Advances in multi-megawatt, long pulse operation in Tore Supra

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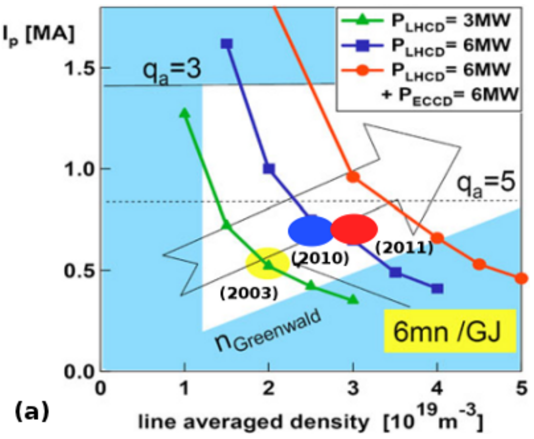
Tore Supra is a large tokamak ($R_0 \sim 2.4$m, $a_0 \sim 0.72$m, $B_0 \lesssim 4.3$T) equipped with superconducting toroidal field magnets and actively cooled plasma facing components, making it well adapted to the study of long pulses and associated issues of prime relevance for the future operation of ITER[1]. The Lower Hybrid (LH) system, a key component of its radiofrequency (RF) capabilities suited to steady-state operation, has been recently upgraded. Whereas in the past, stationary discharges at vanishing loop voltage in which LHCD (LH current drive) is the dominant non-inductive current source had typical line-averaged densities $n_l \sim 1.7 \times 10^{19}\mathrm{m}^{-3}$ and plasma currents $I_p \sim 500$kA[1], the coupling of LH power up to 6MW with this upgraded system has allowed to operate at $n_l \sim 3.0 \times 10^{19}\mathrm{m}^{-3}$, $I_p \sim 700$kA (poloidal beta $\beta_p \sim 0.6$, normalized toroidal beta $\beta_N \sim 0.7$) with high non-inductive fraction ($f_{ni} \sim 80\%$) either with LH power only, or combining the three RF systems available on Tore Supra viz. LH, Ion Cyclotron (IC) and Electron Cyclotron (EC). As an example, a stationary plasma (#46569) was sustained with a total injected/extracted energy $E \sim 650$MJ using 4.5MW LH power during 150s. Alternatively, steady-state pulse #47979 has been obtained by combining 5.3MW LH power and 1MW IC power during 160s, with an injected/extracted energy $E \sim 950$MJ. The corresponding extension of the TS domain of operation in the (I_p, n_l) plane[2] is represented in Fig. 1(a).

In Fig. 1(b) is shown the loop-voltage measured during the steady-state phase versus normalized LH power $P_{LH}/n_l/R/I_p$ in combined LH/IC discharges. In this figure, the dashed lines show the apparent LH efficiency, and the actual efficiency (η_{LH}) obtained by subtracting the bootstrap contribution computed with the CRONOS code[3]. During this campaign, an average value of $\eta_{LH} \sim 0.65 \times 10^{19}\mathrm{A/W/m^2}$ has been obtained. The choice of the parallel refractive index ($n_\parallel$) peak of the LH spectrum results from a trade-off between η_{LH} (which scales as $\sim 1/n_\parallel^2$) and the MHD stability of the considered plasmas. Indeed, at these levels of LH power, the obtained discharges are sawtooth-free and characterized by significantly reversed safety factor (q) profiles. A consequence of this reversal is the systematic presence of electron internal transport barriers (ITB), but this situation is also prone to the triggering of double tearing modes. In this respect, higher values of $n_\parallel$ are desirable, since they result in broader power deposition



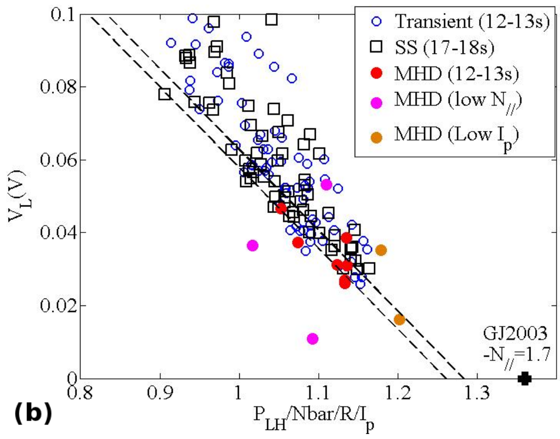


Figure 1: (a) Overview of the Tore Supra domain of operation. The giga-joule discharges performed in 2003 are shown as a yellow domain. The blue (resp. red) ellipse shows the discharges performed with LH power only in 2010 (resp. combined LH/IC power in 2011) {adapted from Ref. [2]}. (b) Loop voltage versus normalized LH power in combined LH/IC discharges.

