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Flow Velocity Measurements Using ChERS in the HSX Stellarator

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A Charge Exchange Recombination Spectroscopy (ChERS) system has been used to measure the velocity, density, and temperature profiles of fully stripped carbon impurities in the Helically Symmetric eXperiment (HSX). Velocity measurements have been obtained by reversing the magnetic field between sets of shots in order to reverse the plasma flow velocity. This essentially doubles the Doppler shift of the measured photons. It also eliminates the need to accurately determine the exact wavelength of the unshifted emission line which can depend on plasma conditions. Because two viewing angles are used for each radial location, the velocity magnitude and direction can be determined. The intrinsic velocity is found to move primarily in the direction of quasihelical symmetry with a peak velocity ∼20 km/s. The velocity increases with increasing ECRH power.

1 Introduction

Understanding and controlling plasma flows are critical for stability and confinement in all toroidal plasma confinement devices. Plasma flows have many beneficial properties such as improving tolerance to magnetic field errors [1], and stabilizing resistive wall modes [2] and neoclassical tearing modes [3]. Sheared ExB flows have been shown to quench turbulent transport, creating transport barriers. This effect is especially important in HSX where sheared flow quenching of TEM turbulence has been used to explain the highly peaked electron temperature profiles [4]. Not all flow velocity effects are beneficial. The Kelvin-Helmholz effect caused by large parallel flows can destabilize a variety of modes [5, 6]. An understanding of intrinsic plasma flow is critical. Driving significant plasma flow using external momentum input will be impractical in larger devices such as ITER. This has led to an interest in the effects of 3D magnetic field structures on plasma flow velocity in tokamaks [7] as well as stellarators. Asymmetries in magnetic field strength lead to transport which is not intrinsically ambipolar. A radial electric field arises as ambipolar transport is achieved in steady-state. The radial electric field drives flow in the direction perpendicular to the magnetic field. The direction of the net flow is determined by viscosity. "Conventional" stellarators possess large flow damping in all directions. HSX has a helical direction of approximately constant magnetic field strength. This leads to reduced flow damping in the helical direction of symmetry [8]. In this paper ChERS measurements of large intrinsic flows in the direction of symmetry for HSX are shown for the first time.

HSX is a four field period stellarator with an average major radius of 1.2 m and an average minor radius of 12 cm. The magnetic field is dominated by a n=4, m=1 magnetic field component which is responsible for HSX's unique helical symmetry [9]. Heating of up to 100kW launched ECRH power is available. For the data presented here the magnetic field strength is 1T on-axis. First harmonic O-mode ECRH at 28GHz is used. Hydrogen is injected to create the plasma.

2 ChERS System on HSX

Charge Exchange Recombination Spectroscopy (ChERS) is used to measure impurity ion density, temperature and velocity in HSX. A neutral beam is used to induce spatially localized charge exchange between the beam

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and plasma ions. Most of the exchanged electrons move from an excited energy level to a lower energy level; they emit photons in the process. The intensity, Doppler broadening and Doppler shift of the photons can be used to measure the ion density, temperature and velocity, respectively. On HSX a 4A mp, 3 ms, 30 keV diagnostic neutral hydrogen beam is used. In order to accurately measure the impurity ion density the energy of the beam must be known. It is common for neutral beams to have components which have only a fraction of the nominal beam energy. On HSX the beam components are monitored by a single channel spectrometer. The measured Hα spectrum shows that the beam is primarily monoenergetic.

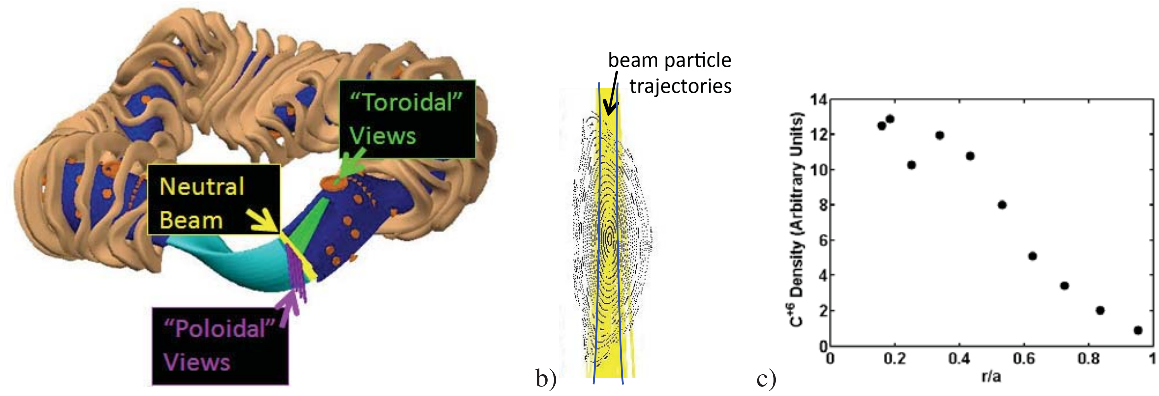

Fig. 1 a) A model showing the geometry of the beam and the two view directions on a section of the machine where coils and vessel have been cut away b) Poincaré plot showing the flux surfaces with neutral beam particle trajectories super-imposed to show the relative beam/plasma geometry c) C^{+6} density profile measured with ChERS. (Color figure: www.cpp-journal.org).

