MODELLING ONE-THIRD FIELD OPERATION IN THE ITER PRE-FUSION POWER OPERATION PHASE

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Abstract

In the four-stage approach of the new ITER Research Plan, the first Pre-Fusion Power Operation (PFPO) phase will only have a limited power available from external Heating and Current Drive (H&CD) systems: 20 to 30 MW, provided by the Electron Cyclotron Resonance Heating system (ECRH). Accessing the H-mode confinement regime at such low auxiliary power requires operating at lower magnetic field, plasma current and density, i.e. 1.8 T and 5 MA for a density between 40% and 50% of the Greenwald density. H-mode plasmas at 5 MA / 1.8 T are also considered for the second PFPO phase when ITER will have its full installed H&CD capabilities, i.e. 20–30 MW of ECRH, 20 MW of Ion Cyclotron Resonance Heating (ICRH) and 33 MW of Neutral Beam Injection (NBI). The present paper describes the operational conditions of such scenarios in hydrogen and helium plasmas and the H&CD capabilities for these plasmas, to assess the viability of such scenarios and the issues that will be possible to address with them. The modelling results show that 5 MA / 1.8 T scenarios are viable and will allow the exploration of the H-mode physics and control issues foreseen in the ITER Research Programme in the PFPO phases.

1. INTRODUCTION

The ITER Research Plan [1] is divided into four stages starting with First Plasma, followed by two campaigns consisting of hydrogen and helium plasmas, split into Pre-Fusion Power Operation phases 1 and 2 (PFPO-1 and PFPO-2) and finally the Fusion Power Operation phase (FPO). The H&CD systems in PFPO-1 phase will consist of 20 MW of ECRH and a possible additional 10 MW from an upgrade presently under assessment. For the PFPO-2 phase the full Heating and Current Drive (H&CD) capabilities, i.e. at least 73 MW of H&CD power, including ECRH, ICRH and NBI will be available, as described in Table 1. Operation with H-mode plasmas early in the Research Plan is considered an important risk mitigation measure: it allows the determination of the additional heating power required to operate ITER in H-mode as well as to commission/demonstrate ELM control schemes, both of which are key to the development of the subsequent stages of the Research Plan. According to the analysis in [1] on the basis of results in [2], the optimal density corresponding to the minimum of the L-H power threshold for ITER q95 = 3 operation (where q95 is the edge safety factor) is predicted to be n/n0 ~ 0.36, where n0 is the Greenwald density. This corresponds to the minimum density at which the ion and electron power flux channels are well coupled. At half field (7.5 MA /2.65 T) for n/n0 ~ 0.4, the L-H power threshold, evaluated according to Martin’s scaling [3], predicts H-mode access to be unlikely in PFPO-1 in hydrogen and marginal in helium for additional heating power levels of 20–30 MW. For this reason, 5 MA / 1.8 T plasmas (with q95=3) are considered to make H-mode access more likely in PFPO-1 by reducing plasma current and field and thus the required power level. These same plasmas can then be further explored in PFPO-2 at higher power levels and with different heating mixes and can be used to determine the effects of specific components that will be installed between PFPO-1 and PFPO-2 (Test Blanket Modules leading to local TF ripple wells) on H-mode plasmas. Therefore, these scenarios have been developed for the two phases of the low activation period, as described in this paper. The key questions to address are whether these H-mode scenarios at 5 MA / 1.8 T can be achieved and sustained in practice in ITER taking into account all physics and technical considerations into account and what plasma parameters such
plasmas will have. To evaluate the plasma parameters of these scenarios, integrated simulations of ITER 5 MA / 1.8 T plasmas have been carried out with various H&CD models and transport codes by the ITPA topical group on Integrated Operation Scenarios (ITPA-IOS) in collaboration with the IO and with support from the ITPA Transport and Confinement and Energetic Particles groups. The present contribution reports the results of self-consistent transport and H&CD analyses to assess the efficiency of EC, IC and NBI heating in L- and H-mode 5 MA / 1.8 T plasmas. The integrated modelling suites applied include Astra [4],Corsica [5,6], Cronos [7],Dina [8], Jintrac [9], Metis [10], Task [11], Topics [12] and Transp [13], used in association with either simplified H&CD models or more sophisticated codes such as Gray [14], OGray [15] and Rema [16] for ECRH modelling, Pion [17], Tomcat [18], Cyrano [19] or STIXRedist [20] for ICRH modelling, Toric [21] and Ascot [22] both for ICRH and NBI modelling. Finally, the IC coupling performance is evaluated with the Antiter-II semi-analytical fast coupling code [23].

