Multi-machine analysis of termination scenarios, providing the specifications for controlled shutdown of ITER discharges

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1. Introduction

The termination phase should achieve a simultaneous ramp-down of the magnetic energy (plasma current) and kinetic energy while maintaining control over the radiation levels, plasma position and shape (i.e. avoid overheating the first wall) and vertical stability (VS), staying within the capabilities of the power supplies, poloidal field coils and heating systems. To improve our understanding of the dynamics and control of ITER terminations, a study has been carried out on data from existing tokamaks. The aim of this joint analysis is to compare the assumptions for ITER terminations with the present experience basis to show whether the specific ITER design features allow a stable well-controlled termination [1]. The study examined the parameter ranges in which present day devices operated during typical terminations, as well as the dynamics of these parameters. The results from this analysis can be used to better prescribe the inputs for the modelling and preparation of ITER termination scenarios.

2. Specifics of ramping-down an ITER discharge

A controlled termination of an ITER discharge needs to reduce the input power, ending the fusion burn and causing an H -L back transition and ensure a controlled ramp-down of the plasma current. Stability boundaries and general operational limits must also be avoided. ITER is projected to operate at 85% of the empirical density limit and a controlled density decay is important to avoid this limit, while also managing the H-L transition timing and exit from fusion burn. At the start of the current ramp-down, in H-mode, the Greenwald density limit (n_{GW}) should be avoided while towards the end of the current ramp-down in L-mode the detachment limit may be more relevant. ITER power supply limitations and the thick vessel slow the control response for vertical stability (VS) and the radial position. It was found that VS control can be maintained in ITER by restricting the increase in internal inductance ℓ_i (e.g. by keeping the temperature high) and reducing the elongation, κ [2-4]. Changes to the shape are obviously restricted by the PF coil limits and for elongation changes the power flow diverted to the upper part of the blanket and the position of

upper strike points also need to be controlled. In ITER, plasmas heated by auxiliary power should remain diverted, while at currents of I_p~7.5MA or above, the blanket can sustain Ohmic power for only a short time (~a few secs). A fast drop in β_p during the H-L transition may result in an uncontrolled inward radial motion. This means the plasma could touch the inner wall or become less vertically stable as it loses its proximity to the vessel. Typically, the volume is reduced by 25% and the elongation to κ~1.68 in the first quarter of the current ramp-down. The elongation is then further reduced to κ~1.5. The volume reduction also allows for a larger radial movement at the time of the H-L transition. But as a consequence of this volume change, q_{95} remains around 3 for almost half of the current ramp-down (i.e. up to ~100 s after the start of the Ip ramp-down), only to increase afterwards.

Various solutions are proposed to overcome these issues for ITER terminations. The design of a termination scenario can place different weights on each constraint, e.g. reducing the plasma volume allowing a larger radial excursion, hence a larger drop in β_p [5]. These weights also depend on the goal of the termination. A normal ITER termination should aim to be in full control until the current is below I_p=3MA, when the direct disruption impact is expected to be benign. The limit may be lower when runaways are considered. The fastest ITER current ramp-down is limited by the PF coil voltages and by the requirements to control shape, position and VS stability with a specified precision. In ITER, a fully controlled current ramp-down from I_p=15MA to below I_p=1MA is possible in ~60s.

3. Multi-device analysis

A database has been created consisting of typical, special and ITER-like terminations from Alcator C-Mod, ASDEX Upgrade, DIII-D, EAST, JET, KSTAR, NSTX/NSTX-U and TCV. Wide ranges of heating schemes were used in the database terminations. The emphasis of the analysis presented in this paper is on the termination from H-mode. It should be noted that the database only comprises a small selection of discharges that do not necessarily span the full capabilities and parameter ranges of each device.

