OBSERVATION OF NEOCLASSICAL TRANSPORT IN REVERSE SHEAR PLASMAS ON THE TOKAMAK FUSION TEST REACTOR

P. C. EFTHIMION, S. VON GOELER, W. A. HOULBERG[**], E. J. SYNAKOWSKI,
M. C. ZARNSTORFF, S. H. BATHA[+], R. E. BELL, M. BITTER, C. E. BUSH[**],
F. M. LEVINTON[+], E. MAZZUCATO, D. MCCUNE, D. MUELLER, H. PARK, A. T. RAMSEY,
A. L. ROQUEMORE, AND G. TAYLOR

Princeton Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08543

Abstract

Perturbative experiments on the Tokamak Fusion Test Reactor (TFTR) have investigated the transport of multiple ion species in reverse shear plasmas. The profile evolution of trace tritium and helium, and intrinsic carbon indicate the formation of core particle transport barriers in ERS plasmas. There is an order of magnitude reduction in the particle diffusivity inside the reverse shear region. The diffusivities for these species in ERS plasmas agree with neoclassical theory.

1. INTRODUCTION

Core transport barriers have been formed in many tokamak plasmas with reversed or weak magnetic shear [1-4]. While these enhanced core confinement states may provide a path to a more economical tokamak-based fusion reactor, the possibility of reduced and even neoclassical transport in the core make it essential to ascertain the nature of working ion transport and its relation to the transport of helium ash, background impurities, and thermal energy. For example, if neoclassical transport processes are dominant in the core, then the interplay between the impurity fluxes and the fluxes of the fuel ions will play an essential role in determining fueling efficiency. In addition, the question of whether the benefits of favorable energy transport are outweighed by helium ash retention is of significant concern if neoclassical processes prevail, especially if confinement in the electron thermal channel is not significantly improved.

To improve the understanding of the particle transport in reverse shear plasmas, a series of perturbative transport experiments with multiple ion species was performed [5]. The experiments provide characterization of the ion transport to supplement the electron transport results. Tritium and helium gas puffs were injected into the steady state period of reverse shear plasmas. On TFTR, tritium operation provided a unique tool for studying hydrogenic ion transport [6]. The tritium density was inferred from the measurement of the 14 MeV t(d,n)α neutrons. Helium and carbon density profiles were measured by charge exchange recombination spectroscopy (CHERS) [7]. The study of multiple ion species provides a stringent test of transport theory. In addition, measured time-dependent profiles and fluxes of carbon, the dominant impurity on TFTR, were measured routinely. Neoclassical theory predicts that the transport of these ions should be much faster $[O(m_i/m_e)^{1/2}]$ than the electron transport because their behavior is governed by collisions with the deuterium and major impurities (e.g. carbon in TFTR) rather than collisions with the electrons. Therefore, these studies may determine if ion particle transport is governed by neoclassical effects or by microinstabilities that lead to comparable transport of electrons and ions.

To examine if the tritium, helium, and carbon transport approaches neoclassical values, we utilized the NCLASS code [8]. NCLASS is a multi-species fluid model for the steady state parallel and radial force balance equations. The bootstrap current, electrical resistivity, and particle and heat fluxes are evaluated in terms of the rotation velocities, friction and viscosity utilizing the measured profile data and plasma equilibrium.

2. TRITIUM AND HELIUM TRANSPORT

The tritium density profile evolution for the ERS and RS plasmas following a tritium gas

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[**] Permanent address: Oak Ridge National Laboratory, Oak Ridge, TN 37830.

[+] Permanent address: Fusion Physics and Technology, Torrance, CA 90503.

