Off axis NBCD experiments on MAST

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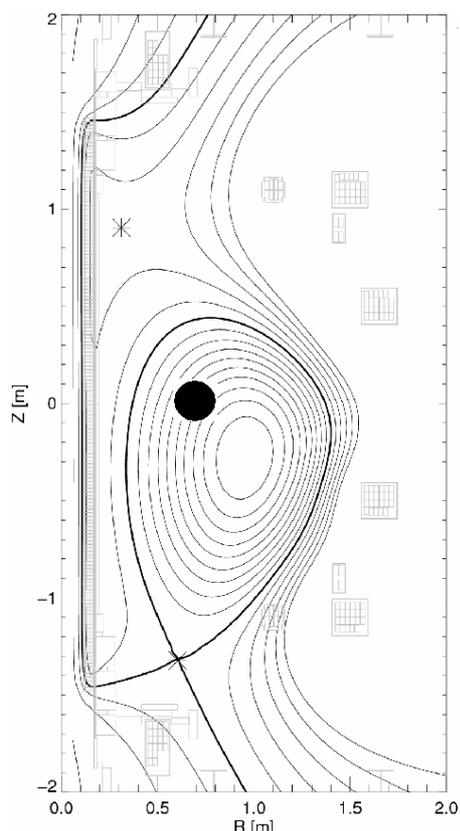*EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, OX143DB, UK*

Fig. 1. Example of typical plasma configuration attainable for studying off axis NBCD and heating on MAST. Schematic position of NBI is also highlighted.

Neutral Beam Current Drive (NBCD) is an important element of many burning tokamak plasma concepts and is particularly important in Spherical Tokamaks (STs) due to the limited applicability of other non-inductive current drive schemes and the limited space available for neutron shielding of the solenoid. The high neoclassical resistivity observed in STs with consequently faster current penetration rate, provides additional challenges for initiating q>1 regimes, desirable for long pulse or steady-state spherical devices. To achieve these high central q scenarios, both high efficiency off axis current drive and current profile control is required which can potentially be provided by NBCD. Therefore, one of the main operational aims of the MAST experiment and the proposed MAST upgrade is to investigate and demonstrate off axis NBCD. The flexibility offered by the large MAST vessel has been exploited in present experiments for the study of off-axis heating and NBCD in vertically displaced Single Null Divertor (SND) plasmas as shown in Fig.1. The MAST tokamak is equipped with two mid-plane co-injected deuterium Neutral Beam Injectors (NBI), each potentially capable of delivering up to 2.5MW neutral beams, injected at a tangency radius, R_{tan}, of 0.7m. Recent MAST experiments have benefited from the replacement of one ORNL duo-pigatron beam source by a long pulse, high power JET-style PINI, thereby allowing neutral beam injection at higher power (up to 3.8MW) and for longer durations (up to 0.5s). The operational window of MAST has also been extended by the installation of error field correction coils, implementation of digital plasma control systems

and a real time optical plasma edge detection and position control system. The NBCD SND scenario was further improved by increasing the plasma volume and by optimizing the plasma formation (Fig.1).

First 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 are achieved and are limited only by present machine and NBI engineering limits. These off axis heated plasmas have shown high plasma performance with high sustained β_N (~3.5-4). Efficient off axis NBI heating has been experimentally confirmed by the behaviour of plasma parameters such as plasma energy, ion and electron

Fig. 2. TRANSP simulated distribution of the total plasma current, I_p, between Ohmic, the bootstrap and neutral beam driven components for D_b= 0.5 m^2s^{-1}. Experimental measurements and TRANSP simulations of neutron flux and stored energy for D_b= $0m^2s^{-1}$ and $0.5m^2s^{-1}$ are also presented.