Using the database one can compare time scales relevant to the ramp-down of the magnetic and kinetic energy. Fig. 1a shows the average input power ramp-down time, normalized to that of the current. Some terminations in present day devices, aimed to limit the increase of internal inductance, have relatively long power ramp-downs. But, for typical ITER terminations, the power ramp-down, and consequently the decay in thermal energy, is relatively fast.
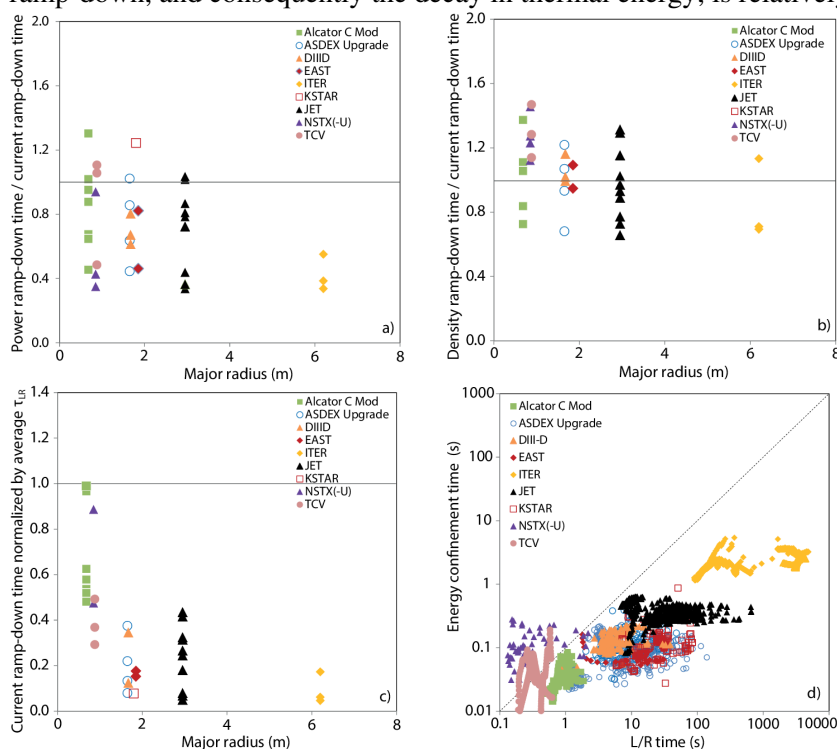

Fig. 1: *a) The ramp-down of the heating power time normalized to the current ramp-down, for each database entry, arbitrarily plotted against the device major radius. b) Normalized ramp-down of the density. c) Current ramp-down time normalized to the plasma resistive time, τ_{LR}. d) For all database entries, the energy confinement time, at each time step during the termination, versus the L/R time, where L is the plasma inductance and R its resistance. Note that the τ_{LR} is related but not identical to the L/R time.*

The reason is that a large fraction of the power is due to α-heating. Ramping down the current, the loss in confinement will quickly reduce this important heating component, making it difficult to maintain H-mode over a large part of the current decay. Secondly, Fig. 1b shows that the average ramp-down of the density is relatively slow compared to the current ramp-down, for most entries. Fig. 1c, shows that current ramp-down times in the database for larger devices are generally a smaller fraction of the L/R time (with L the plasma inductance and R the plasma resistance): $\tau_{L/R}$ (here averaged over the first half of the current decay). Finally it is shown in Fig. 1d that for larger devices the L/R time increases relative to the energy confinement time.
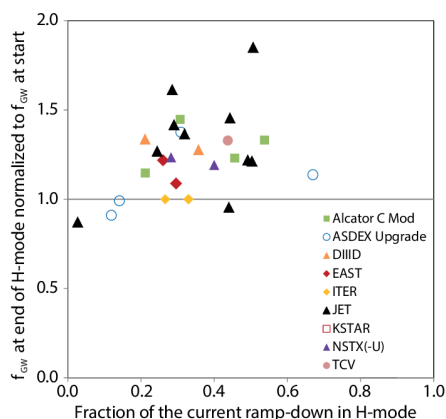

Fig. 2: *The change in Greenwald fraction from the start of the current ramp-down until the H to L transition. b) The scaling of the radiative power with the density over the entire ramp-down for all time steps for all entries in the database.*

3. Density decay in H-mode

It was found that usually β_p and Greenwald fraction, f_{GW}, (= n/n_{GW}) increase when ramping down the current, while still in H-mode. Fig. 2 shows the change in, for example, f_{GW} during the ramp-down, until the H-L transition. It means that the H-mode density, likely linked to the pedestal density, decreases slower than the plasma current. The consequence is that the time one can keep the plasma in H-mode is limited. For a termination of a discharge with an already high f_{GW}, one cannot allow this to increase much further and one has to limit the H-mode duration, making an earlier transition to L-mode to avoid the density limit. This affects the possibility to control the increase in ℓ_i by staying in H-mode and maintain a high temperature, during the current ramp-down.

4. H to L mode back transition

The magnitude and duration of the H-L transition itself affect the ability to control vertical and radial position. The drop in β_p over the H-L transition was determined by calculating the peak derivative normalized to the average energy confinement time. Fig. 3a shows the values are lower for those cases that gradually ramp-down the input power (i.e. the power at the HL transition is smaller with respect to the power at the start of the termination) or those that have a shorter H-mode phase with respect to the current ramp-down. Similar observations are made for the change in density or f_{GW} [1]. The H-L transition duration was determined by calculating the FWHM (i.e. Full Width at Half Maximum) of the time derivative of β_p, over the transition.

