2D fluid simulations of interchange turbulence with ion dynamics

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Introduction

In this paper we present a first principle global two-dimensional fluid model. The HESEL (Hot Edge SOL Electrostatic) model is a 2D numerical fluid code, based on interchange dynamics and includes besides electron also the ion pressure dynamic. In the limit of cold ions the model almost reduces to the so-called ESEL model, which has successfully modeled profiles in JET [1], and profiles and fluctuations in MAST [2], EAST [3] and TCV [4]. It is a four-field Braginskii model including generalized vorticity, density, electron and ion pressure equations. The generalized vorticity consist of an ExB vorticity as well as the ion diamagnetic vorticity. The 2D domain includes both open and closed field lines and is located on the out-board midplane of a tokamak. On open field field lines the parallel dynamics are parametrized as sink terms depending on the dynamic quantities; density, electron and ion pressures and generalized vorticity.

Model

The numerical scheme is embedded into the the older ESEL numerical scheme. It is a finite difference scheme with second order accuracy in space and third order in time, employing a stiffly stable integration scheme. All non-linear terms are evaluate as Arakawa bracket [5]. The domain is decomposed into radial sub-domains enable us to parallelize the code using MPI. For large resolutions, 1536×512, we are able to use up to 64 CPU's obtaining nearly a linear speedup.

Beside the ion pressure equation we have included other dynamics compared to the ESEL scheme. A background level for both density and temperatures have been included. Typically we are using $n_b = 2.5 \times 10^{-17}\text{m}^{-3}$ and $T_{i,b} = T_{e,b} = 1\text{eV}$. If any of these field drop below its background value we force this field with a characteristic time of $\tau_b = 1\mu s$, until it retain its background value again . In order to minimized the effect of in the inner wall we have doubled the size of the edge region. In this new part of the simulation domain we force the poloidal averaged profiles toward pre-described profiles, leaving the fluctuation untouched, and which characteristic time of $\tau_{\text{profile}} = 1\mu s$.

A more dramatic change than the above is that we apply sheath condition on the generalized vorticity in the open field line regions, e.g. the SOL and the wall regions. During the turbulence interaction momentum cascades either towards smaller wavelengths, where collisional effects remove the energy or it cascades towards $k_y = 0$, where collisional effects are weak and momentum leave the system by slow parallel loss to the divertor. In ESEL we could observe quite high poloidal velocities reaching values comparable to ion acoustic velocity, C_s, a feature not seen in experimental observations. On the outboard midplane we typically observe fluctuations with perpendicular length scales of $\delta_b \sim 1$cm and these scales, or blobs, moves with a speed of some percent of the ion acoustic speed, $V_b \sim 0.05C_s$. The time it takes a fluctuation to travel its own width are thus comparable to the time an Alfven wave takes to travel from the outboard midplane to the divertor and back again along a magnetic field line, e.g. $\delta_b/V_b \sim 2L_{\|}/V_A$. We therefore assume that fluctuations are uncorrelated with the condition at the divertor. The background vorticity profile, and thus also the potential profile, on the other hand, evolves on a much slower time scale than the fluctuations and we thus assume that the profile feel the full effect of sheath condition at the divertor. In the generalized vorticity equation we have thus included the sheath conditions in the SOL and wall region as

$$\frac{\partial \omega^*}{\partial t} ... = ... \frac{enC_s}{L_{\|}}(1 - \exp(\psi_m - \frac{e < \psi >}{< T_e >})), \quad (1)$$

where $\psi_m = log(\sqrt{\frac{Am_i}{\pi m_e}})$. The brackets, <f>, denotes running average, see [6], of the radial profile of f; $A_n = \delta t \alpha f + (1 - \delta t \alpha) A_{n-1}$. Here $1/\alpha$ is chosen to be an Alfven transient time, $\sim 2L_{\|}/V_A$. For $\delta t \to 0$ we obtain the solution $A(t) = \int_{-\infty}^{t} f(r,t') \exp(-\alpha(t-t'))dt'$.

Results

We present numerical results based on typical EAST parameters in L-mode (shot 22111); density $n_0 = 0.5 \times 10^{19}\ m^{-3}$, electron temperature $T_{e,0} = 20$ eV, magnetic field strength on axis $B_0 = 2.0$ T, safety factor $q_0 = 10$, major radius $R = 1.65$ m, minor radius $a_0 = 0.35$ m and width of SOL $\Delta_{SOL} = 2.4$ cm. The ion temperature is not know from experiment, but is assumed to be $T_{i,0} = 25$ eV. All quantities, except magnetic field, refer to the Last Closed Flux Surface (LCFS) values.

