Modeling of an advanced scenario on ITER with CRONOS

V. Basiuk, J.F. Artaud, F. Imbeaux, X. Litaudon, Y.Peysson, M. Schneider

Association Euratom-CEA, CEA Cadarache,
F-13108, St Paul Lez Durance, France

1.   Introduction

Integrated modeling of a plasma becomes of great importance to prepare the various scenarios in fusion tokamaks, in peculiar ITER. They was developed using the 1.5 D code CRONOS [1] with its up-to-date modules (heat sources, neoclassical source, transport models), Recent feedback control algorithm, so called "search optimization control" (SOC), has been implemented to the integrated code CRONOS and tested on specific experiments done at Tore Supra.

In this paper we will focus on the advanced scenario in ITER using the prescribed additional heating : 32 MW of neutral beam injection (P_{NNBI}), 20 MW of ion cyclotron resonance heating (P_{ICRH}) in second harmonic tritium scheme. The α source terms (current and heat) is computed by means of the Monte-Carlo code SPOT [2] coupled to CRONOS.

The papers reported on :

-the need of an off-axis current seed to generate and maintain the internal barrier: We choose as candidate the Lower Hybrid wave (LH) with a a level of 20 MW to generate this current. Only simple model of deposition are used (Gaussian). The location of the ITB is directly link to the LH current seed.

-the SOC (itself) , trying to optimize the fusion power (P_{fus}) or the amplification factor Q (ratio between the fusion power and the total injected power) during a discharge characterized at a fraction of non-inductive current greater than 95%, and a Greenwald fraction limit of 75%.

The simulations begins at 30 s to avoid the ITER start phase and last 400 s.

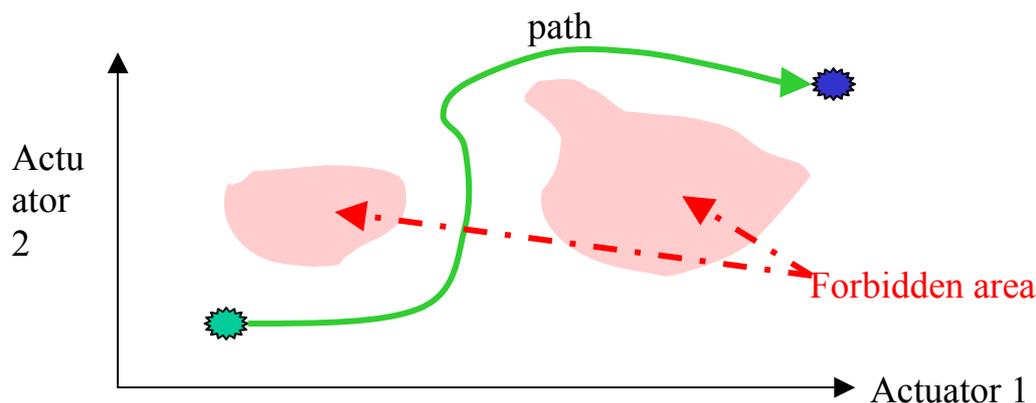## 2.   Search optimization control algorithm (SOC) : principle

Figure 1 : dot line = First test wrong way change direction, double line = Return to the last good value and change of actuator

In this control, the algorithm will have to find a path in a way to improve one given plasma parameter (called the sensor) using various actuators. First experiments[3] was performed at Tore Supra increasing the hard X ray width[4] using both the injected power P_{lh} and the parallel index, $n_{//}$.

The figure 1 shows a schematic view where the path is in green. To achieve this path, the feedback control has to keep in memory the latest state the plasma reached before

modifying one of the actuators. After the actuator change, as the plasma equilibrium state evolve, the control has to wait a given time (typically one second for a TS plasma, τ_a), to reach the new equilibrium, before comparing the new sensor value to the older. If this value increase, the algorithm continues with the same actuator, otherwise it moves to the next actuator. Furthermore, forbidden area (such as given by MHD limit) could be predicted and avoided by the algorithm. The first experiments[4] carried during the last campaign at Tore Supra have been fully successful.

