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ABSTRACT

The good confinement and stability of JET hybrid plasmas strongly depends on the optimisation of the q-profile at the start of the high β phase [1]. In experiments so far this has been achieved using a plasma current 'overshoot' before the main heating phase. But this technique has limited applicability for high current operation in future devices like ITER due to limitations on the flux consumption and potential disruption forces. Therefore plasma simulations have been performed to investigate alternative techniques for the q-profile formation. The analysed techniques include: a monotonic current ramp up, current 'overshoot', plasma volume variation and off-axis non-inductive current drive. The current diffusion has been modelled with the TRANSP [2] and JETTO [3] transport codes and the results compared with simulations of a reference current 'overshoot' scenario. The main goal of the analysis is the minimisation of the magnetic flux consumption constrained by the requirements of the q-profile shape and MHD stability of the plasma with respect to external kink-modes before the main heating phase.

1. MAIN FEATURES OF THE TECHNIQUES

The best confinement has been achieved in hybrid plasmas with a q-profile that has a broad region of low magnetic shear at $q \approx 1$ in the plasma core and a narrow region of high magnetic shear near the edge [1]. Such a q-profile is formed using a current 'overshoot', which employs a successive current ramp-up and ramp down. Low shear is produced in the core during the fast plasma current ramp up due to current pile up and slow poloidal field diffusion. This remains essentially frozen during the following fast current ramp down phase, which generates large magnetic shear in the plasma periphery.

The first alternative technique for q-profile formation is based on a plasma volume variation during a monotonic current ramp-up phase. Specifically, the plasma volume is gradually reduced during the current ramp up and then rapidly increased to the original value at the start of the current flat top. The aim of the modelling in this case was to specify the requirements for the current ramp rate and plasma volume evolution to reproduce the simulated q-profile shape provided by the current 'overshoot' reference case at the start of the main heating phase.

The second alternative technique employs non-inductive current drive. This technique has also been modelled using the transport codes. The aim of the modelling was to establish the amplitude and localisation of the non-inductive current needed to reproduce the required target q-profile shape.

In each case the modelling has been performed using the kinetic plasma profiles from the reference plasma. This approach allows the effect of the inductive and noninductive current drive to be understood separately from the additional effects of heating and thermal transport. The sensitivity of the results to the uncertainty in the resulting electron temperature and Zeff have been analysed and discussed in the end of the paper for the case of the plasma volume variation. The results of the simulations are shown in figure 1 for the alternative techniques compared to the reference 'overshoot' case and the case of a simple monotonic current ramp-up.

It has been found that the desired target q-profile can be reproduced by a successive plasma volume compression (CV/V~0.25) and expansion during the current ramp-up and early current flat-top phase. Low core magnetic shear is generated in the current ramp-up phase as the plasma volume is gradually reduced, while the high peripheral shear is generated by a rapid volume expansion at the start of the current flat-top.

The off-axis ($r/a \geq 0.5$) and narrowly localised ($\Delta r/a \leq 0.2$) non-inductive current, as may be produced by EC or LH, was also found to be effective at qualitatively reproducing the desired features of the target q-profile using a relatively small fraction of non-inductive current (25-30%) (Fig.3). As mentioned above the effect of plasma heating has been neglected, which may reduce the required fraction of non-inductive current. The off-axis current drive method was found to be very efficient for the target q-profile modification provided the magnitude and power deposition of the driven current can be controlled as in the case of ECCD. The q-profile with low magnetic shear in the plasma centre ($r/a < 0.5$) can be obtained with a relatively small non-inductive current ($I_{ni}/I_p < 0.15$, see case II in Fig.3). An outward shift of the non-inductive current and an increase in Ini (compare cases II and IV,V) is required to further broaden the low magnetic shear region. If the outward shift becomes too large the low magnetic shear is only maintained in the region, where jni is comparable to the jp. The core magnetic shear can not be affected by peripheral j_{ni} if I_{ni}/I_p <<1 unless temperature profile broadening due to off-axis heating is involved.

Minimisation of the magnetic flux consumption is an important constraint in the choice of the preferred method of q-profile formation. Figure 4 shows the consumed magnetic flux within the plasma boundary for the four techniques demonstrated in figure 1. As expected the method involving the largest non-inductive current provides the lowest flux consumption (case 4 in Fig.4).

The sensitivity of the target q-profile and consumed flux $\Delta\Psi$ to the electron temperature Te and Z_{eff} has been tested in the framework of the Bohm/gyro-Bohm transport model. The result is shown for the case of the plasma volume variation in fig.5. The results of the qprofile prediction for the kinetic profiles are compared with the case where the q-profile and T_e variation was predicted using the Bohm/gyro-Bohm transport model (Fig.5 case B). The predicted q-profile sensitivity has been tested in addition assuming an arbitrary 40% increase in Zeff (Fig.5 case C) compared to the reference case. Only a small change in the target q-profile and $\Delta\Psi$ was found.

