Modeling development for control for ITER low-activation scenarios

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Abstract

The final design of the ITER poloidal-field coil system converged after recent design reviews leading up to the start of construction. Significant effort has been spent on modeling details of the baseline 15MA inductive discharge and recent exploration of advanced inductive (or hybrid) and steady state scenarios. However, the early operation of ITER will rely on non-activation scenarios to validate performance of heating and current drive systems, diagnostics and plasma control before going to full operation. In this paper, we present results from a new effort to define and develop a low activation scenario and demonstrate its performance.

1.0 Introduction

Recent modeling of the baseline inductive operation, 15MA, Q=10, P_{fus}=500MW for 400s duration burn, has included all modifications to the ITER coils, first wall and power supplies and provides a set of credible scenarios within the predicted operating space [1, 2]. Modeling of advanced operation [3] has been initiated with initial results [4] indicating the potential for development of successful alternative performance scenarios at Q=5 in long pulse (1000s) or steady-state. Additional modeling efforts are needed to develop the Plasma Control System (PCS) for which a conceptual design effort has recently been initiated [5]. The early operational phase of ITER will rely on scenarios where we wish to limit machine activation and tritium inventory during validation of new systems and the PCS before going to full deuterium-tritium (DT) operation. In parallel with on-going CORSICA [6] simulations of advanced scenarios, we are using simulations to develop low-activation scenarios and to explore their controllability. We present an initial look at ITER operation at half plasma current (I_P=7.5MA) and half toroidal magnetic field (B_T=2.56T) so as to estimate the performance achievable and the amount of tritium produced and, thus, the activation resulting from operation in deuterium (D) rather than non-activation operation in helium.

2.0 Tritium build-up

ITER operation with DD allows for a more direct comparison in benchmarking expected performance with the significant experience obtained in the presently operating tokamaks. Early operation at half I_P and B_T significantly reduces performance as desired to minimize buildup of tritium produced from DD-fusion reactions and neutron activation of structures. We must reduce activation to a manageable level to more easily modify and upgrade newly installed systems and test the PCS. To begin development of this scenario and estimate the maximum amount of tritium buildup in ITER, we are using free-boundary time-dependent transport simulations with the CORSICA code under the assumption of perfect confinement of tritium (no particle diffusion). The tritium particle source is determined by the fusion reaction rates with tritium production from the reaction $D+D \rightarrow T+p^+$ (DDp) and burn-up $D+T \rightarrow He^4+n^0$ (DT) of the tritium (T) produced from the DD reaction rate where p^+ and n^0 are the protons and neutrons produced in these reactions. The above DDp reaction occurs with roughly 50% probability; the additional reaction rate $D+D \rightarrow He^3+n^0$ (DDn) is also included in these simulations along with the alpha heating power produced in the reactions that is incorporated in the heating of confined plasma species.

In these simulations, we use the Coppi-Tang (C-T) model for thermal transport [7] to determine the electron and ion temperature profiles from applied auxiliary heating and the self-generated heating in the reactions (minimal for these low performance scenarios). This model has been used previously [1,2,4,8] to model ITER operation and provides a robust transport model defined over normalized toroidal flux (ϕ) extending from the magnetic axis to the separatrix as required for the free-boundary control. As is done in simulations at 15MA, we use analytic models for the density profile with a parabolic profile assumed in L-mode and a flat profile in H-mode at peak electron density set to the Greenwald density of $0.51 \times 10^{20}/m^3$. For these simulations, we assume auxiliary heating power (P_{aux}) is applied to the electrons and use an analytic shape heating profile for simplicity and speed. For simplicity in modeling time evolution, it is assumed that the L-H transition occurs when P_{aux} is applied. In figure 1, we show results from a low-activation simulation using P_{aux}=53MW with transport models parameterized as in the 15MA studies [2]. Unlike the 15MA scenario [1,2], there is no

