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ECRH/ECCD in Advanced ITER Scenarios

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Introduction

Electron cyclotron (EC) waves can perform a variety of roles in ITER including start-up assist, heating to ignition, on and off-axis current drive and instability control. EC wave absorption is robust and well understood producing highly localised heating with total absorption anticipated for almost all parameters foreseen in ITER. Other advantages for ITER include the easily adjustable absorption location, the absence of damping on alpha particles, no requirements on edge plasma control for wave launching and no specific impurity generation problems. Extensive calculations with the BANDIT-3D code at Culham (1) have helped to determine the optimum EC system configuration on ITER and its capabilities in both standard ignited and 'advanced tokamak' equilibria. BANDIT-3D is a relativistic and self-consistent ray tracing and Fokker Planck code incorporating 2D velocity space (speed and pitch angle) and 1D real space effects. Electron radial diffusion, trapping, toroidal dc electric fields and realistic magnetic geometry can all be included. Calculations in the standard scenario will be briefly discussed with more emphasis on the results for the 'advanced tokamak' regime.

Initial BANDIT-3D calculations were performed in a standard ignited single null x-point ITER equilibrium (B_ϕ=4-5.7T at R_0=8.1m) assuming profiles of the form $T_e(r)=(T_{e0}-T_{ea})(1-r^2/a^2)+T_{ea}$ and $n_e(r)=(n_{e0}-n_{ea})(1-r^2/a^2)^{0.26}+n_{ea}$ with T_{e0}=20-30keV, T_{ea}=0.5keV and $n_{e0}=1.4 \times 10^{20}/m^3$, $n_{ea}=0.8 \times 10^{20}/m^3$ ($\langle n_e \rangle=1.3 \times 10^{20}/m^3$). A flat Z_{eff} profile (Z_{eff}=2) was assumed. The proposed scheme for efficient heating and current drive is O-mode launch near the outboard mid-plane with absorption mainly at the fundamental resonance. A cone of rays with Gaussian power distribution and cone half angle 3° was used, with the launch direction specified by the poloidal (θ) and toroidal (ϕ) launch angles, measured with respect to the major radius. Due to the high temperatures in ITER, strongly upshifted ($\omega>\omega_{ce}$) absorption is expected for waves launched with a finite toroidal angle enabling good control of the absorption location with a system employing a variable toroidal launch angle. BANDIT-3D results for this configuration identified a 170GHz toroidally steerable system as the most flexible, enabling effective core heating and current drive over a range of plasma parameters and toroidal fields. For ϕ=20°, strong central heating is predicted at 170GHz from the initial ohmic phase of the discharge (T_{e0}=5keV, $n_{e0}=3 \times 10^{19}/m^3$) through to the ignited regime (T_{e0}=20keV, $n_{e0}=1.4 \times 10^{20}/m^3$). With the provision of modest toroidal steering ($\Delta\phi$=15°), significant core heating and current drive may be maintained over the toroidal field range (B_ϕ=4-5.7T) whilst avoiding significant second harmonic absorption. Core current drive efficiencies ($\eta_{20}=\langle n_e \rangle I_{rf} R_{axis}/P_{rf}$ A/W/m^2) in the range 0.16 A/W/m^2 at B_ϕ=5.7T (ϕ=25°) to >0.25 A/W/m^2 at B_ϕ=4.3T (ϕ=40°) (2) were attained with T_{e0}=20keV. The current drive efficiency is limited at higher temperatures due to relativistic effects and the need to avoid second harmonic damping (3). Increasing the toroidal angle with a 170GHz system at full field results in significant off-axis current drive with the efficiency typically reduced by 30% (at r/a~0.5) and 50% (r/a~0.7) compared to that attained in the core. For r/a>0.7 the current drive efficiency decreases significantly

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due to increased trapping and incomplete absorption at high toroidal launch angles. A technically feasible step-tuneable ECH system operating at 131, 150 and 170GHz with fixed launch angle (ϕ=20°) allows reasonable core heating and current drive (η_{20}= 0.12-0.17 A/W/m^2) over the full magnetic field range, but off-axis capabilities at full field are more limited than for a fixed frequency, toroidally steerable system.

