Full Steady State LH Scenarios in Tore Supra

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Abstract. Lower Hybrid discharges have been realised in Tore Supra using feed-back control of the primary circuit voltage (V_{oh}) such that the loop voltage was maintained exactly zero near the plasma surface. This new scenario allows the plasma current to float and quickly reach an equilibrium value determined by the current drive efficiency and Lower Hybrid power. Recent experimental results show that, with the new "constant flux" scenario the coupled plasma and primary currents reach a steady state in less than 10 s which is in good agreement with theoretical expectations. A complete analysis of this scenario is presented.

1. INTRODUCTION

The main objective of the Lower Hybrid (LH) experiments performed on Tore Supra is to define and realise non-inductive steady state scenarios (1-2). Discharges have been obtained using feed-back control of the primary circuit voltage (V_{oh}) such that the loop voltage was maintained exactly zero. A model of coupled plasma-poloidal field (PF) coils system is described and used to compare two types of operation modes where V_{oh} is either kept constant or controlled such that the transformer flux is maintained to a prescribed value. The theoretical advantage of the "constant-flux" scenario is presented and confirmed by the experimental studies. The 0-D circuit analysis is completed with 1-D current diffusion simulation performed with CRONOS (2). The importance of the non-inductive current profile shape on the time evolution of the discharge is discussed. This allows to assess the time evolutions of the electric field and current density profiles inside the plasma within the constraints given by the experimental measurements.

2. ANALYSIS OF THE COUPLED PLASMA-POLOIDAL FIELD SYSTEM

In the 1992 campaign, LH experiments had been performed in Tore Supra, in which V_{oh} was kept constant, while the coupled plasma-PF coils system reached freely its equilibrium. Until the end of the discharge whose duration exceeded 25 seconds, no plasma current equilibrium was clearly observed. To understand this behaviour, the Tore Supra coupled plasma-PF coils system has been fully modelled using equivalent circuit equations, where the inductance matrix of the poloidal field circuits were numerically calculated with a finite element equilibrium code (CEDRES) (3). Calculations showed that the equilibrium would have been reached on a time scale of the order of 60 seconds, which was much longer than the resistive time $\tau_p = L/R_p$, where L and R_p are respectively the total inductance and resistance of the plasma loop. The good agreement between theoretical predictions and the measured variation of the primary coil current as a function of I_p validated the assumptions in the model, and therefore the value of the equilibrium time constant. Thus, this operation mode was not the most appropriate to achieve a fully non-inductive regime on a short time scale for Tore Supra (4). Using that model as a tool to test various feed-back methods, it has been found that an alternate and promising scheme was a feedback control of V_{oh} such that the transformer flux is imposed, and consequently, a zero loop voltage is obtained. Indeed the calculated equilibrium time constant in that case was then shorter than the resistive time, $\tau_{eq} = \tau_p (1 - \mu^2)$, were μ the coupling coefficient is close to 1 in Tore Supra. The comparison between the two types of scenarios is presented on fig 1 and clearly shows the advantage of a "constant-flux" scenario. During the last experimental campaign, that operation mode has been explored.

