Shear Flow Generation in Stellarators - Configurational Variations

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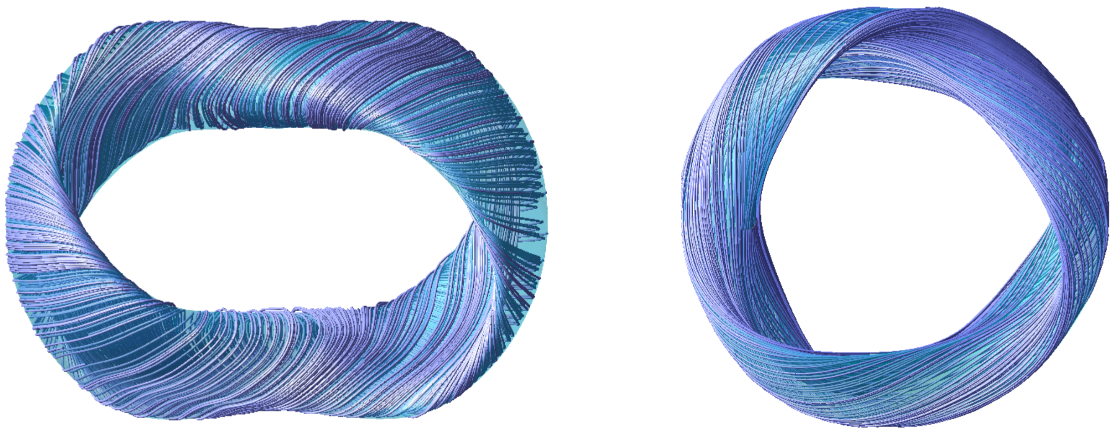
Plasma momentum transport within magnetic surfaces plays a fundamental role in a number of toroidal plasma physics issues, such as: turbulence suppression, impurity transport, bootstrap current generation, and the shielding of resonant magnetic error field perturbations. Stellarators provide opportunities for improved understanding of plasma flow effects because (a) new forms of quasi-symmetry (e.g., helical, poloidal) can be produced that differ significantly from the tokamak; and (b) symmetry-breaking effects (always present to some degree) remove the degeneracy between parallel and cross-field transport characteristic of symmetric systems. External control coils can also be used to further enhance or suppress such effects. A method has been developed to evaluate the variation of neoclassical self-generated plasma flows in stellarators both within and across magnetic surfaces. This introduces a new dimension into both the optimization of stellarators and to the improved understanding of the existing confinement database. Application of this model to a range of configurations indicates that flow directionality and shearing rates are significantly influenced by the magnetic structure. In addition, it is demonstrated that flows in stellarators are sensitive to profile effects and the presence of external momentum sources, such as neutral beams.

1. Introduction

In the early development of stellarator neoclassical theory, attention was predominantly focused on the topics of neoclassical cross-field transport and bootstrap current. The former was motivated by the large levels of ripple transport present in conventional stellarators (in some cases on a competitive level with anomalous transport). The interest in bootstrap current was perhaps motivated first by the fact that such currents could be readily measured experimentally and secondly by an interest in suppressing them due to their potential as a drive for MHD instability. However, with the successful development in recent years of powerful stellarator optimization/design techniques, associated with credible target functions for neoclassical transport and bootstrap current, these two transport issues have become less urgent. In quasi-symmetric devices, ripple transport losses have now been suppressed to such an extent that, at least for parameters of near-term interest, they are negligible compared with anomalous losses. Similarly, improved MHD stability codes, coupled with stellarator experiments that have explored ohmically and beam-driven current regimes, have lessened the perceived need to completely suppress bootstrap current; in fact, hybrid configurations are now routinely considered that utilize plasma currents (bootstrap + ohmic) to provide part of the rotational transform and thus simplify the modular coil design geometries.