profiles. It has been found that stable operation was possible using the combined FAM (Fully-Active multijunction) and PAM (Passive-Active multijunction) antennas with spectra peaked at $n_{\parallel} = 1.9$ and $n_{\parallel} = 1.8$, respectively. It should be noted that the power balance between both antennas is an important parameter: the PAM coupler spectrum features a secondary peak at relatively moderate $-n_{\parallel}$, which results in a globally more hollow LH current profile than would be driven with FAM antennas only[4]. It is also worthwhile mentioning that discharge durations exceeding the current diffusion time are necessary in order to properly assess the possibility of extending a given scenario to stationary operation. Other phenomena (fast particle losses, hot spots, impurities…) can manifest themselves even after several resistive times. In this respect, the operation of steady-state devices such as Tore Supra is crucial in order to prepare for ITER.

During the development of combined LH/IC scenarios, it was confirmed that the IC power had a stabilizing effect[5]. In several instances, accidental IC power switch-off have occurred, resulting in the triggering of MHD activity. Fig. 2 shows time traces corresponding to shot #47319 in which the IC power is switched-off at $t = 25$s, whereas the LH power is still at its nominal value. A marked increase of the MHD signal picked up by the Mirnov coils is clearly seen $\tau_{MHD} \sim 500$ms after the IC termination, immediately followed by a LH switch-off by the real-time control system due to the presence of significant MHD activity in the discharge.

A possible candidate to explain this observation is the kinetic contribution of fast ions. However, calculations performed with the ICRF code EVE[6] show that the typical slowing-down time for a maximum 3MW IC power coupled during this campaign is significantly shorter than

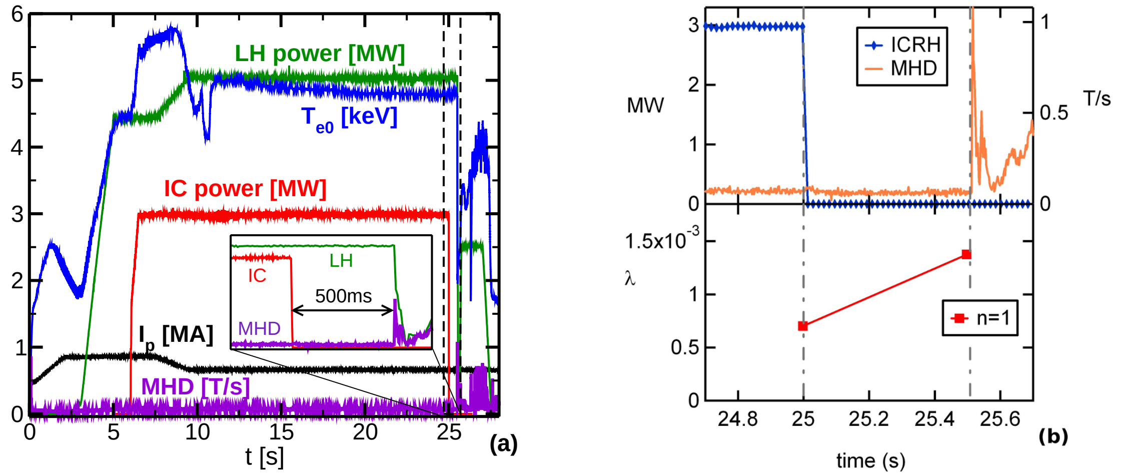


Figure 2: (a) Time traces for shot #47319. (b) IC power and MHD signal (top); linear growth rate of $n = 1$ resistive modes, calculated with CASTOR (bottom).

