Effects of Quasisymmetry on Particle and Thermal Transport in HSX

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Abstract

The density profile in the Quasi-Helically Symmetric (QHS) configuration is centrally peaked for both on- and off-axis heating. In a magnetic configuration with the symmetry broken, the density profile is flat or slightly hollow with on-axis heating, where the temperature profile is centrally peaked. In QHS plasmas, the experimental particle flux is much larger than the neoclassical flux across the entire minor radius. In plasmas without quasisymmetry, however, the neoclassical flux is comparable to experiment in the core ($r/a < 0.4$). In this region, the thermodiffusive flux is the dominant term in the total neoclassical particle flux, suggesting that neoclassical thermodiffusion is the cause of the hollow density profile.

The central temperature in a configuration without quasisymmetry is much less than that in QHS. It is found that, in the configuration without quasi-symmetry, the thermal diffusivity is anomalous at the plasma edge, and close to neoclassical in the core. In the QHS configuration, the thermal diffusivity is also anomalous towards the edge, and roughly a factor of three lower in the core, reflecting the reduction of neoclassical transport. At 50 kW of injected power, this reduced transport results in a core electron temperature that is ~200 eV larger in QHS than in the non-symmetric configuration.

1. Introduction

The Helically Symmetric Experiment [1] (HSX) is the first operational quasisymmetric stellarator, with a helical direction of symmetry in the magnetic field strength. As a result of this symmetry, the neoclassical transport is reduced to the level of an axisymmetric device. HSX is a medium sized device, with a major radius of 1.2 m and a minor radius of 12 cm. The quasihelically symmetric (QHS) magnetic field, with a toroidal mode number of $n=4$ and poloidal mode number of $m=1$, is produced with 48 non-planar modular coils. For all results reported here, plasmas are produced and heated with 50 kW of 2nd harmonic electron cyclotron resonance heating at 28 GHz, and a magnetic field strength of 0.5 T.

The symmetry can be intentionally broken using a set of 48 planar auxiliary coils, which add a toroidal mirror term ($n=4$, $m=0$) to the magnetic field spectrum. In these so-called Mirror configurations, neoclassical transport is raised towards the level of a conventional stellarator. In the Standard Mirror configuration, the auxiliary coils add to the field of the modular coils at the ends of each field period, and subtract magnetic field at the half-field period. In this configuration, the magnetic axis shifts inward 1 cm from its location in the QHS configuration. This axis shift is problematic from a diagnostic point of view: the HSX Thomson Scattering system was designed to make on-axis measurements in QHS, and because of the axis shift, no on-axis measurements can be made in the Standard Mirror configuration. To overcome this, a new Mirror configuration has been explored, called the Phase Shifted Mirror configuration. In Phase Shifted Mirror, the auxiliary coils are energized so that they add field in one half of a field period, and subtract field in the other half. This is

Coil Type	1	2	3	4	5	6	6'	5'	4'	3'	2'	1'
Standard Mirror	+	+	+	-	-	-	-	-	-	+	+	+
Phase Shifted Mirror	+	+	+	+	+	+	-	-	-	-	-	-

Table 1: Auxiliary coil currents in one field period for two configurations. +'s indicate current in the same direction as the main coils, -'s indicate the opposite

illustrated in table 1. The magnetic spectrum for Phase Shifted Mirror is similar to that of Standard Mirror, except that the n=4,m=0 term has a different toroidal phase. In Phase Shifted Mirror, the magnetic axis does not shift in the major radial direction, but does shift vertically, moving downward about 2 cm. The axis position is then still along the laser path of the Thomson system, and on-axis measurements can be made. However, due to the downward axis shift, heating is slightly off-axis in Phase Shifted Mirror, being localized at r/a ~ 0.1.

