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CENTRE EUROPÉEN DE RECHERCHE ET DE FORMATION AVANCÉE EN CALCUL SCIENTIFIQUE

SAFRAN

The behavior of the electron cyclotron drift instability (ECDI) inside Hall Effect Thruster with a fluid code

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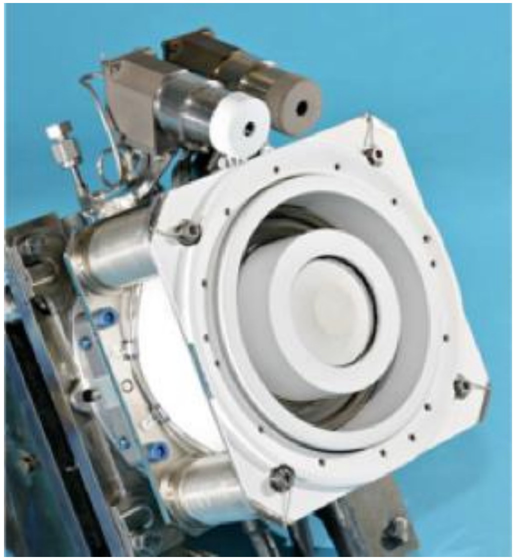
ExB Workshop - Princeton Plasma Physics Laboratory

1 November 2018

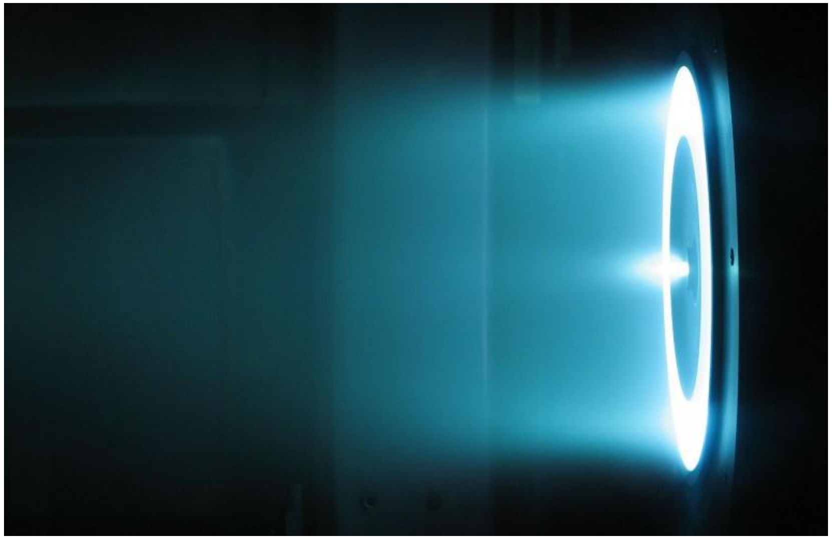
1)CERFACS, Toulouse FRANCE
2) SAFRAN Aircraft Engines, Vernon, FRANCE

Hall effect thrusters: the industrial point of view

SAFRAN industrializes a complete range of plasma Hall effect thrusters for low power electric propulsion:



The PPS-1350 Hall thruster (SAFRAN)



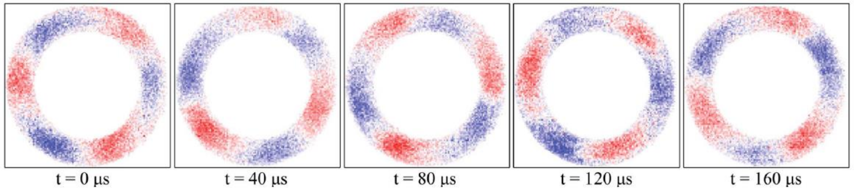
The PPS-5000 Hall thruster (SAFRAN)

→ Long and costly qualifications in vacuum test facilities

- Until now, no industrial numerical solver is mature enough to help them in the conception and understanding of Hall effect thrusters

