Plasma Sources Science and Technology

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To cite this article: D Andruczyk *et al* 2006 *Plasma Sources Sci. Technol.* **15** 533

INSTITUTE OF PHYSICS PUBLISHING PLASMA SOURCES SCIENCE AND TECHNOLOGY

Plasma Sources Sci. Technol. **15** (2006) 533–537 doi:10.1088/0963-0252/15/3/032

Langmuir probe study of a titanium pulsed filtered cathodic arc discharge

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Received 25 October 2005
Published 9 June 2006
Online at stacks.iop.org/PSST/15/533

Abstract
A Langmuir probe has been used to make measurements of plasma parameters as a function of time at the substrate position in a magnetically-filtered pulsed cathodic arc discharge. Electron density, n_e, and effective electron temperature, T_{eff}, were calculated as a function of time from the I–V curves. The Druyvesteyn method was used to determine the electron energy distribution. Ion density was calculated using the assumption of plasma quasi-neutrality and an average ion charge state. Results show that over the plateau region (350–600 μs) of the pulse, the electron energy distribution is Maxwellian with $T_{eff} = T_e = (10 \pm 1)$ eV. During the rise and fall times of the pulse, the electron energy distribution is non-Maxwellian with an effective temperature of up to 15 to 20 eV during the rise time and ∼7 eV during the fall time. The electron density during the plateau is $n_e = (3.0–6.0 \pm 0.5) \times 10^{17}$ m^{-3}.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Pulsed cathodic arc discharges are an effective method of producing highly ionized metal or carbon plasmas for thin film preparation or ion implantation [1]. The cathodic arc plasma is generated by ablation processes (cathode spots) on the cathode surface during high current pulses. These processes result in a highly ionized, energetic plasma plume directed normal to the cathode surface. The directed velocity of the ions is supersonic and is in the range of $v_i = (1–2) \times 10^4$ ms^{-1}, which is an order of magnitude higher than the thermal velocity of the ions. Due to the need to remove small droplets and clusters (‘macro-particles’) produced during the ablation process, cathodic arc plasmas are often ducted through curved magnetic fields. The properties of the deposited films in such systems are strongly dependent on the properties of the plasma, such as plasma density and electron temperature or the electron energy distribution function (EEDF).

Langmuir probes are one of the most commonly used tools for diagnosing plasmas. A difficulty arises in using a Langmuir probe in pulsed cathodic arc plasmas since the plasma parameters vary with time during the pulse. The pulse length is typically 300–600 μs which is much shorter than the usual voltage sweep time used in Langmuir probe measurements. Provided that the pulses have a high level of repeatability, an I–V curve at a specific time in the pulse can be constructed from measurements of current as a function of time for a series of constant probe voltages.

In this paper, we report the use of such a technique to investigate the properties of the plasma at the substrate position in a titanium, magnetically filtered, pulsed cathodic arc discharge.

2. Experimental

The Langmuir probe studies were conducted in a pulsed cathodic arc system [1], constructed within a half-torus vessel, rectangular in cross section (120 mm wide, 360 mm high) with a major radius of 440 mm. The system has cathodic arc sources at each end, with the substrate mounted at the midpoint of the half-torus. At each end a double-cathode system has been

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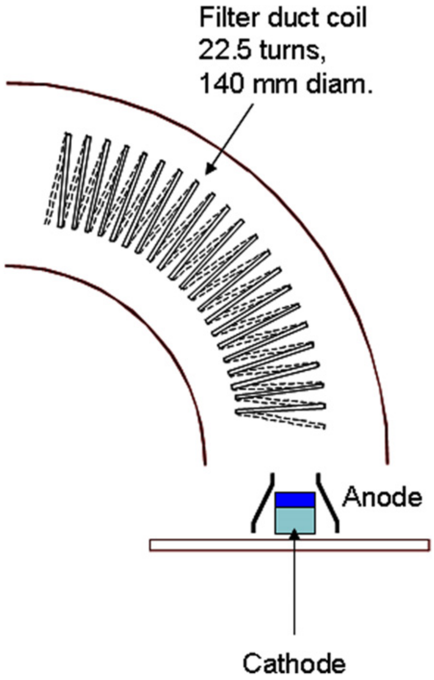

Figure 1. Schematic of one arm of the half torus, showing positions of the substrate, the magnetic filter and the cathode assembly.

developed to allow the production of multi-layers and alloys of up to four different cathode materials. For all of the studies referred to in this paper, a single cathode at one end of the half-torus with the substrate at the mid-point of the half-torus was employed. Figure 1 shows a schematic of the experimental set up. The system is evacuated to better than 10^{-6} Pa by a turbo-molecular pump supplemented by a helium cryopump at 12 K.

