Current profile control studies on MAST

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Abstract.

One of the main operational aims of the MAST experiment [1] and the proposed MAST upgrade is to investigate possible mechanisms to control the q-profile and drive off-axis current. Experiments were carried out to determine the extent to which the q-profile may be modified using two different approaches, transient and steady-state. Transient effects during the plasma current ramp-up phase were investigated with the aim of developing a start-up regime that can later be used as a target plasma for non-inductive current drive or to access advanced modes of operation such as the hybrid or improved H-mode. The most significant effect in this case was observed when early Neutral Beam Injection (NBI) was applied to the fast current ramp-rate start up plasmas causing reversed magnetic shear and the plasma current to 'pile-up' off-axis.
In steady-state experiments, in which off-axis NBI was studied, results indicate that broadening the fast ion deposition profile by off axis neutral beam (NB) injection helps to avoid harmful plasma instabilities and significantly extends the operational window of MAST. Long pulse (>0.65s) H-mode plasmas were achieved with plasma duration limited only by present machine and NBI engineering limits. In order to match the experimentally observed neutron rate and stored energy a low level of anomalous fast ion diffusion (D_b~$0.5m^2s^{-1}$) is required. The introduction of the fast ion diffusion broadens the Neutral Beam Current Drive (NBCD) profile and degrades the relative contribution of NB driven current from ~40% to ~30%. To obtain direct measurements of the current profile, a multi-chord MSE diagnostic has been commissioned on MAST and is currently delivering first results in order to confirm the off axis location of the NB driven current.

1. Introduction

The Mega Ampere Spherical Tokamak (MAST) is a midsize low aspect ratio fusion research facility. The MAST plasma has a cross-section comparable to those of medium sized conventional tokamaks like ASDEX Upgrade and DIII-D, and has typical operational parameters of R~0.85m, a~0.65m, I_p<1.3MA and B_t=0.3-0.6T. The heating system consists of two mid-plane co-injected deuterium neutral beams injected at a tangency radius, R_{tan}, of 0.7m. Experiments have benefited from the ongoing NBI upgrade to JET-style PINI sources allowing the studies to be extended to higher power and duration (up to 3.8MW, 0.5s). By the end of the current upgrade, each injector will be capable of delivering 2.5MW of power extending the total NBI heating power to 5MW. 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. These improvements help to expand MAST operation space in low density plasmas and to control the current and the plasma shape during ramp up experiments on MAST.
Determining the attractiveness of the Spherical Tokamak (ST) concept in the areas of high-β stability, confinement, non inductive current drive and divertor physics for pulse length longer than energy confinement time is the main mission of the MAST device. The high neoclassical resistivity observed in STs, and consequent faster current penetration rate, results in rapid approach to low values of core safety factor, q. This provides specific challenges for initiating q>1 regimes, desirable for long pulse or steady-state spherical devices. Determining the extent to which the q-profile may be modified during the plasma current ramp-up phase and

developing a transient start-up regime that can later be used as target plasma for non inductive current drive, is an important part of the presented study.
To achieve a steady state scenario in STs with $q_{min}>1$ both high efficiency CD and current profile control is required which can potentially be provided by off axis NBCD. Driving current by NBCD 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.
Finally, the understanding of fast ion physics in tokamak plasmas is important for the modelling and interpretation of NBCD. Redistribution of the fast ions and degradation of the fast ion confinement caused by plasma instabilities is well known. For example, chirping "fishbones" modes were seen to cause fast ion losses at rates up to 20% fast ion loss per burst [2]. This would correspond to as much as 50% reduction in fast ion population in steady state. Thus, understanding of the complex nature of interactions between the plasma instabilities and the beam ions and potential deviation of the transport coefficients from classical predictions can not be underestimated and is extremely important for ITER [3] predictions.

