EBW CURRENT DRIVE START-UP SCENARIO FOR MAST

V. F. Shevchenko[1], *Y. Baranov*[1], *A. N. Saveliev*[2], *F. Volpe*[1], *J. Zajac*[3]

[1]EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK

[2]Ioffe Institute, Politekhnicheskaya 26, 194021 St.Petersburg, Russia

[3] Institute of Plasma Physics, Za Slovankou 3, P.O.Box 17, 18221 Prague, Czech Republic

e-mail: vladimir.shevchenko@ukaea.org.uk

The use of an existing 28 GHz gyrotron (200 kW, 40 ms) for pre-ionisation and plasma current start-up in the MAST tokamak is under consideration. The proposed scheme assumes that low-density plasma will be produced by RF pre-ionisation around the fundamental electron cyclotron (EC) resonance layer. Then a double mode conversion scheme is considered for electron Bernstein wave (EBW) excitation in plasmas with densities lower than the O-mode cut-off density (10^{19} m^{-3} for 28 GHz). The scheme consists of the conversion of the O-mode, incident from the low field side of the tokamak, into the X-mode with the help of a grooved mirror-polariser incorporated in a graphite tile on the central rod. The X-mode reflected from the polariser propagates back to the plasma and experiences a subsequent X-EBW mode conversion near the upper hybrid resonance. Finally the excited EBW mode is totally absorbed at the EC resonance. The absorption of EBW remains high even in a cold plasma. Furthermore, EBW can generate significant plasma current during the plasma start-up phase giving the prospect of a fully non-inductive plasma start-up scenario.

Introduction

One important technological difficulty with a tokamak fusion reactor is the high toroidal voltage required to initiate the gas breakdown and to provide a sufficient plasma current start-up when the energy losses are dominated by line radiation from low-Z, partially-stripped impurities. There are few possible means for reducing the loop voltage during the initial stage of the discharge. All of them are based on the idea of producing plasma of modest conductivity before the onset of Ohmic heating. ECRH pre-ionisation is the most popular scheme for such plasma production in tokamaks. ECRH-produced plasmas are easy to control in a wide range of parameters. Plasma localisation is defined by the position of the electron cyclotron (EC) resonance (or its harmonic) surface, which can be controlled by the toroidal field (TF) or RF source frequency. The plasma density can be varied by the gas pre-fill and RF source power. The highest density is limited by the plasma cut-off for the chosen frequency. Another advantage of ECRH pre-ionisation techniques is a possible non-inductive current generation based on the pressure driven current mechanism [1] and/or the EBW current drive (CD) mechanism [2].

RF Pre-ionisation in MAST

The major radius of the plasma is about 0.8 m in the majority of the discharges in MAST [3]. However, during the start-up phase the major radius is usually smaller or about 0.5 m. It is desirable to allocate the fundamental EC resonance within this range of radii in order to provide maximum plasma density and conductivity close to the position of magnetic axis. This gives an estimate for the optimum frequency of the RF pre-ionisation source. Assuming a moderate I_{TF} of 80 kA (I_{rod} = 1.92 MA) and intermediate major radius of 0.65m one finds f_{opt} = 16.5 GHz. Higher frequencies can also be employed providing a breakdown closer to the central rod with further expansion of the current channel to the optimum major radius. Let us restrict ourselves by the smallest major radius of 0.3m for the resonance position. This would provide a reasonable separation ($100\cdot\rho_i \approx 0.1$m for $T_i \approx 100$ eV and I_{TF} = 80 kA, where ρ_i is the ion gyroradius) of the breakdown region from the central rod to prevent plasma contamination. This gives an estimate for the highest acceptable breakdown frequency of 35.8 GHz. Hence, the frequency range of 16 – 36 GHz is a suitable range for breakdown and plasma start-up in MAST.

