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Off axis neutral beam heating and current drive on MAST

M.R. Tournianski, R. J. Akers, D. L. Keeling, P. G. Carolan and G. Cunningham

EURATOM/UKAEA Fusion Association, Culham Science Centre,
Abingdon, Oxon, OX14 3DB, UK

Neutral Beam Current Drive (NBCD) is an important element of next generation burning plasma devices, particularly Spherical Tokamaks (ST). For example, the latest Culham component test facility [1] design cannot operate with a solenoid in DT operation and relies on 100% of the plasma current to be driven non-inductively. Therefore, one of the main operational aims of the MAST machine and proposed MAST upgrades is to investigate NBCD. Efficient NBCD in MAST is predicted by theory and has been observed tentatively in a number of experiments. However, to achieve a desirable steady state scenario in STs with q(0)>1, avoiding the detrimental effects of sawteeth both high efficiency NBCD and current profile control is required which can potentially be provided by an off axis NBCD system.

MAST experimental set up

The MAST tokamak is equipped with two mid plane Neutral Beam Injectors (NBI), each capable of delivering up to 2.5MW of 40-70 keV deuterium neutrals at a tangency radius, R_{tan}, of 70cm. The experiments reported here were conducted with a single co-injected neutral beam with power up to 2MW and duration up to 0.4s. The access offered by the large MAST vessel, has been exploited for the study of off-axis heating and NBCD in vertically displaced Single Null Divertor (SND) plasmas, an approach adopted by DIII-D [2]. Experiments have benefited from improvements in the operational flexibility of MAST, namely implementation of digital plasma control, real time optical plasma edge detection for plasma position control and error field compensation which have allowed extension of the MAST operational space to lower density plasmas. Typical configurations attainable for studying off and on axis NBCD and heating during the last MAST experimental campaign are shown in Fig 1. Plasmas with beam deposition at about half minor radius have been achieved in SND discharges by displacing the MAST plasma by up to 0.3m vertically with the beam cross section highlighted.

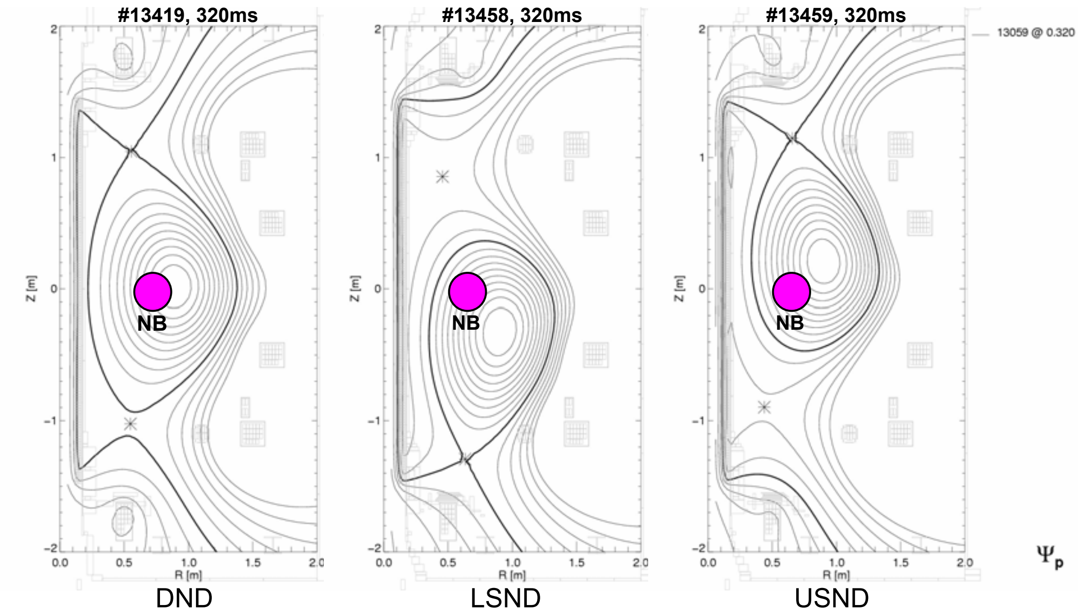

Fig 1. Typical configurations employed to study off and on axis NBCD and heating in MAST.