2. Particle Transport

In order to study particle transport in HSX plasmas, a Thomson Scattering system has been implemented to measure the electron temperature and density profiles [2]. This system has 10 spatial channels with 2 cm resolution along a 20 cm laser beam path. The particle source has been measured using a suite of absolutely calibrated H_α detectors [3], with an array covering the plasma cross-section and several detectors distributed toroidally around the machine. This data from the H_α suite is interpreted using neutral gas modeling with the DEGAS code [4]. DEGAS is a three-dimensional Monte Carlo neutral gas code, which takes as its input the 3D plasma geometry and profiles, and for a given gas puff yields the distribution of various neutrals-related quantities. A single point normalization is performed to calibrate the DEGAS results to the absolutely calibrated H_α measurements, resulting in good agreement in the profiles of the H_α brightness calculated from DEGAS and that from experiment [5]. The quantity of interest from the DEGAS calculation is the particle source rate density, which can be integrated to give the total radial particle flux. In summary, the absolutely calibrated H_α measurements coupled to DEGAS modeling allow the experimental particle flux to be estimated.

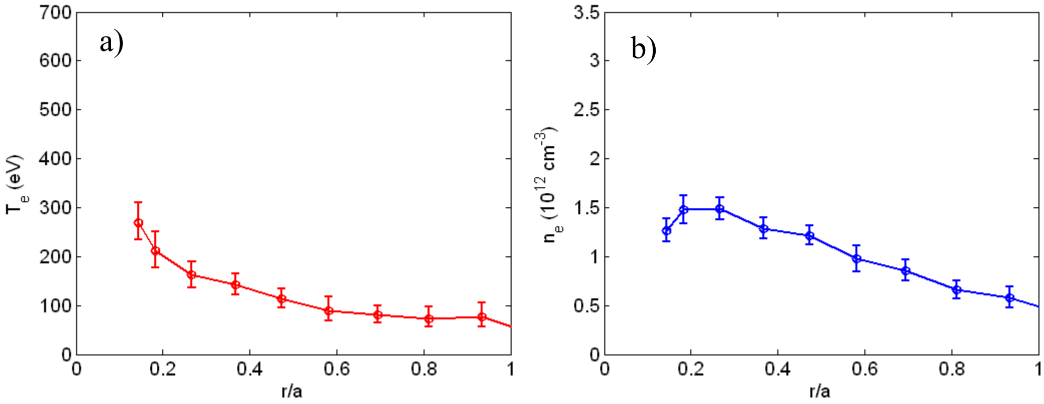

Figure 1: Electron a) temperature and b) density profiles for a Standard Mirror plasma with central heating

The temperature and density profiles for a Standard Mirror plasma are shown in figure 1. Recall that in Standard Mirror, no on-axis measurements can be made with the Thomson scattering system. It can be seen that the density profile appears to be hollow in the core. To support a hollow density profile in steady state requires an outward convective flux in addition to standard diffusion. One candidate for this outward particle flux is thermodiffusion, such as is provided by neoclassical theory [6]. A simple test for a thermodiffusive flux is to perform off-axis heating: by eliminating the temperature gradient inside the heating radius, any particle flux driven by the temperature gradient should also be eliminated. The results of such an experiment are shown in figure 2, which shows the electron temperature and density profiles for a Standard Mirror plasma with heating at r/a ~ 0.4. It can be seen that the temperature profile in the core is flattened, and the density profile is now centrally peaked. This anticorrelation between the temperature and density gradients is strong evidence that a thermodiffusive particle flux causes hollow density profiles with on-axis heating in the Standard Mirror configuration.

