Electron Cyclotron Power Management in ITER, the Path from the Commissioning Phase to Demonstration Discharges

F. Poli[1], E. Fredrickson[1], N. Bertelli[1], R. Andre[1], D. Farina[2], L. Figini[2], M. Henderson[3], S. Nowak[4], E. Poli[5], and O. Sauter[6]

[1]*Princeton Plasma Physics Laboratory (PPPL), Princeton, NJ 08540, USA*
[2]*Istituto di Fisica del Plasma (IFP), Consiglio Nazionale delle Ricerche (CNR), 20125 Milan, Italy*
[3]*International Thermonuclear Experimental Reactor (ITER), Cadarache Centre, 13108 Saint-Paul-lès-Durance, France*
[4]*Associazione EURATOM-ENEA, Istituto di Fisica del Plasma (IFP), Consiglio Nazionale delle Ricerche (CNR), 20125 Milan, Italy*
[5]*Max-Planck-Institut für Plasmaphysik, Garching, Germany*
[6]*Swiss Plasma Center (SPC), École polytechnique fédérale de Lausanne (EPFL), 1015 Lausanne, Switzerland*
Corresponding Author: F. Poli, fpoli@pppl.gov

Among the external heating systems planned in ITER, the electron cyclotron system has the highest flexibility. By combining the equatorial and the upper launcher, the EC can cover the whole plasma radius, from the axis to the edge, allowing for combined central heating, current profile tailoring and MHD stability control.

This work discusses how to best use the EC system in synergy with the other systems for MHD control and optimal plasma performance, by looking separately at the different phases of the discharge, moving from nonactive operation to the demonstration baseline. Time-dependent simulations with the TRANSP transport solver evolve self-consistently the plasma pressure and the heating and current drive profiles. Priority in the study is given to the power requirements for the stabilization of the neoclassical tearing modes (NTMs), because this sets constraints on the power that is available for the other applications, like active control of sawteeth and profile tailoring.

The evolution of the NTMs is calculated during the discharge and a real-time controller in TRANSP manages the steering of the upper launcher, calculates the power needed for stabilization and distributes the power between mirrors for combined applications. Simulations indicate that the NTMs evolve to their saturated size on time scales of a few seconds and that losing alignment with the NTM island, for example because of sawtooth crash, can be deleterious. This implies that preemptive control might be more effective than active control, especially in the case of the more dangerous $(2, 1)$ mode. It is found that at half-field, an optimal steering of the neutral beams can change the sawtooth period by a factor three. Discharge design plays therefore an important role in the EC power management, by relaxing some of the requirements for MHD stability over central heating and profile tailoring.

Published as a journal article in Nuclear Fusion
http://iopscience.iop.org/article/10.1088/1741-4326/aa8e0b

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F.M. Poli[1], E. Fredrickson[1], M. Henderson[2], N. Bertelli[1], D. Farina[3], L. Figini[3], E. Poli[4], V. Parail[5], S. Nowak[3], O. Sauter[6]

[1]Princeton Plasma Physics Laboratory, Princeton NJ 08543 - USA
[2]ITER Organization,
[3]Istituto di Fisica del Plasma, Milano, Italy
[4]Max-Planck-Institute for Plasma Physics, 85748 Garching, Germany
[5]CCFE, Abingdon OX14 3EA, United Kingdom
[6]Swiss Plasma Center, Lausanne, Switzerland

E-mail contact of main author: fpoli@pppl.gov

Abstract. The Electron Cyclotron (EC) system has high flexibility, covering the whole plasma radius and potentially allowing for combined applications, like central heating, current profile tailoring and MHD stability control of sawteeth and Neoclassical Tearing Modes. However, the ability to perform combined applications is subject to a need to maintain MHD stability. The power needed for NTM stabilization is calculated by evolving self-consistently the plasma profiles and the NTM island width. The main conclusion from this work is that in H-mode the EC power needs to be reserved for NTM stabilization both at half-field and full-field and that combined applications are limited by the time scales of NTMs.

