ITER ramp up and ramp down scenarios studies in helium and deuterium plasmas in JET

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Abstract. Recently, attention is given to documenting the current ramp up and current ramp down phase of tokamak discharges in preparation for ITER. Until 2008, the experimental data from JET were been obtained in deuterium. The latest JET experiments in helium reproduce the experimental conditions of previous deuterium experiments at 2.66MA and 2.36T. Helium neutral beam injection is used together with argon frosting on the divertor cryo-pumps to provide effective pumping of helium. Results show that flux consumption for helium discharges during plasma initiation is higher compared to deuterium. For the current rise phase, matched ohmic discharges show little difference in the plasma inductance values ($l_i(3)$) at the end of the current rise. The data in helium have been extended to plasma densities $\sim<n_e>/n_{GW}\sim0.5$, producing $l_i(3)\sim0.92$ at the end of the current rise, surprisingly lower than ohmic discharges at $\sim<n_e>/n_{GW}\sim0.2$ and $l_i(3)\sim0.98$. In helium, a current rise phase in H-mode can produce $l_i(3)\sim0.75$, however, in heated L-mode discharges $l_i(3)$ is systematically higher compared to the deuterium references cases. TRANSP analyses of these L-mode cases shows that although the total heating power is comparable, the electron heating in JET is reduced in the centre for helium leading to lower temperatures and higher values for $l_i(3)$. For the current ramp down it is important to maintain a divertor configuration to the lowest possible plasma current. Studies without additional heating (ohmic), show that the flux consumption and $l_i(3)$ excursion can be controlled during the ramp down using a (strong) reduction in plasma elongation, although at a slow current ramp down rate. When additional heating is available, it is important to stay in H-mode during the current ramp down phase allowing operation at $l_i(3)<1.3$. Discharges in L-mode still observe an increase of $l_i(3)$ comparable to ohmic reference cases. Overall, deuterium and helium discharges have similar plasma inductance evolution and flux consumption during ramp down.

1. Introduction

In the preparation of discharge scenarios for ITER, experimental documentation of the current ramp-up and current ramp down phase is important. These key parts of the ITER baseline scenario are determined by the capability of the proposed poloidal field coil set, power handling of the first wall and capabilities of the proposed heating systems to produce a safe and reliable ramp up and ramp down phase of the discharge. The bulk of the experimental data from JET and other tokamaks have been obtained in deuterium. However, the experimental exploitation of ITER calls for a non-active phase using hydrogen or helium plasmas to test key components of the device in preparation for the active phase using deuterium and deuterium-tritium mixtures.

In ITER, the ohmic (OH) transformer must provide sufficient flux for the plasma ramp up to 15MA within 60s to 100s with an early X-point formation at ~3.5MA (15s-20s), maintain a flat top of typically 400s (at 15MA) and provide a robust plasma termination phase. The proposed ramp up scenarios for ITER have a plasma inductance, $l_i(3)$ of 0.7 to 1.0, using a

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[*] See the Appendix of F. Romanelli et al., paper OV/1-3, this conference

density, $<n_e>/n_{GW}$, in the range 0.2 to 0.5. The ramp down phase must terminate the burn, exit from H-mode, avoid vertical instability by controlling the increase in $l_i(3)$ and remain in X-point as long as possible to maintain particle and power handling while avoiding additional flux consumption from the OH coil.

JET completed a full set of experiments on the ramp up phase in deuterium in 2008 using a current ramp up phase of 6s-10s to 2.65MA at 2.36T [1]. These experiments documented the conditions in ohmic plasmas with various current ramp rates, comparing small bore versus full bore plasma during limiter phase and highlighting the benefit of using an early X-point formation. Both L-mode and H-mode plasmas were studied at various different heating powers, using ion cyclotron resonance heating (ICRH) and neutral beam injection (NBI). Using TRANSP analysis [2], the consistency of the available experimental data was checked, providing input for extensive modelling activities [3]. The results contributed to proposals for design modifications to the ITER coil set and divertor. In 2009, experiments in helium were performed at JET. For the ramp up phase, the 2008 results [1] are a reference for the helium discharges obtained in 2009.

