Analysis of small scale fluctuations in Hall effect thrusters using virtual Thomson scattering on PIC simulations

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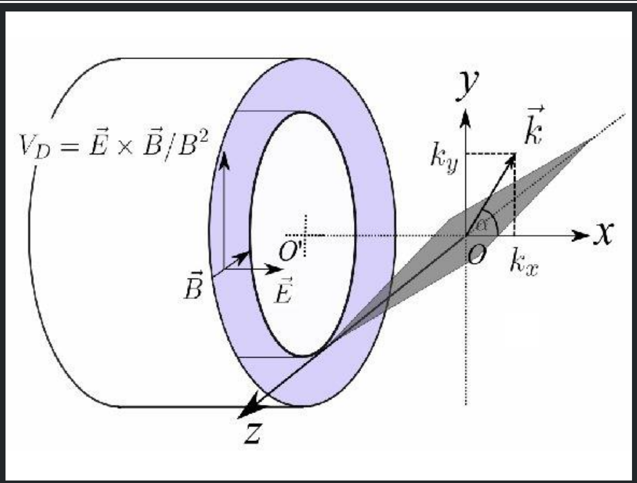
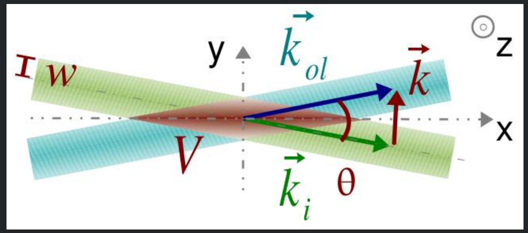
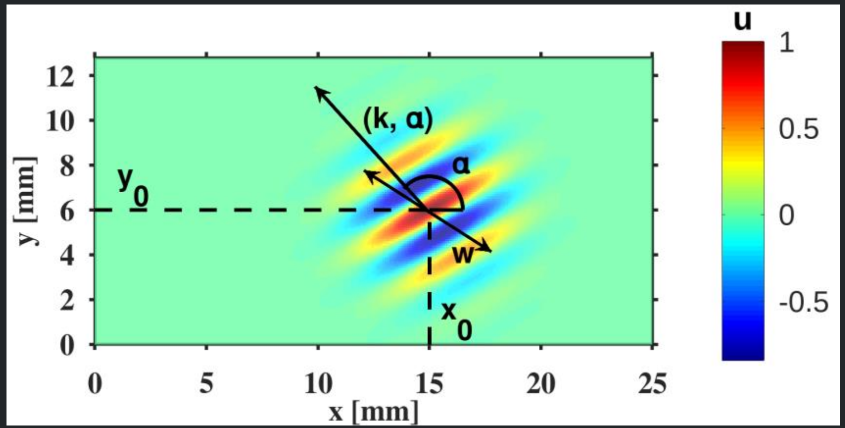
2D modelling of Collective Thomson Scattering = Introducing Virtual Collective Thomson scattering





Typical CTS geometry in HET configuration [1]



2D model of the scattering volume [2]

- CTS is a diagnostic tool to probe millimetric fluctuations in a plasma. Two laser beams intersect at **a fixed position $\mathbf{r_0} = (x_0, y_0)$** and define *the scattering volume.* The scattered signal collected along the scattering vector $\vec{k}$ is proportional to the **Fourier transform of the local electron density**:

$$s_{r_0,\vec{k}}(t) = \int n_e e^{i\,\vec{k}.\vec{r}}\, d^3r$$

- The EM field of the laser beam can be modeled with a Gaussian intensity profile:

$$u_{r_0}(r) = I_0 e^{-\frac{(r-r_0)^2}{w^2}}$$

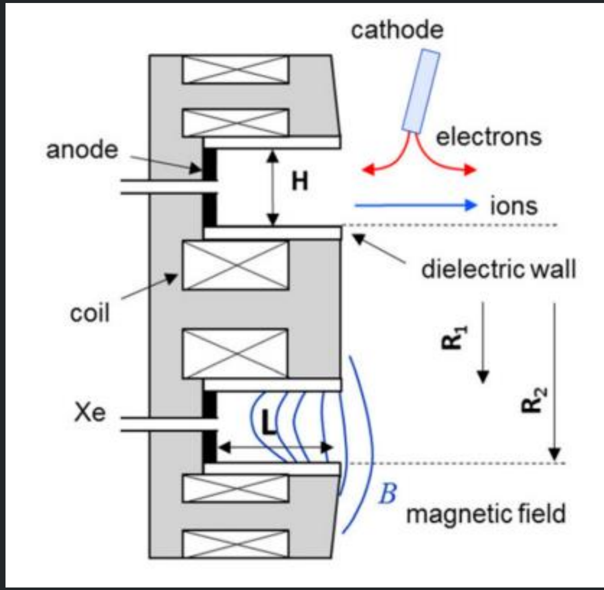
- The **virtual scattered signal** is calculated from the spatial Fourier transform along $\vec{k}$ and can be seen as a gaussian windowed FT:

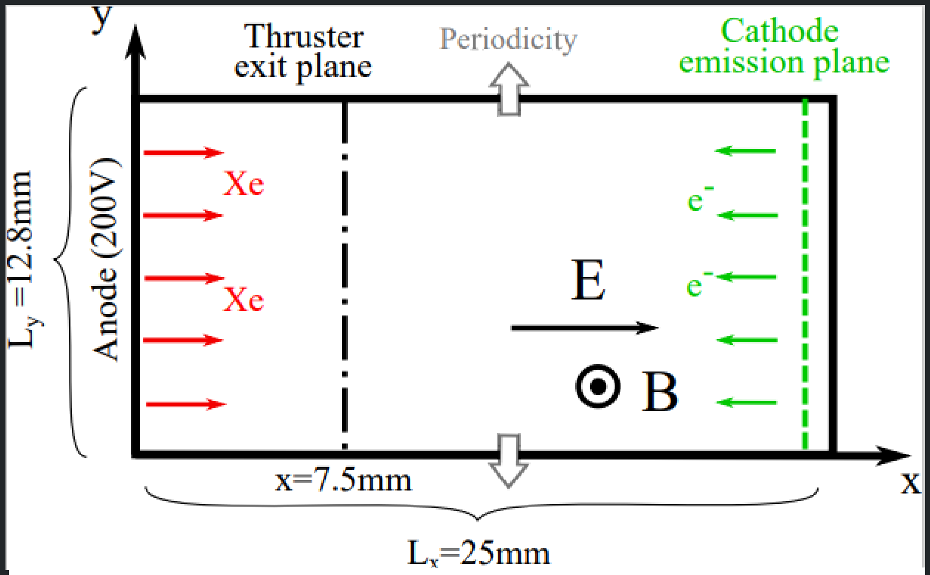
$$s_{r_0,\vec{k}}(t) = \int n_e u_{r_0} e^{i\,\vec{k}.\vec{r}}\, d^3r$$

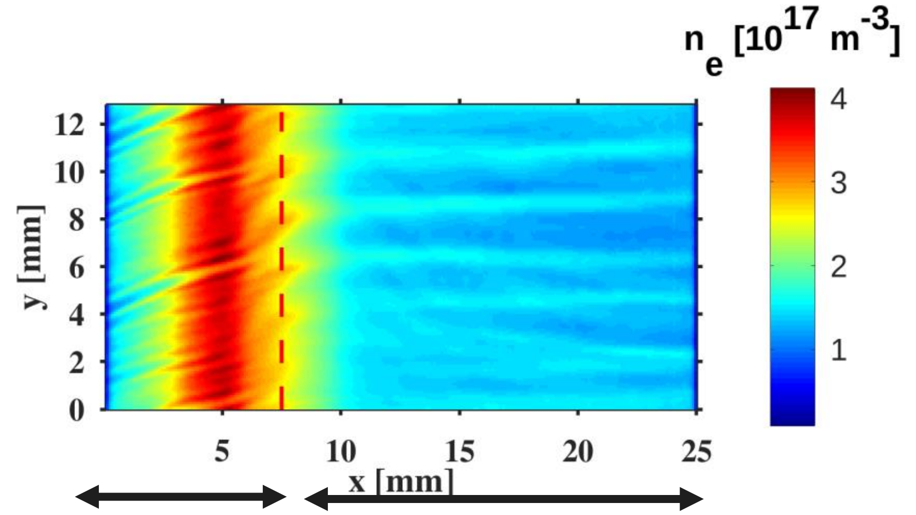
[1] Tsikata,S et al. *« Dispersion relations of electron density fluctuations in a Hall thruster plasma, observed by collective light scattering "*, Physics of Plasmas 16, 033506 (2009)