1. Introduction

Among the external heating systems planned in ITER, the EC system has the highest flexibility; by combining the equatorial and upper launcher, the EC system can cover nearly the whole plasma radius, from axis to edge, potentially allowing for combined central heating, current profile tailoring and MHD stability control of sawteeth and Neoclassical Tearing Modes [1]. In a typical plasma discharge, the EC system is therefore envisioned to provide (a) breakdown and burn through assist in a limited plasma for flux consumption saving, (b) current ramp-up assist, central heating and H-mode access (c) MHD control, central heating and current profile control in the flattop phase (d) ramp-down assist and exit from H-mode. Every application has to be balanced with the other heating and current drive sources for optimization of capabilities and resources. An important application of the EC system is NTM control and stabilization, for which the Upper Launcher (UL) has been specifically designed. The available 20MW can be distributed with up to four beams on each UL mirror and 8 beams on the EL mirrors [1, 5]. Assessment of the power needs for NTM control and stabilization in the ITER baseline scenario are summarized in the review by E. Poli [6]. In order to assess the EC control system requirements and the capability of performing multiple, combined applications, it is important to assess how much power needs to be reserved for NTM control in each phase of the discharge. In addition, it is critical to assess how fast the NTMs grow compared to the time needed to switch power between launchers or to steer mirrors over half the minor radius.

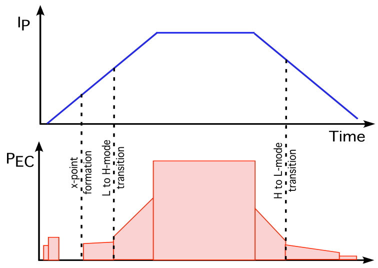

FIG. 1: Schematics of the applications of the Electron Cyclotron system during the various phases of a plasma discharge [1].

The latter criterion constraints the capability of performing multiple applications with the same launcher, for example triggering a sawtooth crash with the UL and steering the mirror on the rational surfaces where the NTM is expected to appear. Similarly, it constrains the capability of performing combined applications, like simultaneous core heating and current profile tailoring and NTM control.

Section 2 describes the approach undertaken and the simulation assumptions and Sec.3 summarizes assumptions in the power management that are common to all simulations. Section 4 discusses the NTM stability in the baseline scenario, while Sec. 5 discusses features and NTM stability of scenarios at half-field for plasmas of hydrogen, helium, deuterium and a mix of deuterium and tritium.

2. Simulation assumptions

The TRANSP transport solver [7] has the unique capability of interfacing with so-called ”expert files”, external coding that are linked to the main executable and that allow users to manipulate the simulations by including additional features. In this respect expert files can provide valuable input for control requirements, diagnostic sensitivity or combined actuator control, because they allow to test the plasma response to external perturbations in the presence of high-fidelity physics models. In order to provide a real-time simulated response of the plasma to NTMs, as they evolve in response to the EC heating and current drive, a Generalized Rutherford Equation has been interfaced with TRANSP and combined with a feedback control for the EC steering angle and power level.

The equations for the evolution of the island width w are based on the work done by E. Fredrickson [2], to which the terms for the EC heating and current drive have been added:

$$\frac{dw}{dt} = 1.22\frac{\eta}{\mu}\left[\Delta'(w) + \Delta'_{nc} + \Delta'_{pol} + \Delta'_{GGJ} + \Delta'_{CD} + \Delta'_{ECH}\right] \quad (1)$$

where μ the magnetic permeability and η the neoclassical plasma resistivity.
In the simulations described herein the Glasser-Green-Johnson Δ' and the polarization term Δ' are set to zero. The first has a stabilizing effect for small island size, but is negligible otherwise, while the second - also affecting primarily small size islands - is destabilizing if the island rotates in the electron diamagnetic direction or when its frequency exceeds the ion drift. Preliminary analysis in time-dependent simulations indicates that results are barely affected by including the rotation and this term is dropped here for simplicity. The simulations described herein should therefore be considered an upper limit to the NTM stability, since all stabilizing contributions that play a role for small island size are not included. The contribution from the ECCD and from the ECH follows the work by Bertelli et al [3] and includes the effect of misalignment and power modulation, as introduced in [4].

