Groupement de recherche
EMILI Étude des milieux ionisés
Plasmas froids créés par décharge et laser

Diagnostics optiques

Journées 2021
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Electrons: probing their properties and collective dynamics

Introduction

The complexity of the plasma state requires the use of experimental tools which can provide information on particle properties and dynamics. This is essential to understand processes such as:

- energy exchange
- ionization dynamics
- development of plasma instabilities and particle transport,

among other features. Information on these aspects is key to the development of theoretical models and numerical codes for all plasmas. Regardless of the plasma state and type (magnetized or unmagnetized, hot or cold, high or low pressure) **electrons play a key role in determining the discharge features**. Diagnosing their properties and dynamics is therefore critical.

Non-invasive versus invasive techniques

Invasive

example: **Langmuir probes**

Pros
- simplicity of implementation
- low cost
- high spatial and temporal resolution may be achievable

Cons
- assumptions necessary (Maxwellian EVDF)
- unsuited to magnetized plasma regions
- perturbative: physical size, sputtering
- non-direct interpretation generally necessary

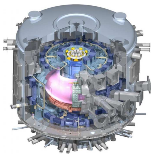
Non-invasive

example: **incoherent Thomson scattering**

Pros
- direct information often accessible
- suitable for investigations in magnetized plasma regions
- high spatial and temporal resolution, depending on implementation

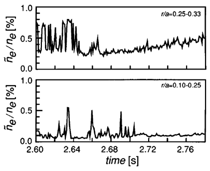
Cons
- complexity of implementation
- high cost
- optimization of implementation required to maximize signal-noise ratio and minimize stray light

Coherent Thomson scattering implementations in hot plasmas



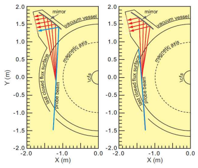
Coherent Thomson scattering has been used for decades in the investigation of **turbulent fluctuations in tokamaks and pinch devices**. In recent decades, it has also proven key to the identification and characterisation of instabilities in **low-temperature plasmas.**

examples from hot plasmas

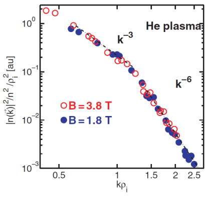


Study of electron density fluctuations in different tokamak operating modes: e.g. reversed shear [1]

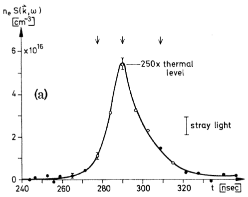
probing wave at 280 GHz



NSTX implementation for study of identification of modes driving anomalous electron transport (e.g. electron temperature gradients) [2]

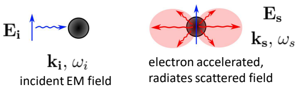


Identification of key scaling laws on Tore Supra [3] and other plasmas

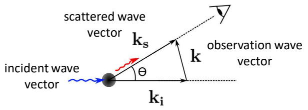


Intensity of density fluctuations n_e S($\mathbf{k}$, ω) measured within a collisionless shock wave (Mach number 2.5, deuterium plasma) in a theta pinch [4]

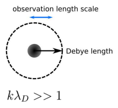
Thomson scattering is electromagnetic wave scattering on free charges. Two regimes - incoherent and coherent - provide different and complementary insights into particle properties and dynamics.



scattered power $\frac{dP}{d\Omega} = r_e^2 \, sin^2\phi \; c\varepsilon_0 \left|E_i^2\right|$



Incoherent Thomson scattering (ITS)



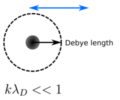
$k\lambda_D >> 1$

$$\frac{d^2P}{d\Omega_s d\nu_s} = \left[2\pi r_e^2 \int_V \langle S_i \rangle \, d^3r \, |\hat{\mathbf{s}} \wedge (\hat{\mathbf{s}} \wedge \hat{\mathbf{e}})|^2\right] f_k\left(\frac{\omega}{k}\right)\frac{1}{k}$$

$f_k(v_k) = \text{1D velocity distribution function along } \mathbf{k}$

- electron temperature
- electron density
- electron drift velocity

Coherent Thomson scattering (CTS)