τ_{MHD}. Although the fast ion contribution can not be ruled out, a stabilization due to modifications of the equilibrium is also needed. Linear MHD calculations have been performed with the CASTOR code. They predict the potential destabilization of a double-tearing mode on the $q = 2$ surfaces. This is the combined result of 1) a decrease of the central electron temperature (T_e) after the IC switch-off, which results in enhanced shear reversal, 2) a decrease of the total pressure, leading to lower curvature stabilization. The linear growth rate, λ, computed by CASTOR is shown in Fig. 2(b). Non-linear calculations with the XTOR-2F code show the same trend although in this case, the inclusion of diamagnetic effects results in the destabilization of several MHD modes located near the q_{min} surface[7].

A recurring observation in these scenarios is the manifestation of various non-linear interplays between the plasma quantities, which translates into T_e oscillations with periods extending up to a few seconds. Discharges performed during the last campaign exhibit features reminiscent of the giant oscillation regime seen before in Tore Supra[8], which were caused by double/triple tearing modes appearing on the $q = 2$ surfaces. In this case, however, only MHD modes compatible with $q = 4/3$ are present. The common point between $q = 2$ and $q = 4/3$ oscillations is thus the presence of MHD modes at the pivot of the oscillation cycle, although the latter have a lesser overall impact on the discharge than the former. Even though the precise role of this MHD activity remains to be clarified, these new observations call for reconsidering the effective oscillation drive. A particular occurrence of slow oscillations is shown in Fig. 3(a).

After the pre-forming phase, T_{e0} clearly exhibits an oscillatory behavior. In the meantime, the Hard X-Ray emission signal in the 60-80keV range of energy does not evolve, which indicates that the LH power source remains unchanged. The CRONOS code has been used to interpret

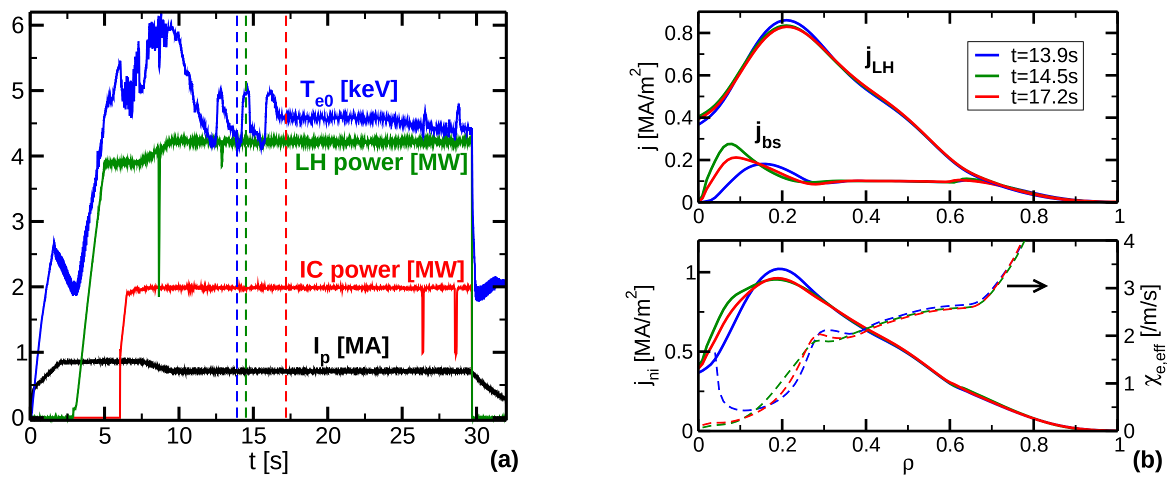


Figure 3: (a) Time traces for shot #48161; (b) LH and bootstrap current (top), total non-inductive current and electron heat diffusivity (bottom) at various times during the cycles.

these observations. It is found that the radius of maximum bootstrap current, which locally amounts to $\sim 30\%$ of the total current, oscillates between the electron ITB foot and the magnetic axis. This results in an inward shift of the total non-inductive current, and a subsequent degradation of the electron confinement, as shown in Fig. 3(b). This manifestation of the general current misalignment phenomenon[9] opens the way to new experiments in Tore Supra in which the central bootstrap current plays a crucial role. In particular, since the compatibility of these discharges with EC resonance heating has been experimentally checked, using EC waves as an actuator is an appealing perspective, provided the available power is sufficient for this purpose. The possibility of aligning the bootstrap current and the LH driven current profiles fits the TS longer term objectives: a feedback algorithm modulating P_{LH} with β_p constitutes a method to experimentally simulate discharges with high levels of bootstrap current in ITER[2].

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