Incoherent Thomson Scattering (ITS) applied to low temperature plasma sources

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Introduction

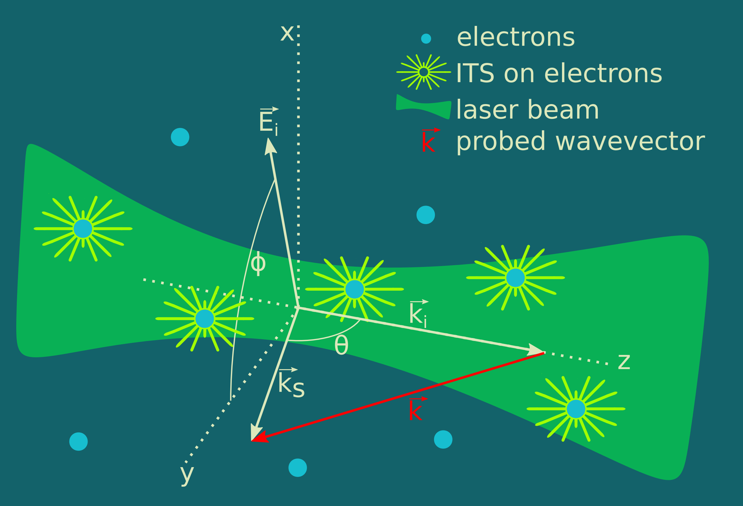
Low-temperature plasma sources have wide ranges of applications such as in electric propulsion, thin film deposition and particle sources for accelerators. As the behavior of such plasmas is strongly correlated to electron properties, reliable diagnostics able to probe electron properties are needed. Access to these information would help to increase our understanding of the physics of such complex plasma sources and validate predictive simulations under development[1].

Aim

In this work, our objective is to develop a new highly-sensitive and compact Incoherent Thomson Scattering (ITS) diagnostic for the measurement of electron properties in different low temperature plasma sources with the spatial and temporal resolution required.

Method

ITS methods involves the analysis of scattered photons by free charged particles (electrons in our study) at length scales smaller than the Debye length. Averaged over the scattering volume and the solid angle of observation, the scattered photon spectral intensity measured in the case of Maxwell-Boltzmann Electron Velocities Distribution Function (EVDF) can be expressed as:



$$I_T(\lambda, \Delta\lambda_g, \lambda_0, n_e) = c_1 n_e P_i L\delta\lambda \frac{d\sigma_T}{d\Omega}(\theta,\phi)\left(\frac{e^{-\frac{(\lambda-\lambda_0)^2}{2\Delta\lambda_g^2}}}{\Delta\lambda_g\sqrt{2\pi}} * I\right)(\lambda) \quad (1)$$

With c_1 the total transmission factor obtained after a Raman calibration, $P_i L\delta\lambda$ some known experimental parameters, $\frac{d\sigma_T}{d\Omega}(\theta,\phi) = r_e^2(1-sin^2\theta cos^2\phi)$ the differential Thomson scattering cross section along the observation direction and $I(\lambda)$ the normed instrument function. From a fitting of the scattered photons spectral intensity the electron density (n_e) is directly obtained, $\Delta\lambda_g$ gives the electron temperature (T_e) and $\lambda_0 - \lambda_i$ the electron drift velocity ($v_{e,drift}$).

In case of Thomson signals with high signal to noise ratio, the Electron Energy Distribution Function (EEDF) can be extracted from the normed derivative of the spectral intensity[2]: $f_E(E) \propto \frac{dI}{d\lambda}$ with $E = \frac{m_e}{2}\cdot\frac{c(\lambda-\lambda_0)}{2\lambda_i sin(\theta/2)}$.