$k\lambda_D << 1$

$$\frac{d^2P}{d\Omega_s d\nu_s} = \frac{r_e^2 P_i}{A} |\sqcap \cdot \hat{\mathbf{e}}|^2 n_e V S(\mathbf{k},\omega)$$

$S(\mathbf{k},\omega) = \text{scattering form factor}$

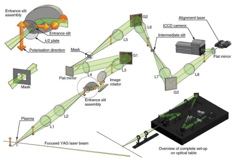
$$S(\mathbf{k},\omega) = \frac{1}{n_e T V} |N_e(\mathbf{k},\omega)|^2$$

$N_e(\mathbf{k},\omega) = \text{Fourier transform of electron density}$

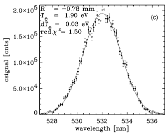
- correlated fluctuations in presence of wave activity

Incoherent Thomson scattering in low-temperature plasmas

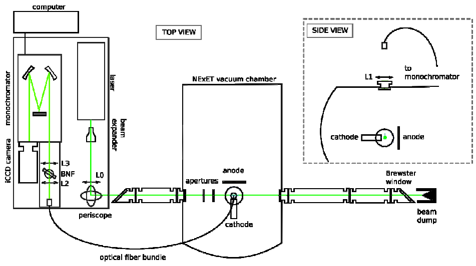
ITS provides access to detailed measurements on electron properties, and in recent years, its application to low-temperature plasmas has expanded considerably.



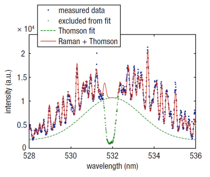
Example of standard triple grating (TGS) spectrometer assembly used for redistribution of scattered light [5]



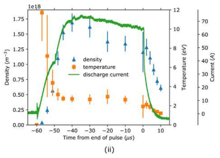
Example of Thomson scattered spectrum observed using a high-performance ITS system on the linear plasma machine Pilot-PSI [6] for the study of plasma-surface interactions. Calibrated electron density values were measured in the range 10^{20} – 10^{21} /m^3.

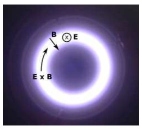


Components of a full ITS implementation on a hollow cathode plasma [7], with the TGS replaced with a volume Bragg grating (VBG) [8] and single monochromator to filter stray light. This considerably reduces photon collection losses and allows a detection limit as low as 10^{16}/m^3 to be achieved.



Simultaneous observation of Thomson and Raman spectra in investigations of atmospheric pressure plasma jets [9]

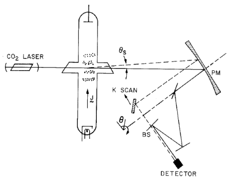




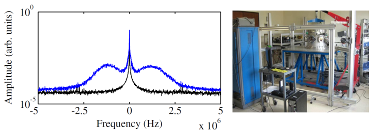
Electron density and temperature variations [10] (left) during pulsing of a planar magnetron Ar plasma at 7.5 mTorr (right)

Coherent Thomson scattering in low-temperature plasmas

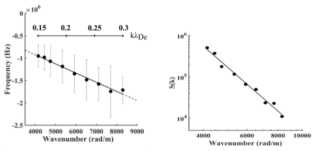
Implementations of CTS have provided new information on microturbulence across a range of magnetized plasmas. Indirect information on plasma large-scale structuring can also be obtained from certain implementations.



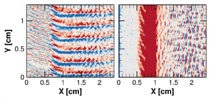
Schematic view of an early CTS setup used for the investigation of ion acoustic turbulence in a plasma column using infrared scattering [11]



(left) CTS spectrum showing identification of the MHz-frequency electron cyclotron drift instability in an ExB annular plasma configuration [12] and (right) experiment setup



(left) Dispersion relation and scaling law identification for ion acoustic turbulence in a hollow cathode made using CTS



Recent 2D PIC simulation results confirming the coexistence of two small-scale modes in an ExB discharge configuration: the electron cyclotron drift instability along the ExB drift direction and the ion-ion two stream instability along the electric field direction [13]

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