However, there remains a strong interest in further stellarator confinement improvement due to its direct impact on reactor size and economic viability. This must necessarily involve micro-turbulence suppression since that persists as the dominant remaining transport mechanism. There is now considerable evidence that sheared plasma flows play an important role in reducing the transport of particles and energy in tokamak experiments. For this reason, interest has shifted to improved understanding of neoclassically-driven flows in stellarators [1,2,5,6]. Momentum transport and flow generation in stellarators differs in a number of fundamental ways from that in tokamaks. First, since ion and electron loss rates are not automatically ambipolar, an electric field will develop to equalize these rates; due to the fact that transport coefficients depend nonlinearly on this field, this introduces the complexity of multi-valued solutions and discontinuous jumps from one root to another. Physically, this is resolved by anomalous diffusion in the electric field profile, which can be related to finite orbit effects [3,4] and anomalous momentum damping. The electric field also provides an additional drive for flow that is not present in the tokamak. Second, since stellarators generally have no direction with perfect symmetry, finite levels of flow damping will exist to some extent for all flow directions. However, due to the fact that flows are continuously being driven by the $E \times B$ and diamagnetic flows, a steady-state flow structure will form (depending on magnetic structure and collisionality) that minimizes the total viscous stress tensor. An example of the range of vector flow structures that are possible in recent compact stellarator systems is shown in Fig. 1 in the form of flow streamlines for (a) a quasi-poloidal stellarator and (b) a quasi-toroidal stellarator.



(a) (b)

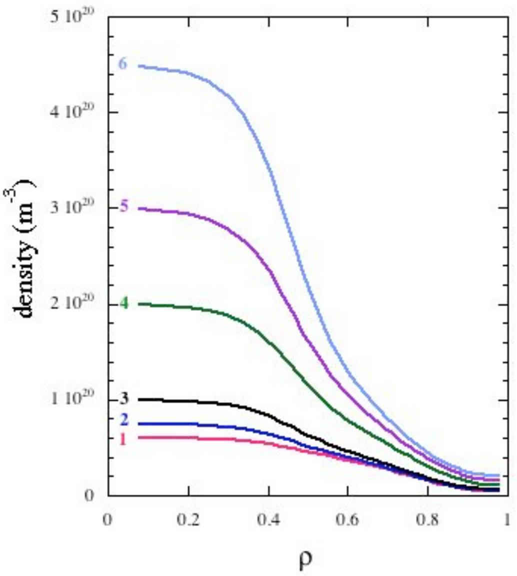
Figure 1 – Ion flow velocity streamlines on a flux surface for (a) the QPS (Quasi-Poloidal Stellaraor and (b) NCSX (National Compact Stellarator Experiment).

In the following we will evaluate flow velocities in a variety of stellarators using the PENTA code [5]. This uses methods developed by Sugama and Nishimura [6] for deriving the parallel component of the viscous stress tensor in terms of transport coefficients provided by the DKES [7] code. An extensive database of transport coefficients must first be generated as a function of flux surface location, collisionality and electric field and integrated over a Maxwellian distribution function for each configuration. With this, the parallel component of momentum balance coupled with the ion/electron ambipolar condition is solved for the neoclassical parallel flow velocity and radial electric field. Finally, a divergence-free total flow velocity is constructed by calculating the Pfirsch-Schlüter flow and adding this to the $E \times B$, diamagnetic, and parallel neoclassical velocities. From this total flow velocity, various components and averages can be taken to reduce the dimensionality of the data. Alternatively, direct 3-D visualizations of the data (such as used in Fig. 1) are useful to develop a more intuitive understanding of the structure.

