Active Control of a Hall Thruster Discharge

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A parametrical study of Hall thruster PID control via discharge voltage modulation is performed, where thruster operation is mainly characterized in terms of time-resolved discharge current and discharge voltage measurements. A side-by-side comparison of current and voltage spectra reveals that proportional control is most effective, while integral control suffers from excessive low frequency signal amplification. Measurements show that a large attenuation of discharge current can be achieved even with very small relative variations of the discharge voltage.

I. Introduction

Low frequency ionization oscillations in the 10-30 kHz range constitute one of the most characteristic physical phenomenon accompanying the discharge of Hall thrusters. Although no firm correlation could ever be established between the amplitude of discharge current oscillations and thruster efficiency,[1,2] their mitigation seems desirable to reduce the ac load transmitted to the power processing unit and the electromagnetic emission radiated onto the spacecraft, or to reduce possible cross-talk between thrusters for propulsion system based on thruster clusters.[3]

Passive control has been successfully used by Tamida *et al*[4] to reach a target operating point without crossing unstable regions, using a predefined variation of the discharge potential and magnetic induction during start-up. More robust control could be theoretically achieved with active control, which from a formal viewpoint is actually already in wide use in Hall thrusters since external LC or RLC networks[2,5–7] relate discharge voltage variations to discharge current variations. Proportional-Integral-Derivative (PID) control is a more advanced control method, which attempts to minimize the error between the current state and a desired setpoint by changing a parameter of the system in proportion to the error, its integral and its derivative. Active PID control via the magnetic field has been attempted, but its practical implementation was found difficult due the induction of eddy currents in the magnetic circuit as a result of Lenz's law.[3,7] In recent theoretical works, it was suggested that PID regulation could be alternatively accomplished by varying the discharge voltage as a function of the discharge current.[8] Such a closed loop control scheme has been investigated experimentally by the authors, using voltage modulation with a fast, custom-designed electronic PID controller in conjunction with a dedicated high-current shunt regulator.[9]

This work provides additional insights to the experiment reported in Ref. 9, with a focus on the effectiveness of each of the P, I and D terms based on extensive parametrical explorations.

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II. Experimental setup

A. Power supply circuit

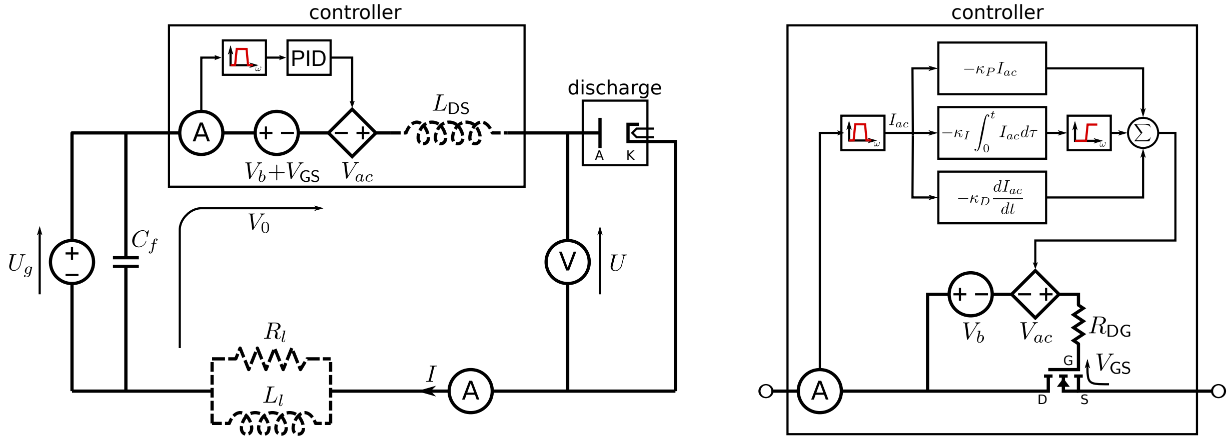
The motivations and the rationale behind the PID design are discussed in detail in Ref. 9. The suppression of discharge current oscillations is attempted using discharge voltage modulation, which is achieved by varying the voltage drop across a controller connected in series with a conventional power supply. Only the ac component of the discharge current is monitored, extracted with a band-pass filter.