2. Current ramp phase

A test set of MAST plasma discharges has been established in order to investigate the extent to which the q-profile may be modified during the current ramp-up phase. Three different parameters were investigated separately: the current and density ramp rates and the NBH start-time. Two rates of current ramp, fast (7MA/s) and slow (3.5MA/s) were used in combination with fast (8.8×10^{20}/m^3.s) and slow (4.9×10^{20}/m^3.s.) density ramps. In all beam heated discharges, NBI (1.4MW, 45keV) was applied at four different stages of the current ramp, corresponding to the beginning, third, two thirds and the end of the current ramp. Other plasma parameters such as shape, position and current value at the flat-top were kept constant. The TRANSP [4] code was used to model the current penetration in these experiments. The code interpretive analysis uses experimentally obtained plasma profiles and solve the poloidal field diffusion equation self-consistently with the neoclassical resistivity and calculated non-inductive current drive. The analysis was started at the earliest time an acceptable EFIT equilibrium [5] could be produced. An EFIT equilibrium reconstruction, constrained only by external magnetic measurements, was used as the initial condition for TRANSP. Experimentally observed MHD signatures such as values of q_{min} at specific times as well as radius and timing of q_0=1 appearance, obtained from Alfvén cascades and sawtooth precursor modes respectively, were used to benchmark the modelling results and enabled the TRANSP simulation setup to be adjusted so as to achieve the best match to the available MHD data. It is very important to choose the correct initial conditions in TRANSP for reliable modelling of the current ramp. It has been found that Alfvén cascades may be used to fix the value of q_{min} at a particular time in the simulation which then leads to

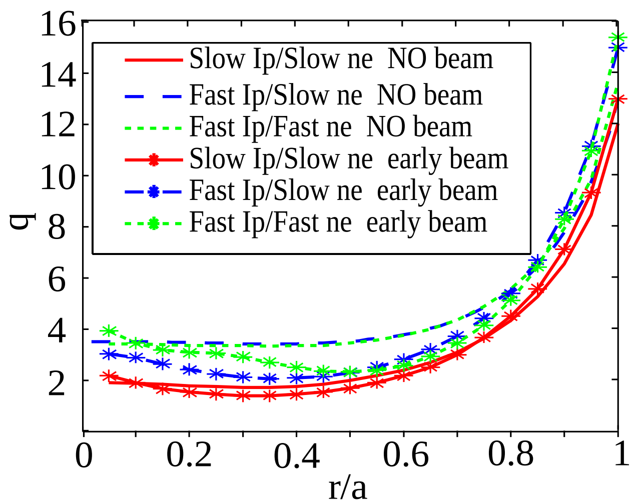

Figure 1. Comparison of q-profiles at the end of the current ramp from experiments with no NBI and with NBI starting 35ms (70ms for slow I_p ramp case) i.e. at the time when Ip=1/3I_p(flat-top).

an accurate prediction of the time of the first sawtooth without invoking any anomalous resistivity.

Results and discussions

The q-profiles for each discharge were examined at the start of the current flat-top (200ms for the slow current ramp experiments, 105ms for the fast current ramp experiments) and shown in Figure 1. All simulations performed for NB heated plasmas show negative values of magnetic shear, $s = \left(r/q\right)\left(dq/dr\right)$ (i.e. reversed magnetic shear), a necessary condition for the observed Alfvén cascades. The most significant effect was observed when early NB was applied which caused reversed magnetic shear with the most pronounced effect seen with the fast current ramp-rate. In these scenarios a strong reversed magnetic shear developed with the addition of early beams with q_{min} positioned at 0.3<r/a<0.55 as illustrated in Figure 1. In Ohmic discharges, neither current nor density ramp rate had a very strong effect on the core of the MAST plasma. However, in the outer half of the plasma, 0.5<r/a<1, magnetic shear moderately increases for the faster density and decreases for the faster current ramp rates.

The generation of negative magnetic shear by on-axis beams is explained by the TRANSP modelling. The changes in the q-profile shown in Figure 1 are due to changes in the Ohmic current profile rather than the presence of beam driven current which is peaked close to the plasma axis (r/a=0.15-0.2) and, in these discharges, accounts for only 5-7% of the total plasma current, I_p. In contrast the Ohmic current contribution by the end of ramp up phase (~120ms, in $8.8\times10^{20}/m^3.s$, fast current ramp discharges) accounts for around 90% of total I_p and peaks off-axis (r/a=0.4-0.5). Simulations show that the on axis NBH heats the core and peaks the electron temperature profile consequently lowering core plasma resistivity and the current diffusion rate and causing the current to 'pile-up' off-axis. Increased off-axis current density results in reversed magnetic shear. Examination of later times in the TRANSP runs shows that this is a dynamic effect and the plasma relaxes to a state with a monotonic q profile as the Ohmic current slowly penetrates into the core. Despite being a transitory effect, a combination of the described technique with off axis NBCD represents a powerful tool for generating the necessary q-profiles for steady state plasmas.

