The non-resonant streaming instability: from theory to experiments

A. Marret[1,2,3], A. Ciardi[1], R. Smets[2], J. Fuchs[3]

[1] *Sorbonne Université, Observatoire de Paris, Université PSL, CNRS, LERMA, Paris, France*

[2] *Sorbonne Université, Ecole Polytechnique, CNRS, Observatoire de Paris, LPP, Paris, France*

[3] *LULI, CNRS, Ecole Polytechnique, Sorbonne Université, CEA, Palaiseau, France*

Plasma instabilities play an important role in numerous astrophysical environments as they can efficiently redistribute the energy between the fields and the ionized particles. This is of particular importance for the acceleration and transport of cosmic rays, in the Galaxy and beyond. Among the observed sources of cosmic rays, the shocks of supernova remnants are believed to be very efficient in accelerating galactic cosmic rays, through a process known as diffusive shock acceleration, or First Order Fermi acceleration. Estimates show that if cosmic rays are to be accelerated to high energies diffusively, then the turbulent magnetic field at the shock front needs to be amplified, by more than one order of magnitude with respect to the average interstellar magnetic field intensity [1]. The non-resonant (NR) mode, also called Bell's mode in the astrophysical literature, constitutes a promising candidate this amplification, by converting the drift kinetic energy of the cosmic rays crossing the shock front and leaking in the ambient medium into magnetic energy [2].

This research is dedicated to the study of the NR mode in the large variety of environments where it can develop, ranging from the cold and dense molecular clouds to the hot and diffuse intergalactic medium. A first approach consisted in modelling the NR mode using a modified MagnetoHydroDynamic (MHD) approach, considering the background plasma as an electrically charged fluid traversed by a population of drifting cosmic rays. Quantitative predictions on the fastest growing modes and associated unstable wavelengths were obtained for arbitrary ion mass and charge, which is of interest for the study of heavy ions accelerated in supernova remnants [3], and in the context of laboratory experiments where heavy ions such as carbon and argon are frequently used. I then investigated the effects of the ambient plasma temperature on the instability within the framework of linear kinetic theory, and derived analytical expressions of its growth rate in the hot and demagnetized regime of interaction, where the background ions Larmor radius is larger than the unstable wavelengths. One of the main results obtained was that the instability may be strongly damped, but not suppressed, in weakly magnetized and high temperature plasmas such as the intergalactic medium, implying that the NR mode may still amplify the magnetic field and modify the transport of cosmic rays in such environments.

Using the massively parallelized hybrid-Particle-In-Cell (hybrid-PIC) code HECKLE [4]

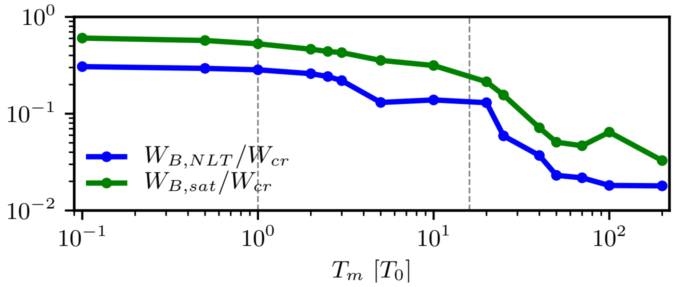

Figure 1: *Magnetic field energy density* $W_B = B^2/2\mu_0$ *normalized to the initial cosmic rays drift kinetic energy density* $W_{cr} = n_{cr} m_p u_{cr}^2/2$*, as a function of the background ions temperature. The blue curve corresponds the transition to the non-linear phase of growth (noted "NLT") and the green curve to magnetic saturation (noted "sat"). The two dashed vertical lines corresponds to the limits of the warm and hot regimes of interaction respectively.*

