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Adiabatic expansion of electrons in a magnetic nozzle

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The first law of thermodynamics is that the change in the internal energy of a closed system (ΔU) is equal to the added heat (Q) minus the nett work (W) done by the system: ΔU = Q+W, and for an expanding system W can be calculated by the pressure P and the change in volume ΔV as ΔU = Q - PΔV . These changes are identified using a calorimeter; for plasmas, a detailed energy distribution of the charged particles can be obtained using a Langmuir probe as performed a number of experiments, e.g., Ref. [1].

The expansion of a gas has been understood using traditional thermodynamics. It is convenient to characterize the expansion of a gas using the concept of a polytropic index as PV^{γ} = constant, where γ is equal to unity for the isothermal expansion and to 5/3 for the adiabatic expansion for monatomic gas.

Whereas experiments with simple gases can be easily carried out in laboratories, those involving gaseous plasmas of astrophysical and solar interest pose a number of extremely difficult problems. Observations near the Sun and at Earth orbit have been interpreted as demonstrating that the solar wind does not expand adiabatically from the Sun as would have been expected for this near collisionless environment. Rather, it expands isothermally, implying that heating of the plasma occurs as it propagates through inter-planetary space. Many laboratory experiments under adiabatic conditions have also shown a nearly isothermal expansion with γ ~ 1.0-1.2 in the magnetic nozzle and the relation with the astrophysical plasmas has been discussed [2]. However, in these expanding adiabatic systems, it appears that electric fields may have a significant nonlocal effect on the dynamics of electrons; many of them are trapped in the system by the ambipolar and wall sheath electric fields, allowing an isothermal equilibrium to be established, while some of electrons having the energy overcoming the potential drop can escape from the system. Hence, both the trapped and free electrons coexist in different proportions.

A very fundamental question then arises: *What would happen if there were no electric fields trapping the electrons?*

Here, energy distribution of the magnetically expanding electron gas whose charges are neutralized by background ions is measured when removing the electric field from the system. Since the magnetic field can behave as a flexible wall with no physical boundary, it can be considered as a boundary with no heat transfer, i.e., an adiabatic wall. The results demonstrate that the electron gas behaves like an ideal gas expanding adiabatically in the absence of electric fields, while showing isothermal properties when trapped by the electric fields in the system.

Our experiment demonstrates that the plasma potential can be varied in the range of 0 – 50 V. When the plasma potential is set zero over the whole region in the system, the sheath electric field trapping the electrons is absent, while almost of the electrons are trapped for the high plasma potential case. The results in Fig.1 shows that the polytropic index close to 5/3, i.e., the nearly adiabatic expansion, is demonstrated, while showing the isothermal value of γ ~1 is obtained for the high potential case. This implies that the expanding magnetic field can be considered as the adiabatic wall that has work done on it [3]. This picture is consistent with our previous measurement of the force exerted to the magnetic nozzle [4] and the diamagnetic feature [5].

In summary, the thermodynamics of the electrons expanding in the magnetic nozzle is investigated for the absence of all the electric field in the system; showing the nearly perfect adiabatic expansion where the electron gas do the work on the magnetic wall.

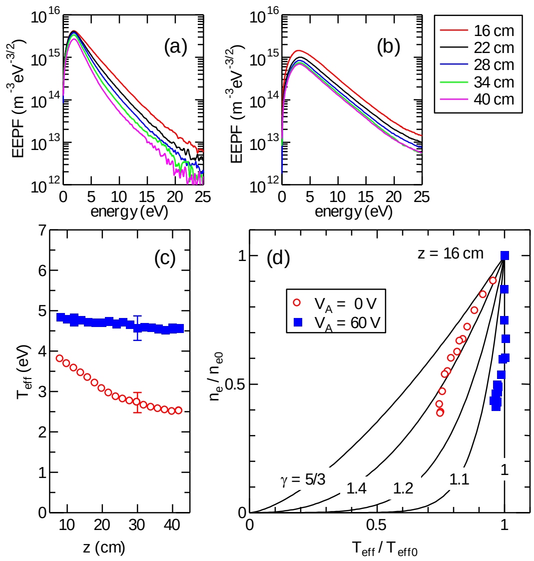

Figure 1: Measured eepfs along the magnetic nozzle axis for the (a) zero and (b) high plasma potential cases (labelled as V_A = 0V and 60 V). (c) Axial profile of the effective electron temperature and (d) polytropic relation with theoretical curves for various values of γ.

References

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