The current ramp down phase was studied starting at q_{95}=3 (2.65MA/2.36T). The experiments in 2009 concentrated on the ohmic ramp down phase and the merits/demerits of staying in H-mode or L-mode during the ramp down in order to document heating requirements during ramp down in both deuterium and helium.

In this paper we report the new results and analysis on the ramp up phase in helium and of the ramp down phase, concentrating on the ohmic ramp down experiments in deuterium.

2. Current ramp up experiments in helium

New experiments in helium duplicated the conditions of previous deuterium experiments. The neutral beam injection system was converted to helium for these experiments. Helium pumping was provided by using argon frosting of the in-vessel divertor cryo-pumps, allowing a match of the plasma density to the deuterium reference cases. In 2009, the diagnostics provided better time and spatial resolution (compared to 2008) for the n_e and T_e profile measurements, using a new reflectometer system and a High-Resolution Thomson scattering respectively.

For the plasma breakdown phase, both the deuterium reference pulses and the recent helium discharges use a low loop voltage (~0.3-0.4V/m on axis), comparable to the maximum reference loop voltage foreseen in ITER. Even after optimising the prefill pressure, the helium discharges have a slower initial plasma current build up and have higher flux consumption from the ohmic transformer during plasma initiation compared to deuterium. This is due to the higher ionisation potential for helium, while recycling of the helium prefill gas leads to a more resistive plasma initiation at higher density. The increased flux consumption is seen in Figure 1; the ohmic power and current increase in the transformer circuit are higher in helium at t=0.4s.

Detailed studies of the ramp up phase in helium included variation of the plasma current ramp up rate for ohmic helium plasmas from 0.28MA/s to 0.36MA/s, a comparison of full bore with early X-point formation vs. aperture expansion and the effect of heating in L-mode and H-mode during the ramp up.

Apart from higher flux consumption for helium discharges during plasma initiation, ohmic discharges with the same plasma current ramp rate and plasma density, show little difference in the plasma inductance values at the end of the current rise phase (see Figure 1 and Table I). Moreover, similar to the deuterium cases, helium discharges do confirm that good control of the plasma inductance is obtained by using a full bore plasma shape with early X-point formation at 0.8MA (equivalent to forming a diverted plasma shape at 4.5MA in ITER).

