Asymmetry of parallel flow on the Large Helical Device

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Abstract
An asymmetric parallel return flow, which modifies the parallel component of the flow, is expected to meet the zero divergence of the flow on a flux surface based on the common neoclassical theory for torus plasma. The full flow structure is measured by charge exchange spectroscopy on the Large Helical Device. Inboard/outboard asymmetry of the parallel flow is observed according to the full flow profile measurement. Flow asymmetry is considered to be induced by the Pfirsch–Schlüter flow closely associated with the radial electric field. A linear relationship between the integrated flow asymmetry and the electric potential difference is obtained in different magnetic fields and configurations. A model based upon the incompressibility of the flow is applied to acquire a geometric factor $hB$, which only connects to the magnetic configuration from the experiment. The asymmetric component of the parallel flow measured is compared with the asymmetric component of parallel flow calculated in the incompressibility conditions of flow on the magnetic flux surface. The measured asymmetric flow is consistent with the calculation in plasma with a small toroidal torque input in the inward shifted configuration. However, the measured asymmetric flow is significantly smaller than that calculated for plasma with a large toroidal torque or in the outward shifted configuration. One possible explanation for this variation could be radial transport due to anomalous perpendicular viscosity as well as strongly poloidally asymmetric radial flow.

Keywords: stellarator, flow asymmetry, Pfirsch–Schlüter flow, radial electric field

(Some figures may appear in colour only in the online journal)
after the flux surface average, it redistributes the parallel flow and results in variation of the parallel flow on a flux surface.

For axisymmetric systems, such as tokamaks, toroidal flow is expected to be dominated by mechanisms other than NC theory because viscosity in the toroidal direction vanishes. In stellarators, however, the strong toroidal viscosity damps toroidal flow. Poloidal flow is mainly driven by the radial electric field determined by the ambipolarity conditions on the NC radial particle fluxes. Since poloidal flow is coupled to toroidal flow due to the zero divergence of flow (or flow incompressibility), poloidal asymmetry of toroidal flow has been employed to evaluate the poloidal flow on DIII-D [8] and TCV [9], and to calculate the radial electric field on HSX [10, 11]. The poloidal flows are well reproduced by NC theory on DIII-D and TCV, while discrepancies between experimental measurements and predicted radial electric field calculations are observed on HSX, where the indications are that the radial electric field could be dominated by non-NC processes for a quasi-symmetric configuration. However, poloidal flows on DIII-D during QH- and H-mode operations [12] and on JET with an internal transport barrier [13] are not fully understood.

The radial electric field can be modified by changing auxiliary heating and density. In W7-AS, a negative radial electric field in the edge region agrees rather well with the expectations from the ambipolarity condition of NC particle fluxes in neutral beam injection (NBI) L-mode discharge [14]. Furthermore, the ‘electron-root’ feature (a positive radial electric field in the core) achieved by electron cyclotron heating (ECH) with central deposition in W7-AS and W7-X shows good agreement with the NC predictions [15, 16]. In addition, on TJ-II, a comparison with NC theory shows quantitative agreement with the measured radial electric field and parallel flow in the electron root, and low density plasma without external momentum input [17], while deviations from NC prediction are found for the total incompressible flow in the ion root and medium density plasma with NBI [18]. In the NBI case, regardless of the fact that asymmetry of the impurity density driven by ion-impurity parallel friction is introduced to explain the observed plasma flows, those modifications due to impurity inhomogeneity are too small to reproduce the compressible flow.

Nevertheless, the particle conservation is usually satisfied and impurities indeed undergo a spontaneous rearrangement on each flux surface at the edge with steep pressure and temperature gradients, making impurity flows compressible [19]. Additionally, asymmetry of impurities is present in strongly rotating plasma where the centrifugal force pushes impurities to the outside of the torus [20]. On C-Mod [21] and ASDEX Upgrade [22], in order to satisfy the particle conservation equation, the asymmetry of impurity density is postulated to be a factor of 3–6 in the steep gradient region with impurities accumulating in high field side. Recently, in–out asymmetric high-Z impurity accumulation was observed in C-Mod. This asymmetry is found to be well described by a combination of centrifugal force, poloidal electric field and the ion-impurity friction effects [23]. Meanwhile, the dependence of compressible flow on the poloidal variation of impurity density is also observed on CHS [24] and ASDEX Upgrade [25], on which the flow structure and impurity asymmetry are in line with NC calculation.

In the Large Helical Device (LHD), plasma flows have been also studied in previous works which focus on the spontaneous flows driven by the radial electric field and ion temperature gradient [26–28]. The measured radial electric fields are found to be in qualitative agreement with those evaluated by NC theory [28–30]. However, toroidal flows show some deviations from NC predictions in the discharges without a net external input torque [27, 30]. Evidence shows that the residual stress driven by turbulence can be a candidate for the spontaneous torque [30]. Meanwhile, the flow studies in [30] also suggest that 3D geometric effects on spontaneous flow is of importance in the peripheral region for the LHD as well as in the edge of tokamaks when resonant magnetic perturbation (RMP) is applied. Additionally, in order to understand the mechanism of spontaneous flow generation, it is also necessary to isolate the terms of driving or damping from those due to 3D geometry configurations.