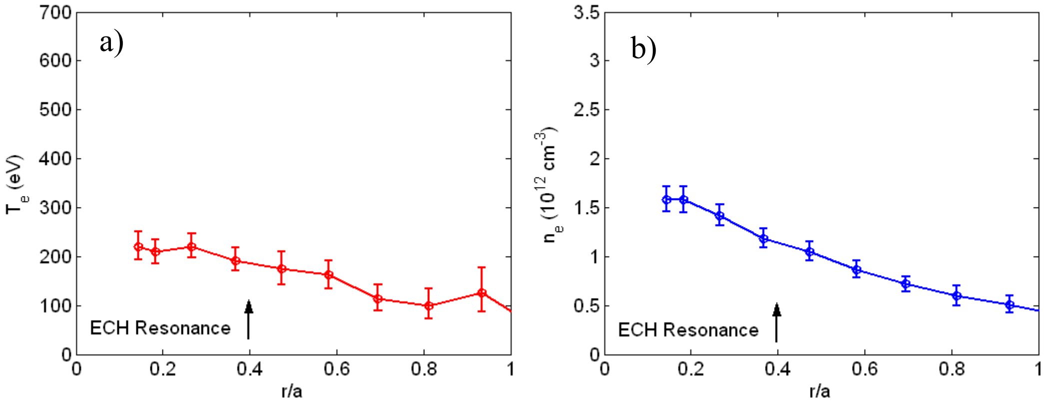

Figure 2: Electron a) temperature and b) density profiles for a Standard Mirror plasma with off-axis heating

In order to determine whether it is neoclassical thermodiffusion that causes the hollow density profiles, the experimental particle flux has been compared to the neoclassical prediction. Figure 3 shows this comparison, showing the experimental particle flux inferred from the H_α array and DEGAS modeling, along with the neoclassical value calculated using the ambipolar radial electric field. It can be seen that in the region of hollow density profile, the experimental and neoclassical particle fluxes are comparable. The thermodiffusive component of the particle flux is dominant in the neoclassical prediction, as the density gradient is very small. This suggests that neoclassical thermodiffusion causes the hollow density profiles observed in the Standard Mirror configuration. This is very similar to results from other stellarators, in which hollow density profiles could be attributed to neoclassical thermodiffusion [7].

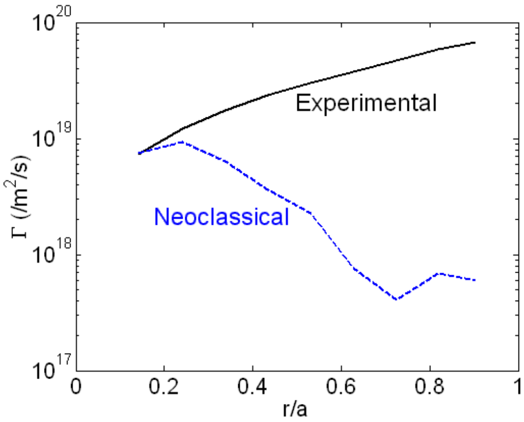

Figure 3: Experimental and neoclassical particle fluxes for a Standard Mirror plasma with central heating

The temperature and density profiles for a QHS plasma with central heating are shown in figure 4. It can be seen that the profiles are significantly different with quasisymmetry: even with central heating and a very peaked temperature profile, the density profile is peaked. This can be understood as a direct result of the quasisymmetric magnetic field: because of the greatly reduced neoclassical transport, the neoclassical thermodiffusive flux is much smaller than in the Standard Mirror configuration, and is not large enough to hollow out the density profile. This is verified in figure 5, which shows the experimental and neoclassical particle fluxes for the QHS plasma. Because of the neoclassical transport reduction with quasisymmetry, the neoclassical flux in QHS is much less than the experimental, suggesting that the particle flux is dominated by anomalous transport.

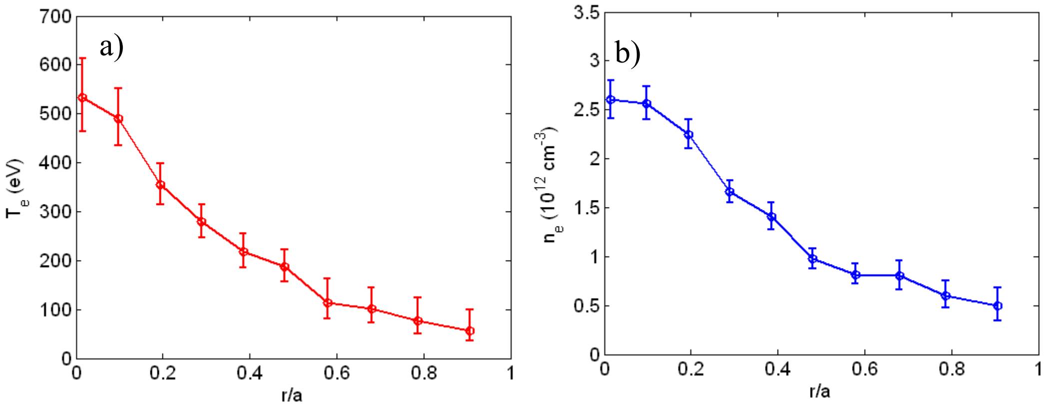

Figure 4: Electron a) temperature and b) density profiles for a QHS plasma with central heating

