

Off axis NBCD experiment on MAST

M. Turnyanskiy, R. J. Akers, M. F. M. de Bock, I. T. Chapman, G. Cunningham, H. Meyer,
C. A. Michael and S. D. Pinches

EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, OX143DB, UK

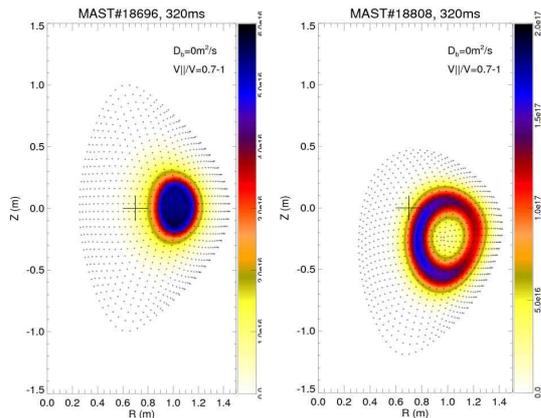


Figure 1. TRANSP simulated poloidal projections of co passing fast ion distributions with $V_{||}/V \sim 0.7-1$ under an assumption of classical beam deposition and collisional thermalisation with on (left) and off (right) axis NBI. The tangency point of NBI is highlighted as a cross at $R=0.7\text{m}$, $Z=0\text{m}$.

One of the most promising approaches for broadening and shaping the plasma current profile in tokamaks is off axis Neutral Beam (NB) injection. Driving current by an NBCD (Neutral Beam Current Drive) scheme is particularly important in STs due to the limited applicability of other non-inductive current drive schemes and because of the limited space available for neutron shielding of a solenoid. The MAST tokamak is equipped with two mid-plane co-injected deuterium Neutral Beam Injectors (NBI) injected at a tangency radius,

R_{tan} , of 0.7m and each potentially capable of delivering up to 2.5MW of beam power. At present, the MAST NBI systems can not be reoriented to study off axis NBCD in DND (Double Null Divertor) plasmas. However, the flexibility offered by the large MAST vessel has been exploited for the study of off axis heating in vertically displaced SND (Single Null Divertor) plasmas. Plasma configurations with beam tangency at about half the minor plasma radius have been achieved in SND discharges by displacing the MAST plasma by up to 0.3m in the vertical direction as shown in Figure 1 for the lower SND plasma configuration. The tangency point of NBI is highlighted as a cross at $R=0.7\text{m}$, $Z=0\text{m}$. Recent improvement in optimization of the plasma formation allowed an increase of the plasma volume in MAST SND scenarios, reaching up to 90% of the volume of a typical MAST DND discharge. Optimisation of magnetic field alignment with NBI was also carefully considered as it has a significant impact in NBCD efficiency in STs [1].

The future generation of STs relies heavily on off axis NBI power for both generating and controlling the current profile and for efficient plasma heating which is a particular concern in discharges with off axis NB deposition. Examples of typical distributions of co-

