ITER Hybrid Scenario optimization by integrated modelling

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Introduction

The ITER "hybrid" advanced scenario aims to provide a discharge with an extended burn time ($> 1000\ s$) while still maintaining a moderately high fusion power ($P_{fus} > 350\ MW$) and significant α-particle heating ($Q > 5$), without the drawback of the stringent active control requirements which characterize steady-state scenario discharges [1]. The extended burn time is achieved via reducing the flux consumption by operating at both reduced current ($I_p = 11 - 13\ MA$) and a higher non-inductive current fraction ($\sim 50 - 60\%$) compared to the ELMy H-mode ITER reference scenario. In this work, we utilize the CRONOS [2] integrated modelling code in order to make predictions on the ITER hybrid scenario, with particular emphasis on gauging the relative merit of various heating and current drive (H/CD) mixes, informing the choices of proposed ITER H/CD future upgrades. Towards this end, the GLF23 [3, 4] first-principles based transport model is applied for energy transport prediction.

Modelling techniques and methodology

The central point of this work is assessing and comparing the ability of various heating and current drive systems to provide a 'satisfactory' hybrid scenario for ITER. The target, 'satisfactory' hybrid scenario that we define here is one that provides a fusion power performance of $P_{fus} = 350\ MW$, $Q > 5$, $P_{loss} <\sim 110 MW$, and $t_{discharge} > 1000\ s$. In ITER, deleterious NTM's are predicted to be unstable even for $\beta_N > 1.8$ [5]. We assume a $\beta_N > 1.8$ scenario without transport reduction from NTM's, or alternatively assume that no auxiliary power need be diverted to NTM control. Thus, we aim for $q > 1$ throughout the simulations, or at least to maximize the time until a $q = 1$ surface forms and/or minimize the $q = 1$ radius at stationary state, in order to avoid NTM triggering sawteeth.

The core of CRONOS is a 1.5D transport solver, whereby 1D current diffusion, particle, energy, and momentum transport equations are solved up to the separatrix, self consistently with 2D magnetic equilibrium. The main assumptions made are as follows: Equal ratios of D and T are assumed. Only electron and ion heat transport is predicted, whereas the density profile is prescribed flat. Rotation is set to zero - a conservative assumption. GLF23 is applied with α-stabilization off. Scenarios are considered with prescribed pedestal heights ranging from $3-5\ keV$. Typical Z_{eff} values of ~ 1.7 are taken.

Results

The H/CD mix of NBI and EC was found to provide the best combination of a high degree of non-inductive current drive, due to the NBI, as well as q-profile shaping capability for core confinement maximization, through the deposition radius flexibility inherent in the EC system. A summary of the optimum results achieved for pedestal heights between $3-5\ keV$ are displayed in table 1. 'Optimum' in these cases refers to a maximization of t(q=1) and minimization of x(q=1) at the target fusion power of $P_{fus} = 350\ MW$, achieved by varying the components and settings (such as ECCD launcher angles) of the H/CD mix.

Table 1: Summary of results for optimum performance scenarios for various T_{ped}. Values are quoted at t=3000 s for the $T_{ped} = 4,5\ keV$ cases, and at t=1200 s for the $T_{ped} = 3\ keV$ case.

T_{ped}	I_p [MA]	f_G	NBI/EC	f_{boot}/f_{ni}	P_{fus} [MW]	Q	β_N	H_{98}	P_{loss} [MW]	t(q=1)	x(q=1)
5	11.5	0.9	33/17	0.36/0.62	365	7.2	2.15	1.23	99	∞	0
4	11.8	0.95	33/37	0.31/0.59	351	5	2.02	1.08	114	1050	0.02
3	12.2	0.95	16.5/50	0.26/0.47	348	5.2	1.82	0.98	109	360	0.44

These results state that a satisfactory hybrid scenario may be achieved - where even at stationary state $x(q=1) = 0.03$ - with a pedestal of 4 keV (assuming a EC upgrade to 37 MW). For a pedestal of $5\ keV$ a $q > 1$ profile can be maintained at stationary state with the currently designed ITER H/CD mix. For a $3\ keV$ pedestal, no satisfactory hybrid scenario may be obtained: a q=1 surface appears rather early in the discharge from t=360 s, and x(q=1)=0.44 by t=1200 s. The flattop loop voltage of the $T_{ped} = 5/4/3\ keV$ cases is $\sim 21.5/31/49.8\ mV$ respectively, calculated as an average up to 1200 s. For the $4\ keV$ and $5\ keV$ cases particularly, this loop-voltage may be sufficiently low to allow a flattop of up to 3000 s, provided that flux consumption

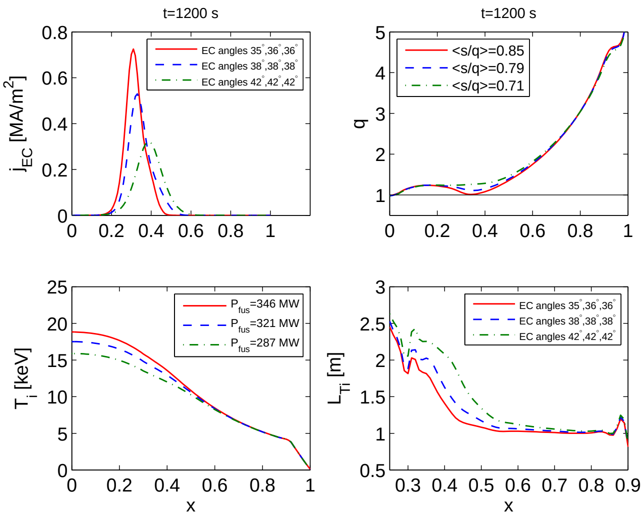

Figure 1: GLF23 predicted sensitivity of fusion power performance to ECCD deposition radius

is saved during the ramp-up phase by application of early heating [6].