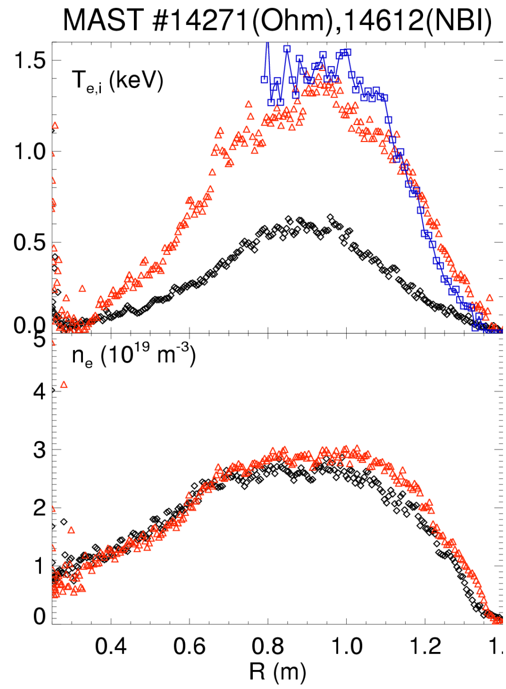

Figure 2. Comparison of the electron temperature and density profiles in Ohmic (diamonds) and off axis NBI heated SND plasmas (triangles), P_{NBI}=1.7MW, B_t=0.55T, I_p=620kA. The ion temperature profile (squares) is also presented for NBI heated case.

3. Off axis NBCD

The flexibility offered by the large MAST vessel has been exploited in recent experiments for the study of off-axis heating in vertically displaced SND plasmas (see Figure 5 where the tangency point of NBI is highlighted as a cross at R=0.7m, Z=0m.) The NBCD SND scenario

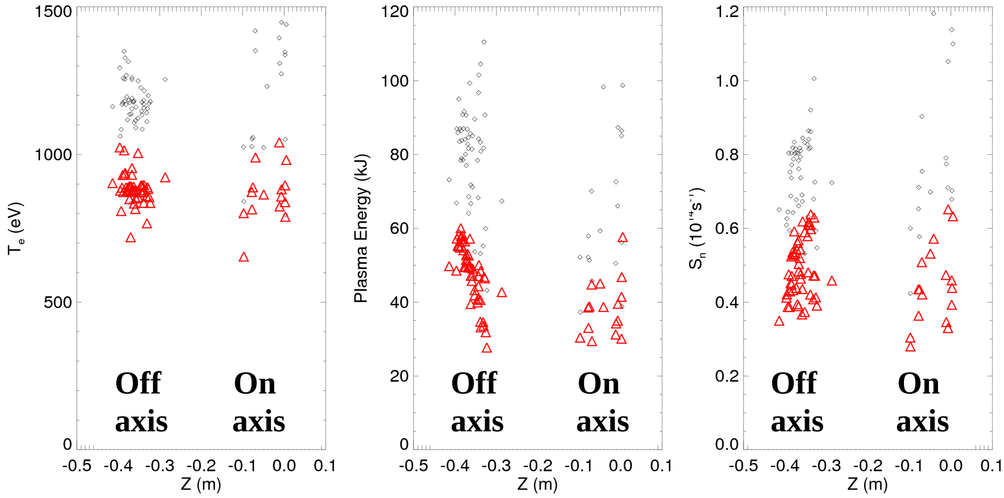

Figure 3. Central electron temperature, stored energy and neutron yield in on (|Z|~0cm) and off (|Z|>0.3m) axis NBI discharges. Red triangles and black diamonds are the flattop average and discharge maximum values respectively.

in MAST was further improved by increasing the plasma volume (reaching up to 90% of the volume of a typical MAST DND discharge) and by optimizing the plasma formation. 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. 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 temperature and neutron yield [6]. 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 5). Comparison of the electron temperature and density profiles in Ohmic (diamonds) and off axis heated lower SND plasmas (triangles) is shown in Figure 2.The ion temperature profile (squares) is also shown for the NBI heated case. Both electron and ion temperatures have risen significantly almost tripling from ~0.5keV to ~1.5keV. The recent introduction of digital plasma density feedback allowed