A curved magnetic filter, wound in a spiral from 6 mm copper tubing, was inserted between the cathode and the substrate holder. The major radius of the magnetic filter is the same as that of the half-torus. The filter, which has 22.5 turns and a minor radius of 70 mm, is mounted on curved rails by insulating supports and is connected to its own power supplies for current and voltage bias. There is a separate power supply for the cathodic arc.

Cathode currents of up to 5 kA, with pulse lengths of 100–1000 μs at repetition rates of up to 10 Hz are achievable with this system. Within the duct the diameter of the plasma is ~40 mm, depending on the magnitude of the magnetic field produced by the magnetic filter. After the plasma leaves the magnetic filter and drifts towards the substrate, the plasma diverges along the magnetic field lines, reaching a diameter $\geqslant$80 mm at the substrate position. The results presented in this paper were obtained with a cathode current of 1.5 kA, a duct magnetic field on average 20 mT, a duct bias voltage of 60 V and pulse length of 600 μs at 10 Hz.

The Langmuir probe used is of the single wire type without compensation. The probe consisted of a 0.2 mm diameter tungsten wire, inside a ceramic tube, which was itself inside a stainless steel tube that is sealed to the vacuum. The probe was further protected by glass tube shielding from which metal deposition from the plasma was removed at regular intervals. The length of the tip exposed to the plasma was approximately 0.9 mm. The probe bias was supplied by a purpose-built probe driver and was varied from −80 to +80 V. The system was driven by LabView® VIs and integrated with the automated running of the cathodic arc system. The data were stored in an MDSplus database [2].

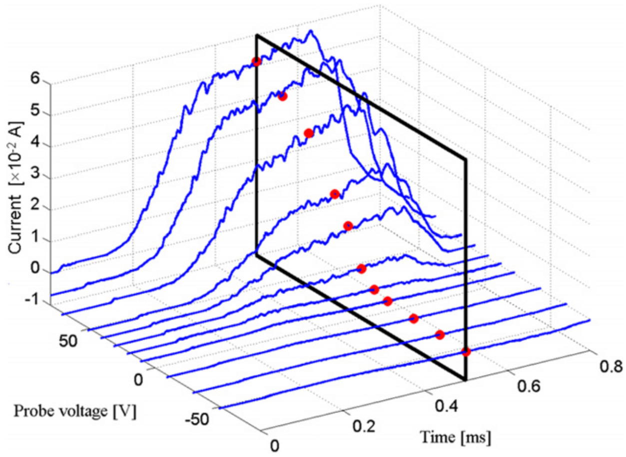

Figure 2. A slice is taken through the current versus time curves at a particular time (e.g. 0.5 ms shown here). The current values at that time, together with the voltages for each curve, are used to determine the I–V curve for that point in time. I–V curves, constructed in this way, were then used to obtain the EEDF and T_e and n_e.

The Langmuir probe was placed 10 mm in front of the substrate plate (a 117 mm diameter circular metal disc), at the mid-point of the half-torus, with the probe aligned parallel with the surface of the substrate plate, i.e. orthogonal to the direction of plasma drift. The probe tip was positioned in the centre of the plasma stream. The voltage bias on the probe was stepped up in increments of 0.5 V from an initial −80 to +80 V. Each signal was averaged over 16 plasma pulses and 9-point averaging was employed to further smooth the data before analysis. The I–V curves as a function of time were constructed from the current values at each voltage step, as indicated in figure 2.

