Microwave current drive for STEP and MAST Upgrade

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The STEP (Spherical Tokamak for Energy Production) program is the UK's Spherical Tokamak (ST) reactor design endeavour. In the first tranche (2022-2024), the program aims to produce a concept design for a steady state ST reactor, producing ~100 MWe. As such, the auxiliary current drive system is a critical user of recirculating power. Due to the technological advantages of microwave systems, the present STEP concept uses microwave techniques exclusively for the heating and current drive (HCD) system.

Electron Cyclotron Current Drive (ECCD) will be the primary mechanism for current drive due to the relative maturity and flexibility of the technique. Electron Bernstein Wave Current Drive (EBCD) is adopted as the secondary technique, due to the promise of higher overall current drive efficiency and the ability to operate at high density. Due to the relative uncertainty and reduced flexibility of an EBCD system, two plasma concepts are being developed, one which uses ECCD exclusively and one which uses a combination of EBCD and ECCD, where a balance is found which plays to the relative advantages of the two techniques.

To optimise the EC configuration for current drive efficiency for the STEP concepts, a number of candidate launcher positions were selected, as can be seen in Fig. 1. GRAY was then used in single ray configuration to scan the frequency over fundamental, 2nd and 3rd harmonics (70 – 240 GHz), and toroidal and poloidal angles from each launcher for X and O mode [1]. The result was a rich dataset for the operational space of the ECCD system for that plasma concept, a selection of which is shown in Fig. 2. The efficiency ζ_{CD} [2] is comparable to the optimal values found for EU-DEMO [3], and the most efficient launchers over a wide range of radii are E, F, G and M.

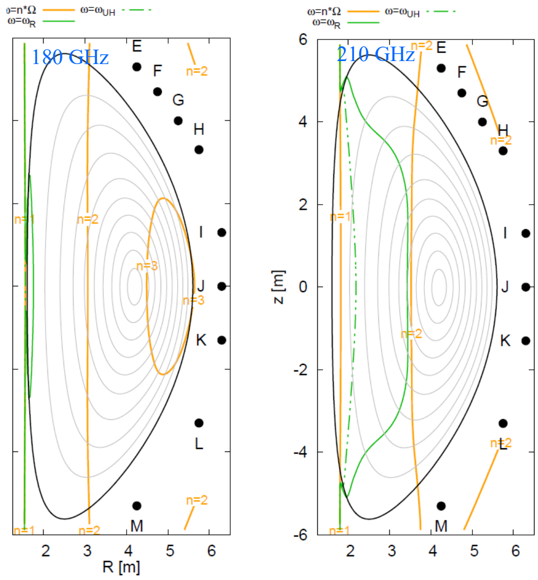


Fig. 1*: The plasma equilibrium and candidate launch locations for the SPR-045 concept. Harmonics, X-mode cut-off and upper hybrid resonance are shown for 180 GHz (left) and 210 GHz (right)*

The STEP EBW concept is still under development, so here we present the analysis approach and some preliminary results of this analysis. A low-field side (LFS) coupling to the EBW via the O-X-B process was chosen, similar to the schemes demonstrated in W7-AS and TCV [4,5] as coupling from the high-field side (HFS), such as was demonstrated in [6], is limited in density by the left-hand X-mode cut-off, presenting too strict a density limitation. Direct X-B tunnelling from the LFS is also not appropriate as the overall coupling efficiency is very sensitive to the density gradient and is only efficient at $k_0 L_n$ values far below what is expected for any of the STEP concepts.

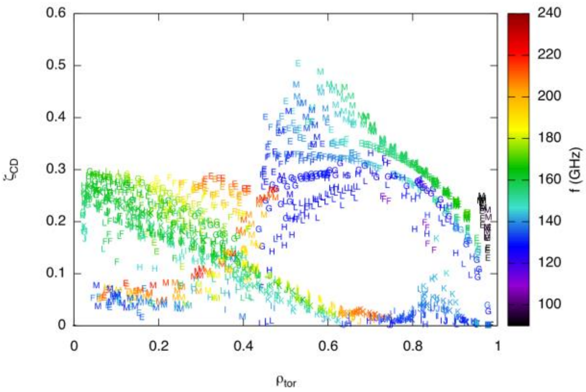


Fig. 2: A selection of the configurations and their normalised current drive efficiency. Launch points are represented by letters and the colour denotes the launch frequency

