35th EPS Conference on Plasma Phys. Hersonissos, 9 - 13 June 2008 ECA Vol.**32D**, P-5.068 (2008)

Simulation of present-day Tokamak Discharges Mimicking a Fully non-Inductive Burning Plasma

J.F. Artaud, X. Litaudon, V. Basiuk, G. Giruzzi

Association Euratom-CEA, CEA Cadarache, CEA-DSM-IRFM,
F-13108 St Paul lez Durance, France

Introduction

The control of a burning plasma in a tokamak has very specific features compared to present-day plasmas. In particular, the input power is only a small fraction of the total power and, for steady state discharges, the self-generated bootstrap current is the dominant current source. Additionally, non linear coupling between transport, α-heating and bootstrap current makes the control complex. In order to address reactor-relevant control issues, one can simulate burning plasmas conditions in present-day tokamak experiments by developing control algorithms that mimic self-generated alpha heating [1] and self-generated bootstrap current behaviours with external heating and non-inductive current drive sources. Some experiments have already been performed on inductive scenarios [2-4]. Here, we propose to discuss the use of this method for discharges at zero loop voltage preparing steady-state tokamak operation. The case of Tore Supra with extended RF heating capabilities is chosen in this study.

Control algorithm to mimic steady-state burning plasmas

The control algorithm to mimic steady-state burning plasmas imposes the following constraints: the fraction of heating power that simulates the alpha heating is proportional to the thermal neutron flux of DD reactions; the fraction of driven current that simulates the bootstrap current is proportional to the poloidal beta, $\beta_{P,th}$ the thermal pressure normalised to the poloidal field. The remaining heating and non-inductive current drive power is used for control purposes: burn control, profile control and flux control to reach steady-state fully non-inductive operational regime.

The proposed algorithm has been tested in our simulations using the Tore Supra tokamak parameters but with extended RF heating capability (up to 12 MW of ICRH in H minority scheme, up to 8MW of LHCD and up to 6 MW of ECRH).

The simulated alpha heating is given by: $P^{\alpha}_{ICRH} = g_{fus} R_{DD}$ where R_{DD} is the calculated (or measured) neutron flux resulting from D-D fusion reactions and g_{fus} is a fixed gain in the open loop algorithm. The simulated bootstrap current is given by: $I^{boot}_{LH} = g_{boot} I_{boot}$ where I_{boot} is the real bootstrap current of the discharge ($I_{boot} \propto \beta_{P,th}$). This current is driven with LH waves. The following reference input powers are obtained: $P_{ICRH} = P^{control}_{ICRH} + P^{\alpha}_{ICRH}$ where $P^{control}_{ICRH}$ is the ICRH power reserved to control the discharge; $P_{LH} = P^{control}_{LH} + P^{boot}_{LH}$ where $P^{control}_{LH}$ is the LH power reserved to control the discharge and $P^{boot}_{LH} = \eta_{LH} I^{boot}_{LH}$ where η_{LH} is the LHCD current drive efficiency. $P_{LH,boot}$ is the power requires to simulate the missing bootstrap current to simulate high bootstrap operation. The ECRH power is mainly used to decouple the control of fusion power from the control of bootstrap current (the ECRH wave can be either injected in perpendicular or balanced between positive and negative toroidal angles in order to insure that no current is generated). Indeed, the ECRH power is given by: $P_{ECRH} = P^{offset}_{ECRH} + r_{ECRH} P^{\alpha}_{ICRH} - P^{boot}_{LH}$. This control maintains constant input power when the bootstrap current effect is amplified. Here r_{ECRH} is a relative weight factor and P^{offset}_{ECRH} is an offset power insuring that the ECRH power does not saturate or become negative.

In addition, the fraction of minority hydrogen, C_{min}, is adjusted to tune the ratio of electron to ion heating from ICRH power. The ratio between the ion (T_i) and electron temperature (T_e) can be also controlled by changing the plasma deuterium density (n_D). Notice that the plasma density and dilution modify the open loop fusion gain, since they control, together with the ion temperature, the neutron rate: $R_{DD} \propto n_D^2 f\left(T_i\right)$.

Finally, we add a controller that pilots $P_{ICRH}^{control}$ in order to obtain the target fusion gain Q_{target} or the target fusion power, and a controller that pilots $P_{LH}^{control}$ to reach the target plasma current $I_{P,target}$ at zero loop voltage.

The equivalent fusion power is $P_{fus}=4.941\left(1+r_{ECRH}\right)P_{ICRH}^{\alpha}$ and the equivalent amplification factor is given by

$Q=\dfrac{P_{fus}}{P_{ICRH}+P_{LH}+P_{ECRH}-\left(1+r_{ECRH}\right)P_{ICRH}^{alpha}}$. The equivalent bootstrap fraction is given by

$f_{boot}=\left(1+g_{boot}\right)I_{boot}/I_P$.

