THE USE OF ECRH AND LHCD TO OPTIMISE HIGH β PLASMA PERFORMANCE IN COMPASS-D

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1. Introduction

High β operation in tokamaks at low collisionality can be limited by non-ideal MHD instabilities which degrade the confinement and may lead to a disruption. On COMPASS-D, the β limit has often been reduced by (m=2, n=1) neo-classical tearing modes which are driven by the high bootstrap current [1]. However, scenarios have also been developed in which the full development of the (2,1) mode is actively avoided by adjustment of the timing of the ECRH heating pulse and the addition of LHCD. In this way, high β (β_N~2, β_p>1) plasmas have been sustained for timescales (>150ms) that are an appreciable fraction of the current diffusion time.

Experiments were carried out in ITER-like single null divertor plasmas (I_p=145-180kA, q_{95} ~ 3.1-4.0, κ ~ 1.6). The 60GHz ECRH system was utilised in these experiments launching up to 1.3MW of ECRH power from antennas on both the high and low field side. As far as possible, balanced injection was employed to give zero net non-inductive current drive. On COMPASS-D, high β can only be achieved at low field, with the available power, so second harmonic ECRH heating was used (B_ϕ=1.1T for on-axis heating) and the line averaged electron density was maintained at 0.8-1.0 $\times 10^{19}/m^3$, below the second harmonic cut-off. With ECRH there is no momentum input and no central fuelling, which is characteristic of the predominant heating mechanisms in an ITER-like device. The 1.3GHz LHCD system was employed in some of these experiments, utilising a conventional eight waveguide 'grill' antenna.

2.1. Optimisation of performance with ECRH alone

Quasi-stationary, high β performance has been achieved on COMPASS-D using just the ECRH system, by careful optimisation of both the current ramp-up and, more critically, timing of the ECRH heating pulse. In this way, high β plasmas (β_N ~ 2, β_p > 1) at q_{95} ~ 4.0 have been maintained for 150ms using >1.2MW of ECRH power. The presence of a continuous (m=3, n=1) mode was observed which was interspersed with fast 'sawtooth-like' events (identified as a (2,1) mode) observed on the Mirnov coils and soft x-ray cameras [2]. At a lower, ITER-like q_{95} (3.1) with ECRH alone, the high β phase was transient, despite careful optimisation of the ECRH timing and the current ramp-up, and ended with a disruption.

2.2. Optimisation of performance with ECRH and LHCD

Recent experiments have been undertaken to assess the effect on performance of modest levels of LH co-current drive, in addition to the high power ECRH. In these cases, the programmed ECRH power waveform and timing were not fully optimised. Consequently, in experiments at q_{95} ~4 with ECRH alone, the high β phase was reliably interrupted by the appearance of a large (2,1) mode at β_N = 1.7-1.8 causing a roll-over in performance. It is likely but not yet proven that this mode is a neo-classical tearing mode. The absence of a disruption in these cases is thought to be due to operation at higher q_{95} and reduced ECRH power levels (1-1.1MW). With the addition of modest levels of LH power (~50kW) before and during the high β phase, the large (2,1) mode did not appear and a longer high performance regime at higher β was normally achieved (see Figure 1). The best plasma performance achieved to date using this method was β_N > 1.5, peak β_N ~ 2 for up to 180ms. If normalised to the current diffusion time, this duration is ~20% of the equivalent normalised time expected for a nominal ITER discharge. Fast bursts of smaller amplitude 'sawteeth-like' MHD activity were observed during the high performance phase, but had negligible effect on the observed β values.

In additional experiments with ECRH alone at an intermediate q_{95} (~3.8) with increased ECRH power levels of up to 1.3MW, a disruption invariably terminated the discharge after a transient high β phase. Again, the ECRH pulse was unoptimised. With the addition of similarly modest levels of LH launched power, the duration of the high β phase was systematically extended (β_N ~ 2 for up to 80ms). As before, with LHCD present, the 'sawteeth-like' fast MHD events were observed more frequently but with a smaller amplitude compared to shots with ECRH alone.

