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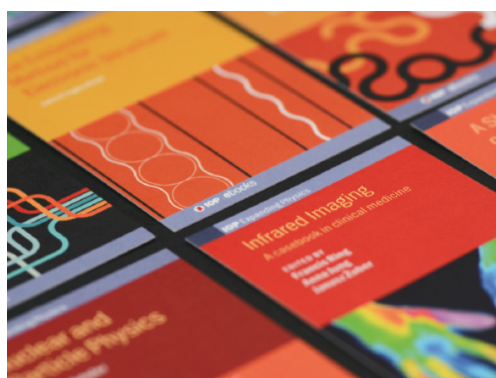
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To cite this article: T.J. Dobbins *et al* 2019 *Nucl. Fusion* **59** 046007

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The role of neutral friction in governing parallel flows in the HSX stellarator

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Received 1 November 2018, revised 22 December 2018

Accepted for publication 17 January 2019

Published 7 February 2019



Abstract

Experimentally measured parallel ion flows in the standard quasihelically symmetric configuration of the HSX stellarator show a large discrepancy with previous neoclassical calculations, whereas flow in a symmetry degraded configuration is in reasonably good agreement with neoclassical theory. To examine this discrepancy, the neoclassical transport code PENTA has been modified to include collisions with background neutrals. It has been found that the flow damping due to ion-neutral friction significantly modifies the ion parallel flows in the standard configuration. This makes the modeling of the ion parallel flow agree better with the experimental measurements. In the symmetry degraded configuration, higher neoclassical viscosity makes the flow damping arising from neutral friction less important. The bootstrap current was found to be insensitive to the neutral friction as the decrease in ion flow was matched by an increase in the electron flow.

Keywords: flow, bootstrap current, neoclassical viscosity, neutral damping, radial electric field, stellarator

(Some figures may appear in colour only in the online journal)

1. Introduction

Plasma flows are strongly damped in stellarators that are not quasisymmetric due to large neoclassical parallel viscosity in all directions. The fact that neoclassical theory has been successfully applied to the modeling of the flow and radial electric field in stellarators [1–5] suggests that neoclassical effects tend to dominate the momentum balance in these devices. In tokamaks and perfectly quasisymmetric stellarators, the neoclassical parallel viscosity is zero in the direction of symmetry. Therefore, other sources of flow drive and damping, like turbulent Reynolds stress [6] or neutral friction [7], can become dominant.

Recent experimental results using the charge exchange recombination spectroscopy (CHERS) diagnostic in the helically symmetric experiment (HSX) stellarator have shown that for the standard quasihelically symmetric (QHS) configuration the measured flows at the core were up to a factor of seven below the neoclassical flow calculations. However, in the symmetry degraded configuration, called Mirror, there is reasonable agreement between the measurements and the

neoclassical calculations [8]. These results indicate that there may be additional sources of damping that had not been included in the flow modeling up to this point. In this work, we examine the role of neutral friction in governing parallel ion flows in the quasisymmetric and symmetry degraded configurations of HSX in order to understand the source for this discrepancy.

Ion-neutral friction has been found to significantly affect the flow in both stellarators and tokamaks [7, 9–12]. Neutrals begin modifying the parallel flow and radial electric field in tokamaks when the neutral density $n_n > 10^{-4}n_i$, where n_i is the main ion density [7, 12]. In HSX, the ratio of the density of atomic hydrogen to ion density is about 10^{-3} throughout the plasma, indicating that neutrals could significantly modify the flow.

The effect of the ion-neutral friction is dependent on the mean free path of the neutrals that have charge exchanged in the plasma [12]. In HSX, their mean free path is around a meter, which is much larger than the average minor radius of 0.12 m. Therefore, any charge-exchange event will lead to a complete loss of the charge-exchanged particle's momentum. In a short

mean free path regime, a charge exchange event would lead to cross-field transport of the momentum, but not to the complete loss of momentum from the plasma seen in the long mean free path regime. The difference between these regimes requires different approaches to the modeling of the flow resulting from the neutral friction. For example, in the regime where charge-exchanged neutrals do not leave the plasma, but are transported across flux surfaces, the neutrals must be modeled kinetically [7, 12], which complicates the analysis.

Previous work on HSX used a biased electrode at the edge of low density plasmas to drive flows [9]. Using a model that calculates the response of the plasma to an external torque, it was shown that neutral damping was more important in the QHS configuration than the Mirror configuration. Still the radial conductivity and flow damping were higher than the neoclassical values even when neutral damping was included. That work did not calculate the ambipolar electric field and parallel flow without the torque, which is the subject of the present paper. This paper also extends the analysis to the plasma core. In order to model the effect of the neutrals on the flow and radial electric field in HSX, the neoclassical code PENTA [13, 14] has been modified to include neutral friction in the long mean free path limit.