The voltage drop within the controller is achieved across the drain and source of a high power Mosfet regulator, as per Fig. 1-b. When the PID output is zero ($V_{ac} = 0$), the voltage drop V_{DS} across the controller is simply the sum of a bias voltage V_b and of the gate-to-source voltage V_{GS}, where the latter remains close to the Mosfet threshold voltage. When the PID output varies ($V_{ac} \neq 0$), however, a transient voltage builds across resistor R_{DG}. Accounting for this resistor and for the gate-to-source Mosfet capacitance C_{GS}, the discharge voltage would theoretically be

$$\begin{aligned} U &= U_g - V_{DG} - V_{GS} \\ &= U_g - R_{DG} I_G - V_b + V_{ac} - V_{GS} \\ &= U_g - R_{DG} C_{GS} \frac{dV_{GS}}{dt} - V_b + V_{ac} - V_{GS} \\ &= \underbrace{U_g - V_b - V_{GS}}_{V_0} + V_{ac} - \underbrace{\frac{R_{DG}}{g_m} C_{GS} \frac{dI_D}{dt}}_{\text{parasitic term}}, \end{aligned} \tag{1}$$

where g_m is the Mosfet transconductance and V_0 is the effective setpoint voltage (*i.e.* time-averaged discharge voltage) which accounts for the fact that the generator voltage is decreased by a nearly constant voltage drop $V_b + V_{GS}$. The additional parasitic voltage can thus be modeled as an effective inductor $L_{DS} = R_{DG} C_{GS} / g_m$ shown in Fig. 1-a. Measurements have shown that this parasitic inductance remains fairly constant at approximately $10\,\mu$H.

A conventional switch-mode power supply is used, which voltage is stabilized with a large capacitance, $C_f = 16.8\,\mu$F (Fig. 1-a). Time-correlated measurements of the currents and voltages at different locations of the power supply circuit have shown that, beside the effective Mosfet inductance L_{DS}, a non-negligible line impedance exists which is presumably related to magnetic shielding effects within the racks. At the frequencies of interest ($10 \div 20\,$kHz), this impedance is well approximated by the parallel RL impedance shown in Fig. 1-a, with $R_l \approx 1.8\,\Omega$ and $L_l \approx 30\,\mu$H.



(a) (b)

Figure 1: (a) Simplified equivalent circuit of the experimental setup; the main parasitic impedances (line impedance and effective Mosfet inductance) are shown with dashed lines. (b) A more detailed schematic of the controller.