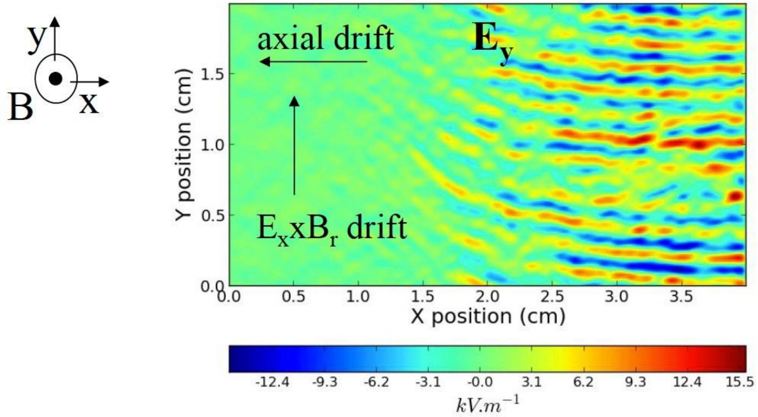
The big complexity of Hall effect thruster plasma flows

- Complex plasma phenomena are highlighted through experiments …

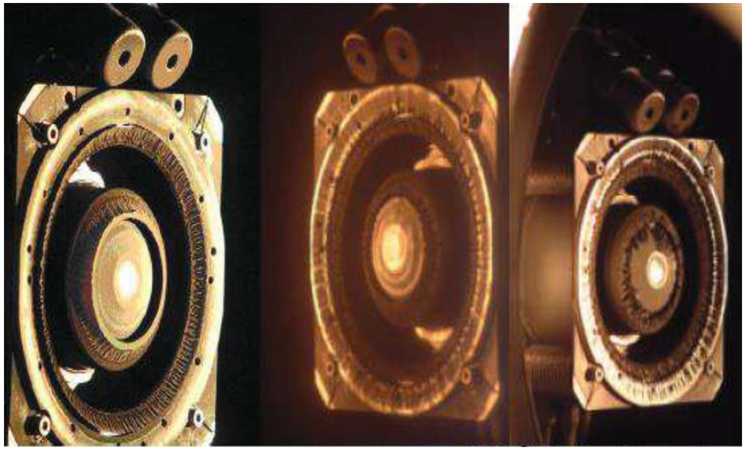


Rotating spoke instabilities of plasma density on a 6 kW Hall Thruster(2)

- … or through simplified numerical problems …



2D structure of the fluctuating azimuthal component of the electric field in a Hall thruster(1)



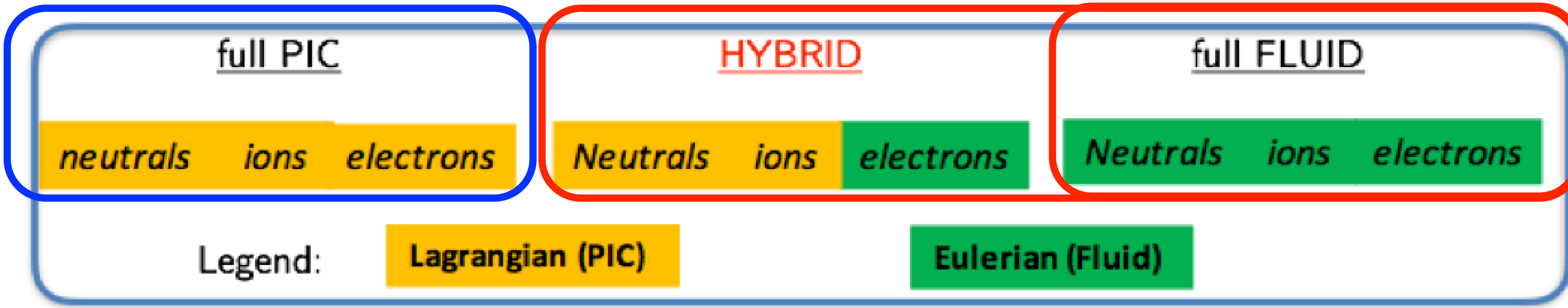
Ageing of the PPS-1350 Hall thruster (SAFRAN)