Full flow structures are well reconstructed by using a charge exchange spectrometer (CXS) on LHD. Parallel flow asymmetry, which mainly results from PS flow, is a general phenomenon in NBI and ECH heated discharges. The incompressibility of flows following the usual NC is applied to data analysis in order to perform a comparison with NC prediction.

2. Experimental setup

The LHD is a device with a heliotron configuration, with toroidal and poloidal periods of $N = 10$ and $M = 2$, respectively. Three tangential NBIs (NB1, NB2 and NB3) with negative ion source and a total power of 16 MW and two perpendicular NBIs (NB4 and NB5) with positive ion source and power of 12 MW have been installed [31]. The injection direction of NB1 is the same as that of NB3 but is opposite to that of NB2. On the LHD, as shown in figure 1, four sets of CXS arrays, which collect the light emitted from the plasma during charge exchange interactions between carbon impurities and the same perpendicular NBI (NB4) atoms, are applied to measure the toroidal and poloidal flow velocity [32].

For the poloidal flow measurement, as shown in figure 1(a), there are two 24 channel viewing arrays. One array views upward and the other views downward. This bi-direction viewing array is employed to eliminate the effect of the energy dependency cross section on flow measurement [33]. The distance between two observation radii of the poloidal CXS changes from 33 cm for the channel farthest inside to 1.3 cm for the channel farthest outside. In order to acquire the full profile of toroidal flow, the radii of two sets of toroidal CXS with 19 channels for the high field side (HFS) and 35 channels for the low field side (LFS) shown in figure 1(b) are arranged along the path of NB4 and three observation radii of these channels cross around the magnetic axis. According to the relationship between the ratio of the correction velocity to ion temperature and beam energy from poloidal CXS, the measured toroidal flow velocity is also corrected by the additional velocity due to the energy dependence cross section.
\[ \nabla \cdot (v_{||} + v_{\perp}) = 0 \]  
(1)

where \(v_{\perp}\) and \(v_{||}\) are the ion flow velocity perpendicular and parallel to the magnetic field line, respectively. It should be pointed out that the radial flow velocity is ignored in equation (1) because it is almost zero in plasma. The perpendicular flow is given by the radial force balance,

\[ v_{\perp} = \frac{E \times B}{B^2} - \frac{\nabla P_i \times B}{Z_i e n_i B^2} = -\left( \frac{d\phi}{d\psi} + \frac{1}{Z_i e n_i} \frac{dP_i}{d\psi} \right) \frac{\nabla \psi \times B}{B^2} \]  
(2)

where \(E\) is the electric field, \(B\) magnetic field, \(P_i\) ion pressure, \(Z_i\) charge, \(e\) elementary charge, \(n_i\) ion density, \(\phi\) electric potential, and \(\psi\) flux surface. Although \(P_i\), \(n_i\), and \(\phi\) are usually the function of the flux surface, poloidal flow, which is mainly determined by the \(E \times B\) term (or \(v_{\perp}\)), has a strong asymmetric structure because of the variation of the radial electric field, \(E_r = -(d\phi/d\psi)/(d\psi/dr)\), on a flux surface. The asymmetry leads to the non-zero divergence of the perpendicular flow, which is compensated for by the PS flow from the parallel flow to satisfy the flow incompressibility condition. Therefore, parallel flow can be written as two terms, divergence free flow and PS flow,

\[ v_{||} = v_{\text{sym}} + v_{\text{asym}} \]  
(3)

where the symmetric flow \(v_{\text{sym}}\) is the zero divergence on a flux surface and asymmetric flow \(v_{\text{asym}}\) varies on a flux surface with the average over flux surface zero.

Using equations (1)–(3), asymmetric flow can be expressed as,

\[ v_{\text{asym}} = \left( \frac{d\phi}{d\psi} + \frac{1}{Z_i e n_i} \frac{dP_i}{d\psi} \right) h B \]  
(4)

where \(h\) is a geometrical factor defined by

\[ B \cdot \nabla h = -2 \left( \frac{B \times \nabla B}{B^2} \right) \cdot \nabla \psi, \]  
(5)

\[ \langle h B^2 \rangle = 0. \]  
(6)

Usually, \(1/h\), which depends only on the magnetic configuration, represents how much the generic field changes along the magnetic field. \(h\) can be solved in Boozer coordinates [35] by using the Fourier series in poloidal (\(\theta\)) and toroidal angles (\(\zeta\)) with poloidal (\(m\)) and toroidal (\(n\)) mode numbers of the spectral component of the magnetic field [36, 37]. Then \(h\) can be expressed as

\[ h = \frac{1}{B_0^2} \sum_{m,n} \frac{nI + mG}{n - im} \delta_{m,n} \cos(n\zeta - m\theta), \]  
(7)

where \(\delta\) and \(I\) and \(G\) are, respectively, the rotational transform, the toroidal current enclosed within a flux surface and the total poloidal current external to a flux surface. \(\delta_{m,n}\) is the coefficient of the Fourier expansion of \(1/B^2\) along a field line. Figure 2 shows one example of the radial profile of the magnetic spectrum on the LHD, where the toroidal components are deduced from the natural periodicity of the LHD, \(n' = n/N\). It can be seen that the dominant components are the modes \((n, m)\) of \((0\), \(1\), \((10, 1), (10, 2), (10, 3)\) and \((-10, 0)\). The mode \((-10, 0)\) is
4. Experimental results