Heating and current drive with off axis NBI.

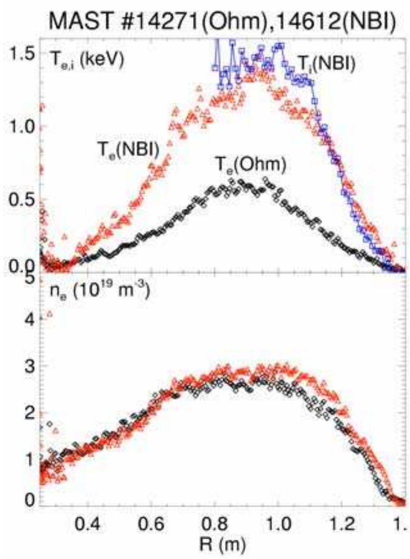

Fig 2. A comparison of electron temperatures and densities in Ohmic (black) and off axis NBI heated SND plasmas (red) measured in vessel mod plane.

Off axis fast ion heating has to be modelled carefully in ST due to the potential for large fast-ion losses or high trapped particle fractions [3]. The initial results from the off-axis heated SND MAST plasmas are however indicative of very efficient beam heating. The discharges studied have a neutron yield, stored energy and H-mode power threshold comparable to up-down symmetric Double Null Divertor (DND) discharges with on-axis NBI. The recent introduction of density feedback control has allowed beam heated and Ohmic discharges to be controlled with very similar density profiles. A comparison of electron temperature and density profiles in an Ohmic and an off axis NBI heated SND plasma is shown in Fig 2. The ion temperature profile from (CXRS) is also shown in an NBI heated case. In the case of the neutral beam heated plasmas, both electron and ion temperatures rise significantly almost tripling from ~0.5 keV to ~1.5keV, with total plasma energy approaching 100kJ despite the modest heating power (P_{NBI}=1.7 MW).

The MAST tokamak is an up-down symmetric machine where Ohmic, inductively driven, lower and upper SND discharges are nearly identical and exhibit a similar low level of impurities. The extreme geometry of low aspect ratio devices, however, can have a strong effect on the NBCD efficiency. For example, a relatively large ratio of poloidal to toroidal field in STs may lead to a significant difference in NBI driven current if the beam is injected above rather than below the magnetic axis providing a means of testing the location of driven current and NBI model predictions. This is mainly due to the narrower angle between the injected beam particles and the magnetic field direction in LSND discharges (for MAST field directions) leading to a higher proportion of the fast particles being deposited on better confined passing orbits. It should be noted that this effect is much enhanced in the ST due to the relatively large poloidal field. In conventional tokamaks the toroidal field greatly exceeds the poloidal magnetic field so the effect on NBCD is negligible. The described model is qualitatively supported by scanning NPA measurements where, as expected from fast ion modeling, USND discharges exhibit a higher population of trapped ions. The higher efficiencies of off axis current drive in lower SND plasmas in MAST should keep the current profile broader for longer, delaying the appearance of the q=1 surface in two otherwise identical L- and U- SND discharges. Soft X-Ray diagnostic (SXR), Thomson scattering (TS) measurements and data from the EFIT equilibrium reconstruction code are compared in Fig 3 for beam injection into similar USND and LSND target plasmas. Estimates of the time of q=1 appearance and l_i from EFIT are presented with lower plasma inductance and a delay in q=1 appearance being observed in LSND plasmas relative to USND and Ohmic discharges, indicative of greater off axis NBCD in LSND, as predicted from simulations.