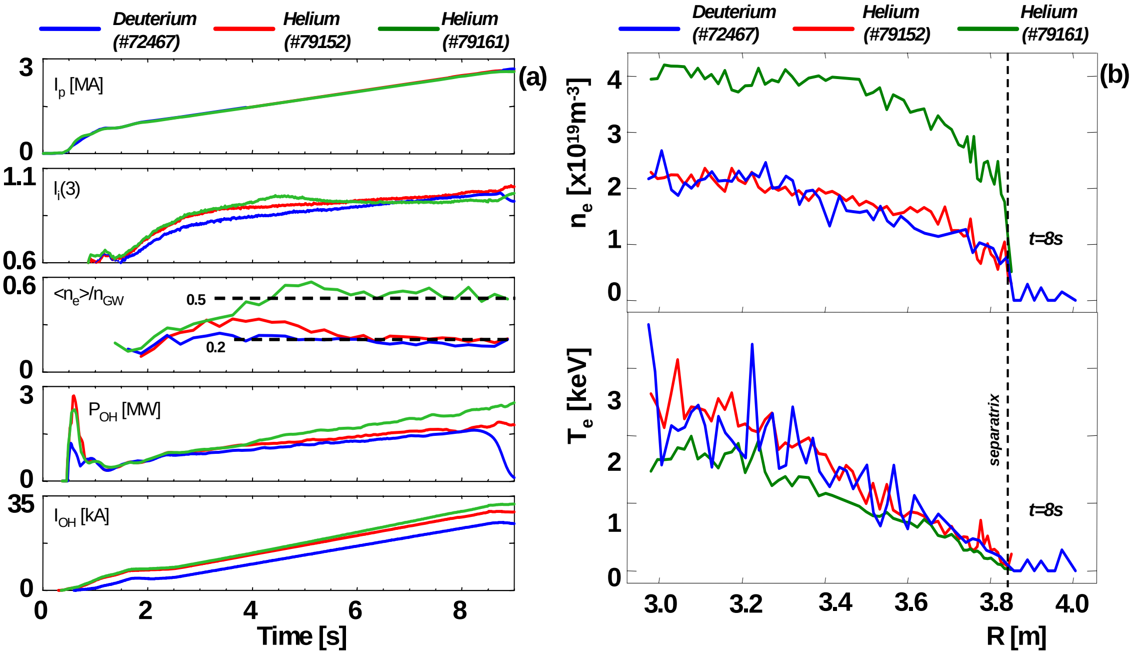

Figure 1: 2.66MA/2.36T (q_{95}=3). A comparison of three ohmic current ramp up scenarios: 1) A deuterium reference case at low density (blue curves), 2) a helium discharge (red curves) matching the deuterium conditions and 3) a helium discharge at higher density (green curves). Figure (a): Plasma current, plasma inductance, plasma density, ohmic power and current in the ohmic circuit. (b): The density profiles and temperature profiles at t=8s.

To extend the data available in deuterium, ohmic discharges at significantly higher density were studied in helium, by increasing in the density from $<n_e>/n_{GW}=0.18$ to $<n_e>/n_{GW}=0.48$ during the ramp up. The ohmic reference discharges in deuterium did not exceed $<n_e>/n_{GW}\sim0.3$. As shown in Figure 1, the discharge at the highest density, has only a slight increase (~6%) in OH current, but produces a lower value for $l_i(3)=0.92$ at the end of the current rise, compared to $l_i(3)=0.98$ at lower density. At higher plasma density, the discharge has increased resistive flux consumption due to a lower average electron temperature, but the profile is flatter resulting in a less peaked current density profile.

Like in deuterium, H-mode transitions during the current rise are possible in helium plasmas. Only during H-mode, $l_i(3)$ values below 0.85 are obtained. This is shown in figure 2. The discharge in H-mode (#79163) does have, however, a rapid density increase after H-mode transition, leading to a back transition to L-mode before making another transition to the H-mode during the final stage of the ramp up, achieving $l_i(3)\sim0.75$. This behaviour is indicative of operation at low power above the L to H threshold power.

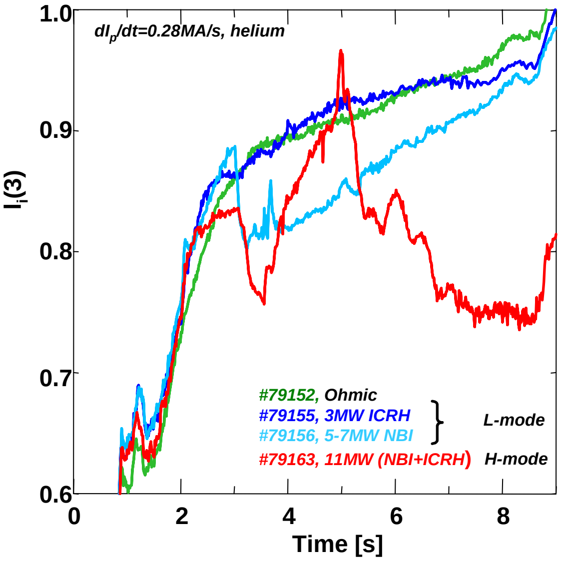

Figure 2: The evolution of the plasma inductance for four helium discharges at various heating levels. Only #79163 makes a transition to H-mode at t=3.0s and t=6.0s

A detailed comparison of a current rise in deuterium and helium with additional heating is given in Figure 3a. The heating power (ICRH=3.5MW) applied in the deuterium reference case is just enough for H-mode, a transition occurs only after 4 seconds of heating. The matched helium discharge stays in L-mode throughout. Due to limited experimental time for ramp-up studies in both deuterium and helium, no detailed scans are available for determining the power required for H-mode access at different plasma densities. Typically, at line averaged densities in the range $<n_e>=1.2$-$1.6\text{x}10^{19}\text{m}^{-3}$, H-mode is achieved in helium using 6-11MW additional heating during the ramp up phase, compared to 3.5-7MW input power in deuterium discharges. The data available are shown in Figure 3b.

