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Improved H-mode access with inboard gas puffing

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Introduction

Predicted threshold powers for H-mode access in the ITER device based on the latest empirical scalings from multi-machine databases exhibit large uncertainties (RMSE of 27%) due to effects which are difficult to quantify, such as wall conditioning and the behaviour of neutral atoms [1]. Experiments on both COMPASS-D and MAST tokamaks have shown that refuelling from a gas puff at the inboard plasma boundary significantly improves H-mode access. Here, the influence of a poloidally localised neutral viscosity on edge plasma flow and radial electric field is investigated for the first time, both experimentally and in terms of neo-classical theory, as a possible explanation of these observations.

Exploratory experiments on COMPASS-D tokamak with refuelling by means of an inboard gas puff [2] were able to extend the H-mode operating window to lower densities than with puffing from the usual outboard location. Furthermore, the gas puff could stimulate a transition to H-mode. On the MAST spherical tokamak inboard gas puffing is now used routinely to achieve reliable access to sustained ELMing H-mode plasmas which has not been possible with other refuelling methods [3].

Stimulated by these observations, neo-classical tokamak theory has recently been extended to investigate the effect of a poloidal variation in the edge neutral density [4] on the edge plasma flow. It is found that the edge radial electric field and outboard toroidal flow velocity tend to be larger if the neutral atoms are concentrated at the inboard side. It is suggested that such an increase in flow shear with inboard refuelling may trigger the formation of the edge transport barrier (ETB) by suppression of turbulent transport [5].

On MAST, instrumentation has been developed to measure detailed edge profiles of the toroidal ion flow velocity $V_{\phi i}$ from spectroscopic observations of a thermal helium jet at the outboard mid-plane. This has been used to investigate the dependence of the edge plasma flow on the poloidal location of the refuelling gas puff in otherwise similar Ohmic discharges.

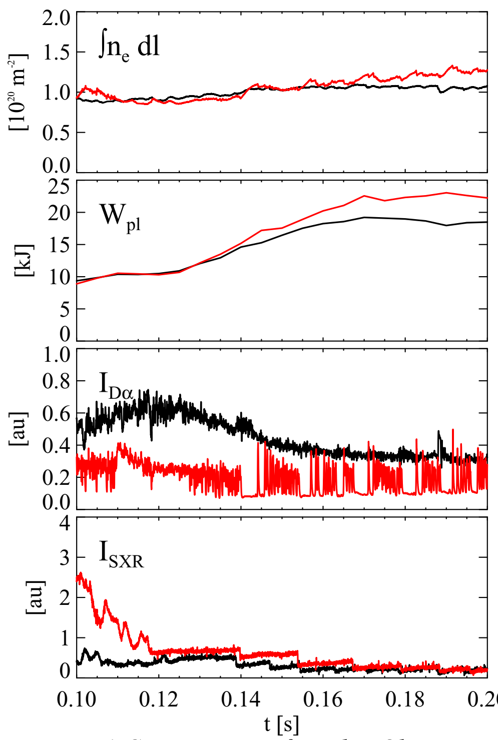

Fig. 1 Comparison of similar Ohmic discharges in MAST refuelled by inboard (#6108, red) and outboard (#6111, black) gas puffing. The D_a emission is from the upper divertor region.

Experimental

The evolution of two otherwise similar Ohmic discharges with inboard and outboard gas puffing is shown in Fig. 1. These discharges, with 700kA plasma current, connected-double-null divertor

(CDND) configuration and line-average density of 2-4×10^{19} m^{-3}, exhibit similar behaviour until ≈ 0.12 s when the inboard refuelled discharge begins a gradual transition to H-mode with the onset of 'dithering' ELMs. A quiescent H-mode phase follows at 0.14 s and thereafter there is an increase in the stored energy and density compared to the outboard-refuelled discharge.