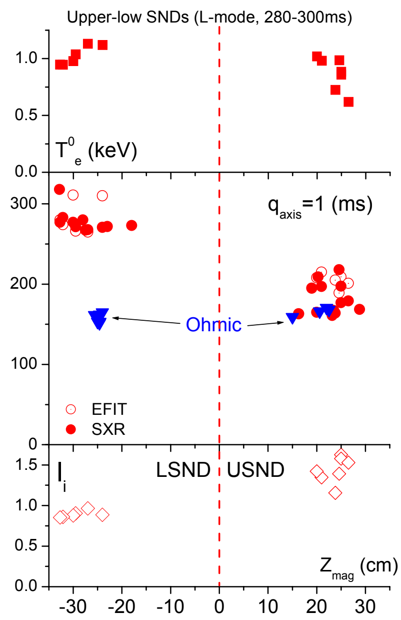

Fig 3. T_e and sawtooth delay for a test set of similar upper and lower SND plasma discharges are compared versus the vertical shift of the MAST magnetic axis relative to the mid-plane. The estimates of the time of q=1 appearance and l_i from EFIT code are also presented.

TRANSP simulations and conclusions

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. Nevertheless transport simulations performed so far using TRANSP show a satisfactory agreement with experimental data. Experimental waveforms (black) and results of TRANSP analysis (red) for the LSND MAST discharge are shown in Fig 4 and are in good agreement. Thermal plasma data typically comprise hybrid T_e and n_e profiles (combining 200Hz NdYAG TS, single time slice high resolution (300 point) TS, Langmuir probe data and interferometry), high resolution (~ thermal ion gyro-radius) time resolved T_i and V_φ profiles and Z_{eff} profile data using 2D visible bremsstrahlung imaging (where C^{6+} is assumed to be the dominant impurity). The plasma boundary is constrained to the EFIT LCFS (confirmed using bremsstrahlung imaging) which in turn is constrained to the low field side mid-plane D-alpha peak radius (which in addition, when combined with T_e and n_e data provides the electron source from gas fuelling and recycling). TRANSP simulations are initiated using the EFIT q-profile with hand-over to solution of the poloidal field diffusion equation typically 100ms into the discharge. The fast ion population is modelled using the gyro-corrected NUBEAM Monte Carlo model and the equilibrium using ESC/RZSOLVER. These TRANSP simulations of NBCD in MAST off axis NBI discharges indicate that around 25% of the plasma current is driven non inductively by the neutral beam and the bootstrap current is relatively small (a few%) as shown in Fig 4. Further experiments using higher NBI power are planned for the near future in order to optimise efficiency and location of the off axis NBCD on MAST.

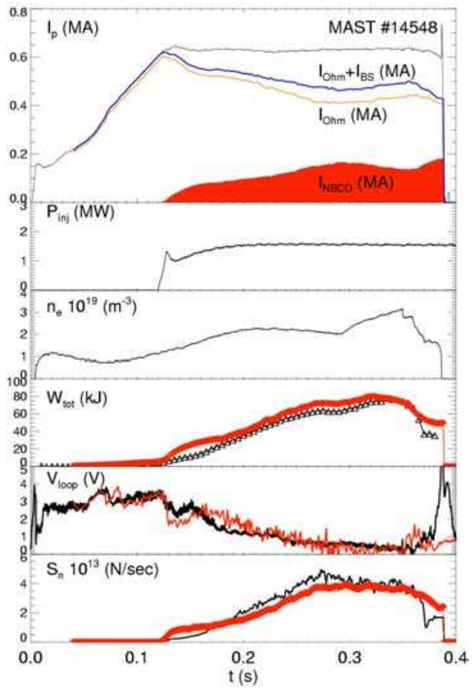

Fig 4. Experimental waveforms of plasma current, injected power, line average n_e, plasma energy, loop voltage and neutron yield, S_n in off axis NBI discharge. The results of TRANSP simulations of plasma energy, loop voltage, neutron yield (red) and bootstrap and NBCD currents are also presented.

[1] A. W. Morris et al, Fusion Eng Des 74 (2005) 67
[2] P. Gohil, K. H. Burrell, T. H. Osborne, Nucl. Fusion 38 (1998) 425
[3] M. R. Tournianski, R. J Akers, P. G. Carolan and D. L. Keeling PPCF 47 (2005) 671

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