Online Confinement Regime Identification for the Discharge Control System at ASDEX Upgrade

P. Franzen, V. Mertens, G. Neu, T. Zehetbauer, G. Raupp,
M. Kaufmann, the ASDEX Upgrade Team, and the NI Team

Max-Planck-Institut für Plasmaphysik, EURATOM Association, Germany;
POB 1533, D-85740 Garching, Germany

Introduction

In present experimental fusion devices, the online control of plasma discharges is necessary to achieve certain plasma configurations. For example, the CDH regime at ASDEX Upgrade [1] is established by feedback control of the radiated power from the plasma and the neutral density in the divertor. In order to avoid applying a not adequate set of control parameters to unexpected plasma configurations, the control system has to 'know' the actual plasma regime during the discharge in real time. This knowledge enables the control system to react dynamically to regime changes enhancing the plasma performance and e.g. reducing the disruption rate.

For this purpose, we developed a regime identification algorithm for the discharge control system of ASDEX Upgrade [2]. The basic requirement was a high identification rate provided by a small number of involved plasma parameters which are also online available to the plasma performance controller [3]. This controller has a cycle time of 2.5 ms which is much lower than the energy confinement time.

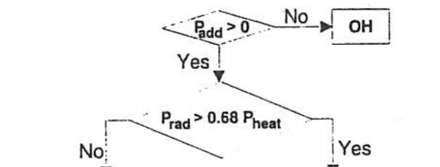


Fig. 1: *Flow chart of the regime identification algorithm at a given moment during a discharge. Additionally, the high confinement regimes H and HRH require the heating power exceeding the H mode threshold power, and the transition from H to HRL is forbidden (see text).*

Regime Identification Algorithm

Figure 1 shows the logical flow chart of a first realization of the regime identification algorithm for the discharge control system at ASDEX Upgrade for a given moment during a discharge. Apart from the OH regime for that the additional heating power P_{add} equals zero, the regimes are divided in low and high confinement regimes with low radiative (L and H regime) and high radiation (HRL and HRH regime) levels, distinguished by the radiated power P_{rad} provided by 10 bolometer channels being below or above 68% of the total heating power P_{heat}.

In the following we describe the regime identification algorithm for the different radiative regimes. The different threshold values and weight parameters (see below) were optimized to match empirically identified plasma regimes for more than 1200 stationary plasma configurations. With the given values more than 95% of these regimes are recognized correctly offline. The hitting rate is slightly lower online due to small deviations of the online signals from their respective offline values.

For low radiative conditions, low and high confinement regimes are distinguished by using two plasma parameters: the internal inductivity l_i of the plasma and the energy confinement time $\tau_E = W/P_{heat}$, W being the stored energy, provided by magnetic data. H regime is established if the ratio of τ_E to the 1989 JET, DIIID H mode scaling law, $\tau_{E_{JET,DIIID}}$, exceeds a value of 0.7. ($\tau_{E_{JET,DIIID}} = 0.16\ M^{0.5}\ I_p{}^{1.03}\ P_{heat}{}^{-0.48}$[4], M being the (mean) mass of the plasma ions in amu, I_p the plasma current in MA and P_{heat} given in MW, respectively.) However, with a few exceptions, this is a necessary, but no sufficient condition for the H regime.

A necessary and sufficient condition for H regime is provided by the internal inductivity which characterizes globally the current profile: lower values represent a flatter profile — i.e. H regime —, whereas higher values are characteristical for the L regime. However, l_i reacts rather slowly — within about 100 ms — to regime changes. Figure 2 shows the dependence of the internal inductivity on the value of q at 95% of the poloidal flux radius, q_{95}, for stationary phases (> 200 ms). As can be seen, the boundary between L and H regime, $l_{i,L\to H}$, is with a few exception unambiguous and depends on q_{95}, as well as on the plasma gas but it seems to be independent on the kind of injected gas by the neutral beams.