The numerical tool : METIS coupled with Simulink

In order to study the potential interest of this technique, a new numerical tool has been developed. This tool is based on the METIS code [5] coupled with Simulink [6]. METIS simulates the whole time evolution of the tokamak plasma with simplified assumptions while Simulink allows to implement and test several controllers. METIS is a fast tokamak simulator: ~1 mn per simulation for a discharge described by 300 time slices and 2 s per time slice when coupled to Simulink. METIS is included in the CRONOS suite of codes [7] as an assistant to prepare full integrated modelling simulations. METIS includes a complete current diffusion solver linked with a fast 2D equilibrium calculation based on moment equations [8]. The bootstrap current and resistivity are computed using the Sauter formulation [9]. The non-inductive current drive sources are computed on the basis of simplified analytical formulations and current drive efficiency scaling laws. The energy content of the plasma is given by scaling laws. Temperature profiles are computed using stationary heat transport equations with transport coefficients scaled on the global plasma energy content. Heat sources are computed with simplified semi-analytical formulations, including fusion power and radiation losses (line, relativistic bremsstrahlung, cyclotron radiation). The density profile is computed using a prescribed line averaged density, peaking factor scaling law and scaling law for the edge density. The plasma composition is deduced from Z_{eff}. Z_{eff} evolves depending on H_e ash transport (Z_{eff} without H_e ash is prescribed). A complete calculation of neutron production is implemented in METIS for DD and DT reactions including thermal and non thermal contributions. The time evolution of the current diffusion is completely treated and the time evolution of 0-D parameters, such as thermal energy and supra-thermal energy content, is computed by solving ODE equations. All physical quantities that appear in the above equations (as η_{LH}, I_{boot}, ...) are available as outputs of METIS.

Simulation setup and results

The starting point consists in the METIS simulation of the Tore Supra discharge 33612 heated with ICRH in minority H scheme (8 MW) and LHCD (1.5 MW) and a plasma current of 0.92 MA with a line averaged density of 42 x10^{19} m^{-3}. Then, the discharge duration is extended and the non-inductive current sources are adjusted in order to obtain a zero loop voltage. Extended RF heating capability is assumed in the proposed modelling with powers up to 12 MW of ICRH , 8 MW (6 MW continuous) of LHCD and 6 MW of ECCD/ECRH.

In the first set of calculation, an L-mode confinement is imposed: i.e. without enhanced core confinement. We simulate Tore Supra steady state (i.e. zero loop voltage) discharges that mimic Q~15 burning plasmas and a bootstrap current fraction of ~80% . The simulations show that external additional power allows to pilot the plasma only for a narrow range of the open loop fusion gain (g_{fus}). An example is given on figure 1. The increase of additional power used for control is not the correct approach to obtain the required Q. Burn plasma control is only obtained by including a control of the open loop fusion gain. The simplest way is to add a control of the plasma density (n_D) that allows to complete the fast control provided by external additional power with a slower control. This widens the operational space available for burn control while minimising the external heating sources.

In a second set of calculations, we simulate in Tore Supra a steady-state burning plasma with enhanced core confinement that leads to higher fraction of bootstrap current but increase the complexity of the systems. The enhanced confinement results from the formation and sustainment of internal transport barrier (ITB) by controlling the q-profile with off axis LHCD and ECCD. The ITB position is locked on the ECCD power deposition [10]. The enhanced confinement results from the formation of a plasma region with zero or negative magnetic shear as in the LHEP regime [11]. We have found, that it was practically impossible to control the Q factor (with a simple PID controller) due to its strong non-linear dependence with the H-factor. Instead, the fusion power is controlled as illustrated on Fig. 2. The target fusion power is set to 85 MW. At 20 s, the enhanced confinement starts to be lost and the controller tries to recover the target plasma state. The behaviour of the discharge and controller is completely different with an ITB with respect to a standard confinement regime since new non-linearities are introduced. We have found (for instance as shown on the l_i graph) that long pulse operation is required to reach steady state, due to the long time scale of current profile diffusion (5 s).

Conclusions

We have shown that the amplification factor Q or the fusion power cannot be controlled uniquely with the additional power: the open loop fusion gain of the device must be adjusted by tuning the plasma fuel density. A fast and precise control is obtained with the help of additional power, whereas a slow and coarse control is made with the plasma fuel density. We have also shown that Tore Supra plasma can reproduce most of the properties of an equivalent burning plasma at zero loop voltage only when the real fraction of bootstrap is at least 30 %. This is obtained when the confinement is enhanced compared to the L-mode (with an internal transport barrier in the present paper). An efficient control of a burning plasma requires more sophisticated algorithms than those used in the present study. This kind of global simulator allowing to simulate the main plasma properties and the controllers is mandatory in order to prepare the burning plasma experiments. More complete simulator for this purpose will be built on the European integrated simulator platform.

