Micro fluctuation control and Hall thruster operation

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Strong electrostatic azimuthal fluctuations in the acceleration region at the thruster output arise during operation of a Hall thruster. These fluctuations were predicted by kinetic theory [1], investigated by PIC simulations [2] and observed by collective laser scattering [7]. They are suspected to control the electron mobility across the B-field. Since kinetic instabilities are related to the microscopic velocity distribution function, partial control of the fluctuations might be provided by a modification of this distribution.

Such modification is possible via the introduction of a small amount of hydrogen in the main xenon feed gas. Thanks to the Landau effect, this light gas addition may damp the azimuthal fluctuations. The thruster plasma is observed with collective scattering. Observations are analyzed with the help of a linear kinetic models. Effects on the thrust and discharge current are shown.

Linear kinetic model

Linear kinetic give a good description of the observed azimuthal mode dispersion relation [3, 4]. A second light ion population is added to the xenon ion and the electron in the plasma description. W. Bleakney [5] showed molecular hydrogen electron ionization is mostly non-dissociative: H_2^+ ions are taken into account. Using the same model as in J. Cavalier reference [4], with the addition of $\eta = n_{H_2^+}/n_{Xe^+}$, the density ratio between the H_2^+ ions and the Xe^+ ions. M_{Xe/H_2} is the Xe atom to H_2 molecule mass ratio. Lengths are normalized to λ_D, the Debye Length, and the pulsations are normalized to ω_{pi}, the ion plasma pulsation value for the pure xenon case. The dispersion relation expression is :

$$1+\hat{k}^2+g\left(\frac{\hat{\omega}-\hat{k}_y\hat{V}_d}{\hat{\omega}_{ce}},(\hat{k}_x^2+\hat{k}_y^2)\frac{\hat{M}}{\omega_{ce}^2},\hat{k}_z^2\frac{\hat{M}}{\omega_{ce}^2}\right)-\frac{1}{2\hat{T}}\left[(1-\eta)Z'\left(\frac{\hat{\omega}-\hat{k}_x\hat{V}_p}{\sqrt{2}\hat{k}\sqrt{\hat{T}}}\right)+\eta Z'\left(\frac{\hat{\omega}-\hat{k}_x\hat{V}_p\sqrt{M_{Xe/H_2}}}{\sqrt{2}\hat{k}\sqrt{\hat{T}M_{Xe/H_2}}}\right)\right]=0 \tag{1}$$

For small hydrogen addition ($\eta << 1$), the main effect is due to the xenon dilution. The only unstable mode is described by the dispersion relation :

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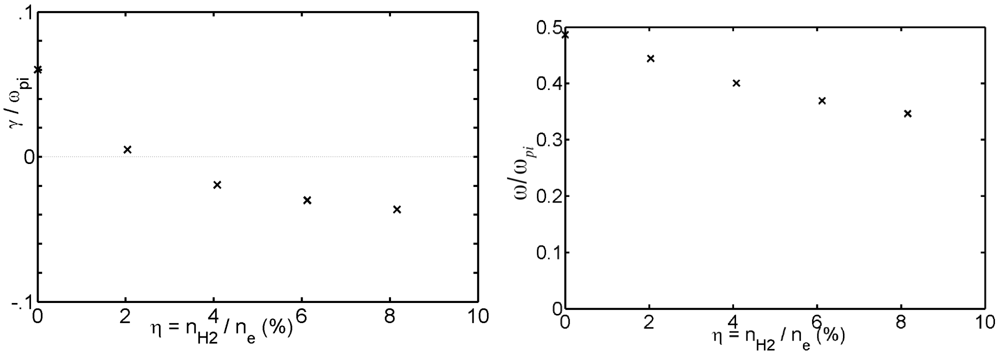

