28 GHz START-UP SYSTEM ON MAST

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It has been shown experimentally that electron Bernstein waves (EBWs), excited with the X-mode launched from the high field side (HFS), are capable of driving a substantial current [1]. A non-inductive plasma current start-up scenario based on EBW current drive (CD) at 28 GHz has been proposed for MAST [2]. This scheme 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 EBW excitation in plasmas with densities lower than the O-mode cut-off density ($n_{e0} < 10^{19}m^{-3}$ 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 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.

The 28 GHz start-up system has now been commissioned on MAST. The gyrotron is capable of delivering up to 200 kW for 40 ms. Low-power tests were conducted using a full scale assembly of the launcher before high power injection into the MAST vessel. The RF beam pattern measured at the graphite tile shows that the beam is very close to Gaussian and 98% of the power is well within the grooved area of the mirror-polariser.

First experiments with the 28 GHz gyrotron have demonstrated reliable breakdown with both the X-mode and the O-mode launched. Plasma currents up to 15 kA have been 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 decreases 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 is generated in the plasma near the midplane. Then as the plasma current increases it gradually shifts downwards. At the same time a rapidly increasing negative current appears 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 and degrade the plasma purely because total plasma current drops and the plasma moves in.

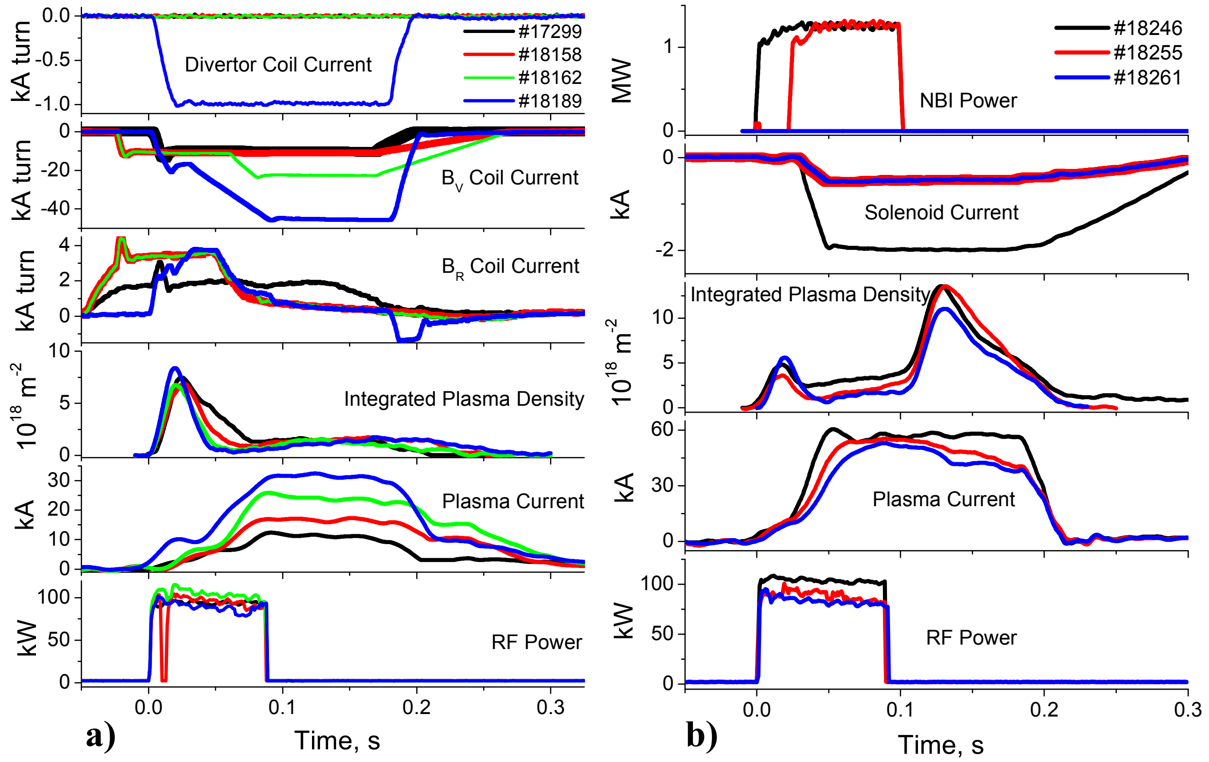

Figure 1. ***a)*** *EBW assisted plasma current start-up with vertical plasma shift.* ***b)*** *EBW plasma current start-up with limited solenoid assist. The density rise after 0.1 s is due to the additional gas puffing.*

