High-performance laser diagnostics for plasma characterization

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Abstract: High-sensitivity Thomson scattering diagnostics have been applied in recent years to studies of low-temperature magnetized plasmas. In the incoherent Thomson regime, detailed maps of electron properties (energy, density and drift velocity) have been obtained, permitting the characterization of pulsed materials processing plasmas. The identification of short-scale waves in multispecies plasmas, carried out using coherent Thomson scattering, has provided information concerning the species created in transient plasmas and the origins of the anomalous transport of electrons.

Keywords: laser scattering, incoherent and coherent Thomson scattering, instabilities, electron properties, planar magnetron

1. Introduction and background

Information on electron properties and dynamics are key ingredients in numerical simulations which aim at capturing diverse features of magnetized plasmas, including the nature of ionization, plasma-wall interaction, wave excitation, and other aspects.

Although Maxwellian electron energy distribution functions (EEDFs) are usually assumed in fluid modeling, there is ample evidence that this assumption is a poor descriptor of many low-temperature magnetized plasmas, such as in the presence of plasma waves inherent in cross-field (orthogonal magnetic and electric fields) configurations. Particle-in-cell simulations, for example, have shown how the growth of short scale waves in ExB plasmas is associated with a progressive deformation of an initially Maxwellian EEDF [1], with a resultant effect on the nature of wave-particle interaction and electron transport. Understanding these and similar plasma features in simulations requires tools to directly measure the electron energy distribution.

Access to electron properties, particularly with high temporal resolution, is also a key goal for materials processing plasma devices, such as planar magnetrons, in which high-current, pulsed regimes [2] are increasingly used to develop tailored thin films for microelectronics, optics, photovoltaics, and other applications. Such regimes are known to be highly transient and to exhibit very large variations in electron properties from discharge initiation into the plasma post-discharge. Such regimes pose a significant modeling challenge currently, with even advanced codes severely limited in terms of duration [3] (far below typical plasma pulse durations) and particle densities. The development of more advanced codes could ultimately facilitate the development of new materials and complex films, and such an objective relies on the application of suitable diagnostics for electron properties which can help clarify how plasma features couple to thin film characteristics.

In addition to direct measurement of electron properties, the identification of plasma waves is critical to understanding the operation of magnetized plasma devices in materials processing, space propulsion, and other applications. In recent years, combined experimental, theoretical and numerical studies have revealed that in devices generating several ion species (different ionization degress or different atoms) and subject to imposed electric and magnetic fields, it is possible to excite key waves which can only be supported in multicomponent plasmas [4]. Furthermore, such waves contribute in complex ways to the transport of electrons. The capacity for identifying such waves and characterizing their effects also, therefore, is key to developing an understanding of different plasma devices.

2. Advanced diagnostics implementations

Recent diagnostics developments (coherent and incoherent Thomson scattering implementations) have been focused on providing key characterizations of electrons in low-temperature magnetized plasmas, with a focus on fundamental electron properties and plasma turbulence.

The PRAXIS laser diagnostic [5] uses scattering of infrared radiation in the coherent (collective) Thomson scattering regime, in which the scattered radiation, at length scales larger than the electron Debye length, allows information on correlated particle motion within the plasma to be studied. The direct measurement of electron density fluctuations in the implementation of this diagnostic has been used to identify multiple types of waves to date, including the electron cyclotron drift instability, ion-ion two-stream instability, and most recently, the ion acoustic instability in thruster cathodes [6]. These waves play key roles in the functioning of different plasma devices and their identification, via non-invasive and direct means, provides a new experimental framework on which simulations can rely, and has laid the groundwork for revisions to existing theory around waves in these devices.

The THETIS diagnostic [6], which uses visible light scattering in the incoherent Thomson regime, provides access to the thermal fluctuations of electrons (at scales below the Debye length), allowing electron properties to be directly measured from scattered spectra. This non-invasive diagnostic has been used to provide time-resolved measurement of such properties and direct comparisons with numerical simulations.

3. Results

This work focuses on recent insights obtained from these diagnostics, notably in implementations on materials processing plasmas. It has been found, through incoherent Thomson scattering measurements of the electron drift in planar magnetron pulsed plasmas, that the highly transient nature of the discharge is associated with a shifting balance of E x B and diamagnetic drifts [7]. It has also been found that the nature of certain excited waves is strongly dependent on the fractions and types of ionized species present, a feature yet to be accounted for in current particle-in-cell simulations of such devices. The advanced experimental characterizations achieved are discussed in the context of existing theory and simulations.

4. References

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