REVERSED SHEAR EXPERIMENTS IN TORE SUPRA WITH CURRENT RAMP-UP AND LOWER HYBRID CURRENT DRIVE

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Current density profile shaping during plasma current ramp-up is nowadays a very powerful tool to produce reversed shear current profile leading to enhanced central confinement and increased plasma reactivity [1,2]. With this method internal transport barrier (ITB) are achieved in many devices with transient reversed or flat magnetic shear. Using the full capability of non-inductive current systems such as LH power (LHCD) and Fast Wave Electron Heating (FWEH), the goal of Tore Supra is to extend these improved confinement regimes to steady state operation [3]. For this purpose, important experimental and operating activity has recently been devoted to optimise the current ramp-up phase and to preform the current density profile in the early time of the plasma discharge taking advantage of the off-axis inductive current induced by the skin effect.

In the experiments reported in this paper the start-up of the plasma discharge (B_T=3.8T; R_o=2.34m, a=0.78m, helium gas) is characterized by very rapid increase of the plasma volume and an early lower hybrid heating to reduce the resistive diffusion of the current density profile. By these means the resistive skin time $\tau_\sigma = a^2 \sigma \mu_o/2$ is being maximized in the first 500ms of the plasma start-up. The start-up phase of the plasma and the early LH power sequence have been adjusted in accordance with the gas feeding and plasma current ramp-up to maximise the resistive skin effect and to avoid the onset of MHD activity.

During this initial phase, the plasma starts on the inner-wall and reaches its nominal size (a=0.78) after 100ms. The lower hybrid power is switched on at 250ms with a power varying between 0.5 and 1.5 MW. The discharge starts with a fast current ramp-up of 2MA/s and this current ramp-up rate is then reduced at t=500ms down to 0.4MA/s to prevent the triggering of low m (in particular m=5 and m=4) edge kink modes destabilised when the edge plasma current is too high. Simultaneously, the LH power is gradually raised up to 4MW in some discharges. In addition to slow down the current diffusion, the LH power also generates non-inductive current. The parallel index $n_{//}$ of the LH wave is set to 2.4 (90° phasing) during the whole power pulse. With this index, the reflected power back onto the grill does not exceed 10% of the injected power.

Using this operational procedure, promising results have so far been achieved with electron temperature reaching 6-7keV in low density experiments ($\langle n\rangle = 1.0 \cdot 10^{19}$ m^{-3}) and 4.5keV at higher density ($\langle n\rangle = 2 \cdot 10^{19}$ m^{-3}). The current density profile inferred from the IDENT-D reconstruction code including polarimetric and total pressure data is showing a large reversed shear region up to r/a=0.45 in correlation with electron temperature increase indicating a possible increase of the core confinement (Fig 1). The error bars shown on the current density profile (Fig 2) are the variance determined by a sequence of 50 equilibria where the Faraday angles of each five chords have been varied randomly within their expected error bar (i.e. ±0.2°). This procedure determined that the code was identifying hollow current profiles at 1.2 s in 95% of the cases. The reversed shear configuration is obtained in a reproducible manner and has been successfully maintained for about 1.0s. However it often terminates with a temperature internal collapse which modifies the current profile into a peaked profile (fig 1).

