29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. **26B**, P-2.082 (2002)

DINA simulations of TCV Electron Cyclotron Current Drive and Heating

D. Raju[1], V. N. Dokouka[2], J-Y. Favez[3], R. R. Khayrutdinov[2],
J. B. Lister[3] and V. E. Lukash[4]

[1] *Institute for Plasma Research, Bhat, Gandhinagar-382 428, Gujarat, India*
[2] *TRINITI, Troitsk, Russia*
[3] *Centre de Recherches en Physique des Plasmas, Association EURATOM-Confédération Suisse, EPFL, 1015 Lausanne, Switzerland.*
[4] *RRC Kurchatov Institute, Moscow, Russia*

1 Introduction

A complete knowledge of the operational behaviour of a tokamak discharge requires a reliable numerical simulation. A great effort has already been dedicated on several tokamaks to benchmarking the 1.5D axisymmetric, time-dependent tokamak plasma simulation code, DINA. Ohmically heated TCV plasma discharges have been validated by the DINA code and this validation exercises encouraged us to extend the simulation to a full discharge evolution of shaped TCV plasmas with electron cyclotron current drive and heating. DINA has been implemented in the user-friendly MATLAB and transparent environment for rapid execution of full discharge simulations. Simulation results are presented in this paper for discharges with fully non-inductive current drive, intense additional heating and a mixture of the two. Discharges with off-axis current drive and with substantial bootstrap current are also being simulated and preliminary results are presented here.

2 Description of SIMULINK model

Increased reliance on detailed models of the operational behaviour of a tokamak discharge requires a positive validation of the reliablity of any numerical code. To simulate a full plasma discharge evolution also requires correct simulation of the diagnostics, the feedback control and the power supplies.

The Tokamak á Configuration Variable (TCV) [1] is specially designed to explore the operational benefits of shaped plasmas over a wide range of plasma shapes. Consequently, in order to provide shaping flexibility, all the polidal shaping coils and Ohmic coils are controlled independently. To simulate the full shaped plasma evolution, we have implimented a user-friendly MATLAB SIMULINK model of the Hybrid Analogue-Digital TCV plasma control system [2] which performs a matrix multiplication onto the measured signals in order to create an estimator which is compared with 24 analogue reference signals. The resulting feedback error vector is integrated, differentiated and amplified to produce 3 signals per element, a total of 72 signals. These signals are then multiplied by a matrix to obtain 24 correction signals. The correction vector along with a vector consisting of the 18 PF coil currents is multiplied by a matrix to get 20 voltage signals which are added to a pre-programmed feedforward time-varying vector. The

SIMULINK control model of the full system was scrupulously tested on various TCV plasma discharges as well as on plasmaless pulses. The measured signals are fed to the inputs and the simulation is performed for the whole discharge duration. The simulated control system outputs of the model are then checked against the experiments. These open loop tests satisfied us prior to connecting any linear or nonlinear model in closed loop.

The DINA code [3] uses an inverse variable technique [4] to find the coordinates of the equilibrium magnetic surfaces and permits the flux coordinates to be determined very quickly and accurately. This code solves the circuit equations for the PF coil currents, vacuum vessel and passive structure eddy currents self-consistently with the evolving plasma equilibrium. Many additional features like Neutral beam and RF heating, pellet injection, runaway electrons, halo current models, current drive and bootstrap currents, α-particles heating and modules for breakdown and null field formations are available inside the code. Two sets of Ohmically heated TCV plasma discharges have been validated by DINA code in previous work on TCV [5, 6]. Firstly, the experimental response of limited and diverted plasmas to low amplitude PF voltage pulses, applied to all coils, were compared with DINA simulations. In a second exercise, the "free-fall" Vertical Displacement Events (VDEs) produced by disabling the vertical position feedback were simulated during the very large vertical movement possible in the highly elongated TCV vacuum vessel. These two validation exercises increased our confidence in the ability of DINA to simulate a full TCV discharge evolution, including the free-boundary evolution of the plasma shape itself.

DINA has now been implemented in MATLAB as a "MEX S-function" which provides a powerful mechanism for augmenting and extending SIMULINK's capability. This S-function block is connected to the TCV control block to make a closed loop (Fig. 1). Many additional inputs for this S-function block can be specified as MATLAB variables. At each fixed integration time step, this coupled system is advanced and the time evolution is progressively simulated.

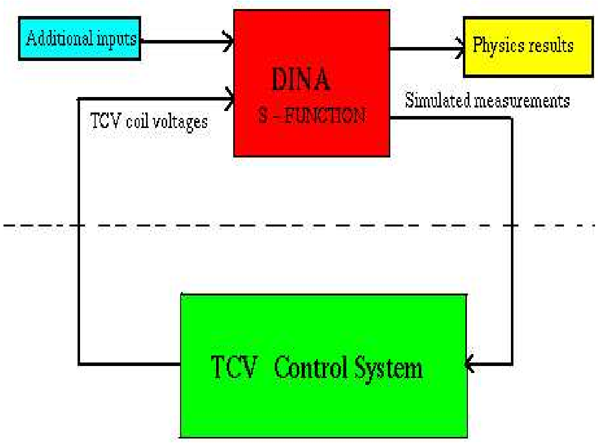

Figure 1: TCV-DINA model in SIMULINK

The first simulation will inevitably disagree. The coil voltage to plasma current transformer transfer function is a lossy integrator. Any inexactitude in the plasma inductance leads to an offset in the primary current. Any inexactitude in the plasma resistance leads to a roughly linear divergence between simulated and experimental primary transformer currents. Trying to tweak a time-dependent plasma resistance, either ad hoc or by tweaking the plasma transport is time-wasting and pointless, since it teaches us nothing. In [5] we detrended the PF currents, with justification. In the full pulse DINA simulations we have chosen a pragmatic approach. A low gain feedback loop is added to the DINA simulations allowing the divergences of the primary OH1, OH2 currents to be corrected by adjusting a linear plasma resistance multiplier, a "Z_{eff} modifier", onto neoclassical resistivity. This feedback has to be turned off as soon as the Electron Cyclotron Current Drive (ECCD) comes in.