- … but are still not fully understood. They can decrease thruster efficiency and cause an anormal erosion of ceramics

1)J.C. Adam, J.P. Boeuf & al , Physics simulation and diagnostics of Hall effect thrusters, Plasma Phys. Control. Fusion (2008)
2)M. McDonald and A. Gallimore, Rotating Spoke Instabilities in Hall Thrusters (2011)

A numerical solver to model Hall-Effect thruster's flows

Objectives: Develop a **3D unstructured massively parallel** PIC/fluid solver to model with accuracy the plasma behavior inside a Hall Effect Thruster (HET) in collaboration with SAFRAN : **AVIP**



- Too costly for an industrial complex simulation

Reference solver for fluid simulations

- More hypothesis / models

More adapted to conception simulations

In most fluid solvers:

Drift-diffusion approximation

Quasineutral hypothesis

need precision for complex phenomena →

A 10-moment or two-fluid formulation

AVIP-Fluid: Equations

- Fluid equation system for **ions and electrons** based on a 10-moment model :

$$\partial_t n_e + \nabla.(n_e \vec{u_e}) = n_e n_n K_{ioniz} \quad , \quad \partial_t n_i + \nabla.(n_i \vec{u_i}) = n_e n_n K_{ioniz}$$

$$\partial_t (m_e n_e \vec{u_e}) + \nabla.(m_e n_e \vec{u_e}\vec{u_e} + k_B T_e n_e \bar{\bar{I}}) = -e n_e (\vec{E} + \vec{u_e} \times \vec{B}) - K_{en} n_n n_e m_e (\vec{u_e} - \vec{u_n})$$

$$\partial_t (m_i n_i \vec{u_i}) + \nabla.(m_i n_i \vec{u_i}\vec{u_i} + k_B T_i n_i \bar{\bar{I}}) = e n_i (\vec{E} + \vec{u_i} \times \vec{B}) + K_{in} n_n n_i m_i (\vec{u_i} - \vec{u_n})$$

$$\partial_t (m_e n_e E_e) + \nabla.\left((\frac{1}{2} m_e n_e \vec{u_e}^2 + \frac{\gamma}{\gamma - 1} P_e).\vec{u_e} + \vec{Q_e} \right) = -e n_e \vec{E}.\vec{u_e} - S^2_{ioniz,e} - S^2_{exc,e} - S^2_{en,e}$$

$$\partial_t (m_i n_i E_i) + \nabla.\left((\frac{1}{2} m_i n_i \vec{u_i}^2 + \frac{\gamma}{\gamma - 1} P_i).\vec{u_i} \right) = e n_i \vec{E}.\vec{u_i} + S^2_{ioniz,i} - S^2_{in,i}$$

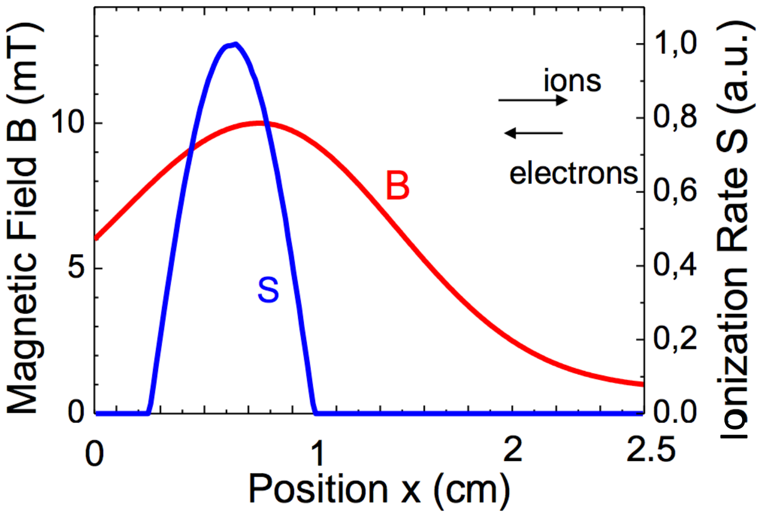
with :