3.   The ITER SOC

For the advanced scenario of ITER (internal transport barrier), 4 actuators were used; the total additional injected power P_{tot}, using both ICRF heating in the second harmonic tritium mode and neutral beam injection (NBI) at 1 MeV; the plasma current; the line-integrated density. The sensor was the plasma fusion power (P_{fus}) or the amplification factor ($Q=P_{fus}/P_{tot}$). The plasma current evolved until a zero loop voltage is reached. The transport models used allow the transition towards an internal transport barrier. An amount of 20 MW of LH power is imposed to generate the off axis current sources to help the transition. The effect is studied using a simple power deposition model (Gaussian with a center around normalized radius x = 0.5) and a given efficiency (2.5 10^{19} A / W / m^2)

The ICRH power deposition is deduced from the PION[5] code (using the ITER parameter for the antenna spectrum) and the fusion power is either deduced from a scaling law allowing a short time of CPU consumption (less than two days for 400 s of an ITER shot, with a calculation of the source term every seconds) or from the SPOT[2] code (which takes around one hour for one time step). The fast module has been compared to the SPOT code (see Fig. 3 b))

In these simulations, the density is prescribed (peaking factor imposed and equal to 1.2) taking into account the new value of the line density. The electron density diffusion equation of CRONOS has not been used.

The algorithm is also associated to the zero loop voltage mode of CRONOS when the non inductive current becomes greater than 95 % of the plasma current. In this case, the plasma current is free to evolve and the plasma edge flux is kept constant. The algorithm tries to optimize the fusion power (P_{fus}), with respect to the beta limit : the Greenwald fraction (f_G between 0.5 and 0.8), and the normalized beta (β_N) below four times the internal inductance (l_i). Low values of l_i are also forbidden in the algorithm (below 0.55)

Among the various parameters of the algorithm, three different time scales τ_a are defined, one for the current (~1 s), one for the injected power (proportional to the fast ion slowing-down time, τ_p) and one for the electron density (arbitrary 5* τ_p). At each given time one reference changes in a given direction (The NBI increase for instance), the plasma parameter to be increased (P_{fus}) is saved in a memory structure. The next time, its new value is compared to the old one to validate or not the direction (continue increasing the injected power,…). The plasma current has a different role : the algorithm try to increase the current until a limit is reached, e.g. :

-Self inductance l_i lower than a given value
-Non inductive current equal to the plasma current or a given maximum value
-Maximum value reached.

The heat diffusion model "kiauto" [6] , which reproduces a given global scaling law, is used in all the simulations. The diffusion coefficient are prevented from being too small (below 0.15-0.4 m² /s), especially around the transport barrier.

4.   **Results**

Most of the internal transport barrier were achieved with the H mode pure GyroBohm DS03 scaling[7] and using the scaling pedestal with low β dependence defined by Cordey[8].