References

1] N.H. Zornig, PhD Thesis, Brunel University, 1998
2] T.T.C Jones et al, 28th EPS conference on controled fusion ans Plasma Physics, Funchal, ECA **25A**, 2001, p 1197
3] H. Takenaga et al,Nucl. Fusion 48 (2008) 035011
4] K. Shimomura et al. / Fusion Engineering and Design 82 (2007) 953–960
5] J.F Artaud, METIS User's Guide , CEA/IRFM/PHY/NTT-2008.001 (2008)
6] http://www.mathworks.com/products/simulink/
7] V. Basiuk et al., Nucl. Fus., **43,** (2003), p 822
8] H.J. de Blank, Transactions of Fusion Science and Technology **49**, 2006, p 111-117
9] O. Sauter et al, Phys. Plasmas **6,**1999, p 2834-
and Phys. Plasmas **9,** 2002, p 5140- (Errata)
10] J. Garcia et al, Phys. Rev. Let., accepted, to be published (2008)
11] G.T. Hoang et al, Nuclear Fusion, vol. 34 n°1 (1994) p. 75-85

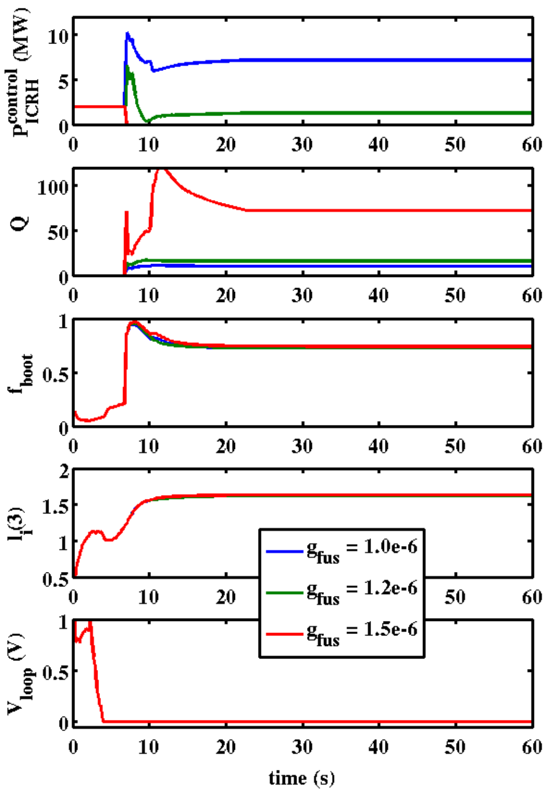

Figure 1: sensitivity to the g_{fus} parameter to the controllability of the amplification factor Q. Green curves show the case where the target Q (15) is obtained. Blue curves show the case where the target is missed. Red curves show the case where the system runs away and cannot be controlled (the control power drops to 0 and the Q factor runs away). The control is possible only for a narrow range of values around $g_{fus}=1.210^{-6}$. The top graph shows the time evolution of the additional power that is used to control the Q factor. The second graph from the top shows the obtained Q factor. The third graph from the top shows the simulated fraction of bootstrap current. The two bottom graphs show the time evolution, respectively, of internal inductance (l_i) and of the loop voltage (V_{loop}).The zero loop voltage control is switched on at 5 s. The control of bootstrap current fraction is switched on at 7 s (the target is 80%). The Q factor control is turned on at 10 s (the target is 15) . The delay (about 10 s) needed to obtain a stationary plasma is due to the current diffusion delay (see the l_i evolution) and the controller time response.

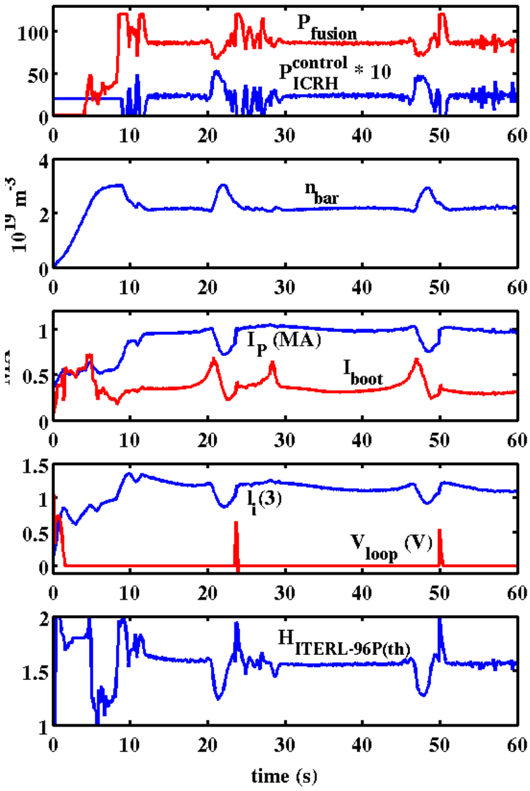

Figure 2: time evolution of plasma parameters simulating a burning plasma experiment. This simulation is performed with an ITB. The top graph shows the equivalent fusion power and the additional power that is used for control. The second graph from the top shows the plasma density that is used to tune the open loop fusion gain. The third graph from the top shows the plasma current and the real bootstrap current. The fourth graph from the top shows the internal inductance (l_i) and the loop voltage (V_{loop}). The bottom graph shows the confinement enhancement factor. The zero loop voltage control is switched on at around 3 s. The control of the bootstrap current fraction is switched on at 5 s. The fusion power control is turned on at 9 s (the target is 85 MW in this case). The simulation shows controlled phases that alternate with reorganisation phases. The plasma is never strictly stationary (as it can be seen on l_i, V_{loop} and I_p curves).