Electron density profiles are prescribed in shape and time evolution, with a conservative peaking factor of about 1.1. Impurity profiles are assumed to be the same as electron density profiles, and rescaled by a constant fraction, which is in the flattop 2% of the electron density for berillium and a fraction of $10^{-5}n_e$ for tungsten. Argon is used in the baseline scenario for control of core radiation, with a fraction of about 0.1%, but it is not used in the scenarios at half-field. The ion density is calculated by particle balance assuming quasi-neutrality. The electron and ion temperature, as well as the momentum transport, are predicted using the GLF23 turbulent transport model. Sawtooth crashes are modeled using a Porcelli trigger. The pedestal width and height are interpolated over a lookup table of about 8500 EPED1 [8] simulations that cover variations of pedestal density, shape parameters, Z_{eff} and β_N, for operation at half-field and full field [9].

3. Power management

All scenarios use similar assumptions in the power management in the various phases of the discharge. RF heating is used as soon as the plasma is diverted to heat the plasma in L-mode and for H-mode access and the NBI power is used only when admissible density is achieved. In the baseline scenario the Neutral Beams are needed to access H-mode, since at 50% of Greenwald density, the power threshold for H-mode access would be 40 MW and in order to stay in H-mode a gain of about 1.4 over the threshold level is needed. In scenarios at half-field the NBI management depends on the plasma background species. In plasmas of deuterium (D) and a mix of deuterium and tritium (DT), where the power threshold is about 20-30 MW, and densities are at a level of 5.0×10^{19} m^{-3} and below, NBI can be injected only after entry to H-mode and when the integrated shine-thru levels are below limits. In plasmas with hydrogen and helium, where hydrogen Neutral Beams need to be used and the conditions for shine-thru are more stringent, it is preferable to use a combination of modulated power and low acceleration voltages to maintain low shine thru power.

The IC heating scheme used here for the baseline scenario is thermal ion heating on tritium second harmonics, while scenarios at half-field compare simulations with thermal ion heating and with hydrogen minority heating. It is important to note that, at half-field, all plasma species have a resonance in the plasma; deuterium beams in D and in D-T plasma, and hydrogen beams in hydrogen and He/H plasmas do resonate with RF waves. For these plasmas the absorption of IC waves on fast ions can be as large as 50% of the injected power in pure thermal heating regimes. As discussed in Sec.5, using minority heating with at least 10% hydrogen concentration is needed to reduce the absorption to fast ions below 5-10% of the total power. The IC power is stepped down to 10MW and only one antenna is used in all scenarios. This is done to increase the fusion gain by reducing the input power in the case of DT plasmas, but primarily to have reserved power in case one of the neutral beams fail.

The EC power is stepped down to zero in the flattop phase, primarily under the hypothesis that the EC power should be reserved for NTM control. Once the NTM stability has been assessed the scenarios are re-calculated allowing for combined applications with the EC power to assess what is the effect of using or not the EC on the global performance and on the sawtooth period. The only exception is the hydrogen plasma at half-field, for which the power threshold for sustaining H-mode is high and the full available power is required to sustain good quality H-mode. This scenario is operating at a density of 50% of the Greenwald limit. In order to provide efficient EC absorption the electron density should reach levels of about 2×10^{19} m^{-3} by about 20s.

The ramp-down phase also uses similar assumptions that are adjusted case by case, depending on the presence of the alphas and on the current and magnetic field. The electron density is reduced at constant Greenwald fraction and the H-L back transition is programmed when the plasma current is reduced by one third compared to the flattop value. All scenarios analyzed need to step-down both the NBI and the IC power at the end of the flattop phase to reduce the absorption of RF to fast ions and orbit losses, which can be significant in this phase of the discharge. The NBI power on ITER can be modulated with a frequency of 25Hz in order to provide gradual stepping down. Modulation is not modeled here, instead the beams are turned-off in sequence. The IC power is maintained during H-mode, primarily for impurity control by providing core heating, following the experience on JET and ASDEX-U. ITER discharges will terminate by progressively shrinking the plasma shape and drifting the plasma centroid downward after exit from H-mode while the plasma current is reduced. Under these conditions the use of the EC in the ramp-down L-mode phase for core heating might be compromised; the simulations described herein turn-off the EC system right after the H-L transition. Another problem in the ramp-down, as it will be discussed in the next section, is that NTMs are pre-