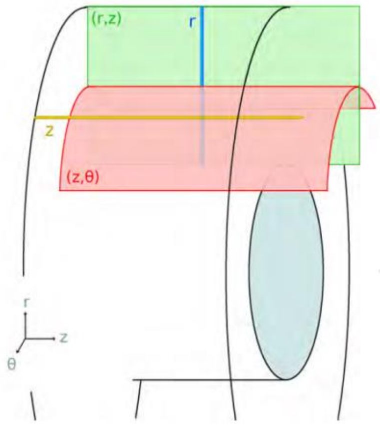
- $q_\alpha n_\alpha (\vec{E} + \vec{u_\alpha} \times \vec{B})$ the Lorentz force with $\vec{E}$ and $\vec{B}$ the electromagnetic fields, $\vec{B}$ is supposed constant, a Poisson equation solves the variation of the electric potential: $$\Delta\phi = \frac{e}{\epsilon_0}(n_i - n_e)$$
- $\vec{Q_e}$ the electron heat flux is first neglected: $$\vec{Q_e} = 0$$

- A mass continuity equation for neutrals at constant speed: $$\partial_t n_n + \nabla.(n_n V_{0,n}) = - n_e n_n K_{ioniz}$$

A 2D z-$\boldsymbol{\theta}$ test case to observe the ECDI [1)]

- Extracted from a z-$\boldsymbol{\theta}$ collisionless PIC simulation with given ionization rate [1)]





$$J = e\int_0^d S(x)dx = 400\ \mathrm{A/m^2}$$

<u>Given magnetic field and ionization source term for the test case</u>

- Applied voltage of 200V
  $n_{e,init} = n_{i,init} = 5.10^{16}\ m^{-3}$
- $T_{e,init} = 5eV = 58000K\ ;\ T_{i,init} = 300K$

<u>Goal :</u> Study this test case with our fluid formulation and observe if the ECDI is triggered by fluid equations

1) ExB Electron Drift Instability in Hall thrusters: Particle-in-Cell simulations vs theory, J.P Boeuf and L. Garrigues, PoP, 2018

A 2D z-$\boldsymbol{\theta}$ test case to observe the ECDI [1)]

A simplified fluid model :

$$\partial_t n_e + \nabla.(n_e u_e) = S \;, \quad \partial_t n_i + \nabla.(n_i u_i) = S$$

$$\partial_t(m_e n_e V_e) + \nabla.(m_e n_e V_e V_e + k_B T_e n_e I) = -en_e(E + V_e \times B)$$

$$\partial_t(m_i n_i V_i) + \nabla.(m_i n_i V_i V_i + k_B T_i n_i I) = en_i(E + V_i \times B)$$

$$\partial_t(m_e n_e E_e) + \nabla.\left((\frac{1}{2} m_e n_e V_e^2 + \frac{\gamma}{\gamma - 1} P_e).V_e \right) = -en_e E.V_e + \Theta_e$$

$$\partial_t(m_i n_i E_i) + \nabla.\left((\frac{1}{2} m_i n_i V_i^2 + \frac{\gamma}{\gamma - 1} P_i).V_i \right) = en_i E.V_i + \Theta_i$$

How to express energy source terms ?