3. Modelling of the LH driven current profile

Calculations of the LH driven current profile in the most recent experiments (q_{95}~4) have been performed with the BANDIT-3D combined Fokker Planck and ray tracing code [3]. The measured electron density profile was used in the simulations. There is a significant broadening of the density profile during ECRH. In the absence of a direct measurement of the electron temperature profile in these experiments, various profiles have been assumed. Bunches of rays were launched from three positions (defining the poloidal extent of the LH antenna) with a Gaussian power distribution in $N_{\parallel}$ ($N_{\parallel}$ between 1.7 and 2.5 for the $\Delta\phi$ = 60° antenna phasing adopted in these experiments). Due to the high temperatures (T_{e0} ~ 6-8keV) employed in these calculations, most of the driven current is located in the outer regions of the plasma (r/a ~ 0.7-0.9) regardless of the central temperature and temperature profile assumed (see Figure 2). A small amount of current is driven in the plasma core. LH driven currents are between 20-45kA (P_{LH} ~ 50kW) after taking into account the directivity of the LH antenna (~70%) and the reflected power (~30%). This is a reasonably small fraction (<30%) of the total plasma current (145kA).

Initial runs of the ASTRA code [4] have been performed to assess the effect of the calculated driven current profile on the evolution of the total current profile. Runs of ASTRA incorporating time-evolving electron temperature and current profiles, with and without the time evolving driven current contribution have been performed until the calculated q profile is reasonably stationary in the quasi steady state high performance regime. The final q profile predicted by ASTRA is somewhat dependent on the initial current profile chosen and, as there is no direct measurement of the current profile on COMPASS-D, this choice was rather arbitrary. However, for reasonable choices of the initial current profile, there is a clear steepening of the final quasi-stationary q profile at and inside mid-radius and a corresponding inward shift of the q=2 surface, with the LH off-axis driven current and the bootstrap current components included. For example, adopting a broad initial current profile, the location of the q=2 surface at steady state is r/a=0.33 with LHCD present compared to r/a=0.47 without LHCD. Qualitatively, this behaviour presents a possible explanation for the observed absence of the large (2,1) mode with LHCD. The q=2 surface first appears in the centre of the plasma as the q profile relaxes and where the (2,1) mode is classically unstable. In the presence of LHCD, the q=2 surface remains close to the centre, consistent with the repetitive m=2 'sawteeth-like' relaxations observed. Without the additional off-axis LH driven current, the q=2 surface expands further out towards the region of high pressure gradients, where the (2,1) mode amplitude may be enhanced by neo-classical effects, leading to the formation of large m=2 islands which terminate the high performance phase. The bootstrap fraction calculated by ASTRA is ~40% in these runs and is also peaked off-axis.

4. Summary

Quasi stationary high performance plasmas have been achieved on COMPASS-D with ECRH alone at q_{95} ~ 4 by careful optimisation of the current ramp-up and the ECRH timing. At lower q_{95} values (~3.1) and/or with non-optimised ECRH timing, the high β phase is transient. LHCD is reliably observed to delay or prevent the onset of significant m = 2 when the ECRH pulse is not optimised at q_{95} ~ 3.8-4.0, thus extending the high β regime (β_N > 1.5 for 180ms). BANDIT-3D simulations suggest the LH driven current profile is well off-axis. Using these predictions in the ASTRA transport code, initial simulations show that the effect of the LH driven current profile is to move the q=2 surface towards the centre of the plasma to a region of reduced pressure gradient, providing a possible explanation for the improved m =2 stability.

Acknowledgements

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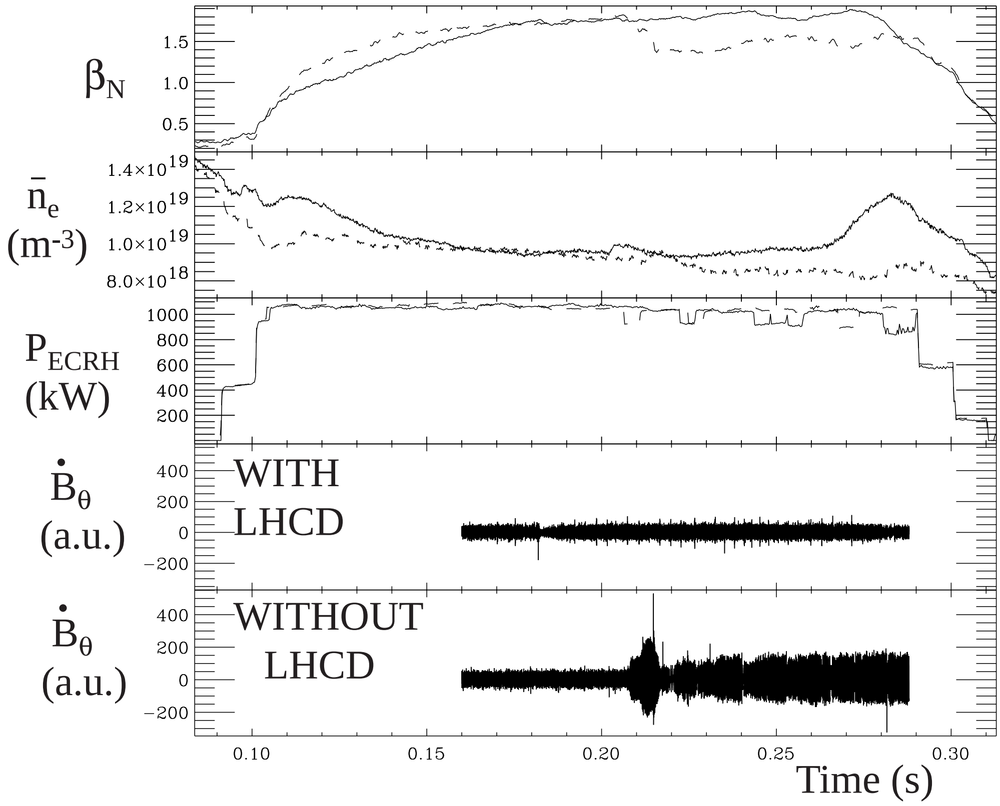

