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

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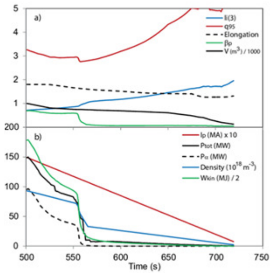
Introduction

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 β_p. These weights also depend on the goal of the termination.

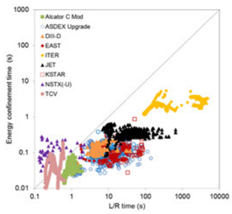


- What is the goal of the termination?
- Reduce magnetic and kinetic energy
- Maintain vertical stability ➔ control li and elongation
- Maintain radial control ➔ smooth H to L back transition
- Remain diverted for power exhaust ➔ shape control
- Avoid other operational limits ➔ density limit
- Control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

➔ A modelled, typical, ITER termination (Corsica Hmode_15MA_13) from I_p=15MA at full performance (W_{kin}=350MJ, P_α=100MW). Note that other variants are possible

Database of tokamak terminations

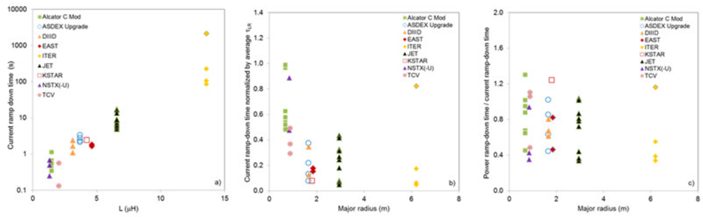
A database has been created consisting of typical, special and ITER-like, terminations from Alcator C-Mod, ASDEX Upgrade, DIII-D, EAST, JET, KSTAR, NSTX/NSTX-U and TCV. Hence, there are examples from devices with full metal walls that can be compared with those with carbon walls, and two devices that, 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 τ_E and $\tau_{L/R}$.

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

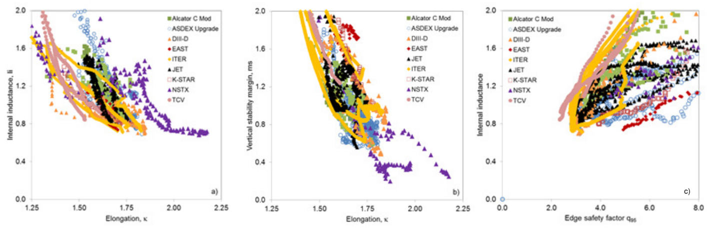
For typical ITER terminations
- Power turn-off in ITER, relatively fast
- Current decay fast compared to $\tau_{L/R}$



Comparison of stability aspects

Maintaining VS is an important aspect for a termination. The VS of the plasma depends on a complex function of li, β_p and elongation κ, 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, β_p, κ, can be expressed by the so-called marginal stability parameter [1,2]:

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

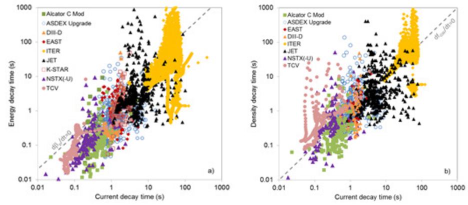


- To counter the relatively fast power shut down, the modelled ITER cases apply a more aggressive reduction in k, than most present day devices, to maintain VS.
- The result is that in these cases, q remains low (~3) for the first half of the current ramp-down.
- These ITER cases track the upper boundary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

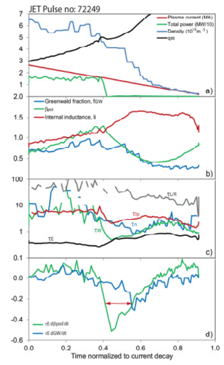
Comparison of dynamics

While in most cases the current is ramped down at a constant rate, the decay rates of thermal energy, or β_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 $n_{GW}=I_p/pa^2$, 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.

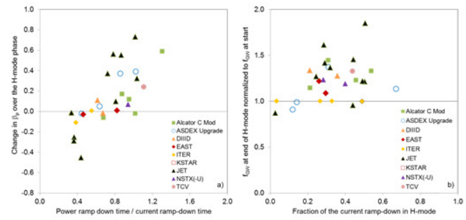
The decay time of the energy and density is compared with that of the current. The decay time of parameter X is defined as: X /|dX/dt|



- At times during the termination, the decay of energy, W, and especially density, n, decay is slower than that of the current ➔ increasing β_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 the order of the energy confinement time, are found at the time of the H-L transition.

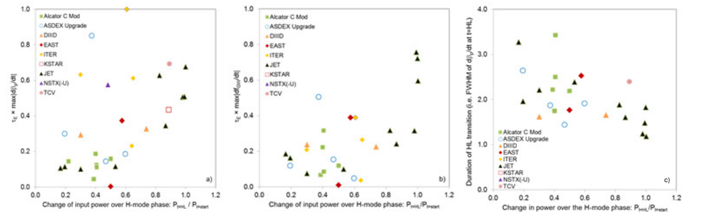


➔ Example of a single entry from the database, showing the temporal behavior of a number of plasma parameters and their dynamics using typical time scales, including the H-L back transition at about t=0.5-0.6.*



- Usually, both β_p and f_{GW} increase up to the H-L transition.
- Depending on f_{GW} at the start of the termination, an 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 are drop in β_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 β_p and f_{GW} was normalized to the energy confinement time, τ_E.



- The magnitude of the drop in β_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 τ_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 β_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 β_p.

Summary

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]. 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 analysis of a database, built using a selected set of experimental termination cases, showed:

- ITER will ramp down faster (relative to the L/R time) than most present-day devices
- VS control is manageable in ITER, even at high li, because of a strong elongation reduction
- This means that ITER remains longer, at lower q (q_{95}~3) than most present-day devices
- In H-mode, the density decays slower than the plasma current ramp-down
- The consequential increase in f_{GW}, limits the duration of the H-mode phase
- Fast power ramp-down lead to a larger change in β_p at the H-L transition ➔ affecting radial control

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)

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