ECRH/ECCD in the advanced tokamak regime

The BANDIT3-D calculations have been extended to an ITER 'advanced tokamak' equilibrium (I_p=12MA, $B_{\phi 0}$=5.7T at R_0=8.1m, B_{axis}=4.7T at R_{axis}=9.437m, κ~2.0). This is a high β_N, reversed shear, high bootstrap fraction plasma proposed for steady state tokamak operation in ITER. The equilibrium is more strongly shaped than the standard one and has a large Shafranov shift resulting in compressed flux geometry on the low field side (LFS) of the magnetic axis. In this case $T_e(r)$ again was assumed to be parabolic (T_{e0}=20-30keV, T_{ea}=0.5keV) but $n_e(r)$ was taken to be more peaked than in the standard regime (parabolic$^{0.5}$) with the same central density (1.4 × 10^{20}/m^3) but a lower edge density (0.14 × 10^{20}/m^3) and thus a reduced volume average density (<n_e>=1 × 10^{20}/m^3). The main requirement of a heating and current drive scheme in steady state operational regimes in ITER is to provide significant off-axis current drive (r/a>0.5) to supplement the large bootstrap current (ensuring full non-inductive operation) and maintain an optimised current profile for improved MHD stability and confinement. The other requirement is the provision of a small core seed current for maintenance of the bootstrap current.

Studying the utilisation of the 170GHz fully steerable system in the advanced configuration using BANDIT-3D immediately indicated very efficient core heating and current drive (η_{20}~0.2 A/W/m^2) at T_{e0}=20keV compared to η_{20}~0.16 A/W/m^2 at full field in the standard scenario (see Fig 1). This is because, in the advanced regime, the magnetic field is lower on the magnetic axis thus requiring a larger toroidal launch angle (ϕ=40°) and increased Doppler shift to ensure fundamental resonance in the centre.

Obtaining reasonable off-axis current drive with the 170GHz steerable system, however, is more difficult. Using smaller toroidal launch angles (ϕ~10-20°) current can be driven on the high field side (HFS) of the magnetic axis but the efficiency is poor (η_{20}<0.1 A/W/m^2) as the upshift is small and second harmonic absorption in the core starts to become significant (>10%). Using larger toroidal angles (ϕ=50°) leads to damping on the LFS of the magnetic axis but absorption is incomplete and the driven current profile is very broad (0<r/a<0.7). This poor localisation is partly due to the compressed flux surface geometry on the LFS and also due to the weak absorption and increased refraction at high toroidal launch angles. This also results in a sensitive dependence of the absorption location and current drive efficiency on both frequency and toroidal launch angle. The off-axis capabilities of a fixed toroidal angle, step tuneable system optimised for the standard regime are even more limited (see Fig 1). Using higher frequencies (>170GHz) offers little benefit in this regime due to the increased impact of second harmonic absorption.

However, more favourable combinations of frequency/toroidal angle can be found. For example, by combining the step tuneable and toroidally steerable system (150GHz, ϕ=40°) much better off-axis current drive is predicted (η_{20}~0.13-0.14 A/W/m^2 at r/a~0.65) with improved localisation (see Fig 1). Even better results are achieved by using a poloidal launch angle (θ) leading to significant enhancements in off-axis current drive efficiency and improved localisation (see Fig 2). The latter is

due to the poloidally launched waves propagating (and absorbing) almost tangentially to the compressed flux surfaces on the LFS. Using θ=30° at 170GHz, η_{20} >0.13 A/W/m^2 is achievable at r/a~0.6 with ϕ=55°, despite the absorption being incomplete because of the large toroidal angle. Increasing T_{e0} to 30keV ensures complete absorption with η_{20} ~0.24 A/W/m^2 at r/a~0.6 for ϕ=55°, with better localisation (0.5<r/a<0.8 see Fig 3). This is equivalent to an off-axis driven current of ~1.3MA for 50MW of launched power. However, due to the compressed flux surfaces, the location will be rather sensitive to the frequency and exact toroidal and poloidal launch angles employed. Therefore, poloidal steerability is desirable to maintain an optimum off-axis current drive profile for a range of equilibria.
Interestingly, in principle, a core seed current (for maintaining the bootstrap current) can also be provided in ITER advanced scenarios using the proposed ECH start-up assist system. This is a lower frequency system (90-140GHz) that will be used to ensure robust, prompt outboard wall plasma breakdown and burn-through. BANDIT-3D runs utilising a 140GHz, ϕ=20° start-up system in the advanced regime produced very localised central current drive (η_{20}~0.13 A/W/m^2, 0<r/a<0.1) at T_{e0}=20keV (see Fig 1). This could be large enough to provide the required seed current, especially if the available power was somewhat higher than the 3-4MW currently proposed. This could be achieved with no increase in installed start-up power by utilising a step tuneable system rather than several separate fixed frequency 3-4MW systems as presently proposed (4).