From the signals discussed above we can derive a single function R which 'measures' the plasma regime in the low radiative scenario:

$$R = \left(\frac{w_{\tau_E}\ \tau_E}{\tau_{E_{JET,DIIID}}}\right)\left(\frac{w_{l_i}}{l_i}\right), \quad w_{\tau_E} = \left(\frac{\tau_E}{0.7\tau_{E_{JET,DIIID}}}\right)^{\alpha}, \quad w_{l_i} = \left(\frac{l_{i,L\to H}(q_{95})}{l_i}\right)^{\beta}, \quad (1)$$

introducing the weights w_{l_i} and w_{τ_E} of the respective parameter in order to reduce the influence of the ambiguous τ_E parameter on R. They are chosen in such a way that they equal unity when the respective parameter equal the L to H boundary value ($\tau_E = 0.7\tau_{E_{JET,DIIID}}$ and $l_i = l_{i,L\to H}$, respectively), hence being a measure for the distance to the boundary. The powers α and β are optimized empirically by the number of identified stationary regimes (see above), resulting in $\alpha = 0$ ($\Rightarrow w_{\tau_E} = 1$) and $\beta = 10$.

The L $\to$ H boundary (and vice versa) for low radiative scenarios, R_b, can be expressed as a combination of the respective boundary values of l_i and $\tau_E/\tau_{E_{JET,DIIID}}$

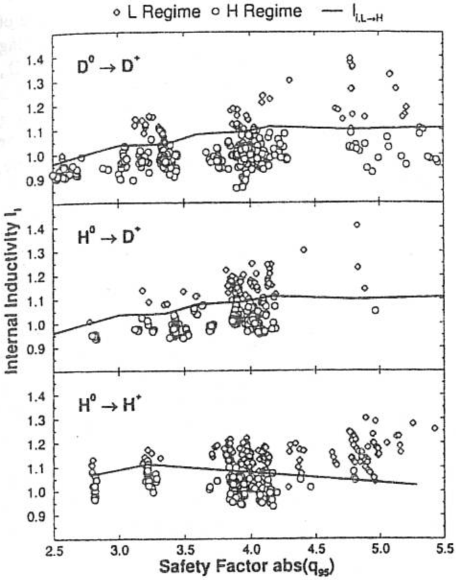
$$R_b = 0.7/l_{i,L\to H}(q_{95}) \quad (2)$$

Hence, an unambiguous condition for H regime is that R is larger than R_b. A second condition for H regime is that the total heating power exceeds the H regime threshold power P_{th} including the L$\to$H$\to$L hysteresis.

In spite of the fact that l_i reacts rather slowly to changes of the plasma properties — typical time constants are of the order of 100 ms — also the transitions between L and H regime are described sufficiently well within a few 10 ms due to the influence of τ_E on the time constants of R.

As can be seen in the flow chart the high radiative regimes HRL and HRH are obtained if more than 68% of the input power is radiated by injected impurities like Ne or Ar. The CDH regime is a special case of the HRH regime, but up to now the regime identification algorithm does not distinguish the CDH regime with a detached plasma from an attached H regime with a high radiated power level.

For the detached regime, l_i also is increased with respect to the attached H regime; hence it cannot be used for identifying the detached HRH regime. However, this regime can be identified by the changes in the plasma radiation profile characteristic for the detachment. This radiation profile can be characterized by a combination of several line integrated radiation power densities



— $l_{i,L\rightarrow H}(q_{95})$

Plasma Gas			
Deuterium		Hydrogen	
q_{95}	l_i	q_{95}	l_i
2.2	0.92	2.8	1.07
3.0	1.035	3.21	1.113
3.35	1.04	5.27	1.023
3.6	1.08		
3.95	1.09		
4.15	1.112		
4.8	1.1		
6.5	1.12		

Fig. 2: *Internal inductivity l_i for L and H regime as function of the safety factor q_{95} for different combinations of plasma ions and injected neutrals. The boundary lines are fitted by a composition of straight lines fixed at the points given in the tables.*

along certain line-of-sights through the plasma measured by bolometer. The resulting parameter B is given by [1]

$$B = \frac{\int \epsilon_{21}\, dl}{\int \epsilon_1\, dl} \frac{\int \epsilon_7\, dl}{\int \epsilon_{11}\, dl}, \tag{3}$$

where ϵ_i denotes the emission from a point $l\, dl$ of the line-of-sight with index i. $\int \epsilon_1\, dl$ gives the radiated power just above the outer divertor plates, $\int \epsilon_7\, dl$ close to the X-point, $\int \epsilon_{11}\, dl$ from a region just above the X-point, and $\int \epsilon_{21}\, dl$ from the equatorial plane, respectively. The first ratio (#21/#1) in Eq. 3 is a measure for the radiated power in the divertor with respect to the main plasma region, being high in the case of detachement. This signal, however, can be falsified by MARFEs which is corrected by the second ratio (#7/#11).