The rest of the paper is organized as follows: details of the HSX experiment is given in section 2. The addition of neutral friction into the PENTA model is described in section 3. Experimental flow measurements are compared with the modified PENTA model in section 4 for the QHS and the Mirror configurations. The effect of the neutral friction on the bootstrap current is described in section 4.1. Discussion and conclusions are given in section 5.

2. Experimental setup

HSX [15] is a quasi-helically symmetric stellarator with 1T magnetic field and two 100 kW, 28 GHz gyrotron heating sources. Measurements in this work have been made in two magnetic configurations, called QHS and Mirror. The magnetic field in a stellarator is described by $B = \sum B_{n,m} \cos(n\zeta - m\theta)$, where n, m are toroidal and poloidal mode numbers respectively. QHS is the standard quasi-helically symmetric configuration of HSX, which is dominated by the $(n, m) = (4, 1)$ term in spectrum. In Mirror, the quasisymmetry was intentionally broken using auxiliary coils with the introduction of $(n, m) = (4, 0)$ and $(8, 0)$ modes as shown in plots of the Hamada spectrum in figure 1.

Measurements were carried out in each configuration using 100 kW ECRH-heated plasmas with closely matching line-averaged densities. The electron temperature and density profiles from Thomson scattering for the two configurations can be found in figure 2 along with the fits used as inputs into the neoclassical modeling. The figure shows that there is a peaked temperature and density profile for both cases, but that the temperature in QHS is higher. This is due to improved confinement and higher absorbed power in this configuration [16]. In HSX, ions are relatively cold (~ 60 eV at the core), relatively flat across the minor radius and similar between the

two cases. The ion temperature profile used in the neoclassical calculation shown in figure 2(b) is based on CHERS measurements of C^{+6} [8, 17].

The neutral density in HSX was calculated using the DEGAS code [18]. DEGAS is a Monte Carlo code that models the neutral transport in a background plasma. It is used to model the behavior of neutrals resulting from recycling at the wall as well as from gas fueling. This calculation is scaled by the H_α detector array measurements in order to find the neutral density profile [19, 20]. The neutral profiles in HSX are peaked at the edge, but with a significant neutral population in the core.

The neutral density calculated by DEGAS is plotted in figure 3. The two magnetic configurations examined in this work have very similar neutral profiles in the core, though there are slight variations past the mid-radius. Thus the neutral friction is roughly the same for the two configurations. The ion-neutral collision frequency used to calculate the ion-neutral friction is: $\nu_{in} \approx 10^{-8} n_n T_i^{0.318}$ [21, 22], where n_n is the atomic hydrogen density in m^{-3} and T_i is the ion temperature in eV. The diatomic hydrogen does not significantly add to the ion-neutral collision rate due to its lower cross section at the plasma parameters found in HSX.

Measurements of flow and radial electric field have been carried out with the CHERS diagnostic using CVI emission at 529.1 nm. Initially, measurements of the poloidal and toroidal flow in HSX were used to obtain the radial electric field using the force balance equation [17, 23]. In order to improve the resolution of the measurements, the diagnostic was modified to make two measurements of parallel flow on a flux surface in order to calculate the flux surface-averaged parallel flow and the Pfirsch–Schlüter flows. The Pfirsch–Schlüter flows are then used to calculate the radial electric field. This method for measuring the radial electric field and mean parallel flow is described in [8, 24].

In order to have sufficient signal for the CHERS measurement, methane is used as a fill gas for the plasmas used in this work. This results in a relatively large carbon density in the plasma. A mix of one carbon to four hydrogen was used in the calculations in this work and the density of each of the charge states of carbon has been calculated using ADAS [25]. This calculation was then used as an input to the PENTA code.

3. Adding neutrals to the neoclassical code

The neoclassical code PENTA is used to calculate the radial electric field and flux surface averaged parallel flow by solving the momentum balance and transport equations. It calculates the neoclassical viscosity by using the monoenergetic coefficients calculated using the DKES code (drift kinetic equation solver) [26, 27]. A pitch angle scattering collision operator is used by DKES and neglects field particle collisions. The approach used by Sugama and Nishimura [28] restores momentum conservation using a moments method approach.

Neutral friction is included in PENTA by solving the following equations.

