# Fluid simulation of the Farley–Buneman instability

Enrique Rojas*[1] and David Hysell[1]
(1) Cornell University, NY, USA.

## Abstract

In the present work we summarize our results on simulating Farley–Buneman instabilities for the first time using a fully fluid thermal model.

## 1 Introduction

The magnetosphere couples with the high-latitude ionosphere through the Earth's magnetic field lines. This coupling occurs mainly through energetic particle precipitations and electromagnetic fields. In the auroral E region, these processes cause Hall currents that drive Farley-Buneman instabilities, generating a spectrum of field-aligned plasma density irregularities [1]. Although fully kinetic particle-in-cell (PIC) simulations of Farley-Buneman instabilities offer the most complete description of the underlying physics, its computational cost for studying non-local phenomena is tremendous. To capture non-local physics, new methods based on hybrid and fluid approaches have to be explored.

In this work, we will summarize our results using a fully fluid model where the role of Landau damping is emulated by the inclusion of a fluid operator. For this summary, we focus on illustrating some of the nonlinear features from our simulation that are aligned with experimental observations. Due to space limitation we will omit some plots but comment on the results nevertheless. Finally, we will briefly describe some applications of these new fluid solvers.

## 2 A Fluid Model With A Twist

As is usually argued in the literature, Farley–Buneman instabilities evolve mostly aligned to the plane perpendicular to the geomagnetic field [1]. Furthermore, its plasma can be characterised by magnetized, drifting electrons and unmagnetized ions on a electrostatic field. Although this scenario is well captured by a five moment fluid model, linear analysis shows that smaller wavelengths have a larger growth rate, which makes the fluid approach unfit. Nevertheless, by adding kinetic effects we see that these larger wave modes are Landau damped, for this reason PIC methods have been most often used for this task.

Eliasson [2] proposed a fluid operator to capture some of the physics of linear Landau damping and used it for solving the Zakharov equations. This operator was added as a

viscosity term in the momentum equation and was proportional to

$$\nu(k) = -C_s \left( \frac{T_e}{T_i} \right)^{3/2} \exp -\frac{T_e}{2T_i} |k| \qquad (1)$$

in Fourier space. As usual, $C_s$, $T_e$, $T_i$, and $k$ indicate the ion acoustic speed, electron temperature, ion temperature, and wave vector, respectively. Moreover, in the linear regime, it can be shown that 1 corresponds to the ion linear Landau damping. Notice that it produces a decreasing damping rate as the electron temperature grows larger than the ion temperature, as expected.

We assumed that the regularization proposed by Eliasson captures enough damping to stabilize the system and used the five moment equations with this added viscosity term. Because this system can be taken as periodic bounded and no shocks are expected, we decided to use a spectral solver.

## 3 Simulation Setup And Results: Some Highlights

In order to compare our simulation results to a PIC simulation, we replicated the plasma parameters used by Oppenheim [3]. These parameters correspond to normal conditions on the E-region but to an overestimated background electric field and larger electron mass. These two artificial parameters were chosen to accelerate the instability onset.

Figure 1 shows a snapshot of the evolving system during linear growth. The first plot in the upper left shows a normalized electron density perturbation. Notice that the maximum perturbation is indicated within the plot and just below, a dotted line that correspond to a cut in the density profile expanded in the plot just below this one. The two plots on the first row on the right, show the ratio between the anomalous convection speeds induced by the instability and the local ion acoustic speed. Colored regions indicate that the threshold for instability has been reached and secondary unstable growth is expected. If the number is larger, the growth will be faster. Below these, in the second row, you can see on the right, the power spectra of half of the wave number domain and on the left, a zoom around the dominant wave modes. Finally, at the bottom we have the time series of several relevant parameters, the root mean square electric field and density perturbation together with