Stability analysis of the volume variation case has been performed using MISHKA [4] code. The scheme was found to be stable with respect to external kink modes, which are the most dangerous in the current ramp-up phase. The result of this analysis is in agreement with qualitative assessment of the stability based on the empirical Li-q diagram valid for the limiter plasma [5].

CONCLUSIONS

Alternative methods to the current 'overshoot' technique used in JET hybrid scenarios for target q-profile formation have been analysed using modelling with the JETTO and TRANSP codes. The plasma volume variation technique was found to be useful for present devices as it provides the required target q-profile while avoiding excessive Ip before the main heating. The off-axis non-inductive current drive method has the potential to be useful in future devices as it allows flexibility in the target q-profile formation and a significant saving of magnetic flux consumption. The sensitivity of the modelling results to the uncertainty in Te and Zeff has been tested using Bohm/gyro-Bohm transport model and the MHD stability has been analysed with respect to the external kink modes. If these modelling results are confirmed by the experiment it will demonstrate the wider applicability of the JET hybrid scenario.

ACKNOWLEDGMENT

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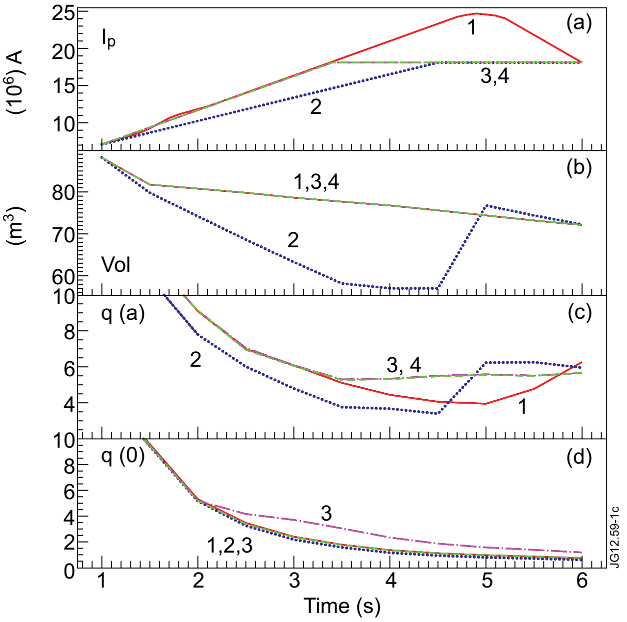

Figure 1: (a) Plasma current, (b) plasma volume, (c) safety factor at the modelled plasma edge,(d) safety factor on the magnetic axis. 1-reference case with current overshoot, 2-plasma volume variation case, 3- non-inductive current drive case with $I_{ni}/I_p = 0.28$ *, 4- monotonic current ramp case.*

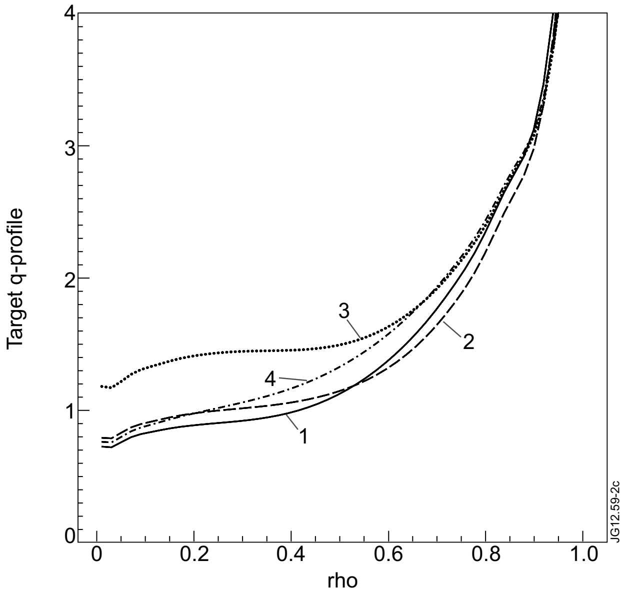

Figure 2: Modelled target q profile. Current ramp rate and volume variation are as in fig.1 (1,3,4) t = 6s, (2) t = 5s.