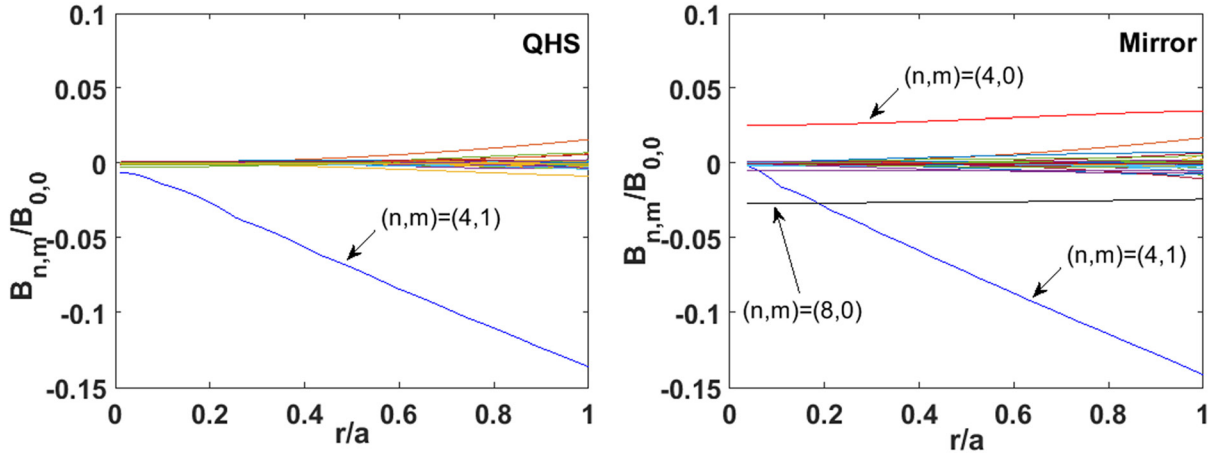


Figure 1. The Hamada spectrum is plotted in QHS (left) and Mirror (right). The Mirror configuration has large (4,0) and (8,0) modes in the magnetic spectrum. The (0,0) mode is suppressed in the plots for clarity.

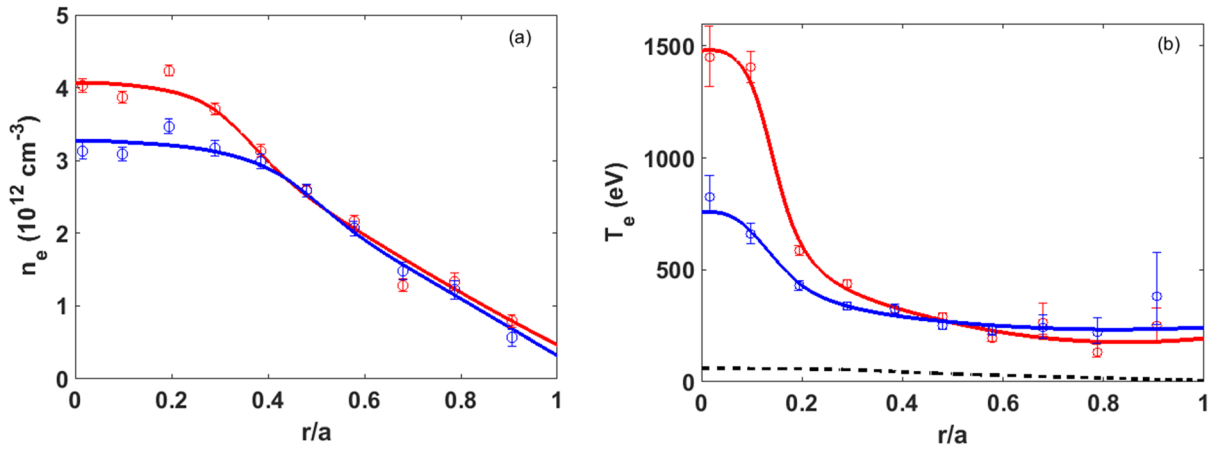


Figure 2. Electron density (a) and temperature (b) profiles measured by the Thomson scattering diagnostic in 100 kW QHS (red) and Mirror (blue) plasmas. The fit of the electron temperature and density that were used in the modeling is also shown. The dotted black line in (b) is the ion temperature profile used in the neoclassical calculation.

$$\langle \mathbf{B} \cdot (\nabla \cdot \Pi_a) \rangle - n_a e_a \langle B E_{||} \rangle + \delta_{i,a} F_{i1}^n = \langle B F_{||a1} \rangle \quad (1)$$

$$\langle \mathbf{B} \cdot (\nabla \cdot \Theta_a) \rangle + \delta_{i,a} F_{i2}^n = \langle B F_{||a2} \rangle, \quad (2)$$

where the subscript a represents the plasma species (the electron and the ion species included in the calculation). The $\langle B F_{||aj} \rangle$ term is the friction between individual species, where j is the order of the moment expansion, in which the first order expansion describes the parallel flow and the second the parallel heat flux. F_{ij}^n is the ion-neutral friction term added in this work. $\delta_{i,a}$ is equal to one for ions and zero for electrons because the electron-neutral friction was ignored due to the small amplitude of the term compared to the ion-electron friction term in the electron momentum balance equation. $\langle \mathbf{B} \cdot (\nabla \cdot \Pi_a) \rangle$ and $\langle \mathbf{B} \cdot (\nabla \cdot \Theta_a) \rangle$ are the parallel neoclassical viscosities for the parallel flow and parallel heat flux, respectively. The parallel electric field term, $\langle B E_{||} \rangle$, is set to zero in this work because HSX has no applied loop voltage.