The CXS arrays on the LHD can provide a full profile of the toroidal flow and a half profile of the poloidal flow on the LFS. The parallel and perpendicular flows are acquired from the measured flow by considering the angles between toroidal flow and poloidal flow and the magnetic field lines. The explicit relation can be written as

\[
\begin{align*}
\nu_{\parallel} &= \frac{v_{\text{tor}} B_\varphi - v_{\text{pol}} B_\theta}{B}, \\
\nu_{\perp} &= \frac{v_{\text{tor}} B_\theta + v_{\text{pol}} B_\varphi}{B},
\end{align*}
\]

where \(v_{\text{tor}}\) is toroidal flow velocity, \(v_{\text{pol}}\) poloidal flow velocity, \(B_\varphi\) magnetic field in toroidal direction and \(B_\theta\) magnetic field in the poloidal direction. The sign of poloidal flow is defined as positive for the ion diamagnetic and negative for the electron diamagnetic directions.

Two assumptions are made in order to obtain the full flow structure because of the lack of poloidal flow measurement in the HFS. First, \(\phi\), \(P_i\), and \(n_i\) are functions of \(\psi\). Second, the inverted poloidal flow is used to eliminate the integration effect on the flow structure. \(E_z\) in LFS is calculated through the radial force balance equation (2),

\[
E_{z,\text{LFS}} = \frac{\nabla P_{\phi,\text{LFS}}}{\nabla \psi_{\text{en, LFS}}} + v_{\text{tor, LFS}} B_\theta, LFS + v_{\text{pol, LFS}} B_\varphi, LFS,
\]

where the subscript LFS means that the parameters are in the LFS. Then, \(\phi\) in the LFS is expressed as

\[
\phi_{\text{LFS}} = \int_0^{R_{\text{edge}}} E_{z,\text{LFS}} dR_{\text{LFS}},
\]

where \(R_{\text{LFS}}\) and \(R_{\text{edge}}\) are the observation major radius in the LFS and the farthest outside major radius in the LFS, respectively. Given that the observation radii in the HFS are not exactly equal to those in the LFS, interpolation using \(\phi_{\text{LFS}}\) is used to obtain the electric potential in the HFS \(\phi_{\text{HHS}}\) with constant \(\phi\) on a flux surface. As a result, \(E_z\) in the HFS is

\[
E_{z,\text{HFS}} = \frac{d\phi_{\text{HFS}}}{d\psi_{\text{HFS}}},
\]

where \(R_{\text{HHS}}\) is the major radius in the HFS. According to equation (10), the poloidal flow in the HFS can be written as

\[
v_{\text{pol, HFS}} = \left(\frac{E_{z,\text{HFS}} - \nabla P_{\phi,\text{HFS}}}{Z_{\text{en, HFS}}} - v_{\text{tor, HFS}} B_\theta, \text{HFS}\right)/B_\varphi, \text{HFS},
\]

where the subscript HFS means that the parameters are in the HFS. It should be mentioned that \(P_i\) and \(n_i\) in equation (13) are considered to be the same as those in the LFS based on the first assumption. Therefore, parallel and perpendicular flows are obtained by applying equations (8) and (9). Then, the symmetric flow is the averaged flow of the measured parallel flows in the LFS and HFS because it is a flux function. The asymmetric flow is the difference of parallel and symmetric flows. Since symmetric flows, \(\phi\) and \(P_i\) have been obtained from experiments, these quantities can be used to verify the consistency of the factor \(hB\) which appears in NC theory, see equation (4). In order to distinguish the measured asymmetric coefficient from the equilibrium \(hB\) calculated from equations (5) and (6), the measured asymmetric coefficient \(C_{\text{asym}}\) is defined as the ratio of the measured asymmetric parallel flow to the sum of the pressure and electric potential gradient terms,

\[
C_{\text{asym}} = \frac{v_{\text{asym}}}{\frac{d\phi}{d\psi} + \frac{1}{Z_{\text{en}} \frac{dP_i}{d\psi}}}. \tag{14}
\]

It should be noted that the spatial resolution of the poloidal CXS is degraded in the core region by the integration effect due to the long cross path between the line of sight and the NB1, which is defined as the effective intersection \(\delta_{\text{eff}}\) shown in figure 1(b). Figure 3 shows the effect of the integration on flow velocity and the radial electric field. It can be observed in figure 3(a) that the integration effect is larger in the core and smaller in the edge. The angle between line of sight and NB4 increases gradually up to 90° as the observation radius moves outward, which results in the reduction of the effective flux surface region that the line of sight crosses. As a consequence, as shown in figure 3(b), the real poloidal flow in the core is smoothed much more strongly by the integration effect than that in the edge, especially in the region with peaked flow profile where the difference can reach approximately 30%.
However, the measured poloidal flow is almost the same as the inverted poloidal flow in the outer region with a small cross path. The fitted and inverted poloidal flows are obtained by using a cubic spline function with the condition that the poloidal flow velocity is zero at the core. The fitted poloidal flow is directly calculated from the original data by least square curve fitting. The inverted poloidal flow is acquired in another indirect way. First, an inverted poloidal flow satisfying the formerly mentioned function is assumed. Then, integration along the cross path at each observation radius is made by using the assumed poloidal flow to calculate the integrated flow. Finally, the integrated profile including the integration effect is utilized to fit with the original data in order to obtain the inverted poloidal flow.

