Chapter 8
Conclusions and Suggestions for Future Work

8.1: Conclusions

This dissertation has presented detailed measurements and modeling of electrode bias induced plasma flows and electric fields in HSX. Brief conclusions from this work are presented in this final section.

From the experimental standpoint, the measurements of flow evolution during electrode bias are among the most detailed ever presented from a fusion device. A biased electrode with a fast switching power supply has been constructed for generating plasma flow; two Mach probes have been constructed to measure the dynamic response of the plasma to the electrode bias. The results show that for the electrode biasing scheme that has been implemented at HSX, there is a distinct asymmetry in the response of the plasma at the turn-on and turn-off of the bias pulse. At bias turn-on, the electrode imposes an electric field on the plasma, and the electrode current and plasma flows respond. At bias turn-off, the electrode current is terminated, and the electric field and plasma flows decay. In each case, the plasma responds with a two time scale evolution. A method has been developed which allows the extraction of multiple time scale information from the measured flow evolution.

HSX is capable of operating in a quasi-helically symmetric (QHS) configuration or in configurations where a large toroidal mirror term in the magnetic field spectrum significantly increases the predicted neoclassical viscous damping (the Mirror configuration). The time scales associated with the flow dynamics have been measured in the QHS and Mirror configurations of HSX. The slower time scale for the flow to rise is longer in the QHS configuration, implying reduced damping of the plasma flows. There is more flow associated with this time scale, further implying reduced flow damping in the QHS case.

A comprehensive array of H_α detectors has been built to monitor hydrogen fueling of HSX plasmas. One array of detectors is located at the toroidal angle of the gas puffer, allowing the penetration of the gas puff to be monitored. A second array of detectors in distributed toroidally around the machine to allow the monitoring of recycling. The data from these detectors is used with the DEGAS[1] code to infer the neutral hydrogen density and the hydrogen source rate.[2]

The second thrust of this dissertation has involved extensive modeling work. The first step in this modeling has been to accurately characterize the Hamada coordinate system for HSX. The Fourier decomposition of the magnetic field strength in Hamada coordinates has been calculated for different configurations of the device. A novel technique has been developed to numerically calculate the Hamada basis vectors for arbitrary toroidal geometry. The lab frame components of the contravariant basis vectors are integrated along a field line, as first described by Nemov for calculating $\nabla\psi$.[3] The initial conditions for this integration are derived by equating a numerical[4] and analytic[5] formulation of the Pfirsch-Schlueter current. This technique has been used to calculate the Hamada basis vectors for the QHS and Mirror configurations of HSX.

The dynamic response of the plasma to the electrode bias has been modeled by solving the continuity equation with the poloidal and parallel momentum balance equations.[6] The radial conductivity and flow direction are predicted by the steady state solution of these equations. Based on experimental observation, a new flow rise model has been developed assuming that a fast increment of the electric field initiates the spin-up process. This causes some flow (the **E**x**B** and Pfirsch-Schlueter like flows) to grow on the time scale over which the electric field is applied, and a second component of the flow (bootstrap like) to grow on a slower time scale. This "hybrid" time scale is determined by damping in both the toroidal and poloidal directions, and is significantly faster than the flow damping in the direction of symmetry. The electrode pulse is terminated by breaking the electrode current; neoclassical modeling of this situation leads to a two time scale flow decay.[6] One neoclassical time scale corresponds to damping of flows in the direction of symmetry, the other to damping of flows across the direction of symmetry and their compensating and force-free flows. The electric field is expected to decay with these two time scales as well.

Detailed comparisons between the neoclassical modeling and measurements have been carried out. The steady state radial conductivity in HSX is anomalous. The measured radial conductivity is ~10 times larger than the neoclassical prediction for the QHS configuration, and ~5 times larger for the Mirror configuration. The model by Rozhansky and Tendler[7] is more accurate in predicting the radial conductivity, illustrating that the radial conductivity in HSX is not dissimilar to that in an L-mode tokamak.