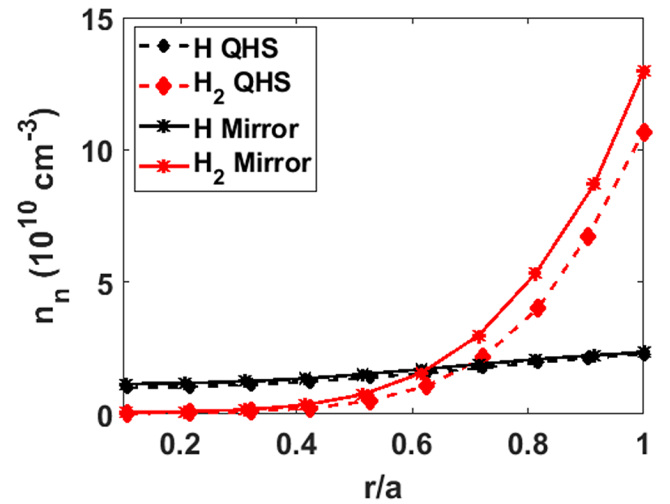


Figure 3. The neutral density of hydrogen calculated by DEGAS in HSX is plotted for the QHS and Mirror configurations for both the atomic and molecular hydrogen.

In this work, the neutral friction formulation developed by Monier-Garbet for neutrals in the long mean free path regime in the edge of D-III-D [10] was applied to PENTA. The neutral friction is given by [10]

$$\begin{bmatrix} F_{i1}^n \\ F_{i2}^n \end{bmatrix} = -n_i m_i \nu_{in} \begin{bmatrix} 1 & 0 \\ 0 & \frac{E}{T_i} \end{bmatrix} \begin{bmatrix} \langle u_{||a} B \rangle / \langle B^2 \rangle \\ \frac{2}{5p_a} \langle q_{||a} B \rangle / \langle B^2 \rangle \end{bmatrix} \quad (3)$$

where E is the energy of the neutrals, T_i is the ion temperature, ν_{in} is the ion-neutral collision frequency, and $u_{||a}$ and $q_{||a}$ are the parallel flow and parallel heat flux of species a , respectively. The friction between plasma species is

$$\begin{bmatrix} \langle BF_{||a1} \rangle \\ \langle BF_{||a2} \rangle \end{bmatrix} = \sum_b \begin{bmatrix} l_{11}^{ab} & -l_{12}^{ab} \\ -l_{12}^{ab} & l_{22}^{ab} \end{bmatrix} \begin{bmatrix} \langle u_{||a} B \rangle \\ \frac{2}{5p_a} \langle q_{||a} B \rangle \end{bmatrix} \quad (4)$$

where the l 's are the classical friction coefficients. The neo-classical viscosities and fluxes are also calculated, giving

$$\begin{bmatrix} \langle \mathbf{B} \cdot (\nabla \cdot \Pi_a) \rangle \\ \langle \mathbf{B} \cdot (\nabla \cdot \Theta_a) \rangle \\ \Gamma_a \\ Q_a/T_a \end{bmatrix} = \begin{bmatrix} M_{a1} & M_{a2} & N_{a1} & N_{a2} \\ M_{a2} & M_{a3} & N_{a2} & N_{a3} \\ N_{a1} & N_{a2} & L_{a1} & L_{a2} \\ N_{a2} & N_{a3} & L_{a2} & L_{a3} \end{bmatrix} \begin{bmatrix} \langle u_{||a} B \rangle / \langle B^2 \rangle \\ \frac{2}{5p_a} \langle q_{||a} B \rangle / \langle B^2 \rangle \\ -\frac{1}{n_a} \frac{\partial p_a}{\partial s} - e_a \frac{\partial \Phi}{\partial s} \\ -\frac{\partial T_a}{\partial s} \end{bmatrix} \quad (5)$$

where Q_a is the radial heat flux, $\frac{\partial p_a}{\partial s}$ is the pressure gradient, $\frac{\partial \Phi}{\partial s}$ is the potential gradient, Γ is the radial particle flux, and $\frac{\partial T_a}{\partial s}$ is the temperature gradient. The matrix elements M_{ai} , N_{ai} and L_{ai} are given in [28]. The elements in turn are calculated from a database of monoenergetic transport coefficients using the DKES code. More details of the actual method involved can be found in [13]. The friction coefficients in equation (4) are given in [29].

PENTA calculates the particle fluxes of each species as a function of radial electric field using equation (5) in order to find the ambipolar radial electric field, where the ambipolarity condition is

$$\sum_i Z_i \Gamma_i = \Gamma_e, \quad (6)$$

where Z_i is the ion charge.

To summarize the role of each equation in PENTA, equations (1) and (2) are the momentum and parallel heat flux balance equations. The ion-neutral friction is given in equation (3), and the friction between each of the plasma species is given in equation (4). Equation (5) equates the flow and the driving gradients to the viscosities, particle, and heat fluxes. Equation (6) is the ambipolarity constraint that equates the ion and electron radial fluxes. Taken together, the flows and fluxes of the electron and ion species can be found by solving this coupled set of equations.