temperature and neutron yield. Experiments to date demonstrate plasma heating for off axis heated discharges (strongly SND) comparable to that achieved with on axis heated discharges with similar plasma current and electron density. Efficient generation of off axis plasma current by NBCD and bootstrap mechanisms 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 present NBI power (up to ~3.8MW) MAST plasmas have an NB driven current contribution of up to ~40%. However throughout the time of NBI injection, the experimentally measured volume average neutron rate is significantly smaller that the rate calculated by the TRANSP code using an assumption of classical beam deposition and collisional thermalisation. The measured neutron flux is a good monitor of the fast ion behaviour in MAST as it is dominated by the beam-plasma reactions. Due to the large energy difference between the energy of the
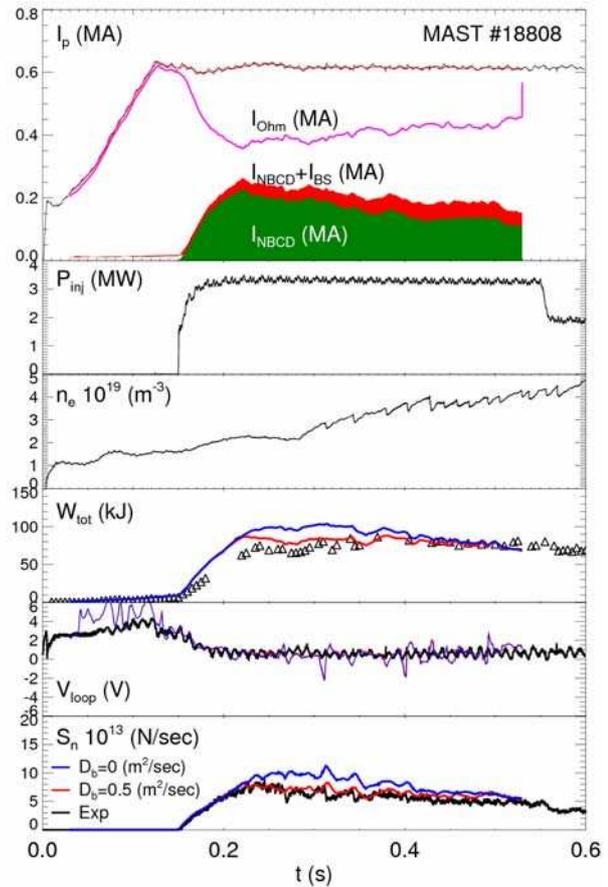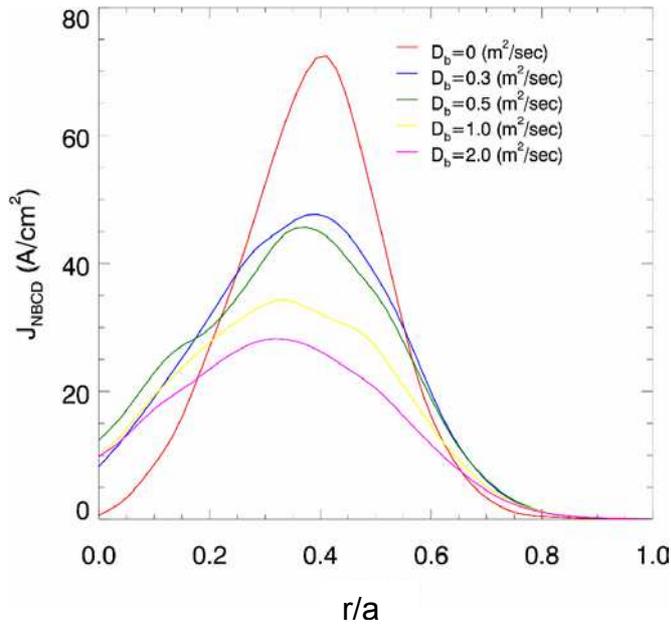
Fig. 3. TRANSP simulations of NB driven current density for various values of D_b

beam (~60keV) and the plasma ions (T_i~1.5keV), the cross-section for D-D fusion is higher for such beam-plasma reactions than for the thermal plasma-plasma reactions. The time of the largest discrepancy between simulated and measured neutron rates (0.2s-0.35s) correlates well with the highest magnitude of the observed n=1 fishbone magnetic activity suggesting appreciable anomalous beam-ion radial transport associated with this beam driven MHD [1]. Fig. 2 analyses the degradation of the beam-ion confinement in more detail. The TRANSP code permits introduction of an *ad hoc*, spatially constant, beam-ion diffusion coefficient that is independent of pitch angle. Comparison with the experimentally measured neutron rate indicates that a diffusion coefficient of roughly D_b= 0.5-1m^{2}s^{-1} is required to account for the measured rate, comparable to that previously reported from DIII-D [1] and AUG [2]. An assumed level (D_b= 0.5-1 m^{2}s^{-1}) of the fast ion diffusion also improves the agreement between the stored energy measurements and its classical prediction and provides a useful check on this hypothesis. The application of anomalous fast ion diffusion only during observed n=1 fishbone activity and for fast ions with energy above 40keV proved to be sufficient in order to match the experimental measured stored energy and neutron rate with TRANSP simulations. Other plasma parameters with systematic uncertainties that could affect fast ion confinement such as neutral density, edge electron temperature and for the discharge studied here, toroidal velocity were varied within realistic upper and lower limits. The resulting simulated neutron and stored energy have proven to be very robust to those variations. For example, increasing the neutral density by a factor of ten led to only a very modest (2-3%) drop in simulated neutron rate and stored energy. The expected fractions of the total plasma current, I_p, distributed between Ohmic, bootstrap and neutral beam driven components for D_b= 0.5 m^{2}s^{-1} are shown in Fig. 2. TRANSP simulations and experimental measurements of some plasma parameters are also presented. Although this analysis is useful as an indication of the magnitude of the anomalous beam ion transport, this simplistic *ad hoc* model can not predict the actual beam ion profile, which depends on details

of the resonant interaction between the instabilities and the beam ions. The inferred fast ion diffusion broadens the neutral beam driven profile and degrades the relative contribution of NB driven current from ~40% to a around ~30% of the total plasma current. TRANSP simulations of NB driven current density profiles for various values of D_b are shown in Fig. 3. Work is ongoing, using the HAGIS δf MHD model, to introduce spatially limited, energy and pitch angle dependent beam-ion diffusion which can describe the resonant nature of the interaction between the plasma instabilities and the beam ions in more detail.

Summary

Extensive current drive and transport simulations performed for MAST plasmas further support the theoretical predictions of the efficient generation of plasma current by NBCD in the ST. Results show that about ~30% of the total plasma current in MAST is driven by NBI non inductively. However, in order to match the experimentally observed neutron rate and stored energy a low level of anomalous fast ion diffusion (D_b~0.5 m^{2}s^{-1}) is required. The introduction of the fast ion diffusion broadens the NBCD profile and degrades the relative contribution of NB current from potentially ~40% to ~30% of the total current. TRANSP simulations show that despite some decrease in current drive magnitude and broadening of the NBCD profile, the driven current profile remains off axis at least for current power levels (<3.8MW) and the corresponding magnitude of the beam driven instabilities. Direct measurements of the current profile are clearly desirable; a multi-chord MSE diagnostic has been installed on MAST to confirm the current 30% magnitude and off axis location of the NBI driven current.

References

[1] W. W. Heidbrink et al, Nuclear Fusion 42 972 (2002)

[2] S. Gunter et al, Nuclear Fusion S98 (2005)