In the following four sections, we will examine four different methods for controlling the flow velocity structure in stellarators. We first look at an interesting recent example from the world's largest stellarator, the LHD experiment [8], where rather extreme profile variations were produced by pellet injection. Strong drive for flow shearing was caused both by the very steep profiles and changes in the collsionality regime within the profile variations. Next, we look at a collection of different stellarator configurations and examine the influence of magnetic structure on flow shearing. Following that, we examine flexibility through auxiliary coil current variations for a particular stellarator, QPS, whose magnetic design has been demonstrated to lead to high degrees of flow shearing. Finally, we examine the influence of an external momentum source such as a neutral beam on flow shearing effects in the quasi-toroidal NCSX [13] device. In all of these cases, by judicious (but reasonable) choice of plasma temperature and density profiles, it has been possible to find single ambipolar electric field roots that remain continuous across the radius of the plasma. An extension of the PENTA code [5] is currently development to treat cases with electric field root-jumping.

2.1 Profile Control Effects on Plasma Flows: LHD SDC Mode Modeling

A recent experimental achievement of substantial interest has been the generation of super dense core (SDC) plasmas in the LHD device [8] with low recycling and high density gradient internal diffusion barriers. This regime has been accessed by pellet injection and offers extrapolation to high density/low temperature ignition scenarios. We have modeled the evolution of plasma flows for such a regime using the density profiles shown in Fig. 2(a), which attain peak densities of 4.5 x 10^{20} m^{-3}. The associated model temperature profiles are less peaked and pass through a range of $T_e(0)$ = 0.45 (case 1) to 0.85 keV (case 6) with $T_e = T_i$. For these calculations, the transport coefficients are calculated only for the highest β in the sequence ($\langle\beta\rangle \approx 1.5\%$). Solving the ambipolar equation leads to ion root electric field profiles as indicated in Fig. 2(b), showing gradients increasing with density peaking.



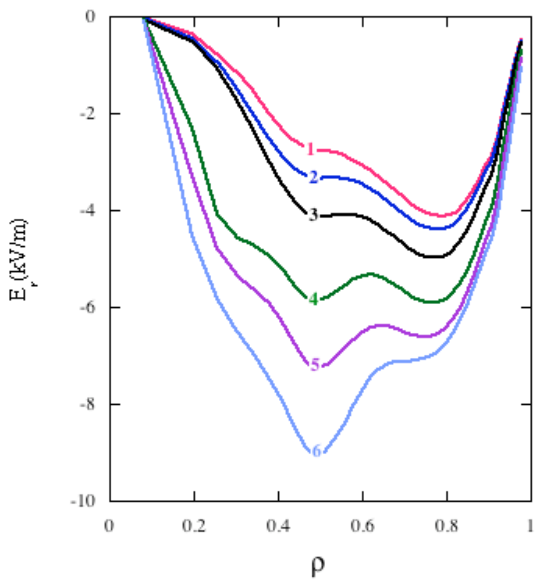


Figure 2 – (a) Sequence of density profiles used in modeling LHD SDC mode, (b) associated sequence of radial electric field profiles.

The variable ρ in the above and subsequent plots is (normalized toroidal flux)$^{1/2}$. Figure 3 shows the evolving profiles for the contra-variant poloidal and toroidal flow velocity components associated with the profiles of Fig. 2(a). These become increasingly peaked in going from profile 3 to profile 4 and the poloidal component becomes >> the toroidal component. This change can be related to the fact that the collisionality parameter $\nu_* = \nu R_0/\iota v_{th}$ changes from decreasing in the core region for profiles 1 to 3 to increasing in the core region for profiles 4 to 6. This change in collisionality increasingly places the ions above the peak in the poloidal viscosity coefficients, leading to the rapidly increasing central flow velocities. Comparison of the high rate of $E \times B$ velocity shearing ($3 - 4 \times 10^4\ sec^{-1}$) in the ρ = 0.4 region with estimated ITG growth rates ($\gamma \sim c_s/R_0$) indicates that shearing rates are reaching about 80% of the local growth rates. Since there are additional sources of damping not included here (neutrals, MHD turbulence, 2/1 islands, etc.) in the outer region of the plasma, which can lead to higher shearing rates, these results are not inconsistent with the experimental observation of an internal transport barrier in this regime.