Experimental setup (THETIS[3])

Transmission branch:

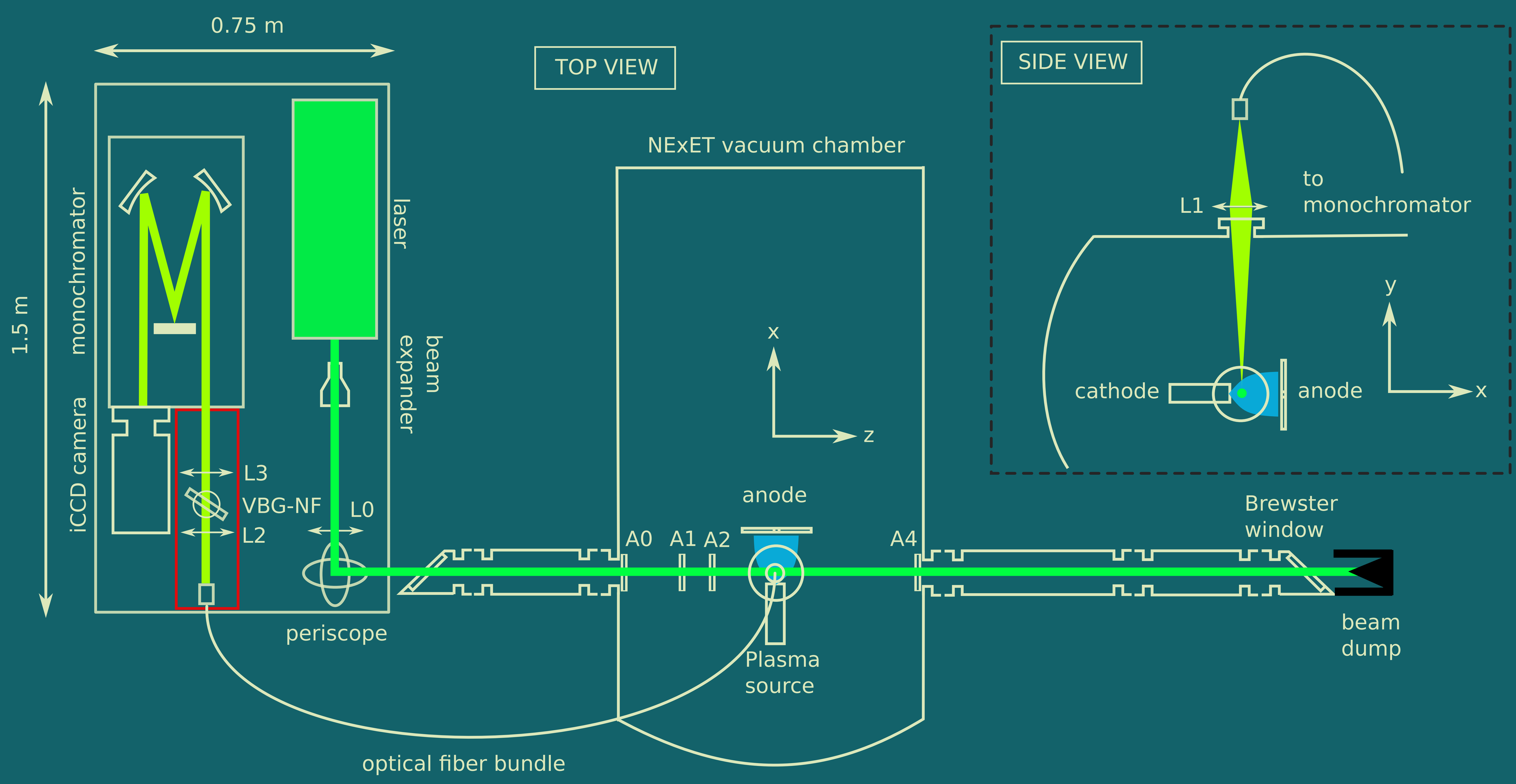
- Q-switch Nd:YAG laser ($\lambda_i = 532\ nm$; $\tau = 5\ ns$; $f = 10\ Hz$; $E = 0.43\ J$)
- $2\ m$ focal lens $\Rightarrow$ laser beam waist $w_0 \approx 0.3\ mm$
- Brewster windows, apertures and large aperture beam dump $\Rightarrow$ reduce stray light propagation