According to our understanding the positive plasma current is predominantly generated by the asymmetry in the velocity space of electrons introduced by RF heating. The negative current is due to the EBW CD mechanism. It appears later when the plasma becomes relatively hot and rarefied near the resonance to provide high enough CD efficiency. The EBW CD is in the counter direction at this moment due to the fact that during breakdown the external B_V is predominant over the plasma poloidal field. The external B_V has an opposite curvature at the UHR providing the counter direction for EBW CD. To test this hypothesis it was suggested to shift the plasma centre upwards in order to provide the right curvature of the magnetic field in the mode conversion zone [3]. The shot #17299 in Fig. 1a illustrates the RF start-up at constant B_V with the B_V minimum shifted by ~15 cm above the midplane. Plasma current is gradually rising up to the end of the RF pulse and remains for some time afterwards.

There is a small loop voltage applied in this case due to B_V ramp-up during breakdown phase. The plasma forms closed flux surfaces (CFSs) at about 50 ms (from EFIT reconstruction) and the EBW CD mechanism is totally responsible for the further increase of plasma current.

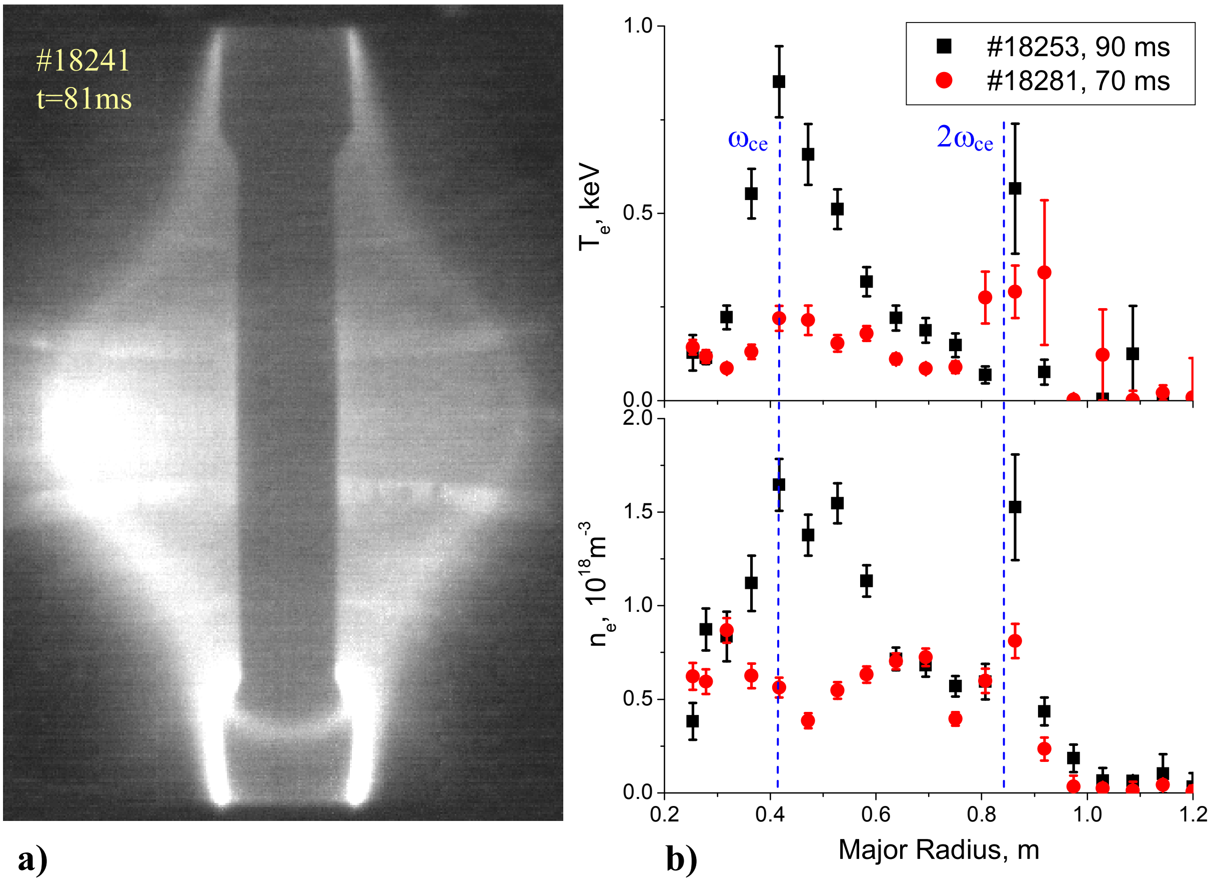

Figure 2. ***a)*** *CCD image of the plasma formed during EBW start-up with limited solenoid and NBI assist.* ***b)*** *Thomson scattering profiles measured during EBW start-up with (shot #18253) and without (shot #18281) limited solenoid assist. NBI was applied in these shots.*

In the shot #18158 the minimum B_V was vertically shifted by ~25 cm prior the breakdown and then after CFSs were formed (at 50 ms) the plasma has been shifted down to the midplane. The maximum plasma current of 17 kA has been achieved in this case without any loop voltage applied. Shots #18162 and #18189 illustrate how EBW assisted plasma start-up can be improved with the help of B_V ramp-up and inversed current in the divertor coil. Plasma currents up to 33 kA have been obtained without the use of central solenoid flux.