Fig. 1: Growth rate and frequency mode variation with hydrogen to xenon density rate

$$(\hat{\omega}-\hat{k}_x\hat{V}_p)^2=(1-\eta)\frac{\hat{k}^2}{1+\hat{k}^2+g\left(\frac{\hat{\omega}-\hat{k}_y\hat{V}_d}{\hat{\omega}_{ce}},(\hat{k}_x^2+\hat{k}_y^2)\frac{\hat{M}}{\omega_{ce}^2},\hat{k}_z^2\frac{\hat{M}}{\omega_{ce}^2}\right)}$$

Growth rate and frequency are shown in Figure 1 for small hydrogen ion rates. The frequency and growth rate decrease with η. The growth rate remains positive only if $\eta < 2.7\%$. For this value, the mode frequency is reduced to 88 % of the initial value. Another unstable mode appears only for $\eta > 10\%$.

Hydrogen addition effect observation

The experiment was performed on the PPS®X000 thruster developed by Snecma at the PIVOINE-CNRS facility, where fluctuations are observed by means of the CO_2 laser collective scattering bench PRAXIS [6]. The xenon gas flow rate is 12 mg/sec, the discharge voltage, 250 V and the maximum magnetic field value, 150 G. The additional molecular hydrogen flux is measured, but η the hydrogen ion to xenon ion density ratio can not be directly measured.

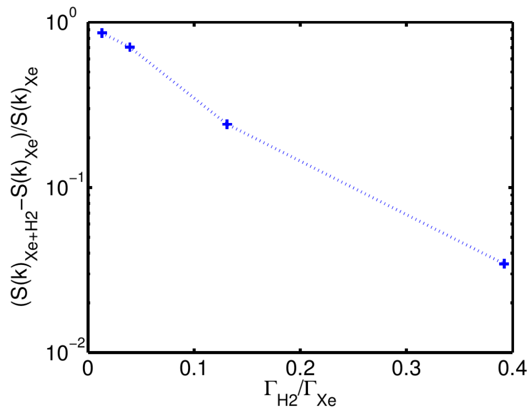

Fig. 2: Fluctuation intensity variation with hydrogen injection rate

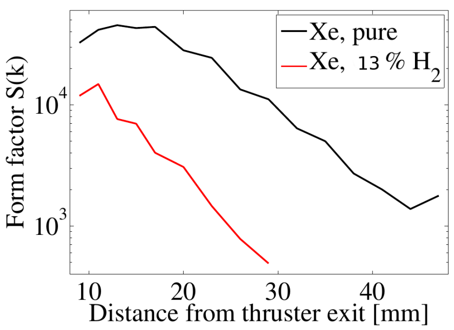

Fig. 3: Fluctuation intensity variation with the axial position

Figure 2 shows the variation of the electron density fluctuation intensity with the ratio of the number of injected hydrogen molecules to the number of injected xenon atoms per unit time. The fluctuation intensity (the form factor $S(\vec{k})$) is measured at a distance of 11 mm from the thruster output. The observed exponential decay is consistent with a damping rate proportional to the ion population, as expected from Landau damping, if we suppose the hydrogen ionization level is linear with the hydrogen gas injection rate.

The phenomenon is also observed on Figure 3. The mode spatial damping rate along the thruster axis increases with the hydrogen injection. We observe also the mode maximum axial position is closer to the thruster when hydrogen is injected.

Figure 4 shows the mode frequency variation with the H_2/Xe flux rate at a propagation angle α. The figure shows the frequency reduction appears linear with the hydrogen addition. If we suppose the frequency variation is completely related to the linear model effect, the 5 % frequency reduction observed when 13 % molecular hydrogen is injected in the xenon flow corresponds to a hydrogen to xenon ion density ratio η of 1.2 %. The results for the largest hydrogen injection (39 %) are not shown on this figure : the mode frequency is larger than for the pure xenon case, and the variation with the mode orientation α does not show any significant trend. For this injection rate the thruster operation was not stable.