Detection branch:

- Fiber bundle (5×3, $0.3\mu m$) $\Rightarrow$ increase the etendue collected
- Volume Bragg Grating based Notch Filter (VBG-NF) $\Rightarrow$ filter laser stray light contribution[4] with fewer losses than Triple Gratings Spectrometer (TGS)
- Acton SP-2750 spectrometer $\Rightarrow$ disperse the collected light
- ICCD PI-MAX 5 camera (Gen II intensifier) $\Rightarrow$ gated detection to reduce plasma stray light contribution and obtain temporal resolution

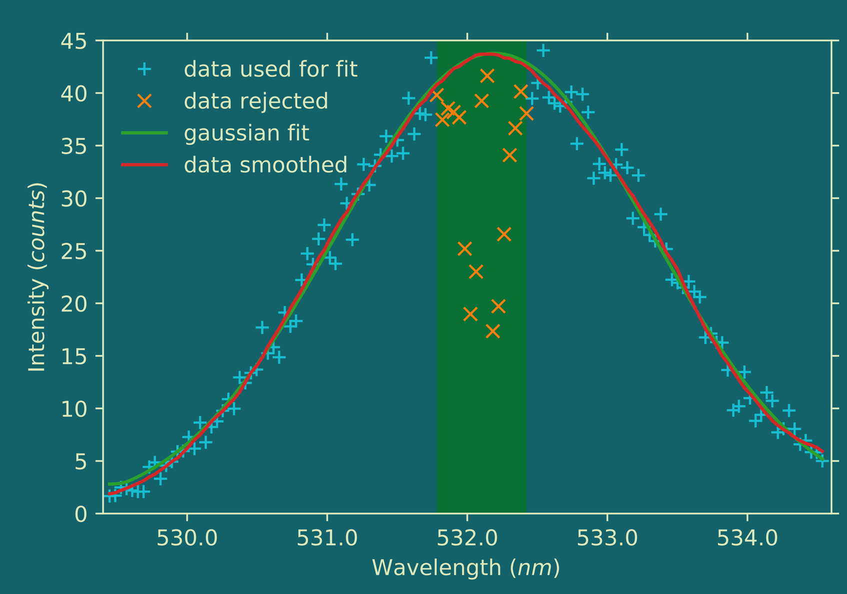
Plasma sources under study:

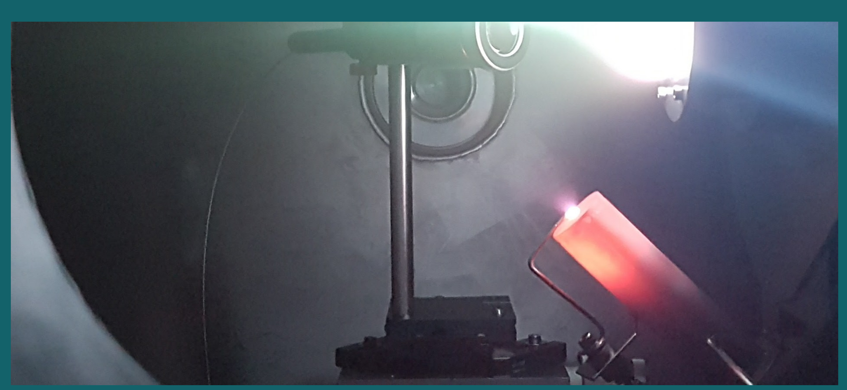
- Hall thruster and its electron source (thermo-emissive cathode)
- Planar magnetron (plasma assisted thin film deposition)
- ECR source (ion source for particle accelerators)