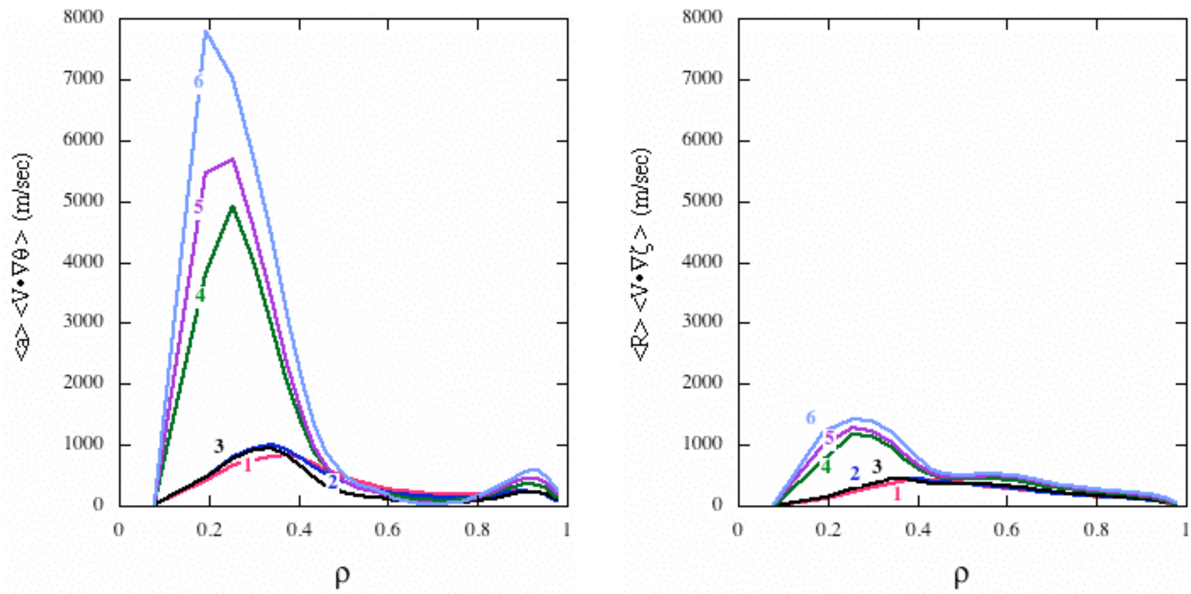


Figure 3 – Evolution of (a) poloidal flow and (b) toroidal flow profiles for LHD SDC mode.

2.2 Configurational Effects on Plasma Flows: Stellarator Design

Stellarators offer an immense design space, leading to configurations with a wide variety of magnetic field structures, and thus different neoclassical flow damping characteristics. In previous work, the PENTA code [5] has been applied assuming a fixed set of plasma profiles and parameters to different configurations to illuminate these differences. This is continued here for several additional configurations and based on one of the profiles (case 3) of Fig. 2(a). This case has a central density of $10^{20}\ m^{-3}$ and central electron and ion temperatures of 0.6 keV. In addition to a number of stellarators (LHD, TJ-II, HSX, W7-AS, QPS), we have also included a rippled tokamak ($R_0/\langle a\rangle$ = 2.74, κ = 1.2, δ = 0.1) with about 0.2% edge toroidal field ripple. In Fig. 4(a) the ambipolar electric field profiles are shown. These are at different levels both due to the different magnetic structure of the devices, but also since the transport is based on applying the same profiles to devices with different dimensions and magnetic field levels (i.e., the devices with the smallest minor radii have larger density/temperature gradients and thus larger electric fields). In Fig. 4(b) the poloidal flow profiles are plotted after scaling with an additional factor of $\langle a\rangle\langle B\rangle$ to equalize the effects of differing machine parameters on the flow velocity (i.e., since the basic $E \times B$ and diamagnetic flow drives scale as $\langle a\rangle^{-1}\langle B\rangle^{-1}$). As can be seen, a range of poloidal flow profiles are possible. In Fig. 5 the local poloidal flow shearing rates are calculated and plotted vs. the local value of the effective ripple coefficient ($\varepsilon_{eff}^{3/2}$) based on applying the NEO code [9] to each configuration. This type of plot is motivated by the recent observation [10] that improved fits the stellarator confinement database can be obtained by extracting a machine-dependent factor related to ε_{eff}.

