Investigating Field Aligned Scrape-Off-Layer Flow Structures at MAST with the EMC3-EIRENE Code

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Introduction

Methods for density control are of critical importance for future long pulse tokamaks. The EMC3-EIRENE edge plasma fluid and neutral kinetic transport code is being used to investigate the applicability of 3D non-axisymmetric fields for density control in standard and advanced divertor configurations in spherical tokamaks. Part of this effort is understanding Scrape Off Layer (SOL) transport mechanisms once the axisymmetry is broken. Unique experimental measurements of SOL flow structures at the Mega Ampere Spherical Tokamak (MAST) present an ideal laboratory for comparison and interpretation with simulation results to inform these larger studies.

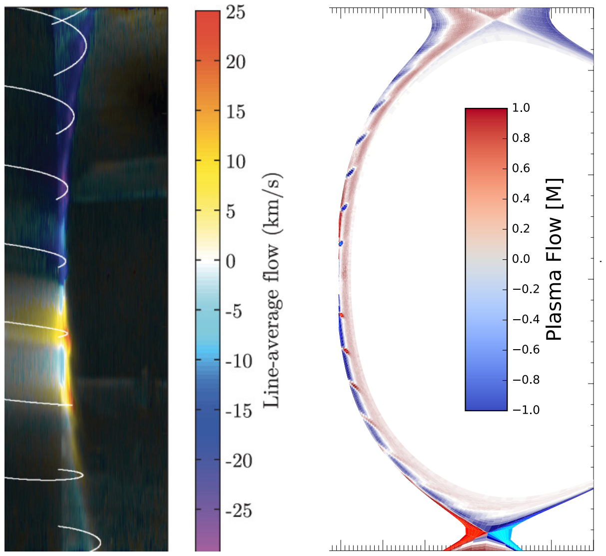

Figure 1: *Image from CIS diagnostic showing field aligned structures in CIII+ (left) with EMC3-EIRENE simulation showing qualitatively similar field aligned flows in the bulk plasma (right).*

Coherence Imaging Spectroscopy Shows Field-Aligned Flows

A Coherence Imaging Spectroscopy (CIS) diagnostic was deployed for the MAST 2013 scientific campaign to measure flows in the SOL [7]. CIS makes use of doppler shifts in impurity ion emission lines, based on the concept of Fourier transform spectroscopy. This technique provides time resolved images with good spatial resolution in 2D–making it ideal for studying localized and dynamic phenomena in the plasma edge [5, 6]. Measurements at MAST looked at Carbon and Helium impurity ion emission lines in the SOL with typical measured absolute flows of 5-30km/s. During the campaign the CIS diagnostic was used to image field-aligned flow structures–like those in Figure 1–that formed during high field side gas puffing experiments [7].

EMC3-EIRENE Simulations Qualitatively Agree with CIS Observations

The EMC3-EIRENE code was then deployed to better understand these novel measurements of high field side structures. EMC3-EIRENE is a fluid edge plasma code, coupled to EIRENE–a kinetic transport code for neutrals. While originally designed for inherently 3D magnetic systems (e.g. stellarators [1]), EMC3-EIRENE has also been used for 3D perturbations to largely axisymmetric systems (e.g. tokamaks with applied resonant magnetic fields [4, 2, 3]), and–of particular interest for this work–has the capability to include non-axisymmetric fueling sources.

A series of simulations was carried out that included the full toroidal and poloidal extent of the MAST edge plasma. Neutral particles were then thermally sourced from a single location on the centre column. Additional fueling via neutral recycling from plasma facing components was then self consistently adjusted to maintain a user defined density at the inner surface boundary of the modeling domain. Power and inner simulation boundary density were held fixed while neutral puffing rates, and cross-field terms were varied. These simulations showed good qualitative agreement with experiment in that the same field-aligned flows were observed around the centre column when high field side neutral fueling was included.

Important plasma parameters such as flow, temperature, plasma density, and plasma source density can be extracted along the entire field line to get a better picture of steady state plasma behavior in the parallel direction. Irrespective of the neutral puffing input rate, similar features are seen in the evolution of the flow in the flux tube. All fueling cases are characterized by a highly localized plasma source, and–as shown in Figure 2–a rapid increase in parallel flow away from the source location in both directions along the field line. This is followed by a more gradual decay of flow further along the field line. While the ionization of neutrals results in a local drop in plasma temperature, the increase in density results in static plasma pressure ($p = n * (kT_e + kT_i)$) increasing dramatically (Figure 2 (bottom)) in the region of the neutral puff, resulting in pressure driven flows along the field lines.