3.1. The effect of neutral friction on parallel ion flows and radial electric fields

Figure 4 shows the parallel flow as a function of the radial electric field as calculated by PENTA with and without neutral friction. The neutrals dramatically reduce the flow for a

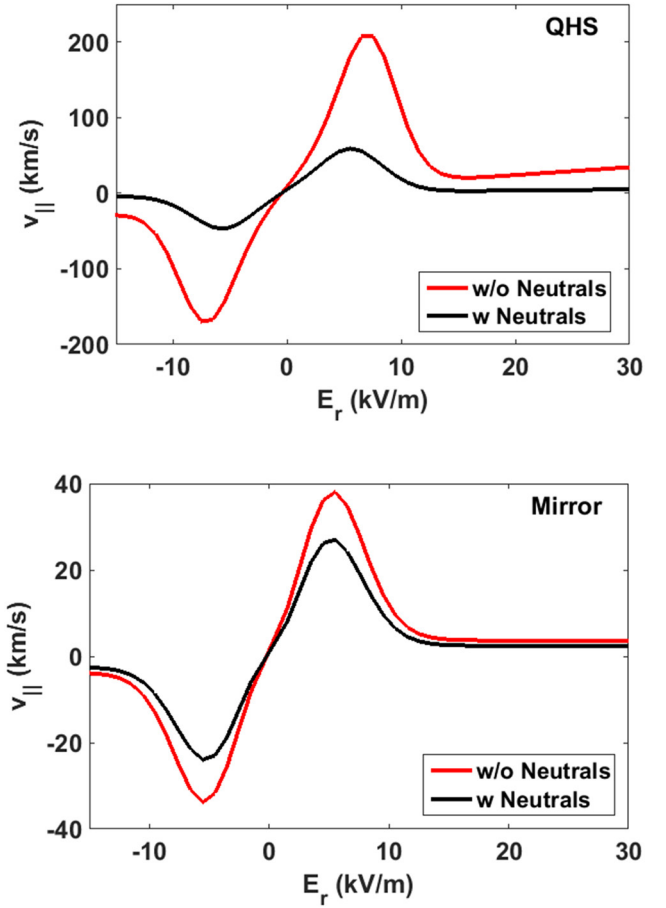


Figure 4. The flow as a function of E_r with and without ion-neutral friction is calculated for QHS on the left and Mirror on the right at an r/a value of 0.2.

given value of the radial electric field in QHS but only slightly change the flow dependence on the radial electric field in the symmetry broken Mirror configuration. This is due to the relative importance of the neutral friction and neoclassical viscosity in these configurations.

The overall level of the parallel flow for a given level of radial electric field is also much lower in Mirror than in the QHS case, with or without including neutral friction, as can be seen in figure 4. This is because the parallel neoclassical viscosity in this symmetry-broken configuration is larger than the total flow damping in QHS, even when neutral friction is included.

In addition to the decrease in flow, the neutrals also change the ion radial flux, thereby modifying the ambipolar radial electric field. This is due to the fact that the ion flux has a dependence on parallel flow and the neutrals significantly lower the parallel flow velocity. In PENTA this comes in through the N coefficient in equation (5), which is multiplied by the flow to get the flux.

In QHS, the ion flux was found to change significantly with neutrals, while in the Mirror configuration the ion flux only changes slightly as a result of neutrals, as can be seen in figure 5. The change in flux is most evident in the region at or before the ion resonance, where the ion flux is at its peak. The

