Reducing Radial Movement in ITER H-L-mode Back Transitions

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Introduction Prolonged contact between the plasma and the inboard first wall remains an issue of concern for the ITER design. A large and rapid drop of β_p when returning from H-mode to L-mode leads to a sub-second shift of the internal flux surfaces and a slightly slower displacement of the Last Closed Flux Surface, slowed by the induced passive shell currents. This type of perturbation has always been factored into the design of the Poloidal Field (PF) coil design in ITER, but the margins are extremely small, if any. Consequently, an increase in the inner wall gap between separatrix and plasma facing components is probably needed before an H-L back transition takes place. However, around a 1 second warning is required to move the plasma so as to provide this margin. There remains the possibility that an H-L back transition will occur without warning. Handling this exception is the purpose of this paper.

Approach taken We decided to examine the use of a bang-bang controller since it can give a time-optimal response to a perturbation such as the H-L back transition, given limited power supply voltages. The principle of the bang-bang controller is to replace the active linear controller used to regulate and track the equilibrium shape by a fixed voltage control action for a brief period. The equilibrium shape reaction will be the best achievable controller response if the power supplies are saturated and the detailed controller design can be discounted in evaluating the responses obtained. However, saturating the PF coil power supplies will create undesired equilibrium changes. We therefore proceeded step-wise, through an analysis using a linear response model and then using the non-linear full tokamak simulator DINA-CH&CRONOS [1]. We chose to exploit an existing hybrid mode ITER scenario, already including the H-L back transition. It is assumed that the details of the transport modelling and of the initial equilibrium will not invalidate the conclusions.

Initial linear modelling Our initial concern was the interaction between a bang-bang controller and the vertical movement, fearing that we would saturate the VS1 power supply. The RZIP linear plasma response model was therefore used to estimate the ratio of the voltages applied to the fairly up-down symmetric PF coil pairs which, in principle, should provide a dominantly vertical field to counteract the radial displacement due to the drop in β_p.

This first study gave us pairs of voltages which could subsequently be used for bang-bang controller studies using DINA-CH&CRONOS.

Bang-bang control action using the PF coil supplies The bang-bang control action was triggered by the exception handling module of DINA-CH, detecting an excessive value of the filtered time-derivative of the current-weighted plasma current centroid error. The bang-bang controller was instantly switched on and the linear gap controller was switched off until the time-derivative went back below the chosen threshold. The bang-bang controller was simply programmed to deliver a pre-defined voltage demand on all PF coil power supplies.

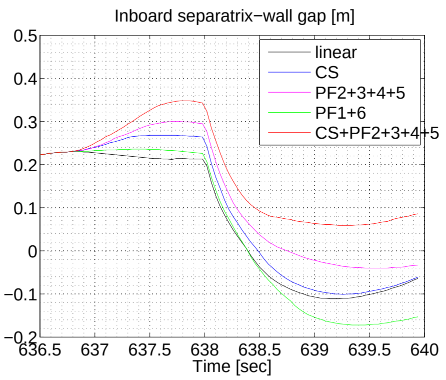

Figure 1: Comparison between the various coil combinations with saturated power supply voltages

The first results were obtained using various combinations to counteract the radial movement, namely CS1, CS2, CS3, PF1+6, PF2+5 and PF3+4. The effect on the vertical position excursion was surprisingly benign. We therefore enhanced each coil pair to the maximum voltages on each power supply, Fig.1, including a pre-emptive radial excursion. As expected, PF1+6 provided no interesting advantage at a high reactive power cost. In Fig.1, The combination of all CS coils plus the four external coils PF2+3+4+5 demonstrates a considerable reduction in the maximum radial excursion during the H-L back transition, reduced from xxcm obtained with the linear controller (by A. Kavin) to xxcm obtained with the bang-bang control action. The voltage required by the VS1 vertical position power supply remained well inside its limits.