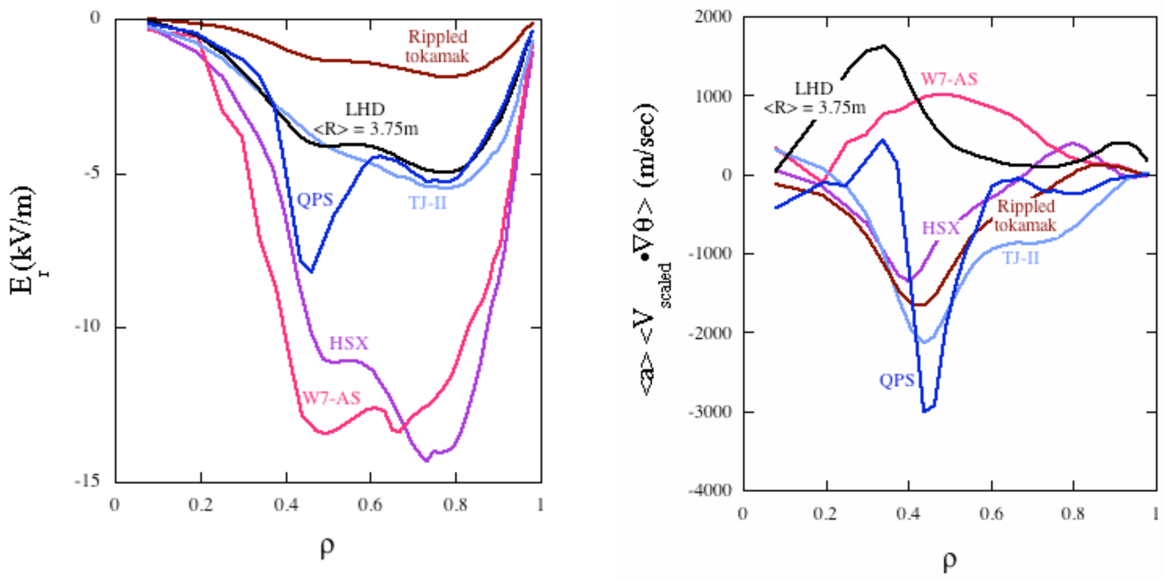


Figure 4 – (a) Electric field profiles for different and (b) scaled poloidal velocity profiles for different stellarator configurations.