- An ion is created at T_i = 0.5 eV

$$\Theta_i = S k_B T_i$$

- An electron is created at T_e = 10 eV

$$\Theta_e = S k_B T_e$$

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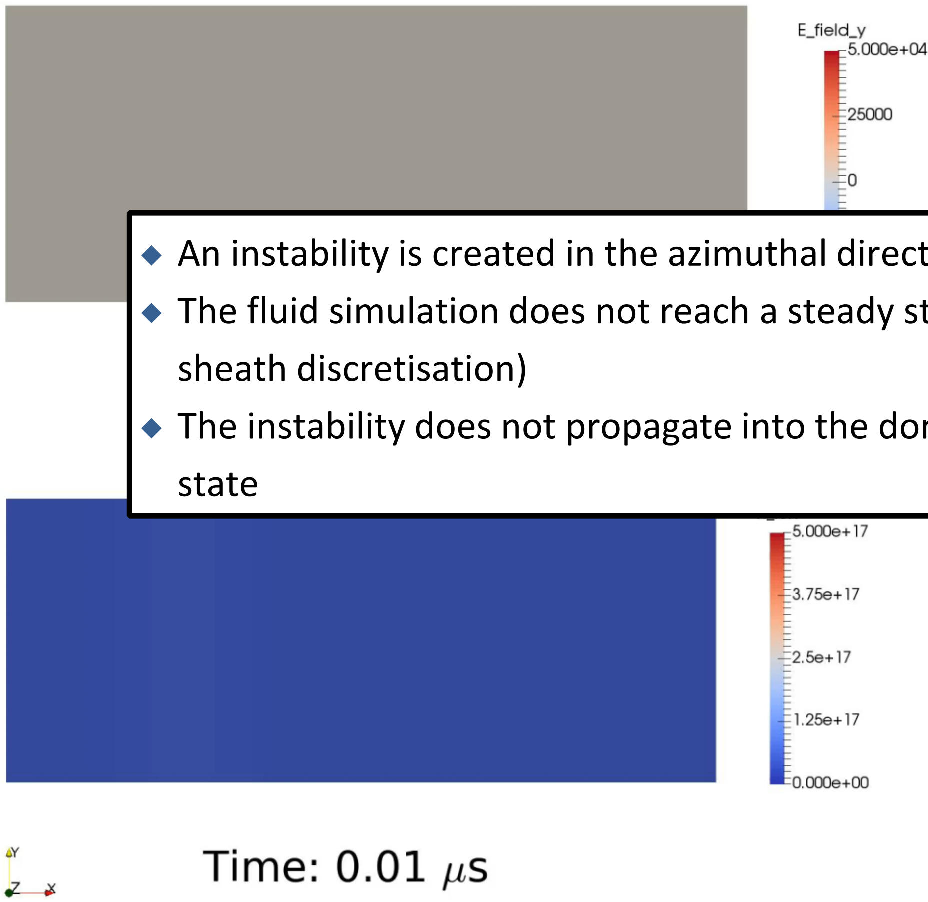
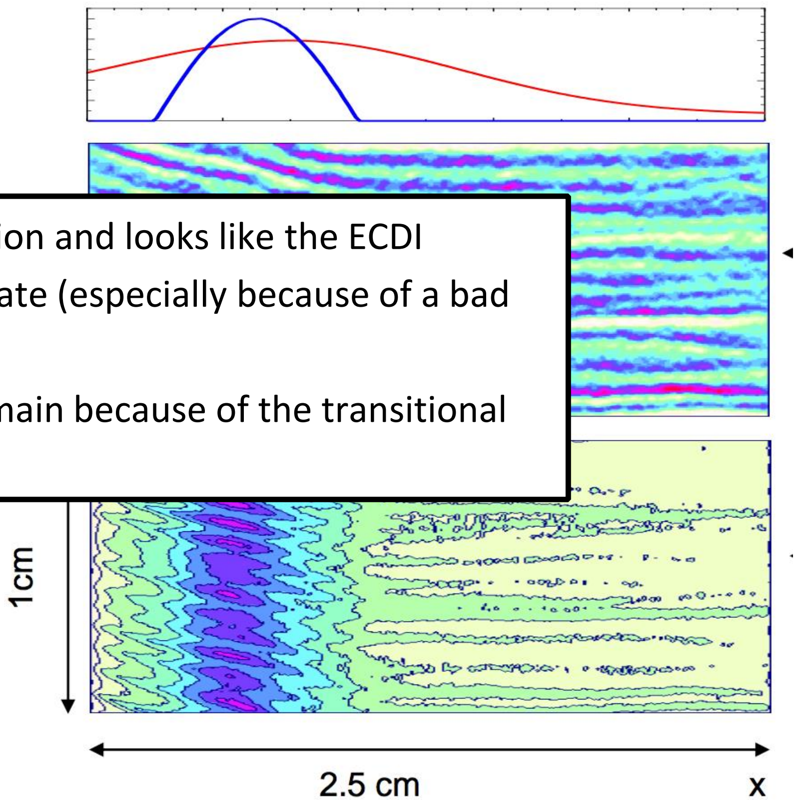
A 2D z-$\boldsymbol{\theta}$ test case to observe the ECDI [1)]