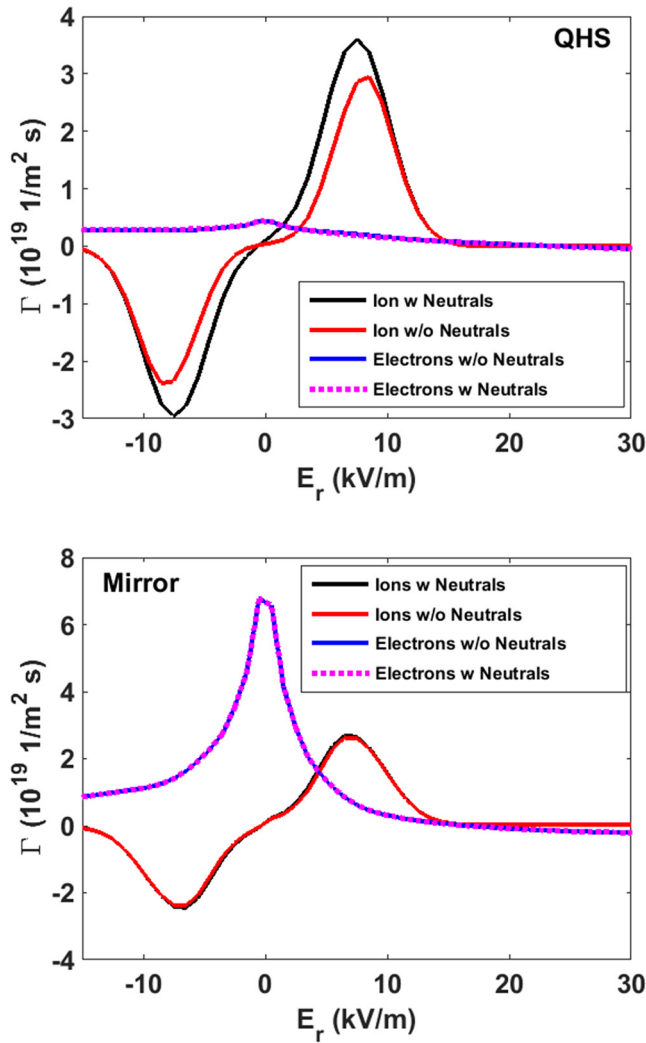


Figure 5. The radial flux of the ions and electrons with and without neutral friction is calculated for QHS on the left and Mirror on the right at $r/a \sim 0.2$.

neutral friction also changes the value of the resonant radial electric field due to the changes in the parallel flow as a function of the radial electric field.

The electron flux is not significantly changed by the ion-neutral friction in QHS or Mirror, however, as can be seen in figure 5. The significantly higher electron flux in Mirror compared to QHS is due to the increase in the neoclassical transport from the breaking of quasisymmetry in the low collisionality regime when $E_r = 0$. Across the minor radius, the change in ion flux as a result of neutral friction leads to a $1\text{--}2 \text{ kV m}^{-1}$ change in the ion root ambipolar radial electric field in QHS and a $0.1\text{--}0.4 \text{ kV m}^{-1}$ change in Mirror.

4. Comparisons of flow calculations and measurements in QHS and mirror

The measured flows are smaller than the calculated values without neutral friction by a factor of three in the edge and up to a factor of seven in the core. When neutrals are included in the calculation, the parallel flow is reduced by a factor of three to seven compared to the case without neutrals. As can be seen

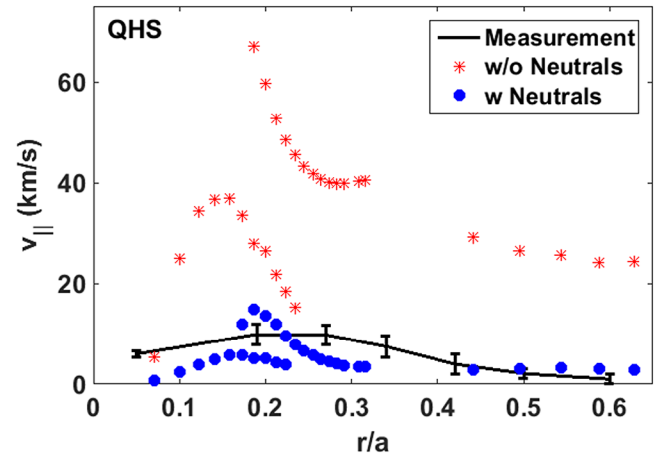


Figure 6. Comparisons of parallel flow measurements (black) to the calculations with and without neutral friction in QHS (blue and red respectively). The multiple roots in the calculation are the ion and electron root solutions to the ambipolarity condition, where the electron root solutions have the smaller flow values.

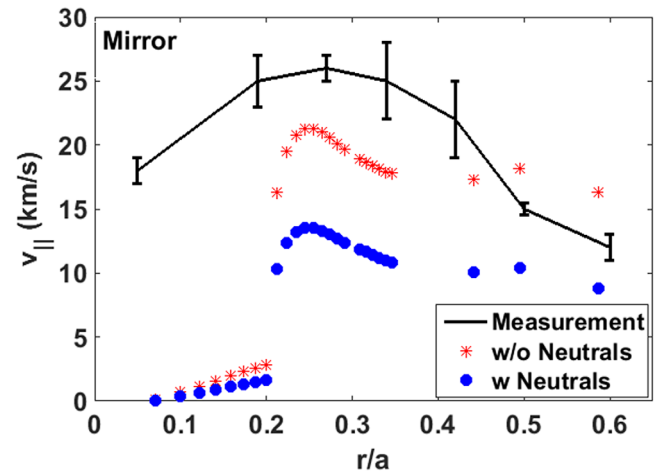


Figure 7. Comparisons of parallel flow measurements (black) to the calculations with and without neutrals in Mirror (blue and red, respectively).

in figure 6, much better agreement has been found between the measurements and modeling for the QHS configuration.

The multiple roots in the figure with different values of flow occur due to the different solutions of the ambipolarity condition, called ion and electron root solutions. The electron root solutions typically have a smaller parallel flow and larger radial electric field than the ion root solutions in HSX. The electron root solutions are calculated to exist in the core of most plasmas in HSX, and only the ion root is calculated to exist in the rest of the plasma. There is a third, intermediate, unstable root to the ambipolarity condition, but these solutions were not plotted to make the figure more readable.