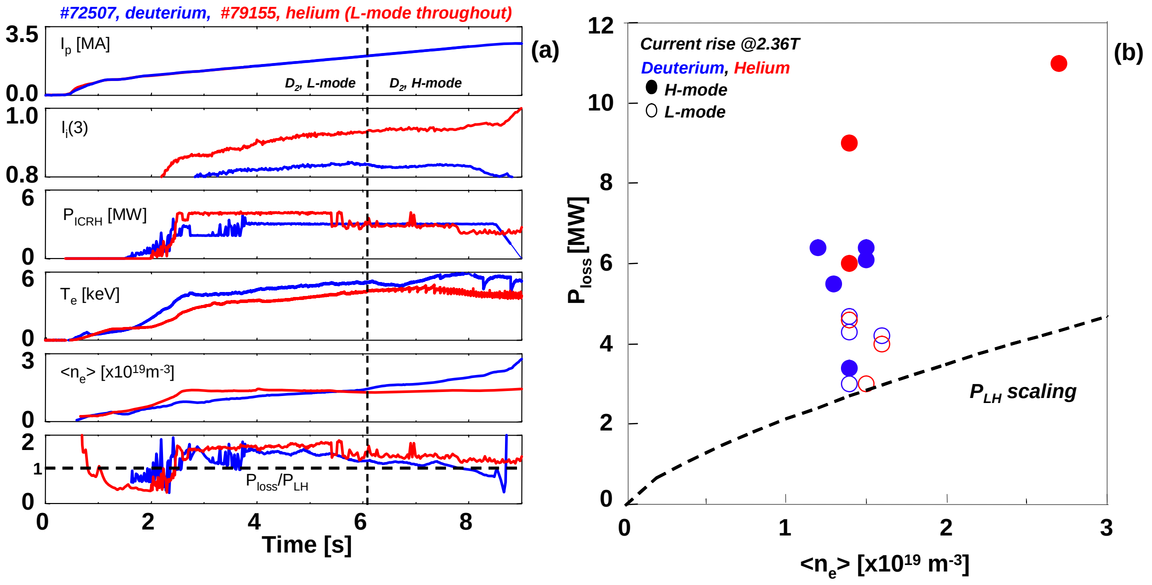

Figure 3: Comparing the H-mode behaviour in deuterium and helium during the current rise phase. Figure (a): Plasma current, plasma inductance, ICRH power, central electron temperature, plasma density and input power normalised to the H-mode threshold scaling for deuterium. (b) Overview of the heating power applied during the current rise phase in deuterium and helium.

An overview of the deuterium and helium ramp up experiments is given in Table I. The main difference between deuterium and helium in JET is for L-mode plasmas with moderate heating. To clarify these differences, analyses of the L-mode cases using TRANSP have been performed, the result of which are reported in the next section.

	Deuterium		Helium	
Type	**Heading**	$l_i(3)$	**Heating**	$l_i(3)$
Small bore	Ohmic	**1.0-1.1**	Ohmic	**1.1**
Full bore	Ohmic	**0.96**	Ohmic	**0.97**
Fast dI_p/dt	Ohmic	**0.83**	Ohmic	**0.86**
L-mode	LHCD: 1-2MW ICRH: 3-4 MW NBI: 2-5 MW	**0.81-0.87**	ICRH: 3 MW NBI: 3-6 MW	**0.93-0.95**
H-mode	ICRH: 5-6 MW NBI: 6-10 MW	**0.67-0.76**	ICRH+NBI: 11 MW	**0.75**

Table I: Values for $l_i(3)$ at the end of the current ramp phase, evaluated using EFIT, in deuterium and helium: 2.66MA/2.36T (q_{95}=3).