RF breakdown in gas is possible if the ionisation rate exceeds the losses. Losses are primarily determined by the gas pressure and characteristic connection length Λ, which depends on the magnetic field geometry. In a tokamak the characteristic connection length can be estimated if stray magnetic fields are known, $\Lambda \approx 0.25\, a_{eff}\, B/B_{str}$. Usually Λ is about a few hundred meters. According to RF breakdown theory [4] the breakdown voltage increases with RF frequency due to the fact that the amplitude of electron oscillations becomes smaller and the electrons get a smaller energy from the elecromagnetic field of higher frequency. The effective electric field E_{eff} is often used as a representative value in RF breakdown estimates. For deuterium one can write:

$$E_{eff} = \frac{E}{\sqrt{1+(55.6/p\lambda)^2}} \approx \frac{p\lambda}{55.6}E\,,$$

where E is the vacuum RF electric field, p is the gas pressure in Torr and λ is the vacuum wavelength in cm. At high frequencies, in contrast to DC plasma breakdown, the minimum electric field required for RF breakdown does not depend on Λ. It was estimated and confirmed experimentally in MAST that at 60 GHz the minimum RF breakdown field is about 1.5 kV/cm and it remains almost constant over a wide range of connection length/gas pressure (see Fig.1). Hence, we will rely on this figure in further estimations. Assuming the same cross-section (20 cm in diameter at e^{-1} of E-field) of the RF beam with the resonance surface one can re-scale the breakdown RF power for the range of frequencies considered above (see Fig.2).

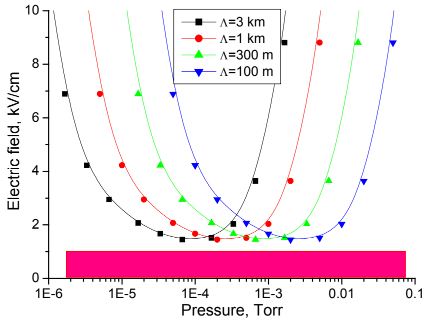

Fig. 1 RF breakdown curves for 60 GHz in pure deuterium.

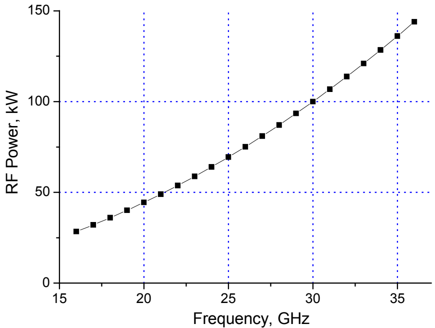

Fig.2 RF power required for breakdown in MAST.

In the above estimate it was assumed by default that the RF beam interacts with the EC resonance only once, i.e. the reflected power was not taken into account. That is reasonable in the MAST vessel because after the first reflection from the wall or central rod the RF beam becomes strongly divergent and its contribution to the total electric field at the EC resonance is negligible.

EBW Start-up Scenario in MAST

So far a conventional scenario of ECRH pre-ionisation was considered. The main result of it is a reduction of the loop voltage required for plasma start-up. It was assumed by default that the RF power is launched from the lower field side (LFS) because the higher field side (HFS) launch is technically very difficult in an ST. To provide effective breakdown the beam must be extraordinary polarised. For LFS X-mode launch, as soon as the initial ionisation occurs the X-mode cut-off layer appears in front of the EC resonance and reflects the RF power back to the antenna. At low plasma densities the evanescent layer is very thin, allowing a tunnelling of the X-mode through the cut-off with further absorption at the EC resonance. As the density increases the reflection becomes stronger. It reaches a maximum when the O-mode cut-off ($n_{\text{cut-off}} = 1.24{\cdot}10^{-4} f^{2}$, where n is in 10^{20} m^{-3} and f is in GHz) appears in the plasma. Starting from this moment the plasma absorbs only the fraction of power, which is necessary to sustain the O-mode cut-off. Further increase of plasma density is impossible in this way. Hence, the higher frequency allows higher density of plasma production. For instance, $n_{\max} = 3.4{\cdot}10^{18}$ m^{-3} for 16.5 GHz and $n_{\max} = 1{\cdot}10^{19}$ m^{-3} for 28 GHz. For this reason it seems to be more practical to employ an existing 28 GHz gyrotron for plasma start-up. The gyrotron is able to generate up to 200 kW in a 40 ms pulse (or longer pulse with reduced power), which is adequate for breakdown/start-up assist needs in MAST.