[2] Ben Slimane,T. et al. "Analysis of small scale fluctuations in Hall effect thrusters using virtual Thomson scattering on PIC simulations", Physics of Plasmas 29, 023501 (2022)

PIC Case presentation







Ionization zone Acceleration zone

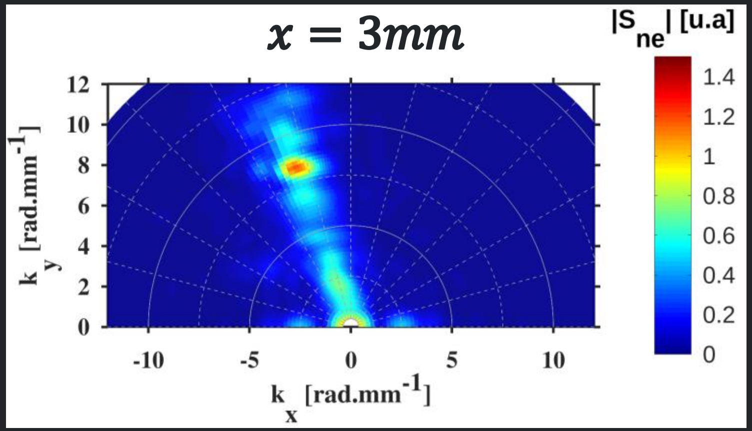
- We apply the virtual CTS on the PIC results of the test case from Charoy et al.[3]. The test case reaches a quasi-steady state ⇒ Appropriate to validate the diagnostic
- The results presented in the following have been recently published in [2]

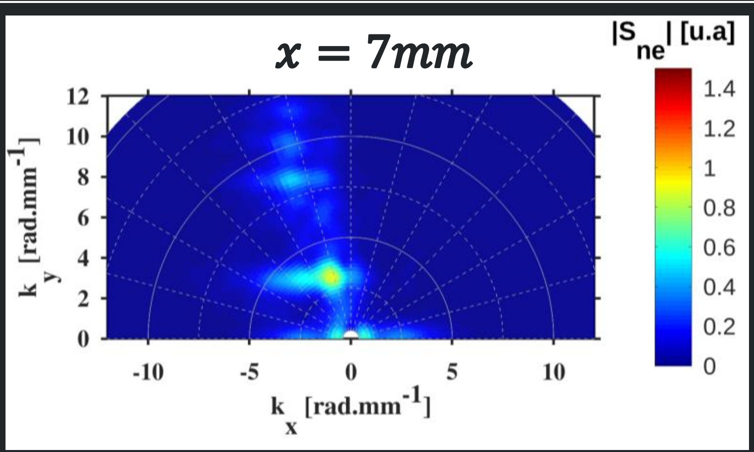
[3] Charoy et al. (2019*). 2D axial-azimuthal Particle-In-Cell benchmark for low-temperature partially magnetized plasmas*. Plasma Sources Sci. Technol. 28, 105010, (2019)

[2] Ben Slimane,T. et al. "Analysis of small scale fluctuations in Hall effect thrusters using virtual Thomson scattering on PIC simulations", Physics of Plasmas 29, 023501 (2022)