The radial electric field calculated according to the radial force balance is shown in figure 3(d). The radial electric field shows the same tendency as the poloidal flow but with a smaller difference of approximately 20%. It should be mentioned that the integration effect for the toroidal CXS on LHD shown in figure 3(a) is relatively smaller with $\delta e_{\text{eff}}$ less than 0.1 because each line of sight of the toroidal CXS is closely located in the region parallel to the flux surface. Hence, the measured toroidal flow in figure 3(c) is utilized to calculate the radial electric field. Although the influence on the radial electric field becomes smaller due to the ignorable integration effect on toroidal flow, the difference between the measured and inverted poloidal flows and radial electric fields cannot be neglected. Therefore, it is necessary to consider the integration effect to acquire the actual flow structure.

Figure 4 shows the time traces of the flow structure in two density decay discharges, with one discharge decreasing from $2.0 \times 10^{19}$ m$^{-3}$ to $0.9 \times 10^{19}$ m$^{-3}$ (figure 4(c)) and another from $2.1 \times 10^{19}$ m$^{-3}$ to $1.7 \times 10^{19}$ m$^{-3}$ (figure 4(d)). As shown in figure 4(a), the heating power of the tangential NBI $P_{\text{tan}}$ is 8.7 MW and that of the perpendicular NBI, $P_{\text{perp}}$ is 9.0 MW for SN133708. As shown in figure 4(b), the heating power of $P_{\text{tan}}$ is 1.6 MW and that of $P_{\text{perp}}$ is 13 MW for SN138706. As shown in figures 4(e) and (f), the ion temperatures for both cases are almost symmetric in the HFS ($e_{\text{eff}} < 0$) and LFS ($e_{\text{eff}} > 0$). The ion temperature for SN133708 is much higher than that for SN138706 due to the higher NBI powers. The parallel flow for SN133708 in figure 4(g) shows strong asymmetry with flow negative in the HFS and flow positive in the LFS. In addition, the strength of asymmetry of the parallel flow (asymmetric flow), as shown in figure 4(k), increases with decreasing density in the decay phase and reaches a constant level in the steady density phase. It seems that electron density is the key measure which affects the asymmetry of parallel flow. However, the flow structure for SN138706 overthrows this prediction. On one hand, the parallel flow shown in figure 4(h) presents a steady peaked profile despite the density decrease. Meanwhile, the asymmetric flow shown in figure 4(l) almost stays unchanged during the reduction in density as well. The steady parallel and symmetric flow is due to the small change of the electron density. On the other hand, the parallel flow in the LFS is slightly lower than that in the HFS and the asymmetric flow reversing, being positive in the HFS and negative in the LFS, which is opposite to the situation of SN133708. Therefore, what affects the asymmetric flow is not directly associated with electron density.

Figures 4(i) and (j) show the perpendicular flow. Weak asymmetry is also seen in the perpendicular flow and the magnitude of the perpendicular flow in the LFS is slightly larger than that in HFS in both cases. In order to satisfy the continuity condition, the non-zero divergence of the perpendicular flow is compensated for by the asymmetric flow in the parallel

![Figure 4: 2D structures of plasma flow in density scan discharge with positive (SN133708) and negative (SN138706) radial electric field. Panels from top to bottom are (a) and (b) tangential (red) and perpendicular (blue) NBI heating power, (c) and (d) line averaged electron density (blue line) and electron temperature (red line with square) in the core, (e) and (f) ion temperature, (g) and (h) parallel flow velocity, (i) and (j) perpendicular flow velocity, (k) and (l) asymmetric flow, (m) and (n) radial electric field, and (o) and (p) coefficient of the asymmetric parallel flow measured from experiment. The magnetic configurations for SN133708 and SN138706 are $(R, \delta, \gamma, B_q)$ of (3.60, $-2.85$, 1.2538, 100) and (3.90, $-1.375$, 1.2538, 100), respectively. $R$, $\delta$, $\gamma$, and $B_q$ the vacuum magnetic axis, toroidal magnetic field strength, pitch parameter, and quadruple field, respectively. The dash lines indicate the time slice for profiles shown in figure 5.](image)
The frequency of ECH is 2.5 Hz and the density increases from asymmetric flow and the radial electric field. The modulation figure 6, shows clearer evidence for the relationship between the magnetic configuration changes. Therefore, there would and can be distorted from the anti-symmetric structure when \( hB \) is a geometric factor based on the magnetic configuration.