The PENTA calculation without neutrals is in reasonable agreement with the experimental measurements of flow in the Mirror configuration, as can be seen in figure 7. The inclusion of neutral friction leads to around a $5\text{--}10 \text{ km s}^{-1}$ reduction in parallel flow in Mirror, leading to an underestimation of flow compared to the measurements.

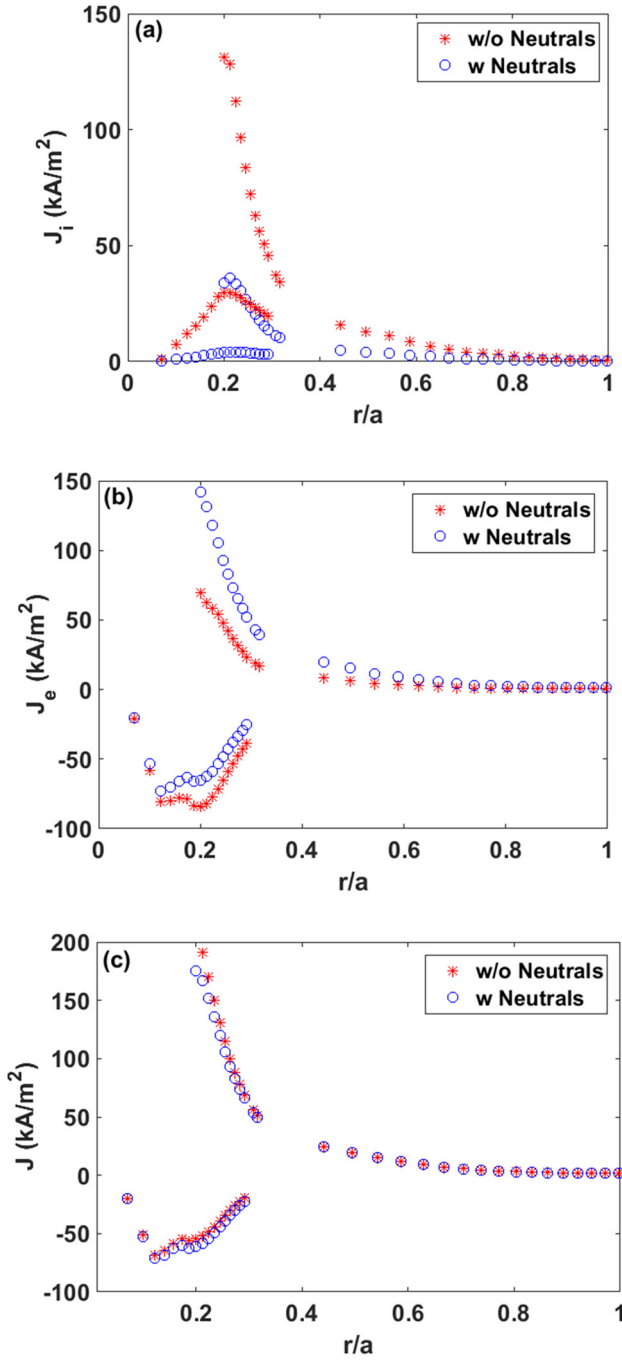


Figure 8. The plasma current density calculation of PENTA with and without neutral friction in the QHS configuration. The plasma current density carried by the ions is shown in (a), the electron current density in (b), and the total plasma current density in (c). Both the ion and electron root current densities are shown whereby the larger absolute values towards the core correspond to the ion root and the smaller absolute values are for the electron root.

4.1. The effect of neutral friction on the bootstrap current

The plasma current density, $\mathbf{J} = en_e \langle \mathbf{B} \rangle (\langle u_{\parallel i} \mathbf{B} \rangle / \langle B^2 \rangle - \langle u_{\parallel e} \mathbf{B} \rangle / \langle B^2 \rangle)$, can be calculated to determine the effect of the neutral friction on the bootstrap current. The result of this calculation for the QHS configuration can be seen in figure 8,

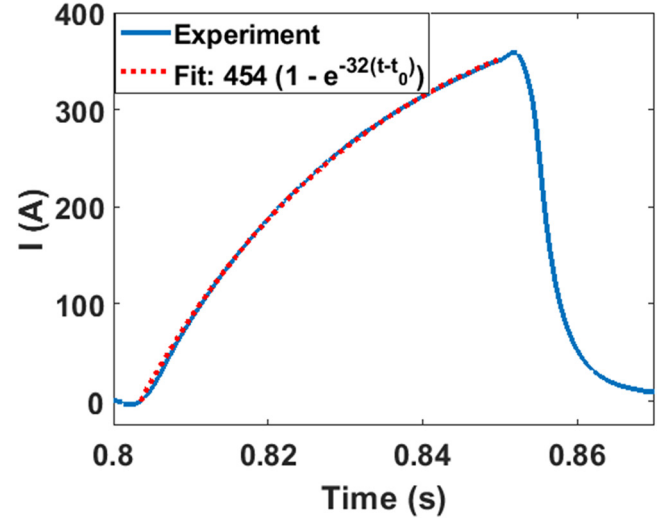


Figure 9. The evolution of the plasma current in QHS is plotted along with the fit of the plasma current that is used to find the steady state plasma current. The time at plasma breakdown is given by t_0 . The coefficient for time in the exponent 32 s^{-1} , yields a time constant of 31 ms that is consistent with the modeling of the bootstrap current evolution as discussed in [30].