The electron temperature attained in the ECRH plasma is typically very low because of poor plasma confinement. This makes RF CD inefficient at this stage. However, the confinement of the plasma can be improved if a seed current is generated in the plasma. An initial current can be generated with the application of a small vertical magnetic field. The pressure driven currents obtained by this method are able to form closed flux surfaces leading to a tokamak-like equilibrium [1]. The improved confinement due to pressure driven currents should result in an increase of electron temperature. As soon as the temperature exceeds the 5-10 eV barrier, the EBW CD mechanism can be activated if a sufficient fraction of the incident RF power is converted into EBW [2]. Consequently, further improvements in confinement and CD must be self-consistent until the stationary plasma current and equilibrium are reached.

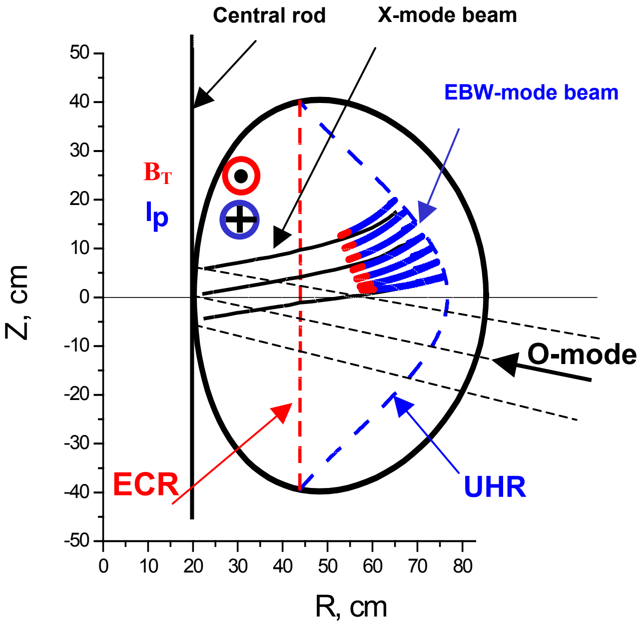

Fig. 3. Schematic (poloidal view) of the EBWCD plasma initiation. EBW ray-tracing simulations were performed with experimental data. The equilibrium was taken from a solenoid start-up scenario at 30 ms, shot #9867 in MAST

During the breakdown phase, if the plasma density is sustained lower than the O-mode cut-off density, the EBW-mode can be excited via double mode conversion. The ordinary polarised beam launched radially from LFS close to the midplane will pass through the plasma and reflect from the central rod. If a grooved mirror-polariser is placed on the central rod with grooves oriented at 45^o to the incident polarisation, the reflected beam will change polarisation to perpendicular, i.e. X-mode. Then the X-mode propagates through the EC resonance, being partly absorbed, and reaches the UHR layer where it is totally converted into the EBW-mode (see Fig. 3). The grooved mirror-polariser can be fabricated directly on a graphite tile covering the central rod. The polycrystalline graphite EK986 used in MAST has a good reflection (>98%) at 28 GHz and it can be used as a mirror material. The grooved area must extend over the beam diameter ~25 cm at the central rod and is located at the midplane.

The graphite mirror-polariser has been designed with the aid of the commercially available FEMLAB Elecromagnetics software. It allows a full wave 3D solution to be obtained in a medium with arbitrary electromagnetic properties. In the case of almost perpendicular reflection the problem can be simplified to a 2D calculation. A method of resonances was used for groove depth optimisation. Let us imagine a resonator formed by the grooved mirror and a perfect dielectric mirror. First, the length of this resonator is optimised to have a resonance for the TE mode (electric field is parallel to the grooves) at 28 GHz (see Fig. 4). Then the perfect dielectric is replaced with a perfect conducting mirror (to provide π/2 phase shift) and now the groove depth is optimised to have a resonance for the TM mode at the same frequency (see Fig. 5). Alternatively, the length of the resonator can be reduced by a quarter wavelength to provide π/2 phase shift. As a result the optimised mirror will introduce π/2 phase shift between reflected TE and TM mode. Rounded rectangular grooves were used in this model. A similar technique can be applied in 3D for the design of a grooved lossy mirror with arbitrary groove shape and angle of reflection. The graphite polariser has been fabricated and tested. Low power tests demonstrated about 98% reflection with about 92% polarisation conversion efficiency of the mirror-polariser, which is in good agreement with modelling results.