the average electron (dashed) and ion (smooth) tempera-
tures. The black dashed line corresponds to the background
electric field, which was set to vary from a value below the
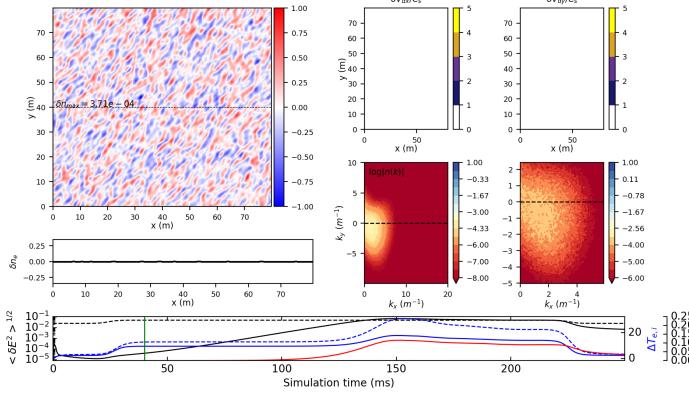instability threshold, to 50 mV/m and back.



**Figure 1.** Linear growth.

As expected, during linear growth there are not secondary
waves growing perpendicular to the $E \times B$ (x axis). Notice
how the power spectra shows the damping caused in part by
the Landau proxy. Figure 2 shows the system after satura-
tion. Here we can see that secondary instabilities are been
generated by anomalous convection mostly in the y direc-
tion and to a less extent in the x direction. The structuring
of the electron density perturbations is remarkably similar
to what is obtained by PIC simulations. Furthermore, no-
tice how the local density perturbations in the section plot,
are effectively evolving around the values expected from
radar and rocket measurements. The power spectra of $n(k)$
shows a dominant wave mode and a dynamical range of
a couple orders of magnitude resembling the values from
PIC simulations. Moreover, see how the perturbation elec-
tric field saturates at values close to the background field
and the density saturates at around ten percent of the back-
ground density, as expected. Also, we can see that there is
a clear wave turning effect, as reported by PIC simulations
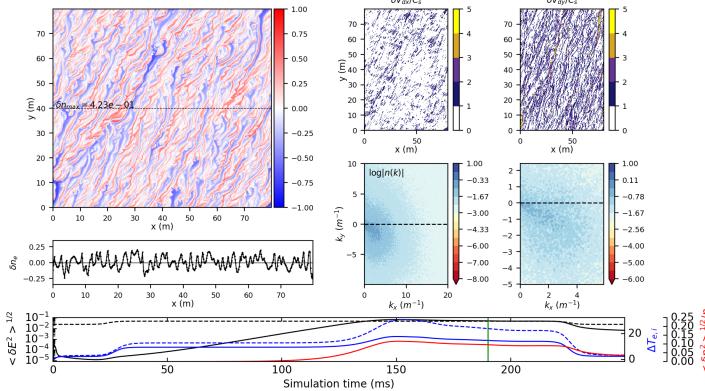and related to thermal instabilities.



**Figure 2.** After saturation.

Finally, although not shown in these plots, we also have
measured the saturation of wave phase speed, closer to the

ion acoustic speed, as measured with coherent back-scatter
radars. It is important to notice that the computational cost
to solve this system is a fraction of the cost required for a
PIC solver with similar parameters.

## 4 Some Conclusions And Future Work

We have shown that a fluid plasma model can capture the
salient features of Farley–Buneman instabilities when a
Landau damping proxy is added. Furthermore, it is impor-
tant to notice that this system can be significantly simpli-
fied, for instance by reducing the number of wave modes,
writing the ion equations using stream functions, neglect-
ing the electron inertia, etc. In future work we will examine
further simplifications and also the possibility of training
a surrogate model to map local plasma parameters to met-
rics that can be measured by coherent back-scatter radars
and the possibility of embedding this solver into a Global
Circulation Model.

## 5 Acknowledgements

## References

[1] E. L. Rojas and D. L. Hysell, "Hybrid plasma simu-
lations of Farley-Buneman instabilities in the auroral
E-region," *Journal of Geophysical Research: Space
Physics*, **126**, April 2021, e2020JA028379.

[2] B. Eliasson and L. Stenflo, "Full-scale simulation
study of stimulated electromagnetic emissions: The
first ten milliseconds," *Journal of Plasma Physics*, **76**,
369-375, 2010.

[3] M.M. Oppenheim and Y.S. Dimant, "Ion thermal ef-
fects on E-region instabilities: 2D kinetic simula-
tions," *Journal of Atmospheric and Solar-Terrestrial
Physics*, **66**, 2004, 1655-1668.