The degree of ITG dominated turbulence is predicted to increase with decreasing s/q, (for $s - \alpha > \sim 0.5$) [7]. This leads to a sensitivity of the predicted fusion performance to the position of the deposited ECCD, as can be seen in figure 1. The volume averaged s/q parameter ($< s/q >$), as displayed in the figure, is compared in the region x=0.4-0.9, which corresponds to the region up to the pedestal in which $s > \sim 0.5$.

Replacing some or all ECCD with LHCD leads to a significant reduction in predicted fusion performance due to far off-axis current drive lowering the average s/q. This can be seen in figure 2. The decrease in fusion power in the LHCD case is almost purely due to the now non-optimal q and s profiles, and not due to the reduction in heating at the more inner radii where the ECCD power is deposited. This is a typical consequence of the highly stiff GLF23 model, where pure heating has a minor influence on the temperature profiles, and the primary influence of the H/CD mix on the temperature gradient lengths is through the current drive q and s profile shaping, setting the degree of GLF23 predicted turbulence. We note however that the capability of LHCD of driving far off-axis current drive may still be a vital tool for the ITER steady state scenario [8].

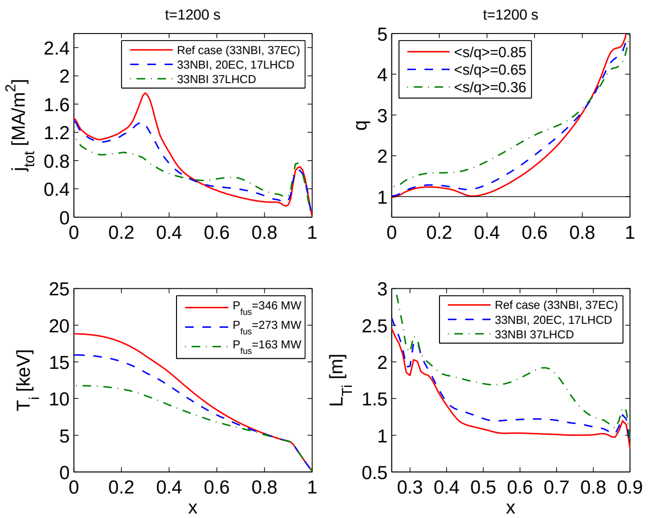

Figure 2: GLF23 predicted sensitivity of fusion power performance to replacing some or all ECCD with LHCD

In figure 3 we summarize the predicted dependence of P_{fus} on $< s/q >$ in the ECCD and LHCD simulations described above, where I_p, f_{GW}, and total P_{aux} have been kept constant. The strong correlation between $< s/q >$ and P_{fus} is a consequence of the linear relationship between s/q and the normalized inverse ion temperature gradient scale length, R/L_{T_i}, which can be seen in the right panel of the figure. This linear relationship can be expected

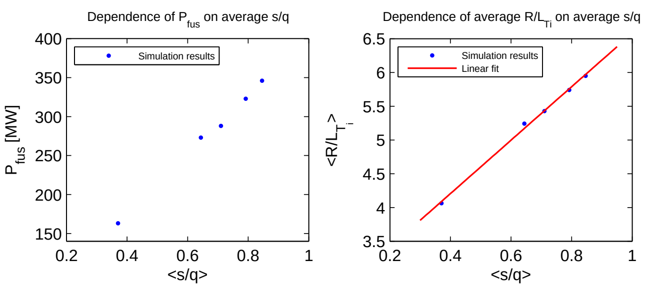

Figure 3: Correlation between volume averaged s/q and fusion power

from ITG dominated turbulence in the flat density limit, particularly since in our case neither the T_i/T_e nor the Z_{eff} profiles vary by more than 5% between the various simulations in the dataset, further isolating the instability threshold dependence on the q-profile.

Finally, we note that replacing 17 MW of EC from the reference case with 17MW of ICRH (53 MHz 2nd T harmonic) leads to both a marked decrease in $t(q=1)$ to 420 s, and an increase in the stationary state $x(q=1)$ to 0.13, compared to the optimum $T_{ped} = 4\ keV$ case. The reason for this is twofold: (i) no current is being driven by the ICRH scheme assumed here, (ii) the central ICRH electron heating raises T_e such that the resistivity and thus current profile is sharper, decreasing q near the magnetic axis.

Discussion and conclusions

A study of the H/CD mix for the ITER hybrid scenario has been performed, with the GLF23 anomalous transport model predicting transport in the energy channel, and for a range of prescribed pedestals. According to GLF23, the key point for scenario optimization is tailoring the q-profile with a judicious choice of current drive, in order to minimize the predicted q and s dependent transport. This then allows a minimization of n_e and thus I_p needed for the scenario target $P_{fus} = 350\ MW$, raising the q-profile towards 1 as desired in a hybrid scenario. For $T_{ped} = 5\ keV$, $q > 1$ was predicted to be maintained at stationary state with a 33/17 MW NBI/ECCD mix, with Q=7. For a more conservative $T_{ped} = 4\ keV$, $x(q=1) = 0.03$ was predicted at stationary state with a 33/37 MW NBI/ECCD mix, with Q=5. Including LHCD or ICRH in the H/CD mix is predicted to be sub-optimal. The inclusion of LHCD reduces confinement due to deleterious shaping of the q-profile. The inclusion of ICRH, particularly in a stiff model, does not lead to significantly increased fusion power and furthermore does not contribute to the non-inductive current fraction. An upgrade of the ITER EC system to 40 MW is thus predicted to be highly beneficial for the hybrid scenario.

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