3. Langmuir probe theory

Langmuir probes are an indispensable tool for plasma diagnostics, allowing measurements to be made locally over a wide variety of plasma conditions. However, standard Langmuir analysis techniques assume a Maxwellian electron energy distribution, but this is often not a valid assumption. For a non-Maxwellian electron energy distribution, the effective electron temperature, $T_{\rm eff}$, (measured in electronvolts), is often defined such that $3/2kT_{\rm eff}$ is equal to the measured average electron energy [3].

The Druyvesteyn method [4] of probe analysis is used here as it first determines the EEDF and does not assume a Maxwellian distribution. The electron density, n_e and average electron energy are then calculated by integrating over the EEDF. The plasma potential, V_p, corresponds to the point where the I–V curve has an inflection. This point is located by finding a zero of the second derivative, i.e. where

$$\frac{d^2I}{dV^2} = 0. \qquad (1)$$

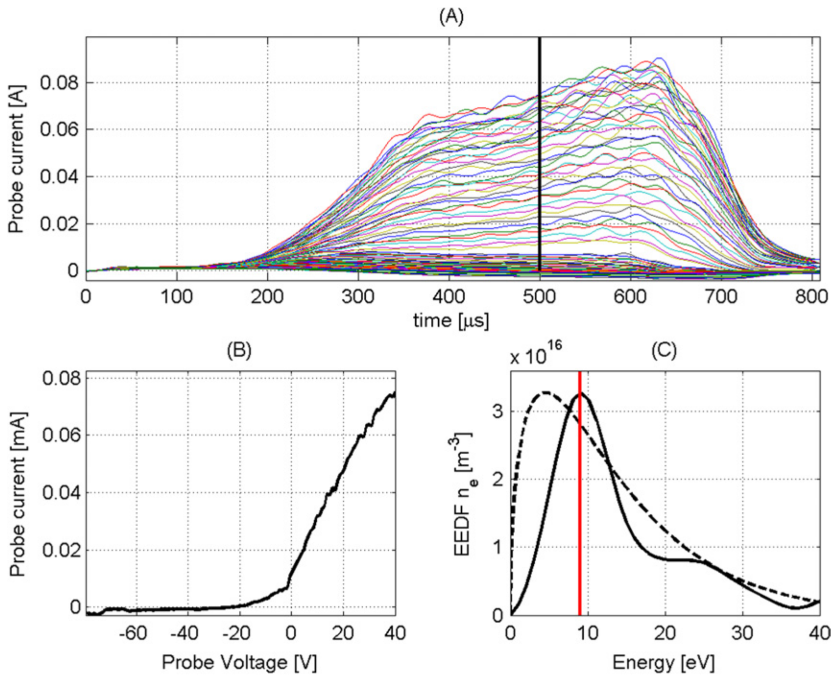

Figure 3. (*a*) The current curves for all probe voltages. (*b*) The I–V curve using the data slice at 500 μs (intercepted in (*a*)). (*c*) The EEDF (——), calculated from the I–V curve shown in (*b*), compared with a Maxwellian distribution (- - - -). The effective electron temperature for this time slice is 9 eV and the electron density is 7.5×10^{17}.

The second derivative of the I–V curve is related to the EEDF, $f(\varepsilon)$, by the relation [3]

$$f(\varepsilon) = \frac{2}{eA}\left(\frac{2m_e\varepsilon}{e}\right)^{1/2}\frac{\mathrm{d}^2 I}{\mathrm{d}V^2}, \tag{2}$$

where the energy, $\varepsilon = e(V_p - V)$. V is the applied probe voltage, V_p is the plasma potential, A is the surface area of the sheath plasma boundary surrounding the probe, e and m_e are the electron charge and mass, respectively.

The EEDF can be integrated to obtain the electron density as well as an average electron temperature [3] as follows.

$$n_e = \int_0^\infty f(\varepsilon)\,\mathrm{d}\varepsilon, \tag{3}$$

$$\langle T_{\mathrm{eff}}\rangle = \frac{2}{3n_e}\int_0^\infty f(\varepsilon)\varepsilon\,\mathrm{d}\varepsilon. \tag{4}$$

If the EEDF is Maxwellian, T_{eff}, is equal to T_e, the electron temperature in electronvolts. Using traditional Langmuir probe analysis for plasmas with non-Maxwellian distributions is of uncertain value [5]. The advantage of the second derivative method is that there is no assumption of a Maxwellian EEDF.