Figure 3b shows that for all devices the duration lasted between 1.5-3×τ_E. The shortest transitions were found for those entries that had the transition later in the termination, at a higher value β_p prior to the transition. Slower, and thus softer, transitions are found for those cases that ramped down the input power rather than to step it down instantly.
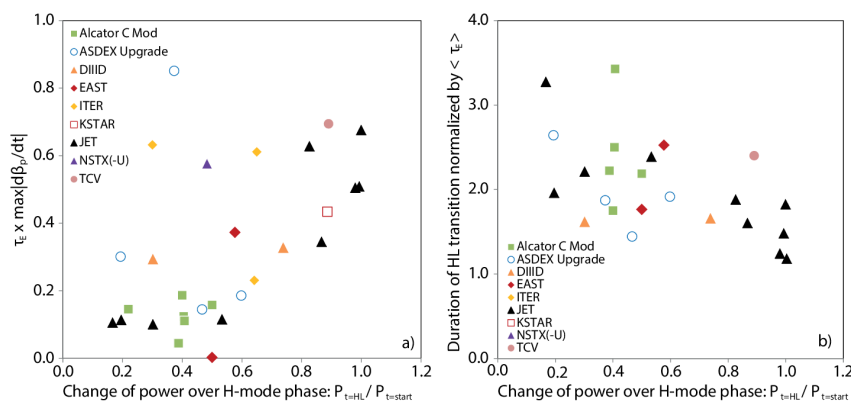

Fig. 3: a) The peak change (i.e. decrease) in β_p, at the time of the H-L transition, normalized to $<\tau_E>$ (averaged over the duration of the H-L transition). Note that in both graphs the ITER points represent assumed changes. b) The duration of the H-L transition, defined as the FWHM of $d\beta_p/dt$, normalized to $<\tau_E>$.

5. Radiation

Radiation can have a strong influence on the termination, changing dynamics and affecting plasma behaviour. For example Fig. 4 shows the variation in the H-L transition time with the radiative power faction for a series of 121 identical JET H-mode terminations (not included in the database). Higher radiation results in an earlier H-L transition. Assuming the right radiation and impurity levels is therefore important for accurate modelling of these scenarios. Fig. 4b, shows how the assumed ITER radiation falls below the experimental cases, when normalized with the volume and density squared. The modelled ITER cases usually start the termination with a dominant contribution of bremsstrahlung and a lower level of low-Z line radiation, which contribution increases towards the end of the current ramp-down. It is however not evident if the values used in these modelled ITER terminations are consistent. Self-consistent calculations of the impurity content and resulting radiation would improve the modelling of ITER termination scenarios [6].

Fig. 4: a) The duration of the H-mode, normalized to the energy confinement time, as a function of the radiative power. b) Radiative power over the entire termination, normalized to the plasma volume, versus the electron density. The dashed lines indicate the radiation quality values of 0.1 and 1.0×10^{-40} (MW m3).
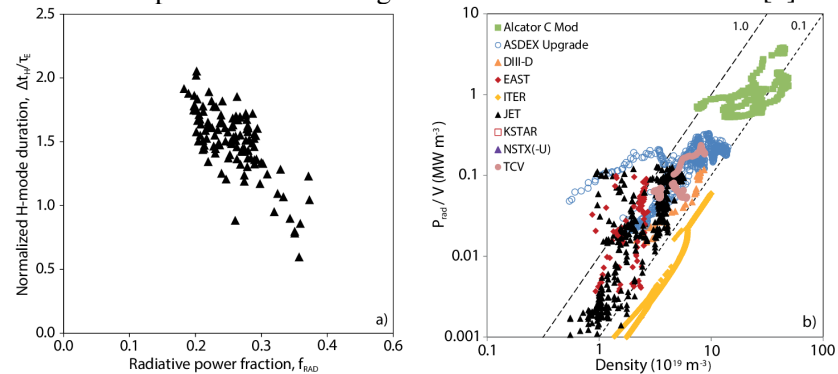
6. Conclusions

The database, built using a selected set of experimental termination cases, showed many similarities in the particle dynamics and current density behaviour. Differences are usually related to the specific control and heating capabilities of each device. Relevant for ITER is to maintain vertical, radial position, and shape control during the termination, especially at the time of the relatively fast H-L transition. ITER terminations will benefit from controlled H-L transitions. The task is to show that the specific ITER design features allow a stable well-controlled termination. This is a joint effort in control, exception handling development and physics modelling.

In the development of termination scenarios, the basic scaling of parameters used for steady-state situations may not be valid for dynamic situations. For example, assumptions how the pedestal pressure (and pedestal density) scale with plasma current are known for steady-state but may differ when ramping down the current. The same is true for the HL threshold. Furthermore, the dynamics of the changes (ramp-down) of magnetic and thermal energy, are coupled, and do not scale the same from present-day devices to ITER. The dynamics also depend on the available actuators. Thus a full integrated assessment of the robustness of proposed ITER terminations can only be performed by detailed modelling of the plasma dynamics and control.

References

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