3. TRANSP analyses of L-mode ramp up discharges in deuterium and helium

TRANSP analyses have been used extensively for the deuterium reference cases [2], to check the consistency of the available experimental data. The electron density profile and the electron temperature profile are provided by LIDAR or High-Resolution Thomson scattering systems, the electron temperature is also measured with ECE diagnostics. For ohmic and ICRH heated discharges, typically no information is available on the ion temperature (T_i), plasma rotation (V_{tor}) and the profile for Z_{eff}. For the interpretation of the deuterium data, TRANSP uses the thermal DD neutron yield for a rough estimation of T_i. For helium discharges, no ion temperature data is available (not even during NBI heating), while no DD neutron yield data is available to provide estimates for T_i. Typically, TRANSP interpretation shows the safety factor in the centre (q_0) dropping too quickly in time below 1, compared experimental estimates based on the start of sawteeth activity. The peaking factor of the Z_{eff} profile can be increased to obtain better agreement with the experiments.

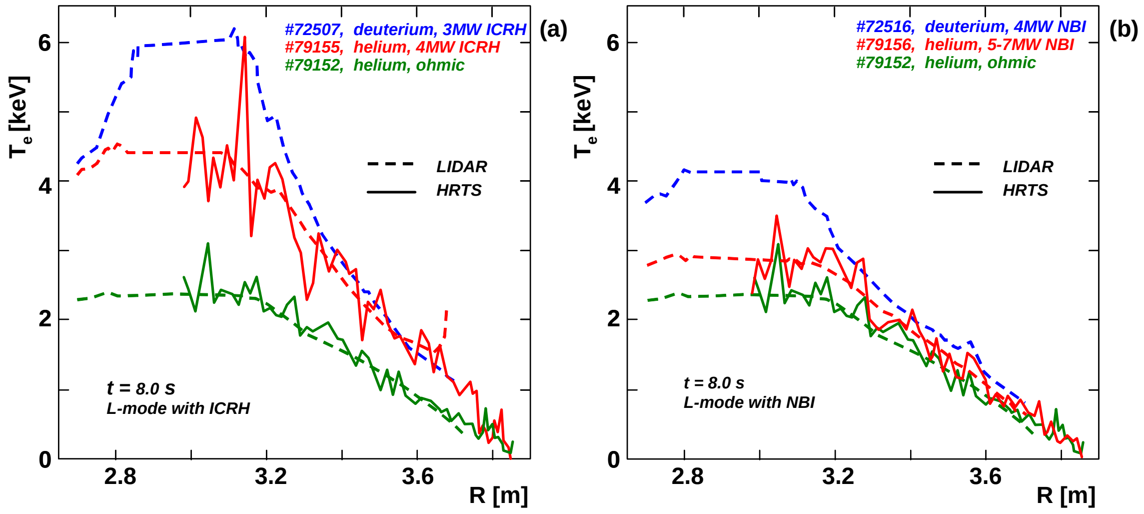

Figure 4: The electron temperature profile for two L-mode cases: (a) ICRH heating and (b) NBI. The helium data are compared to deuterium reference cases and ohmic helium discharges.

Two L-mode discharges in helium at moderate input power of 3-4MW have been analysed with TRANSP. The first discharge, also shown in Figure 3a, has ICRH using hydrogen minority heating at a minority concentration of ~1%. During the helium campaign, no hydrogen gas was used leading to significantly lower hydrogen concentrations compared to the deuterium reference case (~5%). The second discharge is heated by neutral beams, using a similar injection energy compared to the deuterium cases. In helium neutral beams inject 100% at full energy, while in deuterium the neutral beams have ½ and ⅓ energy components. The temperature profiles at the end of the current rise phase of these ICRH and NBI helium discharges are given in Figure 4 and are compared to the deuterium reference cases. The temperature of helium discharges reaches only ~70% of the temperature in deuterium discharges. TRANSP analyses using TORIC to compute the ion and electron heating in the ICRH discharges, shows a distinct difference between helium and deuterium caused by the much lower hydrogen minority concentration in helium. For a 1% minority concentration, the dominant electron heating from ICRH has a much broader power deposition compared to electron heating at 5% minority concentration. This results in a lower electron power density on-axis as can be seen in Figure 5a. Analyses of the neutral beam heating (NUBEAM) shows an increase in shine-through of 41% in helium, compared to 23% in deuterium. Moreover, the electron heating of the helium beam is roughly a factor 3 lower compared to deuterium. We conclude from these analyses that while the total power is matched in the helium and deuterium discharges in JET, the reduced core electron power density may explain a reduction in electron temperature in both ICRH and NBI.