During the ECH phase and the parallel flow is almost static direction. Additionally, it is clear that the perpendicular flow is in the ion diamagnetic direction for SN133708 but changes to the electron diamagnetic direction for SN138706. The radial electric field, determined mainly by the perpendicular flow term, shows the same tendency of the perpendicular flow and is reversed in two cases. The radial electric field is positive for SN133708 as shown in figure 4(m) and negative for SN138706 as shown in figure 4(n), which corresponds to the reversal of the direction of the asymmetric parallel flow. Meanwhile, the strength of the radial electric field also remains consistent with that of asymmetric flow. Therefore, it can be concluded that the asymmetric flow depends mainly on the radial electric field. It should be mentioned that the sign of the radial electric field can be controlled by changing the collisionality [29, 38]. The transition of the radial electric field from a negative to a positive value (i.e. from ion to electron root, which is the concept first proposed in [39]) can happen when the collision frequency is low enough. As shown in figures 4(c) and (d), the electron density for SN133708 is lower than that for SN138706, while the temperature for the former is higher than that for the latter. Since the collisionality decreases with the decreasing electron density and increasing temperature, the collisionality for SN133708 is much lower than that for SN138706, which could result in the reversal of the radial electric field. The asymmetric coefficient \( C_{\text{asym}} \) shown in figures 4(o) and (p) almost stays constant even though the asymmetric flow varies with time. Scatters of \( C_{\text{asym}} \) for density decay before 4.7 s are caused by the small radial electric field.

Figure 5 shows the profiles of the flow at two time slices indicated by the dashed line in figure 4. It is seen much more clearly that the radial electric field shown in figures 5(i) and (j) and changes sign because of the different directions of perpendicular flow shown in figures 5(c) and (d) for both cases, which results in the reversal of asymmetric flow shown in figures 5(e) and (f). It should be noticed in figures 5(i) and (j) that the radial electric field is not symmetric in the HFS and LFS because the distance between the two neighboring flux surfaces is different for the two sides. In contrast, the electric potential shown in figures 5(g) and (h) is symmetric. The denser the flux surface, the larger the radial electric field becomes. In addition, \( C_{\text{asym}} \) shown in figures 5(k) and (l) is anti-symmetric in the HFS and LFS because of the assumption that \( \phi, P_e, \) and \( n_i \) are the function of the flux surface. In fact, the equilibrium \( hB \) is a geometric factor based on the magnetic configuration and can be distorted from the anti-symmetric structure when the magnetic configuration changes. Therefore, there would be a difference between \( C_{\text{asym}} \) and the equilibrium \( hB \).

Another discharge with modulated ECH, shown in figure 6, shows clearer evidence for the relationship between asymmetric flow and the radial electric field. The modulation frequency of ECH is 2.5 Hz and the density increases from \( 0.8 \times 10^{19} \text{ m}^{-3} \) to \( 1.1 \times 10^{19} \text{ m}^{-3} \). It can be seen in figure 6(d) that the parallel flow is positive and shows strong asymmetry during the ECH phase and the parallel flow is almost static without ECH. As shown in figure 6(f), the asymmetric flow calculated from the parallel flow also responds to ECH modulation. The asymmetry is strong in the ECH phase and almost zero without ECH. The change of the measured asymmetric parallel flow with ECH is due to the enhanced \( E \times B \) drift driven by ECH. Although the strength of asymmetric flow decreases with the increasing electron density slightly, the asymmetric flow shows the same tendency as the radial electric field shown in figure 6(g). The asymmetric flow becomes stronger with a large radial electric field and almost disappears with a small radial electric field. Electron density is merely an indirect way to influence the radial electric field. Figure 7 is the comparison between the profiles of the flow with ECH and those without ECH. It can be seen from figure 7(a) that the parallel flow profile is flat in the absence of ECH and becomes positive with ECH. Further, the increase of parallel flow in the LFS is larger than that in the HFS. The change of parallel flow results from two contributions. First, ECH drives parallel flow to increase in co-direction. Second, the induced flow is redistributed by the appearance of the asymmetric flow on a flux surface. It should be noticed in figure 7(c) and (e) that...
there is almost no asymmetric flow even with a finite radial electric field when ECH is off. There seems to be some offset of the radial electric field. This offset may result from the scattering of the experimental data shown in the next section.