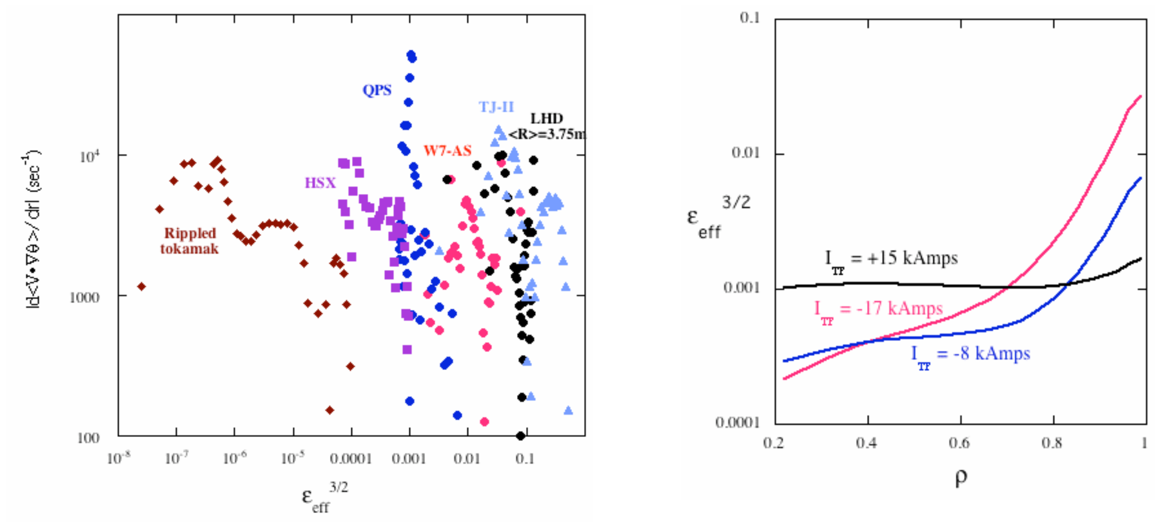
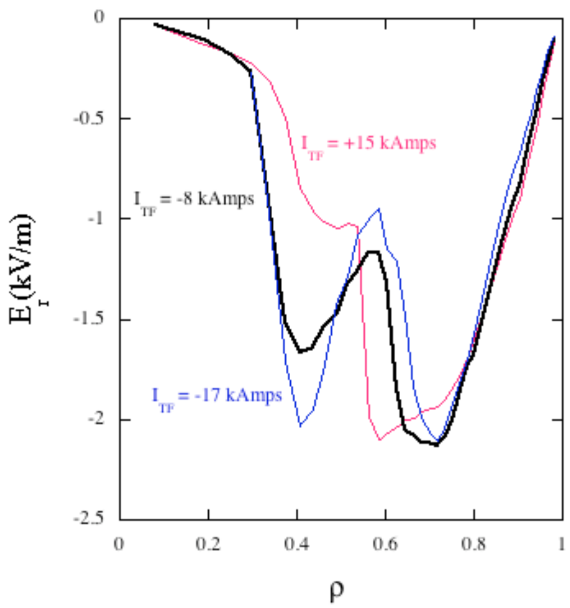


Figure 5 (left) – Correlation between samples of poloidal velocity shearing rates and local effective ripple for a range of stellarator configurations; Figure 6 (right) – Effective ripple coefficient for QPS configuration for different planar toroidal field coil currents.

Although Fig. 5 does not indicate any clear dependency of shearing rates on ε_{eff} between devices, it does show that, at least for this study, within each configuration there is a tendency for the highest shearing rates to occur at the lower values of ε_{eff}. As mentioned earlier, the parallel neoclassical transport properties in stellarators are not as closely linked to the transport across flux surfaces (of which $\varepsilon_{eff}^{3/2}$ is a low collisionality measure) as in the case of tokamaks. We expect in the future to extend this type of study to include a larger range of profiles/parameters and further stellarator configurations.

2.3 Configurational Effects on Plasma Flows: Flexibility Through Auxiliary Coils

Stellarators offer significant flexibility in their magnetic configurations both by allowing current variations in their main modular coils as well as in various auxiliary coil-sets (vertical, planar toroidal, OH, error field correction, etc.). Such flexibility can be used to control physics properties such as transport, stability and presence/absence of magnetic islands. In order to understand the influence of different levels of plasma flow shearing on confinement, it is of interest to apply the PENTA model [5] to equilibria within a given device that can be produced by varying auxiliary coil currents. For simplicity, we have chosen to study the QPS configuration when only the planar toroidal field coil currents are varied. QPS is a quasi-poloidal stellarator design that has been shown to particularly enhance the poloidal flow shearing that is thought to play a role in turbulence suppression [11]. Previous studies [12] have addressed the available flexibility ranges when full control is possible over modular + auxiliary coil currents. For the case of quasi-poloidal symmetry, the magnetic fields produced by planar toroidal field coils can act in a symmetry-destroying manner since they introduce tokamak-like (1/R) varying field components. Normally, at full magnetic field levels, this effect would be insignificant, but if the main field from the modular coils is lowered to about 0.3 Tesla (as might be appropriate to the early operational phases of such an experiment), the planar toroidal field coils can be used for flexibility. Fig. 6 indicates the amount of change that is possible in the effective ripple coefficient through variation in these coil currents. Figs. 7(a) and 7(b) show the associated changes in E_r and the poloidal flow velocity for the same coil current variations.



