Repetitive Operation of Inductive Plasma Source

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Abstract – An experimental scaling study of a plasma source operating in a rep-rate (10 to 30 Hz), short pulse train (6 to 30 pulses) mode on a test bed is reported. The plasma source, with average diameter of 28 cm, is based on an inductive discharge in a supersonic radial divergent H_2 gas flow (supplied by a central fast electro-dynamic puff valve) formed using a Laval nozzle. The HV oscillating discharge is driven by an LC circuit consisting of a shock coil and 1.35 μF capacitor. The typical operating voltages, plasma density, ion current density, plasma streaming energy for repetition rates in the range of 10-30 Hz were 12-17 kV, 10^{12}-10^{14} cm^3, 2-20 A/cm^2, 25-40 eV, respectively. Dependence of plasma flow parameters and reproducibility as functions of pulse rep-rate, puff valve plenum pressure, shock coil discharge voltage, and build-up of gas pressure are presented and evaluated.

1. Introduction

Pulsed plasma sources, (aka - plasma thrusters), based on the microsecond inductive high voltage discharge and organized in a supersonic gas flow are widely used in magnetically insulated ion diodes (MID) in a single pulse mode of operation for the generation of microsecond duration high current ion beams [1-3]. The problems of extending these MIDs to a rep-rate mode of 10-100 Hz pertain to issues of heat load on the puff valve coil, gas loading of the diode, and the reproducibility of the required plasma parameters. The present paper addresses these issues.

Experiments were performed using a H^+ plasma source operation in a rep-rate (10 to 30 Hz), short pulse train (6 to 30 pulses) mode on a test bed. A scaling study of the dependence and reproducibility of the plasma flow parameters as functions of pulse rep-rate, puff valve plenum pressure, shock coil discharge voltage, and build-up of gas pressure are reported and analyzed.

2. Experimental setup

The experimental setup is presented in Fig. 1. The plasma thruster was placed in a cylindrical chamber with a total volume of 58 liters. The pumping of the chamber was done through a 9.5 cm diameter, 9 cm long port by a Pfeiffer TPH 2000 turbo-pump with a pumping speed of 2500 L/s for H_2 gas in the pressure range of 10^{-3} to 10^{-10} Torr. The base pressure of the vacuum chamber was ≤ 2 x10^{-5} Torr.

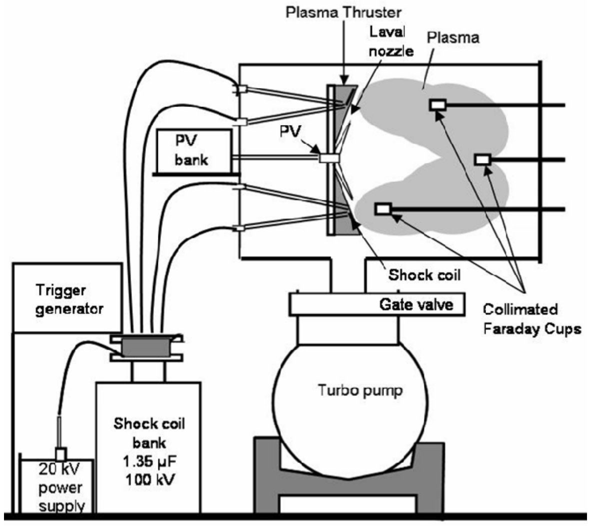

Fig. 1. Experimental setup

The proper plasma thruster, which is similar to the one used in [3, 4], consisted of: *a central puff valve*; *a shock-coil*, featuring one turn-18-thread windings (0.8 μH) with average diameter of 28 cm encapsulated in a Lucite body, which has a truncated conical face surface with apex angle of 135°; and *a profiled disk*, which along with this conical surface forms a disk-shaped Laval nozzle.