To achieve a better understanding of the relationship between asymmetric flow and radial electric field, one global comparison is applied. Asymmetric flow is integrated from the HFS to LFS along $\psi$, which is expressed as $\pi B_{\text{eff}}$. The integration of the radial electric field is twice the difference of the electric potential in the core and of that in the edge. Figure 8 shows the relationship between the integrated asymmetric flow and electric potential with different magnetic fields (1.375 T, 2.75 T and 2.85 T) in the same magnetic configuration of the magnetic axis ($R_{\text{ax}}$) of 3.6 m. Although there are more experimental data scattered in the correlation, it can be observed that the integrated asymmetric flow increases linearly with the electric potential. In addition, the integrated asymmetric flow becomes negative in the negative electric potential difference, which means that the asymmetric flow reverses when the direction of the radial electric field changes. It should be pointed out that the data shown in figure 8 come from a sequence of discharges nearby with the same magnetic field and that one point denotes a time slice. Additionally, for the same magnetic configuration, the linearity between the integrated asymmetric flow and the electric potential difference are nearly the same in different magnetic fields. The slope shown in figure 8 which
eff/region (\( r \)) and the increase in the LFS. It can be seen from figure 9 that asymmetric flow with a decrease in the HFS and a significant gradient in the radial electric field almost peak at the same position (\( r_{\text{eff}}/a_{99} \) \( > 0.5 \)) where the flow gradient is relatively small. However, a difference between experiment and calculation is observed in the inner region (\( r_{\text{eff}}/a_{99} \) \( < 0.5 \)) where the flow gradient is large. Since \( C_{\text{asym}} \) is obtained according to equation (14) based on the incompressibility of the flow, the distinction between experiment and calculation indicates that the flow is compressible in the inner region. As shown in figure 9(c), the radial electric field reaches its peak at \( r_{\text{eff}}/a_{99} \) \( \sim 0.35 \) and is large in the core while the asymmetric flow is almost zero, which leads to the discrepancy with the calculations. For the case of the small flow gradient, there is no net torque input and the flow is driven by pure ECH and perpendicular NBI blips for diagnostics. As shown in figure 9(b), plasma flows in the direction parallel to magnetic field in the LFS and reverses in the HFS because of the existence of the asymmetric flow. Combined with figure 9(d), the asymmetric flow and radial electric field almost peak at the same position of \( r_{\text{eff}}/a_{99} \) \( \sim 0.4 \). It can be seen in figure 9(f) that \( C_{\text{asym}} \) is consistent with the calculation in the region (\( r_{\text{eff}}/a_{99} \) \( < 0.9 \)) with a small flow gradient though some scatter of \( C_{\text{asym}} \) appears in the edge because of the zero radial electric field, which is also observed in the peaks flow profile case.

Since \( hB \) is a factor that depends only on the magnetic configuration, as shown in figures 9(e) and (f), the equilibrium \( hB \) for the same magnetic configuration are similar to each other not only in profile but also in magnitude. Therefore, it is necessary to perform some comparison between experiments and calculations in different magnetic configurations in order to investigate the availability of incompressibility of the flow.

In the LHD, the magnetic configuration can be modified by the shift of \( R_{\text{ax}} \) from 3.50 m to 4.00 m. Magnetic field configurations with \( R_{\text{ax}} \) equal to 3.55 m, 3.60 m, 3.75 m and 3.90 m are used to investigate the influence of magnetic configuration on asymmetric flow. The sets of discharges with \( R_{\text{ax}} = 3.55 \) m, 3.75 m and 3.90 m are heated by balanced NBI with ECH, tangential NBI with modulated ECH, and perpendicular NBI, respectively. Figure 10 represents each magnetic configuration. Figures 10(a)–(c) show the measured and calculated asymmetric flow, where the calculated asymmetric flow is obtained by using the equilibrium \( hB \) according to equation (4). The measured asymmetric flow shows quantitative agreement with the calculated flow for \( R_{\text{ax}} \) of 3.55 m. Nevertheless, disagreement is observed for \( R_{\text{ax}} \) of 3.75 m and 3.90 m especially in the LFS. For \( R_{\text{ax}} \) of 3.55 m, \( C_{\text{asym}} \) is consistent with the equilibrium \( hB \) when there is no net torque input. However, a discrepancy is seen for \( R_{\text{ax}} \) of 3.75 m and 3.90 m. Additionally, as shown in figures 9(e), (f) and 10(g)–(i), the equilibrium \( hB \) increases with the increasing magnetic axis from 3.55 m to 3.90 m, which means that the \( hB \) factor is higher in outward shifted magnetic axis.

Figure 8. Relationship between integrated asymmetric flow and electric potential with different magnetic fields in the same magnetic axis of 3.6 m. The magnetic fields are 1.375 T (olive diamond), 2.75 T (blue square) and 2.85 T (red circle).

Figure 9. Measured coefficient of the asymmetric parallel flow in comparison with the equilibrium \( hB \) in the discharge with large (SN133625) and small (SN133508) gradient of symmetric flow. (a) and (b) Parallel (red square) and symmetric flow (blue circle), (c) and (d) inverted radial electric field and (e) and (f) measured asymmetric coefficient from experiment (red square) and the equilibrium (blue line) \( hB \). The magnetic configurations for SN133625 and SN133508 are \( (R_{\text{ax}}, B_c, \text{gama}, B_q) \) of (3.60, −2.85, 1.2538, 100) and (3.60, −2.75, 1.2538, 100), respectively.