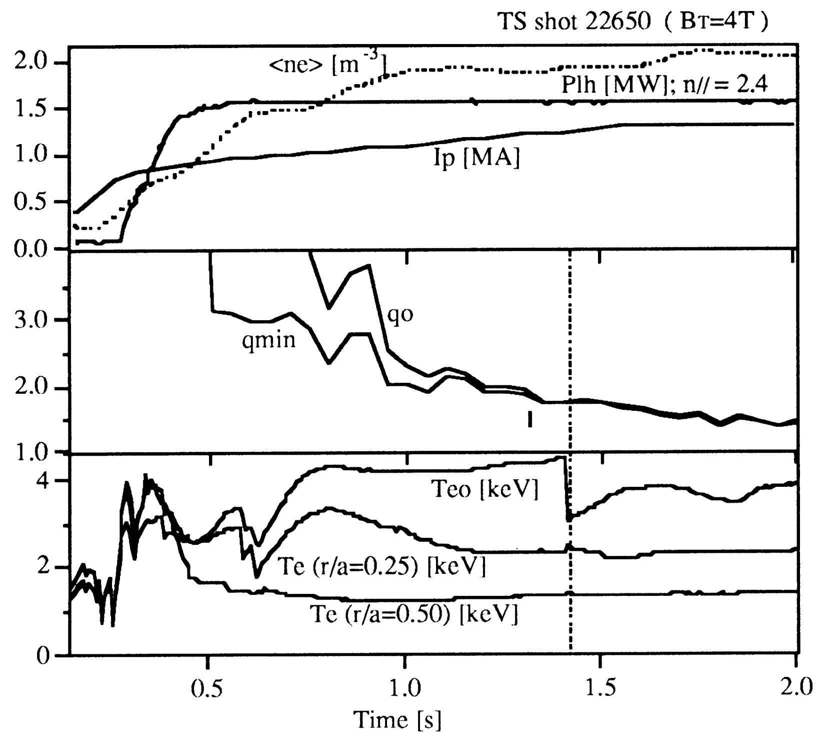
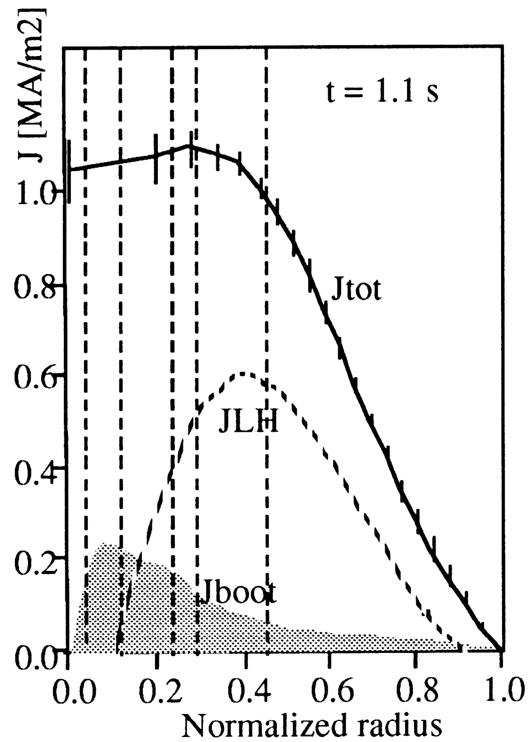


Fig 1: *Experimental scenario to preform the current profile in the current ramp-up phase with lower hybrid heating. The reversed shear configuration is maintained during almost 1s but terminates at 1.4s by a temperature collapse.*

Non-inductive current analysis is carried out using time sequence equilibria during (0.6s $\leq$ t $\leq$ 1.4s) and after the reversed shear phase (t $\geq$ 1.4s). The loop voltage profile is inferred from the time derivative of the poloidal flux and the inductive current is then deduced using the neoclassical resistivity. The bootstrap current is computed with the full matrix formulation from Houlberg [4]. At t=1.2s, the LH-current is peaked off-axis and represents about 50% of the total current (fig 2). The bootstrap current contributes to the total current for about 10%, and its maximum is located inside the reversed shear region. After the temperature collapse (t=1.6s), the plasma has lost its reversed shear configuration and the non-inductive current is peaked on axis. This effect related to the current profile shape is also observed on the inverted hard X-ray profiles obtained with the new cameras installed on Tore Supra [5]. During the reversed shear regime, the inverted HXR emission profile (using 20 detectors of the vertical camera) between 60 and 80keV is hollow with one broad peak at r/a~0.3 (fig 3). As the reversed shear domain shrinks, the core emission increases gradually. Such a behaviour, which could be the consequence of the local variation of the safety factor in the plasma center, indicates that off-axis LH power deposition could be obtained when a negative shear region is achieved in the plasma [6]. However, recent reversed shear experiments at much lower density (<ne>=0.7 10^{19} m^{-3}) are showing that the same LH-wave is deposited on axis. This density effect is likely related to the wave accessibility conditions and could become essential in the ultimate goal to control steady state reversed shear configuration with the LH power as non inductive current source.