<table>
<thead>
<tr>
<th>Period</th>
<th>ITPA-1</th>
<th>ITPA-2</th>
<th>FPO</th>
</tr>
</thead>
<tbody>
<tr>
<td>2025 – 2026</td>
<td>2028 – 2030</td>
<td>2032 – 2034</td>
<td>2035 and beyond</td>
</tr>
<tr>
<td>Main ion</td>
<td>H</td>
<td>D, DT</td>
<td>D</td>
</tr>
<tr>
<td>EC</td>
<td>6.7 MW</td>
<td>20 (+10^3) MW</td>
<td>20 (+10^3) MW</td>
</tr>
<tr>
<td>IC</td>
<td>-</td>
<td>20 MW</td>
<td>-</td>
</tr>
<tr>
<td>NBI</td>
<td>-</td>
<td>≤870 keV^1 H^+ ≤33 MW</td>
<td>≤1 MeV^1 D^+ ≤33 MW</td>
</tr>
<tr>
<td>Max H&amp;CD</td>
<td>6.7 MW</td>
<td>20 MW</td>
<td>≤73 (+10^3) MW</td>
</tr>
</tbody>
</table>

Table 1 - Availability of H&CD systems in the ITER Research Plan.

2. OPERATION CONDITIONS FOR ITER 5 MA / 1.8 T H-MODE SCENARIOS

The 5 MA / 1.8 T H-mode plasma scenarios will operate at low density, n_nHe ~ 0.4 - 0.5, to enable H-mode access and sustainment with the thermal H&CD power of 20 - 30 MW in the ITPA-1 phase. The L-H power threshold for ITER is evaluated using the 2008 Martin’s scaling for hydrogen isotopes (i.e. 2 times the deuterium threshold), while the helium-L-H threshold is assumed to be a factor of 1 – 1.5 greater than for deuterium based on results from present-day tokamaks [24] [25] [26] [27]. The available H&CD power considered for ITPA-1 is 20 – 30 MW while for ITPA-2 it depends on ICRH coupling and on the maximum NBI power that can be injected with tolerable NBI shine-through losses. A total of 30 MW power in ITPA-1 (i.e. including the additional 10 MW of EC power) would allow access and sustainment of hydrogen H-modes and a robust operational margin (in terms of power above the threshold) for helium H-modes. For ITPA-2 the NBI injected power is limited by shine-through loads and therefore, the maximum energy of H_0 beams needs to be reduced to keep them below the design limits of the blanket shield modules in ITER; an initial evaluation of the maximum NBI energy (E_{NBI}) as a function of density has been performed in [28]. From this maximum energy the total input power that can be injected with acceptable shine-through loads is evaluated through the beam perveance criterion P_{NBI} \propto E_{NBI}^{2.5} to be matched for optimal beam optics with P_{NBI} = 33 MW (with 2 injectors) at E_{NBI} = 870 keV. The results for 5 MA / 1.8 T plasmas are given in Table 2, which have been used in the ITER Research Plan. As the shine-through loads depend on the plasma density, temperature profiles and effective charge of plasma ions, it is important to determine if the results provided by the evaluation above are accurate or not; the results of this modelling evaluation are presented in section 5.

