EBW ASSISTED PLASMA CURRENT STARTUP IN MAST

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EBW current drive assisted plasma current start-up has been demonstrated for the first time in a tokamak. It was shown that plasma currents up to 17 kA can be generated non-inductively by 100 kW of RF power injected. With optimized vertical field ramps, plasma currents up to 33 kA have been achieved without the use of solenoid flux. With limited solenoid assist (0.2V·20ms, less than 0.5% of total solenoid flux), plasma currents up to 55 kA have been generated and sustained further non-inductively. Experimentally obtained plasma currents are consistent with Fokker-Planck modelling.

1. Experiments on MAST

A 28 GHz start-up system has been commissioned on MAST [1]. The start-up method relies on the production of low-density plasma 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 ($n_{e0} < 10^{19}\mathrm{m}^{-3}$ 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 column. 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 (UHR). Finally the excited EBW mode is totally absorbed before it reaches the EC resonance, due to the Doppler shift. The absorption of EBW remains high even in cold plasma. Furthermore, EBW can generate significant plasma current during the start-up phase giving the prospect of a fully non-inductive plasma start-up scenario.

First experiments with the 28 GHz gyrotron demonstrated reliable breakdown with both the X-mode and the O-mode launched. Plasma currents up to 15 kA were observed during RF breakdown without the use of solenoid flux.

This was achieved with 100 kW, 90 ms O-mode injection and vertical field (B_V) ramp-up. However, the plasma current generated by this method could not be sustained for longer than 50 ms. After reaching the maximum value the plasma current decreased slowly to zero regardless of further B_V ramp-up and RF power injection. The analysis of the vertical field component, measured on the central column, showed that immediately after RF breakdown a pressure driven current was generated in the plasma near the midplane. Then as the plasma current increased its centre gradually shifted downwards. At the same time a rapidly increasing negative current appeared above the midplane. These opposite currents repel each other and cause the plasma to expand in the vertical direction. Finally these currents cancel each other causing the total plasma current to drop and the plasma to move to the lower major radius.

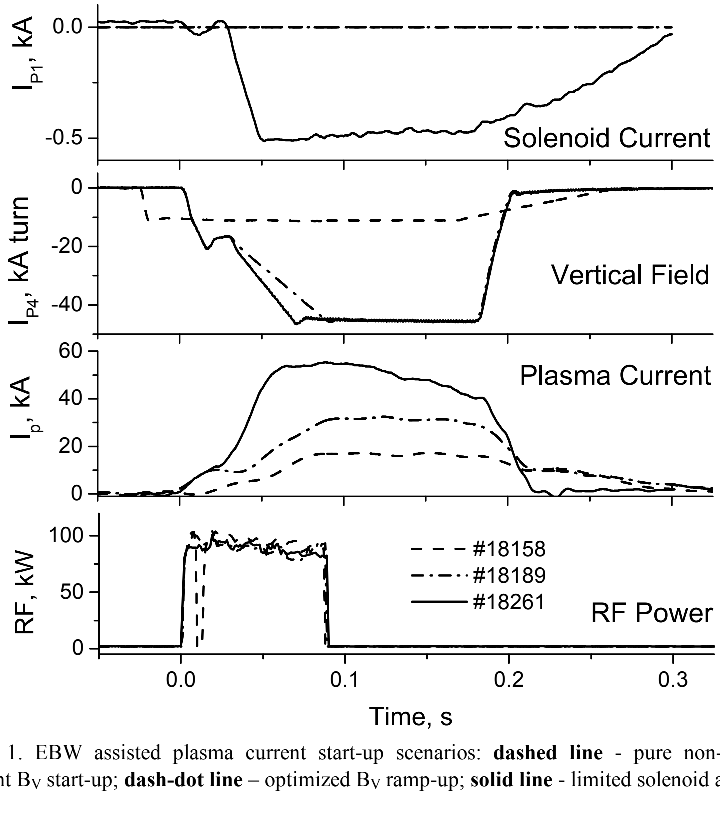
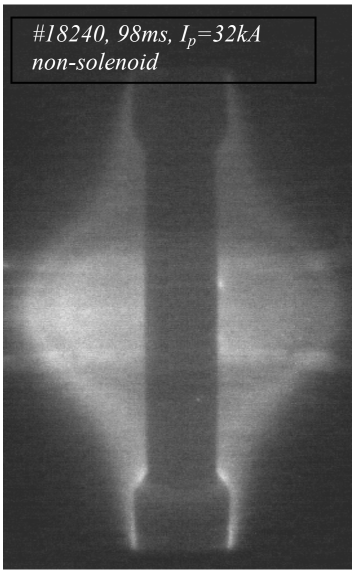
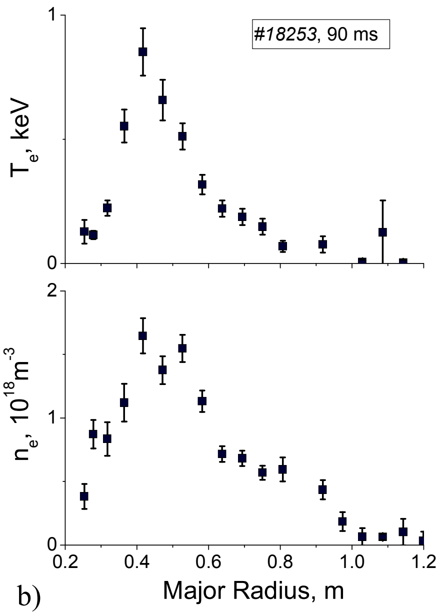


