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Spontaneous generation of suprathermal electron beams in a stationary magnetic arc discharge

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Introduction

Albeit the plasma generator PSI-2 has been designed and constructed to run under completely stationary conditions fluctuations of a number of parameters cannot be suppressed even in long term operation. Most evident are low frequency (a few Hz) intensity variations of the plasma column which can be observed with the naked eye. These do occur in particular during the conditioning phase after venting of the machine; most likely they are caused by sudden gas release from the walls.

In this paper we concentrate on another fluctuation phenomenon which seems to be present under all plasma conditions and, is still found after many hours of operation: short spikes in the voltage between the heated cathode and the grounded anode. The variations are up to about a factor of two and are followed by a similar change of the floating voltage of the neutralizer plate at the end of the device. From the time difference it can be inferred that suprathermal electrons are produced during each spike in the relatively short anode-cathode region which can pass the whole plasma region without suffering collisions. Interestingly, each spike event seems to have a small precursor.

Plasma Generator PSI-2

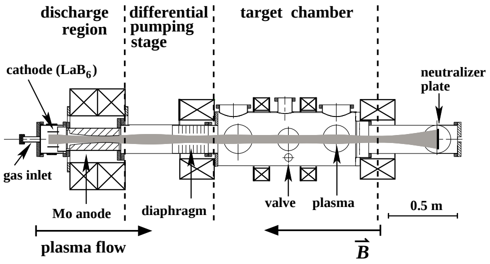

Figure 1: Plasma Generator PSI-2

PSI-2 is a linear plasma device with a stationary arc discharge. A steady discharge current in the range 50 to about 500 A can be chosen. For stabilization a resistor of 1 Ohm is in series with the plasma (about 0.1 to 1 Ohm). The plasma is produced in the discharge region which consists of a heated, cylindrical, hollow LaB_6-cathode and a cylindrically-shaped Mo-anode. The geometry of the discharge region is the same as in [1]. Guided by an axial magnetic field the plasma streams through a differential pumping system and a so called target chamber and is terminated at the neutralizer plate ($l \approx 2.66$ m) (cf. Fig. 1). Parameters for this work are: $I_{AC} = 100 \ldots 125$ A, $B = 0.1$ T, $n_e = 10^{18} \ldots 10^{19}$ m^{-3},

$T_e = 2\ldots15$ eV, $T_i = 0.5\ldots0.7\ T_e$, $p_{\text{neutral}} = 0.04\ldots0.6$ Pa, $p_{\text{AC}} = 4\ldots7$ Pa.

Experimental Results

Voltage Traces

In Fig. 2 a typical temporal course for a spike event in a hydrogen plasma is shown. Such events happen irregularly with a similar signature but are less pronounced in argon discharges. The anode-cathode voltage (U_{AC}) is suddenly enhanced by a factor of two (from -70 V to -140 V) within time intervals of about 1 μs. The same signature but delayed by 0.5 μs is found in the floating voltage of the neutralizer plate (U_{np}) which covers the whole plasma cross section at the end of the discharge. In the case of argon a time delay of 1 μs was measured.

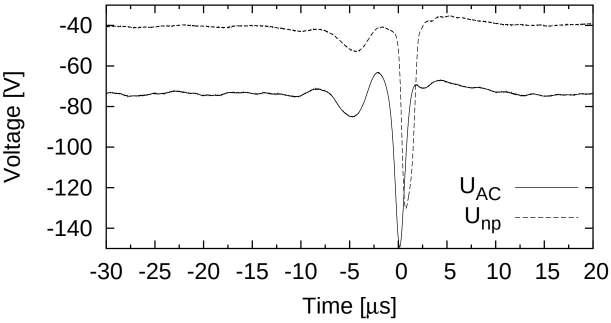

Figure 2: Voltage traces in hydrogen

With the measured time of flight τ and the length $l = 2.66$ m the velocity of the suprathermal electrons can be calculated. This value can be compared with the theoretical velocity of an electron accelerated with the corresponding voltage.

$$v_{\text{meas}} = \frac{l}{\tau} = 5.5 \pm 0.2 \cdot 10^6 \frac{\text{m}}{\text{s}} \qquad (1)$$

$$v_{\text{theo}} = \sqrt{\frac{2e}{m_e}} \sqrt{U_{\text{AC}}} = 7.3 \cdot 10^6 \frac{\text{m}}{\text{s}} \qquad (2)$$

The measured velocity is in fair agreement with the theoretical value in this approximation. For argon we get $v_{\text{meas}} = 2.7 \pm 0.1 \cdot 10^6 \frac{\text{m}}{\text{s}}, v_{\text{theo}} = 3.1 \cdot 10^6 \frac{\text{m}}{\text{s}}$. There is no other reasonable process in the plasma (e.g. waves) that could transfer the information of the spike at such a high velocity.

While varying the trigger voltage one can see that there is up to one event per minute for a voltage of $U_{\text{AC}} \leq -164$V. There is a saturation of about 3500 events per minute at $U_{\text{AC}} \leq -100$V. Estimating the capacitance of the neutralizer plate as $C_{\text{np}} = 8\varepsilon_0 R$ (a thin disk a Radius R = 8.5 cm), we get $Q = CU = 1.7 \cdot 10^{-9}$Coulomb for one event.