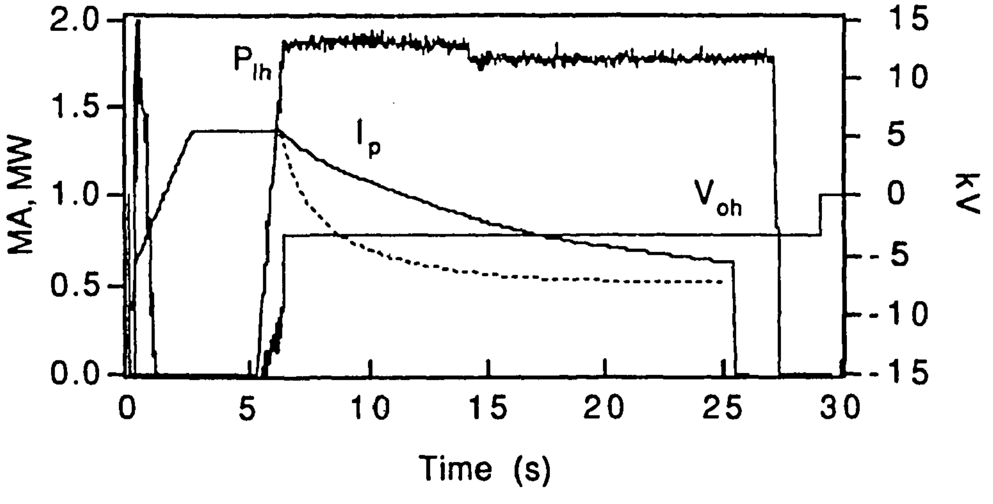

FIGURE 1. Time evolution of plasma current (I_p) when the LH power (P_{lh}) and V_{oh} are kept constant (shot 8212). The dashed curve represents the predicted time evolution of Ip if the LH power and the transformer flux were kept constant and Voh varied. The prediction is performed with the same plasma parameters.

3. "CONSTANT-FLUX" TORE SUPRA OPERATION

Using the "constant-flux" operation mode, a stable fully non-inductive plasma current flat-top of 0.8 MA has been sustained during 15 seconds in the 4-Tesla Lower Hybrid enhanced confinement regime (LHEP) (5-6) (fig. 2.a). The phase shift was -30 deg. ($n_{//o} = 1.8$ where $n_{//o}$ is the parallel index at the peak of the launched spectrum). The electron thermal energy content is about 40 % above the Rebut Lallia Watkins prediction (7). By applying the LH power ($\approx$ 3.7 MW), q_0 varies from 1 to 1.4, while the internal inductance l_i is larger than in the ohmic phase. The inductance matrix of the poloidal field circuits was calculated by CEDRES (8) taking into account the characteristics of the discharge.A comparison was then possible between the model predictions and the experiment. A good agreement with the model predictions was obtained (4) and confirmed that the current in the poloidal field coils reached an equilibrium on a time scale of 6s (fig. 2.b.c).

The current diffusion code CRONOS allows to assess the time evolution of the electric field and the LH current deposition profiles by comparing theoretical and experimental time evolutions of plasma parameters.(fig. 3). The electric field is stationary on a time scale of the order of 3 s which is 10 times shorter than the usual typical plasma resistive time. In fact, by maintaining the loop voltage exactly zero at the edge and by cancelling the on-axis electric field with a central and a broad LH current deposition profile, the electric field profile is forced to reach an equilibrium on a fast time constant.

Therefore, in these plasma conditions and antenna phasing a stable fully non-inductive equilibrium state has been reached for the thermal energy, impurity content, current and pressure profiles and finally the electromagnetic fields of the poloidal system. The duration of that type of shots can therefore be extended, and this provides a target for studying continuous operation (heat exhaust, plasma-wall interaction, etc...).