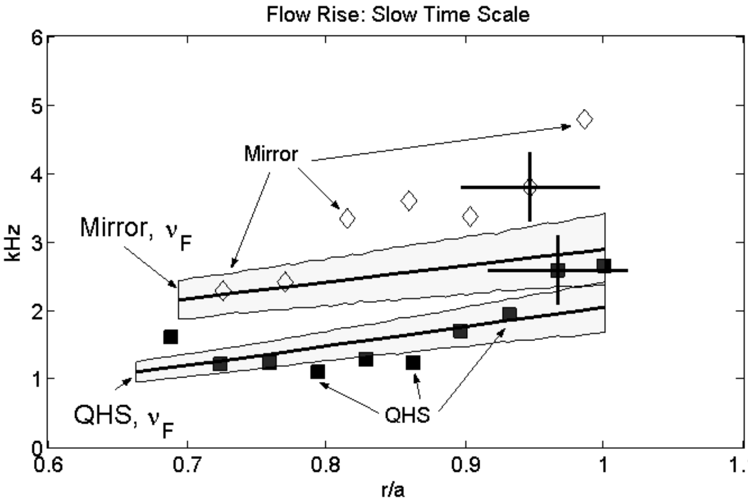

Figure 8.1: Comparison of the measured and modeled slow spin-up time, for the QHS and Mirror configurations.

The modeled "hybrid" spin-up rate (ν_F) is in reasonable agreement with the measured rise rate of the slower flow, both in radial profile and as a function of plasma density. The agreement holds for both the QHS and Mirror configurations. The data for the QHS and Mirror configurations on the low field side are shown in figure 8.1, as well as the modeled rise times. The modeling agrees reasonably well with the measurements, providing the strongest evidence of a reduction of neoclassical flow damping with quasi-symmetry. The spin–up model also predicts the initial spike in the electrode current that is observed in the measurements. The neoclassically predicted direction of the slow flow rise is similar to what is measured, although some discrepancy exists.

The relaxation of the flows and floating potential after the electrode current is terminated is only partially described by neoclassical theory. The fast part of the flow decay and the decay of the floating potential all occur on a time scale similar to the neoclassical fast time scale. The neoclassical slow time scale is not observed in the floating potential decay, and the slower part of the flow decay is much faster than the neoclassical slow time scale. The directions associated with the flow decay cannot be understood from a neoclassical picture.

A final product of this research has been an extensive study of the HSX configuration space. This dissertation has compiled detailed information on magnetic surface shape, plasma volume, vacuum magnetic island locations, rotational transform and well depth profiles, and currents for shifting the ECH resonance. The neoclassical viscous damping has been calculated in many of these configurations. It is hoped that these calculations will assist the students and staff at HSX to more easily and accurately design experiments in the future.

8.2: Directions for Future Work

This work can only be viewed as the beginning of flow and electric field studies in HSX. Many new areas can yet be explored, and some points from this work further clarified. Some ideas along these lines are presented below.

1. Nonlinear Viscosity Studies

One avenue of study involves looking for regimes of nonlinear viscosity, which have been observed in the smaller stellarators IMS[8] and the Tohoku University Heliac.[9] The maxima in the viscosity is predicted to occur when the poloidal Mach number M_P is equal to $|m-Nq|/m$.[10] There is a peak in the viscosity for each of the various terms in the magnetic field spectrum. For a tokamak, the peak should occur at $M_P=1$, while the corresponding value from this simple estimate for HSX is $M_P=3$. A more detailed calculation for HSX yields a value of 4.3.[11] Noting that the poloidal Mach number is defined as $M_P=E_r/v_tB_p$, and using $\bar{\iota}=RB_P/rB_t$, the poloidal Mach number can be estimated as $M_P= E_rR/rB\bar{\iota}v_t$. The parameters for the HSX biased electrode plasmas yield an estimate of M_P as

$$M_p \sim \frac{(300V/.04m)\cdot 1.20m}{.07m\cdot 0.5T\cdot 1\cdot 5e4m/s} \approx 5.$$

This calculation illustrates that the current biasing experiments are in the regime where a bifurcation might be expected. Understanding the lack of bifurcation, or characterizing it should it occur, would represent an opportunity to explore new physics.

The theoretical aspects of these studies would include numerical solutions of the fluid equations using nonlinear toroidal and poloidal neoclassical viscosities. The nonlinear neoclassical viscosity studies in stellarators in the past have always assumed that the toroidal flow is zero.[10] This assumption simplifies the analytic theory, and is based on the notion that the strong toroidal viscosity in a stellarator will damp toroidal flows. This assumption is not well satisfied in HSX according to the data presented in this work. Fortunately, a numerical solution of the fluid equations allows this assumption to be eliminated.

The experimental side of this investigation would involve construction of a new electrode power supply. It would be convenient if the voltages for these investigations were ~5 to 10 times larger than the voltages applied in this work, so that larger M_p could be achieved. Fortunately, these studies would not require the voltage to be applied as quickly as in the work presented here, allowing smaller transients. It is possible that if a bifurcation occurred, it would be accompanied by a transition to some enhanced confinement regime.[12] Even if this transition did not occur, the nonlinear viscosity studies would make the effort worthwhile.

