Analysis of plasma termination in the JET hybrid scenario

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Within the last few years significant progress has been made on the hybrid scenario in JET[1]. However most of the analysis concentrated so far on the high performance phase of the plasma. Another important aspect is to terminate such high performance plasmas safely. Especially with introducing the ITER like wall (ILW) in JET the plasmas often are hampered by impurity accumulation and mode activity when ramping down the power or even before [4]. In figure 1 time traces of a representative plasma termination are shown. The plasma starts to accumulate heavy Z impurities (mainly W) in the main heating phase which can be understood using neoclassical transport theory [2]. This is visible on the peaking of the Soft Xray Radiation (SXR) diagnostic calculated as a ratio of horizontal channels in the 3rd row of figure 1 and the W concentration shown in the 6th row [3]. After most of the heating is switched off the radiation profile is still peaked and the total radiation is of similar magnitude than the heating power (see row 2), the electron temperature drops within 500ms and the profile flattens as can be seen on the T_e time traces in row 5. Subsequently the SXR profile and W concentration profile flatten as well before the NBI power is switched off. Then a second phase of impurity peaking starts now mainly seen on the bolometer in row 3 with some indication of the W concentration. The estimate of the W concentration then fails because the plasma temperature becomes too low to detect the SXR radiation trough

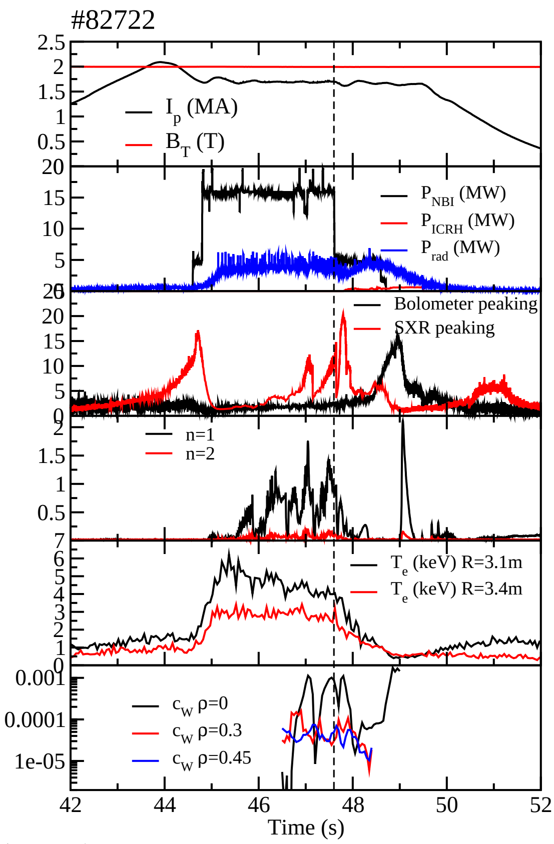

Figure 1: Overview of a typical hybrid pulse termination

*See the Appendix of F. Romanelli et al., Proceedings of the 24rd IAEA FEC 2012, San Diego, US the thick Be filters. The peaking factors of the SXR and the bolometer diagnostic are very different in the main heating phase due to a strong T_e dependence in the SXR radiation which is much weaker on the total radiation. The increasing radiation peaking leads to flat or hollow T_e profiles before finally a n=1 mode is excited (row 4) which locks shortly afterwards (as reported in [4]). As a consequence the control system stops the pulse by initiating a fast current ramp as seen in row 1. In this pulse the electron temperature recovers and the radiation peaking reduces before a disruption could occur this is in about 80% of the hybrid pulses the case. For this paper a database is developed in order to reveal the intricate relationship between various plasma parameters at different times in the discharge affecting the landing of the plasma. The database consists of 180 pulses (all hybrid pulses in the ILW which reached the main heating phase) of which 114 pulses had a locked mode and 23 of them disrupted (2 in the main heating phase due to a stop of vertical position control and 17 in the ohmic phase). In the 14 pulses with $q_{95} < 3.8$ (nominal value for a JET hybrid pulse) 12 had a locked mode and 6 disrupted.