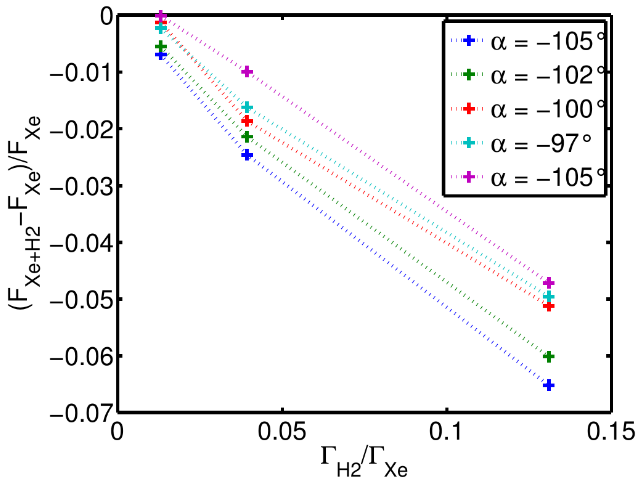

Fig. 4: Azimuthal mode frequency reduction with the hydrogen injection rate

Effect on the discharge current and thrust

Hydrogen injection induces an additional ion part to discharge current. It depends on the ion density rate η:

$$\frac{I_{H_2^+}}{I_{Xe^+}} = \frac{q_e n_{H_2^+} v_{H_2^+}}{q_e n_{Xe^+} v_{Xe^+}} = \eta \sqrt{\frac{m_{Xe}}{m_{H_2}}}$$

For the 13 % hydrogen injection, using the η estimation from the mode frequency reduction observation ($\eta = 1.2\%$), the ion current increase should be $I_{H_2^+}/I_{Xe^+} = 9.7\%$. Measurements are shown in Figure 5. This estimation is close to but lower than the observed current increase (8 %). This estimation does not take into account the purely electron part of the discharge current. We also observe the current increase is not linear with the hydrogen injection. For small hy-

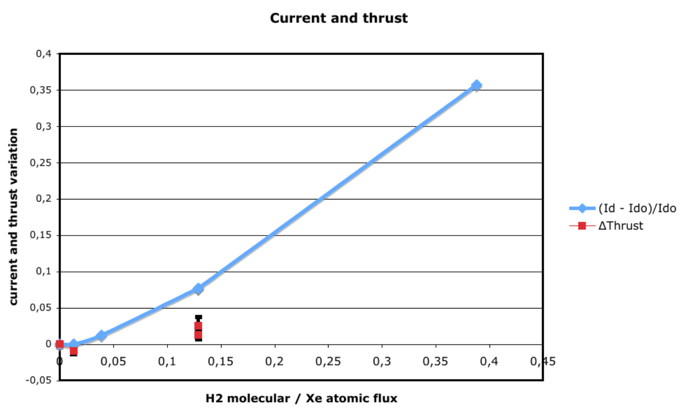

Fig. 5: Discharge current and thrust variation with the hydrogen injection rate

drogen injection, the current increase is vanishingly small: the additional ion current might be compensated by an electron current reduction.

The additional hydrogen should also increase the thrust :

$$\frac{T_{H_2^+}}{T_{Xe^+}} = \frac{m_{H_2} n_{H_2^+} v_{H_2^+}^2}{m_{Xe} n_{Xe^+} v_{Xe^+}^2} = \eta$$

For the 13 % hydrogen injection, using the same η estimation, the thrust increase should be $T_{H_2^+}/T_{Xe^+} = 1.2\%$. The thrust measurement shows a thrust increase close to this value. The difference is smaller than the thrust measurement accuracy.

Conclusion

The addition of a small amount of molecular hydrogen to the xenon main gas directly affects the micro-fluctuation intensity and structure as well as the thruster discharge current and thrust. These modifications are consistent with the linear kinetic theory. The decrease of the fluctuation amplitude appears to decrease the electron current inside the discharge as expected from a fluctuation controlled electron mobility in thruster operation.

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