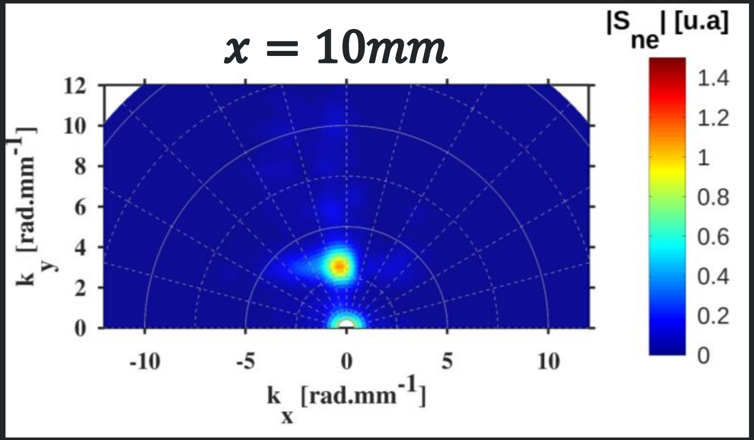
Amplitude variation of the dominant modes: 2D Maps in $k - space$

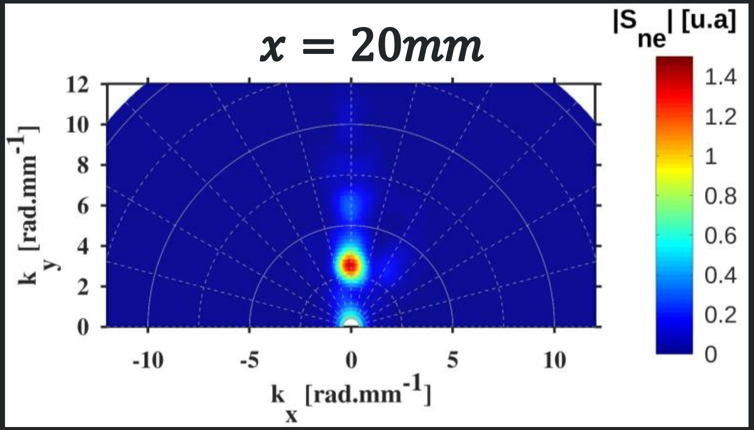
Ionization zone





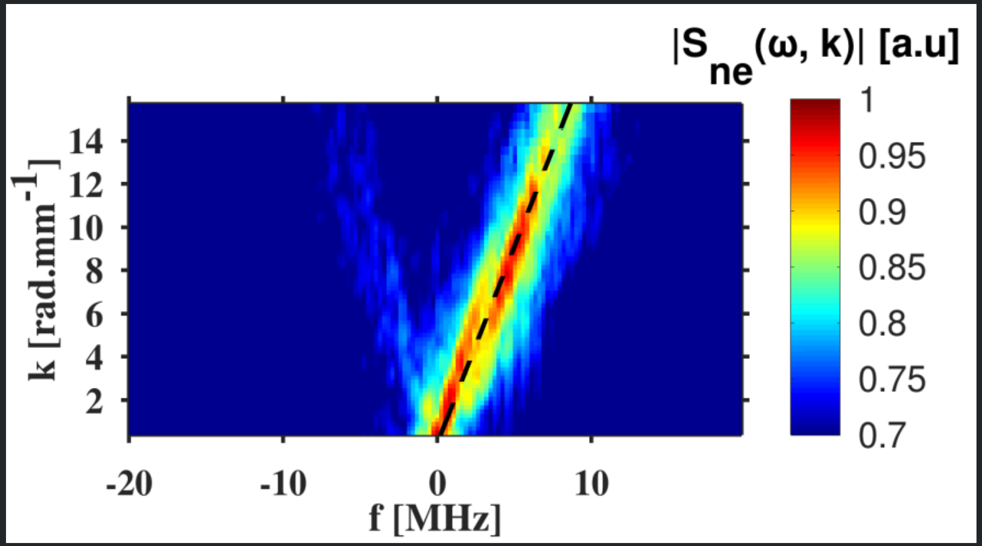
Acceleration zone

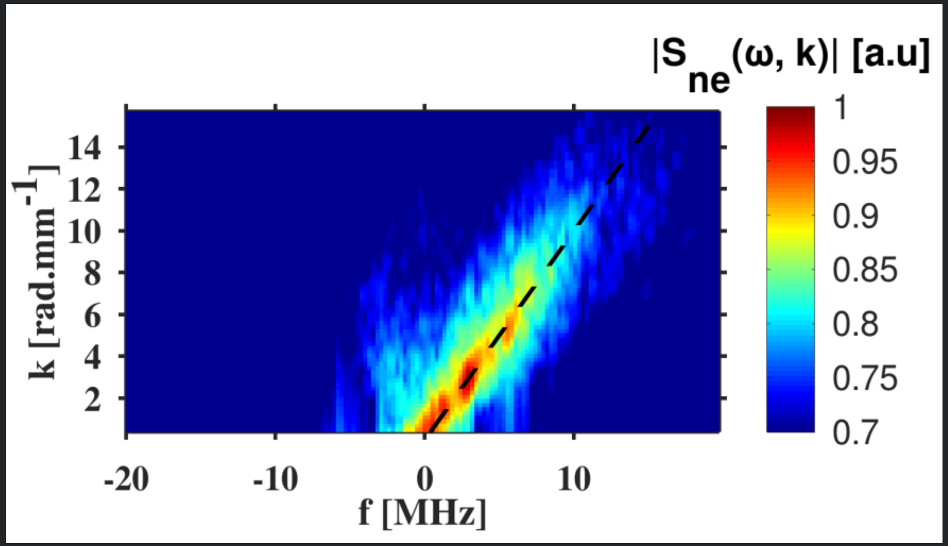




- Two dominant modes are observed approximatively at $3\ rad.mm^{-1}$and $8\ rad.mm^{-1}$. The $8\ rad.mm^{-1}$ was identified as the Ion Acoustic Wave (IAW)
- The change in the direction of propagation of the modes concurs with a change in the amplitude. The 3 $rad.mm$–1 transitions smoothly while the 8 $rad.mm$–1 is damped sharply near the ion sonic point

