5] have been predicted in the 1MA / 2MA scenarios respectively. Pellet injection in the 2MA scenarios will be explored as an actuator to further boost nTτ above the Lawson threshold for burning plasma conditions.

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