treating the ions kinetically and the electrons as a massless fluid, I extended my study to the non-linear regime by performing numerical simulations of the instability for a wide range of background ions temperature. I first investigated the cold regime where the background ions Larmor radius is negligible with respect to the unstable wavelengths, such that it may be correctly described both by the modified MHD model and by a fully kinetic approach. I confirmed analytical predictions on the growth rate and saturated magnetic field which strongly depend on the cosmic rays flux, and described one possible saturation mechanism, where the combined effect of the increasing magnetic tension at small scales and magnetization of the cosmic rays population at large scales breaks the instability feedback loop. Despite this effect, I highlighted the existence of a non-linear phase of growth, where additional magnetic field perturbations are generated because of the background fluid inertia. By increasing the temperature, I was then able to explore the warm regime where the background ions Larmor radius is no longer negligible but still smaller than the unstable wavelengths, as well as the hot and demagnetized regime. The strong damping for large temperatures obtained with my analytical calculations was verified by the simulations (see Fig. 1), which showed that the large mobility of the hot ions weaken the coherent fluid motion with the magnetic perturbation required to grow the instability, thus producing a damping of the unstable waves. These numerical results, together with the theoretical work on the demagnetized regime of the NR mode, have been published in MNRAS [5]. They point toward a reduced magnetic field amplification in astrophysical environments such as supernova propagating in superbubbles, and in galaxy cluster shocks which may in turn reduce the maximum reachable energy by cosmic rays.

In addition to large amplitude magnetic perturbations, the instability produces significant

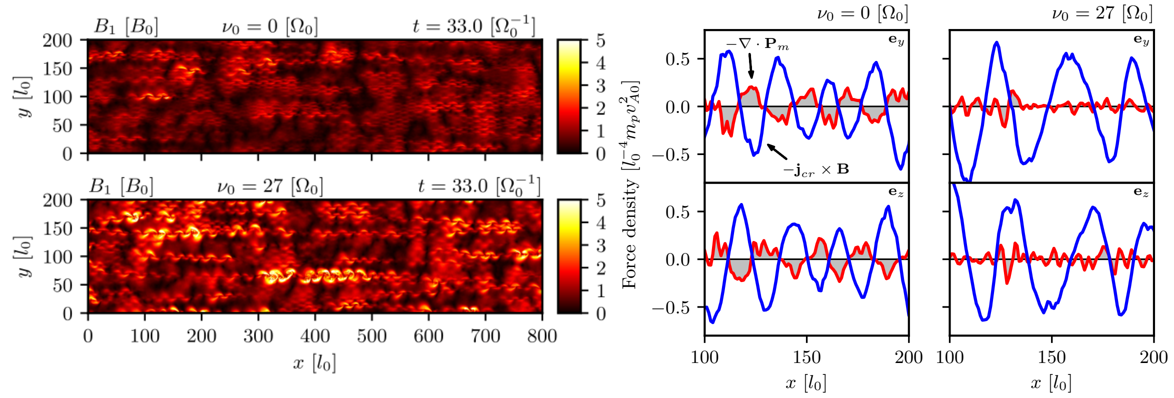

Figure 2: *Left panels: Map of the perturbed magnetic field intensity B_1, in units of B_0, during the exponential phase of growth in 2D simulations without collisions (upper panel) and including Coulomb collisions (lower panel). The Coulomb collision frequency ν_0 is normalized to the ion cyclotron frequency Ω_0. Right panels: Cosmic rays induced magnetic force $-\mathbf{j}_{cr} \times \mathbf{B}$ (blue solid line) driving the instability and background ions pressure gradients $-\nabla \cdot \mathbf{P}_m$ (red solid line) components in a 1D collisionless simulation (left column) and including Coulomb collisions (right column).*

pressure anisotropies in the background plasma due to the conservation of the adiabatic invariants, which were described for the first time in my simulations of the instability. Owing to the helical spatial structure of the unstable electromagnetic waves, strong gradients of the non-diagonal terms of the full ions pressure tensor are created and oppose the cosmic rays magnetic force that drives the instability, leading to a reduced magnetic field growth rate and intensity at saturation. Using a Monte Carlo module for Coulomb and neutral collisions, I pursued my investigations of the instability microphysics by studying the non-linear evolution of the unstable waves for a wide range of plasma collisionality, as well as the interplay between the anisotropic heating and collisional pressure isotropization. Accounting for collisions is of particular interest in dense astrophysical environments such as H II regions and molecular clouds, where collisions occur on time scales comparable with the growth time of the instability. I showed that protons-hydrogen collisions yield an important damping of the unstable waves, in agreement with linear fluid theory calculations [6]. In contrast, I demonstrated for the first time that Coulomb collisions can actually promote the growth of the unstable waves, by reducing the self generated pressure anisotropies that would otherwise oppose it (see Fig. 2). This work has been published in the journal Physical Review Letter [7].

