

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



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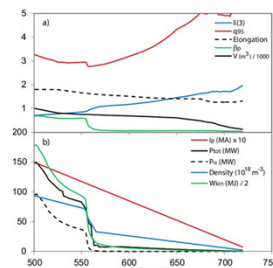
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## Introduction

The controlled shutdown is an often overlooked, though important, phase of the tokamak discharge. The dynamics during this phase complicate control, making it difficult to avoid operational limits, which in the worst case, may lead to a disruption. This is exacerbated by the fact that at the end of the discharge, the device is already operated close to many of its technical limits. For unplanned terminations, triggered by off-normal events, the situation complicates further. The ability to carry out a well-controlled termination contributes significantly to the avoidance of disruptions. 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. The study examined the parameter ranges in which present day devices operated during their terminations, as well as the dynamics of these parameters.

## ITER termination scenarios: restrictions and example

There is no single solution to ensure ITER terminations remain within its technical restrictions and physics limits. The design of a termination scenario can place different weights on each restriction, e.g. reducing the plasma volume allowing a larger radial excursion, hence a larger drop in  $\beta_p$ . These weights also depend on the goal of the termination.

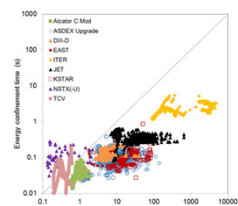


- What is the goal of the termination?
- Reduce magnetic and kinetic energy
- Maintain vertical stability → control li and elongation
- Maintain radial control → smooth H to L back transition
- Remain diverted for power exhaust → shape control
- Avoid other operational limits → density limit
- Control radiation and impurities
- Avoid disruptions

← A modelled, typical, ITER termination (Corsica Hmode\_15MA\_13) from  $I_p=15MA$  at full performance ( $W_{tot}=350MJ$ ,  $P_e=100MW$ ). Note that other variants are possible

## Database of tokamak terminations

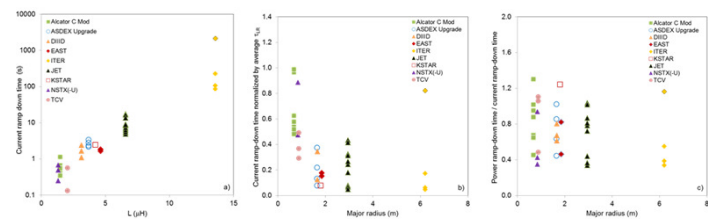
A database has been created consisting of typical, special and ITER-like, terminations from Alcator C-Mod, ASDEX Upgrade, DIII-D, EAST, JET, KSTAR, NSTX/NSTX-U and TCV. Hence, there are examples from devices with full metal walls that can be compared with those with carbon walls, and two devices that, like ITER, have super-conducting coils. Wide ranges of heating schemes were used in the database terminations. DIII-D JET and TCV provided also ohmic terminations, although the emphasis of the analysis presented in this paper is on the termination from H-mode.



The dynamics of a discharge termination can be described by typical parameters as: the current and power ramp-down time, the duration of the H-mode phase, the decay of the density or  $\tau_E$  and  $\tau_{L,R}$ .

These parameters do not always scale similarly between devices and large variations within a terminations are possible

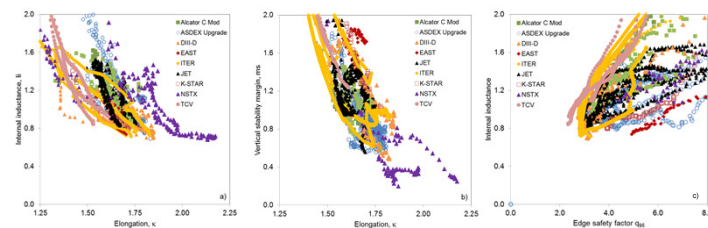
- For typical ITER terminations
- Power turn-off in ITER, relatively fast
- Current decay fast compared to  $\tau_{L,R}$



## Comparison of stability aspects

Maintaining VS is an important aspect for a termination. The VS of the plasma depends on a complex function of  $l_i$ ,  $\beta_p$  and elongation  $\kappa$ , and furthermore, on the proximity of the plasma to stabilizing passive components, such as the vacuum vessel in ITER, and on the capability of the VS control circuit. The latter factors differ from device to device and this does not make a comparison straightforward. The complex relationship between vertical instability  $l_i$ ,  $\beta_p$ ,  $\kappa$ , can be expressed by the so-called marginal stability parameter [1,2]:

$$m_s = \frac{1.47(1 + e^{-2l_i+1})}{2(\kappa - 1.13)} - 1 \quad (1 + 0.6(\beta_p - 0.1))$$

