EUROPEAN FUSION DEVELOPMENT AGREEMENT
JET

EFDA–JET–CP(03)01-63

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Modelling of the Current Profile Control with Neutral Beam Injection at ASDEX Upgrade

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**See Annex of J. Pamela et al., "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).*

Preprint of Paper to be submitted for publication in Proceedings of the EPS Conference on Controlled Fusion and Plasma Physics, (St. Petersburg, Russia, 7-11 July 2003)

ABSTRACT.

Recently, fusion performance has been considerably improved in advanced tokamak scenarios via optimisation of current density profiles. Experiments at ASDEX Upgrade have concentrated on scenarios with low or zero magnetic shear in the centre. These discharges have improved confinement and stability in stationary conditions. The current density profile is maintained by MHD modes (fishbones). As extrapolation of these MHD activities for a reactor is unclear, it would be desirable to sustain this type of current profile with external current drive methods.

1. MODELLING OF THE CURRENT PROFILE CONTROL AT ASDEX UPGRADE

For real-time current profile control at ASDEX Upgrade, preparations are made to have current density profiles identified in real-time via the Functional Parameterisation (FP) method from on-line MSE and magnetic probe measurements, NBI has been proposed as an actuator. Four tangential beam sources at 93kV are going to be used for the current profile control. Among them, particularly two sources are adjusted to do off-axis current drive.

Change of the current profiles using four tangential sources is checked by ASTRA code. The ASTRA code is a 1.5-dimensional transport code with realistic tokamak geometry but no divertor geometry. It solves coupled equations of the MHD equilibrium, current diffusion and heat transport self-consistently. For the simulations using ASTRA, the energy transport is calculated by applying the Weiland transport model, which has been proven as an appropriate transport model for advanced scenarios in ASDEX Upgrade [1][2] while the electron density is taken from experimental measurements ($n_e = n_e^{exp}$). An advanced regime with low plasma current is used for the simulations where the effect of the NB current drive is more pronounced. Simulations are performed for a high poloidal beta discharge at 400kA, 2T [3] using two nearly perpendicular beam sources and changing one of the four sources at 93kV. The calculated current density profiles are shown in figure 1. In the simulation, a clear difference is observed in the current density profiles when different beam sources are switched on. Here the different NBI sources change the ohmic, the bootstrap and the directly driven current density profiles due to changes in the temperature profiles, density profiles and NBI tangential injection angle. The localisation of the NBI driven current is under discussion at ASDEX Upgrade [4]. Figure 1 shows that for the plasma configuration used (Z_{axis} = 11cm), beam source 6 gives most off-axis and beam source 8 gives most on-axis current drive at a stationary state. These differences form the basis to propose NBI as tool to control current profile at ASDEX Upgrade.

ASTRA simulations are done with modulated NB power for each beam source for system identification. The NB power from each beam sources is modulated for optimum response on current diffusion time scale. The variation of the current density during the modulation computed using ASTRA is stored as a training dataset. System modelling is performed where the current density at three radial positions and poloidal beta are selected as output parameters while NB powers from four tangential beam sources are used as input parameters. The system model is constructed using the 15th order of state-space model, which is well suited for multi-input multi-output systems.

A dataset, used for validation, contains current density profile variation computed by ASTRA using a step response to NBI heating and current drive. The identified system model is validated with this dataset. The worst result for the system validation is presented in figure 2 (a). Oscillations, which are caused by the time grid of the simulation, are observed on the reference signal. It gives rise to lower accuracy of the model.

If the oscillation is removed by reducing the time grid of the simulation, then the accuracy can be improved. The validation accuracy for radial points at 0.09, 0.225, 0.435 and poloidal beta with 4 beam sources are given in figure 2 (b).

2. COMPARISON TO EXPERIMENTAL OBSERVATIONS AT ASDEX UPGRADE

For validation of the identified system model and the ASTRA simulations, an experiment is carried out where the total beam power is kept constant at 5MW and the beam sources are changed at 3.5, 4.5, 5.5, 6.5sec as shown in figure 3(a). The measured MSE signals are given in figure 3(b) where measured MSE angles are compared to those calculated by ASTRA code using experimental profiles. The modelled MSE angles do agree well with the measured polarisation angles. The main contribution to the change of the MSE angles is the change in the stored energy. But even though changes in current profile are still under discussion at ASDEX Upgrade [4], the agreement here is satisfactory and if at different plasma parameters it can be reproduced, then the ASTRA simulations for system identification can be used as a basis for computing the control parameters for current profile control with NBI.

3. APPLICATION TO JET

In JET, model-based control method for current profile has been proposed [5] and current profile control experiments have been performed with LHCD in a preheat phase [6] and with combined LHCD/ICRH/NBI in an ITB scenario with a significant bootstrap current fraction [7]. For JET, current profile control could be obtained using the NB power from six beam sources at 80kV. For the system modelling, the current density at five radial positions and poloidal beta are selected as output parameters. As above, the system identification is done through ASTRA simulations and 15th order of state-space model is employed for this.