As power supplies we use EA-PS 9072-120 from EA company with a guaranteed current control time of less than 1 ms. If the plasma resistance changes for some reason the device adjusts the voltage in order to keep the current constant. According to our observations the actual control time constant is, however, much lower than stated and certainly in the range of 1 μs or less. The voltages and currents were measured with a digital signal analyzer (Tektronix TDS 754C, 500 MHz, 2 GS/s) and cross-checked with a Tektronix DSA 602A (1 GHz, 2 GS/s). We performed non-averaged as well as averaged measurements in order to approve the signal-to-noise ratio.

Floating Potential of a Probe

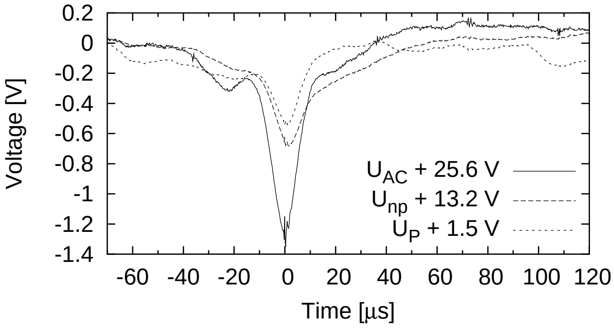

Figure 3: Voltage traces in argon

Additionally we put a double probe in the target chamber and measured the floating potential of both tips alternately. The spikes could also be found in the floating potential of the probe. In Fig. 3 the probe was just outside the visible plasma column. The same course can be found also inside the plasma but the signal to noise ratio is worse. In Fig. 3 the average respective voltages were subtracted from the curves in order to compare the height of the three voltage spikes. For a biased probe the qualitative behaviour was about the same for both probe tips (biased and non-biased).

Increment of Electron Density

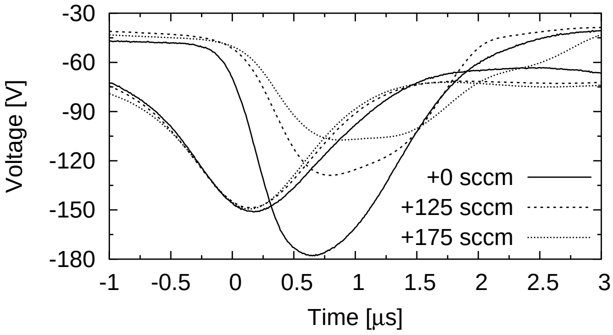

Figure 4: Voltage traces in case of additional gas puffing. U_{AC} (*left set*) and U_{np} (*right set of curves*).

We also used a valve in the target chamber (cf. Fig. 1) to inject additional working gas. This results in an increase of the electron density in this area without increasing it in the discharge region. As to be seen in Fig. 4 the fast electrons are now slowed down in the target chamber (τ is 470 ns, 640 ns, and 730 ns, respectively). Estimating the mean free path lengths of the thermal ($\lambda \sim T_e^2/n_e$) and the suprathermal electrons ($\lambda \sim U_{AC}^2/n_e$) for a plasma density of $n_e \approx 1 \cdot 10^{19}$ m^{-3} these are found to be 0.1 m and 200 m, respectively. In case of the increased density also the motion of the suprathermal electrons becomes affected by collisions. The peaks in U_{np} are consequently decreased and broadened as expected.

Theory

A heated cathode emits electrons as long as the electric field at its surface is positive. For vanishing field conditions severe space charge limitation occur and the extracted current density is determined by the Child-Langmuir law [2]

$$j = \frac{4}{9}\varepsilon_0 \sqrt{\frac{e}{m_e}} \frac{U_{AC}^{3/2}}{L^2}, \tag{3}$$

where L is the characteristic length over which the potential drops from 0 to $-U_{\mathrm{AC}}$. Under plasma conditions this coincides with the electrostatic sheath length, i.e. a few times the Debye length ($\lambda_{\mathrm{D}} = \sqrt{\frac{\varepsilon_0 k_{\mathrm{B}} T_{\mathrm{e}}}{e^2 n_{\mathrm{e}}}}$) and we get the relation:

$$j \sim U_{\mathrm{AC}}^{3/2} n_{\mathrm{e}} / T_{\mathrm{e}}. \tag{4}$$

We are not yet in the position to identify the proper reason for the occurrence of the voltage spikes but density fluctuations in front of the heated cathode could be causal. In fact, a sudden decrease of the electron density would cause a reduction of the extracted current and thus reduce the density further because there are now less ionization events in the neighboring discharge region. There is hence an instability tending to quench the discharge. For this reason a control system is needed which rises the voltage to avoid current quenching. Until now we have no satisfying explanation for the occurrence of the precursor event.

Conclusions and Summary

We observe short voltage spikes in the anode-cathode voltage in a linear stationary plasma device PSI-2. The voltage of the spikes is twice as high as the mean discharge voltage. The current of the discharge is controlled. Each event seems to have a smaller precursor about 5 μs ahead.

The spikes can also be found in the floating voltage of the neutralizer plate at the end of the discharge. It is inferred that suprathermal electrons are produced during the short phases with enhanced voltage. The corresponding energy of the electrons in the pulse is of order 100-150 eV and thus much larger than the electron temperature which is measured to be $T_{\mathrm{e}} \leq 10$ eV. Such suprathermal electrons can pass nearly collisionless the whole plasma length of 2.6 m under the prevailing low density conditions.

Density fluctuations that lead to variations of the electrostatic sheath length in front of the cathode are identified as a possible mechanism to produce the spikes.

Apart from being an interesting physical phenomenon by itself the effect could have also practical aspects since the distortion of the electron Maxwellian distribution (bump in tail) can have consequences for the interpretation of various measurements and moreover may lead to excitation of plasma waves.

References

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