passing fast ions ($V_{||}/V \sim 0.7-1$), simulated by the TRANSP code under an assumption of classical beam deposition and collisional thermalisation with on and off axis NBI are shown in Figure 1. The energy range of the fast ion distribution here extends to the end of the high energy tail of the Maxwellian distribution with the lower cut-off energy at $3T_i$. The effect of the off axis NB deposition is clearly visible and results in much wider deposition of the passing fast ions. Experimental results indicate that broadening the fast ion deposition profile by off axis NB injection helps to avoid harmful plasma instabilities such as sawtooth driven disruptions and significantly extends the operational window of MAST. Long pulse plasmas ($>0.65s$) with a long H-mode duration were achieved and were limited only by present machine and NBI engineering limits. Efficient off axis NBI heating has been experimentally confirmed by the behaviour of plasma parameters such as plasma energy, ion and electron temperature and neutron yield. Experiments to date demonstrate comparable plasma heating for off axis heated discharges (strongly SND) to that achieved with on axis heated discharges with similar plasma current and electron density [1]. Strongly off axis SND discharges pose a challenge for detailed transport analysis on MAST, due to the majority of diagnostic measurements being located in the vessel rather than plasma mid-plane (see Figure 1). Some data extrapolation into the region with $0 < \psi < 0.15$ is unavoidable. Sensitivity studies, where missing diagnostic data was varied within realistic upper and lower limits, produced robust results, insensitive to such variations, and resulted in an uncertainty in simulated NBCD current of less than a few % at most. Modelling assumptions for diagnostic measurements used in SND simulations were further validated by shifting the SND plasma back to the vessel midplane (to optimise diagnostic measurements) in a time scale much faster ($<1ms$) than both MAST confinement and beam ion slowing down times. Efficient generation of off axis plasma current by NBCD and the bootstrap effect in MAST are also predicted by theory but determining the exact non-inductive contribution is currently a challenging task due to the large Ohmic fraction of the plasma current. TRANSP simulations indicate that with the present NBI power (up to ~ 3.9 MW, $E_b = 60keV$) MAST plasmas have an NB driven current contribution of up to $\sim 40\%$. Moderate NBI power discharges ($P_{NBI} < 2$ MW) on MAST usually exhibit a low level of fast particle driven MHD and TRANSP modelling, assuming classical beam deposition and using the Chang-Hinton model agrees well with the experiment [2]. Introduction of high power off axis NBI (up 3.9MW) led to appearance of high intensity $n=1$ fishbone magnetic activity in these initial experiments. The measured neutron flux is a good monitor of the fast ion behaviour in MAST as it is dominated by the beam-plasma reactions. Comparison of experimentally measured volume averaged neutron rate and stored

plasma energy with the rates calculated by the TRANSP code, using an assumption of classical beam deposition and collisional thermalisation in these discharges, shows that the experimental values are significantly overestimated (by ~25-30%). The time of the largest discrepancy between simulated and experimental data correlates well with the highest magnitude of observed $n=1$ fishbone magnetic activity suggesting appreciable anomalous beam-ion radial transport associated with this beam driven MHD. A level of anomalous fast ion diffusion with diffusion coefficient of roughly $D_b = 0.5\text{-}1\text{m}^2\text{s}^{-1}$ applied only during $n=1$ fishbone magnetic activity is sufficient to account for the experimental measurements and comparable to that previously reported from DIII-D, AUG, JET and NSTX. Anomalous beam-ion radial transport associated with this beam driven instability broadens the NBCD profile and degrades the relative contribution of NB driven current from ~40% to ~30%. Even with this enhanced diffusion, TRANSP simulations suggest that the driven current remains off axis and amounts to a substantial non-inductive contribution (~200kA).

The TRANSP modelling is also consistent with the data from the new multi-chord MSE diagnostic which has recently been commissioned on MAST. Polarisation angles in off axis NBI discharges together with the resulting current density distributions for a set of MAST discharges with identical plasma current and boundary are shown in Figure 2. Three plasma discharges are presented; Ohmic reference shot with line average electron density $\sim 2 \cdot 10^{19} \text{ m}^{-3}$ and two NBI heated discharges, where 1.85MW of NB power was injected, with line average electron densities $\sim 2 \cdot 10^{19} \text{ m}^{-3}$ and $4 \cdot 10^{19} \text{ m}^{-3}$ respectively. Ohmic MSE data has been obtained by short pulsing the MAST heating beam at the time of interest (0.2s) i.e. using the MAST NBI as a non-perturbative diagnostic tool and preserving the Ohmic plasma properties. As NB driven current is predicted to diminish rapidly with increased plasma density, one of the test discharges was repeated with line average electron density doubled from $2 \cdot 10^{19} \text{ m}^{-3}$ to $4 \cdot 10^{19} \text{ m}^{-3}$ in order to minimise the amount of beam driven current. To