<table>
<thead>
<tr>
<th>Main ion</th>
<th>Density</th>
<th>P_{NBI} (MW)</th>
<th>Applicable H&amp;CD power in ITPA-1 (MW)</th>
<th>Applicable NBI energy (keV) / power (MW)</th>
<th>Applicable H&amp;CD power in ITPA-2 (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>0.4 n_g</td>
<td>20</td>
<td>20 (+10^3)</td>
<td>500 / 8.3</td>
<td>48.3 (+10^3)</td>
</tr>
<tr>
<td></td>
<td>0.5 n_g</td>
<td>23</td>
<td>20 (+10^3)</td>
<td>530 / 9.4</td>
<td>49.4 (+10^3)</td>
</tr>
<tr>
<td>He</td>
<td>0.4 n_g</td>
<td>[10–15]</td>
<td>20 (+10^3)</td>
<td>580 / 12</td>
<td>52.0 (+10^3)</td>
</tr>
<tr>
<td></td>
<td>0.5 n_g</td>
<td>[12–18]</td>
<td>20 (+10^3)</td>
<td>660 / 16.7</td>
<td>56.7 (+10^3)</td>
</tr>
</tbody>
</table>

Table 2 - L-H power threshold, applicable NBI power/energy and H&CD power in H and He plasmas at 5 MA / 1.8 T.

3. EC HEATING OF 5 MA / 1.8 T SCENARIOS

The main open question regarding EC heating of 1.8 T plasmas is the fact that this has to be performed with 3rd harmonic heating because the gyrotron frequency is 170 GHz. Heating of ohmic plasmas at 1.8 T with 3rd harmonic is not efficient in its initial phase because the central temperature in the Ohmic phase of such plasmas is of the order of 2–3 keV, too low for efficient 3rd harmonic absorption. The single pass EC absorption efficiency has been evaluated for various values of plasma temperature and density with the Gray ray-tracing code [14]. The fraction of absorbed EC power from the Equatorial Launcher for various plasma densities and

*10 extra MW of EC power is an option presently analyzed as an upgrade to be implemented before ITPA-1, if approved.
temperatures is displayed in Figure 1. These results show that for the typical Ohmic temperature of such plasmas (~2–3 keV) at around 50% of the Greenwald density (~2.10^{19} m^{-3}), the EC single pass absorption efficiency is limited. In order to determine if there is a viable scheme for heating of 1.8 T plasmas with 3rd harmonic, simulations accounting for the self-consistent interplay between the EC deposition and plasma kinetic profiles using an accurate transport model have been performed, as reported in section 6. As discussed in detail later, due to the interplay between ECRH and the plasma temperature, the central plasma temperature evolves rapidly after the application of the EC power, thus leading to an increased absorption and further increase in the plasma temperature in a positive feedback loop, as seen in 3rd harmonic EC heating experiments [29] [30], resulting in a very high level of 3rd harmonic absorption in timescales of less than 1–2 s if the EC power is 10 MW or higher. One open issue remains the inefficiency of 3rd harmonic ECRH to provide plasma start-up. If Ohmic start-up is not sufficiently robust at 1.8 T, some lower frequency (~110 GHz) gyrotrons may be required to provide plasma start-up; this will be decided after the First Plasma/Engineering Operations campaign.

![Figure 1](image.png)

**Figure 1** – Fraction of EC single pass absorbed power for each mirror of the Equatorial Launcher versus the central electron temperature and density as calculated by GRAY for ITER 5 MA / 1.8 T scenarios with 170 GHz gyrotrons (3rd harmonic).