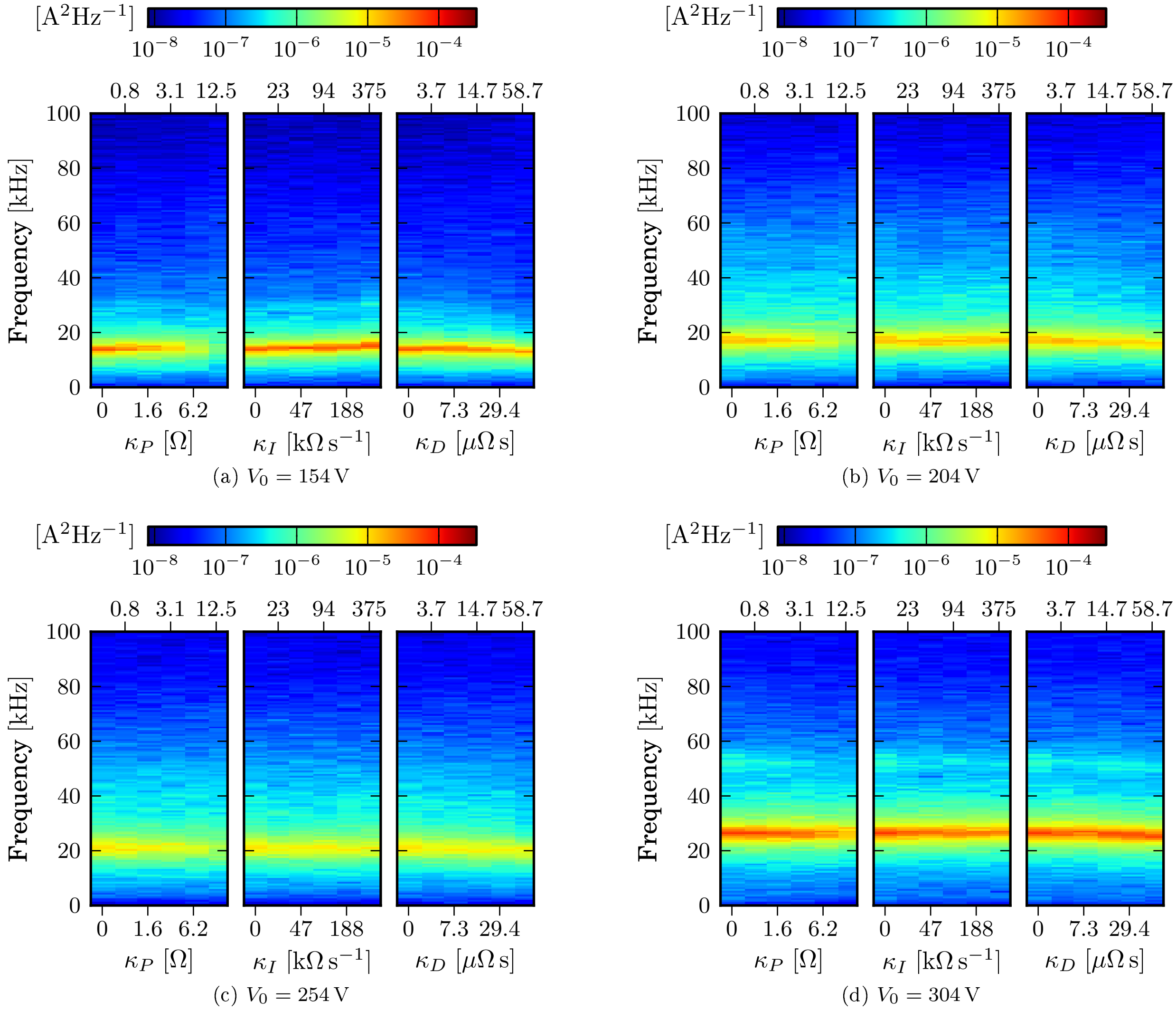
B. Vacuum facility and thruster

Both experimental sessions have taken place in Orléans (France) in the PIVOINE facility of the ICARE laboratory (CNRS), using the PPS-100ML laboratory Hall thruster. The anode and cathode xenon flow rates were maintained at respectively 4 mg/s and 0.42 mg/s. The vessel pressure was kept lower than 2×10^{-5} mbar in all cases. The magnetic coils current was identical in all measurements.

III. Results and discussion

A. Parametrical exploration of the PID settings

A parametrical study has been performed by changing the PID settings within the range $\kappa_P = 0 \div 12.5\,\Omega$, $\kappa_I = 0 \div 375\,\mathrm{k\Omega s^{-1}}$ and $\kappa_D = 0 \div 58.7\,\mu\Omega\mathrm{s}$, shown in Fig. 2. Although simultaneous changes of the different PID settings have also been explored, it was found that the results were mostly determined by the κ_P setting when it was used. For this reason, we report here only single-parameter explorations.



(a) $V_0 = 154$ V

(b) $V_0 = 204$ V

(c) $V_0 = 254$ V

(d) $V_0 = 304$ V

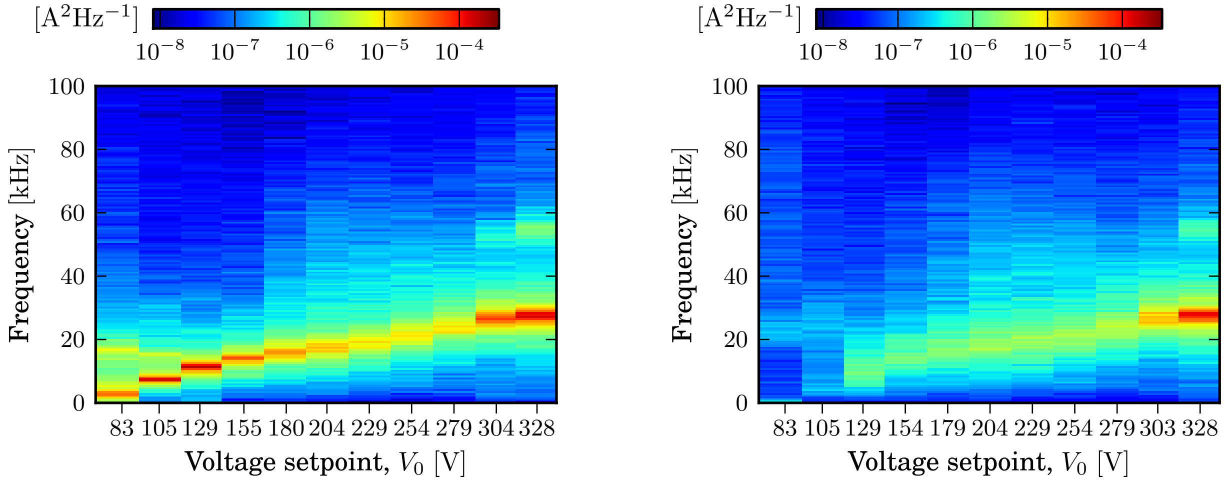
Figure 2: Effect of proportional, integral and derivative terms on the discharge current frequency spectrum at different voltage setpoints (V_0).

