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High Power ICRH scenarios in Tore-Supra : a potential route towards improved core confinement at high density ?

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Introduction

Before the complete refurbishment of the Tore-Supra inner vessel in 2000-2001, an experimental scenario had been successfully developed which achieved low/negative magnetic shear in the plasma core by means of a very fast current ramp-up. With up to 4 MW of ICRH power, in (H)He^4 minority electron heating, a region of reduced core transport was transiently observed, leading to a strong increase of the core electron pressure [1]. This scenario is potentially well suited for studies of Internal Transport Barrier triggering and sustainment. Experiments in such conditions have been recently resumed with the aim of expanding the operational parameter range towards higher density and higher levels of injected power.

Experimental Setup and Results

In this paper we shall present the latest results obtained in Tore-Supra by high power injection during and after a fast plasma current ramp-up, in a scenario similar to those developed in most tokamaks in order to tailor the current profile. In these new experiments (fig. 1), in Deuterium plasmas at Bt=3.8 T, a low current phase at Ip=0.4 MA is followed by a fast, ~ 1.4 MA/s, current ramp-up and a flat-top at Ip=1.1 MA. Lower Hybrid Current Drive (LHCD) is applied throughout the low current phase and into the second flat-top, while Ion Cyclotron Resonance Heating (ICRH) starts towards the end of the fast I_P ramp-up. The total applied power reached 11 MW, with up to 8 MW of ICRH in (H)D minority heating scenario. No Hydrogen was injected in these plasmas, the minority concentration is low, ~ 5%, and ICRH provides dominantly bulk electron heating. The time evolution of the plasma current profile is inferred from a number of independent diagnostics. The analysis of the MHD activity, via fast ECE superheterodyne data, suggests that during the fast current ramp-up phase the safety factor profile is reversed: (2,1) double modes are clearly identified at separated radial locations. In addition, line integrated Faraday Rotation measurements indicate that the safety factor in the core of the discharge is well above 1. The current profile slowly evolves during the high power phase and the sawtooth activity resumes after ~1.5s. During the current ramp and the high power sawtooth-free period a significant unfuelled density rise is observed, the line average electron density reaching 5-5.5 x 10^{19} m^{-3}, or ~75-

80% of the Greenwald Density Limit. The density rise is in part due to the increase in particle confinement with increasing plasma current, and it is therefore unavoidable; a significant part of it, however, can be attributed to increased recycling when the high power is applied to relatively unconditioned sections of the LPT limiter, and could be minimised by an appropriate vessel conditioning programme. During the high power sawtooth-free phase the core electron pressure increases by up to 40 % within approximately half radius, mainly due to the increase of n_e (fig. 2). This is qualitatively similar to the high confinement characteristics of the 1999 experiments, but the value of the core thermal electron pressure is increased by about a factor 2 with respect to the best data reported in [1]. Disappointingly, however, that there are no indications of development of an electron Internal Transport Barrier (ITB). The global confinement during the sawtooth-free phase of these discharges, in terms of total energy confinement time τ_E normalised to the confinement time predicted by the ITER89 L-mode scaling $H_{89}=\tau_E/\tau_{89}$ [2], is significantly lower, $H_{89} \sim 0.7$-0.9, than during sawtoothing pulses at comparable power and density levels, where $H_{89} \geq 1$. A relatively low normalised global confinement is not uncommon in Tore-Supra in low internal inductance and/or low shear conditions [3] and indeed, for this subset of data, the H_{89} factor appears to increase with internal inductance when the other plasma parameters are constant.

For the first time in this scenario, density fluctuations measurements with Doppler reflectometry were available [4], providing information on the radial profile of the fluctuations perpendicular velocity, as well as on the fluctuation $k_\perp$ spectra. Because of the somewhat uncontrolled density rise, the measurement does not cover the central plasma region. In the outer region, for $\rho \geq 0.6$-0.7 the perpendicular velocity is in the range 2.5-3.5 km/s. By comparison, the perpendicular velocity measured in sawtoothing high confinement discharges is ≥ 4 km/s.