4. **IC HEATING OF 5 MA / 1.8 T SCENARIOS**

During the PFPO-2 phase of the ITER Research Plan, 20 MW of ICRH will be available in addition to the 20–30 MW of EC power and up to 33 MW of NBI. For low field/low current operation (5 MA / 1.8 T), an area of concern is the confinement of IC-accelerated ions near the plasma edge, where the toroidal field ripple is expected to be \( \delta_{\text{rip}} = -1.3\% \) at the nominal outer midplane separatrix position, due to the overcompensation by ferromagnetic inserts at 1.8 T. This could potentially lead to increased fast-ion ripple losses and associated first wall heat loads. DINA modelling has demonstrated that the magnetic field ripple in 1.8 T plasmas can be decreased to \( \delta_{\text{rip}} = -0.5\% \) if the gap between the plasma and the wall is increased by 40 cm [31]. This reduced magnetic field ripple may be necessary to ensure a high pedestal H-mode pressure as well as to limit ripple-induced losses from IC-accelerated and NBI ions but the associated plasma-antenna distance can reduce the coupling resistance and thus limit the ICRH power that can be coupled. The most efficient ICRH scheme at 1.8 T is 2nd harmonic H heating (\( \omega = 2 \omega_{ce} \)), both in H and He plasmas. Even without magnetic field ripple, the confinement of the 2nd harmonic ICRH-accelerated ions may be reduced for 5 MA / 1.8 T scenarios due to low current / low density / low collisionality, possibly leading to enhanced plasma-wall interactions as seen at JET [32]. Therefore detailed studies have been carried out to determine the capability of IC heating for 5 MA / 1.8 T plasmas. A first study has been performed to evaluate the ICRF coupling efficiency for 2nd harmonic H heating at 53 MHz in H plasmas where the plasma-wall gap has been varied from the nominal 23 cm to 63 cm required to reduce the ripple to \(-0.5\%\). The modelling has been carried out with: 1) a simplified 1D fast wave code that accounts for the full toroidal antenna spectrum but adopts a simplified description of the antenna geometry (infinite straps in the poloidal direction, no side limiters, …), and 2) the full ANTITER-II code [23] which uses a more realistic description of the antenna. The latter used a scrape-off-layer (SOL) density profile calculated with SOLPS-ITER [33] [34] for 5 MA / 1.8 T scenarios in D plasmas, here extrapolated to H plasmas. Both results lead to the same conclusion: the coupled power drops by a factor of \( \sim 10 \) when the distance from the separatrix to the antenna increases by 40 cm, as shown in Figure 2. A scan in SOL density has been carried out with ANTITER-II to evaluate the minimum applicable density for various phasings of the antenna strap, i.e. phasings \( 0 \pi \), \( 0 \pi \pi \). As expected, the best coupling is achieved with the \( 0 \pi \pi \) heating phase with normal antenna-plasma gap (23 cm), since it excites modes with the lowest parallel wave vectors \( k_{\parallel} \), for which the cut-off density is the lowest, i.e. \( \sim 2 \times 10^{17} \text{ m}^{-3} \). As a conclusion, even with the most appropriate strap phasing, the use of ICRH is not compatible with a +40 cm gap increase, meaning that the nominal separatrix position (high ripple) is the only option to provide efficient IC antenna coupling. IC heating schemes have been modelled and optimized using the TOMCAT [20] and CYRANO [19] wave codes. The input kinetic profiles were calculated by the METIS fast transport solver [10] assuming 20 MW of ECRH and 10 MW of ICRH for a density of 0.5 \( n_0 \). The best absorption was found for 2nd harmonic H heating with \( f = 52-54 \text{ MHz} \), both as a majority (in H plasmas) and as a minority (in He plasmas), here with 7\% of H. Achieving efficient 2nd harmonic
minority heating in He plasmas was somewhat unexpected because of the low concentration of minority species. However, operating at low field enhances the 2nd harmonic IC absorption, since this process is based on finite Larmor radius effects for which the absorption efficiency scales inversely proportional to the square of the magnetic field [35]. The resulting power density profiles are displayed in Figure 3 both for H and He plasmas where power densities range up to 0.2 MW/m³ near the plasma centre. The STIXREDIST fast-ion Fokker-Planck solver [20] has been applied to generate fast-ion distribution functions for these scenarios and to calculate the fraction of fast H+ ions accelerated to a specific energy range (corresponding to sharp steps in the RF acceleration capability due to the Bessel function energy dependence of the RF operator used in the model) as a function of the absorbed power density. Results are displayed in Figure 4. As can be seen, in H plasmas, the fast H+ ion energy never exceeds 3.7 MeV, while in He plasmas, higher energies can be reached, but only for power densities above 0.4 MW/m³, which is about the maximum achievable if 20 MW of IC power is applied in these scenarios. An analytical orbit solver applied to these 5 MA / 1.8 T scenarios suggests that ions born within a normalized radius < 0.75 with energies of up to 6 MeV are well confined. Hence, in this simple approximation no fast-ion losses are expected despite operation at low current and low density, unlike in JET experiments [32]. It is important to note that finite orbit Doppler-shifted IC absorption and fast-ion ripple losses have not been taken into account in the modelling described above and they could be significant due to the relatively large value of the field ripple, $\delta_{\text{ripp}} = -1.3\%$, required for good IC coupling. Preliminary studies with the 3D orbit following code ASCOT [22] taking the fast ion distributions provided by STIXREDIST and using the realistic ITER magnetic topology for 1.8 T suggest that $\delta_{\text{ripp}} = -1.3\%$ near the plasma edge does not cause significant enhancement of the RF-accelerated ion losses, as long as the dominant IC absorption is central as expected for these plasmas (see Figure 3). More refined studies using the RFOF ICRH module [36] in ASCOT are planned for the near future.