In general, it was observed that PID control was most effective at low discharge voltages. Also, increasing the PID settings beyond the maximum settings reported here would usually no longer bring benefits in terms of current stability, mainly because of the saturation of the voltage regulator which for technical reasons constrains V_{ac} variations within the range ±8 V. In general, the effect of the PID settings becomes noticeable only when the effective impedance simulated (κ_P, κ_I/ω or $\kappa_D\omega$) is of the order of $1\,\Omega$ or greater.

At all voltages below 300 V, proportional control has a clear beneficial impact on current oscillations, which increases with κ_P until the regulator saturates near $\kappa_P = 12.5\,\Omega$.

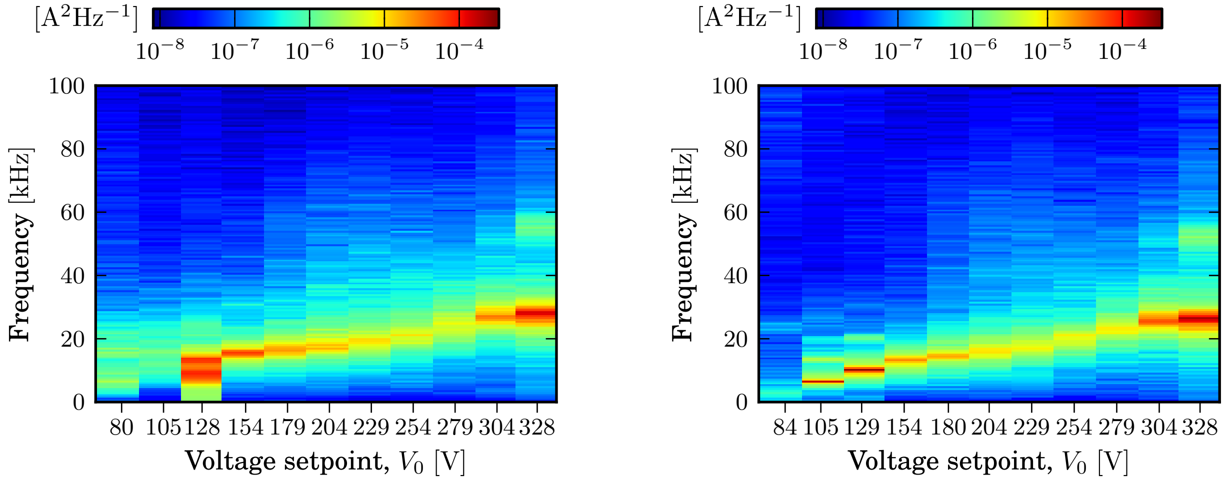
Integral control does not appear to help, which may partially be due to the excessive amplification of low frequencies by the integrator and to the ensuing saturation of the regulator. This phenomenon was anticipated and a high-pass filter with corner frequency at 500 Hz was accordingly added at the integrator output (Fig. 1-b), but the low-frequency trace a the bottom of Fig. 4-c suggests that this 1-st order filter was inadequate.

Derivative control does attenuate current oscillation at low voltage, but in a much less pronounced manner than proportional control. A slight but noticeable decrease of the breathing frequency is also systematically observed as κ_D is increased, in contrast to proportional and integral control where the frequency remains stable in most cases.