5. Comparison of experiments with neoclassical theory

Two typical discharges, one with a large symmetric flow gradient and the other with a small gradient in the same magnetic configuration, are used to make a comparison with calculations in order to validate the measured asymmetric coefficient \( C_{\text{asym}} \). The large gradient flow is induced by two co-directional NBI heating together with one perpendicular NBI modulation for diagnostics. As shown in figure 9(a), the symmetric flow profile peaks with a large gradient and is redistributed by asymmetric flow with a decrease in the HFS and an increase in the LFS. It can be seen from figure 9(e) that \( C_{\text{asym}} \) shows good agreement with calculations in the outer region (\( r_{\text{eff}}/a_{99} \) > 0.5) where the flow gradient is relatively small. However, a difference between experiment and calculation is observed in the inner region (\( r_{\text{eff}}/a_{99} \) < 0.5) where the flow gradient is large. Since \( C_{\text{asym}} \) is obtained according to equation (14) based on the incompressibility of the flow, the distinction between experiment and calculation indicates that the flow is compressible in the inner region. As shown in figure 9(c), the radial electric field reaches its peak at \( r_{\text{eff}}/a_{99} \) \( \sim 0.35 \) and is large in the core while the asymmetric flow is almost zero, which leads to the discrepancy with the calculations. For the case of the small flow gradient, there is no net torque input and the flow is driven by pure ECH and perpendicular NBI blips for diagnostics. As shown in figure 9(b), plasma flows in the direction parallel to magnetic field in the LFS and reverses in the HFS because of the existence of the asymmetric flow. Combined with figure 9(d), the asymmetric flow and radial electric field almost peak at the same position of \( r_{\text{eff}}/a_{99} \) \( \sim 0.4 \). It can be seen in figure 9(f) that \( C_{\text{asym}} \) is consistent with the calculation in the region (\( r_{\text{eff}}/a_{99} \) \( < 0.9 \)) with a small flow gradient though some scatter of \( C_{\text{asym}} \) appears in the edge because of the zero radial electric field, which is also observed in the peaks flow profile case.

Since \( hB \) is a factor that depends only on the magnetic configuration, as shown in figures 9(e) and (f), the equilibrium \( hB \) for the same magnetic configuration are similar to each other not only in profile but also in magnitude. Therefore, it is necessary to perform some comparison between experiments and calculations in different magnetic configurations in order to investigate the availability of incompressibility of the flow.

In the LHD, the magnetic configuration can be modified by the shift of \( R_{\text{ax}} \) from 3.50 m to 4.00 m. Magnetic field configurations with \( R_{\text{ax}} \) equal to 3.55 m, 3.60 m, 3.75 m and 3.90 m are used to investigate the influence of magnetic configuration on asymmetric flow. The sets of discharges with \( R_{\text{ax}} = 3.55 \) m, 3.75 m and 3.90 m are heated by balanced NBI with ECH, tangential NBI with modulated ECH, and perpendicular NBI, respectively. Figure 10 represents each magnetic configuration. Figures 10(a)–(c) show the measured and calculated asymmetric flow, where the calculated asymmetric flow is obtained by using the equilibrium \( hB \) according to equation (4). The measured asymmetric flow shows quantitative agreement with the calculated flow for \( R_{\text{ax}} \) of 3.55 m. Nevertheless, disagreement is observed for \( R_{\text{ax}} \) of 3.75 m and 3.90 m especially in the LFS. For \( R_{\text{ax}} \) of 3.55 m, \( C_{\text{asym}} \) is consistent with the equilibrium \( hB \) when there is no net torque input. However, a discrepancy is seen for \( R_{\text{ax}} \) of 3.75 m and 3.90 m. Additionally, as shown in figures 9(e), (f) and 10(g)–(i), the equilibrium \( hB \) increases with the increasing magnetic axis from 3.55 m to 3.90 m, which means that the \( hB \) factor is higher in outward shifted magnetic axis.
J. Chen et al. show the anomalous flow which is defined as the difference between the measured and the calculated asymmetric flow. It can be observed that the anomalous asymmetric flow is smallest for $R_{ax}$ of 3.90 m and the strength of anomalous flow for $R_{ax}$ of 3.55 m is comparable to that for $R_{ax}$ of 3.75 m. This is because the anomalous flow is proportional to the radial electric field. After the impact of the radial electric field on anomalous flow is eliminated, the tendency will be consistent with what is observed in figures 10(g)–(i).

Figure 11 shows the statistics for different magnetic configurations. It should be mentioned that the calculated lines are based on the flux averaged equilibrium $hB$ according to the calculation from equations (5) and (6). As shown in figure 11(a), for $R_{ax}$ of 3.55 m, the calculation accurately predicts the experimental results without torque input when the electric potential difference is less than 10 kV. However, the calculation underestimates the asymmetric flow with high electric potential difference even though external torque is not input. The relationship between integrated asymmetric flow and electric potential is distorted away from linearity. For $R_{ax}$ of 3.60 m, as shown in figure 11(b), the statistics with ECH and with NBI show the discharges in the neighboring shots of SN133508 and those in the neighboring shots of SN133625.
respectively. The tendencies for discharges with only ECH are similar to the non-linearity of \( R_{ax} \) of 3.55 m. When the electric potential difference is small, the predicted asymmetric flow is larger than the experimental flow. The discrepancy increases along with the electric potential difference. The asymmetric flow of SN133508 is located in the cross of calculation and experiments. For \( R_{ax} \) of 3.60 m with NBI, the asymmetric flow is always overestimated by the calculation though integrated asymmetric flows are linear with electric potential difference. For \( R_{ax} = 3.75 \text{ m and 3.90 m} \), as shown in figures 11(c) and (d), there remains overestimation even without external input when the electric potential difference is small.

6. Discussion and summary

Incompressibility of flows is an approximation of the particle conservation in a steady state with constant impurity density on a flux surface and radial flow eliminated. In fact, impurity density is linked to flow due to the zero divergence of particle flux. As a result, flow becomes compressible in the presence of asymmetric impurity density and poloidal redistribution of impurity density on a flux surface in turn modifies the flow structure. Therefore, one possible explanation of the discrepancy between the measured \( C_{\text{asyms}} \) and equilibrium \( hB \) is the variation of impurity in poloidal direction.