Theory and numerical simulations have been the only means to investigate the non-linear evolution of the instability since its discovery in 1981 [8]. Although the plasma parameters required are potentially within the reach of laser experiments with externally applied magnetic fields [9], the large streaming population densities, drift velocities and ambient magnetic field

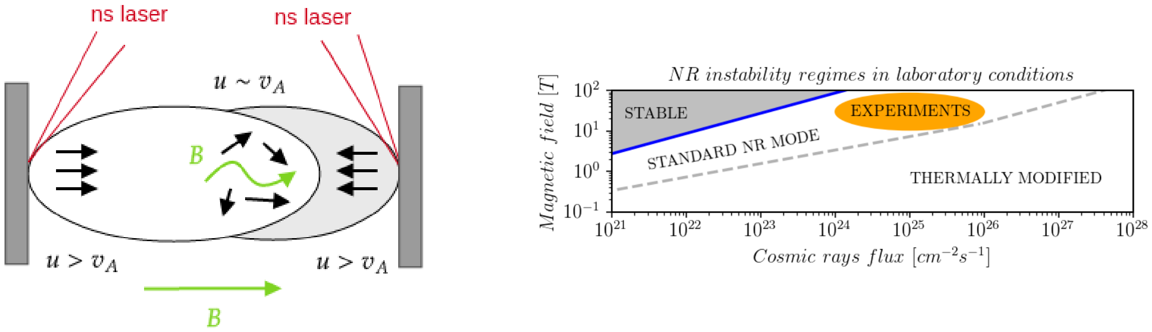

Figure 3: *Left panel: Schematic of a counter-propagating plasma plumes experimental setup. Two plasma plumes are generated from opposing solid targets with high-power lasers, producing plasma fluxes compatible sufficient to destabilize the NR mode. Right panel: Instability regimes in laboratory conditions, as a function of the cosmic rays flux and of the ambient magnetic field intensity. The orange region corresponds to a range of parameters accessible to current experimental facilities.*

required, together with the lack of theoretical knowledge on the effects of particle collisions on the development of the instability, have made its experimental investigations elusive. The final part of this work was devoted to tackle this problematic. I described possible setups aiming at observing for the first time the NR mode in the laboratory, while taking into account the effects of temperature and collisionality in typical laboratory plasmas conditions. The experiments involve high intensity lasers, coupled with source of strong magnetic field ($>$ 10 Teslas) on typical scales of the order of the centimeter for tens of nanoseconds, compatible with the constraints on the size and lifetime of strongly magnetized laboratory plasmas. While my theoretical and numerical work has highlighted the complexity of the NR mode dependency on the background plasma parameters, experiments will be essential to further investigate these issues and to confront the results to the existing fluid and kinetic theory, as well as to better understand the saturation mechanism of the instability.

References

[1] A. R. Bell et al., Monthly Notices of the Royal Astronomical Society **431**, 415 (2013)

[2] A. R. Bell, Monthly Notices of the Royal Astronomical Society **353**, 550 (2004)

[3] V. Tatischeff et al., Monthly Notices of the Royal Astronomical Society **508**, 1321 (2021)

[4] R. Smets et al., Physics of Plasmas **18**, 102310 (2011)

[5] A. Marret et al., Monthly Notices of the Royal Astronomical Society **500**, 2302 (2021)

[6] B. Reville et al., International Journal of Modern Physics D **17**, 1795 (2008)

[7] A. Marret et al., Physical Review Letters **128**, 115101 (2022)

[8] D. D. Sentman et al., Journal of Geophysical Research: Space Physics **86**, 7487 (1981)

[9] V. V. Ivanov, Matter and Radiation at Extremes **6**, 046901 (2021)