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Thermodynamics of magnetized plasma through experimental observations: superadiabaticity, entropy and energy content

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The study of thermodynamics serves as a crucial tool for comprehending the key concept of self-organization of particles associated with the change of macroscopic magnetic moment in response to plasma heating. Thermodynamic methods have been implemented to investigate magneto-fluid coupling, dusty plasma, plasma heat pump and heat engine. The polytropic index (γ) is an important parameter that characterizes compression or expansion in a thermodynamic system, and equivalently heat transfer processes. In the present study polytropic index of electrons in a magnetized plasma is experimentally investigated under external heating and anisotropic work done in the presence of a dipole magnetic field, incorporating the effective dimensionality [1]. Further, the energy content of the plasma is determined through extensive measurements and modeling within a fluid mechanical and thermodynamic framework [2].

The study is performed in an electron cyclotron resonance (ECR) generated plasma confined in a dipole magnetic field, created using a single permanent cylindrical magnet, and operated at steady state. The schematic of the device is shown in Fig. 1 [3-6]. Langmuir and electric field antenna probes [5] are employed for plasma and wave diagnostics. In the first part of the work, the polytropic index is determined from,

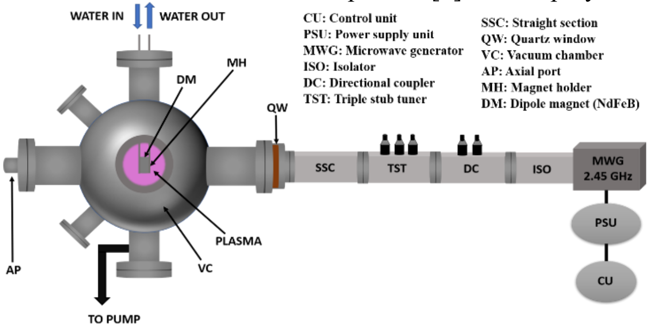

Fig. 1. Schematic of the experimental setup.

$$\gamma_{\perp \text{ or } \parallel} = 1 + (\gamma_a^* - 1)\left(1 - \left(\frac{dQ}{dw}\right)_{\perp \text{ or } \parallel}\right), \quad (1)$$

where dQ is the heat supplied to the system, dw is the work done signifying plasma expansion (or compression) and γ_a^* $(= 1 + 2/f^*)$ is the modified adiabatic index in an anisotropic plasma, f^* being the effective dimensionality [1], which depends on kinetic degrees of freedom f and anisotropicity $\alpha\left(= T_{e\perp}/T_{e\parallel}\right)$, given by $f^* = (1 + (f-1)^2\alpha^2)/(1 + (f-1)\alpha^2)$. The rate of change of total kinetic energy (in eV/s) is given by,

$$\frac{dQ}{dt} = \frac{eE^2_{1(\perp \text{ or } \parallel)}}{m_e}\frac{\nu_{h(\perp \text{ or } \parallel)}}{\nu^2_{h(\perp \text{ or } \parallel)} + (\omega - \omega_c)^2}$$
$$+ \frac{T_{e\perp}}{B}\left[\frac{\partial B}{\partial t} + \overrightarrow{v_E} \cdot \vec{\nabla} B\right] + \left[T_{e\parallel} + \frac{m_e}{e}u_\parallel^2\right]\left(\overrightarrow{v_E} \cdot \vec{\kappa}\right), \quad (2)$$

where $\overrightarrow{\widetilde{E_1}}$ is the wave electric field, ν_h is the electron-neutral collision frequency, ω and ω_c are the angular wave and electron cyclotron frequencies respectively, $T_{e\perp}$ and $T_{e\parallel}$ are the electron temperature perpendicular and parallel to the magnetic field $(\vec{B})$, $\overrightarrow{v_E}$ is the $\vec{E} \times \vec{B}$ drift velocity, $\overrightarrow{u_{\parallel}}$ is the fluid flow velocity parallel to $\vec{B}$ and $\vec{\kappa}$ $(=(\hat{B} \cdot \vec{\nabla})\hat{B})$ is the magnetic curvature. In the magneto-static field, $(\partial B/\partial t) = 0$. Apart from the local wave-induced heating given by the first term of Eq. 2, particles also gain energy due to acceleration arising from grad-B (second term) and curvature (third term) drifts when it couples with $\overrightarrow{\widetilde{E_1}}$. The measurements demonstrated localized regions of superadiabatic electrons when the heating associated with the $\vec{\nabla} B$ and curvature drift is higher than dw [6]. In regions where wave-induced heating through ECR dominates, the plasma electrons behave adiabatically.

Furthermore, we have derived an expression for the Helmholtz free energy (F) of the plasma, using total kinetic energy and entropy equations. The internal energy ($U = T_eS + F$) is determined by incorporating entropy (S) which is independently obtained from the Saha's equation [7], and using the experimentally measured plasma parameters such as electron density and temperature (N_e and T_e), $\overrightarrow{\widetilde{E_1}}$ and $\vec{B}$. Results indicate that U is governed by the combined effect of S, T_e and F in the stronger B region, and primarily by F in the weaker B region. It was also found that U had an anticorrelated spatial profile with T_e. This may explain the brighter and darker regions in the observed optical emissivity [8] of the dipole plasma.

References

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