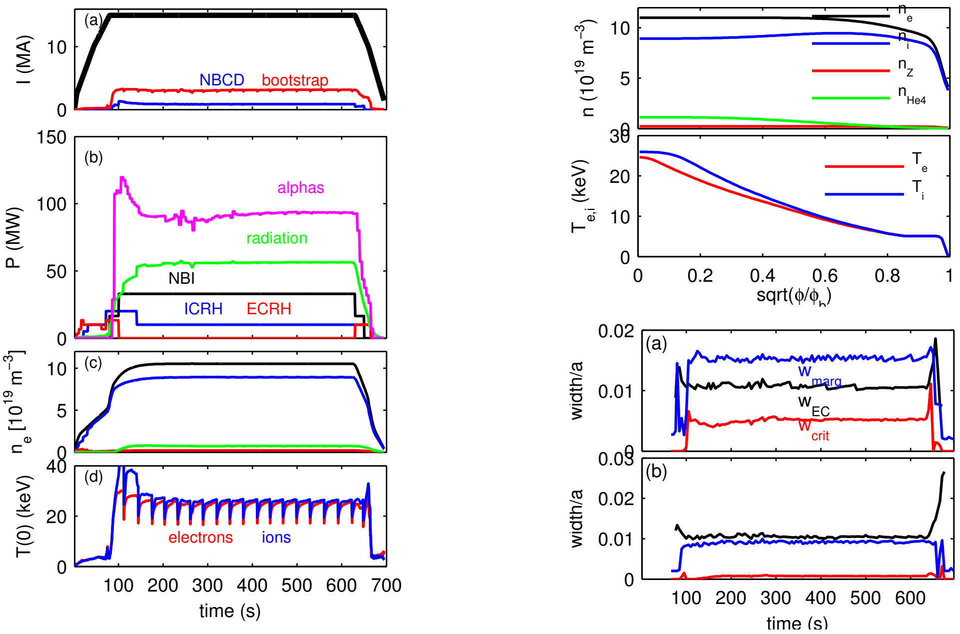

FIG. 2: Left column: Time traces for the baseline scenario (a) plasma current, NB driven current and bootstrap current (b) injected external power, radiated power and α power. (c) line integrated density for electrons, ions and impurities, (d) electron and ion temperature, central value. Right column, top figure: (a) density profiles at 480s (b) temperature profiles at 480s. Right column, bottom figure: time evolution of the width of the critical island (w_{crit}, red), of the size that correspond to the maximum growth rate (w_{marg}, blue) for the $(3,2)$ (top) and for the $(2,1)$ mode (bottom). For comparison it is reported the EC deposition width at the respective rational surfaces (w_{EC}, black).

dicted to be unstable in H-mode, but the EC deposition width broadens, reducing the efficiency. The ramp-down should be designed in order to minimize the drive to NTMs, because control in this phase becomes challenging. At half-field it might be envisaged to exit H-mode shortly after the end of the flattop phase. At full field this is still possible, but the current ramp-down duration has to be reduced to about 65 seconds, with 30 seconds of H-mode. This ramp-down duration is compatible with coil currents limits and with the PF coil control capabilities. It remains to be assessed whether they are also controllable and safe against disruptions when self-consistent time-dependent simulations are undertaken that evolve equilibrium, heating and current drive sources, plasma pressure profiles and radiation profiles consistently with divertor physics.

4. EC power management in the baseline scenario

Figure 2 shows a TRANSP simulation of the ITER 15MA ELMy H-mode. The plasma enters H-mode at about two thirds of the ramp-up phase duration, at an electron density of 50% of the Greenwald limit. The flattop phase starts at 80s, at which time the density has achieved $0.85n_{Gw}$.

Figure 2 shows the evolution in time of the parameters of the islands at $q = 1.5$ and at $q = 2$, as calculated by the GRE in TRANSP, when no ECCD is applied on the rational surfaces. The EC deposition width from a simulation of the same plasma, but with a minimum level of power of 1 gyrotron on each rational surface is shown for comparison. The width corresponding to the maximum growth rate of the island is indicated as w_{marg}. This is comparable in the flattop phase to the EC deposition width, calculated with minimum power input. The width of the critical island is about half this size in the case of the $(3,2)$ and much smaller in the case of the

$(2,1)$. It is noted that the EC deposition width broadens significantly during the ramp-down phase, which might limit the ability to control NTMs in this phase.