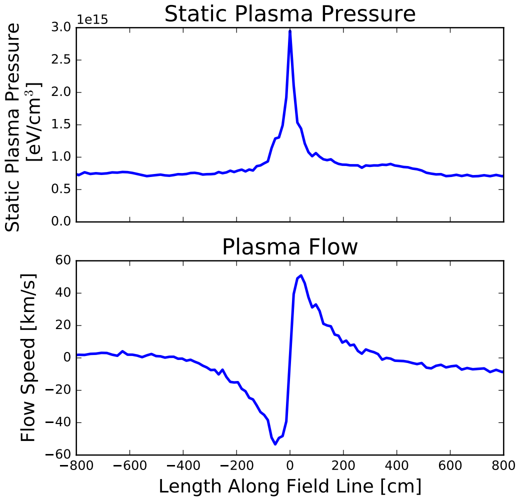

Figure 2: *Static plasma pressure (top) drive flow (bottom) along a field line launched from immediately in front of the neutral puff.*

Perpendicular Diffusion Drives a Decay in Parallel Flow

To better understand the features of the EMC3-EIRENE results, comparative modeling was carried out using a 1D isothermal fluid model (see [8] Chapter 10.2). Particle (Eq. 1) and momentum (Eq. 2) conservation equations were used in an unbounded flux tube:

$$\frac{d}{dx}(nu) = S_{part} \tag{1}$$

$$\frac{d}{dx}(\frac{1}{2}m_i nu^2 + 2kTn) = S_{mom} \tag{2}$$

In this ideal model, a localized particle source leads to pressure driven flows that stabilize and remain constant in these unbounded calculation. By introducing cross field transport losses into the 1D model, behavior similar to EMC3-EIRENE along a field line was recaptured as shown in Figure 3.

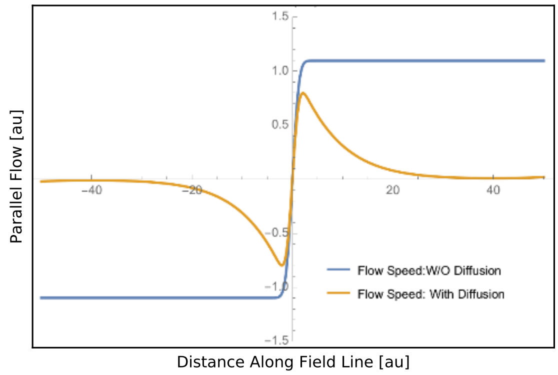

Figure 3: *Flow response to local source in 1D isothermal model with (yellow) and without (blue) cross field diffusion terms.*

To further investigate this behavior, it is useful to look not along a single field line, but along a set of neighboring field lines to build a ribbon of plasma information. This flux ribbon provides a cross section of the behavior in the flux tube from the area immediately in front of the neutral puffing location, to areas deeper into the plasma. By launching field lines from sufficiently close positions (~within one mm from point to point) and constraining our investigation to within ~4 meters of the neutral puffing along a field line, geometric impacts of flux expansion can be ignored.

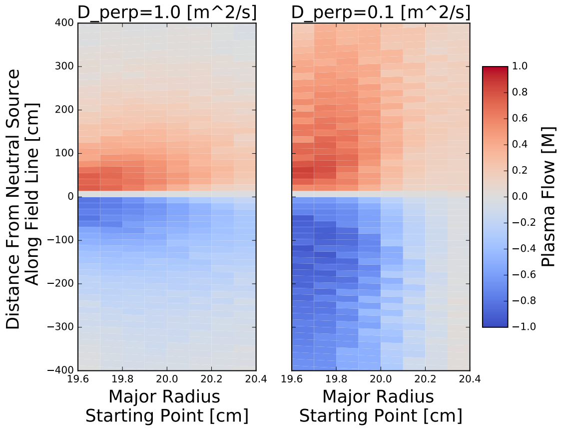

Figure 4: *Normalized parallel flow for two different anomalous cross field diffusion values. Parallel flow rapidly decays with higher diffusion coefficient (left).*

These ribbons can then be used to compare the behavior of the field-aligned flows with varying cross field diffusion rates ($D_\perp$, and $\chi_\perp = 3D_\perp$). In the high diffusion case (left), the flow extends further out across the flux tube but decays much more quickly along the field line direction. The low diffusion case (right) is then characterized by long lived parallel flows. This suggests that the decay is the result of cross field terms between one field line and its neighbors. In the Braginskii equations at the heart of EMC3-EIRENE, the anomalous cross-field transport terms act as a momentum and particle sink in high flow regions which in turn act as a momentum and particle source in neighboring low flow regions. This behavior repeats itself across the flux tube leading to the smooth acceleration of flows across the flux tube and smooth decay along the flux tube.

Discussion and Next Steps

This work provides an opportunity to validate a full 3D plasma edge code against unique experimental measurements. The insights gained from detailed analysis of the modeled results–namely the characteristic decay of the flow along a field line–motivates further analysis of experimental results. Post-processing can extract the speed parallel to the magnetic field lines from the CIS diagnostic results. Field line tracing can then be used to correlate measured flow values with distance along a field line–away from the neutral puff. The experimentally observed characteristic decay length can then be compared with the modeled decay. Work is ongoing to understand observed asymmetry in the experimental measurement between the forward and backward direction along a field line. Further simulations are also being carried out to determine the role of parallel viscosity on the acceleration of flows in explaining differences between models and experimental observations. This experimental comparison also allows for a validation of assumptions about SOL diffusion in edge modeling–independent of Thompson scattering measurements or other codes.

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