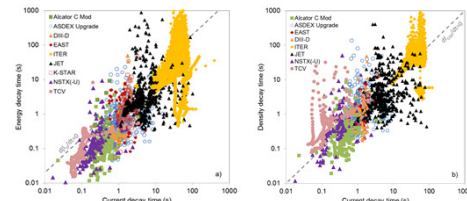


- To counter the relatively fast power shut down, the modelled ITER cases apply a more aggressive reduction in  $\kappa$ , than most present day devices, to maintain VS.
- The result is that in these cases,  $q$  remains low ( $\sim 3$ ) for the first half of the current ramp-down.
- These ITER cases track the upper boundary of the  $l_i$ - $q$  diagram.
- The marginal stability parameter remains (well) above 0.5 for the modelled ITER cases

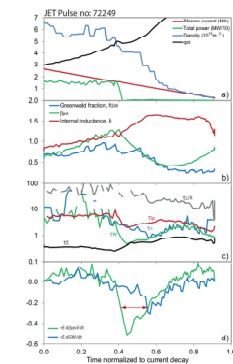
## Comparison of dynamics

While in most cases the current is ramped down at a constant rate, the decay rates of thermal energy, or  $\beta_p$ , density or Greenwald fraction,  $f_{GW}$  will vary. Here  $f_{GW}$  is the average density (in  $10^{20} m^{-3}$ ) normalized by the Greenwald density  $n_{GW}=I_p/a^2$ , with  $I_p$  in MA and  $a$  in m. The decay of these parameters will differ between the H and L-mode phase, and fast changes are expected during the H-L transition itself.

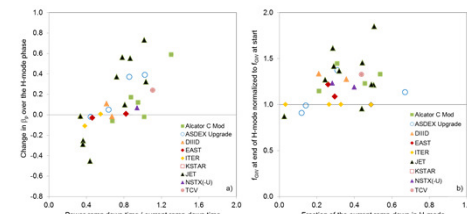
The decay time of the energy and density is compared with that of the current. The decay time of parameter X is defined as the inverse decay rate,  $-1/X \times dX/dt \rightarrow$



- At times during the termination, the decay of energy, W, and especially density, n, decay is slower than that of the current → increasing  $\beta_p$  ( $\propto W/I_p^2$ ) and  $f_{GW}$  ( $\propto n/I_p$ ).
- The fastest energy and density decay, usually of the order of the order of the energy confinement time, are found at the time of the H-L transition.

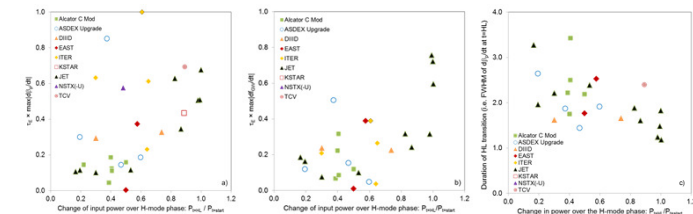


← Example of a single entry from the database, showing the temporal behavior of a number of plasma parameters and their dynamics using typical time scales, including the H-L back transition at about  $t^*=0.5-0.6$ .



- Usually, both  $\beta_p$  and  $f_{GW}$  increase up to the H-L transition.
- Depending on  $f_{GW}$  at the start of the termination, the increasing  $f_{GW}$  will limit the duration of the H-mode phase.

Assumptions on the dynamics of the H-L back transition are often used in the modelling of ITER terminations. These assumptions may influence the stability assessment. The database was used to characterize the magnitude of the drop in  $\beta_p$  and density of  $f_{GW}$  at the time of the H-L transition, and the duration of the process.



- The maximum change in both  $\beta_p$  and  $f_{GW}$  was normalized to the energy confinement time,  $\tau_E$ .
- The magnitude of the drop in  $\beta_p$  and  $f_{GW}$  increased with the ratio of the input power at the time of the transition and that at the start of the termination.
- The duration of the H-L transitions was of the order of a few  $\tau_E$ . And decreased with the ratio of the input power at the time of the transition and that at the start of the termination.
- Tapered power waveforms ensured softer H-L transitions (i.e. slower transitions and smaller peak changes in  $\beta_p$  and  $f_{GW}$ )
- The modelled ITER cases in the database, assumed the correct change in density ( $f_{GW}$ ) but usually a too large change in  $\beta_p$ .

## Summary

A database, built using a selected set of experimental termination cases, showed many similarities in the particle dynamics and current density behavior. Differences are found in relation 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. 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 [2,3]. The results from this analysis can be used to better prescribe the inputs for the detailed modelling and preparation of ITER termination scenarios.

## References

[1] HUMPHREYS, D, et al., Nucl. Fusion (2009) 115003.  
 [2] HUMPHREYS, D, et al., Proc. of this IAEA FEC (EX/P6-37)  
 [3] SNIPES, J.A., et al., Proc. of this IAEA FEC (EX/P6-36)