Similar method can be applicable to JET but using a different time scale for the beam modulation. The current diffusion time scale at JET is longer than that of ASDEX Upgrade. The optimum modulation frequency is 10-15 times lower than that of ASDEX Upgrade.

From the ASTRA simulation and the modelling result, it is observed that it is difficult to get off-axis current drive at JET. As shown in figure 4, pronounced off-axis current drive is not observed at a stationary state even the beam source 3, which is the most off-axis one, is switched on. However, it could be used to maximize the current drive off-axis grouping of the most off-axis PINIs or changing the alignment of the beam sources.

CONCLUSIONS

Modelling of the current profile control with NBI is performed at ASDEX Upgrade. Clear changes in current density profiles are identified in the simulation using ASTRA when different beam sources are applied. In addition, this behaviour is reproduced well in the system modelling. An experiment is performed at ASDEX Upgrade by changing four beam sources, which show good agreement between simulated and measured MSE angles for these experimental conditions. The similar method at ASDEX Upgrade can be applied to JET, provided that appropriate time scale is chosen for the modulation of the beam power. The NB calculation with ASTRA needs more investigation at JET. From the identified system model, a controller can be developed by using the Proportional Integral Derivative (PID) control scheme. This will be tested and implemented to experiments in ASDEX Upgrade.

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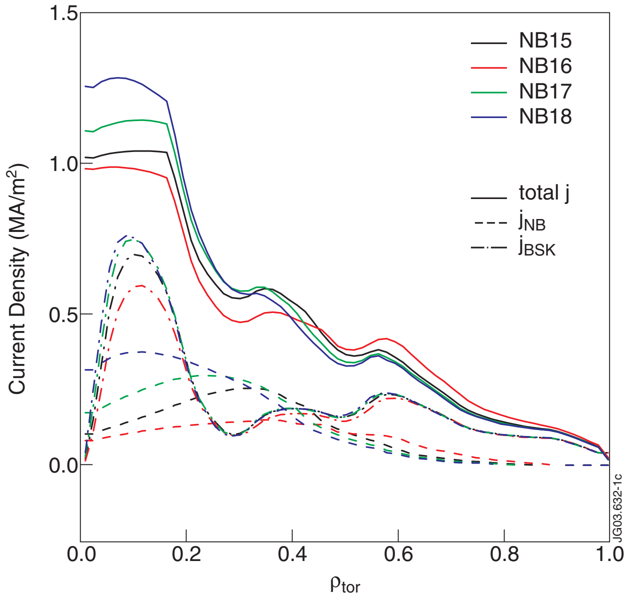
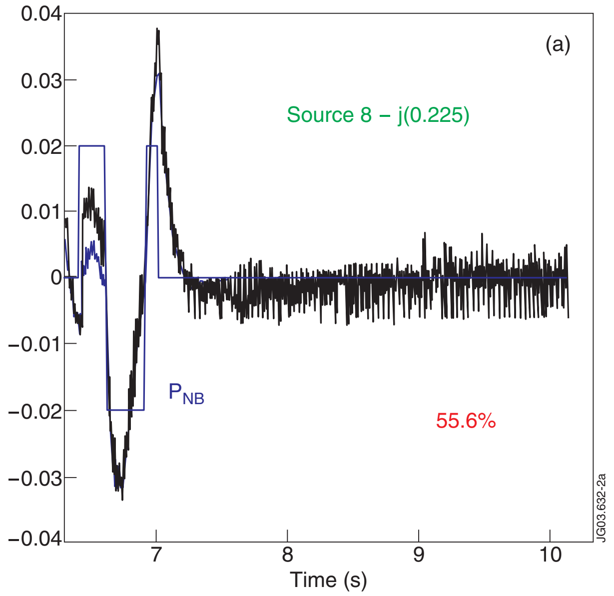


Figure 1: Total, NB driven and bootstrap current density profiles for different beam sources at 6.5sec of Pulse No: 13686



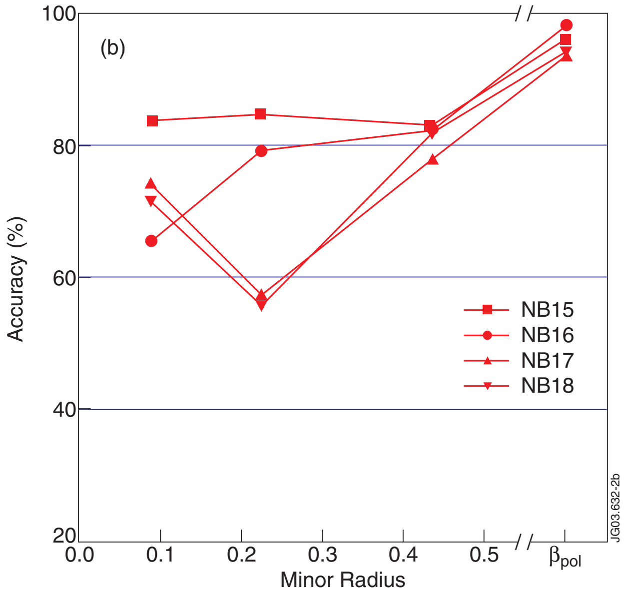


Figure 2. Validation result for the worst case; time trace of the reference signal (with oscillations) and calculated current density by the model (a), accuracy of the validation result for each beam sources and 3 radial points, poloidal beta (b)