The puff valve, with a plenum volume of 1 cm^3, operated in the pressure range of 5 x 10^2 to 10^3 Torr. The 1.7 μH valve coil was driven in a rep-rate mode by a 160 μF capacitor bank, which was charged resonantly via a 640 mH choke to 1.1 kV by a primary electrolytic source of 5.1 mF charged to 1.5 kV. The schematic of the circuit is given in Fig. 2. The puff valve coil was switched by an ignitron with a maximum pulse current of 5 kA and a rise-time of 30 μs. The energy deposited per pulse in the circuitry was ~ 100 J and was mainly damped in the coil and body of the poppet (as Foucault currents). The temperature of the brass puff valve body was measured *in situ* by a thermistor attached to the body by a thermo-conducting contact. The measured rise-time of the gas flow near the thruster face surface was ~ 150 μs.

Pressure monitoring within the chamber during rep-rate operation of the puff-valve was measured by an ion "nude" (not enclosed in glass) gauge with continuous registration on the oscilloscope. Unfortunately, due to strong EM-noise generated when the shock coil fires, pressure measurements could only be carried out without shock coil operation.

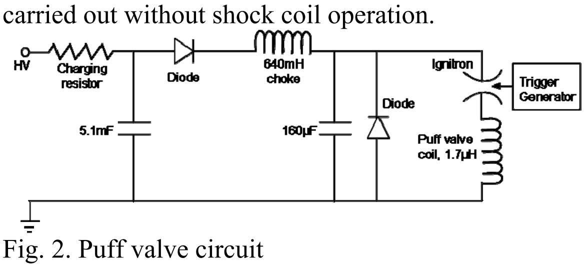

Fig. 2. Puff valve circuit

The shock coil was driven by a 1.35 μF capacitor bank and switched by a Maxwell sparkgap which was triggered by a thyratron-based pulse generator. The capacitor was charged by a commercial 7 kW power supply. Respective charging voltage waveforms of the shock coil and puff valve in the rep-rate mode are presented in Fig. 3. The shock coil current featured damped oscillations with a rise-time of ~ 1.2 μs and maximum current amplitudes of 16-22 kA at charging voltages of 12-16 kV, respectively. This corresponds to stored energies of ~ 100-170 J. Typically, the breakdown of the gas flow took place at the beginning of the second half of the pulse. Shock coil waveforms of the damped oscillations w/o and with gas featured 9 and 5 oscillations, respectively. With these measurements, an estimation of the coupling efficiency of the shock coil to the gas was ~ 20 %.

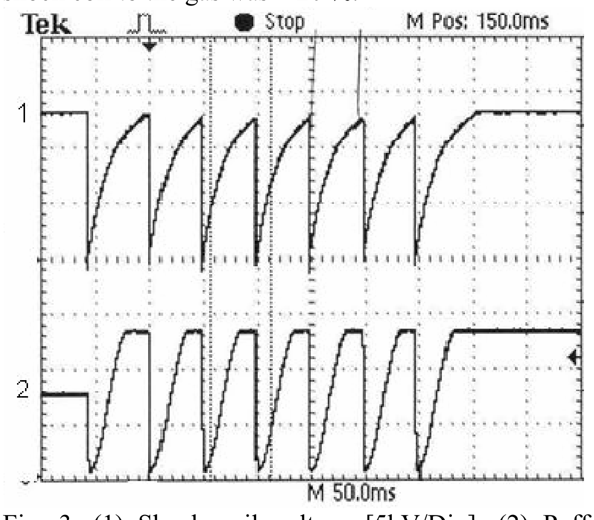

Fig. 3. (1) Shock coil voltage [5kV/Div]; (2) Puff valve voltage [0.5kV/Div]

Rep-rate triggering of the thruster circuits with a preset pulse train frequency, number of pulses in the train, time delays between firing the puff valve and shock coil, and triggering of the oscilloscopes were organized by a multi-channel trigger pulse generator with optical outputs.

No provision was made to monitor the temperature rise of the shock coil during rep-rate operation since its mass was much greater than the puff valve's and they were both driven with equivalent energy per pulse.

