Turbulent transport excited by centrifugal instabilities in plasma columns

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The first part of the proposal will be part of a Master 2 project.

General scientific background.

In plasma columns confined by an axial magnetic field, the existence of radial gradients in pressure and plasma potential (or, equivalently, the existence of a radial electric field) perpendicular to the axial magnetic field leads to strong azimuthal flows. This canonical configuration is known to trigger several types of instabilities such as centrifugal instabilities, Kelvin-Helmholtz instabilities, and drift wave instabilities. The nonlinear evolution of these instabilities can lead to the emergence of large-scale coherent structures or turbulence, triggering strong radial transport of the plasma—and thus degradation of plasma confinement. Understanding the characteristics of radial turbulent transport for these canonical configurations is of particular interest for both fundamental studies and applications [1].

Theoretical modeling of centrifugal instabilities has long been limited to regimes in which the phase velocity of the instability is low relative to the ion cyclotron frequency [2]. However, this low-frequency approximation is generally not applicable to most experiments, for which the phase velocity is of the same order of magnitude as the ionic cyclotron frequency (see, for example, [3]). Recent theoretical work extends the linear stability analysis beyond the low-frequency approximation [4], neglecting collisions and gyroviscous effects (the non-diagonal terms of the viscosity tensor, related to the anisotropy of plasma transport imposed by the magnetic field). However, this model fails to reproduce certain experimental characteristics, such as the emergence of a dominant large-scale mode with a small number of azimuthal modes (typically 1 or 2 – see Figure 1). Furthermore, this linear stability analysis does not allow for accurate estimation of turbulent transport, even though this is significant for predicting equilibrium plasma parameter profiles. `

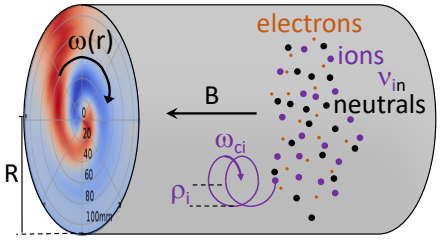


Figure 1: Canonical configuration of a plasma column in an axial magnetic field and measurement of density fluctuations showing the emergence of a large-scale structure (azimuthal mode = 1)

Objectives and provisional schedule.

The thesis project will focus on the detailed experimental characterization of centrifugal instability and associated turbulent transport in the Von Karman plasma experiment (a high-density plasma column 1 m long and 20 cm in diameter, fully operational for several years – see Figure 2) [3]. Particular emphasis will be placed on the influence of two dimensionless parameters, namely

1. the ratio of the plasma rotation frequency to the ion cyclotron frequency (this ratio characterizes the influence of ion magnetization)
2. the ratio of the plasma rotation frequency to the ion-neutral collision frequency (this ratio characterizes the influence of the friction exerted by neutrals on plasma ions).

The first year of the thesis will focus on developing and characterizing plasma rotation drive techniques that will enable high-speed solid body rotation profiles to be obtained. This will allow us to focus specifically on centrifugal instabilities and rule out Kelvin-Helmholtz modes or drift waves. The rotation drive techniques will be based on the use of biased emissive cathodes to control the plasma potential profile and drive strong azimuthal flows, as we have shown in a previous thesis [6]. The novelty here will lie partly in the use of highly emissive cathodes, allowing current injection of up to 20 A, and partly in the implementation of a new plasma ionization source using microwaves. The highly emissive cathodes were designed in 2024, and the microwave source is scheduled to be installed in spring 2025. The strong support of Vincent Dolique, IR CNRS, who is involved in supervising the thesis, will facilitate the integration of new experimental developments.

The second year of the project will focus on a precise experimental description of plasma rotation speeds and plasma parameter equilibrium profiles. In particular, the existence of a very strong electric field at the edge of the plasma column, known as the anodic sheath, has recently been highlighted [7]. Its characterization and detailed modeling will be developed during the second year of the thesis. The experimental data will be compared with models developed in collaboration with the LAPLACE team in Toulouse.

The third year will focus on characterizing the influence of ion magnetization and collisions on the characteristics of centrifugal instabilities. The dynamics of large-scale structures will be probed using high-speed imaging of spontaneous plasma light emission [8], and spatially and temporally resolved plasma parameter fluctuations and turbulent transport will be measured using advanced electrostatic probes [3]. Values and scaling laws for the evolution of turbulent diffusivities as a function of ion magnetization and neutral friction will be extracted from these measurements.

All experimental methods are available and currently fully operational in the laboratory.

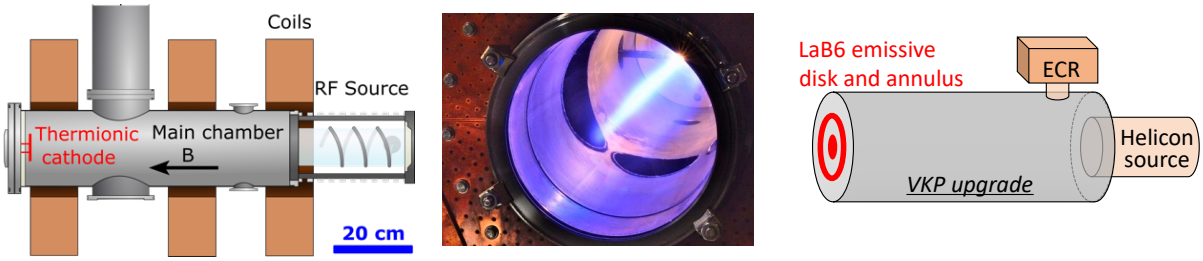


Figure 2: (from left to right) Diagram of the VKP experiment. Photograph showing the injection of current by an emissive cathode into the plasma column. Diagram of the transformations to be implemented during the first year of the thesis (ECR microwave source and highly emissive cathode based on LaB_6 ceramic).

Collaborative environment

Centrifugal instabilities are not limited to magnetized plasma columns in the laboratory, but also occur in astrophysical objects, such as in the plasma disk magnetospheres of gas giants [5]. The cases of Saturn and Jupiter have recently attracted a lot of attention, and the understanding and parameterization of turbulent transport in this astrophysical context is also an open question. This thesis will be part of a joint research program with colleagues in Toulouse (Laplace and IRAP) and Marseille (PIIM), and the doctoral student will be involved in several collaborative projects.

During the second year of the thesis project, the work will be carried out in close collaboration with our colleagues at the Laplace laboratory, where numerical and analytical models are being developed to predict plasma potential control and flux entrainment from polarized electrodes [9].

During the third year of the thesis project, the work will benefit from the complementary expertise of the PIIM and IRAP groups on theoretical modeling and numerical simulations of centrifugal instabilities in the context of laboratory devices [4] and gas giants [5].

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