Formation propsée par l'ED 127 (version May 2021)

Titre "Description fluide et cinétique des plasmas"

1 Quickstart

Before start you may want to verify that everything works correctly on your computer. Here you will learn how to run a simulation and how to load the data produced by the simulation into the visualization software ParaView. We assume that the MHD code and the hybrid code are already installed on your Linux machine.

The files generated by the simulations are `csv` files. They can be loaded directly into ParaView (from within the ParaView window: File –> Open). However, for the non experienced user it may be more instructive to load the files into ParaView through so-called state files (extension .pvsm) which provide an additional treatment of the loaded data and a plot. The treatment applied to the loaded data appears in the `Pipeline Browser` window which does generally appear on the left in the ParaView window.

1.1 Run a MHD simulation and import data in ParView

- Open a terminal and navigate to the top folder of the installed MHD code (the folder with the file `main000.f`)
- In the terminal type: `./run_CIAS/run_test.sh`
- If code compiling and execution terminate successfully, the message `STOP fin` appears in the terminal followed by the path to the folder where the results have been stored (actuelly a sub-folder of the `DATA` folder including date and time informations).
- Start ParaView. For exemple from within the terminal by typing `paraview &`
- In the upper toolbar in the ParaView window select: File –> Load State –> navigate to the folder `PVSM_CIAS` –> select file `read_MHD.pvsm` –> select option `Choose File Names` –> Clic on the tab `[...]` –> Navigate to the folder where the simulation results have been stored and select the Group `Test_xy_all_..csv` –> OK –> OK