Figure 1. EBW assisted plasma current start-up scenarios: **dashed line** - pure non-inductive constant B_V start-up; **dash-dot line** – optimized B_V ramp-up; **solid line** - limited solenoid assist.

Two methods were found to be effective for the negative current suppression. One is the vertical shift of the plasma upwards with a subsequent shift back to the midplane shortly after the closed flux surfaces (CFS) were formed. The second method is the use of the divertor coil with inversed current during the initial phase of plasma formation. Both methods were successfully used in the optimisation of EBW start-up scenarios. Experimental achievements are summarised in Fig. 1. One can see that plasma currents up to 17 kA were generated and sustained non-inductively by EBW CD alone at about 100 kW of RF power injected. With optimized vertical field ramps, plasma currents up to 33 kA have been obtained without the use of solenoid flux. With limited solenoid assist (about 0.2V·20ms which is less than 0.5% of total solenoid flux), plasma currents up to 55 kA have been generated and sustained further non-inductively.



a)



b)

Figure 2. a) CCD image of the plasma formed during EBW start-up with B_V ramp-up. Closed flux surfaces are clearly seen. b) Thomson scattering profiles measured during EBW start-up with limited solenoid assist.

In all the above cases plasma forms closed flux surfaces after optimised up-down shifts using radial field coils (Fig. 2a). The CFS formation was registered as the reversal of the vertical magnetic field component measured with magnetic coils incorporated into the central rod. The use of divertor field coils for negative current suppression worked well in combination with B_V ramp-up. However the CFS formation was not well pronounced. Using a moderate RF power EBW assisted start-up technique produced a high temperature target plasma for further current ramp-up [1]. Thomson scattering profiles measured at the end of the RF pulse in a discharge with limited solenoid assist are shown in Fig. 2b. The electron temperature is higher than 700eV and the density profile is close to parabolic. Both temperature and density are peaked near the fundamental EC resonance (R = 0.41m).

Plasma currents achieved in these experiments are consistent with EBW ray-tracing and Fokker-Planck modelling. However the mechanism of negative current generation and suppression was not fully understood. In the next section the negative current mechanism is analysed with single-particle modelling.

2. Single-particle modeling in a drift approximation

We shall consider single-particle orbits of the electrons taking into account only drift motion because the axi-symmetric toroidal magnetic field is a few orders of magnitude higher than any other component. The numerical formalism used in our simulations is very similar to the method described in [2]. Let's define the initial conditions for the electrons during the start-up phase. The X-mode beam is reflected from the central rod with a tilt of about 10^o to the midplane. For the toroidal field and plasma densities of interest the EC resonance layer is located at R = 0.41m and UHR near R = 0.45m. The beam centre crosses the UHR at about 5cm above the midplane. This cross-point and the vertical size of the RF beam define the origin of the test particles in our modelling. An effective interaction between electrons and waves near the EC resonance is possible only if the resonance condition is fulfilled:

$$1-\omega_{ce}/(\omega\gamma)=N_{\|}V_{\|}/c\text{, where }\gamma=(1-V^2/c^2)^{-1/2}. \qquad (1)$$

The mode converted EBW originating near the UHR has a very large $N_{\perp} \approx 40$ and small $|N_{\|}| << 1$. The wave vector k_{EBW} is essentially perpendicular to the UHR layer near its origin. Thus the sign and the value of $N_{\|}$ are predominantly determined by the projection of the vector k_{EBW} on the local vertical magnetic field. If B_V and UHR were perfectly vertical near the mode conversion layer all EBWs would have $N_{\|} \approx -0.1$ because of the tilt of the incident X-mode beam. However due to the finite curvature of the vertical field and the UHR layer (finite plasma density) near the midplane the sign of $N_{\|}$ can be different above and below the midplane. The sign of $N_{\|}$ for EBW typically doesn't change while propagating along its trajectory except for the specific case near the midplane. Close to the EC resonance $|N_{\|}|$ encreases and reaches the value about 1 at the absorption layer but retains the same sign which was acquired at the UHR. As follows from (1) the sign of $N_{\|}$ determines whether the wave interacts with electrons moving along or opposite to the magnetic field. EBWs are absorbed by electrons. As a result of a single resonance interaction electrons receive an energy of about 5keV [3] predominantly due to the increase in $V_\perp$. The electron can cross the resonance many times and acquire more energy.