B being larger than a threshold value of 3.5 is an unambiguous condition for the (detached) HRH regime [1], but only for ELM free plasma conditions. In the case that B is lower than 3.5, the plasma might be still attached in spite of the high radiation level, and $R = F(l_i, \tau_E)$ (Eq. 1) is again a 'good' function distinguishing low and high confinement regimes.

A further restriction of the regime identification algorithm is that the H $\rightarrow$ HRL transition is forbidden. The radiation profile in the plasma needs a certain time (some 10 ms) for the rearrangement if the radiation level is increased during an H regime, so that the combination of a still low value of B and an increase of l_i due to a possible detachment might lead to the wrong conclusion the plasma being in the HRL regime.

Up to now, the regime identification algorithm can only be used in the flattop phase of the plasma current. This is due the influence of current changes on l_i which might lead to wrong regime predictions.

Example of a dynamically controlled discharge

Figure 3 shows a main application of the regime identification algorithm: the avoidance of disruptions caused by unexpected plasma states. The goal of this discharge was a long lasting CDH regime which is established at about 2 s by neon gas puffing, as can be seen from the D_α and C_{III}^{div} signals. However, due to the high set value of $P_{rad}/P_{heat} = 0.78$, the neon input flux is still increased by the control system after the onset of the CDH regime. Because of the resulting too high impurity concentration, the plasma falls back to the HRL regime, e.g. indicated by the increase of l_i.

Without online regime control, as it was done earlier, the set of controlling parameters would have not been adequate and the discharge might be e.g. driven into a radiation collapse due to too much Ne puffing. But in the case of this discharge, the control system recognizes the falling back to the HRL regime and closes the Ne valve by setting the set value of P_{rad}/P_{heat} down to 0.5 at the moment the plasma leaves the high confinement regime. Due to the further slow increase of the P_{rad}/P_{heat} set value, the high confinement regime is even recovered.

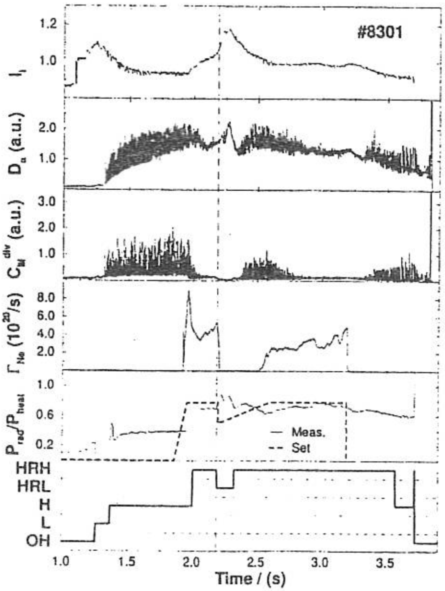


Fig. 3: *Example of a dynamically controlled discharge at ASDEX Upgrade. I_p = 1 MA, B_T = -1.9 T. Neutral beam injection starts at 1.3 second with 7.2 MW. At 2.19 seconds the Ne valve was dynamically switched off by the control system.*

Summary

A regime identification algorithm was developed and tested successfully for the discharge control system of ASDEX Upgrade. The algorithm distinguishes high and low confinement regimes in low and high radiative scenarios by using only a small number of online available plasma parameters — about 20 signals including 10 bolometer channels —, allowing the control system to react dynamically to plasma regime changes within a cycle time of 2.5 ms.

A main application was demonstrated for the first time in a fusion device: an unwanted and unexpected regime transition was dynamically corrected and the planned regime was recovered reducing the disruption probability and enhancing the plasma performance. In a next step, more regimes will be recognized, e.g. detached regimes using the C_{III} signal from the divertor.

References

[1] Dux, R. and Kallenbach, A., Technical Report IPP 10/1, Max-Planck-Institut für Plasmaphysik, 1996, submitted to Nuclear Fusion.

[2] Raupp, G., et al., in *Proceedings of the 17th SOFT*, p. 1072, Roma, 1992.

[3] Neu., G. et al., in *Proceedings of the 18th SOFT*, p. 675, Karlsruhe, 1994.

[4] Schissel, D.P. et al., Nuclear Fusion **31** (1991) 73.