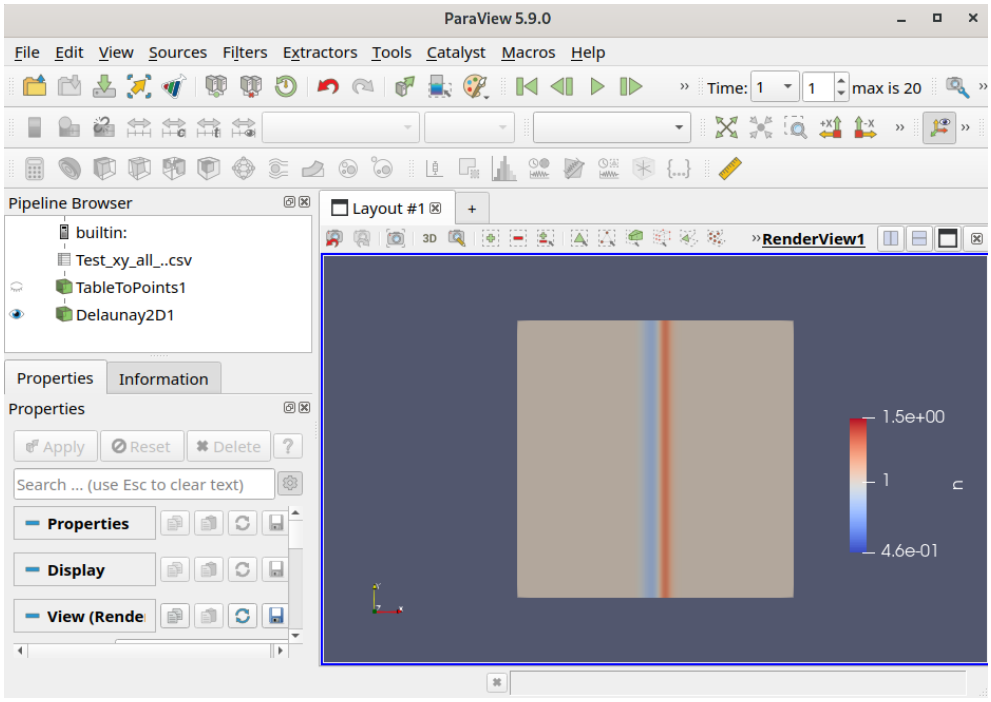


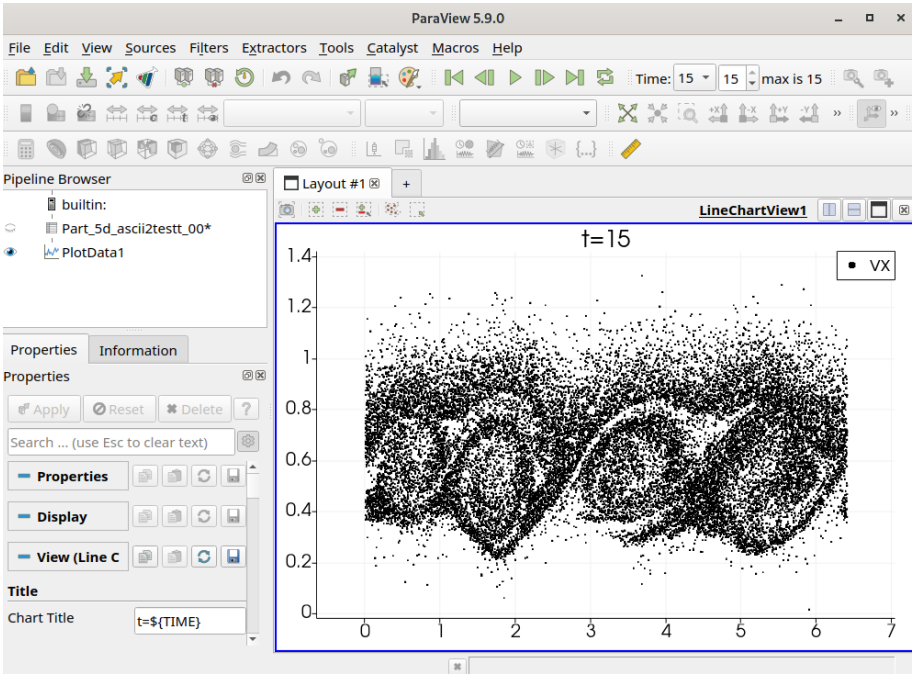
Figure 1. ParaView window after successful import of data from test simulation (file `./run_CIAS/run_test.sh`)

1.2 Run a hybrid simulation and import data in ParaView

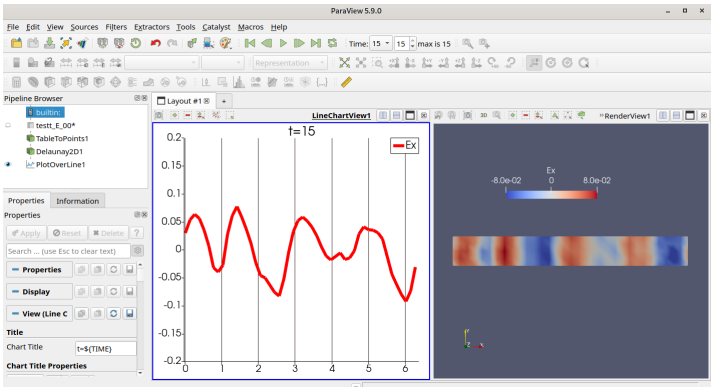
- Open a terminal and navigate to the main folder of the installed hybrid code and proceede to the sub-folder `input` (the folder containing the file `run`)
- In the terminal type: `./run ./run_CIAS/test.in`
- If code compiling and execution are successful the message `Results in folder:` must appear in the terminal followed by the full path to the folder where the data has been stored.

  NB: The hyride code produces 3 different groups of files which need to be loaded separately into ParaView. These are **(1)** the files including the position and velocities of the particles, **(2)** the files including the electric field and **(3)** the files including the magnetic field and various moments of the particle distribution function.

- To load the file with the position and velocity of particles into ParaView:
  - Start ParaView. For exemple from within the terminal by typing `paraview &`
  - File –> Load State –> navigate to the folder `Plot/Paraview` –> select file `read_particles.pvsm` –> select option `Choose File Names` –> Clic on the tab `[...]` –> Navigate to the folder where the simulation results have been stored and select the Group `Part_5d_ascii2testt_..csv` –> OK –> OK



- To load the file with the electric field into ParaView:
  - Start ParaView (if necessary).
  - File –> Load State –> navigate to the folder `Plot/Paraview` –> select file `read_electric.pvsm` –> select option `Choose File Names` –> Clic on the tab `[...]` –> Navigate to the folder where the simulation results have been stored and select the Group `testt_E_..csv` –> OK –> OK



- To load the file with the magnetic field and moments of particles into ParaView:
  - Start ParaView (if necessary)
  - File –> Load State –> navigate to the folder `Plot/Paraview` –> select file `read_mag_field_and_moments.pvsm` –> select option `Choose File Names` –> Clic on the tab `[...]` –> Navigate to the folder where the simulation results have been stored and select the Group `testt_A_..csv` –> OK –> OK

More complex ParaView state file (extension .pvsm) will be presented gradually along the next sections and should suffice to generate the plots required to interpret the simulation. Otherwise, various tutorials on ParaView can be found on the web,

e.g. `https://www.paraview.org/Wiki/The_ParaView_Tutorial`.