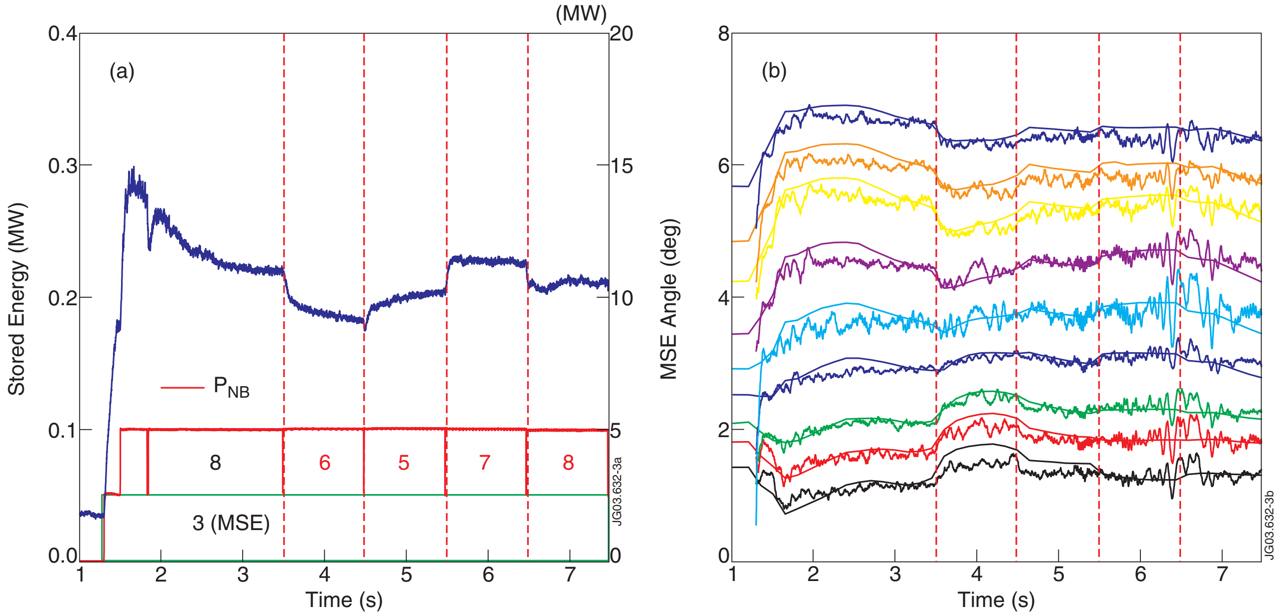


Figure 3. Pulse No: 17530 at ASDEX Upgrade; stored energy and beam power is presented, beam source is changed at 3.5s to 6, at 4.5s to 5, at 5.5s to 7 and at 6.5s to 8 (a), MSE angles from experimental measurement (with small oscillations) and the ASTRA simulation (b)

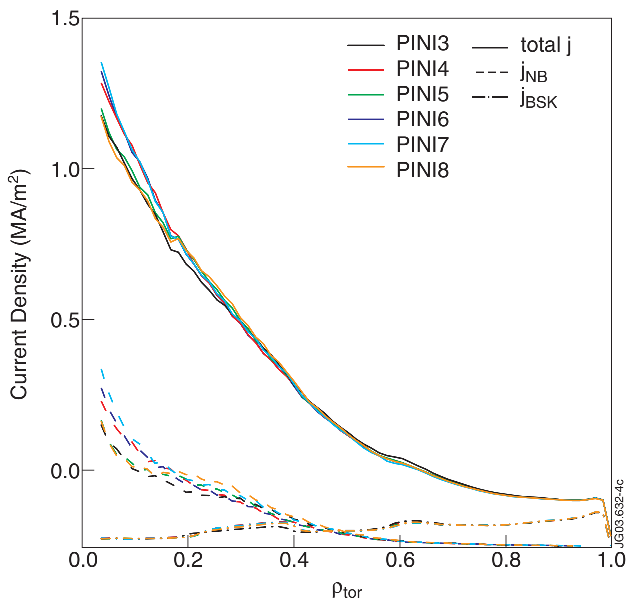


Figure 4. total, NB driven and bootstrap current density profiles for different beam sources at 32.5s of Pulse No: 55425 at JET