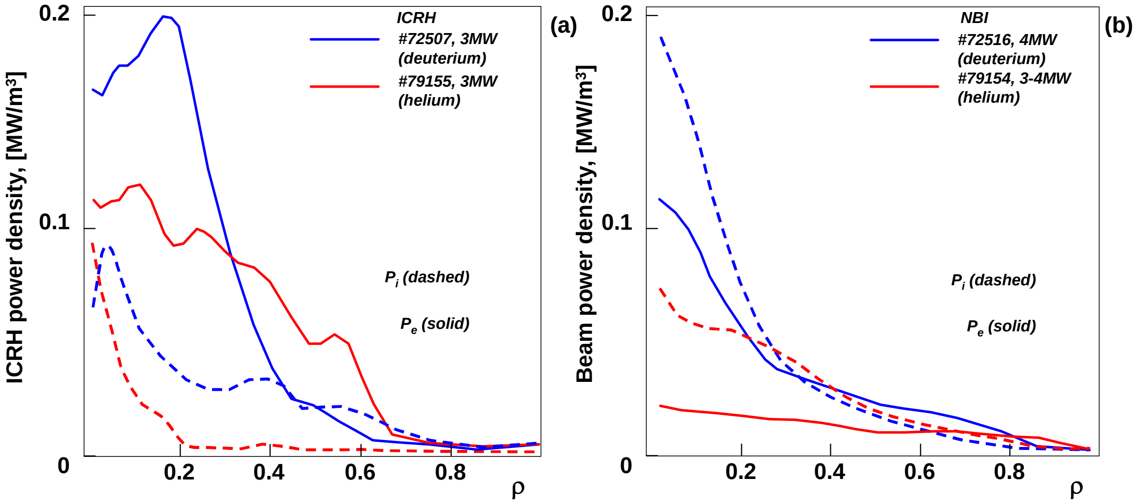

Figure 5: The electron power density profile for two L-mode cases: (a) ICRH heating and (b) NBI. The helium data are compared to deuterium reference cases.

4. Current ramp down studies in deuterium

The current ramp down phase in JET starts at q_{95}=3 (2.65MA/2.36T), the discharges remain diverted during the ramp down to achieve good density control and to allow the use of additional heating. In ohmic deuterium discharges, the current ramp down rate was varied in several steps from 0.07MA/s to 0.65MA/s. Important for ITER is to have no flux consumption during the current decay phase and to limit the excursion of $l_i(3)$ to ensure vertical stability. As shown in Figure 6a, the slowest current ramp down rates (0.07MA/s and 0.14MA/s), lead to an increase in the current in the ohmic transformer, but lead to the lowest increase of the plasma inductance to $l_i(3)$=1.2 for 0.07MA/s and to $l_i(3)$=1.4 for 0.14MA/s. At fixed toroidal field of 2.36T, the plasma safety factor, q_{95}, increases during the ramp down phase. When changing the current ramp rate, the trajectory of the discharge in the $l_i(3)$-q_{95} plane does change, as shown in Figure 6b, indicating that slower ramp rate does reduce the plasma inductance for a given current level. However, using the current ramp down rate alone does not achieve the aim of both avoiding flux consumption and minimising $l_i(3)$ excursion.