2 Experiment 1: Small perturbations

In this firs numerical experiment we consider the propagation of a small perturbation in a compressible fluid (section 2.1) and in a collisionless plasma (section 2.2). The perturbation is initiated by a thin slab of fluid moving at a small velocity with respect to the surrounding resting fluid. The slab is translationally invariant in the y direction and the initial velocity within the fluid is directed along the x direction. We qualify the perturbation as "small" as long as the initial velocity of the slab is small with respect to the sound speed (c=$\sqrt{\gamma T}$ where γ is a constant and T the fluid temperature).

2.1 Fluid case: simulation B1 (run_B1.sh)

Use the MHD code. Open a terminal and change to the main folder of the code (eg where the file makefile is located). Start the simulation by typing ./run_CIAS/run_B1.sh Under successful compilation and execution, the full path to the folder where the results are stored is shown in the terminal.

Change to the folder where the results are stored (eg the file B1_xy_all_0000.csv) and start paraview with the command paraview &

Once in ParaView select the tab File ⟶ Load State and select the state B1.pvsm in the sub folder PVSM_CIAS of the main code folder. In the Load State Options window select the option Choose File Names and load all files generated by the simulation by right-clicking on the Group B1_xy_all_..csv After loading the group of files the following image should appear in the ParaView window:

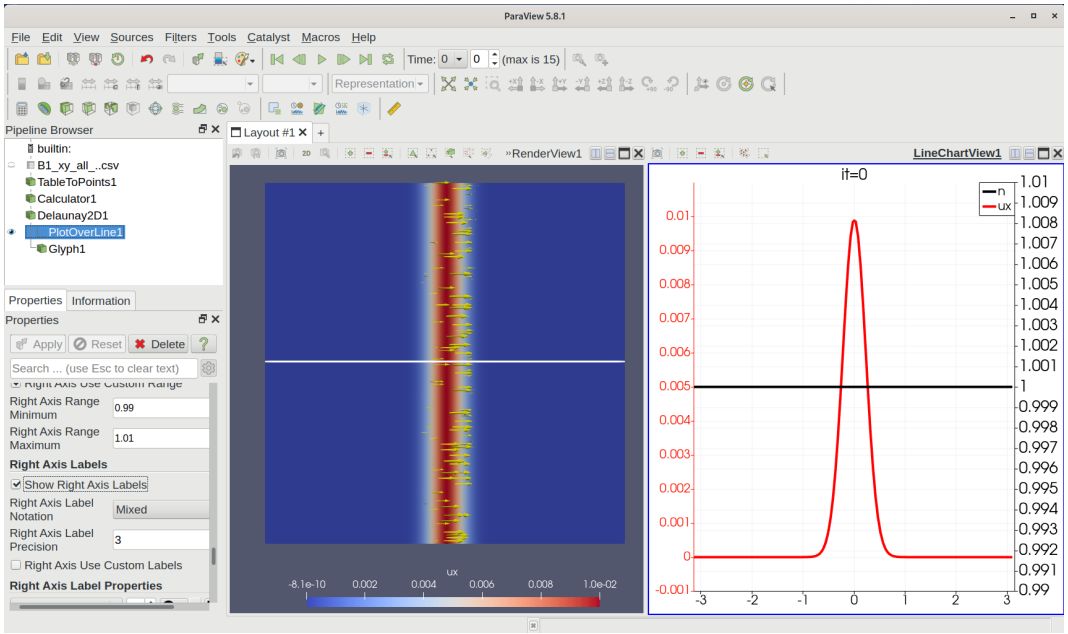


Figure 2. Initial condition for simulation B1. System is uniform except for a positive velocity bump centered on x=0. System is invariant in the y direction. Figure has been produced using the ParaView state file B1.pvsm

Theory: The one-dimensional fluid equations, neglecting viscosity and conductivity are given by the continuity, momentum and energy equations (γ is the polytropic index, $\partial_x \equiv \partial/\partial x, \partial_t \equiv \partial/\partial t$)

$$\begin{aligned} \partial_t \varrho &= -\partial(u\varrho)/\partial x \\ \partial_t u &= -u\partial_x u - (1/n)\,\partial_x p \\ \partial_t p &= -u\partial_x p - \gamma p \partial_x u \end{aligned}$$

Two modes propagating in opposite directions exist which do satisfy $\partial_t u \pm c\partial_x u = 0$ where $c = \sqrt{\gamma p_0/\varrho_0}$ is the sound speed, with p_0 and ϱ_0 the average pressure and mass density. The velocity, density and pressure fluctuations associated with the two modes are related through $u/c = \pm\delta\varrho/\varrho_0$ and $\delta p/p_0 = \gamma\delta\varrho/\varrho_0$ where $\delta\varrho \equiv \varrho - \varrho_0$ and $\delta p \equiv p - p_0$. Note that in the code the normalized temperature is defined as $T = p/\varrho$ (i.e. the normalized Boltzmann constant is $k_B = 1$ and the normalized mass of a plasma particles is $m = 1$ so that the normalized number density n is equal to the normalized mass density ϱ).