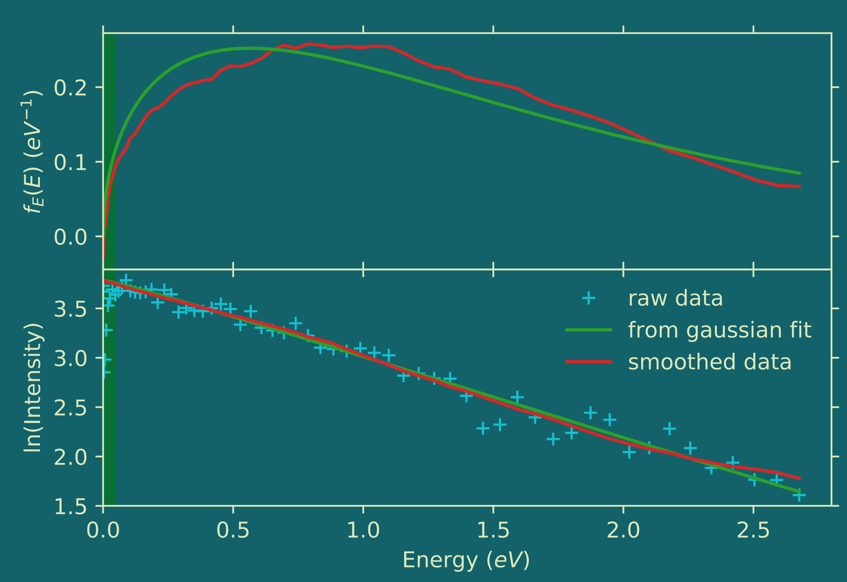
Results

Cathode sources (spatial probing and EEDF):

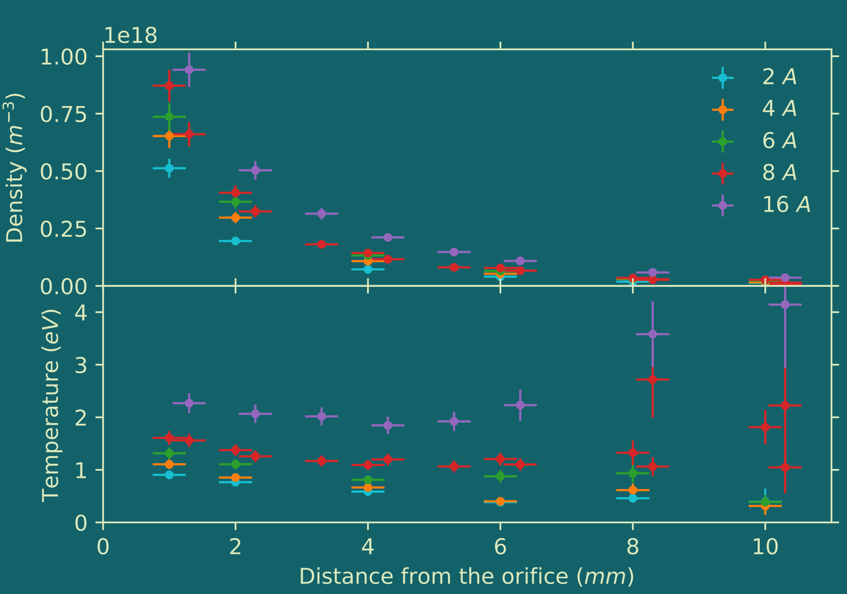




Thomson spectrum obtained $1.3\ mm$ from the cathode orifice ($I_{discharge} = 16\ A$; $D_{Xe} = 0.8\ mg.s^{-1}$; $P_{chamber} = 10^{-3}\ Pa$; $N_{averaged} = 6000\ pulses$).