The plasma is observed at 10 radially spaced locations. Each location has a “toroidal” and a “poloidal” view which intersect in the center of the beam, as shown in figure 1a. Each view has collimating optics which produce a 2 cm diameter spot size. Fiber optics couple the light from the views into two 0.75 m Czerny-Turner spectrometers with electron multiplying charge coupled devices (EMCCDs). The two views are not orthogonal to each other. The measured velocities are transformed into velocity components parallel and perpendicular to the direction of quasihelical symmetry defined as:

$$\text{Symmetry Flow} \equiv \vec{\mathrm{V}} \cdot \frac{\nabla|\vec{B}|^2 \times \nabla\Psi}{|\nabla\Psi \times \nabla|\vec{B}|^2|} \tag{1}$$

$$\text{Cross Symmetry Flow} \equiv \vec{\mathrm{V}} \cdot \frac{\nabla\Psi \times \left(\nabla|\vec{B}|^2 \times \nabla\Psi\right)}{|\nabla\Psi \times \left(\nabla|\vec{B}|^2 \times \nabla\Psi\right)|} \tag{2}$$

Where Ψ is enclosed toroidal flux and $\vec{\mathrm{V}}$ is the total plasma velocity. Flow in the radial direction is negligible. The geometric quantities that relate the view directions to magnetic coordinates are calculated throughout the entire beam/view intersection volumes. A weighted average of the geometric quantities is created using the calculated beam distribution. As shown in figure 1b, near the axis, the beam is large compared to the plasma size. This leads to large variations in the geometric quantities. The uncertainty caused by this variation is included in the errorbars on the velocity measurements. An improved analysis method based on the work of Conway et al [10], is being developed to improve the precision of the measurements near the axis.

The data was obtained during discharges where carbonization had been used to condition the stainless steel first wall. In these plasmas a significant carbon population was present. This facilitated the use of the C^{+5} 529 nm spectral line. The EMCCDs are set to integrate a series of 5 ms frames. Background subtraction is performed by averaging the spectra from frames captured before and after the beam fires. This average is subtracted from the frame taken while the beam was firing. Throughout the frames used, electron density and stored energy were constant. The measured Hα emission remained approximately constant at most of the observation locations. In the location closest to the gas puffing valve, the Hα light decreased linearly with time. This is a result of the linear decrease in the gas puffing used to maintain constant plasma density. The total radiated power increased linearly during the frames used. This implies a linear evolution of plasma impurity densities and background plasma light. Therefore averaging the pre and post beam frames should produce a spectrum equal to that of the background light collected during the beam frame.

As shown in figure 1c fully stripped carbon density decreases towards the edge of the plasma. This leads to reduced signal level towards the edge of the plasma. Spectra from several shots must be averaged together to obtain a reasonable signal level from all views. The repeatability of HSX's discharges facilitates the averaging of several shots. The shape of the C^{+6} density profile agrees reasonably well with coronal equilibrium calculations performed using ADAS [11].

A spectral drift throughout the day on the order of 0.1Å has been observed. The drift is corrected using a Ne calibration lamp placed within an integrating sphere which illuminates 2 fibers for each spectrometer. The position of the Ne line is used to spectrally calibrate the system for each plasma shot. Since changes in plasma conditions and excitation can change the ratios of the different fine structure components of the emission line, it is difficult to know the exact value of the unshifted ChERS line. By reversing the direction of the magnetic field all components of the velocity should change direction. By changing the field direction between sets of shots the velocity can be measured without having to know the exact value of the unshifted wavelength. The measured Doppler shift is effectively doubled. This method also removes any errors in the spectral alignment of the individual fiber images.

3 Flows in a Quasi-Helically Symmetric Stellarator

The electron temperature and density profiles measured by Thomson scattering are shown in figure 2. The electron temperature was higher, as expected, in the 100 kW case. An attempt was made to keep the line averaged density, as measured by the interferometer, constant between the two cases, but the Thomson scattering measurements show a somewhat lower density towards the core in the 100 kW case. The ion temperature is much lower than the electron temperature in both cases because the ions are not heated directly. There is no measurable difference between the ion temperature profiles between the two cases. Proton temperature can be assumed to be approximately equal to the C^{+6} temperature. For HSX the proton/impurity ion energy transfer time is on the order of 0.02 ms. This is much faster than the ion confinement time, which is on the order of 3 ms.