2.2 Hybrid case: simulations RG1, RG4, RG3, RG5

Use the hybrid code: Open a terminal and change to the sub-folder named `input`. In order to run simulation RG1 type `./run ./run_CIAS/RG1.in` which will run the hybrid code using the configuration file RG1.in located in the sub-folder run_CIAS. Files produced by the simulation are stored in the sub-folder `DATA`.

The 4 runs only differ by the electron temperature through the definition of a different electron beta (cf [betae] in the configuration files) which, in normalized units, is given by $\beta_e \equiv 2n_e T_e/B_0^2$. Note that the magnetic field B_0=1 is directed along the x axis so that it has no effect on the ions' dynamics in that direction. Also, the average electron density in the system is n_e=1 so that the normalized electron temperature in the simulations is just T_e=0.5β_e

Run	RG1	RG4	RG3	RG5
β_e	0.05	0.25	0.5	2.5

In all simulations the ion temperature in the x direction (parallel to B_0) is $T_{i\parallel} = 0.5\beta_{i\parallel} = 0.125$.

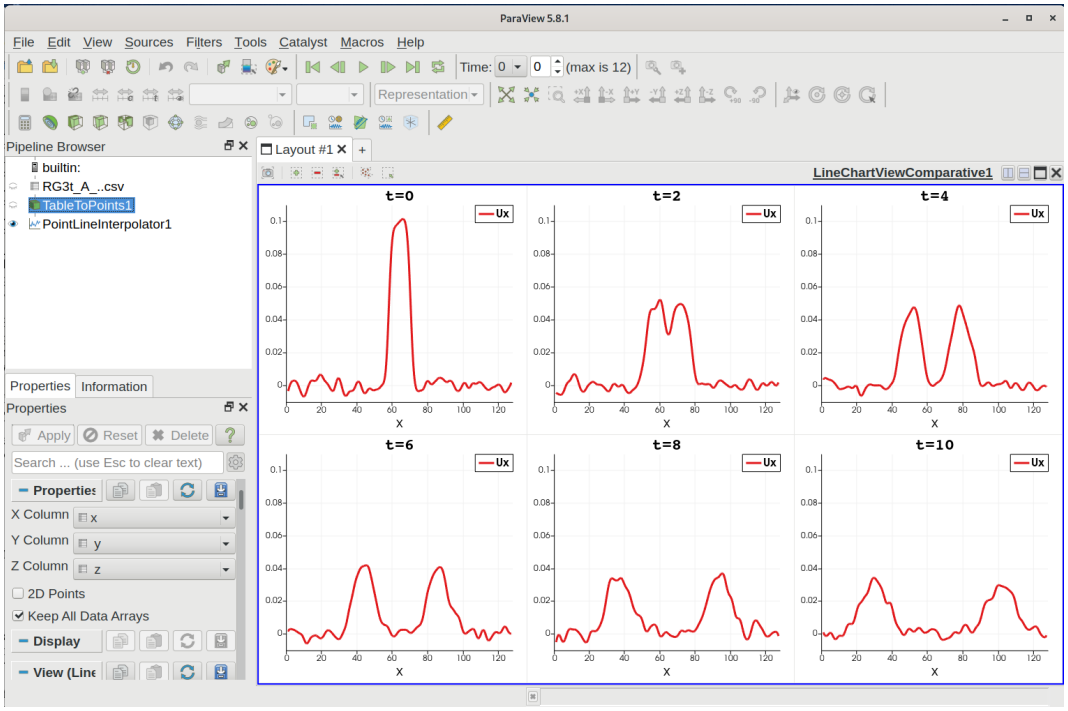


Figure 3. Evolution of the x component of the "fluid velocity" of the ions in simulation RG3. Figure has been obtained using the ParaView state file RG3_6.pvsm.