Figure 1. Figure showing the absence of a large (2,1) mode and the longer high β phase observed in the presence of LHCD at q_{95} ~ 4. The dashed lines show data from a shot with ECRH alone and the solid lines a shot with LHCD present during the whole of the ECRH pulse.

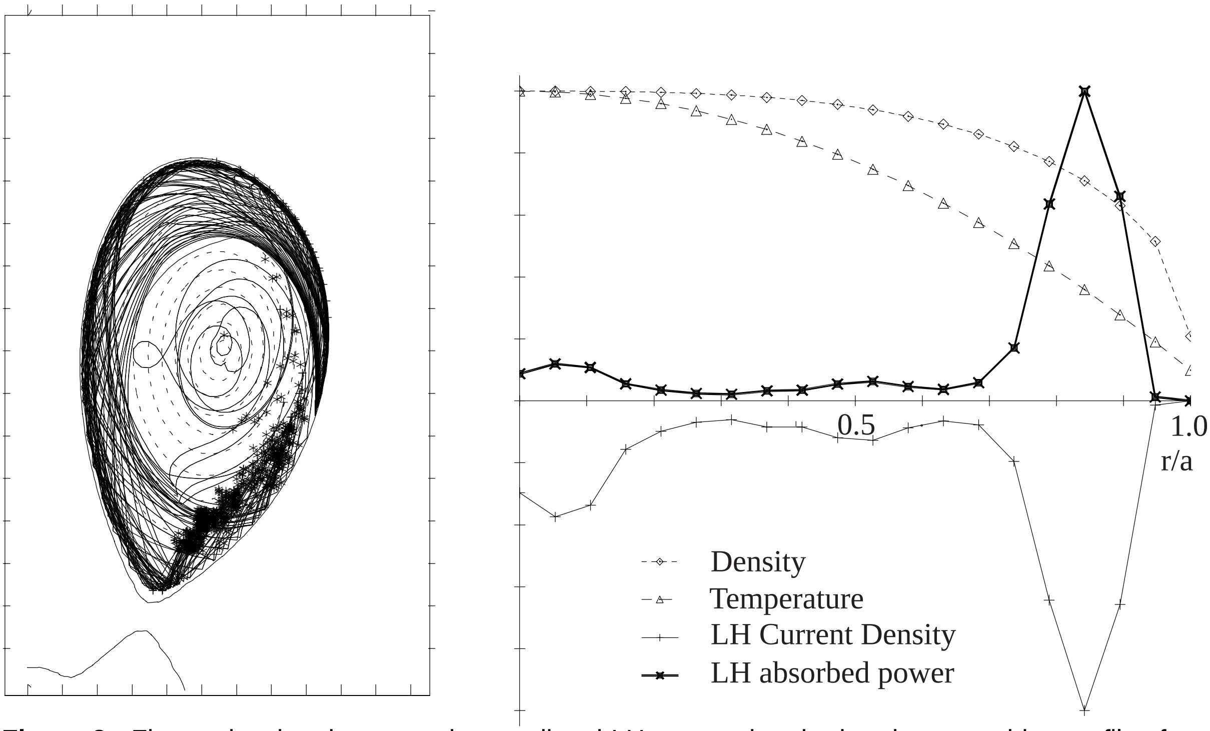

Figure 2. Figure showing the ray paths, predicted LH power absorbed and current drive profiles from BANDIT-3D calculations. The temperature profile is parabolic with T_{e0} = 6 keV. Rays are launched from locations at the outer edge of the plasma to simulate the poloidal extent of the LH antenna.