The NTMs suddenly appear early in the flattop phase, at the time the NBI are turned on, and they grow to a size of about 5-6 cm in less than 10 seconds. Previous, independent work, indicated that NTMs will lock in ITER at a size of about 6 cm to 8 cm in about 5 seconds [11, 12]. The island rotation is not included in the simulations shown here, but the time scale to reach what has been estimated to be the size of locking are comparable. It appears clear that NTMs need to be detected as soon as possible, when their size is comparable to the EC deposition width, and stabilized over time scales of about 5-10 seconds, before they lock. Stabilization might be particularly challenging in the case of the $(2,1)$ mode because the seed island is much smaller than the EC deposition width and even small misalignment of the EC deposition with rational surfaces might hinder the efficiency of the system. This fast growth rises questions on the best strategy to control NTMs in ITER. The time needed to switch power between launchers is constrained by design and has an upper limit of 3 seconds, thus it might be possible to provide the available power when needed. However, this delay has to be evaluated in combination with the relative ratio of the island size to the EC deposition width, with uncertainties in the real-time reconstruction of the magnetic field and with the sensitivity and threshold level of the ECE diagnostics. The first affects the parameter η_{NTM} that is commonly used to determine the amount of power needed for stabilization, the second affects the alignment of the EC to the rational surfaces and can significantly reduce the current drive efficiency when the island is small. In the case of the $(2,1)$ mode, with deposition width of about 2 cm, and assuming that the threshold for the ECE diagnostic detection is 4 cm, the maximum acceptable misalignment is about 2 cm. For islands larger than this value, the ability to stabilize NTMs is greatly reduced. The third affects the delay in the response of the system: for a threshold of 4 cm - as anticipated by the designing group - even 3 seconds time in the power switch between mirrors might be too long a delay.

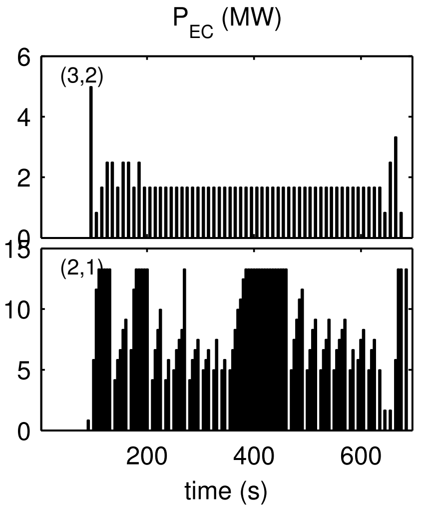

FIG. 3: EC feedback power needed to stabilize NTMs and maintain their size below the critical size, in the case of 5s time step.

Figure 3 shows a simulation where the EC power is adjusted in real time in response to the NTM stability. For simplicity, the maximum misalignment allowed is about 1 cm, which corresponds to almost perfect alignment of the EC deposition to the rational surfaces. The EC feedback in TRANSP calculates at each source time step the NTM stability: if the growth rate is negative (NTM stable) then the power is dropped to zero, if it is positive then TRANSP calculates the power needed to stabilize the mode and adjusts it consequently. An upper limit of 16 gyrotrons has been set on the power available to the LSM for stabilization of the $(2,1)$ and this is reflected in the saturated power level in Fig.3. Two gyrotrons, equivalent to a 1.66 MW are predicted to be sufficient to stabilize the $(3,2)$, while the power needed to stabilize the $(2,1)$ changes in the flattop and it varies between 5 MW and 13.4 MW (saturated value). The gaps between bars in the figure correspond to time steps when the NTMs are predicted to be stable with a fixed level of power and the power is dropped back to zero. However, the NTMs grow fast and the maximum duration of each gap is exactly the source time step. This gap would change if the detection threshold for the island is increased; here we are assuming that the minimum size that can be detected is about 2 cm, comparable to the critical island. It should also be noted that the source time step used here is 5s, thus between two successive calls the island has had the time to evolve for as long this time. As discussed earlier, this is sufficient to increase the size to about the marginal size. Reducing the time step to 3 seconds has no effect on the results, indicating that what really matters is the initial growth phase of the island. Reducing the time step down to 0.5 seconds reduces the power level to about 5 MW over longer time windows. This suggests that reserving power for NTM stabilization is preferable than having to switch it from another application; in fact, the time needed to turn-on a gyrotron is less than 100ms compared to the time needed to switch it from another application, which is up to 3s. What does make a difference in the results is pre-emptive control for the whole duration of the H-mode phase. In this case, in fact, assuming a perfect alignment of the EC deposition with the rational surfaces, depending on the evolution of plasma parameters at entry to H-mode, a minimum of 1-2 gyrotron on the $q = 1.5$ and 2-4 gyrotrons on the $q = 2$ surface would be needed to avoid that the island exceeds its critical size.