3. Experimental results

Typical signals from the "nude" ionization gauge (featuring a sequence of spikes "sitting" on the slowly rising pedestal of residual gas pressure) and from the puff valve firing are illustrated in Fig. 4. Most of the rep-rate pulse trains were performed at a plenum pressure of 1-2 psi gauge, which resulted in a pressure increase per puff in the chamber during $\Delta t \sim 0.2$ ms of 15-20 mTorr. This corresponds to the instantaneous rate of gas production in the range of > 10^4 L/s, which is much greater than the pumping speed of the turbopump. Also, the average pumping rate at this pressure was ~ 25 L/0.05sec, which is ~ 2 times lower than the average gas production rate by the puff valve. Therefore, the resulting build-up of gas pressure during the train of pulses was attributed mainly to the pumping speed of the turbo-pump. Based on this data, we concluded that the upper limit of rep-rate frequency for our experimental conditions was ~ 5 Hz.

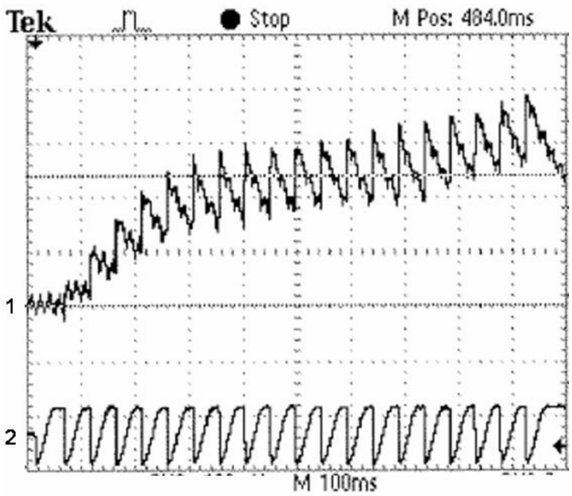

Fig. 4. (1) Nude ion gauge signal [100mV/Div]; (2) Puff valve voltage [1.2kV/Div]

The thermal loading of the puff-valve was monitored by a digital readout connected to a thermistor in thermal contact with the body of the puff-valve. The temperature monitor used provided one degree step readouts. Typically a 1^{o} C change was registered for a 1 second train of 10 pulses with a frequency of 10 Hz and a 1.5^{o} C change for a 1 second train at 20 Hz. The puff valve temperature would eventually build-up during multiple trains of pulses (≤ 30) until it reached ~ 50^{o} C, at which point we let it cool down. This gave us an estimate of the upper limit to the number of pulses per train we could work at without adding a cooling system for the puff-valve body. A useful substitution for the conventional plastic parts and Viton O-ring in the puff valve assembly might be a ceramic insulation material and high temperature resistant sealing gasket.

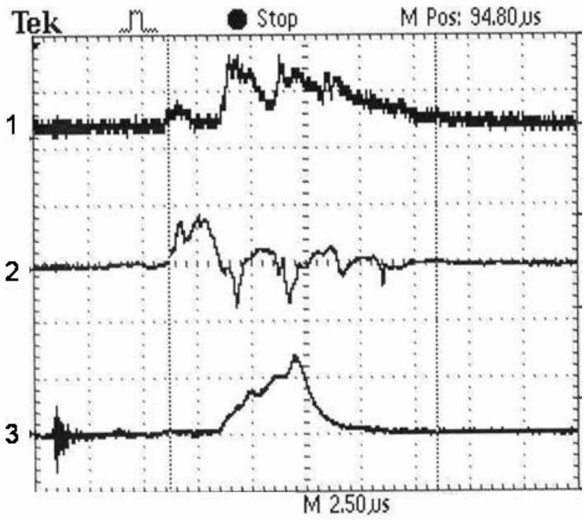

Fig. 5. Ion current density during single pulse mode: (1) CFC1: Z = 5cm, R = 14cm, [15Acm^{-2}/Div]; (2) CFC2: Z = 7cm, R = 14cm, [15Acm^{-2}/Div]; (3) CFC3: Z = 30cm, R = 0, [5Acm^{-2}/Div]