Models which consider the impact of impurity density asymmetry on flow structure have been applied to infer the required impurity density asymmetry [21, 22]. Deductions that the impurity density in the HFS is larger than that in LFS with a factor of 3–6 are expected. For the case with larger flow gradient, the equilibrium \( hB \) is much larger than \( C_{\text{asyms}} \) in the core. Thus, the calculated asymmetric flow according to equation (4) originating from flow incompressibility will be larger than the experimental asymmetric flow as well. In order to remain consistent with experiments, the calculated symmetric flow should be reduced to a lower level, which means that poloidal variations of poloidal flow should be partly compensated for by the inhomogeneity of impurity density on a flux surface. Therefore, accumulation of impurity density in the HFS is necessary for the reduction of asymmetric flow. However, this postulation is not confirmed by carbon density experiments. The carbon density accumulates more in the LFS in this case. This discrepancy shown in the larger flow gradient case indicates that impurity density asymmetry is not appropriate enough to explain the asymmetry of parallel flow although impurity density asymmetry indeed modifies flow structure on a flux surface.

In the assumption of flow incompressibility, the radial flow is also ignored in the usual NC theory. Radial transport could have an impact on the flow structure on a flux surface by carrying particles or momentum from one flux surface to the location of interest when radial transport is comparable to the parallel transport. The radial flux is proportional to the velocity gradient with the expression of \( \mu_\perp \nabla v_{\parallel} \), where \( \mu_\perp \) is the perpendicular viscosity coefficient.

The change of radial transport can result from two reasons, flow gradient and \( \mu_\perp \). On one hand, the diffusion of parallel flow along the radial direction becomes larger when the peaked parallel flow profile driven by strong torque from NBI appears, which may be an explanation for the disagreement for large flow gradients in figure 9(c) though the magnetic configuration is the same in both cases. On the other hand, augmentation of \( \mu_\perp \) may also lead to the increase of radial transport even with a small flow gradient. In such cases, NC theory is not appropriate to describe the flow structure. In the LHD, an enhancement of confinement has been observed in the inward shifted magnetic axis [40], which is an indirect indication that the radial transport becomes larger for the outward shifted magnetic axis. Additionally, in the edge region of the LHD there is a stochastic layer whose width increases with the value of \( R_{ax} \) [41]. The flattening of the electron temperature and that of the delay time of the heat pulse have been observed in the edge [42]. The importance of the magnetic stochasticity has been extensively studied in the RFX-mod reversed field pinch, where huge flow modifications in the edge plasma follows the transition from a magnetic topology with a \((m, n) = (1, 7)\) helical order to chaos [43, 44]. The impact of the magnetic stochasticity on electron and ion heat transport and flow damping has also been investigated in the core [45]. When plasma magnetic flux becomes stochastic, the magnetic stochasticity enhances the radial transport and the flow damping. Therefore, the PS flow should also be very small due to the profile damping (no driving force) and strong flow damping, which is consistent with the small asymmetric flows for the outward shifted \( R_{ax} \) in figure 11. As a result, for \( R_{ax} \) of 3.75 m and 3.90 m, discrepancies between experimental and calculated asymmetric flows are observed even without large flow gradients.

Additionally, when the flow is compressible, the pressure on the inboard side will be higher than that on the outboard side and there should be pressure variation on a flux surface. The radial flux which is constant on a flux surface is not enough to reduce the higher pressure inboard side. In order to balance the variation of the pressure in the poloidal direction, there should be strongly poloidally asymmetric radial flow. In fact, poloidal asymmetries in transport exist naturally in turbulence and collisional transport models. These effects could be considered to explain the observations in the LHD. Therefore, the radial transport due to anomalous perpendicular viscosity plus strongly poloidally asymmetric radial flow other than NC processes could be involved in the modification of the flow structure on a flux surface in the presence of strong flow shear and outward shifted magnetic axis.

In conclusion, the poloidal asymmetry of parallel flow has been observed in both NBI and ECH discharges with the application of four sets of CXS in the LHD. The asymmetry of parallel flow shows a strong connection to the radial electric field. The asymmetry reverses its structure when the electric field changes sign from positive to negative. Comparisons in different magnetic fields with the same magnetic configuration are made. It is found that the integrated parallel asymmetry from the HFS to LFS increases linearly with the
difference between the electric potential in the core and that in the edge. A model based on the incompressibility of the flow is used to explain the parallel flow asymmetry. Good agreement is found for the case with a small flow gradient, but this model fails for the case with a large flow gradient. Further, the results in various magnetic configurations show that the flow incompressibility is valid for $R_{ax} = 3.55 \text{ m}$ and $3.60 \text{ m}$ when there is no external torque input. For $R_{ax} = 3.75 \text{ m}$ and $3.90 \text{ m}$, there remain some discrepancies between experiments and calculations even though the external torque input is small. Poloidal variation of impurity density is also applied, while the postulated density asymmetry is opposite to the experiments results. The radial transport driven by anomalous perpendicular viscosity plus strongly poloidally asymmetric radial flow could be a candidate for these discrepancies.

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