Dispersion relation



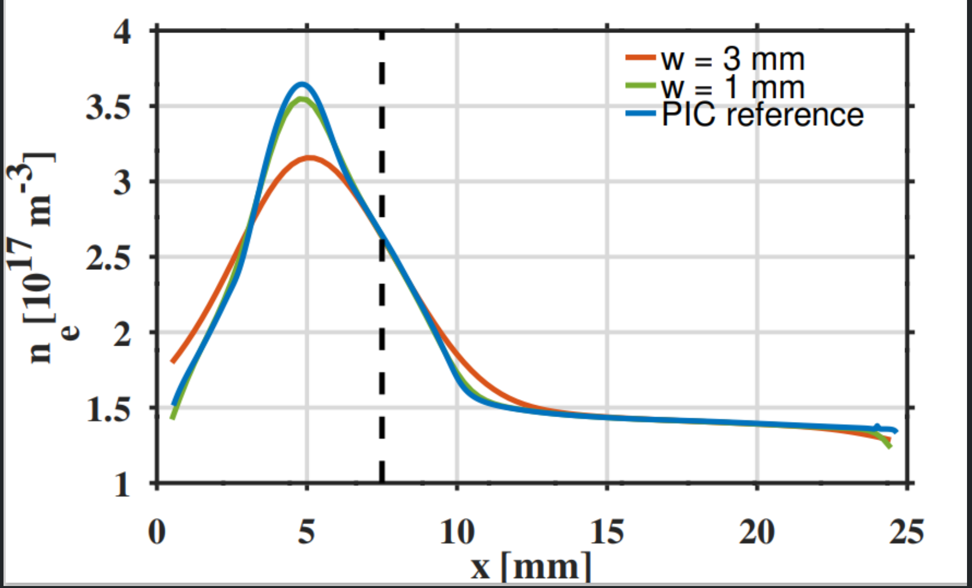


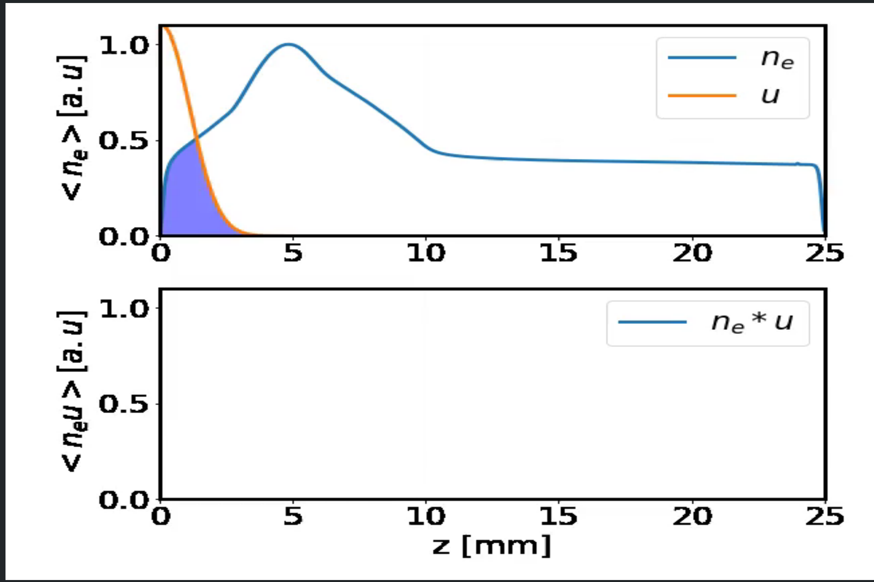
$x = 3\,mm\ with\ \alpha = 110\,°$

$x = 20\,mm\ with\ \alpha = 90°$

- By taking the 2D maps of n_e at different instants and applying the virtual CTS, we generate a temporal scattering signal $s(k,t)$. The dispersion relations are obtained by applying a temporal FFT and show a linear progression of the frequency with respect to the wavenumber
- The most intense signal is observed when the scattering vector is along the propagation direction of the dominant modes
- The curves highlight a change in the phase velocity of the modes: $v_{g,Iz} = 3{,}5\ km.s^{-1}$ and $v_{g,Acc} = 6{,}6\ km.s^{-1}$

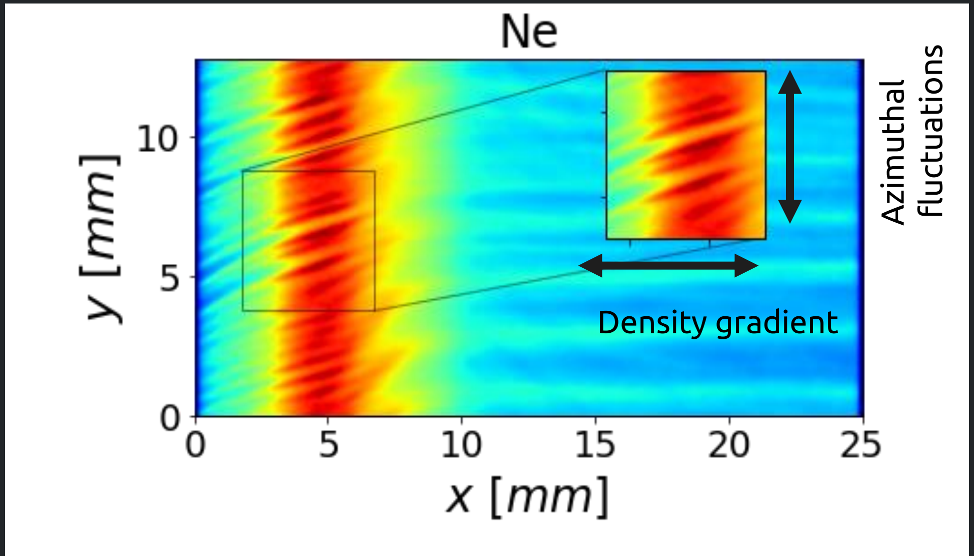
The impact of the laser beam waist on the axial profile of the average electron density and its fluctuation rate