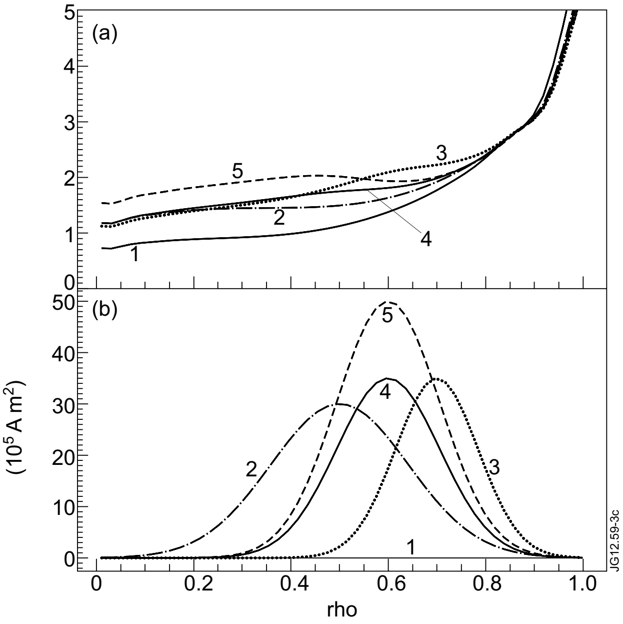

Figure 3: (a) Target q profile obtained with (b) varied non-inductive current profiles. I-reference case with $I_{ni} = 0$, II-I_{ni} = 0.5MA, III-I_{ni} = 0.5MA, IV-I_{ni} = 0.5MA, VI$_{ni}$ = 0.7MA.

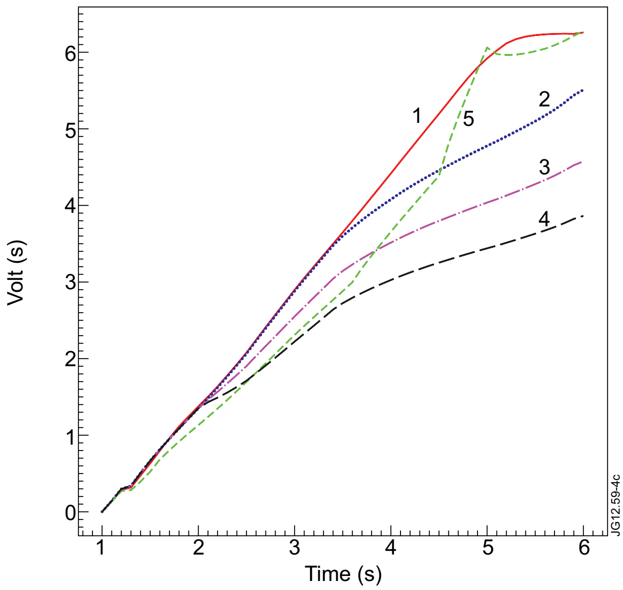

Figure 4: Magnetic flux consumption for the four different schemes. 1-current overshoot, 2-current ramp-up with plasma volume variation, 3,4-non-inductive current application (cases II and IV from fig.3), 5-monotonic current ramp-up

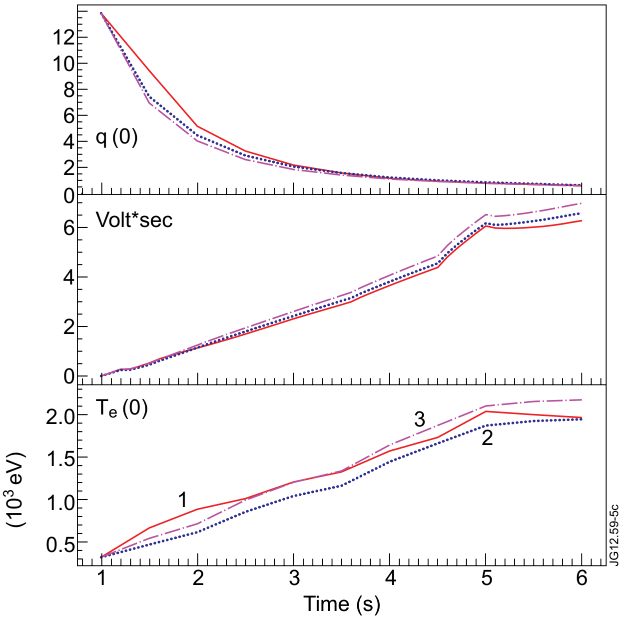

Figure 5: Time variation of the edge safety factor q(a), consumed magnetic flux and central electron temperature $T_e(0)$ for the volume variation method. (a)-results with given (measured) T_e profiles, (b)-using Bohm/gyro-Bohm model and fixed Z_{eff} = 1.05, (c)-Bohm model and fixed Z_{eff} = 1.45.