Theory: The equation of motion of an ion (charge q, mass m) in the x direction is

$$\mathrm{dv}_x/\mathrm{dt} = E(x,t)\, q/m \quad (q = e = m = 1 \text{ in code units}).$$

In the hybrid approximation where $n = n_i \approx n_e$ (therefore assuming ions are singly charged) and the mass of electron is zero, the electrostatic field E can be written as (a reduced version of Ohm's law):

$$\mathrm{eE} = -(1/n_e)\partial p_e/\partial x$$

where $p_e = n_e T_e \propto n_e^{\gamma}$. The fluid equations describing the ions' motion can therefore be written as (here the pressure p is intended to be the tensor component p_{xx}):

$$\begin{aligned} \partial_t n &= -\partial\,(un)/\partial x \\ \partial_t u &= -u\partial_x u - (1/n)\,\partial_x p, \text{ where } p = p_e + p_i \end{aligned}$$

where the pressure p is intended to represent component p_{xx} of the pressure tensor. Note that in the limit $p_e \ll p_i$ a propagating mode exists which is reminiscent of the standard sound mode with a phase velocity $v_\phi = \sqrt{\gamma_e T_e + \gamma_i T_i}$, where $\gamma_e = 5/3$ (value generally adopted in hybrid codes) and γ_i=3 (corresponding to the case of 1 degree of freedom). Given the above fluid equations, the relations for the eigenmodes are those of the standard sound mode: $\pm\delta u/v_\phi = \delta n/n = (1/\gamma)\delta p/p$.

3 Experiment 2: Strong perturbations (fluid limit)

Contrary to the experiment in section 2 we do now address the case of a velocity perturbation comparable or larger than the sound speed c. As for the simulations in section 2 the initial condition is translationally invariant in the y direction, *i.e.* the simulations are one dimensional.

3.1 Fluid case: simulations A1a and A1b

Use the MHD code. Open a terminal and change to the main folder of the code (eg where the file makefile is located). Start the simulation by typing ./run_CIAS/run_A1a.sh Under successful compilation and execution, the full path to the folder where the results are stored is shown in the terminal.

Change to the folder where the results are stored (eg the file A1a_xy_all_0000.csv) and start paraview with the command paraview &

Once in ParaView select the tab File ⟶ Load State and select the state A1a_comparative_view.pvsm in the sub folder PVSM_CIAS of the main code folder. In the Load State Options window select the option Choose File Names and load all files generated by the simulation by right-clicking on the Group A1a_xy_all_..csv After loading the group of files the following image should appear in the ParaView window:

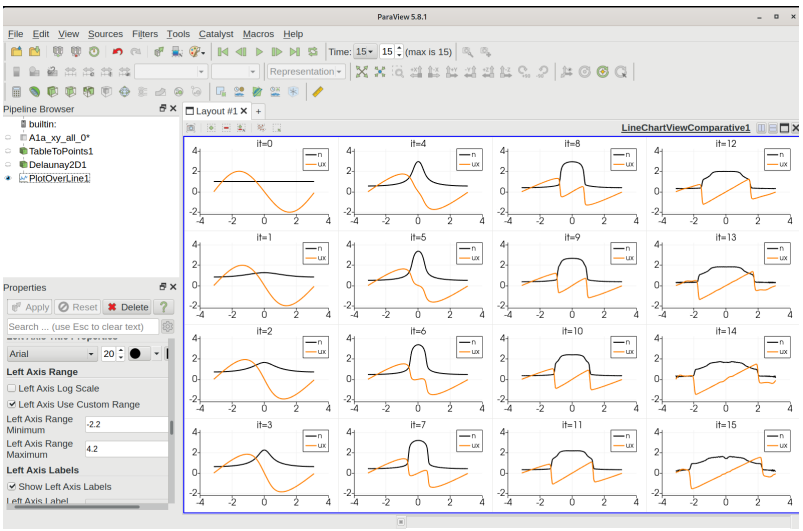


Figure 4. Time evolution of the density n and fluid velocity u_x in simulation A1a. The figure has been obtained with the state file A1a_comparative_view.pvsm.

Note that here the initial velocity profile u_x is sinusoidal and not bell-shaped as in the experiment of section 2 and, more importantly, the amplitude of the initial velocity fluctuation is comparable to the sound velocity ($c = \sqrt{\gamma T} = 1.29$).

Observations:

- Initial steepening of the velocity profile → density growing near the center reaching a maximum at it=6.

- The pressure gradient which builds up during the initial phase pushes the fluid away from the central region and generates two shocks (sharp density and velocity gradients).