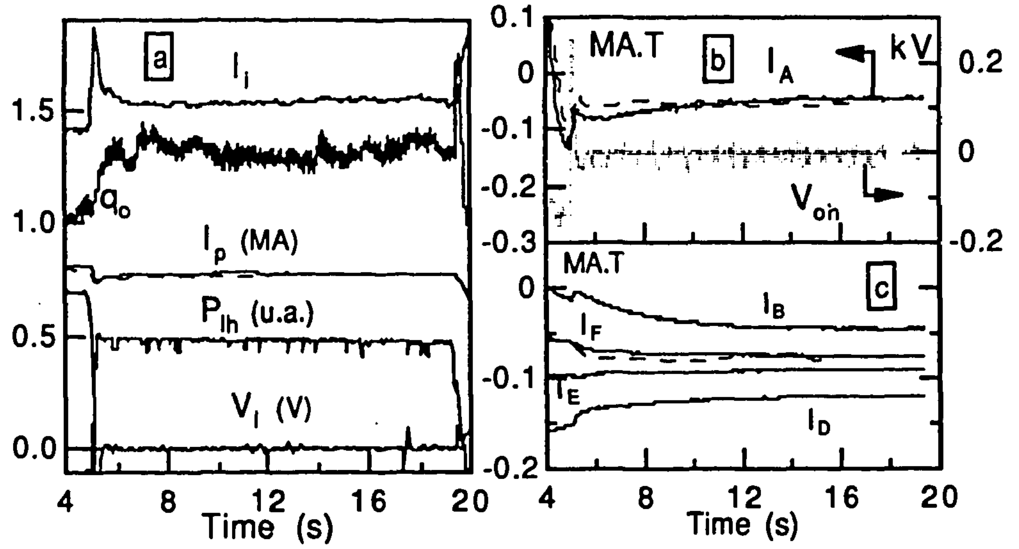

FIGURE 2. Time evolution of plasma parameters during shot 16379. The dashed curve represents a theoretical calculation.
a) Plasma current I_p, LH power P_{lh}, loop voltage V_l, safety factor on axis q_o and self inductance l_i.
b) and c) Time evolution of the poloidal field coils currents ($I_{a,b,d,e,f}$) and primary circuit voltage (V_{oh})

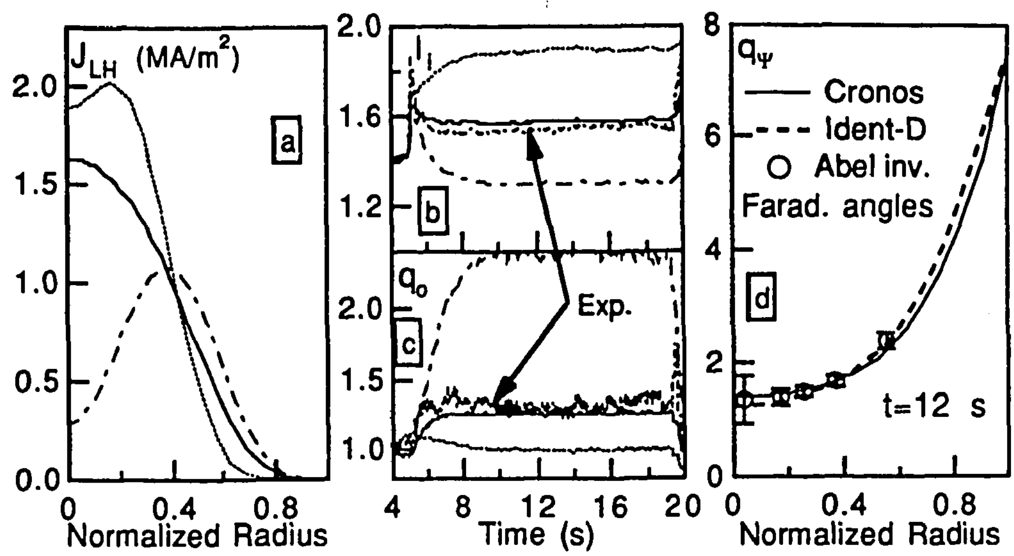

FIGURE 3. Effect of the LH current density profiles on the time evolution of l_i and q_0: (a) assumed LH currents profiles, (b-c) measured l_i and q_0 versus time and simulations d) q_Ψ profiles determinated with CRONOS and compared with Ident-D and Abel inversion of the polarimetry measurements.

4. CONCLUSION

A model of the coupled plasma-PF coils system has been presented and validated by LH experiments. A new operation mode where a zero loop voltage is imposed by a feed-back on V_{oh} has been studied theoretically and experimentally. By choosing an appropriate $n_{//}$ launched spectrum a stable, fully non inductive discharge has been obtained. The feasability of the "constant-flux" operation mode has been demonstrated with LH power alone. In the next experimental campaign, this scheme will be fully used with other non-inductive methods such as fast wave current-drive together with a larger self-generated bootstrap current component.

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