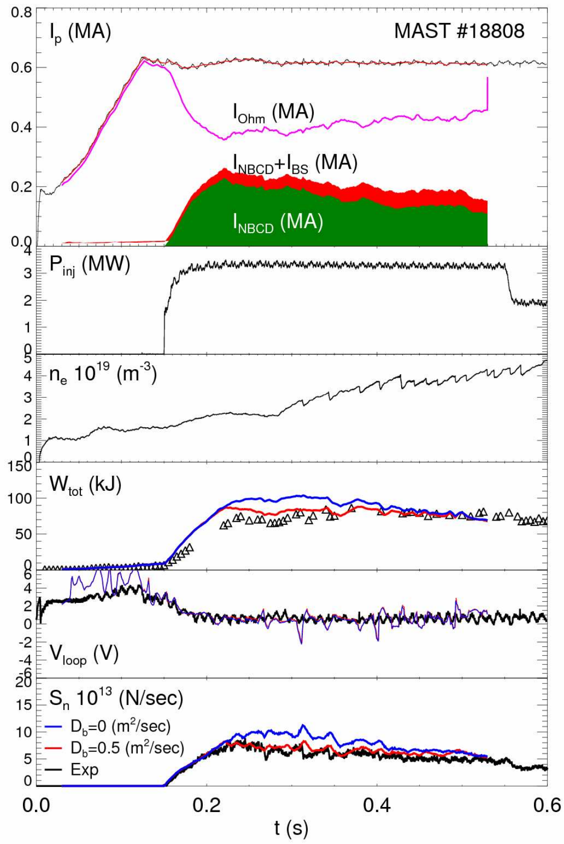

Figure 4. TRANSP simulated distribution of the total plasma current, I_p, between Ohmic, the bootstrap and neutral beam driven components for D_b= 0.5 m^2s^{-1}. Experimentally observed neutron yield, edge loop voltage and stored energy are compared with TRANSP simulations for D_b= 0 and 0.5 m^2s^{-1}.Time history of the total injected NBI power, line average electron density are also shown.

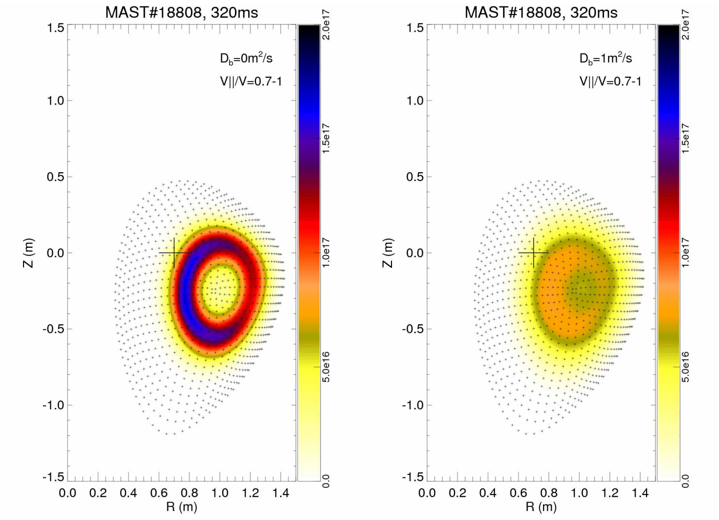

Figure 5. TRANSP simulated poloidal projections of co passing fast ion distributions with V‖/V~0.7-1 with (D_b= 1 m^2s^{-1}) and without (D_b= 0 m^2s^{-1}) anomalous fast ion diffusion. The tangency point of NBI is highlighted as a cross at R=0.7m, Z=0m.

beam heated and Ohmic discharges to be controlled with very similar density profiles which are also presented in Figure 2. 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. Electron temperature, neutron yield and plasma stored energy in on and off axis heated NBI discharges (I_p~600-650kA, P_{NBI}~3-3.5MW, E_b=60keV) are shown in Figure 3. Red triangles and black diamonds represent the flattop average and discharge maximum values respectively. 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, E_b=60keV) 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 lower than 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 beam (~60keV) and the plasma ions (T_i~1-1.5keV), 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 observed n=1 fishbone magnetic activity suggesting appreciable anomalous beam-ion radial transport associated with this beam driven MHD. Figure 4 analyses the degradation of the beam-ion confinement in more detail. The TRANSP code permits introduction of an *ad hoc*, pitch angle independent, beam-ion diffusion coefficient, D_b. The code also has capability of varying the degree of this non–classical, anomalous fast ion diffusion as a function of time, space and energy of the fast particles involved. Comparison with the experimentally measured neutron rate indicates that a diffusion