Detailed profiles of edge toroidal ion flow, $V_{\phi i}$, are measured from the Doppler shift of He^+ ion line emission from a localised thermal helium jet at the outboard mid-plane. This emission is observed tangential to the flux surfaces in the toroidal direction by means of an optical fibre array which relays light to two spectrometers, thereby ensuring that they view the same plasma region. The low spectral resolution HELIOS spectrometer (10 chords, $\Delta R \approx$ 11 mm) is used to determine edge profiles of T_e and n_e from He I emission line ratios and the higher resolution CELESTE spectrometer (17 chords, $\Delta R \approx$ 5.5 mm) to measure the $V_{\phi i}$ profile [6]. Two poloidal views at 0° and +16° to the horizontal are observed simultaneously, as well as a zinc discharge lamp to provide an absolute wavelength reference.

Movements of the outer separatrix radius necessitate mapping of the measured profiles onto surfaces of constant normalised poloidal flux, ψ_N. Fig. 2 shows the evolution of $V_{\phi i}$ of the He^+ ions at three values of ψ_N in the region where the ETB forms. Four similar discharges are compared, with either inboard or outboard gas puff refuelling. The estimated uncertainty in the determination of the absolute flow velocity is ≈ ± 2 km/s. During the sustained phase of the discharges the ion flow is in the negative toroidal direction in (z, R, ϕ) machine coordinates. (In MAST this is in the direction of B_t and opposite to the usual direction of I_p.)

The plasma position is changing in the early phase of these discharges before 0.14 s, detaching from the centre column at ≈ 0.1 s and expanding outwards. In the early L-mode phase, $V_{\phi i}$ is measured only at the outermost flux surface and is similar for both inboard and outboard gas puffing, being about – 4 ± 2 km/s in the counter-current direction. After this time the discharges with inboard refuelling begin a gradual transition to H-mode, exhibiting transition ELMs and then brief 'quiescent' H-mode phases initiated by sawteeth. During the transition phase the toroidal flow increases to ≈ – 10 km/s, accompanied by enhanced flow shear, with higher velocities developing further into the plasma. In contrast, the outboard-refuelled discharges exhibit relatively constant flow during the sustained phase of the discharges. During the quiescent H-mode phases there is a further increase in the flow of $\Delta V_{\phi i}$ ≈ – 5 km/s which is consistent with the presence of a negative (inward) radial E-field in the ETB region of order – 30 kV/m.

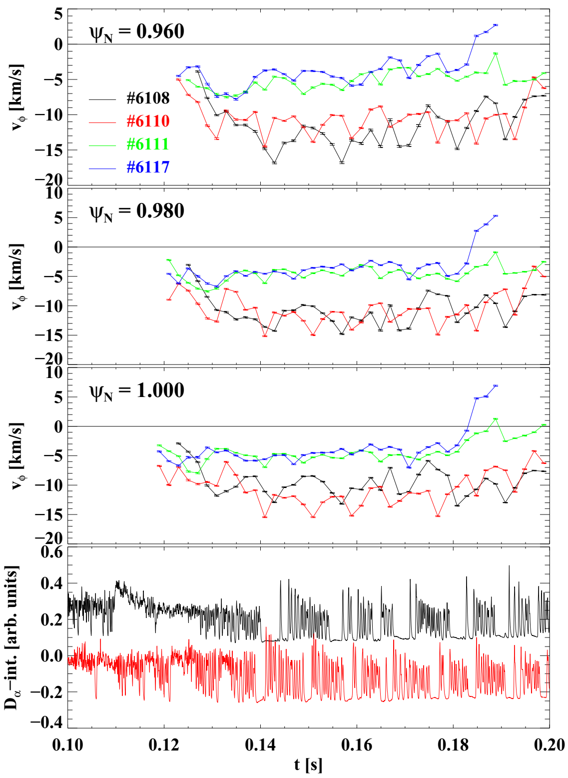

Fig. 2 The evolution of toroidal He^+ ion flow at the outer boundary of discharges with either inboard (#6108, #6110) or outboard (#6111, #6117) gas puff refuelling. Measured velocities are mapped onto surfaces of constant poloidal flux ψ_n.

Neo-classical edge plasma flow

Recent developments of neo-classical tokamak theory have considered the influence of a poloidally localised neutral density on the edge plasma [4]. It is found that, provided the neutral fraction, n_0/n_i, exceeds 10^{-4}, the radial transport of toroidal momentum due to the charge-exchange processes dominates the neo-classical viscosity and can determine the toroidal plasma flow and radial electric field.

