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Current Sustainment in Spherical Tokamaks

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The problem of current sustainment becomes critical for spherical tokamak fusion devices such as the Component Test Facility [1] or Power Plant [2]. In these devices the use of a central solenoid is not possible due to the high neutron loading to the central column so alternative methods of current drive should be investigated. Neutral Beam (NB) current drive, I_{NBCD}, bootstrap current, I_{BS}, and the so-called "B_V ramp up" effect [3], are considered in this report. The latter effect can appear in an evolving plasma due to the movement of the magnetic surfaces (Shafranov shift) in the vertical magnetic field. If the poloidal beta, β_p, rises, this movement leads to an increase in total plasma current, I_{pl}. The contribution of these methods of current drive to I_{pl} for the present MAST and for MAST with NB heating power upgraded to 7MW are analyzed in this report.

The contribution of I_{NBCD} and I_{BS} to I_{pl} can be calculated in a straightforward way. The B_V effect works when β_p rises and ceases when β_p = const(t) (the equilibrium does not change), so to estimate the contribution of the B_V effect, the comparison of these two cases should be made. The electron temperature, T_e, should be the same for these cases (the same resistive losses) and the behavior of β_p is provided by the plasma density, $\langle n \rangle$.

We consider a MAST shot which has a significant fraction of I_{NBCD} (up to 100kA) and a B_V ramp up effect due to the density and poloidal beta increasing during the current flat top stage. A separate scenario for current ramp up and the steady state on current flat top is considered for the MAST with upgraded NBI power. The calculations are carried out using the ASTRA transport code [4]. The NBI power and current drive module, NBEAMS [5], is based on the diffuse beam approximation, and is fitted by the TRANSP calculations for MAST shots.

MAST shot analysis

The calculations are carried out for the MAST shot #8527 with electron temperature, T_e, and density taken from experiment. The loop voltage which is also taken from the experiment is used as a boundary condition for the poloidal magnetic flux equation. As a result of these calculations we obtain the evolution of I_{pl} for different cases shown in Fig.1: (1) with all methods of current drive, (2) $I_{NBCD} = 0$, (3) $I_{BS} = 0$, (4) without B_V effect (β_p = const(t)) and (5) U_{loop}= 0 (no solenoid). The evolution of I_{pl} for cases when one of the mechanisms of the

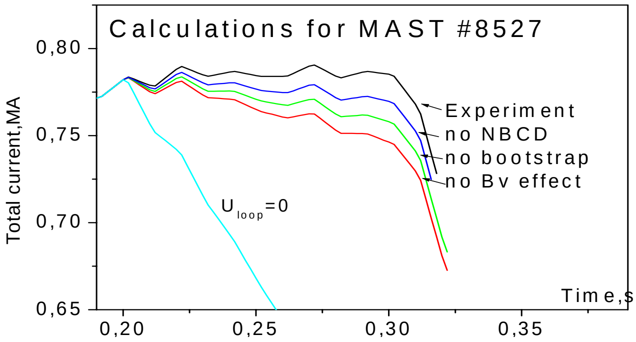

Fig.1 Plasma current evolution for MAST shot in different cases (see text)

current drive is switched off is shown in Fig.1. We consider the time period from 0.2 s to 0.3 s. During this time, values of $T_e(0) \sim 1.1$keV and $I_{pl} \sim 0.78$MA are approximately constant in time. <n>, rises from 3.2 to 5.2 $10^{19}m^{-3}$ and β_p rises from 0.42 to 0.78. We see that the B_V effect is stronger than the I_{BS} effect and can estimate it as ~ 60kA which is based on the value of $I_{BS} \sim 40$kA for this shot.