4. Results and discussion

In order to obtain plasma parameters from the I–V curves, a computer program (written in Matlab) has been developed to analyse the data for each time step. The program takes a slice of data points, at the specified time, through each of the current curves and produces an I–V curve for that time in the plasma pulse. This process is repeated for all times of interest, giving a separate I–V curve for each time. For each I–V curve, the floating potential, V_f, is determined by measuring the voltage at zero current. The plasma potential is determined by finding the voltage where the second derivative is zero (equation (1)) and the EEDF is calculated using equation (2). Integrating over the EEDF gives the electron density, n_e (equations (2) and (3)), and the effective electron temperature, T_{eff}, (equations (2) and (4)).

Figure 3(*a*) shows current as a function of time (sampled throughout the duration of the discharge), for all voltages used. The I–V curve shown in figure 3(*b*) is constructed from the data points at 500 μs after pulse initiation, indicated by the solid line in figure 3(*a*). Figure 3(*c*) shows two curves: (1) the EEDF (solid line) calculated from the I–V curve of figure 3(*b*) and (2) a Maxwellian distribution with temperature, T_{eff} (broken line). Although the EEDF and the calculated Maxwellian curve do not coincide closely, the overall shapes of the two curves are broadly similar. This degree of agreement is present for EEDF curves calculated from data obtained between 350 and 600 μs. In contrast, in the beginning and ending phases of the discharge, the EEDF is strongly non-Maxwellian.

Figure 4 shows (*a*) the electron and ion densities, (*b*) the effective electron temperature, (*c*) the floating potential and (*d*) the plasma potential over the time period 300–700 μs. The electron density, n_e, is between $(3.0 \pm 0.5) \times 10^{17}\,\mathrm{m}^{-3}$ and $(6.0 \pm 0.5) \times 10^{17}\,\mathrm{m}^{-3}$. These electron densities are consistent with microwave interferometer measurements of line-averaged n_e at the same position, shown in figure 5. The ion density curve (grey line), $n_{i,\mathrm{quasi}}$, has been calculated assuming quasi-neutrality and an average charge of the ions while, at the substrate position experimentally measured to be 2.6 using a Hiden mass selected energy analyser [7]. Quasi-neutrality implies that the ion number density is a factor of 2.6 times less than the electron density, giving an ion density between $(1.0 \pm 0.2) \times 10^{17}\,\mathrm{m}^{-3}$ and $(2.0 \pm 0.2) \times 10^{17}\,\mathrm{m}^{-3}$.

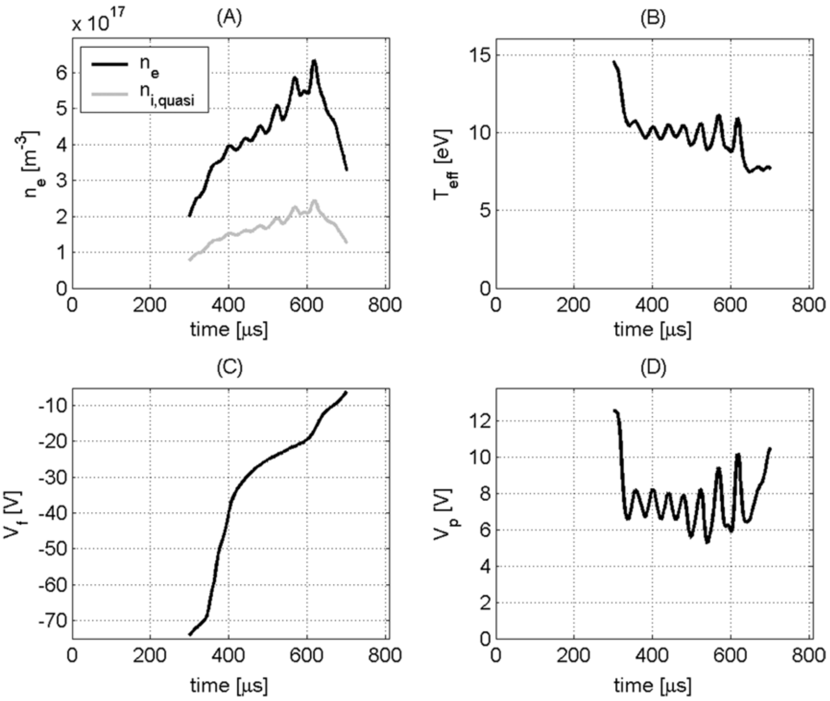

Figure 4. Plasma parameters, n_e, n_i, T_{eff}, V_p and V_f over most of the pulse, 300–700 μs.