Under the assumption that density and temperature are constant on flux surfaces, the incompressible ion flow on a flux surface must be of the form $\mathbf{V}_i = \omega(\psi)R\hat{\phi} + u_{i\theta}(\psi)\mathbf{B}$ where ψ is the poloidal flux and $\hat{\phi}$ the toroidal unit vector. Here $\omega(\psi)$ is a rigid body rotation given by $\omega(\psi) = -d\Phi/d\psi - 1/n_i e(dp_i/d\psi)$, where Φ is the electrostatic potential and p_i is the ion pressure. The poloidal ion flow in a pure plasma $u_{i\theta}(\psi) = kI/e\langle B^2\rangle dT_i/d\psi$ is proportional to the ion temperature gradient, where k is a constant depending on the collisionality, I is RB_ϕ and $\langle\rangle$ denotes a flux-surface average.

With the neutral density localised poloidally at the gas puff, the toroidal ion velocity on a flux surface is calculated using the condition for no net radial transport of toroidal momentum, $\langle R\hat{\phi}\cdot(\pi_i + \pi_n)\cdot\nabla\psi\rangle = 0$ as $V_{i\phi} = F_v I^2/e\langle B^2\rangle R\cdot(dT_i/d\psi)$. This flow is proportional to the ion temperature gradient and is always in the counter-current direction for a peaked T_i profile. Its magnitude is interestingly independent of the neutral density, provided this is sufficiently high for the neutral viscosity to overwhelm the neo-classical viscosity. The constant F_v depends upon the poloidal location of the gas puff, θ.

Fig. 3 shows $F_v(\theta)$ calculated for a MAST equilibrium on an edge flux surface. Note that the toroidal ion flow at the outboard mid-plane is predicted to be much higher when the plasma is refuelled from the inboard rather than the outboard mid-plane. (Corrections for finite neutral mean-free path, which also depend on the neutral velocity distribution, tend to reduce this effect somewhat [4].)

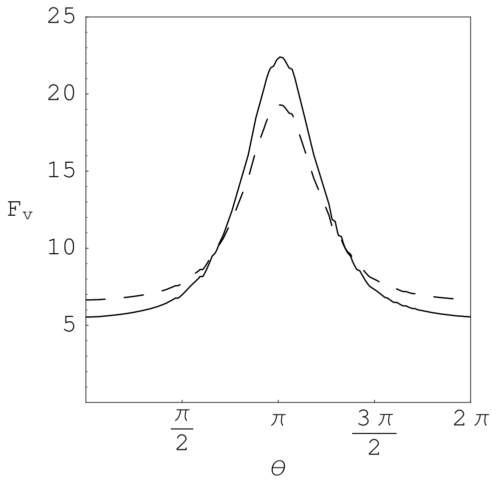

Fig. 3 The dependence of the edge toroidal ion flow at the outboard mid-plane (θ = 0) on the poloidal gas puff location for MAST at $\psi_{98\%}$. (Solid line short mean-free path limit; dashed line for finite neutral mean-free path.)

It is of interest to compare this prediction with the measured toroidal velocities of the He^+ ions shown in Fig. 2. The edge electron temperature gradient $dT_e/d\psi$ is measured using a high-resolution 300-point Thomson scattering system at times during the L- (0.11 s) and H-phases (0.16 s) of these discharges. $dT_e/d\psi$ at the outboard boundary is found to be hardly changed between L- and H-mode phases and with either refuelling location and is ≈ – 6 keV Wb^{-1} r^{-1} at $\psi_{98\%}$. Assuming equal ion and electron temperatures and values of F_v of 6 for outboard and 20 for inboard gas puffing, the predicted flow velocities are ≈ – 9 km/s with outboard gas puffing and ≈ – 30 km/s with inboard gas puffing, in the counter current direction in both cases. Although the direction of the observed flow is in agreement with theory, the predicted values are too high by a factor ≈ 3, at least under the assumption of equal ion and electron temperatures. The magnitude of the effect may be overestimated however as the theory assumes axi-symmetric gas puffing.