Figure 2 shows a 400 s simulation (sim. A) using the fast module for the α heating where the Q factor is maintained around 5 with a transport barrier located near the LH current source (x=0.5). This barrier[9] is formed at 60 s but shrinks from 0.55 to 0.5 at the end of the simulation to match the LH current (as shown the figure 3 where two simulations are plotted (sim. A and sim. B): The main difference is the location of the LH current (0.5 and 0.65 in normalized radius) and the result is an amplification factor lower in the sim B case ($Q = 2$) than in the sim A case ($Q = 5$) with the same plasma current and a higher density in the sim B case (20 % more). The total available level of injected power is not used during these runs. The zero loop voltage arrives earlier when the bootstrap fraction achieves 80 %. All the MHD limits are respected with a Greenwald fraction around 75 % (imposed parameter) and $\beta_N \sim 4*$ l_i. One of this scheme (the first one with a more internal LH power deposition) was extended towards 2000 s keeping the transport barrier at its last location all the time.
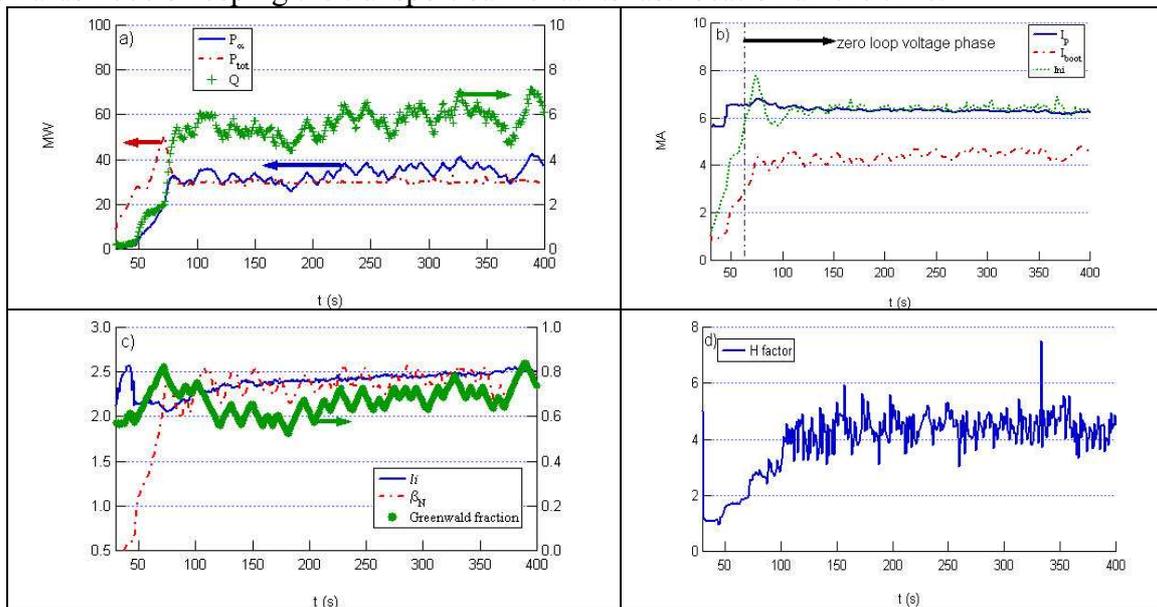

*Figure 2 : sim A a) α Power, total injected power and capital Q b) plasma current, non inductive current and bootstrap current c) β_N, 4 * li and Greenwald fraction d) H factor*
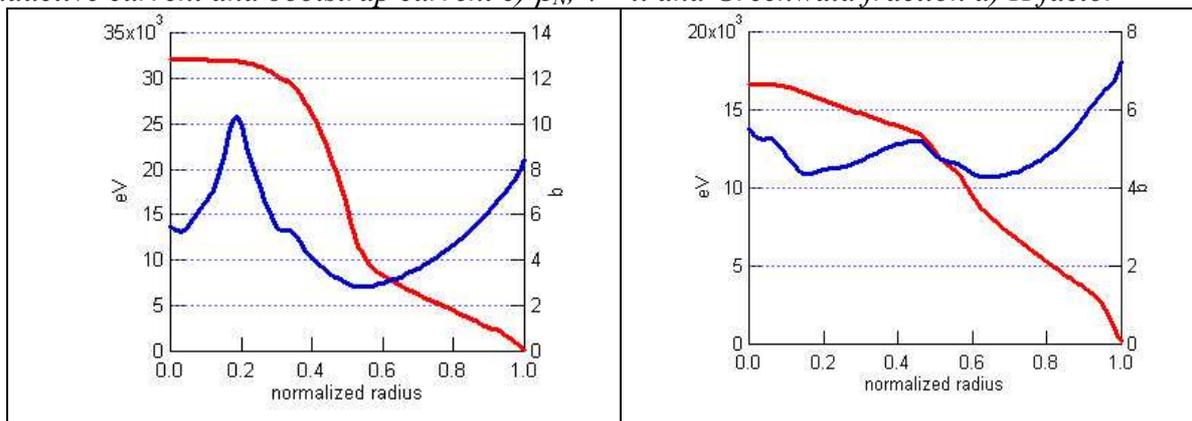