Figure 2 – Input density profile for simplified 1D fast wave model (top-left) and ANTITER-II modelling (bottom-left) and resulting coupled power versus the antenna-separatrix gap (right figures) for 5 MA / 1.8 T scenarios in H plasmas.

Figure 3 – Absorbed power density (top) and integrated power (bottom) for 2nd harmonic H ICRH in H (left) and He (right) plasmas with 5 MA / 1.8 T, as calculated by TOMCAT.

Figure 4 – Fraction of ICRH-accelerated H+ ions with specific energy range versus the absorbed power density for 2nd harmonic H heating in H (left) and He (right) at 5 MA / 1.8 T as calculated by the STIXREDIST Fokker-Planck code.

5. NBI HEATING FOR ITER 5 MA / 1.8 T SCENARIOS

For the PPFO-2 phase, up to 33 MW of NBI power will be available from two beam boxes. As already discussed in section 2, the full NBI power cannot be applied at 5 MA / 1.8 T due to the significant NB shine-through loads caused by the low absolute densities of 5 MA plasmas ($n_{\text{he}} \sim 4.10^{19}$ m⁻³). The limit to the shine-through loads is given by power flux which penetrates into the gap between the first wall panels facing the NB injectors and impinges on the stainless steel shield blocks (SBs). The requirement that the SBs can withstand 30000 cycles, as foreseen for the whole life time of the ITER operation, limits this power flux to 0.8 MW/m² (normal to the wall). An initial evaluation of the maximum NBI power for 5 MA / 1.8 T H-modes in ITER has been performed on the basis of the scaling derived from 7.5 MA / 2.65 T plasmas in [28] and the values provided in Table 2 as a guideline. To provide more accurate estimates of the maximum NBI power that can be
injected in 5 MA / 1.8 T plasmas with acceptable shine-through loads a dedicated study has been performed taking into account the detailed geometry of the first wall, shield block and equatorial port. Similarly, another potential issue is the ripple-induced losses of NBI ions and the resulting heat loads on the first wall as the level of ripple is \( \delta_{rip} = -1.3\% \). To assess these issues the ASCOT orbit following Monte Carlo code [22] has been used together with the BBNBI Monte Carlo code that provides initial beam deposition and shine-through losses [37]. Input kinetic profiles have been predicted by the METIS transport code [10] for helium and hydrogen plasmas at 5 MA / 1.8 T. A first analysis has been carried out with ASCOT for helium plasmas at 0.4 \( n_c \) where NBI fast-ion losses have been estimated for a beam energy and power of 580 keV and 12 MW (with 2 injectors) for both a normal plasma-wall gap (\( \delta_{rip} = -1.3\% \)) and +40 cm increased gap (\( \delta_{rip} = -0.5\% \)). This modelling includes the effect of magnetic field ripple with ferromagnetic inserts and TBMs including plasma response but neglecting charge-exchange losses. The effects of the 3-D fields for ELM control produced by the ELM control coils are not included; this could lead to significant fast-ion losses and will be the subject of future studies. The results show that power losses due to the shine-through (together with fast ion ripple losses) to the SB gap remain within the required limit, i.e. 0.7-0.8 MW/m\(^2\) in the worst-case scenario, i.e. with normal wall-plasma gap where ripple-induced losses are higher. In hydrogen plasmas, two densities have been considered: 1) a low density case at 0.5 \( n_c \), where the beam energy and power have been adjusted to 530 keV / 9.4 MW following the guideline in Table 2 and 2) a high density case at 0.9 \( n_c \) where the beam energy and power have been adjusted to 745 keV / 22.3 MW following the same guideline. Results show that at 0.5 \( n_c \), the NBI shine-through loads in the SB gap are much lower than the limit (~0.2 MW/m\(^2\)) instead of 0.8 MW/m\(^2\)), as shown in Figure 5, while at 0.9 \( n_c \), they approach the limit [38]. These results suggest that the guideline for shine-through loads in [28] for 2.65 T scenarios is not fully accurate when 1.8 T plasmas are considered, as expected. Therefore, the guidance for the NBI beam energy/power that can be used at 5 MA / 1.8 T for low density operation in Table 2 is conservative and high NBI powers with acceptable shine-through loads are possible in these conditions.