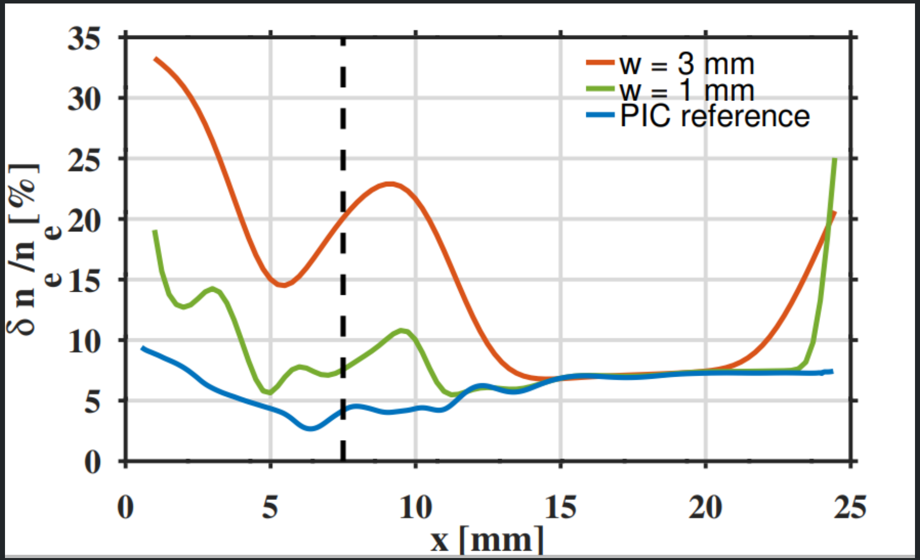




- The axial profile of the mean electron density profile is smoothened by the gaussian laser beam. This effect is more important in the regions where the electron density gradient is significant
- Between 10 and $21mm$, the electron density gradient is smaller and the virtual CTS yields results closer to the reference PIC

The impact of the laser beam waist on the axial profile of the average electron density and its fluctuation rate





- The discrepencies between the different curves could not be explained by the difference in the estimated mean electron density alone.
- Actually, since the scattering volume has both an azimuthal and axial extension. The fluctuation given by the virtual CTS integrates both the azimuthal density fluctuations and the axial density RMS in the final value, leading to a higher fluctuation rate

Conclusions

- As a windowed Fourier Transform, virtual CTS offers a localized and directional tool to analyze PIC data. It also provides an interesting framework to interpret PIC results and relate them to experimental observations:
  - Using this virtual diagnostic allowed an enhanced characterization of the modes present in the stationary state of a 2D axial-azimuthal PIC simulation, both in the plume and inside the thruster channel
  - It was shown that their direction is slightly oblique near the anode and becomes almost azimuthal at the thruster exit plane. The observation shows also that when the ions' acceleration becomes very large, the change in direction concurs with a change in the amplitudes of the modes
  - The dispersion relations (f, k) have been also computed in the ionization zone in the thruster channel and the acceleration zone and the phase velocities are consistent with the observations in CTS experiments
- The estimation of the electron density fluctuation rate showed a strong dependence on the value of the laser beam waist:
  - An accurate measure of the electron density inside the scattering volume is paramount to ensure a consistent definition of the fluctuation rate
  - The spatial extension of the volume defined by the laser waist leads to higher fluctuation rates in regions where the electron density gradient is significant since it integrates the azimuthal fluctuation and the axial fluctuation of the electron density
  - Still, far in the plume, the electron density gardient is close to zero. the virtual CTS yields similar results as the refercence PIC
- In future work, the virtual CTS will be used to analyze a self-consistent time-dependent 2D (axial-azimuthal) simulation closer to the real operation conditions of Hall Effect Thrusters

Thank you for reading

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