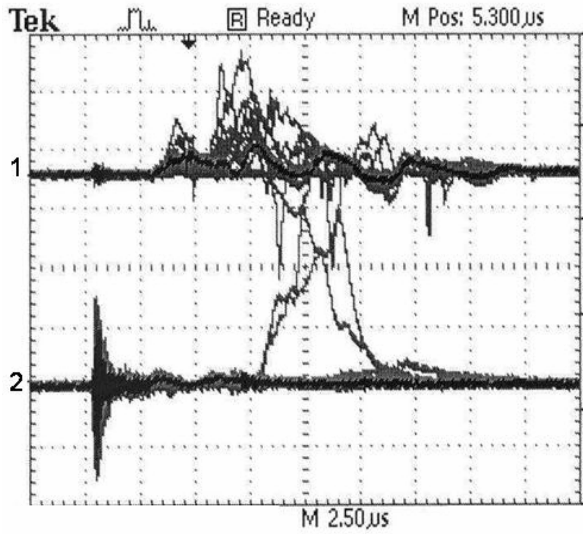

Fig. 6. Ion current density during rep-rate mode and high plenum pressure (~ 700 Torr) operation: (1) CFC2: Z = 7cm, R = 14cm, [6Acm^{-2}/Div]; (2) CFC3: Z = 30cm, R = 0, [2.5Acm^{-2}/Div]

Several collimated Faraday cups (CFC), located at various distances (Z) from the plasma source (CFC1, CFC2 at R = 14 cm radius, CFC3 at R = 0, on axis), were used to monitor the ion current density of the plasma flow. The CFCs had 1 mm diameter apertures, an applied transverse B-field of ~ 200 G (provided by permanent magnets) and negative bias voltages of up to -40 V. Typical ion current density waveforms during one oscillating discharge, illustrated in Fig. 5, demonstrate the generation of multiple ion bunches.

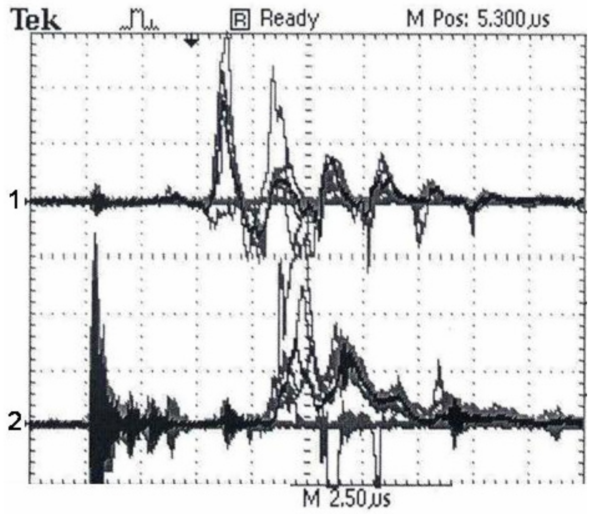

Fig. 7. Ion current density during rep-rate mode and low plenum pressure (~ 500 Torr) operation: (1) CFC2: Z = 7cm, R = 14cm, [6Acm^{-2}/Div]; (2) CFC3: Z = 30cm, R = 0, [0.5Acm^{-2}/Div]

A similar pattern of the ion current density, illustrated in Fig. 6, during rep-rate mode at high puff valve plenum pressure (~ 700 Torr) was registered by CFC2 located 7 cm from the plasma thruster, whereas CFC3 located 30 cm away on axis registered only the first two pulses. This lack of ion propagation in the later pulses may be attributed to charge exchange processes in the plasma flow due to the building up of residual neutral gas. Indeed, for the same rep-rate operation at lower plenum pressures (≤ 500 Torr), ion signals were registered for nearly all pulses in the train on both the 7 cm and 30 cm away CFCs, as illustrated in Fig. 7. The average flow velocity of the plasma was estimated to be ~ 8 x 10^6 to 10^7 cm/s, which corresponds to a translational energy of ~ 25 to 40 eV.