Figure 5 – Power densities of NB shine-through losses with 9.4 MW of 530 keV beams injected from off-axis (left figure) and on-axis (right figure) beam boxes in 5 MA / 1.8 T hydrogen plasmas, as calculated by BBNBI/ASCOT.

6. TRANSPORT MODELLING OF 5 MA / 1.8 T SCENARIOS

Transport modelling is required to predict the stationary kinetic profiles that are expected for 5 MA / 1.8 T plasmas in ITER. Coupled modelling of plasma transport with H&CD codes is essential to predict the time evolution of the plasma parameters when various H&CD schemes are applied. This evolution largely depends on the application of H&CD, whose heating efficiency/operational restrictions, in turn, depend on the plasma kinetic properties. Thus the waveform of plasma density and applied H&CD power has to be properly tuned to optimize the plasma scenarios in terms of H-mode access, H&CD absorption, etc.

Transport modelling of 5 MA / 1.8 T plasmas has been carried out with the ASTRA [4], DINA [8], JINTRAC [9], METIS [10] and CRONOS [7] suites of transport codes using transport models such as GLF23 [39], TGLF [40], CDBM [41], Bohm-Bohm [42] and EDWM [43] for L-mode and H-mode conditions. For PPPO-L plasmas all simulations provide similar results in terms of electron-ion decoupling in the central plasma region where ECRH is absorbed. EC heating of 5 MA / 1.8 T plasmas leads to very high electron temperatures in the plasma centre (\( T_e/T_i \approx 3-4 \)) due to the low operating densities leading to weak electron/ion coupling, as illustrated in Figure 6 from JINTRAC L-mode simulations. It is important to note that especially for PPPO-L the plasma density has to remain relatively low (~0.4–0.5 \( n_c \)) to allow H-mode operation with additional power level of 20–30 MW. Indeed ASTRA modelling shows that, despite the strong electron-ion decoupling in the centre, electrons and ions are well coupled at the edge ensuring sufficient edge ion power flow to access the H-mode provided that \( n/n_0 > 0.4 \) for both hydrogen and helium H-modes.