(a) $\kappa_P = \kappa_I = \kappa_D = 0$

(b) $\kappa_P = 12.5\,\Omega$



(c) $\kappa_I = 375\,\mathrm{k\Omega s^{-1}}$

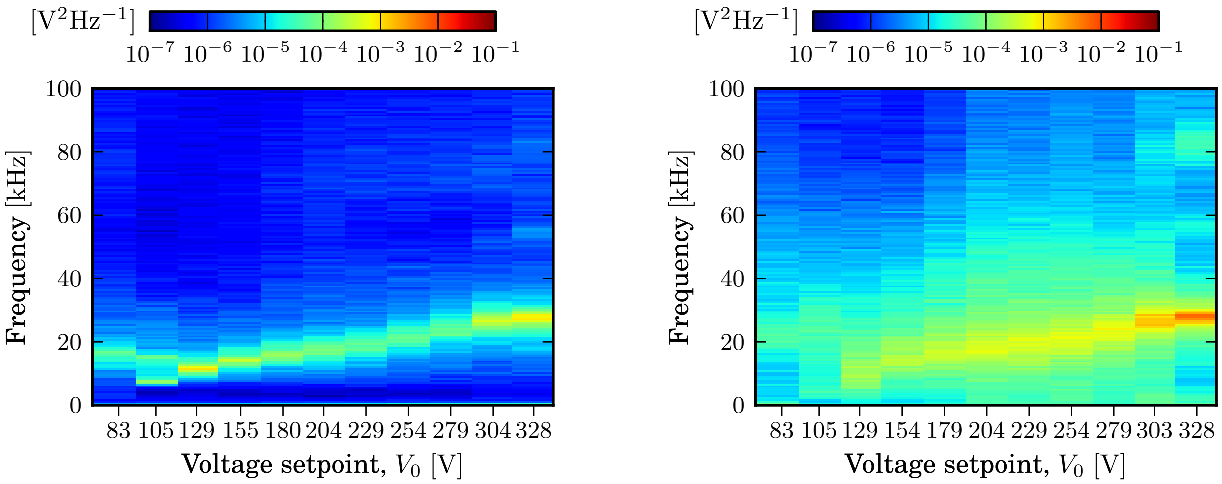
(d) $\kappa_D = 58.7\,\mu\Omega\mathrm{s}$

Figure 3: Effect of the proportional, integral and derivative terms at their maximum settings on the discharge current frequency spectrum, as a function of the voltage setpoint.

B. Voltage exploration at maximum PID settings

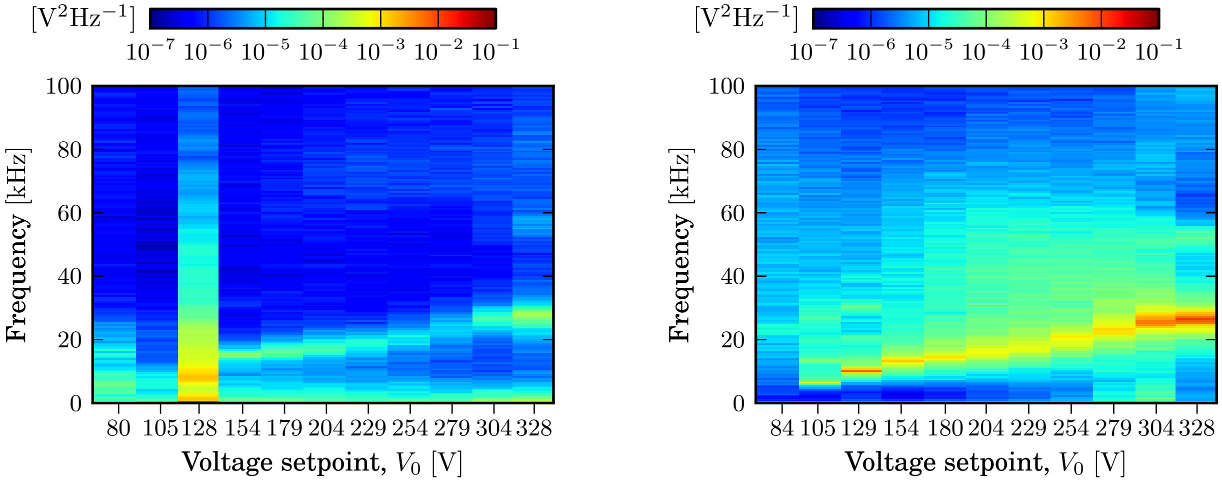
Although the controller could theoretically provide greater amplification, the maximum gains explored in the previous section, namely $\kappa_P = 12.5\,\Omega$, $\kappa_I = 375\,\mathrm{k}\Omega\mathrm{s}^{-1}$ and $\kappa_D = 58.7\,\mu\Omega\mathrm{s}$, are for practical purposes taken as the maximum PID settings since the regulator becomes strongly saturated beyond those values.

The voltage exploration of Fig. 3 confirms that proportional control is indeed the most effective and robust control strategy. Attenuation of oscillations is also noticeable with derivative control, but much less effective. Results are somewhat unconclusive in respect of integral control: indeed, the power spectrum of voltage oscillations (Fig. 4-c) is often dominated by unwanted low-ω oscillations, which leaves very little power for voltage oscillations in the breathing mode range.