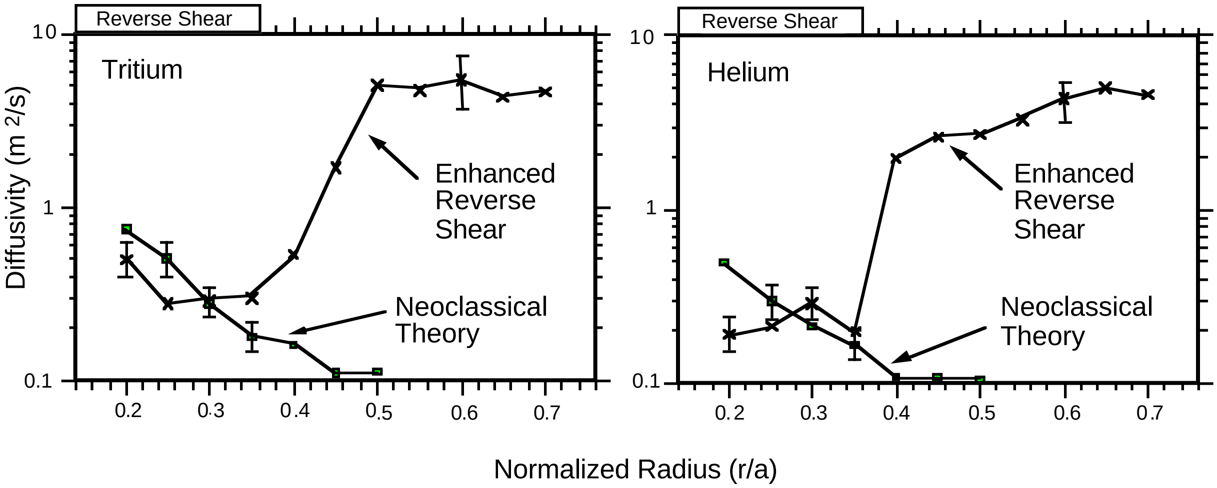

Fig. 1 Comparison of the helium and tritium diffusivities and neoclassical predictions in ERS plasmas.

puff (0.016 s) were compared in reference [5]. The RS profile fills in and becomes flat in ≈ 0.05 s. In contrast, the profile in the ERS plasmas is still hollow after 0.13 s. Eventually the profile becomes peaked by 0.18 s as a result of the plasma outside the reverse shear region diffusing away and not by inward transport. While the profile is still hollow there is a steep density gradient that moves slowly into the reverse shear region. The slow filling in of the profile in the presence of the density gradient is indicative of a particle transport barrier. The helium density evolution is very similar to that of the tritium in the ERS plasma. Its profile also remains hollow for a long period of time in the presence of a steep density gradient which is indicative of a core transport barrier.

The tritium and helium profile data were analyzed using perturbation techniques that ascertain the diffusivity and convective velocity. The details of the analysis are also described in reference [5]. The tritium diffusivities for the RS and ERS plasmas are similar outside the reverse shear region, but inside the reverse shear region the ERS diffusivities are lower by an order of magnitude. Although the tritium diffusivity has been dramatically reduced, it is still a factor of 20 times larger than the effective diffusivity for the electrons. Furthermore, it has previously been shown that plasma fluctuations are very small in the reverse shear region of the ERS plasma, while in the RS plasma the fluctuations can be characterized by large bursts [9]. The reduced electron transport and the suppression of fluctuations motivated comparison of the tritium diffusivities with neoclassical predictions. Figure 1 compares the tritium and helium transport in ERS plasmas with their neoclassical values. The details of the diffusivity profiles are similar for tritium and helium. There is an order of magnitude reduction in particle diffusivities for both helium and tritium across a small region of the plasma radius that is indicative of transport barriers. Within the reverse shear region, the measured diffusivities are comparable to neoclassical predictions. The error bars in the diffusivities were calculated by propagating the uncertainties in each of the experimental profiles. In contrast, the tritium diffusivities in RS plasmas are more than an order of magnitude greater than NCLASS predictions. The neoclassical predictions are lower in RS than in ERS plasmas, due to lower collisionality.

The tritium convective velocities in the RS and ERS plasmas are similar outside the core. The RS plasma has an inward core pinch (≈ 4 m/s) while it is negligible in the ERS plasma. The smaller pinch in the ERS contributes to the slower inward flow of tritium into the reverse shear region. However, the dominant factor in the slower inward transport is the smaller diffusivity.

3. CARBON TRANSPORT

We have also examined carbon transport in both RS and ERS plasmas. The carbon density profile was routinely measured using CHERS. Carbon is the dominant impurity in TFTR. To study the carbon transport it is necessary to examine a large fractional change in its density. This occurs during (1.9 - 2.3 s) and after (t = 2.3 - 2.7 s) the high powered neutral beam-heating phase at 28 MW.

