Impact of ICRF and NBI heating on the fast ion distribution function during the ITER plasma termination phase

A. A. Teplukhina, F. M. Poli, M. Podestà, M. Gorelenkova

Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543, USA

Development of a controlled, safe termination is an essential part of the preparation for the future experimental campaigns on ITER at half and full magnetic field [1]. Challenges in modelling this phase of the discharge lie in its transient nature, with fast and simultaneous changes in multiple plasma parameters. For a safe and controlled plasma termination, these parameters should be kept within the requirements of the ITER control system as well as the plasma stability limits. In particular, maintaining radial position control during the H-L transition, when poloidal beta drops as a consequence of the heating power reduction, is an important issue on which present day experiments could have a critical role in informing ITER. Similarly, schemes for improved core electron heating and control of impurity accumulation should be tested on existing machines under ITER-like conditions.

To better understand the physical and technical limits of the machine, various termination scenarios should be tested during half-field experiments before starting operations at the ITER baseline scenario with full plasma current and magnetic field. In our research, we simulate the final stage of the ITER half-field plasma discharge at B_0=2.65 T, where the plasma current is ramping down from 7.5 MA along with a strong reduction in the input power. We have tested several heating scenarios to investigate how power contribution to plasma species varies and what heating schemes can be used on existing tokamaks to contribute to ITER scenario development, for example exploiting ICRF-NBI synergy to accelerate fast ions and to mimic the alpha particles' dynamic.

Tests of NBI and ICRF heating scenarios

The tokamak transport code TRANSP [2] is used for predictive simulations of the plasma equilibrium evolution and temperature profiles. The NUBEAM module [3], a Monte Carlo code integrated in TRANSP, provides information on the time-dependent deposition and slowing down of fast ions resulting from neutral beam injection. IC and EC heating and current drive are calculated respectively with TORIC [4] and TORBEAM [5]. The TRANSP code predicts time evolution of the plasma equilibrium with the TEQ solver [6]. Electron and ion temperature profiles are predicted by the GLF23 transport model and the EPED1 pedestal model [7].

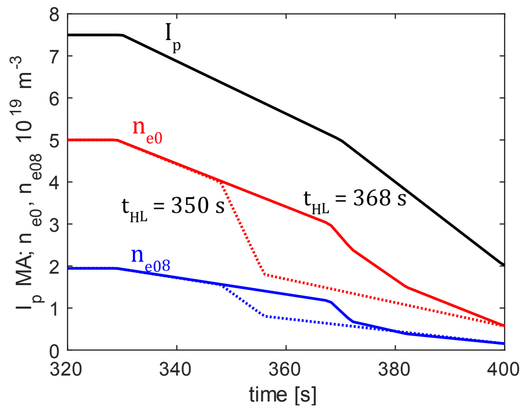

Fig 1. Time evolution of the plasma current and analytical electron density (at ρ=0 and 0.8). The H-L transition: reference at 368 s and tested at 350 s.

For the ITER half-field scenario with I_p = 7.5 MA and B_0=2.65 T, the plasma consists of 50% deuterium D and 50% tritium T in the presence of alpha particles He4 from fusion reactions. We have considered the standard set of ITER impurities such as beryllium, argon and neon. In the reference case 33 MW (2×16.5 MW) of NBI power has been used at the flat-top and gradually reduced during the termination phase. For NTM control 6.67 MW of EC heating and current drive has been added to the flat-top and 13.34 MW at the termination phase. Increased EC power is required to keep high plasma current in the plasma core along with EC current drive decreasing efficiency caused by the plasma current ramp-down and broadening of the EC power deposition profile. Although impurity transport is not modelled here, simulations assume 5 MW of IC heating in the core for impurity accumulation control. Figure 1 shows time evolution of the analytical electron density for the reference (at 368 s) and tested (at 350 s) H-L transitions as well as total plasma current. A slow drop (more than 5 s) in the electron density is assumed to stay within the limits of the ITER control system.

In addition to the reference scenario, shown in Figure 2, two other heating scenarios, have been tested: (1) additional 10 s of NBI and IC power at the ramp-down phase with t_{HL} at 368 s and (2) NBI 15 s and IC 5 s earlier step-down and switch off with t_{HL} at 350 s. The simulations indicate that less IC power is absorbed directly by fast ions in case of the early NBI drop. Figure 3 shows fast ion distributions as a function of the fast ion energy at the end of the flat-top phase and right before NBI switch off, depending on the heating scenario. The

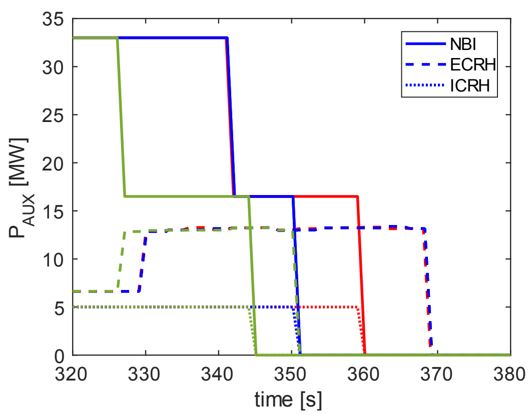

Fig 2. Heating scenarios: reference (blue), +10 s NBI and IC heating (red), -15 s NBI and -5 s IC with the early HL transition (green).