For the assessment of the efficiency of EBCD in these scenarios, GENRAY [7] was used for the ray-tracing component and the bounced averaged, relativistic Fokker-Planck code, CQL3D [8], was used for the radiative transport and current drive calculations. For each of the concepts, the EBWs are launched between the fundamental and second harmonics as normally access at higher harmonics is not possible as the presence of an O-mode cut-off is required. The launch angles are restricted to the critical angles required for coupling and the height and frequency are scanned over the relevant ranges. Exceptional current drive efficiencies were found, as shown in Fig. 3, with normalised efficiencies up to 1.5, three times higher than the ECCD in a similar region. This makes EBCD a very promising avenue and would significantly lower the re-circulating power requirements for the reactor. Access to radii less than $\rho_{\mathrm{tor}} \simeq 0.5$ is limited primarily by a combination of Doppler broadening of the resonance and the non-monotonic B-field profile typical of the high-β ST reactor [9]. The radial restriction was approximately the same across the ST concepts we examined. The coupling to EBW from the low field side has also been examined. The acceptable beam steering tolerance is critically dependent on the density gradient, but preliminary estimates show > 95% coupling for $\pm 1^{o}$ and a beam width $w_0 \gtrsim 15$ cm [10].

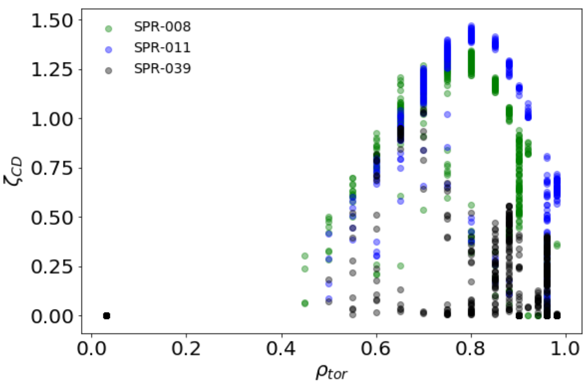
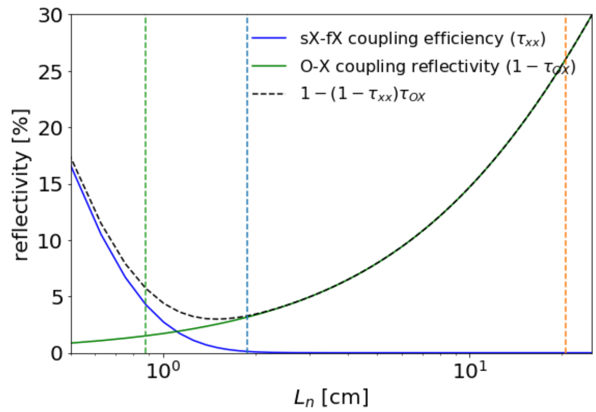


***Fig. 3**: normalised current drive efficiencies for the three different plasma concepts*

There are many physics challenges to be addressed before EBCD can become the default choice for current drive for STEP. Although there has been experimental evidence of efficient EBCD of $\zeta_{\mathrm{CD}} \simeq 0.4$ on the stellarator [4], a more extensive validation of the current drive models for EBWs on STs is required. Furthermore, there has never been an experimental validation for the predictions of highly efficient current drive on STs of $\zeta_{\mathrm{CD}} > 1$ [11,12], which are also seen in our calculations for STEP. It has been shown that high-efficiency coupling from the LFS to EBW can be achieved [13,14], but the effect of density perturbations and non-linear effects require more extensive investigation.

To provide an experimental basis for the use of EBCD on the spherical tokamak, an EBCD system will be installed on MAST Upgrade with two dual frequency gyrotrons (28 and 34.8 GHz), capable of 900 kW (3s) and 800kW (4.5s). The aim of this system is to provide an experimental test of the EBCD efficiency on an ST, examine open issues regarding the LFS coupling scheme, such as the linear coupling behaviour and turbulence [15], examine collisional damping and non-linear effects [16] and extend the original MAST experiments into EBW based solenoid-free start-up [17,18]. A preliminary engineering design of the system can be found here [19]. This is paired with a theory and modelling effort for STEP and MAST-Upgrade to develop the physics basis for the use of EBCD on a reactor.