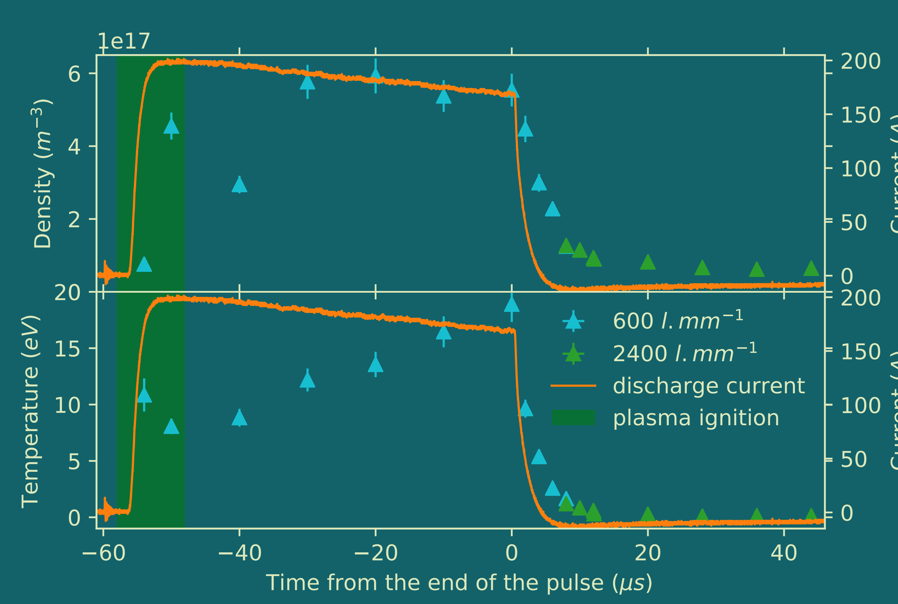


EEDF extracted from the Thomson spectrum derivative.
$\Rightarrow$ Weak deviations from ideal distribution coming from either the VBG-NF spectral distortion or Maxwell-Boltzmann distribution deviations (NB: the commonly used $ln(I_T) vs \Delta\lambda^2$ representation is not sensitive to such deviations).