Simulation 1 with a 500x200 mesh (1 cell per λ_D) and a second order scheme (HLLC-MUSCL) :

Mean azimuthal electric field





Azimuthal electric field and ion density at steady state[(1)]

- An instability is created in the azimuthal direction and looks like the ECDI
- The fluid simulation does not reach a steady state (especially because of a bad sheath discretisation)
- The instability does not propagate into the domain because of the transitional state

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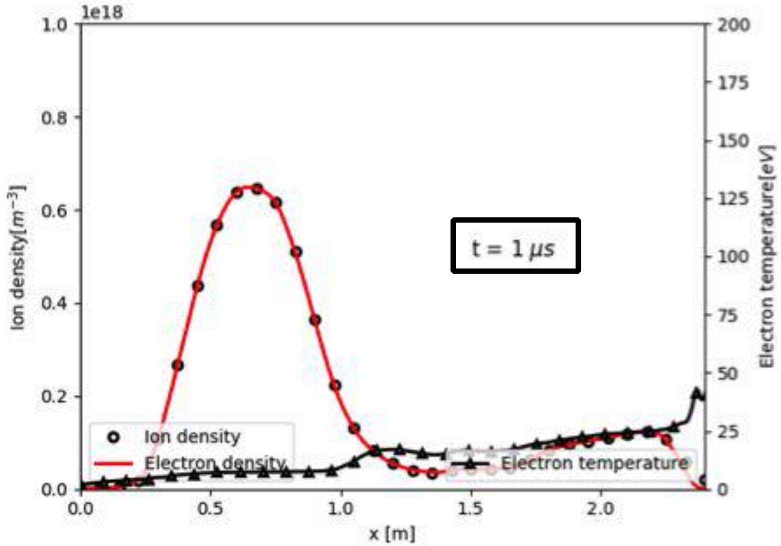
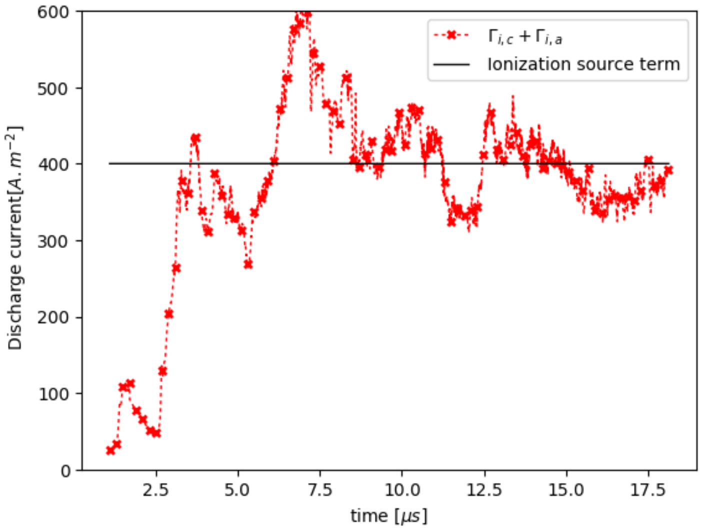
1) J.P. Boeuf and L. Garrigues, ExB electron drift instability in Hall thrusters: PIC simulations vs theory, Physics of Plasmas, 25, 061204 (2018)

