(Placeholder1)**White Paper for *Frontiers of Plasma Science Panel***

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Title:	Turbulence, anomalous transport and structures in low temperature Hall plasmas with ExB drift
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Research frontier and the scientific challenge

Plasmas with moderate values of the magnetic field where the ions are not or weakly magnetized, i.e. the ion Larmor radius being larger or comparable to the characteristic length scale of interest (e.g. the size of the system), have distinctly different properties from strongly magnetized plasmas such as that for fusion applications. The natural scale separation between the ion and electron Larmor radii further exploited by the application of the external electric field offers unique ways to create and control low temperature plasmas [1], e.g. separate, extract and accelerate ions, localize the ionization regions and others. Such regimes, loosely called here as Hall plasmas with ExB drifts, are used in various applications such as magnetrons for material processing [2], various purpose Penning sources [3], magnetic filters [4] and devices for electric propulsion [5], e.g. Hall thrusters. Similar conditions also exist in the lower part of the ionosphere (E-layer) and solar atmosphere [6]. The dynamics of non-magnetized ions is also an essential feature of the reconnection processes in space and in laboratory plasmas [7].

In most applications, plasmas with strong electron currents due to the applied E and B field, involve density, magnetic field and temperature gradients [47]. Often, there are also directed flows of ions which are non-magnetized and thus drifting strongly with respect to electrons. All these represent strongly non-equilibrium conditions with large reservoirs of free energy making plasma prone to a number of instabilities. A resulting turbulent behavior is ubiquitously observed in many devices across a wide range of spatial and temporary scales [8-11].

Despite the long history of experiments and observations in various Hall plasma devices the physical picture of small scale fluctuations and coherent structures is poorly understood. One of the manifestations of turbulent fluctuations is enhanced (anomalous) electron conductivity in such plasmas that typically exceeds the classical values by one or two orders of magnitude [11-13]. Another often observed phenomena is the excitation of meso-

scale structures with a characteristic length scale between the geometric scale length of the device and the characteristic length scale of small scale fluctuations [2,14-17,46]. The prominent feature of such structures is that their rotation frequencies is one order of magnitude lower than the frequency of the ExB drift [18].

Plasmas in similar parameter regimes were studied earlier in the context of anomalous (tubulent) heating in pulsed devices where the studies were focused on the role of low hybrid and modified two stream instabilities as a source of instabilities and turbulence [19-21]. However, only limited applications and extensions of this earlier work related to recent experiments with magnetrons and Hall thrusters exist.

The problem of turbulence and transport in Hall plasmas is of course another incarnation of the fundamental yet unsolved problem of plasma and fluid turbulence. In the last decades, there have been significant advances in the physics of high temperature fusion plasmas, in particular in theoretical understanding of crucial instabilities responsible for anomalous transport in tokamaks as well as in the development of numerical tools capable of quantitative modeling of anomalous transport [22,23]. The ion temperature gradient modes were clearly identified as a source of ion transport, the electron transport was shown to be caused by electron temperature gradient, trapped electron and micro-tearing modes depending on the regime and the device. Mechanisms of shear flow suppression and zonal flows generation and their role in self-organization of drift wave turbulence were established. A number of large scale numerical codes have been developed that are able to provide quantitative predictions of the stability criteria and resulting level of the anomalous transport for different modes [24].

On the contrary, plasma turbulence of low temperature Hall plasmas with ExB drift are poorly studied and poorly understood; the available numerical tools do not match the maturity of those developed for fusion applications and are not able to provide reliable predictions of the anomalous transport. The basic questions are: What are the dominant instability modes responsible for the observed level of anomalous electron current? What is a dominant range of the spatial and temporal scales of fluctuations that contribute to the anomalous transport? What is the role of ionization effects and anisotropy of plasma components, e.g. high energy and secondary electrons? The next level questions concern the nature of the meso-scale structure spontaneously excited in Hall plasma turbulence. Do these structures originate from some primary low frequency large scale instability or are they generated as a result of the secondary nonlinear processes of condensation and self organization of small scale turbulence similarly to zonal flow dynamics in fully magnetized plasmas? What are the controlling parameters that determine the mode transition between homogenous turbulence and various modes with coherent structures?