If this enhanced edge toroidal flow underlies the observed improvement in H-mode access with inboard gas puffing, higher flow would already be expected in the L-mode phase preceding the L/H-transition. Fig. 4 compares edge flow velocities in L-mode discharges with either inboard or outboard refuelling. The transition to H-mode is suppressed by

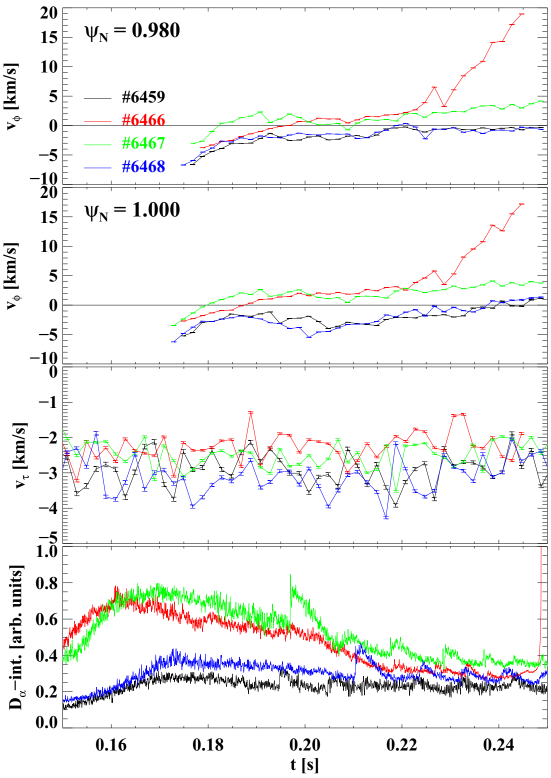

Fig. 4 The evolution of toroidal and poloidal He$^+$ ion flow at the outer boundary of L-mode discharges with either inboard (#6459, #6468) or outboard (#6466, #6467) gas puff refuelling.

shifting the plasma slightly downwards to a lower (disconnected) DND configuration [7]. In this case the zero-velocity reference is provided by the radial-viewing chord. With outboard refuelling the toroidal flow is small $\approx +2 \pm 2$ km/s, in the co-current direction during the sustained L-mode phase. (Discharge #6466 exhibits a strong increase of this flow following the onset of a locked mode at 0.23 s.) With inboard refuelling the toroidal flow changes by $\Delta V_{\phi i} \approx -6$ km/s, now being in the counter-current direction. The observed poloidal velocities are small $\approx -3 \pm 2$ km/s in a direction consistent with the presence of a negative edge radial E-field, being somewhat larger with inboard gas puffing.

Again, the outboard edge temperature gradient $dT_e/d\psi$ hardly changes between inboard- and outboard-refuelled discharges, being ≈ -4.5 keV Wb^{-1} r^{-1} at $\psi_{98\%}$. Calculating $V_{\phi i}$ using the values of F_v as assumed above results in predicted flow velocities of ≈ -5 km/s with outboard gas puffing and ≈ -14 km/s with inboard gas puffing. The observed difference of $\Delta V_{\phi i} \approx -6$ km/s between discharges with inboard or outboard gas puffing is thus in reasonable agreement with the theoretical prediction of ≈ -9 km/s. A comparison of absolute flow velocities of this small magnitude is complicated by the experimental uncertainties and physical effects which are so far not included in the theory, such as the influence of the loop voltage and friction forces with the other particle species on the observed impurity ions.

Summary

During sustained L-mode discharges with inboard gas puffing the toroidal ion flow is increased in the counter-current direction relative to that observed with outboard refuelling, the increase being in reasonable agreement with the neo-classical prediction. The toroidal flow also increases in this direction during the formation of the ETB, being typically a factor ≈ 3 higher in inboard-refuelled H-mode than in comparable outboard refuelled L-mode discharges. Such changes in the edge plasma flow could influence the formation of the ETB, this being favoured by an increase of edge flow shear, which can stabilise plasma turbulence.

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