A second obvious difficulty stems from the positive temperature dependence of current drive efficiency. This will also lead to diverging solutions in the simulation. Several other factors such as transport coefficients, width and location of heat deposition, location of an internal transport barrier, density profile must be adjusted properly to obtain a simulation reasonably close to the experiment. What is "reasonable" depends on the question which the simulation is trying to answer.

3 Discussion

We present one of the typical simulations of TCV discharge # 19692 which is an ECH assisted discharge with far off-axis deposition. During this experiment the vacuum shaping field is preprogrammed and the plasma current centroid is controlled by feedback (R,Z). This allows the plasma shape to evolve as the current profile is modified by the EC heating power, in which case the plasma boundary shape is a strong function of the evolving current profile. The results are shown in Fig. 2, in which we superimpose two simulation results. In the first one, the electron heat conductivity (T-11 scaling) is multiplied by two (red line) and in the second one, it is multiplied by one (green line). We see a significant improvement in the matching of the evolution of the plasma elongation.

There are some other sources of disagreement possible in the DINA simulations. Differences between DINA and LIUQE results for plasma parameters can be due to the different set of equilibrium parametrisation used by these codes. In the case of the LIUQE equilibrium reconstruction code, reconstruction of the plasma evolution is done by means of a set parameterised functions for plasma current and pressure profiles and a fitting algorithm calculates the most suitable plasma parameters. However in DINA, the simulation starts with a set of initial conditions and then the plasma profiles evolve in a totally free manner.

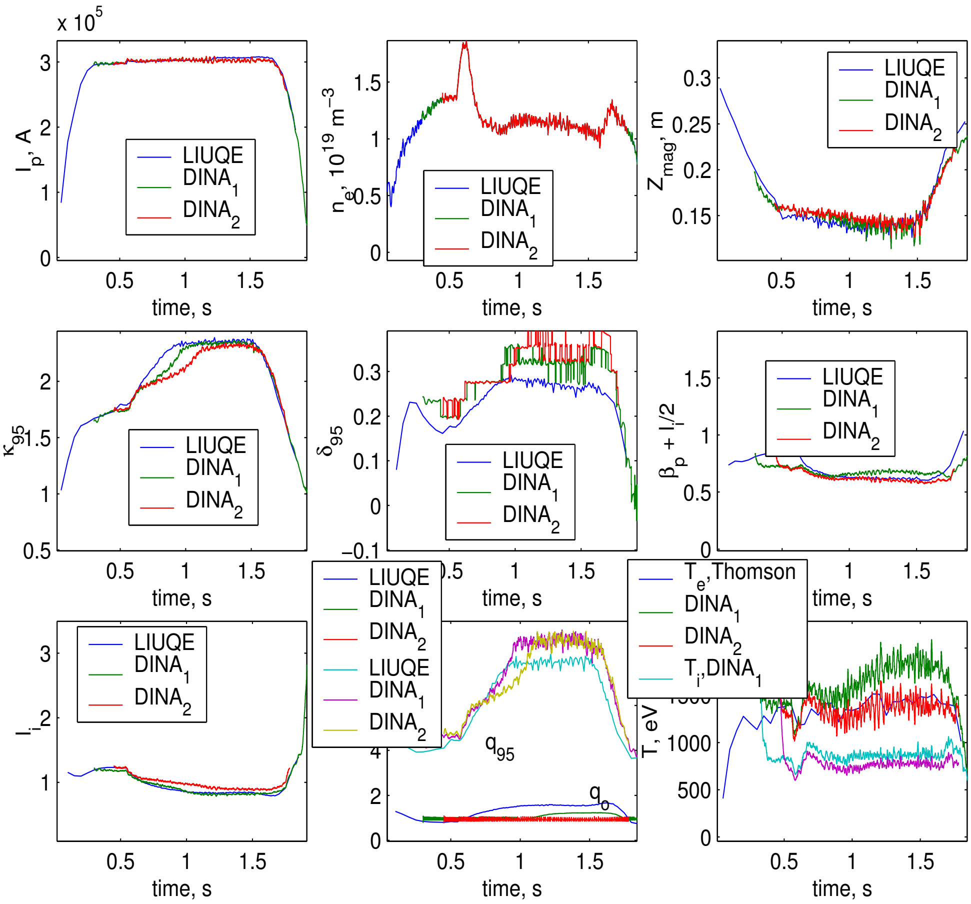

Figure 2: Results of ECH assisted TCV discharge # 19692 with two different simulations with electron heat conductivity multiplied by two (red line) and multiplied by one (green line).

Acknowledgements:

This work was partly supported by the Fonds National Suisse de la Recherche Scientifique.

References

[1] F. Hofmann, et al., Plasma Physics and Controlled Fusion, 36 (1994) B 277.

[2] J. B. Lister, et al., Fusion Technology, 32 (1997) 321.

[3] Khayrutdinov R.R., and Lukash V.E., J. Comp. Physics, 109 (1993) 193

[4] S. C. Jardin, N. Pomphery and J. DeLucia, J. Comp. Physics, 66 (1986) 481

[5] R.R. Khayrutdinov, J.B. Lister, V.E. Lukash, J.P. Wainwright, 43 (2001) 321.

[6] J- Y. Favez, R. R. Khayrutdinov, J. B. Lister and V. E. Lukash, Plasma Physics and Controlled Fusion, 44 (2002) 171.