(a) $\kappa_P = \kappa_I = \kappa_D = 0$

(b) $\kappa_P = 12.5\,\Omega$

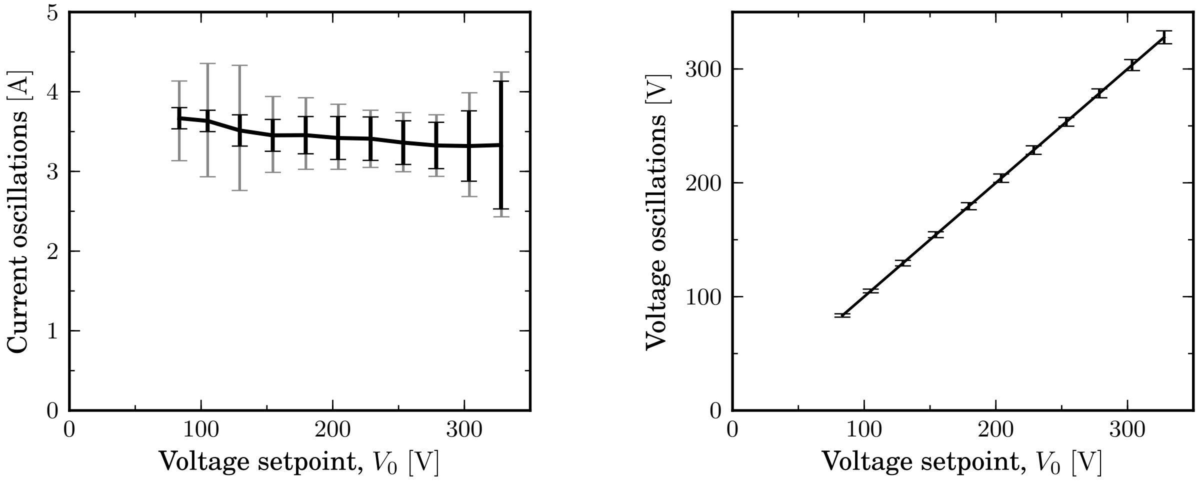


(c) $\kappa_I = 375\,\mathrm{k}\Omega\mathrm{s}^{-1}$

(d) $\kappa_D = 58.7\,\mu\Omega\mathrm{s}$

Figure 4: Effect of the proportional, integral and derivative terms at their maximum settings on the frequency spectrum of the "controlling" discharge voltage, as a function of the voltage setpoint V_0. It can be noted that, even in the no-control case, weak discharge voltage oscillations remain as a result of parasitic impedances (see Fig. 1-a)

It is very instructive to relate the reduction of discharge current oscillations with the relative level of voltage oscillations generated by the controller to attenuate such current oscillations. Although our implementation of PID control is in principle a trade-off between current and voltage oscillations, Fig. 5 shows that the relative level of voltage oscillations necessary to damp current oscillations is typically smaller than the achieved relative reduction of current oscillations by at least one order of magnitude. This peculiarity was numerically predicted in Ref. 9 and is discussed from a theoretical perspective in Ref. 9. Its main practical implication is that the thruster efficiency loss related to ion velocity dispersion via voltage oscillations is negligible, which validates the soundness of active control via discharge voltage as a mean to approach steady-state thruster operation.



(a) no-control (gray) *vs* $\kappa_P = 12.5\,\Omega$ (black)

(b) $\kappa_P = 12.5\,\Omega$

Figure 5: (a) Discharge current oscillations without control (gray) and with $\kappa_P = 12.5\,\Omega$ (black). (b) discharge voltage oscillations with $\kappa_P = 12.5\,\Omega$. It can be observed that even very small relative voltage oscillations suffice to strongly attenuate discharge current oscillations at moderate V_0.

IV. Conclusion

A large range of PID settings was investigated so as to determine the most favorable operating points and the qualitative influence of each PID parameter. Proportional control (*i.e.* dynamic resistance simulation) has proved very effective in general, except at high voltage where the maximum voltage oscillation range authorized by the regulator may have constituted a limiting factor. Results of integral control are less conclusive, due to the predominance of a low-frequency component in the discharge voltage spectrum related to the amplification of low-ω oscillations by the integrator which was not efficiently removed by the high-pass filter used.

This experiment has confirmed the predictions of earlier numerical studies with respect to the very low level of relative voltage oscillations required to significantly attenuate current oscillations, as well as theoretical predictions[10] regarding the low sensitivity of the average discharge current towards current oscillations amplitude.

Acknowledgments

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