A next step spherical tokamak (ST) will possibly allow a small retractable solenoid or iron core to assist the plasma current start-up. Hence, plasma start-up with limited solenoid assist was also studied in this work. Initial plasma was formed in a similar way to that in shot #18189 (Fig. 1a), and then a solenoid current ramp was applied at 30 ms with only 20 ms duration. It was found that the solenoid current ramp has an optimal value of about -0.5 kA/20 ms. At higher solenoid ramps, plasma current can reach higher values but then drops to the stationary level as illustrated in Fig. 1b. With such limited solenoid assist the total volt-second flux consumption is about 4 mV·s, which corresponds to <0.5% of the total solenoid flux available on MAST. Plasma currents reach the maximum value of about 55 kA at the end of the solenoid ramp and then can be sustained until the end of the RF pulse. Neutral beam injection (NBI) doesn't affect the final plasma current but the initial breakdown appears about 5 ms earlier and the whole plasma formation process becomes highly reproducible with the NBI assist. This is partly due to the fact that during the start-up phase NBI provides the additional fuelling, which is easier to control in comparison with the gas puffing at low densities. Perhaps this additional fuelling is predominantly due to the out-gassing from the NBI damp. Plasma is usually brighter from the left (Fig. 2a), where the beam damp is located.

Thomson scattering profiles measured at the end of the RF pulse are shown in Fig. 2b. In the case of non-solenoid start-up the central electron temperature can exceed 200 eV, while the electron density has always a hollow profile. Plasma parameters improve a lot with the limited solenoid assist (about 4 mV·s). The electron temperature increases up to 700 eV and the density profile becomes close to parabolic. Both temperature and density are peaked near the fundamental EC resonance. Another narrow peak is always present in the plasma near the $2\cdot\omega_{ce}$ resonance. The appearance of the $2\cdot\omega_{ce}$ peak on temperature and density profiles is not fully understood yet.

In conclusion, EBW CD 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 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 (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 EBW CD modeling results.

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