where the total bootstrap current density is presented. The figure also contains the ion and electron contributions to the plasma current density ($\mathbf{J}_i = en_e \langle \mathbf{B} \rangle \langle u_{\parallel i} \mathbf{B} \rangle / \langle B^2 \rangle$ and $\mathbf{J}_e = -en_e \langle \mathbf{B} \rangle \langle u_{\parallel e} \mathbf{B} \rangle / \langle B^2 \rangle$). As with the parallel flow calculations, the electron root solutions correspond to the smaller current densities. It is found that the decrease in the current carried by the ions as a result of neutral friction is almost completely compensated for by the increase in the current carried by the electrons. This occurs due to the influence of the electron-ion friction on the electron flow, which is proportional to the difference between the electron and ion velocity.

The total bootstrap current can be calculated by integrating over the bootstrap current density, such that the plasma current is $I_b = \int \vec{J}_b \cdot d\vec{S}$. The large change in the ion flow as a result of neutral friction leads to only a small, less than 10%, change in the total plasma current calculated by PENTA. This agrees with previous modeling and measurements, in which the plasma currents were found to agree with neoclassical modeling of the bootstrap current in HSX without including the effects of neutrals [30].

In QHS, when the ion root solution is used wherever it exists, the calculated plasma current is 490 A without neutral friction and 500 A with neutral friction. When the electron root solution is used wherever it exists, the calculated plasma current is 330 A without neutral friction and 310 A with neutral friction. The experimental current is evolving throughout the discharge, but when the current evolution is fit to find the steady state plasma current, the total current is 454 A (see figure 9 for the fit of the plasma current). The experimental data falls between the ion and electron root solutions. This result indicates that the neutral friction has a small impact on the total plasma current, despite the dramatic change in the ion velocity as a result of the neutrals.

5. Discussion and conclusions

The inclusion of ion-neutral friction into PENTA leads to a more complete model of the momentum balance in HSX and to better agreement with flow measurements in QHS. The neutral friction was found to significantly modify the parallel flow dependence on the radial electric field and the ion radial flux. This led to a change in both the calculated ambipolar radial electric field and the parallel flow. The magnitude of the change in flow was dependent on the magnetic configuration, where the QHS configuration had a 20–50 km s⁻¹ reduction in flow as a result of neutral friction, while the Mirror configuration only had a 5–10 km s⁻¹ decrease in flow.

The inclusion of neutral friction leads to an underestimation of flow compared to the measurements in the Mirror configuration. This underestimation might be explained by an ECRH-driven flux. In particular, it should be noted that at $r/a \sim 0.06$, there is a measured flow of ~ 18 km s⁻¹. This is in a region where the plasma gradients are going to zero and the calculated parallel flow is zero. A torque due to the ECRH might be one explanation for this measurement and is presently being investigated with the GNET code [31]. The radial electron particle flux due to ECRH and the resulting flow calculation will be presented in future work.

Although the ion parallel velocity changed significantly as a result of neutral friction, the total plasma current was only modified slightly by the presence of neutrals in HSX. This is in line with previous measurements and modeling of plasma current in HSX, in which agreement has been found with neoclassical calculations without including neutral friction [30].

The QHS configuration is designed to be a quasisymmetric stellarator, where the introduction of a symmetry direction in the magnetic field strength greatly reduces viscosity in that direction. This leads to very low neoclassical viscosity in the symmetry direction (a factor of ~ 26 smaller than in the Mirror configuration towards the core). When the neoclassical viscosity is lowered, other sources dominate the flow damping in the direction of symmetry. This is the case for QHS, where neutral friction is the largest source of flow damping in the direction of symmetry. Estimates indicate that if the neutral friction were lowered, turbulent Reynolds stress could also be more significant than neoclassical viscosity in QHS [8]. Previous probe measurements of Reynolds stress suggested that the Reynolds stress could drive significant flow in the edge of HSX, though the result was not conclusive because only two measurements of Reynolds stress were made on a flux surface [32].

Acknowledgments

The authors would like to thank the HSX team for their support. This work is supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Science under award number DE-FG02-93ER54222. Data for the figures included in this publication are available for access at <http://hsx.wisc.edu/HSXPublicationData>.

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