A 2D z-$\boldsymbol{\theta}$ test case to observe the ECDI [1)]



Azimuthal mean electron and ion density and electron temperature during the transitional state

$$\Gamma_{i,c} + \Gamma_{i,a} = e \int_0^d S(x)dx = 400 \text{ A/m}^2$$

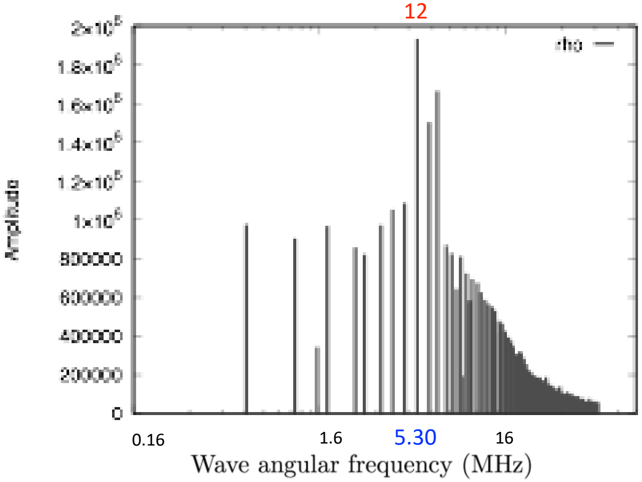


Comparison of the sum of the ion current through electrodes vs creation of ions by ionization

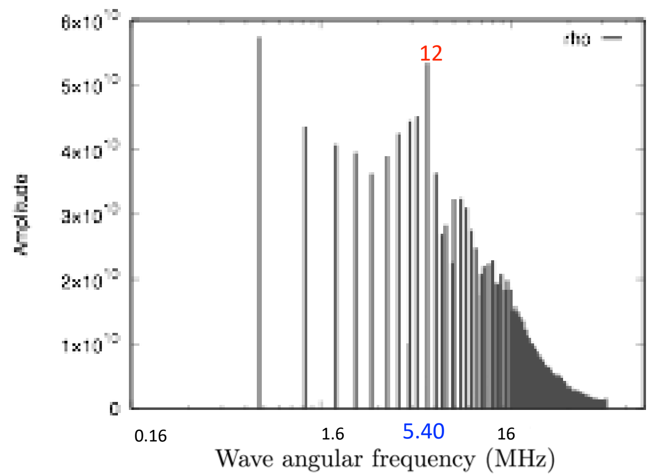
- The plasma density is too high in the ionization region
- The bad discretisation of the sheath creates a high electron temperature which pollutes the entire domain
- The sum of ion currents oscillates around the value of ionization current

A 2D z-$\boldsymbol{\theta}$ test case to observe the ECDI [1)]

Simulation 1 with a 500x200 mesh (1 cell per λ_D) and a second order scheme (HLLC-MUSCL) :



Ion density spectrum of the simulation 1



Azimuthal electric field spectrum of the simulation 1

Theoretical results for the ECDI :