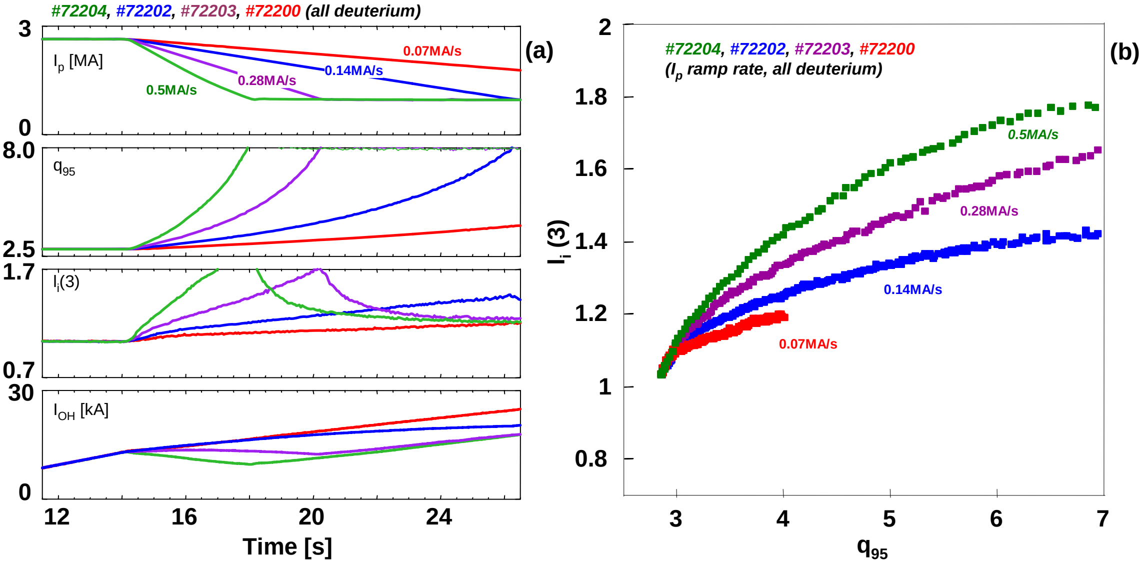

Figure 6: The evolution of four discharges for different current ramp down rates. Figure (a): Plasma current, q_{95}, plasma inductance and current in the ohmic circuit. (b): Evolution in the $l_i(3)$-q_{95} plane.

Reducing plasma elongation, κ, reduces the growth-rate for vertical displacements. JET has studied ohmic ramp down discharges at fixed current ramp down rate of 0.5MA/s, starting at κ=1.75. In a series of experiments the plasma was compressed, until the plasma current reaches ~50% of the flat top value, giving a range for κ =1.63 down to 1.43 (See Figure 7). For a ramp down rate of 0.5MA/s, a strong decrease in κ=1.43 results in an increase in of $l_i(3)$ to only ~1.3, without using flux from the transformer. For comparison, a discharge with a elongation reduction to 1.63, gives an increase in $l_i(3)$ to ~1.7. In the $l_i(3)$-q_{95} plane, the four discharges shown in Figure 7a do follow the same trajectory, as shown in Figure 7b. The change of plasma shape is also shown in Figure 7b.