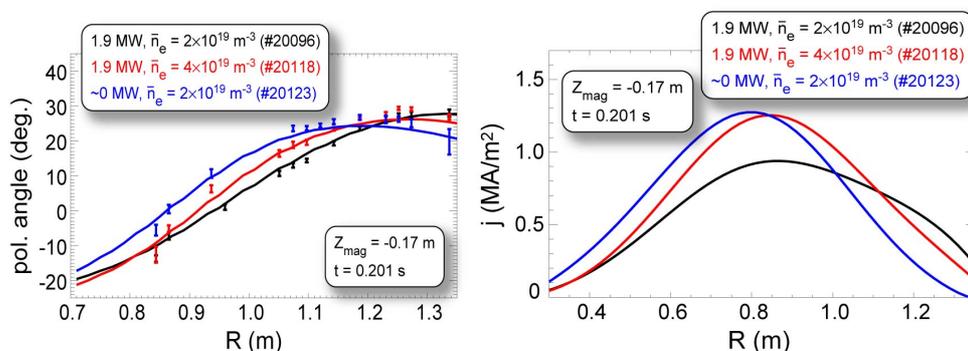


Figure 2. Polarisation angle (left) in off-axis NBI discharges and resulting current density distributions (right) for a set of MAST discharges with identical plasma current and boundary

minimise the influence of $n=1$ MHD instabilities such as sawteeth, the data shown in Figure 2 were obtained just before appearance of the $q=1$ surface but after sufficient time for any effects caused by the current ramp up to have become negligible. Clear differences in polarisation angle are observed in the three cases. The measured current profiles are consistent with significant off axis NBCD at low density, diminishing as the density is increased.

The nonlinear δf wave-particle interaction code, HAGIS [3], has been employed to describe the evolution of the fast ion distribution function in the presence of the observed $n = 1$ fishbone activity, allowing quantification of the fishbone-driven fast ion radial diffusion. The HAGIS simulations predict an MHD induced radial fast ion flux and associated change in

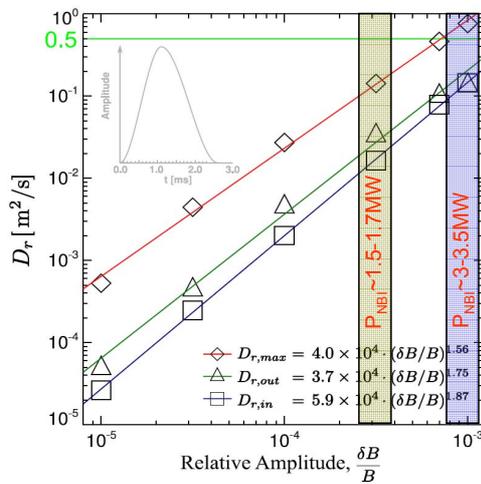


Figure 3. Maximum value of the diffusion coefficient D_r for different amplitudes of the fishbone oscillations. Outward and inward D_r is also shown. The horizontal green line shows the value predicted by transport calculations $\sim 0.5 \text{ m}^2/\text{s}$.

the fast ion radial density, leading to a radial broadening of the fast ion distribution function. Combining these results allows the radial diffusion to be estimated using Eq 1.

$$\Gamma_{\psi_p}(\psi_p, t) = -D_{br} \frac{\partial n(\psi_p, t)}{\partial \psi_p} \quad [1]$$

For experimentally observed fishbone amplitudes, $\delta B/B \sim O(10^{-3})$, the level of anomalous fast ion diffusion is found to be consistent with those required in transport codes to explain the measurements. The average rate of diffusion, predicted by HAGIS simulations, is found to scale with the fishbone amplitude,

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[2] Tournianski M. R. et al, Plasma Phys. Control. Fusion 47 671 (2005)

[3] Pinches, S. D. et al, Comp. Phys. Comm., 111, 1,133-149 (17), (1998)