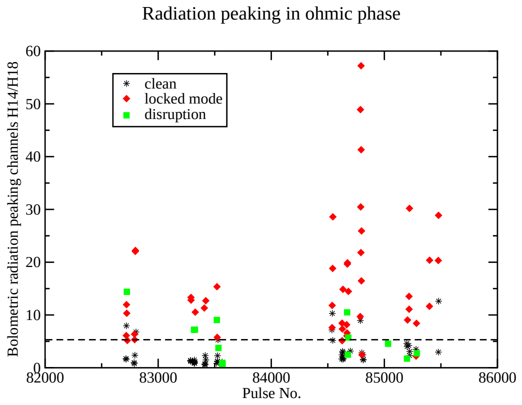

Figure 2: Bolometric radiation peaking in OH phase - definition of threshold

To understand the importance of the different phases of the pulse a set of 50 parameters has been collected in 7 phases of the pulse. The phases are defined as 200ms windows at the end of the main heating phase, the maximum performance (maximum stored energy), the maximum SXR radiation peaking within the main heating, the maximum radiation fraction within the main heating phase and at the beginning of the main heating. In addition the low power phase following the main heating and 0.7s at the start of the following ohmic phase are taken, both cut short in case of a locked mode or disruption. In figure 2 the bolometric peaking factor is shown, the pulses with locked modes have red symbols and clean plasmas black ones. Above a peaking of 5.31 91.7% of the pulses have a locked mode but only 11% are without. This shows that in most pulses the radiation peaking in the ohmic phase is the critical parameter and therefore it has been used as a reference for a correlation analysis with other parameters to get an indication of their importance. The correlation factor of a reduced set of parameters is shown in figure 3. The colours symbolise the different phases and the x-axis is sorted from high correlations on the left to low on the right.

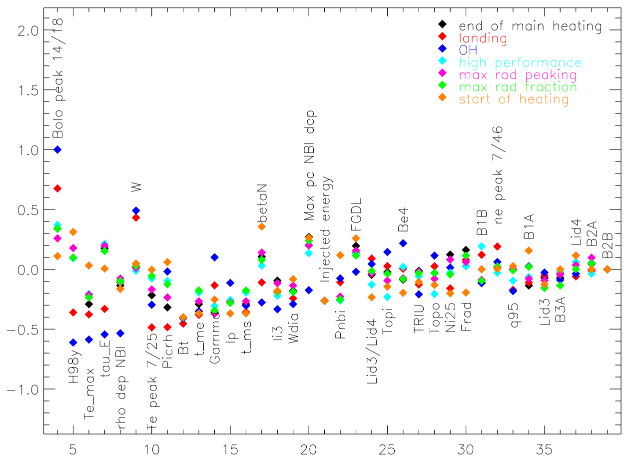

Figure 3: Correlation coefficient of bolometric radiation peaking during the ohmic phase plotted against reduced set of database parameters. X-axis sorted according to global importance of parameter.

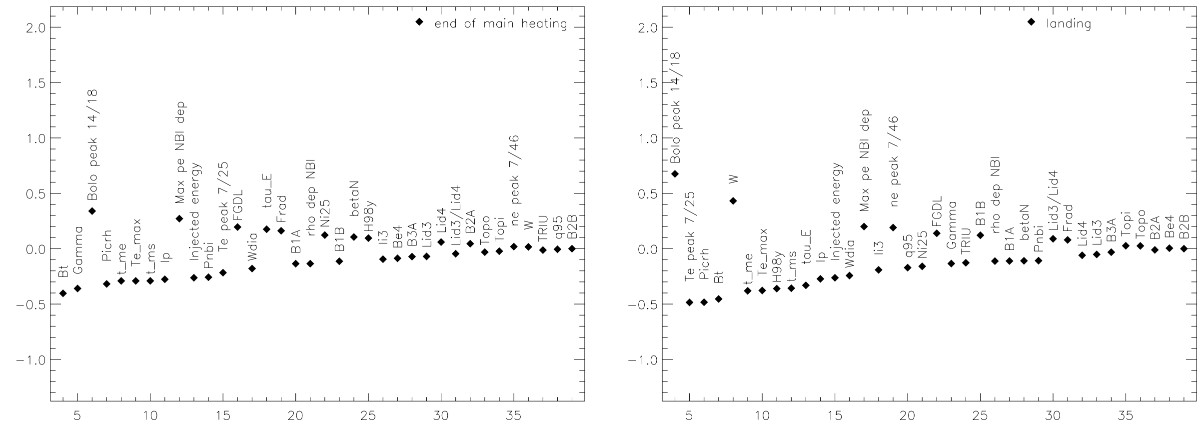

Figure 4: Correlation coefficient as in figure 3. X-axis sorted according to importance in the last 200ms of main heating on the left and during the low power phase following the main heating on the right.