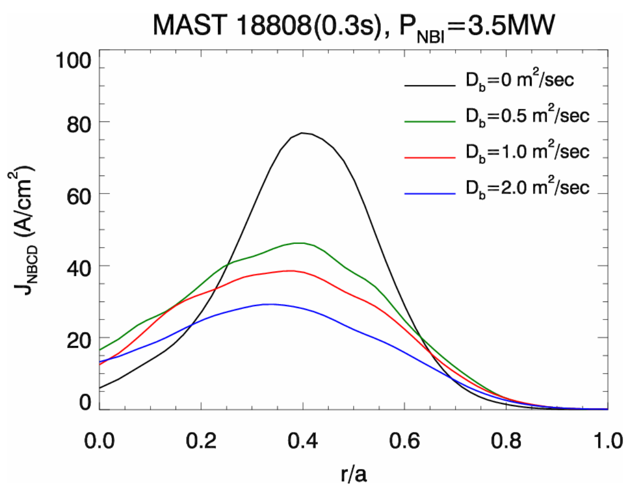

Figure 6. TRANSP simulations of NB driven current density profiles for various values of anomalous fast ion diffusion coefficient, D_b.

coefficient of roughly D_b= 0.5-1m^2s^{-1} is required to account for the measured rate, comparable to that previously reported from DIII-D [7] and AUG [8]. An assumed level (D_b= 0.5-1 m^2s^{-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 the observed n=1 fishbone magnetic activity (0.2s-0.35s) 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 large systematic uncertainties such as neutral density, edge ion temperature and, for the discharge studied here, toroidal velocity affecting fast ion confinement were varied within realistic upper and lower limits. The simulated neutron rate 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 calculated fractions of the total plasma current, I_p, distributed between Ohmic, bootstrap and neutral beam driven components for D_b= 0.5 m^2s^{-1} are shown in Figure 4 together with TRANSP simulations and experimental measurements of various other plasma parameters. Although this analysis is useful as an indication of the magnitude of the anomalous beam ion transport, this simplistic *ad hoc* model can not accurately predict the actual beam ion profile, which depends on details of the resonant interaction between the instabilities and the beam ions. Work is ongoing, using the HAGIS δf MHD model [9], 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.

NB driven current is mainly generated by the fast ions located on co passing orbits. The density of the fast ions and spatial distribution of such orbits are directly correlated with the amount of NB induced current and its location. TRANSP simulated poloidal projections of co passing fast ion distributions with V||/V~0.7-1 with (D_b= 1 m^2s^{-1}) and without (D_b= 0 m^2s^{-1}) are shown in Figure 5. The degrading effect on the fast ion confinement, caused by anomalous fast ion diffusion, is clearly visible and results in both a decrease in the fast ion density and a smearing of the off axis location of the co passing fast ions. As a result, the NB driven radial current profile broadens and its relative contribution to the total current is decreased. Corresponding TRANSP simulations of NB driven current density profiles for various values of D_b are shown in Figure 6. Modelling results show that for the inferred values of D_b= 0.5-1m^2s^{-1}, the NBCD contribution is typically decreased from ~40% to ~30% of the total plasma current. The calculated neutral beam driven current and its relative contribution to the total current are summarized in Table 1.

D_b (m^2s^{-1})	0	0.3	0.5	1.0	2.0
I_{NBCD}(kA)	253	221	209	164	130
I_{NBCD}/I_p (%)	41	36	34	27	21

Table 1. Maximum NB generated current and its relative contribution to the total current calculated by TRANSP for various values of anomalous fast ion coefficient.