Conclusions

A 170GHz fully steerable system is the optimum choice for the standard ignited ITER scenario in terms of efficient core heating and current drive over a wide toroidal field range and reasonable off-axis capabilities. Utilising this system in an 'advanced tokamak' equilibrium results in very efficient core current drive. However, the main requirement in this scenario is to drive off-axis current, maintaining an optimum current profile in combination with the bootstrap current. As it stands, the 170GHz steerable system offers limited off-axis capabilities and reduced absorption localisation. However, higher efficiencies and improved localisation are achievable with some frequency tuneability or the addition of some poloidal steering capability, eg 170GHz, ϕ=55°, θ=30°, T_{e0}=30keV gives η_{20}~0.24 A/W/m^2 at r/a~0.6 equating to ~1.3MA for 50MW of launched power. It has also been demonstrated that the ECH start-up assist system for ITER might, in principle, be used to provide a small core seed current to maintain the high bootstrap current fraction for steady state operation.

Acknowledgement

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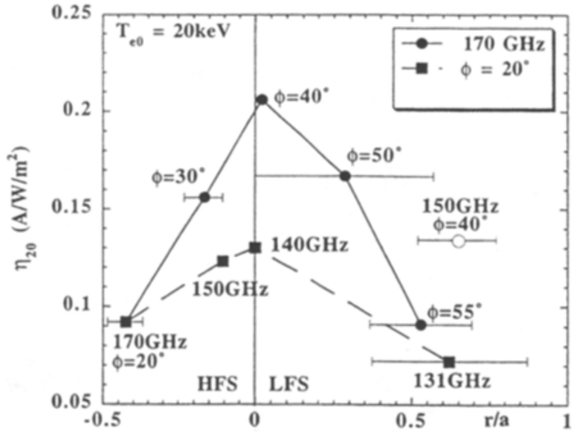

Figure 1 Current Drive efficiency and location of driven current for a toroidally steerable 170GHz system and a step tuneable system at fixed toroidal launch angle (φ=20°). Also indicated is the full width of the driven current profile at half height

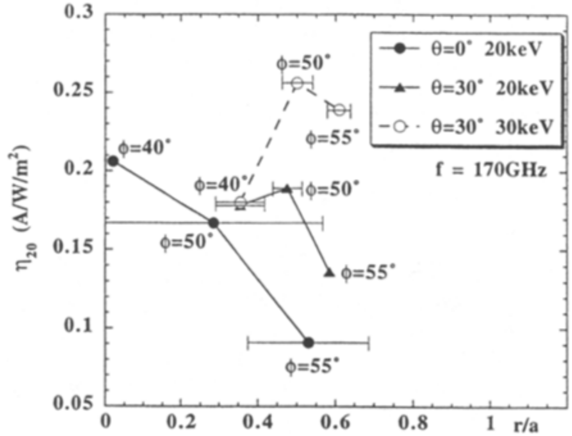

Figure 2 Current Drive efficiency and location of driven current for a 170GHz system with various toroidal and poloidal launch angles at T_{e0}=20 and 30keV.

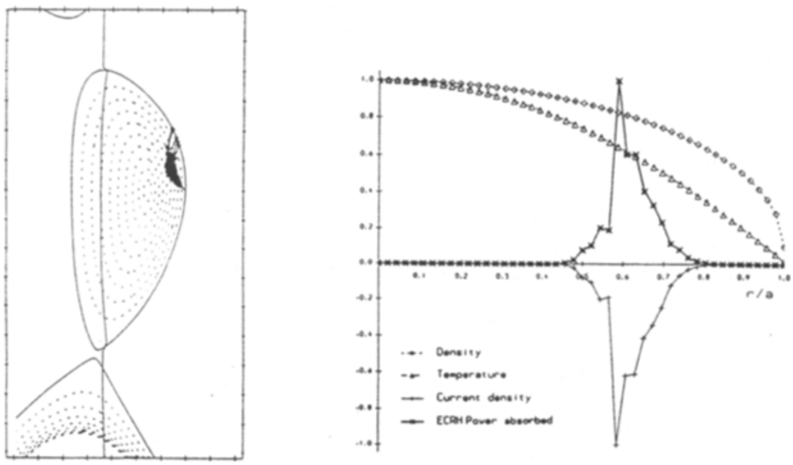

Figure 3 Ray trajectories, power absorption and driven current profiles for 170GHz, φ=55°, θ=30°. Density and temperature profiles normalised to $n_{e0}=1.4\times10^{20}/m^3$ and T_{e0}=30keV are also shown.