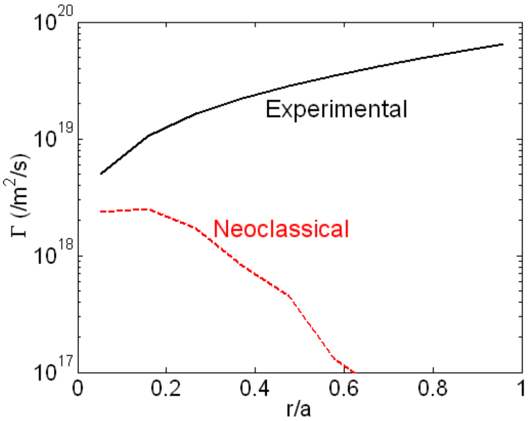

Figure 5: Experimental and neoclassical particle fluxes for a QHS plasma with central heating

3. Electron Thermal Transport

To study thermal transport, measurements of the absorbed power profile have been made. If one assumes that the electron heat flux and all power sources and sinks except for the ECRH power are continuous at the turn-off of the ECRH, then the absorbed power profile can be measured through the time rate of change of the plasma profiles just before and just after the time of the ECRH turn-off (t_0):

$$p_{ECRH} = \frac{\partial}{\partial t}\left[\frac{3}{2}n_eT_e\right]\left(t=t_0^-\right) - \frac{\partial}{\partial t}\left[\frac{3}{2}n_eT_e\right]\left(t=t_0^+\right) \tag{1}$$

This requires time-resolved measurements of the plasma density and temperature profiles, which are obtained on HSX using the Thomson Scattering system. To do this, the time at which the Thomson system makes measurements was varied in increments of 100 µs (compared with the energy confinement time of 1.5 ms). Several similar plasma discharges were taken at each Thomson timing, resulting after many discharges in the time-dependent plasma profiles. The results of this method are shown in figure 6. Each window of the figure represents one spatial location of the Thomson scattering system (1 is on-axis, 10 at the edge), the quantity $(3/2)n_eT_e$ is plotted versus time (t=0 is the ECRH turn-off). Also shown is a fit to the first few data points after the ECRH turn-off, which gives the local absorbed power density. The resulting absorbed power profile is shown in figure 7 for a QHS plasma with central heating. The profile is centrally peaked, and the total absorbed power is about 10 kW, compared to 40 kW injected into the machine. The 25% absorption is consistent with ray tracing, although the profile is somewhat broader than the ray tracing prediction.

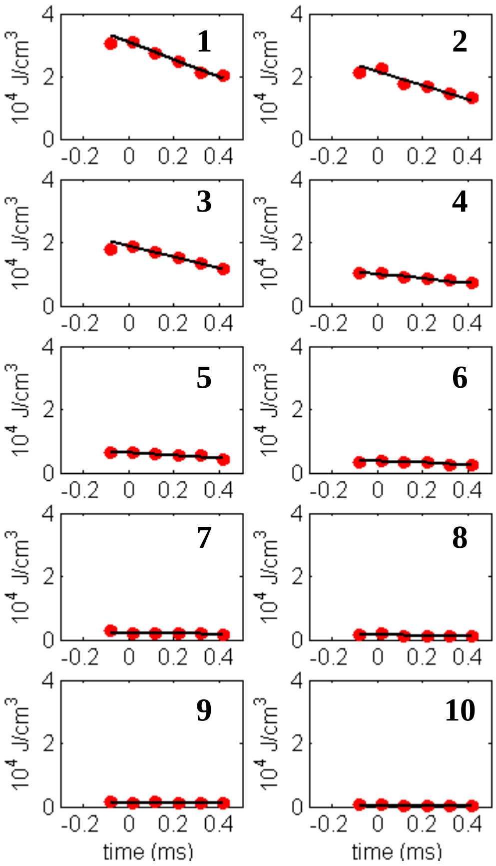

Figure 6: Time-resolved energy density at each Thomson scattering spatial location