4. Towards steady-state

Predictive simulations have been undertaken as part of a study to build a scientific case for a proposed upgrade to MAST. The main features of this proposed upgrade are: a longer pulse duration (up to 5s), cryopumped divertor, higher toroidal field and higher NB heating power. Amongst the intended aims of the project are: the demonstration of a stationary plasma in which q_{min}>2 with no inductive current drive. Simulations show that a large amount of extra off axis NBCD will be necessary to achieve the stated aims because a stationary plasma requires the off axis current to be maintained over a long time scale whereas the current pile-up effect described above is transient over several hundred milliseconds. The fully relaxed q-profiles of several MAST-U baseline scenarios are similar to the dynamically obtained q-profiles obtained with the current pile-up effect (see Figure 7.). This not only demonstrates the need for off-axis NBCD in MAST-U to maintain the off-axis current, but also suggests the current pile-up effect may be useful in starting up such scenarios. Simulations show that it take approximately 1.8 - 2 seconds for the current to relax from a monotonic q profile to the final stationary state in the MAST-U scenarios whereas a fully relaxed current profile may be achieved much more rapidly by making use of the current pile-up effect to pre-shape the q-profile before turning on the off-axis beams.

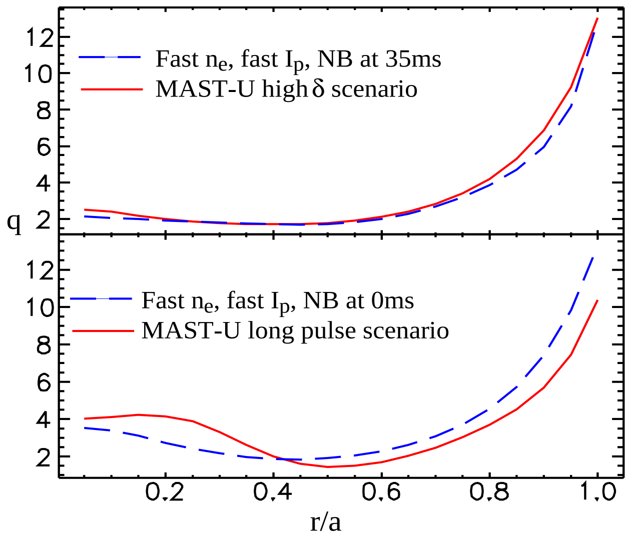

Figure 7. Fully relaxed q-profiles from two MAST-U baseline scenarios compared with transiently obtained q-profiles from MAST experiments exhibiting the current pile-up effect.

5. Conclusions

The generation of negative magnetic shear by on axis beams is explained by the TRANSP modelling. Simulations show that the peaking electron temperature profile consequently lowers core plasma resistivity and the current diffusion rate and causing the current to 'pile-up' off-axis. MHD signatures were used to benchmark the TRANSP modelling. For example, the value of q_{min} during Alfvén cascades appearance which then led to an accurate prediction of the time of the first sawtooth without invoking any anomalous resistivity. Despite being a transitory effect, a combination of the described technique with off axis NBCD represents a potentially powerful technique for shaping the plasma current profile in steady state scenarios.

Off axis NBI experiments on MAST benefited from the ongoing NBI upgrade and demonstrate plasma heating and neutron yield for off axis heated discharges (strongly SND) comparable to that achieved with on axis heated discharges with similar plasma current and electron density. Determining the exact non-inductive contribution is currently a challenging task due to the large Ohmic fraction of the plasma current. Comparison of experimentally measured the 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 shows that the experimental values are significantly overestimated (by ~25-30%). The time of the largest discrepancy between simulated and experimental data (0.2s-0.35s) 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-

$1m^2s^{-1}$ is needed to account for the experimental measurements degrading the relative contribution of NB driven current from ~40% to ~30% of the total plasma current. Nevertheless the TRANSP simulations suggest that, despite some decrease in NB generated current and broadening of the NBCD profile, the driven current remains off axis at least for current power levels and the corresponding magnitude of beam driven instabilities. Direct measurements of the current profile are clearly desirable; a multi-chord MSE diagnostic has recently been commissioned on MAST. The first results are encouraging and preliminary analysis of data from MAST off axis NB heated plasmas is currently underway to confirm the amount and localisation of the NB driven current.

Extensive transport simulations show that a combination of efficient non-inductive current drive and heating is possible in larger scale spherical devices such as MAST-U providing encouraging prospects for the use of off axis NB injection in future plasma devices. The presented technique of early core heating to slow current penetration represents a powerful tool for controlling and shaping the q-profile on MAST. This technique combined with off axis NB, as envisaged for the proposed upgrade to MAST, will allow rapid formation of a steady-state compatible q-profile and maintenance of this profile to demonstrate potential steady-state operation.

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