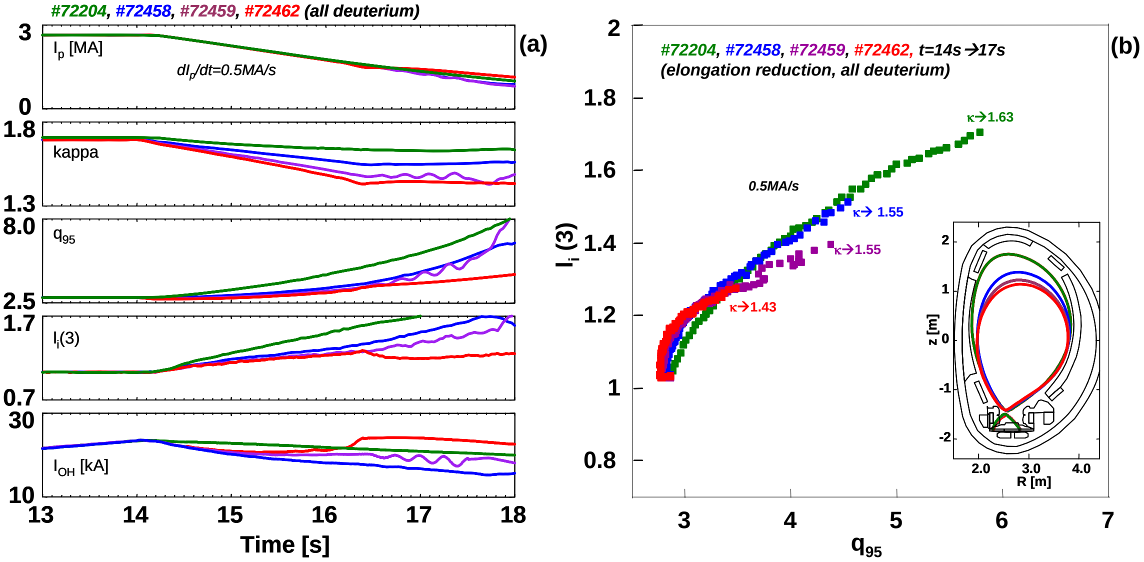

Figure 7: The evolution of four discharges for different elongation reduction during the current ramp down. Figure (a): Plasma current, elongation, q_{95}, plasma inductance and current in the ohmic circuit. (b): Evolution in the $l_i(3)$-q_{95} plane, the inset shows to plasma shape at t=16.5s

This demonstrates that when heating is not available, the flux consumption and $l_i(3)$ excursion of the ohmic discharges can be controlled be choosing the appropriate ramp down rate combined with a (strong) reduction in plasma elongation. However, it remains to be demonstrated that this is a viable scheme for ohmic ramp down scenarios in ITER.

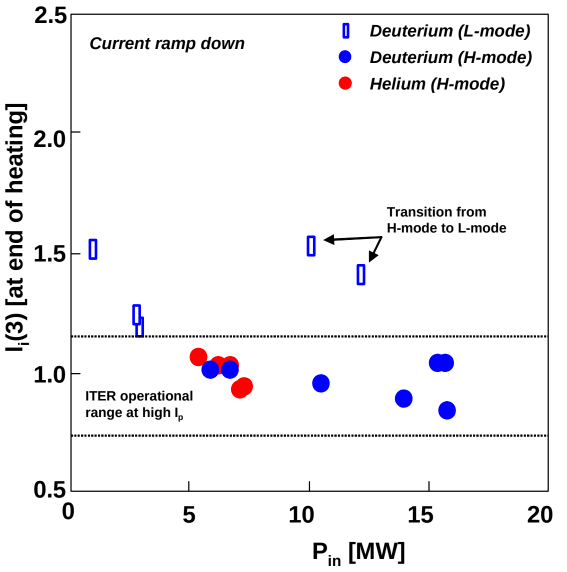

Figure 8: The plasma inductance at the end of the additional heating phase, during the current ramp down, plotted against the applied heating power.

Using >4MW of additional heating, the plasma is typically in H-mode during the ramp down phase, as shown in Figure 8, this level of additional heating is close to the scaling predictions (not including current ramp data). However, some discharges using a fast ramp down rate of ~0.5MA/s do not remain in H-mode, despite applying heating powers well above the L- to H-mode transition power; these are indicated in Figure 8. In H-mode, the plasma inductance during the current ramp down phase can be maintained between 1.0 and 1.2 for a current ramp down rate of 0.14MA/s. It is important to stay in H-mode during the current decay, as discharges in L-mode still observe an increase of $l_i(3)$, independent of heating power, to values of 1.4-1.5, which is comparable to the ohmic reference cases. In general however, deuterium and helium discharges show little difference in $l_i(3)$ values and the flux consumption up to the end of the ramp down is similar.

5. Conclusions

Based on these new JET results, helium operation provides conditions close to deuterium reference pulse and provides a good test of the operational space available for the current ramp up and current ramp down phase of the discharge. Any of the differences observed are linked to the heating systems providing less electron heating in the experimental conditions for helium in JET. Combined with previous experiments, these new data do confirm that the plasma configuration, the current ramp rate, having sufficient electron heating and use of H-mode are the key ingredients in providing the access and control to stable operation during the current rise and current ramp down phase of a plasma discharge.

Acknowledgements

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