In addition to core transport modelling, integrated 5 MA / 1.8 T hydrogen H-mode plasmas with the full-JINTRAC code (including the SOL and divertor plasma) have been performed with the EDWM transport...
model. The results of these studies show that the divertor power flux at the outer divertor is expected to be very peaked ($\lambda_e \sim 5 \text{ mm at the outer midplane, similar to that expected in burning plasmas}$) and its peak can reach values of $\sim 5 \text{ MW/m}^2$ assuming toroidal symmetry. The actual power flux on the ITER tungsten mono-blocks is $\sim 50\%$ higher due to shaping effects [44]. Neon seeding is effective in reducing this power flux by $\sim 2$ while still in attached plasma conditions. The core tungsten concentration in these plasmas is very low despite the fact that no local re-deposition of tungsten is assumed in the simulations; this assumption results in a very conservative upper estimate of the tungsten divertor source. The low core tungsten concentration is due to the very effective screening of impurities in the pedestal plasma. This is due to the neoclassical temperature screening term being dominant in low edge density gradient/high edge temperature gradient conditions at the ITER pedestal leading to an outwards directed neoclassical impurity pinch velocity [45] [46].

The modelling above has been carried out assuming that EC heating with $170 \text{ GHz gyrotrons is efficient for 5 MA / 1.8 T}$. However as mentioned in section 3, this may not be the case for all plasma conditions or phases of the scenario and to evaluate this aspect requires specific modelling studies, which have been performed with the JINTRAC/GRAY suite of codes. Several phases can be distinguished in the 5 MA / 1.8 T scenarios considered: the Ohmic phase (with no additional heating), the EC-heated L-mode phase (with typically 10 to 20 MW of EC power) and the EC-heated H-mode phase (with 30 MW of EC power). The JINTRAC transport modelling suite uses the GRAY EC ray-tracing code (in single pass) and the Bohm-gyroBohm and EDWM transport models, both providing energy confinement times similar to those expected from the ITER-97L scaling [47]. To address the issues associated with $3^{rd}$ harmonic absorption of ECRH in these plasmas, a range of heating scenarios to achieve the H-mode are considered: first having a 10 MW or 20 MW L-mode phase before the 30 MW H-mode phase or going directly from Ohmic to H-mode by applying 30 MW of heating. In addition, the possibility of L-mode operation at low density first ($\sim 0.2 n_C$), then increasing the density to that required for H-mode access ($\sim 0.4 n_C$), has been explored. These simulations have considered a range of sawtooth (ST) frequencies from 1 Hz to 10 Hz, using the Kadomtsev model to calculate sawtooth reconnection [48] [49]. In general it is found that for all plasma conditions starting from Ohmic plasma conditions there is a short phase where ECRH first pass absorption is low. After a typical duration of $\sim 1$ s or less, 90% absorption of the EC power in single pass is achieved. Higher ST frequencies are less favourable for faster EC absorption as they keep the central temperature at lower values while the EDWM model predicts higher electron temperature/better EC absorption than Bohm-gyroBohm. Regarding the optimization of the L-mode density when heating Ohmic plasmas, no major improvement in terms of EC absorption has been observed when operating at 0.2 $n_C$ instead of 0.4 $n_C$, since the degradation of the absorption from lower density compensates the improvement from higher temperature. The evaluated EC power shine-through losses (i.e. non-absorbed power in first pass) for 10 Hz ST using the Bohm-gyroBohm model at 0.4 $n_C$ are summarized in Table 3 and illustrated in Figure 7 for various waveforms of the EC power. The results of this study show that applying higher EC power provides the fastest decay of EC shine-through power losses, but also leads to the highest instantaneous EC shine-through power at the beginning of the EC heating phase. The minimum value of EC shine-through loss is always reached in less than 2 s, and corresponds to an EC absorption above 99% for an applied EC power of 20 to 30 MW, and 90% for an applied EC power of more than 10 MW. In ITER, to remain within limits compatible with first wall power fluxes, the phase with low EC absorption should be shorter than $\sim 5$ s while EC absorption should be at least 90% in stationary conditions for 5 MA / 1.8 T H-modes. Hence no major issue is expected from the application of $170 \text{ GHz EC waves to heat these 5 MA / 1.8 T plasmas}$ and lower frequency gyrotrons are not required for EC heating at this field in ITER. Note that the need for low frequency gyrotrons for plasma start-up at 1.8 T will be determined following the operational experience with Ohmic breakdown in the First Plasma / Engineering Operations phase.