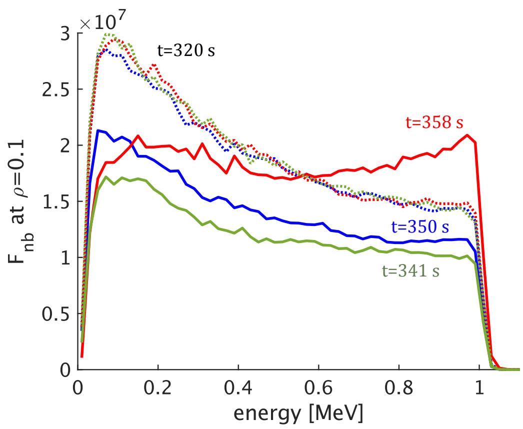

Fig 3. Fast ion distribution function at the plasma core vs fast ion energy at the end of flat-top and NBI heating.

early NBI drop reduces number of fast ions as well as allows to start the H-L transition with less energetic particles. Also, it is clearly seen that longer NBI and IC heating leads to acceleration of fast ions before the H-L transition.

Even though one would avoid accumulation of fast ions at the ramp-down phase to reduce the total pressure, such extended heating scenario can be used for generation of high energetic ions that can be treated as proxy for alpha particles in experiments without fusion reactions. Investigation of the controlled H-L transition in the presence of fast ions is an essential goal for experiments on existing machines in preparation for the ITER operational campaign. Therefore, development of a heating scenario that provides significant amount of fast ions is of practical interest.

Electron heating in the presence of He3 minority ions

Repartition of NB and RF power between plasma species plays an important role in the plasma energy balance and overall performance of a tokamak. There is a well-known process of effective plasma heating by slowing down high energetic minority ions. We have tested various concentrations of the He3 minority ions to see how electron and ion heating evolve. At the plasma termination heating scenario, we allow NBI shut down in steps with 25% power reduction and switch between two IC antennas as shown in Figure 4. The ICRF antenna used in the flat-top phase is switched off at 325 s, and at the same time the second ICRF antenna is started. The frequency of the first antenna equals to 42 MHz, thus IC power is absorbed by D and He4 ions at the second harmonic. The second antenna frequency is fixed at 52 MHz that corresponds to the He3 minority ions second harmonic resonance in the plasma core.

In TRANSP simulations the He3 minority concentration has been varied between 1% and 3% of the electron density. IC power absorbed directly by minority ions is transferred to

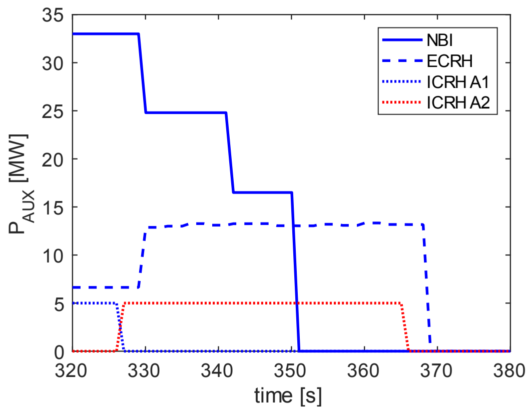

Fig. 4. Tested heating scenario NBI, ECRF and ICRF with He3 minority ions.

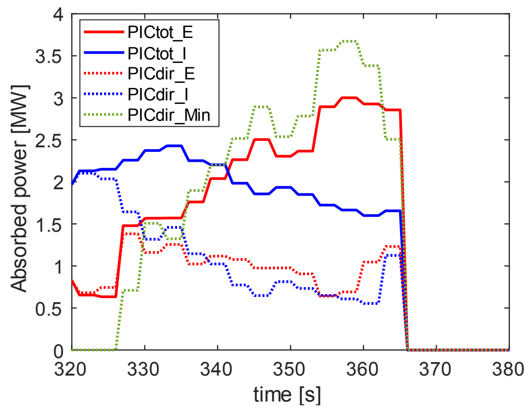

Fig. 5. Total power absorbed by e−, ions and minority ions and via IC direct heating.

the bulk plasma via collisions. Compared to the direct heating scheme, adding minority species increases the total absorption on the electrons from 16% to 60% (with 1% He3) and 50% (with 3% He3). Figure 5 shows the simulation results for direct and total IC heating of plasma species in the case of the 1% He3 concentration. In such type of a plasma scenario, dominant electron heating provides additional plasma core heating and can be used for the impurity accumulation control during the termination phase [8]. It is important to keep concentration of minority ions low, since its increase leads to a reduction of the IC power absorbed by electrons.

Conclusions and further research directions

Simulations of ITER deuterium plasmas with the same heating schemes have large similarities with the DT scenario discussed here. Present-day experiments with IC and NBI heating and with metal wall, like JET and ASDEX-U, can be used to test some of these ideas, to validate the models and to inform ITER on schemes for a safe and controlled exit from H-mode in the presence of alpha particles and without impurity accumulation. Thus, deuterium plasmas with accelerated fast ions from IC heating would allow to study experimentally behaviour of fast ions at the termination phase around the H-L transition. That would be an important contribution to the preparation of the JET DT2 campaign, where exit from H-mode in the presence of alpha particles would be a fundamental step to validate the models before ITER operation. It is important to note that integrated models are still not mature to model self-consistently these transient phases, where the effects of low-n MHD instabilities on fast ion transport need to be accounted for. However, recent progress in the development and validation of reduced models [9], guided by experiments, indicates a path forward.

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