Figure 1 display a snapshot for $t = 2.36$ ms. The figures capture a large event, a blob, being ejected from the edge area into the SOL. From the density plot we observed that the blob is very well separated from the background with sharp and large gradients on the edge of the blob. The two temperature fields, to some extent, also exhibit this feature but they are more fuzzy on the edges. This is especially true for the ion pressure, where, even though the blob just being created, it has already decayed significantly, due to perpendicular diffusion. This reflects that the collisional terms are not equal and for this shot we find; $D_n = 0.022m^2/s < D_{p_e} = 0.049m^2/s << D_{p_i} = 0.58m^2/s$.

Figure 2 show the time traces for a numerical probe positioned just outside the LCFS. At the time of the snapshot for Fig. 1, $t = 2.36$ ms, we observed a positive signal in all the traces. The traces of the 3 fluxes are very intermittent, for most of the time they are oscillating around a zero value, interrupted be notable peaks of positive burst.

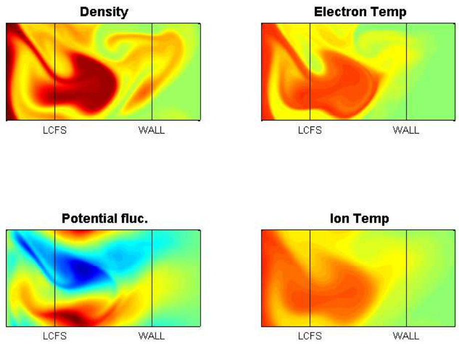

Figure 1: *Snap shot from a HESEL simulation using EAST parameters from shot 22111, time*=2.36*ms*

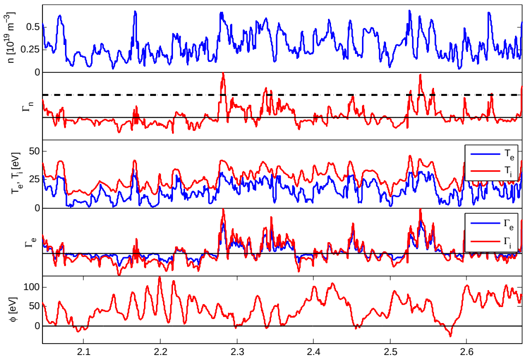

Figure 2: *Time evolution of the density and pressures with their corresponding fluxes and electric potential at a radial positions $r = 7$ mm in the SOL.*

We have employed a conditional average technique[7] for the time signals in Fig. 2 using numerical probes positioned radially across the SOL, see Fig. 3. This technique is widely used in analyzing experiment obtained data from e.g. Langmuir probes. In the density case we can observe a blob, which is hardly changed from it emerges into the SOL, blue curve, and till it leaves the SOL and enters into the Wall region, light green curve. We can therefore conclude that the density of a blob is mostly unaffected by both parallel dynamics and perpendicular collisional in this model. For the electron temperature case we can observe a notable larger width of the average structure. We ascribe this to collisional effects due to $D_n < D_{p_e}$. As the maximum value of the structure stays roughly constant during its transition of the SOL, we conclude that the parallel dynamics do not play any significant role during the transit of the structureand it will enter the wall region with a significant part of the electron energy intact. For the ion temperature case we do observed a drop of maximum value of the ion temperature, as the structure propagate through the SOL. For this field both parallel dynamics and perpendicular collisional effects must this be important.

Summery

The new model display very promising results regarding fluctuation data. Compared to the older but very successful ESEL model we now have included ion dynamics from first principal.

We thus have a tool which allow us to test ion dynamics again experimental obtained probe data from a large set of tokamaks; EAST, ASDEX, COMPASS, JET etc. Recent measurements of T_i in SOL in ASDEX Upgrade using a retarding field analyzer, see [8], reveal that ion temperature are generally larger than electron temperature regarding profiles, which to some extend we also observe in this model. Experimental data on the fluctuating part of the ion dynamics is unfortunately not avaiable at present but several promising diagnostics have potential to give such data, like a retarding field analyzer [8] and Ball-Pen-Probes [9].

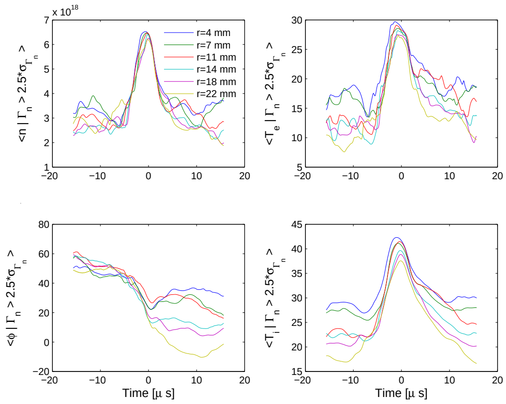

Figure 3: *Conditional average signal for (a) density, (b) electron temperature, (c) electric potential and (d) ion temperature using the particle flux,* $\Gamma_n = n * v_r$*, as condition, see Fig. 2 (b).*

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