$$\lambda_\omega = 2\pi\sqrt{2}\lambda_{De} \approx 1mm$$

$$v_\omega = c_s\sqrt{\frac{2}{3}} \approx 5km/s$$

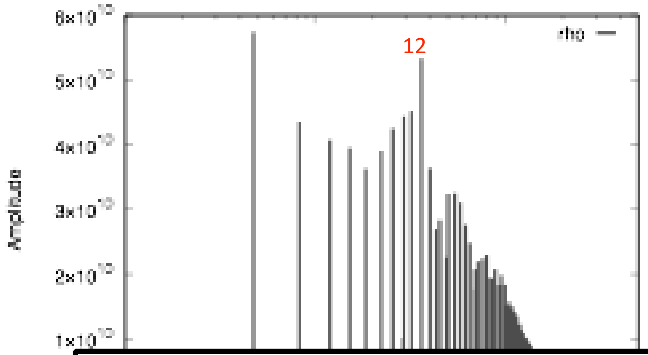
$$f_\omega = \frac{v_\omega}{\lambda_\omega} \approx 5MHz$$

- The 12th mode seems to correspond to the good frequency and is one of the highest mode

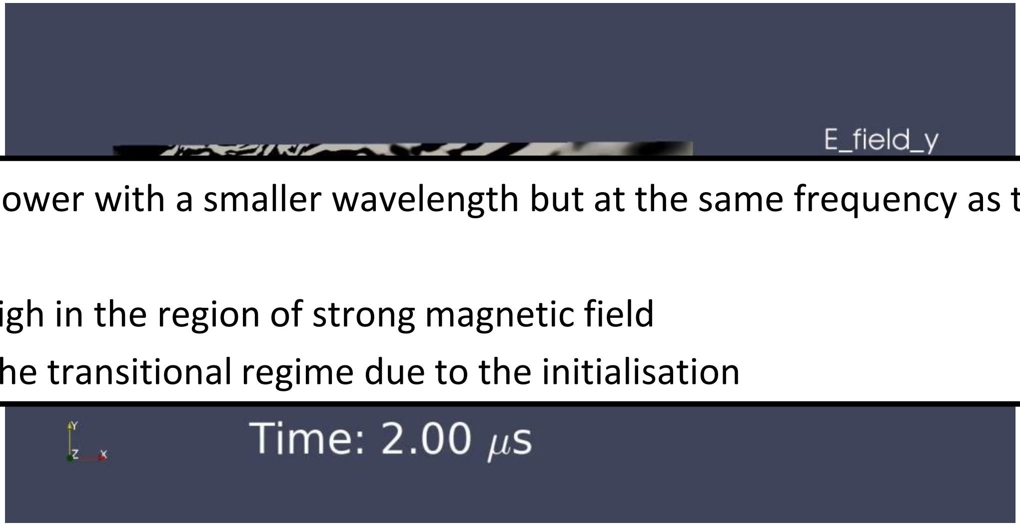
→ Investigate this particular mode using a Domain Decomposition Method

A 2D z-$\boldsymbol{\theta}$ test case to observe the ECDI [1)]

Simulation 1 with a 500x200 mesh (1 cell per λ_D) and a second order scheme (HLLC-MUSCL) :



Electric field 12th mode from the Domain Mode Decomposition



- The instability of the 12th mode is slower with a smaller wavelength but at the same frequency as the ECDI
- The amplitude of the instability is high in the region of strong magnetic field
- However the ECDI is perturbed by the transitional regime due to the initialisation

$$\lambda_\omega = 2\pi\sqrt{2}\lambda_{De} \approx 1mm$$

$$v_\omega = c_s\sqrt{\frac{2}{3}} \approx 5km/s$$

$$f_\omega = \frac{v_\omega}{\lambda_\omega} \approx 5MHz$$

$$\lambda_{mode_{12}} \approx 0.5mm$$

$$v_{mode_{12}} \approx 2.7km/s$$

Conclusions

- An instability appears in the azimuthal direction which has same properties as the Electron Cyclotron Drift Instability
- The fluid simulation fails to reach a steady state, possibly due to the cathode injection model

- Note that a second order numerical scheme is mandatory for a good resolution of electrode sheaths[1)]

1) V. Joncquieres & al, A 10-moment fluid numerical solver of plasma with sheaths in a Hall Effect Thruster, AIAA Propulsion Energy Conference (2018)