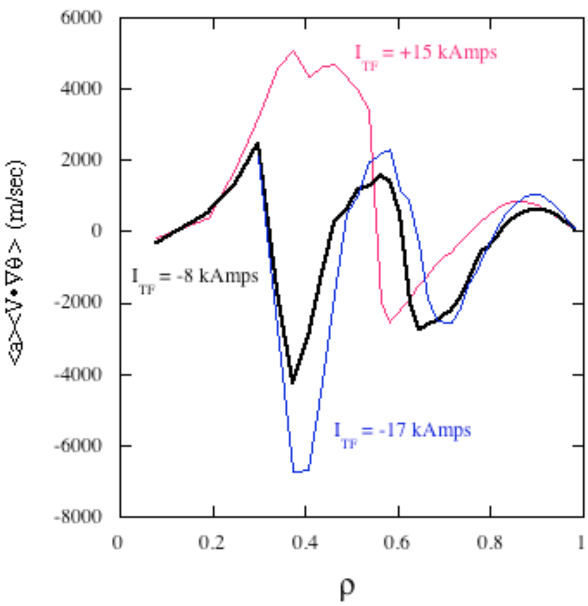


Figure 7 – (a) Electric field profiles and (b) poloidal flow velocity profiles for a low field QPS configuration with varying currents in the planar toroidal field coils.

These results were calculated using the same profiles as section 2.2 above, but with $n(0) = 4 \times 10^{19}$ m^{-3}, $T_e(0) = 0.6$ keV, $T_i(0) = 0.2$ keV. As can be seen, significant changes can be made both in the shearing rate and direction of the plasma poloidal flow velocities.

2.4 Influence of external momentum sources on plasma flows

Plasma flow characteristics in tokamaks in the presence of external momentum sources, such as neutral beams and RF have been studied extensively, and continue to be a topic of much interest, due to the possible role that external sources can play in controlling flow shearing and access to enhanced confinement regimes. Such effects should also exist in stellarators since the introduction of sources into the momentum balance equation will couple directly into both the ambipolar electric field determination and the generation of flows. We have examined such effects in a simplified manner by including a source term in the parallel momentum balance equation. Studies have been done for a variety of stellarators and indicate that the effectiveness of such a source can be related to the size of the off-diagonal viscosities in the stress tensor. Normally, these control the degree to which perpendicular flows (e.g., $E \times B$ and diamagnetic) are damped and converted into parallel flows. Conversely, as a consequence of Onsager symmetry, when a parallel momentum source is introduced, the size of the off-diagonal terms is important in determining the back-influence this source can have on the electric field and on the related poloidal flows. We have generally found that poloidal flows in stellarators, such as NCSX [13], which are close to quasi-toroidal symmetry, indicate a higher degree of sensitivity to momentum input than other stellarator configurations. However, devices with forms of symmetry other than quasi-toroidal may be more strongly influenced by momentum inputs in off-parallel directions. An example the effect of parallel momentum input for NCSX is given in Figure 8, where the ambipolar electric field and poloidal flow velocity profiles are plotted for various levels and directions of parallel momentum input. As can be seen, significant changes in the electric field and shearing rates are predicted as the momentum source is varied.