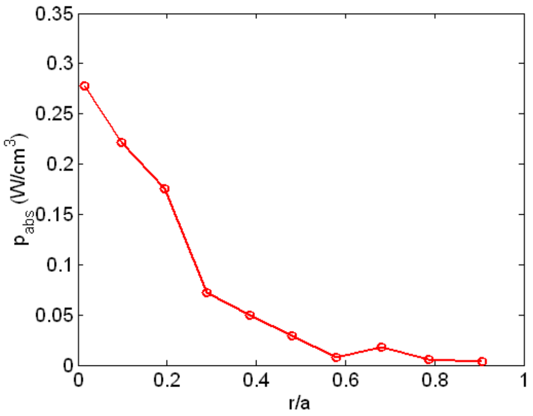

Figure 7: Measured absorbed power density profile for a QHS plasma with central heating

It should be noted that this method cannot be applied to the Standard Mirror configuration: because of the lack of on-axis measurements, much of the absorbed profile would not be measurable. For this reason, this method is applied to plasma discharges taken in the Phase Shifted Mirror configuration, for which on-axis Thomson Scattering measurements can be made. However, in Phase Shifted Mirror the heating is slightly off axis (at r/a ~0.1). Figure 8a) shows the resulting absorbed power and electron temperature profiles for the Phase Shifted Mirror configuration. Neglecting radiation and ion-electron coupling, which are a small fraction of the total power balance at these low plasma densities, the electron thermal diffusivity can be simply obtained using the density, temperature, and absorbed power profiles. The resulting χ_e profile is shown in figure 8b) along with the neoclassical value. The central value of the thermal diffusivity is ~ 3 m^2/s, which is fairly close to the neoclassical prediction in the core.

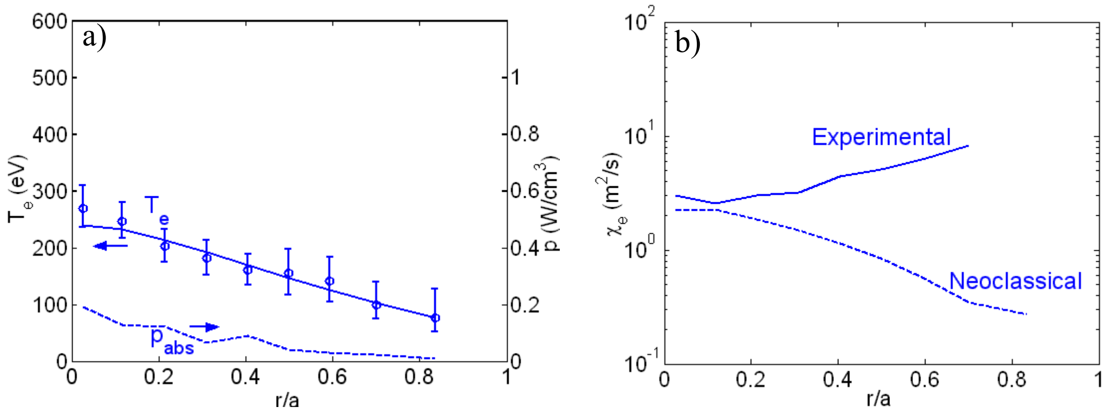

Figure 8: Profiles of a) electron temperature and absorbed power and b) experimental and neoclassical electron thermal diffusivity for a Phase Shifted Mirror plasma