Figure 3: Te profiles (red left axis)) and q profiles (blue right axis) at the end of a simulation (390 s) left, sim A : LH current at r/a 0.5; right, sim. B LH current at r/a 0.65

Using the same SOC parameters, the figure 4 shows the results of two identical simulations, one using the analytical model (sim. A), the other the SPOT code (sim C), for the fusion power deposition (heat and current). The final state was quite similar above 300 s as shown on figure 4b even if the plasma current is not the same: for the SPOT case a plasma current of 8.5 MA is reached , but not in a steady state mode; for the analytical approach the plasma current is lower (6.5 MA) and a zero loop voltage phase is reached. One can conclude that if the path

to reach the final state is sensitive to the input parameters (fusion source term in that case, which slightly differs at the beginning of the shot), the performance of the plasma is the same at the end. The analytical model can be used in most of the simulations (to test effect of one parameter for instance).

   The impact of the location of the LH current deposition was also tested. With a more off axis deposition profile (x=0.7), the minimum limit in l_i (0.55), imposed in CRONOS, was achieved due to a very flat plasma current profile. We can prevent this effect by increasing the LH power more slowly (which is not included in the SOC) and a more off axis transport barrier is then achieved and controlled.
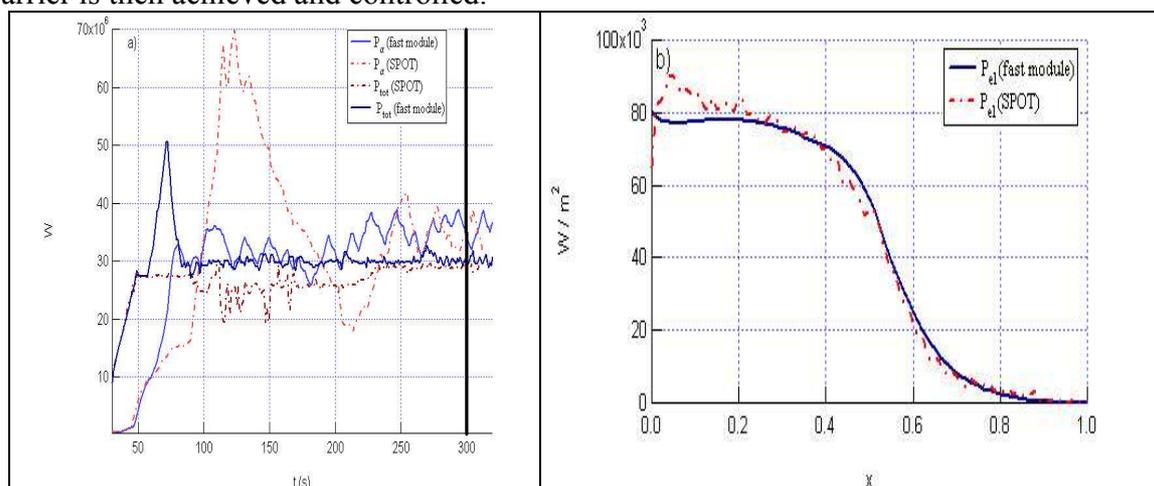

Figure 4 : comparison of sim. A and sim. C a) Fusion power evolution using SPOT or the analytical approach compared to the total injected power b) a power deposition at 300 s for the two cases

5.   Conclusions

   This kind of algorithm, which was successfully tested on Tore Supra, could be useful to prevent the shrinking of an internal transport barrier in ITER. It maintains an advanced plasma with a given value of the Q factor. There are several actuators for the transport barrier : to have a current source located at midradius (which can be the case for LH wave) and to work near the zero loop voltage (low plasma current). One advantage of this plasma control is that :

-    various constraints (MHD, …) can easily be included (even a fast diffusion equation using an analytical model for the source term to predict the next current profile)
-    focus on the main plasma quantity (fusion power)

   The path to reach the final state is not unique and can be chosen varying the internal parameters of the controller.

   The main problem of this control is the possibility to arrive at a secondary maximum, which could be the case for multi actuators (> 2). In this case, more sophisticated algorithms should be developed by which the final state is reached by various different paths.

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