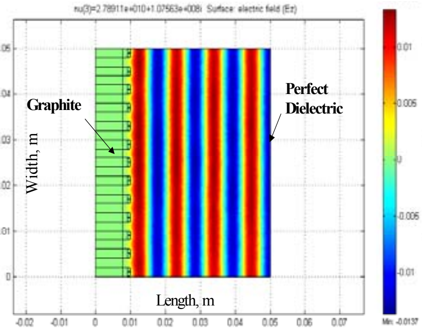

Fig. 4 Eigenfrequency solution for TE mode. Electric field E_z sagging can be seen between grooves.

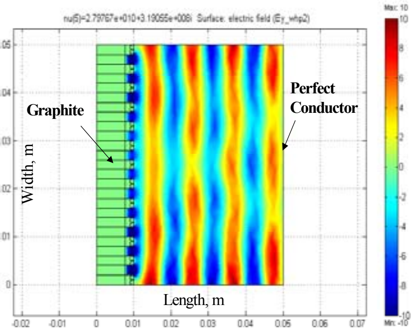

Fig. 5 Eigenfrequency solution for TM mode. Electric field amplification by a factor of 8 can be seen between grooves.

The proposed EBW CD start-up scenario has been modelled assuming that closed flux surfaces were formed with the help of pressure driven currents. The experimental equilibrium obtained in a standard start-up scenario with solenoid (see Fig. 3) was used in EBW CD efficiency estimates. A previously developed

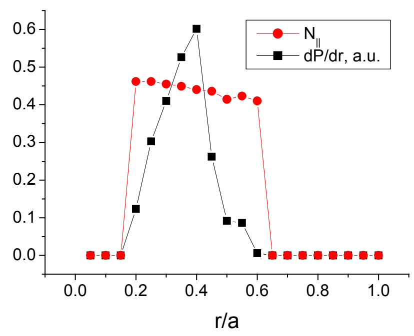

Fig. 6 EBW power deposition and $N_{||}$ profile in the absorption region for the case shown in Fig.3 with n_{e0} =0.4·10^{19}m^{-3} and T_{e0} =0.4 keV.

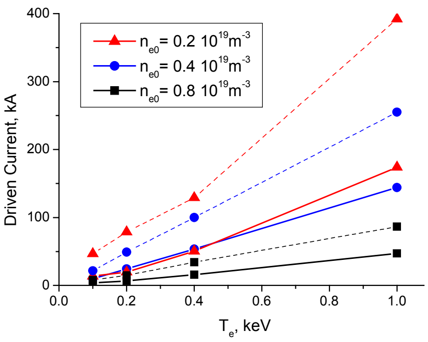

Fig. 7 EBW (150 kW) driven currents over a range of temperatures and densities. For the upper curves (dashed) trapping is not included, lower (solid) with trapping.

EBW ray-tracing code [5] was employed in conjunction with a Fokker-Planck solver [6] for calculations of EBW propagation, absorption and CD.

The power deposition profiles appear to be broad with $N_{||}$ about 0.4-0.5 in the absorption region (see Fig. 6). The EBW driven currents increase almost linearly with electron temperature and are inversely proportional to the electron density.

Summary

An ECRH pre-ionisation scenario based on the use of an existing 28 GHz gyrotron is considered for MAST. It was shown by modelling that a non-inductive current up to 150 kA, fully sustained by RF, could be achieved with EBW CD in MAST. A similar EBW CD technique can also be employed in low-density plasmas with an initial equilibrium achieved by conventional direct induction or merging compression methods.

ACKNOWLEDGEMENTS

This work was funded jointly by the United Kingdom Engineering and Physical Sciences Research Council and by EURATOM.

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