Long pulse operation with the ITER-relevant LHCD antenna in Tore Supra

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The aim of the Tore Supra tokamak is to address physics and technology issues of long pulse discharges. For this purpose, Tore Supra is equipped with two actively cooled Lower Hybrid Current Drive (LHCD) antennas (f = 3.7GHz), designed to operate in 1000s long pulses. One of these is the recently installed passive-active-multijunction (PAM) antenna [1, 2], whose design is chosen for an LHCD system for ITER [3]. The PAM design allows efficient cooling of the waveguides, in order to withstand plasma radiation, RF losses and neutron damping foreseen in ITER. In addition, it gives low power reflection close to the cut-off density ($n_{co} = 3.1\times10^{17}m^{-3}$ at f = 5.0GHz), which will be beneficial in ITER.

The first experiments with the PAM antenna [4] have shown extremely encouraging results in terms of reflection coefficient behaviour and power handling. The maximum power and energy reached after ~500 pulses on plasma was 2.7MW during 78s (exceeding 200MJ injected energy). In addition, 2.7MW has been coupled at a plasma-antenna distance of 10cm. The achieved power density corresponds to the design value ($25MW/m^2$) and is equivalent to the power density foreseen for an ITER LHCD system [3]. The coupling behaviour on the PAM, characterised by the fraction of reflected power (RC), shows good agreement with the ALOHA code predictions [5, 6]. The average RC is < 2% when the electron density in front of the antenna is close to the cut-off density, followed by an increase in RC as the density in front of the antenna increases. Coupling experiments during edge perturbations, produced by supersonic molecular beam injection (SMBI) to mimc ELMs, showed that at least intermediate power (~1.5MW) could be maintained during edge perturbations. In addition, the hard X-ray emission profile from the fast electrons, remained unchanged during edge perturbations [7], indicating that the LH driven current profile was not affected.

Full non-inductive current drive discharges, lasting 50s and performed with feedback control loops to maintain $V_{Loop} = 0$, have been performed with the PAM at low plasma current and density ($I_P = 0.5MA$, line average electron density $n_e = 1.45\times10^{19}m^{-3}$). Modelling with the C3PO/LUKE codes, using the realistic antenna spectrum as input, can well reproduce the hard X-ray emission profile as well as the LH current. The current drive efficiency of the PAM is comparable to that of the full active multijunction antennas, under similar experimental conditions. Finally, the LH current drive efficiency has been studied in high density discharges (up to $\langle n_e\rangle = 5.5\times10^{19}m^{-3}$), comparing gas fuelling and pellet fuelling. The hard X-ray emission is found to decrease as $\sim1/\langle n_e\rangle^{2.7}$ [8], with an even stronger decay for gas fuelled discharges at high density. The density fluctuation rate, as measured by RF probes on the antenna front, increases from ~50% at low density to >100% at strong gas puffing and $\langle n_e\rangle$ above $4\times10^{19}m^{-3}$.

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