Numerical Modelling

Interpretative and predictive numerical modelling has been carried out to shed some light on the physics underlying this scenario. In particular, the Cronos code [5] was used in *interpretative* mode for the analysis of the evolution of the plasma current profile, the local power deposition and the estimate of the heat transport coefficients. The consistency of the current profile calculations is verified by comparing the measured and computed Faraday rotation angles and time evolution of internal inductance, l_i, as well as matching the time of emergence of the q=1 surface with the appearance of sawteeth. The simulation of the discharge with the highest input power, #34163, indicates that the central value of the safety factor q_o increases during the ramp-up phase and a narrow negative magnetic shear region appears (fig. 3). The profile then evolves towards one with positive shear throughout, with q_o decreasing below 1 after approximately 1.3s from the start of the 1.1 MA flat-top, in very good agreement with the start of the sawtooth activity. The LH driven current profile, estimated on the basis of the measured fast electron Bremsstrahlung emission profiles, is mainly off-axis, providing ~0.2 MA of non-inductively driven current during the ramp-up phase and only ~0.1 MA during the high density high power phase. The combination of this limited LH non-inductive current and a similar amount, ~0.10-0.15 MA, of bootstrap current is clearly insufficient to allow sustainment of the reverse shear conditions, let alone to provide a significantly wider negative shear region. *Predictive* Cronos simulations have also been carried out, using a Bohm/Gyro-Bohm model for electron heat transport and imposing the time evolution of the density. When a more moderate density rise than what is observed in the experiments is used, the calculation suggests that, in order to approach steady state conditions with a reversed shear, the injected LH power should be in the range of 8 MW, generating ~ 0.5 MA of LH current and ~ 0.2 MA of bootstrap current (fig. 4). The predicted current profiles have a wide region of mildly negative shear (fig. 3) and an electron ITB is triggered close to the minimum q at half radius.

Using the current profiles computed by Cronos, in interpretative mode, and the measured density profiles a numerical study has also been carried out with the electrostatic linear gyrokinetic code KINEZERO to investigate the microstability of the modes which are thought to be responsible for electron transport [6]. In the collisional limit, the most unstable modes are Ion Temperature Gradient (ITG) driven, with Electron Temperature Gradient (ETG) driven modes unstable only in the plasma core. Neither ITG nor ETG modes show any significant trend towards stabilisation during the high power phase. The Trapped Electron Modes, on the other hand, appear to be stable throughout the period considered.

Summary & Conclusions

As shown by many tokamak experiments, including Tore-Supra, an operational scenario based on tailoring the current profile via a combination of electron heating and fast plasma current ramp is particularly attractive for producing conditions favourable to ITBs development. As we have reported in this paper, however, this is not a foolproof method for producing ITBs. In our case, reversed or flat shear conditions were indeed created, but only transiently and in a very narrow region in the plasma centre, $\rho < 0.3$, and the KINEZERO code microstability analysis does not indicate that any significant stabilization of ITG or ETG modes is taking place. We have used the Cronos transport code to predict how we could redesign the experiment to maximise the probability to obtain more favourable conditions for triggering and sustaining high performance ITBs. Our modelling is done assuming that recycling can be moderated and edge density can be kept lower than in the actual experiments. In this case, with a substantial increase in LHCD power, from 2.5 MW to 8 MW, we could approach conditions of flat current profile over a wide region, extending to half radius, with a significant fraction of the total current, ~70%, being non-inductively driven. The predictive Cronos transport model, which includes local reduction of transport according to magnetic shear, yields a long-lasting wide electron ITB located close to mid-radius. We can, therefore, be hopeful that once the LHCD power upgrade will be available on Tore-Supra, with the completion of the project CIMES [7], this interesting scenario could be realised experimentally. This will open the path not only to formation of electron ITBs, but also to the more ambitious studies of triggering and sustainment of Ion ITBs in conditions of no direct momentum injection, which is widely recognised to be one of the crucial issues for extrapolation of ITB based advanced scenarios for ITER.