Approaches and specific issues

Opportunities exist to advance this frontier via the combination of theoretical analysis, kinetic and fluid simulations and experiments. Full nonlinear kinetic (Particle-in-Cell) simulations remain the ultimate tool for global integrative simulations which covers the regions with vastly different magnetic field and different densities, e.g. from the acceleration region of Hall thrusters with strong magnetic field to their plumes with vanishing magnetic field where even electrons become non magnetized. Recent efforts of kinetic simulations in several groups [25-33] can be cross checked and compared. The goal would be to ensure reproducibility of the key results among different codes and establish common standards of a generic simulation of Hall plasmas (similar to the Cyclon case base project [22]). The provisions could be made for modular introduction of additional effects, e. g. secondary electron emission, anisotropic components, etc. Such work would need to be performed via the collaboration of several groups. Mutually agreed and tested simulation cases would become a standard for future code development.
Full kinetic simulations are the most realistic approach to the experiment, they however can be difficult to interpret and in a number of cases simulations with realistic parameters are still out of reach even for modern high performance computers. Complementary fluid simulations should be developed as faster and cheaper numerical tools for simulations of nonlinear plasma dynamics, because they are easier to interpret and provide much greater flexibility in separating various physics elements. Fluid models have been indispensable contributions to the development of tokamak physics [22,23]. Fluid simulations for Hall plasmas need to be developed in conjunction with kinetic simulations [33,45]. Whenever possible, kinetic simulations should serve as benchmarks for fluid simulations. Kinetic and fluid simulations simulating the same experimental conditions [33] will allow a better understanding of basic physics, faster progress and, via mutual complementarity, in part overcome natural limitations of each method.

Nonlinear multiscale dynamics. Previous works have identified several types of modes that might be operative at quite different spatial and temporary scales in typical conditions of Hall plasmas: gradient (density, magnetic field and temperature) drift modes [34] representing the generalization of the collisionless Simon-Hoh instability [10,35], low hybrid and modified two stream instabilities [33], ion sound instability , resonant small scale electron cyclotron modes and sheath impedance modes [36]. Experiments showed that a significant fraction of the total current (50% and more) may occur within a single coherent low frequency structure such as a spoke [37]. Numerical simulations indicate though that large scale structure coexist together with high frequency modes [26]. Their mutual interaction, saturation mechanisms and contribution to the anomalous transport need to be investigated within the integrative approach.

Ionization, collisional and neutral dynamics effects. Ionization instabilities appear in breathing mode and it has been shown recently that spoke and breathing oscillations are affected by neutral gas pressure . Other experiments have also indicated that the electric field profile is strongly modified by neutral pressure. These results are puzzling because the ionization and elastic collision frequencies for low pressures in these experiments are too low to affect the anomalous mobility directly. Effects of ionization and collisions have been considered in some theories of azimuthal modes, but there is no clear picture how the various modes such as gradient-drift, low-hybrid and ion sound could be affected by neutral gas dynamics. A further optimized approach should be tested using a hybrid approach, where only either electrons or ions are treated kinetically whereas the other species are included by fluid models. A further self-consistent coupling with neutral models, either using Direct Simulation Monte Carlo pseudo-particle techniques or Navier-Stokes fluid models, will allow to study the coupling of plasma length and time-scales with neutral dynamics, especially important e.g. for breathing modes or rotating spokes.

Sheath , secondary emission and energetic/anisotropic components. Another challenge in the transport theory of low temperature plasmas is the role of material boundaries and development of plasma sheath, sputtering or secondary electron emission [41, 42]. Anomalous diffusion of electrons across magnetic field lines results in erosion of the thruster channel wall, which is much higher than expected from classical estimates. The plasma sheath developing in front of a wall is characterized by very strong non-linearities which can create waves and turbulence. For bounded plasmas, sheath instabilities can trigger instabilities in the plasma volume, resulting in an anomalous diffusion of plasma particles.

Sheath instabilities and secondary emission may result in a strong anisotropy of the electron distribution function affecting the ionization balance [41]. The kinetic features in the ion distribution function may also occur due to several physical effects, such as partial magnetization of the ion motion and forming of several distinct groups of ions with different energies due to charge-exchange collisions. Such electron and ion kinetic effects and their role in turbulence and transport in Hall plasmas can be tested with kinetic Particle-in-Cell (PIC) codes [27,33]. Some kinetic effects, such as Landau damping can also be introduced into fluid turbulence models with approximate (linear closures) as it was successfully demonstrated by the gyro-fluid models for ion-temperature gradient turbulence in fusion plasmas [43,44]. The success of such simple model as Hammett-Perkins closure for Landau damping has driven the search for even better and faster numerical implementations of the linear closures for kinetic effects. Recently, a versatile non-Fourier method for the computation of Landau-fluid closure operators of the Hammett and Perkins type for finite difference implementation.

Impact on plasma science, related disciplines and potential societal benefits.

Low temperature Hall plasmas subject to crossed electric and magnetic fields represent a distinct type of plasma relevant to a number of practical applications and also of interest for fundamental problems of space/ionosphere plasma and reconnection. Understanding of such plasmas has been noticeably lagging behind the progress demonstrated in fusion plasmas. Major research opportunity exists in theory and simulations to advance this frontier via the development of theoretical models and numerical tools, cross development of kinetic and fluid codes and model bench-marking against the experiments. It is expected that advancement of this frontier will contribute not only to general knowledge of nonlinear theory, turbulence and transport and the problem of plasma-wall interaction but will also facilitate the development of more efficient thrusters for electric propulsion and plasma processing reactors.

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