![Figure 6](image-url) - Time evolution of electron and ion temperatures at 5 MA / 1.8 T in H plasmas at 0.4 $n_C$ with 10 MW (top), 20 MW (middle) and 30 MW (bottom) EC power, as predicted by JINTRAC using the GRAY ray-tracing code. The 10 and 20 MW plasmas are in L-mode while the 30 MW plasma is in H-mode.
Finally, scenario simulations of 5 MA / 1.8 T plasmas with the DINA code [8] show that, with currents in the central solenoid (CS) below 30 kA/turn for which the CS lifetime consumption is negligible, the largest achievable flattop duration is ~700 s when applying 20 MW of EC power, thus allowing an initial assessment of long pulse operation. ITER routine pulse lengths will be typically of the order of 50–100 s in PFPO but longer pulse operation may be foreseen to test magnetic control and the robustness of plant systems in such conditions. These results indicate that there is no actual limitation on the pulse length from the magnetic control point of view for these scenarios and no lifetime consumption of the central solenoid is expected.

7. CONCLUSION

Integrated modelling of 5 MA / 1.8 T scenarios has been carried out in order to assess the feasibility of these operational conditions in ITER, to enable early H-mode operation in the Research Plan. Specific modelling of the H&CD sources has also been undertaken to address questions regarding absorption efficiency of each H&CD systems for these specific scenarios. Results show that operating the EC system with the 170 GHz baseline gyrotrons provides sufficient absorption for the successful operation of these scenarios and for providing early H-mode access in PFPO-1, assuming the L-H power threshold predicted by Martin’s 2008 scaling [3] and that the minimum density for H-mode access is provided by the scaling in [2]. The modelled H-modes do not appear to have specific problems regarding core/edge integration issues despite the low plasma densities foreseen. The main open issue regarding 1.8 T plasmas is the need for ECRH for plasma-start up assist which is not possible with 3rd harmonic; this will be resolved following the operational experience with Ohmic start-up in the First Plasma / Engineering Operation campaign. The large magnetic field ripple at 1.8 T in ITER, \( \delta_{\text{rip}} = -1.3\% \), had raised concerns about fast-ion ripple losses from the IC and NBI systems in PFPO-2. Operating with a larger gap (+40 cm) between the wall and the plasma to reduce the ripple to \( \delta_{\text{rip}} = -0.5\% \) has therefore been considered. The modelling results have shown that the IC power coupling would be reduced by an order of magnitude. Hence, operating with an increased gap would not be compatible with the application of high IC power. ICRH modelling has been carried out with the nominal plasma-wall distance, showing that the most efficient heating scheme involve 2nd harmonic H heating in both H and He plasmas, leading to efficient IC absorption even at relatively low H concentrations for He plasmas \( (n_{H}/n_{He}=7\%) \). Simple estimates suggest that the ICRH-accelerated ions are well confined at 5 MA / 1.8 T, but a quantitative assessment of the fast-ion losses due to the large magnetic field ripple has only started. NBI modelling results for PFPO-2 show that NBI first wall power fluxes, including ripple losses, remain within acceptable limits for the SBS for a range of 5 MA / 1.8 T H-
mode conditions, while allowing injected powers in the range of 10-20 MW by appropriate tuning of the beam energy. To conclude, operating at 5 MA / 1.8 T in ITER is predicted to provide the required H-mode plasmas to successfully fulfil the ITER R&D goals for the early phases, PFPO-1 and PFPO-2, of the ITER Research Plan.

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BIBLIOGRAPHY