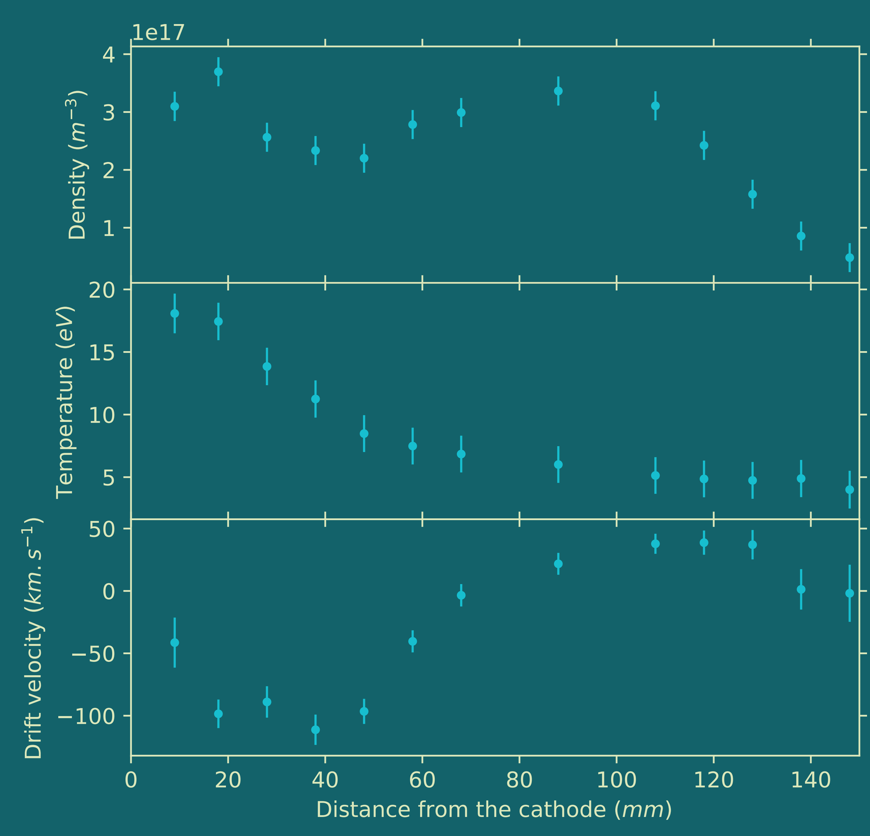


T_e and n_e profiles obtained under the hypothesis of Maxwell-Boltzmann EVDF (i.e. Gaussian Thomson spectrum) for various discharge current and $D_{Xe} = 0.8\ mg.s^{-1}$.
$\Rightarrow$ Expected increase of T_e and n_e with discharge current.
$\Rightarrow$ Unexpected change of trend of T_e at $\approx 5\ mm$ (visible for high discharge current).

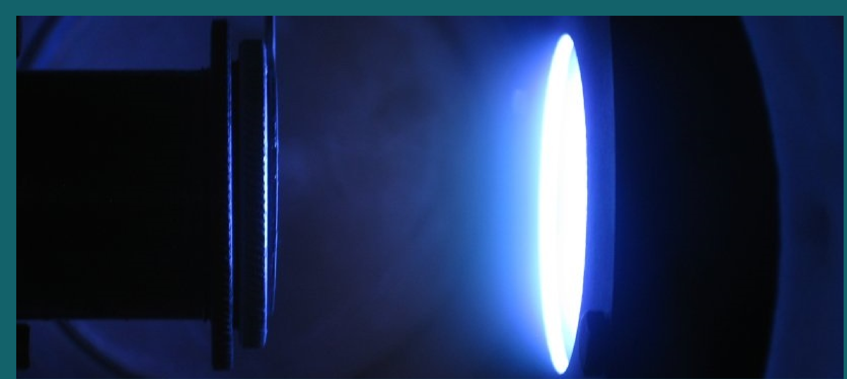
Magnetron source (spatio-temporal probing):



Temporal profile of T_e and n_e at $9\ mm$ from the cathode of the magnetron, with a $10\ Pa$ background pressure of Helium.
$\Rightarrow$ Except during the unstable plasma ignition, precise temporal measurement of electron properties is achieved through synchronization of the discharge with the laser and $N_{avaeraged} = 6000\ pulses$.
$\Rightarrow$ Steady n_e ($\approx 5\times 10^{17}\ m^{-3}$) during the pulse and a linear increase of T_e (up to $\approx 20eV$).



Axial profiles of T_e, n_e and $v_{e,drift}$ obtained at $0\ \mu s$ from the end of the pulse.
$\Rightarrow$ Monotonous decrease of T_e (possibly due to energy diffusion).
$\Rightarrow$ Non-monotonous behavior of n_e and $v_{e,drift}$ $\Rightarrow$ Possibly due to electric field inversion[5] and/or wave energization[6].



Conclusion

A new highly-sensitive ITS diagnostic has been successfully developed and applied for electron property measurement in low-temperature plasmas. Electron properties measurements by ITS have been obtained for the first time in a Hall thruster cathode and a planar magnetron with spatial resolution of $0.3\mu m$ and temporal resolution of $15\ ns$.

References

[1]- Sary, G., Garrigues, L., & Boeuf, J. P. (2017). Plasma Sources Science and Technology, 26(5), 055007.
[2]- Huang, M., Warner, K., & al . (2000). Spectrochimica Acta Part B: Atomic Spectroscopy, 55(9), 1397-1410.
[3]- Vincent, B., Tsikata, S., & al. (2018). Plasma Sources Science and Technology, (accepted)
[4]- Klarenaar, B. L. M., Brehmer, F., & al. (2015). Review of Scientific Instruments, 86(4), 046106.
[5]- Rauch, A., & Anders, A. (2013). Vacuum, 89, 53-56.
[6]- Brenning, N., Lundin, D., & al . (2013). Journal of Physics D: Applied Physics, 46(8), 084005.

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