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Energy exchange in a compact dipole plasma: thermodynamical investigations through measurements and modeling

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Temperature anisotropy prevails both in laboratory and astrophysical plasma. As a free energy source, temperature anisotropy has revealed potential solutions to heating and particle acceleration issues, leading to the disposal of heat in the form of energy. Energy conversion for systems in local thermodynamic equilibrium has been well understood. However, energy conversions in weakly collisional or collisionless plasmas, which are far from thermodynamic equilibrium, widely occurring in astrophysical environments, remains a forefront research problem [1]. Several efforts have been put in recent years to understand thermodynamics of plasma in terms of theory [2] and simulation [1,3] in anisotropic magnetized plasma. However, the thermodynamic potentials have not been explained in terms of plasma characteristic parameters in plasma confined by dipole field. Therefore, the current study seeks to develop a thermodynamic relation that takes into account experimentally measured parameters in response to plasma heating and energy loss processes with varied operating pressure and power in a dipole field.

The measurements will be carried out in a compact dipole device [4] where several fundamental works such as global plasma sustenance [5], diffusion induced transport [6], optical emissions [7], temperature anisotropy governed electrical conductivity [8] and current density [9] have already been addressed. The schematic of the device is shown in Fig. 1. Langmuir probe and antenna probes for measurement of wave electric fields, are employed for measurements at all accessible spatial position (r, θ, ϕ) with varying pressure (0.4, 1.2 and 2.0 mTorr) and input microwave power (300, 350 and 400 W).

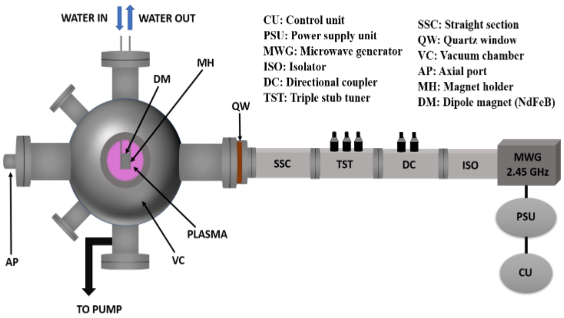

Fig. 1. Schematic of the experimental setup [9].

Initially, the local intrinsic entropy of our system was obtained using Boltzmann's H-theorem of kinetic theory from electron energy distribution function [3], given by,

$$s = \sum_j s_j = \frac{3}{16} n k_B \left\{ 1 + \ln\left(\frac{2\pi}{m_e} \frac{p_r^{1/3} p_\theta^{1/3} p_\phi^{1/3}}{n^\gamma} \right) \right\}, \quad (1)$$

where, $p_j (= N_e k_B T_{ej})$ is the plasma pressure along $\hat{j}$ for $j \to r, \theta$ and ϕ, and γ is the adiabatic index. This will be further disintegrated component wise as entropy being a macroscopic quantity is additive in nature, which will further aid to understand the heat added (Q) to the system from 2nd law of thermodynamics given by $dQ_j = T_{ej} ds_j + s_j dT_{ej}$ along three directions. Furthermore, in an anisotropic magnetized plasma, the magnetic field helps in interchange between parallel and perpendicular energy, and provides additional work [3]. In the presence of dipole field ($\boldsymbol{B}$) it can be improvised as,

$$dW = \sum_j dW_j = \left(p_r dV + p_r V \frac{dB}{B} \right) + \left(-p_\theta V \frac{dB}{B} \right) + V k_B d\left(n\left(T_{er} + dT_{e\theta} + dT_{e\phi}\right)\right), \quad (2)$$

where V is the flux tube volume. This will help us to determine change in internal energy from 1st law of thermodynamics: $dU_j = dQ_j - dW_j$.

A mathematical power balance model is formulated to understand the energy transfer in plasma. In our case, microwave heating adds external heat to the plasma. However, in dipole field, particles also gain energy by betatron and Fermi heating [10] due to the mirror and curvature drifts resulting in conservation of first and second adiabatic invariants respectively. The energy dissipation happens through diffusion cooling, charge exchange, inelastic and elastic collision, isotropization and losses through the walls. The net energy retained from the abovementioned processes will modify dU_j.

The internal energy at every spatial location will be estimated from both the models to observe their agreement with each other. Furthermore, other thermodynamic potentials such as enthalpy, Helmholtz free energy and Gibb's free energy can be determined. In the colloquium, results of the above-mentioned investigation will be presented and the thermodynamics of anisotropic magnetized plasma confined by a dipole field will be discussed.

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