Characterizing non-diffusive transport between self-consistent and external shear flows using Lagrangian trajectories

D. Ogata[1], D. E. Newman[2], R. Sánchez[2], J.-M. Reynolds-Barredo[2]

[1] *University of Alaska Fairbanks, Fairbanks, USA*
[2] *Universidad Carlos III de Madrid, Leganés, Spain*

Introduction

Because of the difficulty in using actual tracer particles in hot plasmas, perturbative experiments have for years been used as diagnostics to measure transport characteristics. For instance, pellets, gas puffs, heats pulses and other density or temperature perturbations have often been added to an existing plasma in order to track the plasma flows and transport characteristics inside a device where probes are not appropriate. In turbulence dominated scenarios where non-linear effects become dominant, a small enough perturbation to the system might be able to characterize the real underlying transport characteristics, however, the addition of too large a perturbation can impact the plasma in a way that changes the local transport characteristics.

In this work, we attempt to evaluate both the impact of a local perturbation on transport characteristics and the evolution of that perturbation as a measure of transport within a general non-diffusive transport framework by comparing the evolution of the local perturbation profile with the transport characteristics extracted from the Lagrangian trajectories [3]. There are two principal questions underlying this study: (1) what are the similarities and differences between the evolution of the perturbation profile and the Lagrangian transport characteristics? (2) what is an acceptable local perturbation amplitude before the transport characteristics changes? In order to simulate the scenario, the starting model equations used are based on the drift-wave turbulence equations (DTEM) [2]. To this, a flux driven background profile is evolved in conjunction with fluctuations. Then, a local perturbation is introduced to the background profile, which is evolved with the background profile by the fluctuations.

Model

The starting equations used in this work are similar to the Hasegawa-Wakatani equations [4] where two quantities - density and potential - are coupled through the quasi-neutrality condition. The separated equations relax the adiabaticity constraint between the non-adiabatic electron density and the potential, which permits frequency shifts between the two non-linearities to affect saturation. Properties of the energy cascades in wave number due to the two non-linearities have been discussed [2].

In this work, the fixed gradient scale length as a driving term is relaxed. This model allows for the principal quantity to evolve due to the first order approximation of turbulence, which is the electrostatic $E \times B$ flow. The deviation from existing work stems from the introduction of an evolving background gradient, which is being advected by the $E \times B$ flow solved from the potential equation. The spatially inhomogeneous profile is then fed back as a driving term to the density and potential equations in the form of diamagnetic drift. In effect, the diamagnetic drift becomes spatially inhomogeneous, which allows for an spatially varying saturated profile. As a result, three equations are now being evolved simultaneously - density, potential, and the background profile.

A symmetric flux source and sink configuration allows for the background profile to develop from the $E \times B$ advection. The evolving background profile enables the developed turbulence to interact with locally varying gradients resulting in spatial local variations due to local growth and relaxations. The basic interplay between the background profile and fluctuations allows local gradients in the background profile to be relaxed by the nonlinearly driven fluctuating density and potential. As a result, the flux driven background gradient and therefore turbulence can become inhomogeneous which can lead to self-consistent flows.
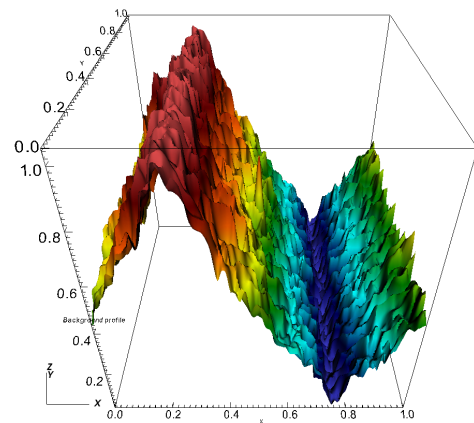

Figure 1: *Background profile with a local perturbation.*

Diagnostics and transport characterization

In order to compare and quantify the evolution of a local perturbation, a distinction between the perturbed and unperturbed states needs to be imposed. For each simulation, a local perturbation is imposed on the nonlinearly saturated state. At this point, the simulation proceeds from the same nonlinearly saturated state in two directions - unperturbed and perturbed. The unperturbed simulation provides a time averaged of the unperturbed background profile, which is then subtracted from the perturbed simulation cases. As a result, the local perturbation profile can be extracted.