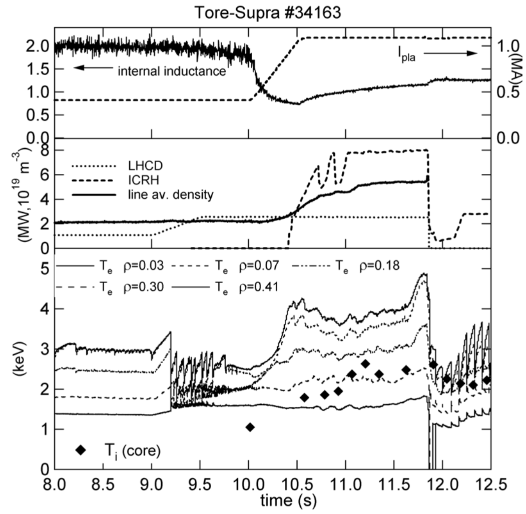

figure 1: time evolution of plasma parameters for a discharge with Ip fast-ramp and high power LHCD+ICRH

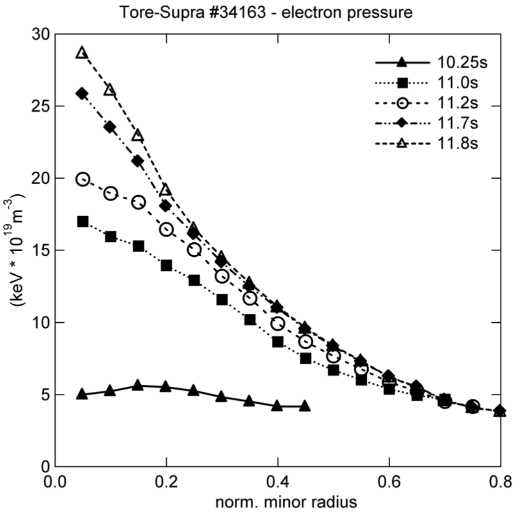

figure 2: electron pressure profiles at different times of the discharge shown in fig. 1

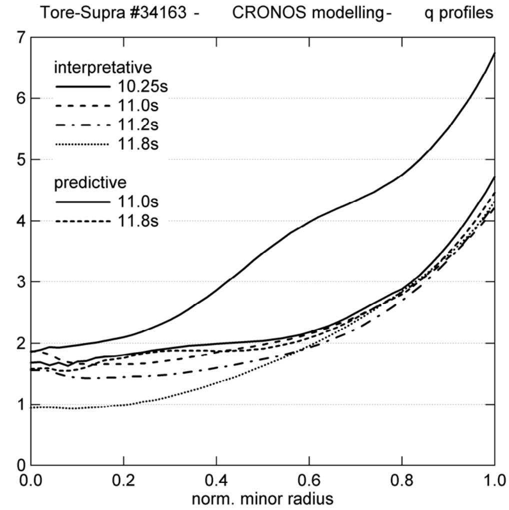

figure 3: q profiles - interpretative for #34163 and predictive Cronos code calculations

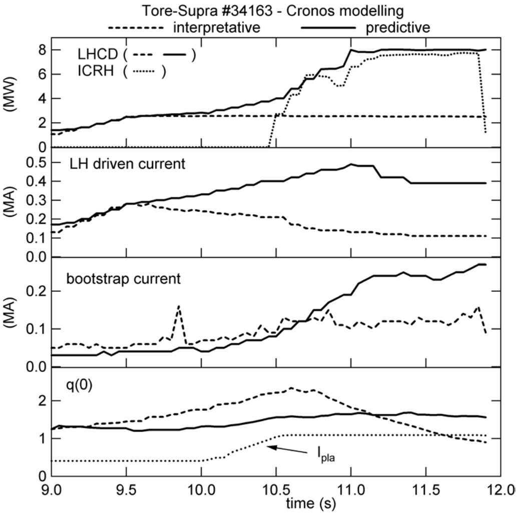

figure 4: time evolution of different current components - interpretative for #34163 and predictive Cronos code calculations

References

[1] G.T. Hoang et al., Phys. Rev. Letters, vol.84 n°20 (2000) p. 4593-4596
[2] Yushmanov P.N. et al, Nucl. Fusion 30 (1990) 1999
[3] G.T. Hoang et al, Nucl. Fusion 38 (1998) 117-132
[4] P. Hennequin et al., Rev. Sci. Instrum., vol. 75 n°10 (2004) p.3881-3883
[5] V. Basiuk et al., Nuclear Fusion 43 (2003) 822-830
[6] C. Bourdelle et al., Nuclear Fusion 42 (2002) 892-902
[7] B. Beaumont et al, Fusion and Engineering Design, vol 56-57, October 2001, pp 667-672