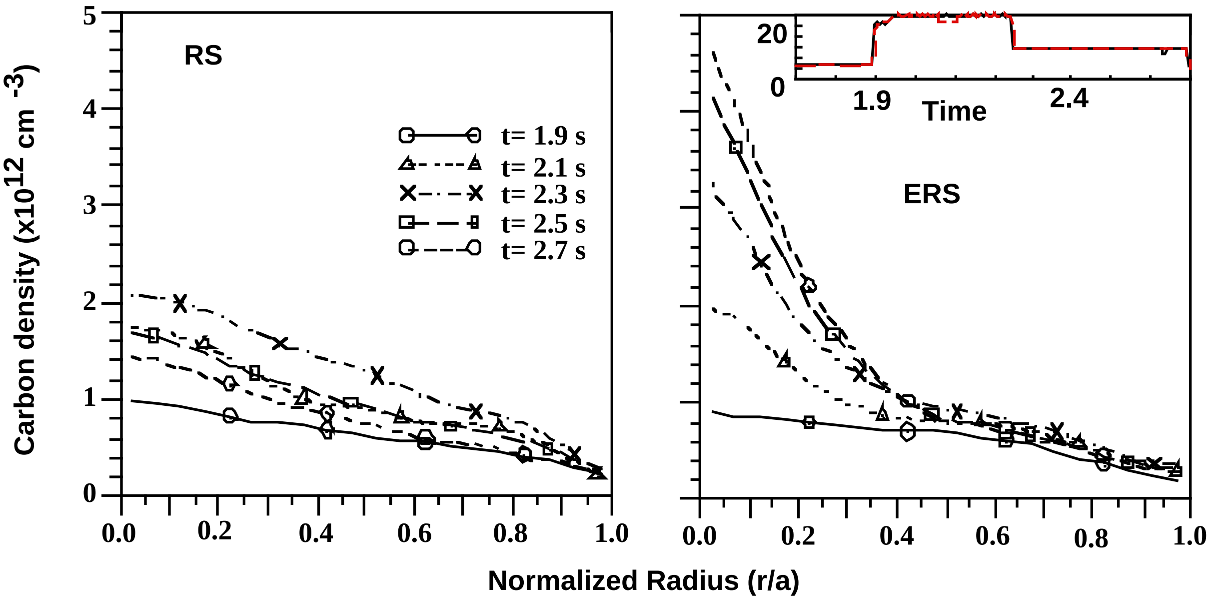

Fig. 2 Evolution of the carbon density profiles during and after neutral beam heating phase (28 MW) in RS and ERS plasmas. The time series of neutral beam heating is inserted in ERS graph.

Figure 2 shows profiles of the carbon density for RS and ERS plasmas during these times. These are the same plasmas used to study the tritium transport. Also inserted in the ERS graph is the neutral beam heating time series. The beam heating before the high power phase (t < 1.9 s) establishes the reverse shear and the heating after the high power phase (t > 2.3 s) maintains a steady state plasma.

At the beginning of the high powered heating phase (t = 1.9 s) the carbon profiles are very similar for both the ERS and RS plasmas (Fig. 2). In the ERS plasma there is a bifurcation at t = 2.05 s to a state with improved core confinement. At t = 2.1 s both plasmas have similar central carbon densities, but the ERS plasma is more peaked within the reverse shear region (r/a < 0.35). At the end of the high powered heating phase (t = 2.3 s) the carbon profile in the ERS plasma is very peaked and has 50% higher central density than the RS case. With the reduction of the beam power at t = 2.3 s to 14 MW, the carbon influx from the carbon limiters is reduced, resulting in the carbon profile in the RS plasma relaxing to lower densities at all radii. However, the carbon profile within the reverse shear region of the ERS plasma continues to peak and slowly increases through the remainder of the neutral beam heating phase (t = 2.7 s). This central carbon density rise is slightly faster than the rise in the central electron density. Clearly, the carbon profile in the ERS plasma with a large gradient within the reverse shear region (r/a < 0.35) exhibits a transport barrier. The strong peaking of the central density with an edge particle source requires the carbon particle transport to have a strong inward pinch component.