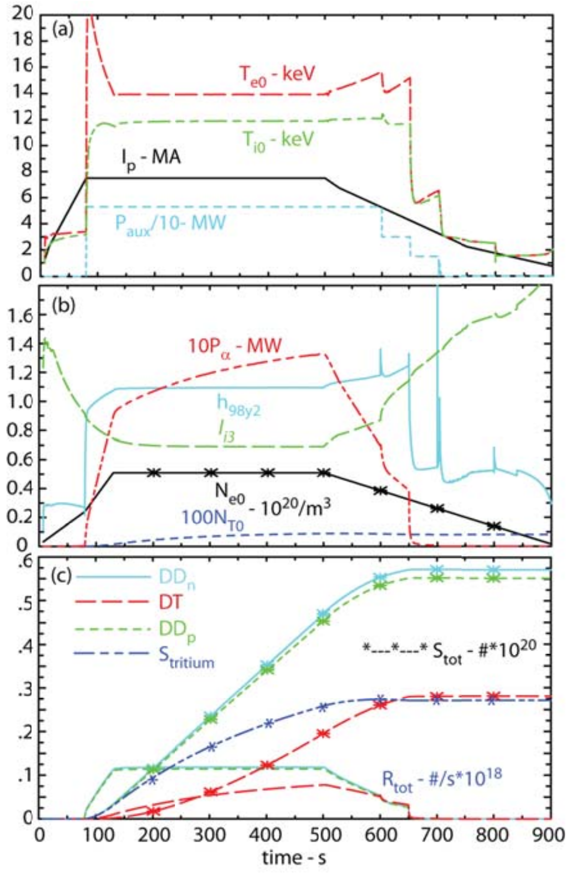

Fig.1 Plasma parameters for the 53MW tritium buildup simulation; (a) I_p, P_{aux} and resulting T_{e0},T_{i0}; (b) prescribed N_e waveform and the buildup of N_T and P_α heating with the resulting h_{98y2} scaling and internal inductance, l_{i3} (c) volume-integrated reaction rates R_{tot}(#/s) and total integrated source S(#) for the nuclear reactions and the tritium particle source .

issue with coil current limitations and early heating power in the current ramp is not needed. In figure 1a, we show the waveforms of the I_P and P_{aux} and the resulting temporal evolution the electron (T_{e0}) and ion (T_{i0}) temperatures at the magnetic axis. The overshoot in T_e at onset of heating is due to the low density (compared with 15MA) at 53MW and can be avoided by controlling P_{aux} during build-up. In figure 1b, we show the prescribed on-axis electron density (N_{e0}) waveform and the resulting buildup of the tritium density from the reaction rates shown in figure 1c. Also shown in figure 1b are the confinement scaling, h_{98y2}, resulting from the C-T normalization, the internal inductance (l_{i3}) and the alpha-heating power (P_α) produced. The profiles obtained during H-mode at I_P=7.5MA (t=450s) are shown in figure 2 including the total current density and q profiles representative of the sawtooth conditions. We note that the resulting tritium density (N_{T0}) is a factor of ~400 less than N_{e0} while P_α is a factor of ~500 lower than P_{aux} as a result of the lower confinement at reduced I_P, B_T and low tritium density from DD reactions and burn up.

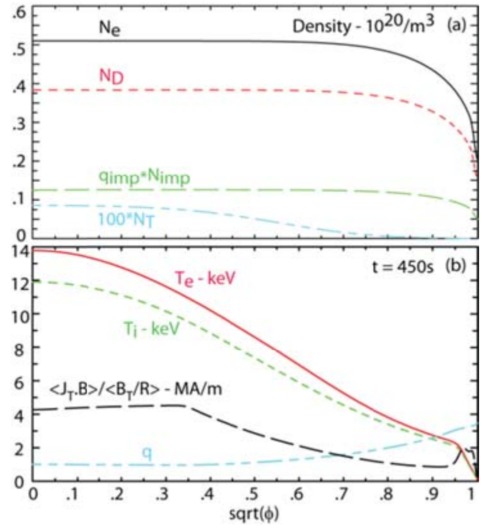

Fig. 2 Profiles Vs flux during current flat top at 430s; (a) input electron and ion density with tritium from buildup, and (b) resulting temperature, current and q