In order to make a comparison to the Phase Shifted Mirror results, QHS plasmas were analyzed in which the heating was localized at r/a ~ 0.1, in an attempt to reproduce in QHS the absorbed power profile from Phase Shifted Mirror. The results of this are shown in figure 9, in which the Phase Shifted Mirror results shown in figure 8 are reproduced for the sake of comparison. The central temperature in the QHS case is much higher than that in Phase Shifted Mirror, being ~ 450 eV compared to ~ 250 eV. The total absorbed power in both the QHS and Phase Shifted Mirror is ~10 kW, so the difference in temperatures is not due to higher absorption in QHS. The χ_e profiles shown in figure 9b) indicate that the difference in temperatures is due to differences in the transport between the two configurations, with the central value of χ_e being ~1 m^2/s in QHS, compared to ~3m^2/s in Phase Shifted Mirror. The difference in the experimental values for χ_e between the two configurations is roughly consistent with the neoclassical differences.

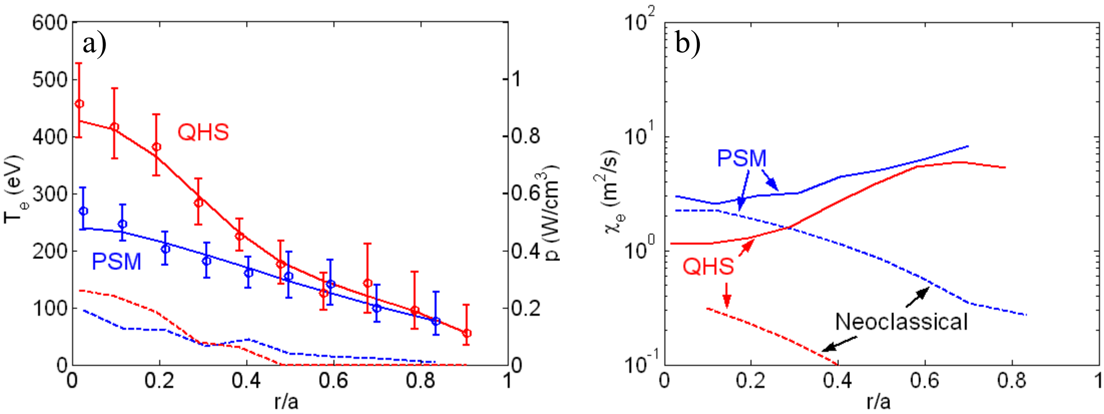

Figure 9: Profiles of a) electron temperature and absorbed power and b) experimental and neoclassical electron thermal diffusivities (solid lines are experimental values) for QHS and Phase Shifted Mirror plasmas

Conclusions

The quasisymmetric magnetic field of HSX has a large impact on the experimental plasma profiles. The density profile in QHS is peaked even with central heating and a very peaked temperature profile. In contrast, the density profile in a configuration without quasisymmetry is hollow, similar to the profiles observed in other stellarators with central ECRH. The differences in particle transport between the QHS and Standard Mirror configurations appear to be due to the reduction of neoclassical transport in QHS: in Standard Mirror, neoclassical thermodiffusion causes the hollow density profile, while in QHS, the thermodiffusive is reduced to a level below that due to anomalous transport.

The temperature profiles also show the effects of quasisymmetry. The central temperature in a configuration without quasisymmetry is ~250 eV, while in the QHS configuration the central temperature is roughly 200 eV higher. The profiles of the thermal diffusivity indicate that the higher temperature is due to the reduction of the neoclassical thermal diffusivity in the quasisymmetric configuration.

References

[1] F.S.B. Anderson et. al., Fusion Technology **27**, 273 (1995)
[2] K. Zhai et. al., Rev. Sci. Instrum. **75**, 3900 (2004)
[3] S.P. Gerhardt et. al., Rev. Sci. Instrum. **75**, 2981 (2004)
[4] D. Heifetz et. al., J. Comp. Phys. **46**, 309 (1982)
[5] J. Canik et. al., 14th International Stellarator Workshop, Greifswald 2003
[6] H. Maassberg et. al., Plasma Phys. Contr. Fusion **41**, 1135 (1999)
[7] H. Maassberg et. al., Plasma Phys. Control. Fusion **35**, B319 (1993)