In order to operate an EBW system on a modern experimental tokamak, it is necessary to show that the power can be efficiently coupled to the plasma and that the stray radiation can be kept to a reasonable minimum. Fig. 4 shows the expected reflectivity for MAST parameters for 34.8 GHz, w_0 = 5.5 cm. One can see that the high-density L-mode and H-mode are either side of the minimum in reflectivity, where the low-density L-mode



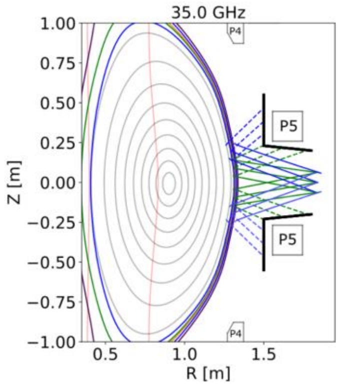


Fig. 4: *Left: The analytical reflectivity as a function of scale length for MAST Upgrade parameters. dashed lines represent the expected scale lengths for 34.5 GHz in H-mode, high-density, and low-density L-modes. Right: A schematic plot of the poloidal cross-section of the beams from the midplane launcher for I_p = 800kA (green) and I_p = 2000 kA (blue).* The dashed lines represent the beam reflected from the plasma after coupling. Thick black lines represent “interceptor plates”.

shows a reflectivity of around 25%. Fig. 4 also shows there is a potential that if the density gradient in H-mode is increased from the estimated value here, the reflectivity could potentially rise significantly. Protective “interceptor” plates are placed in the reflected beam path and are designed to scatter the reflected beam to lower the power density and limit the danger of the reflected beam to the machine components. These plates are monitored for heating and used to quantify the reflected power and thus the coupling efficiency (Fig. 4 left).

GENRAY and CQL3D were also used to examine the current drive efficiency in order to set the power requirements for the system. A maximum efficiency of 0.14 A/W ($\zeta_{CD} = 0.63$) is seen for near axis absorption ($\rho_{tor} = 0.09$), providing good current localisation $\delta\rho < \pm 0.05$. Under these conditions, the MAST Upgrade EBCD system would be capable of driving significant plasma current. The system is designed with a flexible launcher system to allow either co-, counter- or simultaneous co and counter current drive for balanced heating to help experimentally disentangle heating effects. The system can also launch above the midplane to allow for off-axis absorption at the same gyrotron frequency.

In summary, the STEP spherical tokamak reactor will use microwave techniques for all heating and current drive requirements. ECCD is anticipated to be the primary source of auxiliary current drive due to its maturity and flexibility. However, EBCD is a planned opportunity due to its promise of high current drive efficiency at high density. GRAY was used to optimise the launch configuration for SPR scenarios finding efficiencies comparable to similar optimisations for ITER and EU-DEMO. EBCD was analysed using GENRAY and CQL3D and current drive efficiencies of around 3 times higher than ECCD were found, but this is limited to off-axis current drive as the penetration is limited by Doppler broadening and relativistic effects. The coupling to EBW was analysed using known analytical expressions, and the coupling was found to require large diameter beams to maintain high efficiency. The role of non-linearities and density perturbations remain to be investigated.

To provide a firm experimental basis for the use of EBCD, and solenoid free start-up, a 1.8 MW EBCD system will be installed on MAST Upgrade. The system is designed to give co-, counter- and balanced current from the midplane launcher, and could achieve greater than 10% of the total plasma current based on efficiency estimates using GENRAY/CQL3D. A launcher above the midplane will give off-axis deposition at the same frequency and magnetic field. A high coupling efficiency is expected, >96%, and interceptor plates are placed in the path of the reflected beam to decrease the power density of the stray radiation and serve as a measure of the coupling efficiency.

Acknowledgement

This work has been part-funded by the EPSRC Energy Programme [grant number EP/W006839/1] and the STEP program. To obtain further information on the data and models underlying this paper please contact: PublicationsManager@ukaea.uk

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