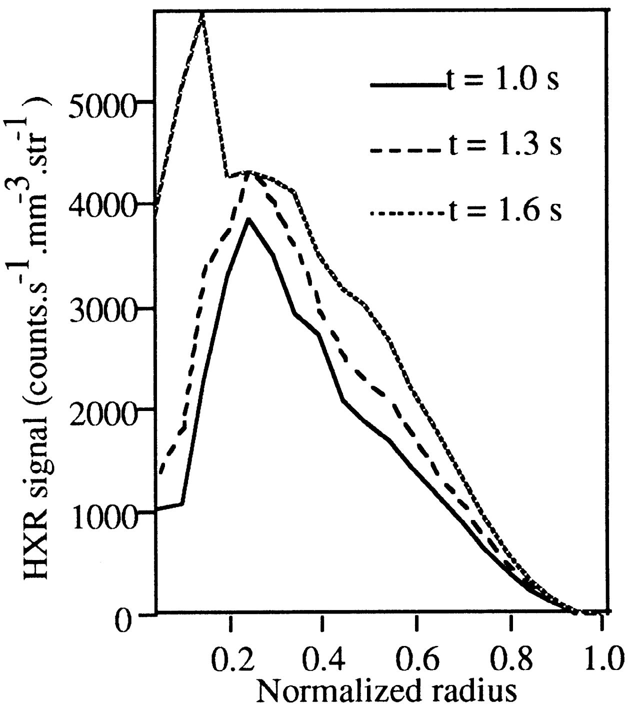


***Fig 2**: Total current and non-inductive currents calculated at 1.1s for the presented discharges. The location of the polarimeter chords are also indicated (--) as well as the variance inferred from the statistical analysis with IDENT-D.*

***Fig 3**: Evolution of the hard X-ray inverted profiles for the 60-80 keV energy band. The core emission increases when the q profile peaks after the temperature collapse at 1.4s.*

The HXR cameras are also providing the Bremsstrahlung emission for lower energy channels at 20-40keV and 40-60keV. All these energy channels are relevant to infer the power deposition profile of the LH wave. In a collision with an ion, a supra-thermal electron of energy E has indeed an equal probability to emit a photon at an energy between 0 and E. The LH-power deposition profile is therefore estimated by the sum of the HXR emission profiles of the three energy channels normalized to the total injected LH-power. Using this profiles, the electron diffusion coefficients are first determined in an interpretative way using the LOCO code [7] with the kinetic equilibrium from IDENT-D and the measured Te and ne profiles. In addition, predictive transport simulations have been made with the ASTRA code using the mixed Bohm / gyro-Bohm model for the electron thermal diffusivity [8,9]. In this model the assumed effect of the shear on electron thermal transport is described by a function F(s) included in the Bohm-like term. F(s) has the effect to cancel the Bohm term as the shear becomes negative. Three different functions have been tested (fig 4). Simulations are showing that a function $F(s)\neq 1$ seems required in the model to account for the observed electron temperature measured by the thomson scattering diagnostic during the reversed shear phase. The resulting diffusion coefficient χe looks consistent with that obtained in an interpretative way using the LOCO code. However, due to the error bars on temperature gradients and LH-power deposition profiles, it is not possible to formely validate the mixed Bohm/gyro-Bohm model for electrons.