Reinforced bang-bang control Since we are trying to increase the negative coil current in the outer coils (i.e. reduce their absolute value), this can be achieved economically by a passive system identical to the Switching Network Unit (SNU) already used in the CS and PF1+6 circuits. We therefore modified the bang-bang control action to include the insertion of such a passive resistance into each of the PF2+3+4+5 circuits. This is not possible for the CS coils, since the coil current polarity is not guaranteed during a full pulse. The coil currents are not known in advance, since the equilibrium will be varying from scenario to scenario and we made no attempt to tune

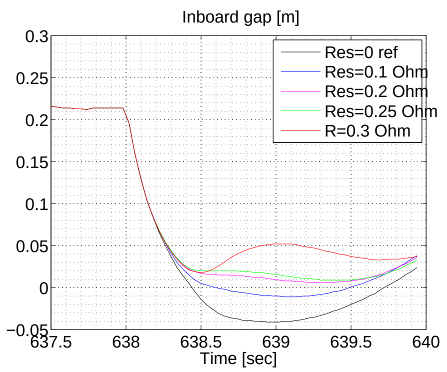

Figure 2: Effect of varying the inserted resistances, without pre-emptive action

the inserted resistances but tested the tolerance to varying them. Figure 2 shows the effect of increasing the inserted resistances, taking the same values for each circuit, not even adapting to the different number of turns in these coils. Inserting larger resistances creates a reduction in the radial gap excursion. Again, the tolerance to not adjusting for the precise PF configuration surprised us.

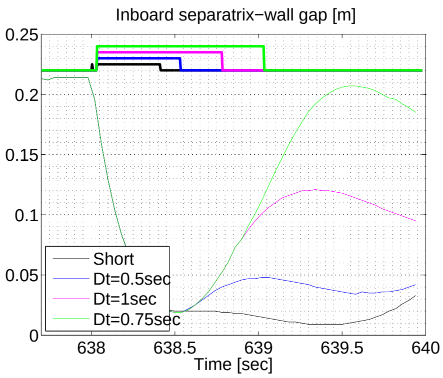

Figure 3: Effect of increasing the duration of the bang-bang control action

During this resistance scan, the bang-bang control action was becoming shorter as it became stronger, because the radial movement was reduced earlier and the threshold determining the control action was crossed again. We therefore changed to a variable duration bang-bang reinforced controller and the results are shown in Fig.3.

Varying the resistance ratios in the upper and lower PF coils changed the vestigial vertical movement, Fig.4, showing the successful reduction in the vertical excursion provoked by the bang-bang

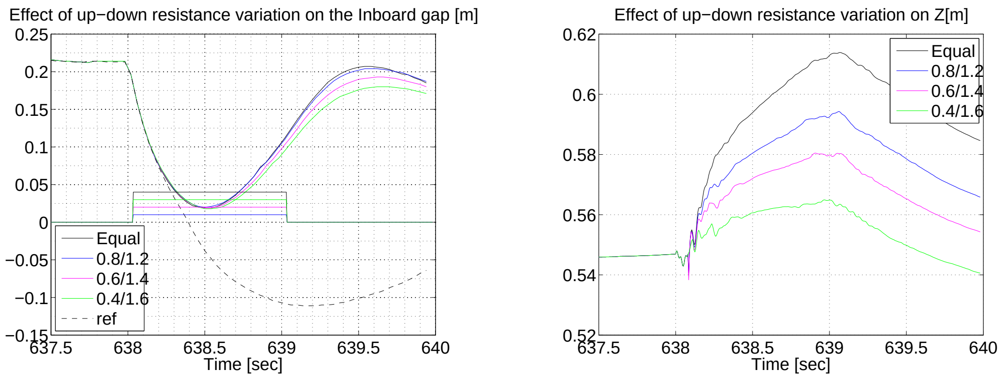

Figure 4: Effects of the up-down PF coil resistances; on gaps (left) and on the vertical position (right)

controller and the little effect on the radial excursion of making these adjustments. The vertical excursion provoked no saturation of the VS1 supplies without worrying about the radial field imbalance, but this result shows that we have a control parameter if needed.