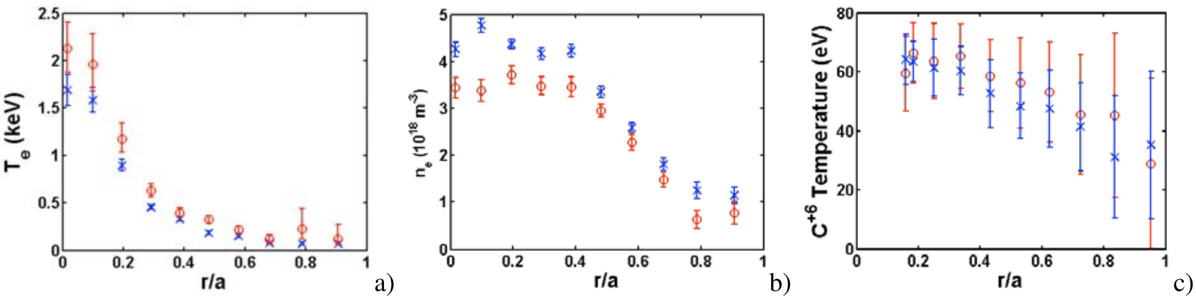

Fig. 2 Plasma profiles for the velocity profiles shown in figure 3b. ◯ 100 kW heating, X 50 kW heating a) electron temperature profiles measured by Thomson scattering b) electron density profiles measured by Thomson scattering c) C^{+6} temperature profiles measured by ChERS. (Color figure: www.cpp-journal.org).

Flow velocity profiles are shown in figure 3a for 50 kW and 100 kW input power. The symmetry flow increases across almost the entire plasma radius when the input power is increased. The cross symmetry flow did not change measurably. All flows shown are intrinsic plasma flows. No external flow drive was used. The neutral beam is aimed perpendicular to the plasma and most of the beam passes through the plasma without interacting. $\vec{E} \times \vec{B}$ and the pressure gradient forces drive flows perpendicular to the magnetic field. Viscosity in the direction perpendicular to the direction of symmetry leads to the appearance of a large parallel flow. If the viscosity in the direction of symmetry was exactly zero, the sum of the parallel and perpendicular flows would produce a net flow that moved completely in the direction of symmetry. This is shown in figure 3b. The measured flows move primarily in the helical direction of symmetry, but have a small component in the cross symmetry direction. This indicates that the actual viscosity in the direction of symmetry is small, but not zero. The diamagnetic flow has been calculated to be small (∼500 m/s) for the impurity ions.

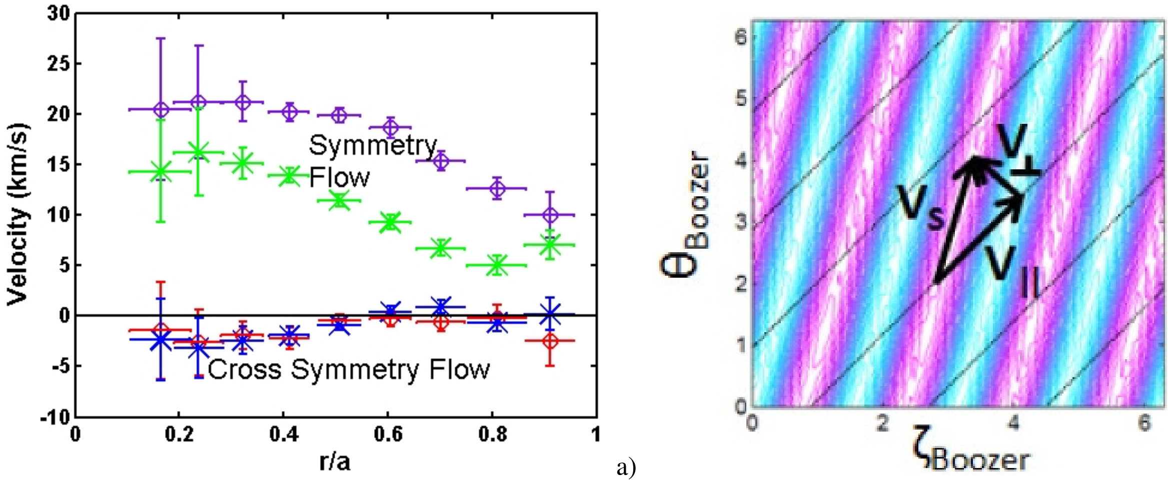

Fig. 3 Flow components a) The measured flow in HSX is primarily in the symmetry direction with a small cross symmetry flow. The flow increases with increasing heating power. ◯ 100 kW heating, X 50 kW heating b) Idealized flow component vectors are plotted over magnetic field strength contours and selected magnetic field lines. If the flow damping in the direction of constant $|\vec{B}|$ was exactly zero then flow driven perpendicular to $\vec{B}$ would lead to the appearance of a parallel flow causing the net flow to move completely in the symmetry direction. (Color figure: www.cpp-journal.org).

4 Conclusions

A ChERS system has been developed on HSX and used to measure flow velocity, ion temperature and impurity ion density. The flow has been found to move primarily in the direction of helical symmetry, consistent with predictions. Flow velocity increased with increasing heating power. The large size of the beam/view intersection volumes relative to the plasma geometry leads to uncertainty in the conversion of the measured velocities into velocity components in magnetic coordinates. Measurements near the edge of the plasma are limited by the weak signal level because of the low C^{+6} density in this region.

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