The perturbative transport analysis is applied to the time dependent carbon density profile of the ERS plasma. Unfortunately, the change in the density gradients in the RS plasma is not sufficient for the application of the perturbation analysis. Figure 3 is a comparison of the carbon diffusivity and neoclassical predictions from NCLASS in ERS plasmas. As is the case for helium and tritium, the carbon diffusivity within the reverse shear region is consistent with neoclassical predictions from NCLASS. A comparison of theory and experiment at r/a < 0.2 is problematic for all species because the poloidal field and density gradients on axis are uncertain in ERS plasmas. The perturbation analysis also indicates an inward core carbon pinch in the ERS plasma on the order of 1.5 m/s. This was not observed in helium or tritium. Shortly after the bifurcation the pinch provides sufficient inward flux to exceed the outward diffusion and peak up the carbon profile. NCLASS also predicts an inward carbon pinch, but is stronger (4 m/s). This prediction has a large uncertainty because it is determined by the gradient in the deuterium profile.

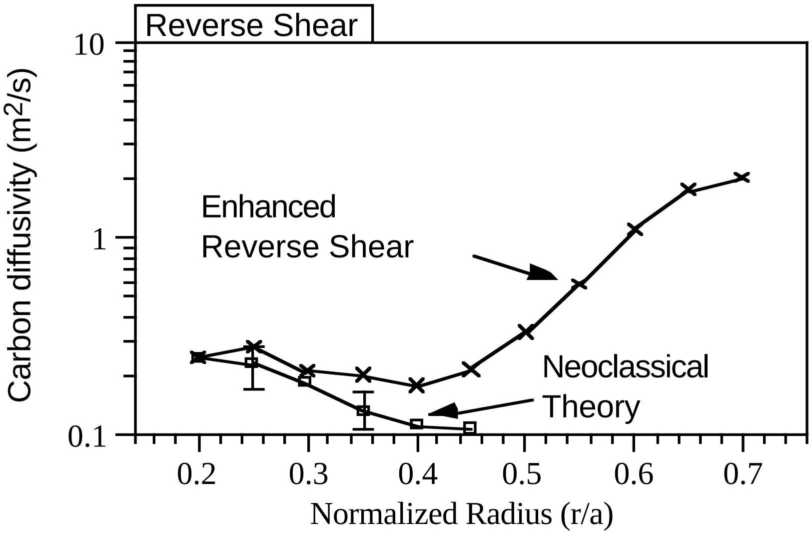

Fig. 3 Comparison of carbon diffusivity and neoclassical predictions in ERS plasma.

4.0 DISCUSSION AND CONCLUSIONS

The particle transport of several ion species (T, He, C) has been studied in reverse shear plasmas. In ERS plasmas the density evolution of the ion species indicate the presence of transport barriers [5]. The transport results complement and support previous observations of suppression of fluctuations and reduction of electron particle and thermal ion transport in plasmas with reverse magnetic shear [1,2,9]. The perturbative experiments have distinguished the contribution of the diffusive and convective components [5]. For tritium and helium the good core confinement is due to low outward diffusion. Neither of these species exhibited peaked profiles with edge fueling. This is not true for carbon, which becomes peaked with an edge source. It has a low diffusivity and a substantial inward pinch, which is responsible for the density peaking. The diffusivities for T, He, C ion species are consistent with neoclassical theory. In particular, the measured and neoclassical diffusivities are in good agreement except on axis where the poloidal field is uncertain.

Since the helium density exhibits a transport barrier, there is a concern that a reactor utilizing reverse shear will have a problem with helium ash accumulation. In steady state and in the absence of a significant pinch, the helium transport will not be a fundamental limiting factor in a reactor if the ash diffusivity is comparable to the effective heat diffusivity (i.e. $D_{He} \approx \chi_{eff}$). Presently there is no good understanding or scaling of the electron heat diffusivity in reverse shear plasmas, and consequently the issue of helium ash accumulation in a reactor with reverse shear is not clear. However, a previous study of neoclassical predictions for a reactor with flat electron density and a slightly hollow fuel profile due to the fusion burn indicates a strong outward convection that limits the central ash accumulation [10].

5.0 ACKNOWLEDGMENTS

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