This improved central confinement is stopped when the central temperature collapses at t=1.4s on the presented discharge. This internal collapse has a global character, lasts for about 500μs and is not accompanied by any detectable MHD activity on the pick-up-coils. The crash seems to occur when the q profile is crossing low (m,n) rational surfaces (typically n=1; m=2 and n=1; m=3). For the presented discharge, the collapse occurs as the q profile reaches the q=2 rational surface. CHEASE code calculations indicate that these discharges are stable with respect to the ballooning instability. This is consistent with the low βN (typically 0.32) of these discharges and also with the absence of high-low field asymetry in the displacement of the perturbation monitored by the soft X-ray vertical camera. Tearing stability analysis using the XTOR code is performed by keeping the equilibrium surface averaged current profile constant and by multiplying the experimental pressure profile by a scale factor. With a Lundquist number of $S=5.10^5$, the growth rate γ of the m=2 n=1 double tearing mode is decreasing with βp. At zero beta, $\gamma=3.6510^{-3}.\tau_a$, and at $\beta p = 0.25.\beta p_{exp}$, the growth rate vanishes. (βp_{exp} =0.23). Moreover, when the experimental pressure profile is scaled so that $\beta p=3.\beta p_{exp}$, the equilibrium remains stable towards resistive low-n ballooning modes. This pressure dependance [10] seems to rule out the infernal modes, however the tearing instability is also not consistent with the global character of the collapse and the absence of postcursor.

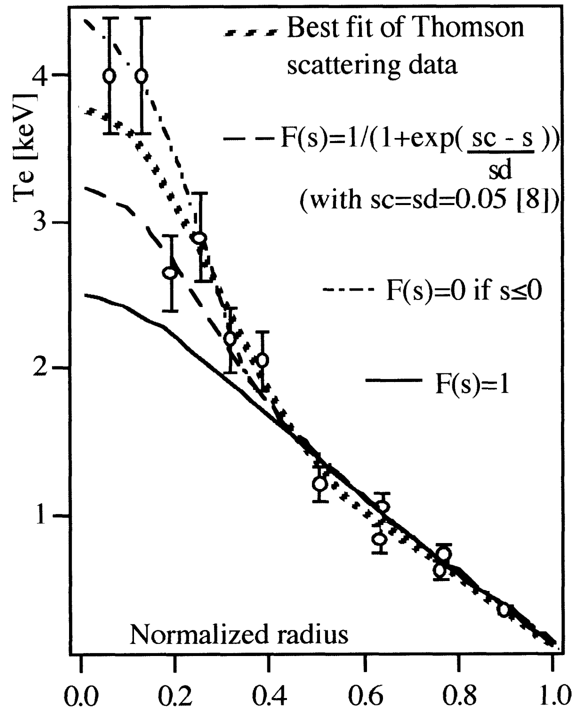


Fig 4: Simulation of Te at 1.4s using the mixed Bohm/gyro-Bohm model and three different shear functions F(s) on the Bohm term. F(s)≠1 seems required in the model to explain the measured temperature.

During experiments at high density ($n_{eo}=5.10^{19}$ m^{-3}), the coupling of the ICRH power has been successfully achieved up to 4MW to increase the power deposition and the pressure gradients in the plasma core and thus, the bootstrap current fraction. Using the combination of these off-axis currents with the slow diffusion of the ohmic current a bifurcation towards self-consistent off-axis current drive regime may be foreseen, in view to reach a steady-state reversed shear configurations.

[1]: S. Ide et al., 16th Int. Conf. Montreal 1996, Vol 3, IAEA, Vienna (1997) 253.
[2]: X. Litaudon, this conference, to be published in Plasma Phys. and Cont. Fus., (1998).
[3]: X. Litaudon and E. Joffrin et al., 12th Top. Conf. on Radio Frequency Power in Plasmas, Savannah (1997).
[4]: K. C. Shaing et al., Phys. Plasmas, Vol 3, N°3, p 965, March 1996.
[5]: F. Imbeaux et al, 2nd EPS Top. Conf. on RF heating and current drive of Fusion Devices, 20-23 January 1998, vol 22A, p141.
[6]: R. Arslanbekov et al., 22nd EPS Conf., Bournemouth (1995), Vol 19C, Part IV, p 393.
[7]: G.T. Hoang et al, Nuc. Fus., Vol 38, No 1 (1998), p117.
[8]: I. Voitsekhovitch et al. , Nuc. Fus., Vol 37, N° 12 (1997), p 1715.
[9]: M. Erba et al, Plasma Phys. Controlled Fusion 1997 39 p 261
[10]: A.H. Glasser, J.M. Green, J.L. Johnson, Phys. Fluid. 18, (1975), p 875.