The time needed to turn-on and off a gyrotron is less than 100ms, which is also the latency of the feedback control. Thus, it is reasonable to assume that optimal requirements for availability of power have a lower limit of 200ms, the time delay between when the feedback tells the system to increase power and the time full power is available on a selected mirror, including small angle adjustments of the mirror. Reserving power for NTM control has implications on the performance of the discharge, because other applications would be limited, and this needs to be assessed. Also, pre-emptive control has implications in terms of the accuracy of magnetic equilibrium reconstruction and island detection threshold.

5. EC power management at half-field

NTM evolution at half-field has similar features compared to full field. It should be noted that the results of the GRE depend on the coefficients that are used to balance individual contributions and should be calibrated against experiments. The neoclassical drive term is calibrated here using previous estimates from Sauter [10]. At half-field the $(2, 1)$ is predicted to be unstable in the deuterium plasmas and D-T plasmas over a range of values for the coefficient of the neoclassical term, while the stability of the $(3, 2)$ mode is sensitive to the value of this coefficient, so that deviations of less than 1% around the reference value can change the growth rate from stable to unstable.

The RF waves are used in the ramp-up to enter H-mode, although the power threshold is sufficiently low that the discharge might use only one or the other at full power. Since the EC is turned-off in the flattop and reserved for NTM stabilization, and the IC power is dropped to 10MW, both beams are used to sustain good quality H-mode. The neutral beams are steered one on-axis and one off-axis, for broader deposition and current profiles. Under this heating scheme good quality H-mode is sustained in deuterium and D-T plasmas also if the NBI energy source is decreased to 0.8-0.9MeV. Since the power is related to the energy as $P_{NBI} = 16.5 \exp(-E_{NBI}/E_0)$, where $E_0 = 1MeV$ for the deuterium beams and 0.87 MeV for the hydrogen beam, decreasing energy is equivalent to decrease the injected power from 16.5MW to 12.7MW at 0.9MeV and 9.4 MW at 0.8 MeV. Since the neutral beams modify the bulk current profile, they have an effect on the average sawtooth period. It is observed that reducing the beam energy from 1MeV to 0.9MeV reduces the sawtooth period by 30%, down from about 35s, and reducing further to 0.8MeV reduces the period by 50%. By reducing the sawtooth period operating on the bulk current profile reduces the possibility that NTMs are triggered by long sawtooth period crashes; it also relaxes requirements on active control of the sawtooth period. We note that this effect is not visible in the baseline scenario because of the larger density, which reduced the current drive efficiency. While the power threshold is very low in these plasmas and good quality H-mode can be sustained also without the use of IC heating, the IC is maintained in these simulations. Turning-off the IC in the flattop phase does not compromise the ability to sustain H-mode, provided the beam energy is maintained at 0.9 MeV, for density of 85% of the Greenwald limit. However the sawtooth period increases by about 30% with variations between 30 and 50s, which is not desirable. Whether this is a direct effect of the balance between the terms that set the triggering criteria in the Porcelli model or an effect of the thermal transport model used here has not been assessed yet. At half-field the H, D and He3 resonances are all inside the plasma. This implies that absorption of RF waves on fast ions is not negligible in all scenarios at half-field, independently of the background plasma species. This would increase orbit losses, favor Alfvénic instabilities and decrease the net power for sustainment of H-mode. Using hydrogen minority in DT and D plasmas reduces the absorption to fast ions from about 50% in the case of pure thermal ion heating down to less than 2% with 10% hydrogen minority.

Deuterium plasmas are very similar to DT plasmas in terms of plasma parameters. However, in this case no contribution from alphas is available and the conditions for staying in H-mode are more restrictive compared to D-T plasmas. Simulations have been run for NBI source energy of 1MeV and 0.9MeV. Reducing the power further would hinder the sustainment of good quality H-mode. Absorption to the fast ions is lower in deuterium plasmas because of the absence of alpha particles. TORIC calculates absorption on both alphas and beam ions, but TRANSP does not distinguish between the two in the output, which shows the direct absorption to all fast ions. Without hydrogen minority, about 30% of the IC power is absorbed by the beam ions at 1MeV and about 25% at 0.9MeV. This level decreases to about 10% when hydrogen minority at a fraction of 10% of the electron density is considered. The absorption decreases to about 5% when the beam energy is decreased to 0.8 MeV.