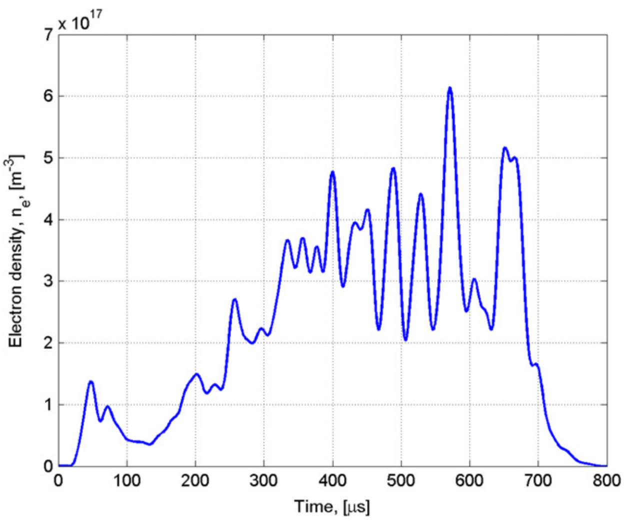

Figure 5. Average electron density measured using an 8 mm microwave interferometer.

Since the EEDF is not Maxwellian through the whole pulse, the interpretation of the electron energy is in terms of an effective temperature, T_{eff}. Figure 4(*b*) shows T_{eff} is high at the beginning of the discharge at about 15 eV. In the middle of the pulse, 350–600 μs, since the EEDF is close to Maxwellian, $T_{eff} \approx T_e$, with a value $T_e = (10 \pm 1)$ eV. The floating potential, shown in figure 4(*c*), starts off at around -70 V and then rises abruptly to around -25 V in the plateau region of the pulse, (350–600 μs). This can be attributed to the difference in drift velocities of the electrons and ions, where electrons are significantly faster then the ions and so arrive earlier in the pulse. The plasma potential is constant over most of the discharge (figure 4(*d*)). The measurements provide for the evidence that the EEDF is reasonably close to a Maxwellian over the interval 400–600 μs, $V_p - V_f \approx 40$–30 V, while if a Maxwellian is assumed corresponds to $T_e \sim 8$–6 eV.

It should also be noted that there is a 23 kHz oscillation present in the measurements, in particular the density, temperature and plasma potential measurements as well as the microwave interferometer measurements. Cathode current measurements, and measurements of the plasma current flowing into the curved magnetic filter made using Rogowski coils surrounding the plasma stream [1], show that this is not due to any oscillations in the cathode current. Thus the oscillations are likely to be caused by instabilities of plasma transport in the magnetic filter. Depending on operating and plasma conditions, the oscillation frequency can vary between 20 and 80 kHz. At present the source of the fluctuations is not known.

5. Conclusions

It has been shown that for Langmuir probe studies of the drifting plasmas in a pulsed cathodic arc, the Druyvesteyn method can be used to calculate electron densities and effective electron temperatures. The electron densities obtained using Druyvesteyn are in excellent agreement with electron densities obtained by 8 mm microwave interferometry. In the plateau region of the plasma pulse, the EEDF is close to Maxwellian and the effective temperature can be interpreted as an electron temperature. In contrast, the rise and fall regions of the pulse show highly non-Maxwellian distributions. Over the Maxwellian region of the pulse, ion densities have been calculated assuming plasma quasi-neutrality and an appropriate mean ion charge state for a cathodic arc Ti plasma for the operating conditions used in this study and found to be in good agreement with previous measurements of ion density [1].

Acknowledgments

The authors would like to acknowledge the help of John Pigott and Phil Denniss and the support from the Australian Research Council and the Science Foundation for Physics.

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