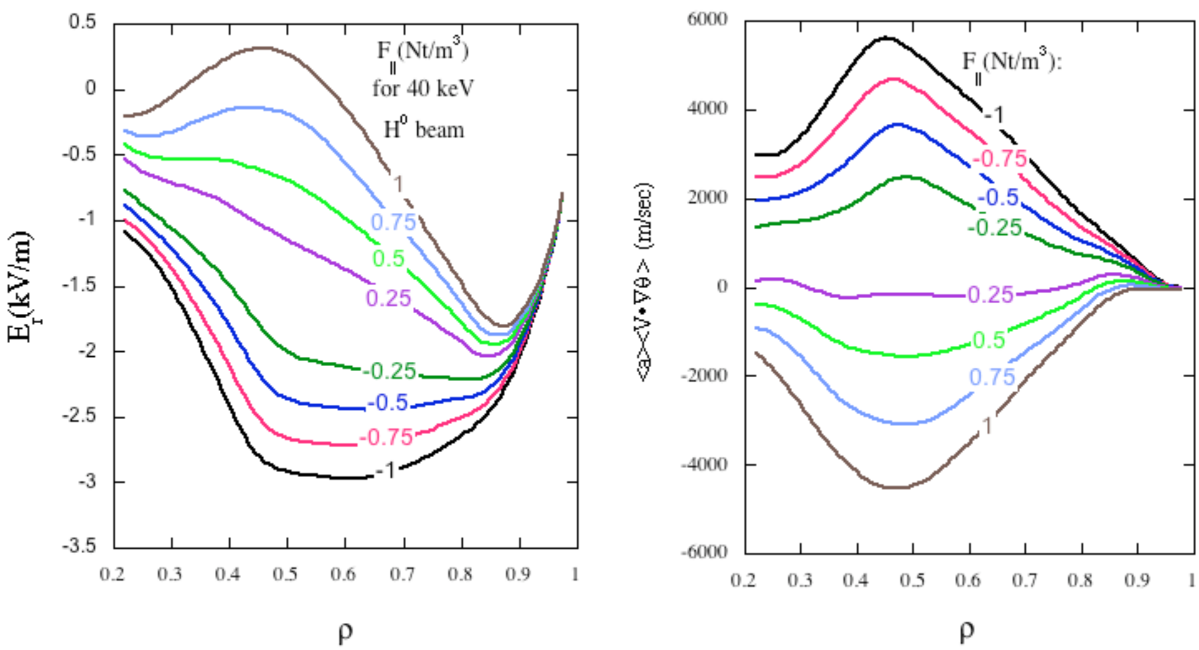


Figure 8 – (a) Electric field profiles and (b) poloidal flow velocity profiles in an NCSX configuration with varying levels of an external parallel momentum source (e.g., neutral beam).

3. Conclusions

It has been demonstrated that stellarators posess significant "elasticity" in their electric field and flow velocity shearing profiles. These can be modified by profile control, configuration design, auxiliary coil currents, and external momentum sources. First, pellet-injection induced profile changes in LHD have been shown, both as a result of the highly-steepened density profiles and nonlinear variations in the viscosity coefficients, to generate strong velocity shearing. These shearing rates approach linear growth rates of the ITG modes that are thought to be responsible for anomalous transport, thus providing a possible explanation for the observed confinement enhancements. Next, it has been demonstrated that stellarator design can influence flow shearing characteristics and, within individual devices, correlations exist between the effective ripple and flow shearing rates. For a particular configuration, QPS, that achieves high shearing rates by design, controlled variation in these rates was shown to be possible by auxiliary coil current variations. Finally, the effect of external momentum sources was considered for the NCSX device and shown to provide an efficient avenue for modifying electric field and flow velocity profiles.

The fact that stellarators can controllably provide plasma flows with a range of shearing rates and directionalities should create significant opportunities for improved basic understanding of anomalous transport and its suppression in toroidal devices. It is anticipated that future diagnostic measurements of flows and turbulence in the configurations analyzed here will permit closer comparison with these theoretical results.

Acknowledgements – Research sponsored by the U.S. Department of Energy under Contract DE-AC05-00OR22725 with UT-Battelle, LLC.

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