The resulting volume-integrated reaction rates are shown in figure 1c along with the particle inventory (time-integrated rate) and the resulting tritium particle source. The tritium source is just the difference in tritium production (DDp) and burn up (DT) and results in the (peak) tritium density at the magnetic axis shown in figure 1b. The reaction rate profiles are similar to the tritium density profile since we are not simulating tritium particle diffusion in these calculations. At the end of the 400s flattop, we have a total produced tritium inventory of ~0.3x10^{20} particles (~.15mg) from the integrated source shown in figure 1c. We interpret this as the maximum tritium production (with burn-up). In operations, tritium inventory and activation can be reduced by limiting the pulse length in actual experiments.

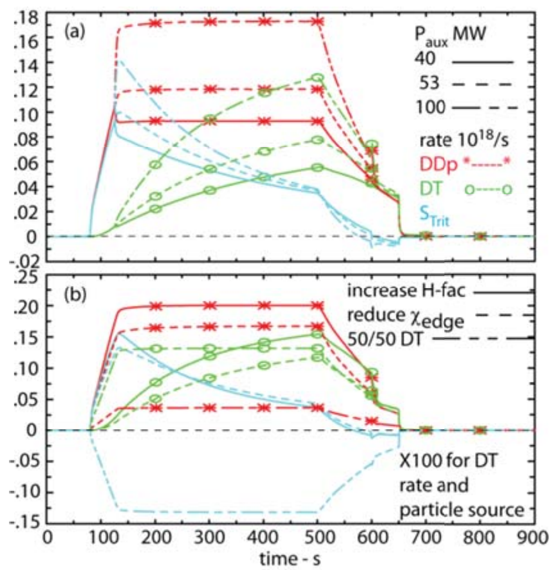

Fig 3. Comparison of reaction rates; (a) P_{aux} heating scan and (b) modifications to confinement and the reference DT operation at I_P/2 and B_T/2

To estimate sensitivity to performance, we have scanned the heating power during flat-top from 40 to 100 MW to determine the variation of tritium production with auxiliary heating power. We show the total tritium production rate (integral over volume) in figure 3a for the power scan. We have also used different performance-level assumptions, figure 3b, to simulate a 25% increase in the core confinement in the C-T model and also a factor of 2 reduction in pedestal transport to increase the pedestal height (no stability limit). We note that there is a moderate sensitivity to tritium production for the heating power and confinement variations assumed. This still allows for the possibility of a range of performance in DD operation without significant activation of the ITER device. In addition, for tritium production rate comparisons, we have simulated a 50/50 DT scenario at the reduced I_P, B_T conditions. As expected, the performance is significantly reduced over the baseline 15MA inductive operation but considerably higher than for DD. The DT rates are included in figure 3 and indicate a factor of more than 100 larger source of T for DT operation. In DT operation, the tritium particle source is negative (DDp-DT) due to the large burn-up rate of tritium when the tritium density is set to a 50/50 DT mix.

3.0 Summary and Future

We have completed an initial study of the reduced-activation operation of ITER at half plasma current and half toroidal field. We have estimated the tritium production likely during such operation and are beginning development of this as a candidate for the early operational phase of ITER. The tritium production appears manageable. Additional free-boundary control simulations indicate that, with no modifications of the shape and position control, this operation should be controllable. Considerably more effort needs to be done to demonstrate these are viable operational scenarios. As with the hybrid and steady-state scenarios, we have begun free-boundary control simulations with full source modeling from neutral beams, electron cyclotron, ion cyclotron and lower hybrid heating and current drive as needed. These control simulations will remove the analytic heating assumptions and provide more definitive demonstration of control and the suitability of ITER heating and current drive systems.

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