The highest correlations are seen within the ohmic phase itself. The leading parameters related to T_e as e.g. τ_E. H_{98y2}, $\rho^{NBI}_{dep.}$, P_{ICRH} are not useful in this phase of the pulse. t_{ms} and t_{me} are the time of the start and ending of the phase and also probably not of much use. Since the database collects mainly $q_{95} = 3.8$ plasmas the magnetic field and plasma current are supposed to be well correlated. The BnA and BnB signals are the amplitude of the first or second n=n mode in the plasma and seem to be rather unimportant. As is the density peaking either calculated by HRTS channels at 3.1m (7) and 3.4m (25) or by the line integrated densities (lid3/4) or the densities themselves. In figures 4 and 5 the same data but reduced to the appropriate phase and sorted just on the data shown is plotted. In general there are two different sets of important data depending on the phase. In case of a low power tail or ohmic the most important parameters are connected to the electron temperature, radiation, ICRH power and W source as can be seen in figure 4. During any of the high power phases the magnetic field, the energy confinement, the NBI power deposition to the electrons and the gas flux are main players but also a tendency can be seen that radiation peaking remains important. In general the further away from the ohmic phase the data is taken the less the correlation is. In table 1 the three most positive and three most negative correlations for all 7 phases are summarised. The data has been selected to reduce the number of strongly related parameters and obvious misleading parameters like H_{98y2} in the ohmic phase have been eliminated.

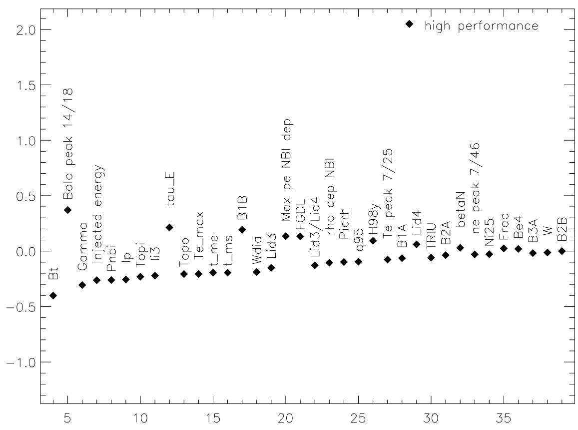

Figure 5: Correlation coefficient as in figure3. X-axis sorted according to importance in the highest performance phase of the pulse.

The data gathered in this database indicates that events which happen closer to the termination of the plasma are more important than events earlier - or in other words if choosing the right termination we might be able to repair damage which has occurred earlier, e.g. by impurity events, MHD or generally impurity accumulation. Based on this assumption a revised

	Max pos	2nd	3rd	Max neg	2nd	3rd
All	Rad peak (0.68) low power	W influx (0.49) OH	P_e NBI (0.27) End of heating	T_e^{max} (-0.59) OH	τ_E (-0.54) OH	T_e peaking (-0.48) OH
End of heating	Rad. peak (0.34)	P_e NBI (0.27)	f^{GW} (0.2)	B_T (-0.4)	Γ (-0.36)	P_{ICRH} (-0.32)
Low power	Rad. peak (0.68)	W influx (0.43)	P_e NBI (0.2)	T_e peaking (-0.49)	P_{ICRH} (-0.48)	B_T (-0.45)
OH	W influx (0.49)	Be influx (0.22)	Γ (0.1)	T_e^{max} (-0.59)	τ_E (-0.54)	B_T (-0.41)
Max. perf.	Rad. peak (0.37)	τ_E (0.21)	P_e NBI (0.13)	B_T (-0.4)	Γ (-0.31)	Injected En. (-0.26)
Max. rad. peaking	Rad. peak (0.26)	P_e NBI (0.2)	τ_E (0.2)	B_T (-0.4)	Γ (-0.37)	P_{ICRH} (-0.23)
Max. rad. fraction	Rad. peak (0.34)	P_e NBI (0.24)	τ_E (0.15)	B_T (-0.4)	Γ (-0.34)	P_{NBI} (-0.25)
H-mode entrance	β_N (0.35)	H_{98y2} (0.31)	Rad. peak (0.29)	B_T (-0.4)	Γ (-0.25)	n_e^{peak} (-0.23)

Table 1: Summary table of most important correlations in all seven phases.

termination scenario is suggested. The first step would be a high heating power H-mode with ICRH and with strong gas fuelling moved onto the vertical target. The vertical target would reduce the effective W influx as the high gas fuelling does. The high power would prevent a flattening of the temperature profile. In addition the lowered power and increased gas flux will reduce the energy confinement time and the radiation peaking is expected to reduce as well. The second step would reduce the NBI heating power and the gas fuelling drastically and keeps the ICRH power on. In this phase the density and the W source should reduce while the central heating may still reduce the impurity peaking. As a last step the ohmic phase will be at zero gas fuelling but density feedback control to avoid error field locked modes. The plasma current would be ramped down during all termination phases (tested to work already by the baseline H-mode community) to reduce the chance of an existing locked mode to trigger a disruption and generally to reduce the energy in the plasma and the possible disruption forces.

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