MAST with upgraded NBI

The benefits of adding off-axis NBI to MAST are considered. We investigate 2.5MW on-axis and 5MW off-axis (displaced 0.6m vertically). We consider the current drive from the point of volt-second consumption minimization. The plasma current ramp up rate and density evolution is prescribed and taken as similar to that of MAST shot #8527. A transport model for T_e with a parabolic heat conductivity profile (the same for electrons and ions) is used with a prescribed H-factor which simulates L-mode (H = 0.5) and H-mode (H = 1) regimes. The heat conduction coefficient rises monotonically from the center to the edge by a factor 2-3. One of the possible scenarios is shown in Fig.2. The central NBI source (2MW absorbed power) is switched on at t = 0.1s when I_{pl} = 0.5MA. The off-axis NBI source (4MW absorbed power) is switched on at t = 0.2s when $T_e(0) \sim 1$keV. After that a strong increase of β_p from 0.5.to 2 occurs which provides the B_V effect and increase of I_{BS} ($I_{BS} \sim 0.14$MA). On the current flat top we have 82% of non-inductive current, and a low loop voltage U ~ 0.15V. The volt-seconds consumption needed to increase from 0.3MA to 1MA is ~ 0.4 Vs.

The current drive effects contributions

Evolution of I_{pl} is shown in Fig.3 for the MAST NBI upgrade scenario with the same prescribed loop voltage for all cases (U_{SOL} = 1.1V at t > 0.1s). These cases are: (1) using the resistive current only with β_p held constant in time, (2) adding the B_V effect (rise of β_p from 0.67 to 1.1 during time period 0.2 - 0.3s), (3) adding I_{BS}, and (4) with all mechanisms of the current drive. The contribution to the current from each mechanism can be seen from the comparison of these cases. During the time period from 0.2s to 0.4s, the B_V effect contributes approximately 200 kA, I_{BS} adds 100kA and I_{NBCD} adds 150kA to I_{pl}. An important point is that I_{NBCD} and I_{BS} give the contribution to the I_{pl} on the resistive time scale, whereas the B_V effect works on equilibrium times (Alfven times) so is more effective for the current ramp up stage [3]. Note that the effect due to I_{NBCD} (Fig. 3) is barely twice the effect due to I_{BS}, although the value of I_{NBCD} is 5 times higher than that of I_{BS} . This is because the bootstrap current is driven nearer the edge of the plasma, lowering the internal inductance and hence (via the increased elongation of the lower l_i plasma), the external inductance also. This overall reduction in inductance encourages the increase in total plasma current. In contrast, the NBI driven current is more central and raises the inductance, reducing the overall increase in plasma current. A similar effect will be discussed in the next paragraph.

Central and non central NBI heating

The off-axis current drive is more effective for the economy of the volt-seconds consumption which is confirmed by the calculations presented in Fig.4. The calculations are carried out with the prescribed scenario for I_{pl} so the loop voltage and volt-second consumption are obtained as a result of calculations. The scenarios for the cases with 2MW/2MW on/off-axis (Z = 0/Z = 0.6m) and with 4MW off-axis heating power are shown in Fig.4. For these two scenarios we have the same values of I_{NBCD} and I_{BS}. For the first scenario the value of $T_e(0)$ is twice that of the second scenario which means low resistive losses. But the external loop voltage needed from the solenoid for this scenario is lower which is shown in Fig.4a. So off-axis heating and current drive are more effective from the point of the minimization of volt-second consumption.

Conclusions

We have obtained the contribution of the B_V effect to I_{pl}. It is visible under MAST conditions at the current flat top stage when β_p rises due to the increase in $\langle n \rangle$, and it corresponds to 60kA of additional current in a typical MAST discharge. For MAST with upgraded NBI power, β_p rises due to the increases in temperature and density, and the B_V effect can contribute significantly to the current ramp up stage, typically providing 200kA of additional current. Calculations for this MAST NBI upgrade scenario have shown that off-axis NBI current drive during current ramp up is more effective in minimizing volt-second consumption.