The evolution of the local perturbation is extracted by subtracting the unperturbed time averaged profile from the perturbed profile. An example of the extracted local perturbation profile is shown in Fig. 2. A local perturbation in a form of a Gaussian bump is placed in the middle of the simulation box. Currently, a slice through the middle of the box in the poloidal direction

is taken to track the evolution of the profile. The poloidal averaged proves to be insufficient for detection due to the small amplitude as a result of taking the poloidal average. With the extracted local perturbation profile, a functional fitting is applied to the profile in order to reveal its evolution. This method attempts to fit general Lévy-type perturbation profiles, which allows for a direct comparison to the transport parameters obtained from the tracers.

To extract the "true" transport characteristics, Lagrangian trajectories are tracked by passive particles or tracers that follow the $E \times B$ flow. Tracers are collocated with the local profile perturbation in the middle of the simulation box, and they are time advanced according to the $E \times B$ velocity. The trajectories are then used to construct probability densities (PDF) as a function of time, which reflect the propagator of the transport equation [3]. By fitting the propagator, the parameters for the generalized transport equations (α and β) can be extracted and related to the different categories of transport regimes. Propagator fitting allows more attention to the development of the heavy tails in the PDFs.

Figure 2: *Extracted local perturbation profile.*

Preliminary results

The advantage of having an evolving background profile is that a local perturbation study can be implemented by permitting the interplay between the driving mechanism generated from the gradient in the background profile and the developed turbulence. In this manner, a local perturbation can affect the local transport in the region near the perturbation due to the feedback between the background profile and the fluctuating fields.

Results can be separated according to the motivating questions. In comparing the transport characteristics with the evolution of the local perturbation profile, results from the outlined methods show that for reasonable perturbation amplitudes, the local perturbation profile dissipates quickly, making it difficult to adequately analyze the evolution of the tails. The local perturbation profile becomes indistinguishable from the normal variations in the background profile. Hence, the local perturbation is only distinguishable from the variations for a short period of time.

The tracer trajectories are shown in Fig. 3 collocated initially with the local perturbation centered in the middle of the simulation box. The tracers are also collocated uniformly near the
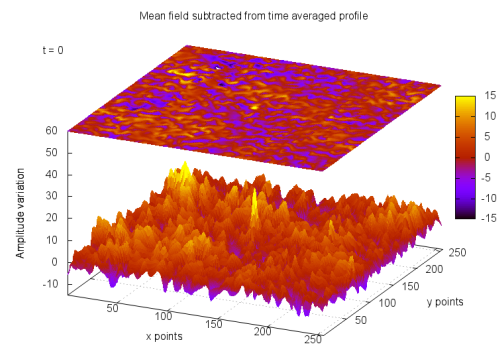
center of the box. As the simulation progresses, the local perturbation decreases within a few time steps whereas the tracers remain relatively localized and just began to spread after the local perturbation has almost completely decay. The interpretation of this is that the tracers follow the flow internal to the perturbation while the profile represent the evolution of the outline of the local perturbation. The tracers are observed to spread slower than the decay of the local perturbation profile, which present some difficulties in interpreting the relations between the dissipation of the local perturbation and the transport properties.

In terms of varying local perturbation amplitude, larger local perturbation amplitudes generate noticeable a local $E \times B$ flow around the periphery where the gradient is the largest. A large enough local perturbation can persist long enough that the tracer statistics also reflect the constrained profile, however this is clearly impacting the transport characteristics. Eventually, the local perturbation profile and the tracers' trajectories dissipates but then become constrained between the source and the sink region.

Figure 3: *Tracer trajectories collocated with the local perturbation.*

This approach shows promise in being able to compare profile perturbation evolution with tracer transport characterization for the transport dynamics. This could allow for experimental evaluation of the transport characteristics using well established perturbation techniques. It also can help inform the experimental perturbation experiments about appropriate perturbation amplitudes for characterization of the real background transport. Techniques are being pursued to get around the issue of the observing the profile perturbation for long enough to fully capture the transport dynamics.
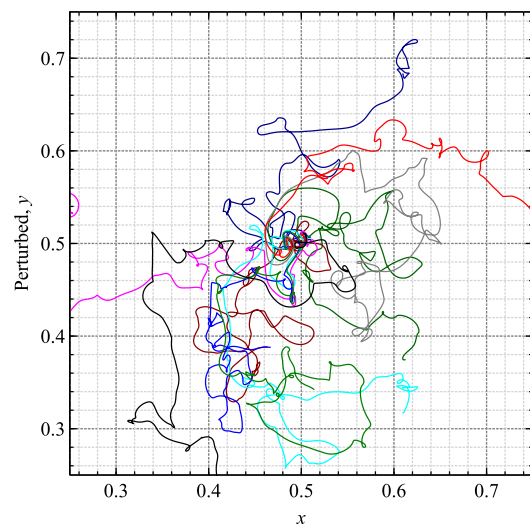
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