<u>Summary of improvements obtained</u> Figure 5(left) shows the radial excursion with the linear controller, with the saturated bang-bang controller and with the reinforced saturated bang-bang controller. The red line shows the duration of the bang-bang control. Not only is the excursion reduced significantly, but the duration of the excursion is vastly reduced. Figure 5(right) shows the PF voltages during the H-L back transition for the three control methods. The additional voltages applied to the PF coils appear to be within the tolerance of the coils which are engineered to withstand the higher voltages of the quench circuits.

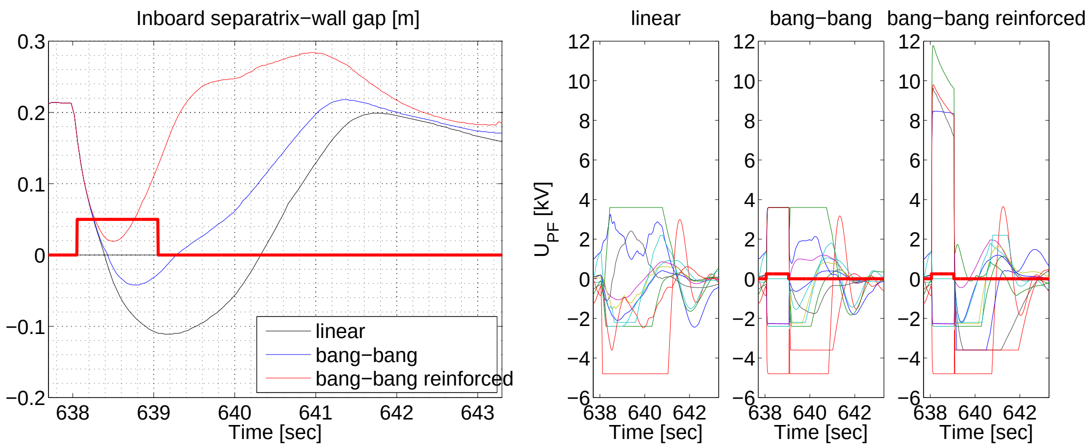

Figure 5: Improvement to the gap control with the three approaches (left) and PF&CS voltages[kV] as a function of time [seconds] (right)

Discussion We have shown that bang-bang control improves the rejection of the H-L back transition on the separatrix-wall spacing for a non-pre-empted H-L-mode transition. The method was then enhanced by the insertion of a SNU module for each of the PF2+3+4+5 circuits, similar to that used for the initial plasma ramp-up, using technology developed for ITER. We are surprised at the robustness of the approach and by the tolerance of the vertical stabilisation system to the residual perturbation of the radial field, suggesting a precise tuning of the injected resistances and of the power supply voltages is not needed.

The robustness or resilience of the method lies partly in the fact that the radial movement is stable, contrasted with the vertical position; the strong coupling inside the 4 coils PF2+3+4+5 must also play a role and this is being studied.

What have we not yet explored? Firstly, the switching back to the linear controller has not been developed. The return to the linear controller without due care and attention is in fact a strong point, since it is adequate. Secondly, we have not examined other scenarios, but the resistance to be inserted is independent of the plasma current, due to the Shafranov vertical field equation, dominating the radial movement. Nonetheless, this should be demonstrated. Thirdly, we have not included any dependence on the β_p change during the transition. However, we have shown that the duration of the bang-bang control action has a significant effect on the radial excursion, and this appears to be an appropriate control parameter to be determined by the exception handler. This also needs demonstrating.

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[1] Kim SH, Artaud JF, Basiuk V, Dokuka V, Khayrutdinov RR, Lister JB, et al. 2009 Full tokamak discharge simulation of ITER by combining DINA-CH and CRONOS Plasma Phys. Control. Fusion (51) 105007.