The scaling results of ion current density, plasma density and plasma flow velocity with various shock coil voltages are given in Figs. 8 - 10. When operating at a plenum pressure of 700 Torr, the ion current density drops from 20 A/cm^2 near the shock coil to 2-5 A/cm^2 at a distance of 30 cm. The drop in current density between different CFCs (distances) can be attributed to plasma divergence while the drop observed between the first and last pulse in the train may be attributed to charge exchange processes. At this pressure and shock coil voltages ranging between 12 to 16 kV, the plasma density increases in the near zone to 1.1 x 10^{13} cm^{-3} with a fairly constant plasma flow velocity of ~ 10-12 cm/µs. Furthermore, by decreasing the plenum pressure we observed a subsequent plasma density drop and an increase in the plasma flow velocity.

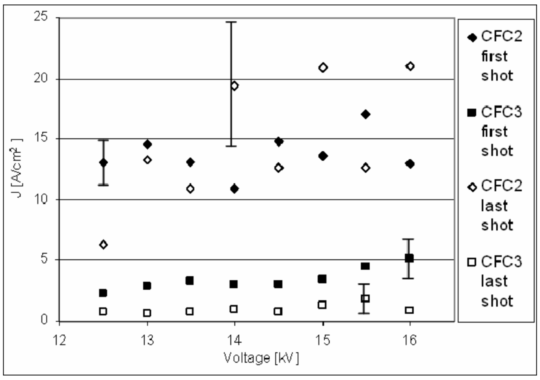

Fig. 8. Average ion current density as a function of shock coil voltage for first and last pulse of train: CFC2: Z = 7cm, R =14cm; CFC3: Z = 30cm, R= 0

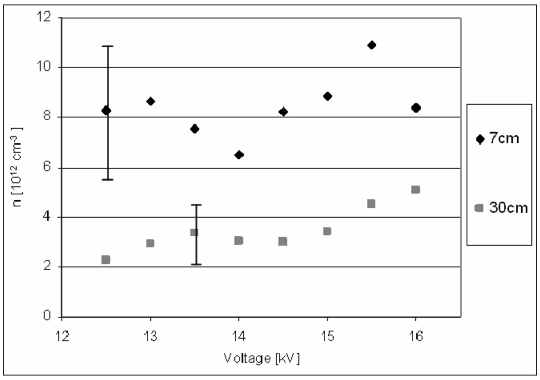

Fig. 9. Average plasma density as a function of shock coil voltage at different distances from thruster

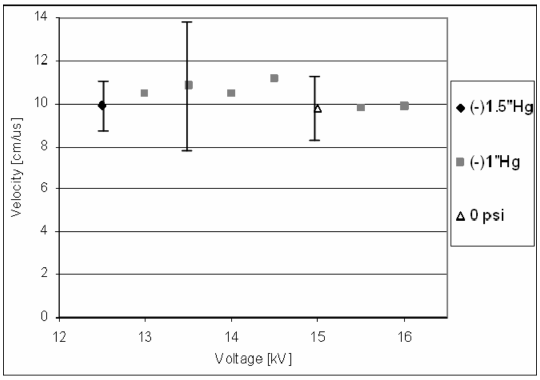

Fig. 10. Average plasma flow velocity as a function of shock coil voltage at various plenum pressures

4. Conclusion

An inductive discharge H+ plasma source in a rep-rate (10 to 30 Hz), short pulse train (6 to 30 pulses) mode of operation was tested and analyzed. A dependence of plasma flow parameters and reproducibility as functions of pulse rep-rate, puff valve plenum pressure, shock coil discharge voltage, and residual build-up of gas pressure were measured. In the rep-rate frequency domain of this experiment, the heat load (1-30^0 C temperature change) on the electromagnetic puff valve is not an issue. For higher rep-rates, an additional puff valve/shock coil cooling system may be needed. Also, the heat sensitive parts of both puff valve and shock coil could be replaced by ceramics or other heat resistant materials.

Thus, this rep-rate plasma source proved to be robust and adequate for providing the necessary plasma flows (2-20 A/cm^2 ion current densities, 10^{12}-10^{14} cm^{-3} plasma densities, 5-30 eV translational energies) in (1-30 Hz) rep-rate MIDs. The only limiting factor observed was residual gas build-up in the test chamber which was attributed to the pumping speed of our turbo-pump.

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