In our modelling we considered electrons with an energy of 5keV and pitch angles corresponding to $-0.1<V_\parallel/V_\perp<0.1$. Same as in tokamak we define co-direction for the current which increases B_V on the outboard side and decreases on the inboard side. In the start-up configuration consisting of strong toroidal and slightly curved B_V only co-passing (carrying co-current) and trapped banana orbits are confined [2]. It was found that banana orbits are dominant in MAST for both co- and counter- launched electrons in the above range of pitch angles and electron energy. Typical orbits for different vertical starting positions are shown on Fig. 3a. Note the electron is carrying co-current on the outboard side of the orbit and counter-current on the inboard side.

It is assumed that the number of electrons generated at particular height is proportional to the vertical RF power distribution. Then current density was integrated over the range of orbits weighted proportionally to the number of electrons/RF power. The grey-scale contour map in Fig. 3b represents the poloidal cross-section of the current density generated by banana trapped particles. The areas darker than the background colour correspond to the counter-current while the whiter areas correspond to the co-current. The total current integrated over the cross-section is positive in this case. It was assumed then that the total current generated in RF start-up can be represented as a combination of the current carried by the fast trapped electrons and the current carried by co-passing electrons from the thermal bulk [2, 4].

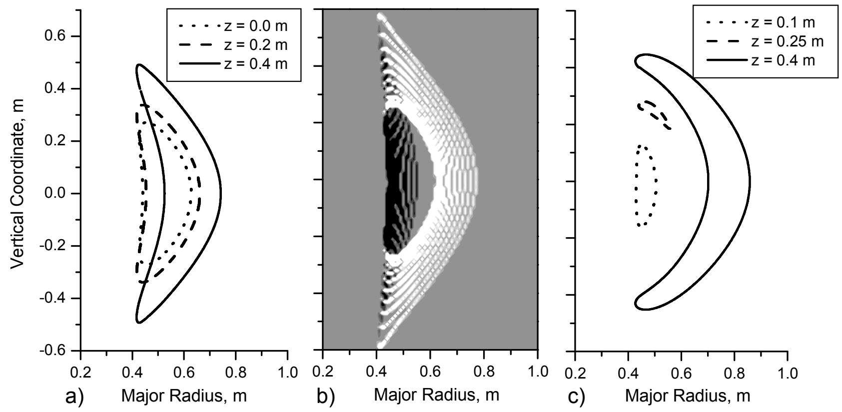


Figure 3. **a)** Trapped particle orbits at zero plasma current during EBW start-up phase in MAST. **b)** Poloidal cross-section of plasma current density generated by trapped particles. **c)** Co-passing (dots), counter-passing (dashed) and trapped (solid) orbits due to the presence of field generated by the 1kA current with distribution shown in **b)**.

The next step was a calculation of the poloidal field generated by the combination of the confined trapped and passing electrons. Then the effects of the poloidal field on the particle orbits were studied. It was found that starting from a plasma current of 1kA carried by trapped electrons (Fig. 3b) the poloidal field curvature does change its sign [5] and consequently the orbits localized in the upper or lower half-plane start to appear. Fig. 3c illustrates such an orbit localized on the upper half-plane. This orbit is carrying negative current. There is an exactly symmetrical orbit located in the lower half plane but it remains unpopulated because fast electrons are predominantly produced above the midplane. These orbits can have very unusual shape. They can be co- or counter-passing or trapped. The general feature is they can destroy up-down symmetry if any asymmetry exists in the fast particle source.

The above mechanism can be responsible for the negative current generation in the EBW start-up experiments on MAST. Two methods of suppression of the negative current were tested separately and in combination in MAST experiments. One is the vertical shift of the plasma upwards with the following return to the midplane. The second one is the increase of the B_V curvature by energising a diverter field coil with reversed current. The first method removes the asymmetry in the fast particle source plus helps to generate more co-passing electrons due to the change of the $N_{||}$ sign [1]. In the second method the increased B_V curvature requires a much higher fraction of trapped particle current to produce asymmetry that in return requires higher total plasma current which can be high enough to form CFS itself. Thus both methods successfully tested experimentally are consistent with the drift approximation model.

Acknowledgments

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