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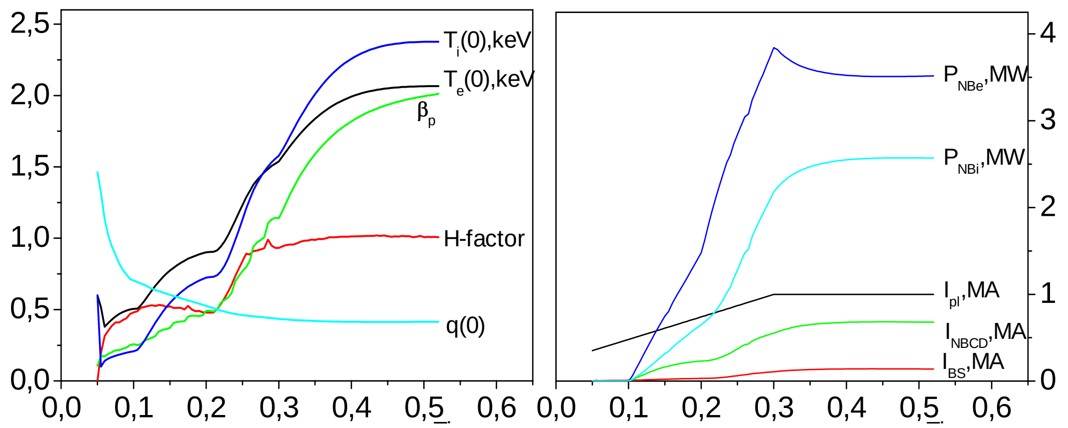
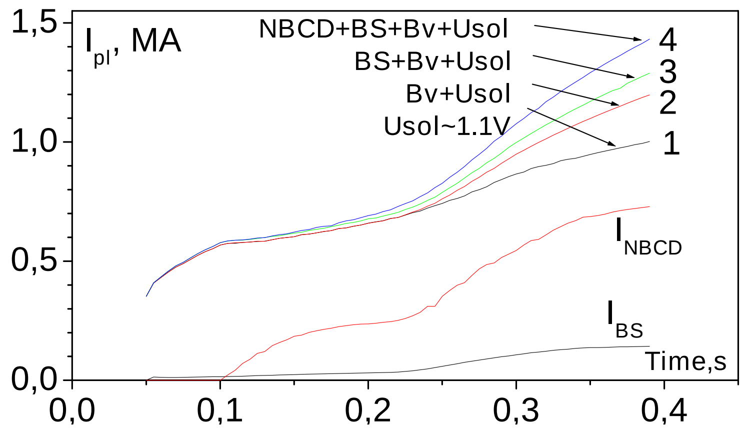


Fig.2 Plasma parameters evolution in current ramp up scenario for MAST with upgraded NBI



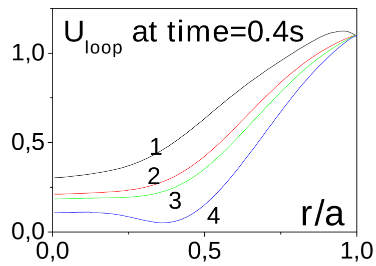
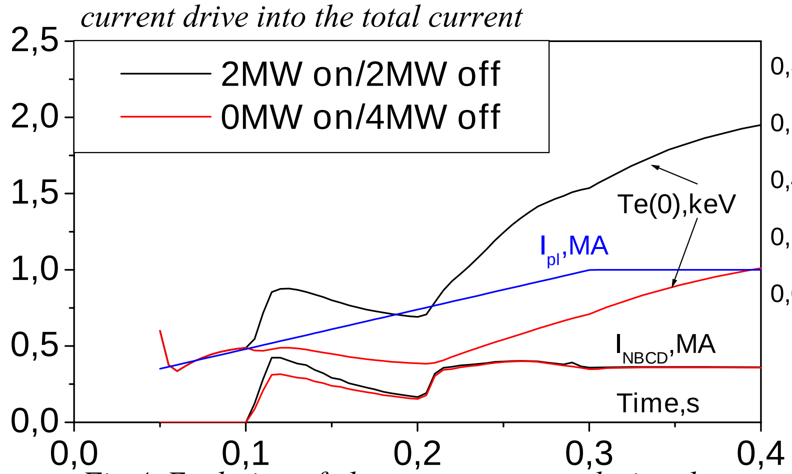


Fig3a Loop voltage profiles at t=0.4s

Fig.3 Contributions of different mechanisms of current drive into the total current



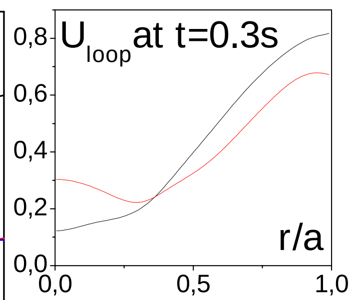


Fig.4a Loop voltage profiles at t=0.3s

Fig.4. Evolution of plasma parameters during the combined on and off axis (black) and in the pure off axis (red) heating and current drive scenarios.

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