Of critical importance to these studies would be means to achieve better density control during long bias pulses. This could possibly be accomplished by a highly tailored gas feed waveform to suppress the external fueling during the bias pulse. If the particle transport were to be studied in these discharges, it would also be important to determine the sourcing due to recycling from the electrode. It is conceivable that H_α measurements at the electrode could satisfy this requirement.

2. Anomalous Transport

As one of the conclusions of this work is that the flow damping is anomalous, it appears that this represents a topic worthy of investigation. The types of measurements discussed in this work could be repeated with turbulence physics in mind. For instance, plasmas in TJ-II have observed greater turbulence amplitudes when the plasma is placed on a magnetic hill.[13] As shown in Appendix 2, it is possible to place the plasma in HSX on a magnetic hill using the auxiliary coils. The neoclassical damping calculations from Appendix 5 illustrate that the neoclassical viscous damping in these configurations is not significantly different than in the QHS case. Should HSX also have increased turbulence in these configurations, it may provide an interesting configuration for studying the effects of turbulence on flow damping.

3. The Equilibrium Electric Field

It was observed in Section 7.1 that the simple neoclassical model in this research fails to describe the pre-bias equilibrium. The model prediction is that the potential gradient would be balanced by an equal and opposite ion pressure gradient, and that no ion flow will occur. It is observed that both of these gradients point inward, so that the aforementioned balance is not maintained. Hence, the question of what determines the steady state electric field in HSX is unresolved.

The steady state electric field in these discharges has the same sign before bias as during positive bias, when electrons are drawn from the plasma by the electrode. Hence, the data is consistent with there being some non-ambipolar electron loss mechanism. A potential source of this non-ambipolar loss might be electrons driven out of the confinement volume by the ECH. Alternatively, experiments in H-1NF have reported non-ambipolar turbulent fluxes, with enhanced loss of electrons over ions.[14] These and other mechanisms should be explored in an attempt to understand the momentum balance in unbiased HSX plasmas.

Should it become possible to increase the ion temperature in HSX, a new series of experiments would become possible. The neoclassical relationship between potential, pressure, and temperature gradients and plasma flows in a three dimensional plasma has been calculated in very general form,[15] and a simplification to an electron-ion plasma in HSX has been provided in Appendix 6. This theory was applied to the stellarator W7-A, and found to be insufficient to describe the rotation during neutral beam injection. The discrepancy was hypothesized to be due to ion loss orbits, which constitute an effective radial current. As hypothesized in the previous paragraph, HSX may have a situation with a significant number of electrons on loss orbits.[16] Hence, it may be interesting to determine under what conditions the equilibrium rotation in HSX can be described via neoclassical theory without a radial current, and which conditions require the hypothesis of a radial current.

Critical to all of these studies would be accurate measurements of the profiles. This could conceivably be accomplished with retarding field energy analyzers[17,18] for the ion temperature profile, emissive probes for the plasma potential profile, and Mach probes for the plasma flow.

4. Spin-up Model Refinement

Another subject of interest would be the refinement of the spin-up model. At present, the model assumes that the electric field is instantly applied to the plasma. In reality, the electric field information must propagate through the plasma. Preliminary measurements with a fast “rake” probe have shown that the electric field propagates from the edge of the plasma inward on a ~1μs time scale. Hence, for the case of positive bias, which makes an outward pointing electric field in steady state, there is a fast inward pointing electric field as the potential change propagates from the plasma edge to the electrode surface. Consideration of these dynamics might, for instance, explain the deviations between the neoclassically predicted fast flow rise direction and the measurement.

At a minimum, these studies would involve designing a new rake probe for detailed floating potential profile measurements (the one described above has been disassembled). Digitizing the floating potential at a very rapid rate (>2MHz) would be necessary to cleanly observe the effect.

5. Increased Damping in the Vicinity of Magnetic Islands

This dissertation has also presented extensive calculations of the neoclassical damping due to magnetic islands (in Appendix 5). This would be a difficult experimental topic, but may be worth studying. These studies would be most easily accomplished by looking at the effects of the $\iota\!\!\!-=4/4$ or 8/7 islands in the Hill and Well configurations. Appendix 5 illustrates that the fast time scale is most affected by the presence of the islands, and it is in this quantity that the impact of the islands would probably be observed.

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