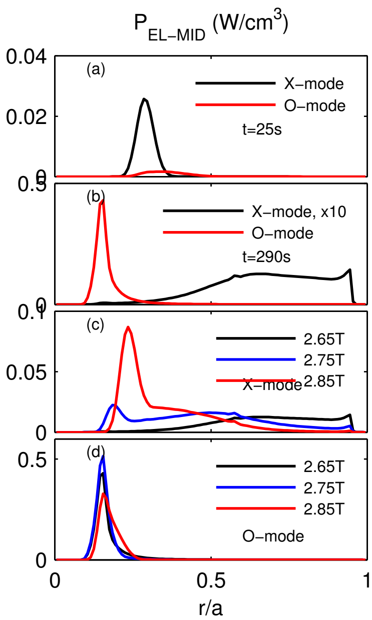

FIG. 4: Power density profiles from the EL-MID launcher ($R = 9.394m$, $z = 0.62m$), at 2.65T (a) in L-mode, (b) in the flattop (power in X-mode multiplied by a factor 10), and for different values of magnetic field for (c) X-mode and for (d) O-mode polarization.

The power threshold for the L-H transition in Helium plasmas is predicted to be quite large by the Martin scaling. However, recent experiments on C-Mod, AUG, and DIII-D indicate no difference between helium and deuterium plasmas. The power threshold is therefore rescaled by a factor 1.4 to take it down to values comparable to deuterium plasmas. Hydrogen plasmas are the most challenging, because of the high H-mode power threshold, which for a density of about 60% of Greenwald, would be 45 MW in the flattop phase. Sustainment of good quality H-mode would require the net power to be 1.4 of the threshold value, thus implying that all the available power should be used. Both hydrogen and helium plasma are predicted to be stable against NTMs.

Figure 4 shows the EC power density profiles in a hydrogen plasma in the case of the MID equatorial launcher, at $R = 9.394$m and $z = 0.62$m. The efficiency and the power deposition change between L-mode and H-mode. In L-mode both polarizations have deposition profiles peaked at well defined locations, with the X-mode being the more efficient. In H-mode the effect of the parasitic third harmonic absorption is visible in the case of X-mode polarization, and invisible in the case of O-mode polarization. It should be noted that this effect is not present in the case of the upper launcher, whose trajectories from the top of the plasma do not cross the resonant layer. The effect is also enhanced by the low temperature profiles at the edge that are predicted in these simulations and were absent in the work by Farina et al, where density and temperature profiles at half-field were rescaled from a JINTRAC baseline discharge [13]. As shown in the figure, the effect is reduced for X-mode polarization by increasing the operational magnetic field to 2.85T, although it is not completely eliminated. These results indicate that a change in the polarization might be needed when transitioning form L-mode to H-mode for operation at half-field, in order to eliminate parasitic absorption at the third harmonics.

6. Conclusions

The Electron Cyclotron system on ITER has ample flexibility in deposition location and can cover the whole plasma radius by combining the equatorial and the upper launcher. Although this flexibility potentially opens a variety of combinations, each application has to be assessed in synergy with the other heating and current drive systems to optimize resources. It is critical that discharges are free from NTMs, since this is one of the principal causes of disruptivity in present-day tokamaks. Time dependent simulations, which evolve the NTM size coupled to a feedback control of the EC steering angle and power level, indicate that pre-emptive control and reserving power are recommended on ITER because the island grows to the locking size in less than 5 seconds, which is comparable to the time needed to switch power between mirrors. Pre-emptive control reduces the required power for $q = 2$ by about half the power needed in case it is not used, even accounting for misalignment effects. Operation at half-field requires adjustment of the polarization in the equatorial launcher, since the beam trajectories close to midplane are affected by parasitic absorption to the third harmonics.

Acknowledgments

Thanks to colleagues at PPPL, F4E and IO who have contributed to the development of this work, which is supported by ITER contract IO/RFQ/13/9550/JTR and by DOE contract DE-AC02-09CH11466. The view and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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