Results of direct measurements of the plasma potential using a laser-heated emissive probe

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Abstract

The reliable diagnostics of the plasma potential is one of the most important challenges in context with the production, control and confinement of plasma. Emissive probes are readily available as direct diagnostic tools for the plasma potential with a good temporal and spatial resolution in many plasmas, even up to middle-sized fusion experiments. We present the results of investigations on the heating of lanthanum hexaboride and graphite with an infrared diode laser and on the development of a laser-heated emissive probe. Such a probe has a higher electron emission, much longer life time and better time response than a conventional emissive wire probe. We have observed that from both materials electron emission current can be achieved sufficiently strong even for dense laboratory and experimental fusion plasmas.

Key words: Plasma diagnostic, plasma potential, laser heated emissive probe, LaB_6, graphite.

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1. Introduction

The plasma potential Φ_{pl} is the most essential parameter for the overall stability and the particle transport in particular in the edge region of magnetically confined plasmas. Its reliable determination is therefore of vital interest, however, there are very few diagnostic methods for this purpose, of which emissive probes are the simplest, least expensive and most suitable for a determination of Φ_{pl} with sufficient temporal and spatial resolution.

Since the 1960's emissive probes have been used in laboratory plasmas for a direct determination of the plasma potential Φ_{pl} [see e.g. 1]. However, only during the last years emissive probes have been applied for the first time also in the edge plasma region of fusion experiments for measuring Φ_{pl} and related parameters such as the electric field and fluctuations of the potential and electric field [2,3,4]. The floating potential $V^*_{fl,em}$ of a probe, which emits a sufficiently high electron current, is close to Φ_{pl}. In contrast to that, with conventional Langmuir probes the plasma potential can only be determined indirectly from the formula

$$\Phi_{pl} = V_{fl} + \alpha T_e = V_{fl} + T_e \ln\left(\frac{I_{es}}{I_{is}}\right), \qquad (1)$$

where $I_{es,is}$ are the electron and ion saturation currents, respectively, and T_e the kinetic electron temperature. This formula can be derived from simple Langmuir probe theory for the probe voltage $V_p \leq \Phi_{pl}$ under the assumption of a Maxwellian velocity distribution function for the electrons. Obviously, for this formula T_e has to be determined at first, which is not easy with sufficient reliability, especially in the edge region of a toroidal plasma, where there can be strong gradients and fluctuations of the temperature. The factor $\alpha = \ln(I_{es}/I_{is})$ is in general around 2.04 for hydrogen in a magnetised plasma [3], but there can be deviations depending on the magnetic field strength B and on the direction of the probe with respect to the vector $\boldsymbol{B}$.

For an emissive probe Eq. (1) becomes

$$\Phi_{pl} = V_{fl,em} + T_e \ln\left(\frac{I_{es}}{I_{is} + I_{em}}\right), \qquad (2)$$

where I_{em} is the current emitted from the probe into the plasma. Eq. (2) shows that for $I_{em} = I_{es} - I_{is}$, the emission current (plus the usually negligible ion current) compensates the electron current from the plasma, and the floating potential of the probe becomes identical to Φ_{pl}. Eqs. (1,2) are, as mentioned above, only valid for $V_p \leq \Phi_{pl}$, purely Maxwellian electrons and for neglecting space charges around the floating probe [5,6].

For comparison with the experimental data it is convenient to define the difference between the actual floating potential and the plasma potential normalised to the electron temperature:

$$\Delta \equiv \frac{\Phi_{pl} - V_{fl,em}}{T_e}. \qquad (3)$$

Eq. (2) shows that Δ is equal to:

$$\Delta = \ln\left(\frac{I_{es}}{I_{is} + I_{em}}\right) \qquad (4)$$

Eqs. (2,4) demonstrate the typical behaviour of an emissive probe: the more it is heated, the larger is I_{em}, the smaller Δ becomes and the more its floating potential approaches Φ_{pl}, until for $I_{em} = I_{es} - I_{is}$, $\Delta = 0$.

For a cold probe these equations reduce to

$$\Delta_0 \equiv \frac{\Phi_{pl} - V_{fl}}{T_e} = \ln\left(\frac{I_{es}}{I_{is}}\right) = \alpha \qquad (5)$$

Up to now, emissive probes have been realised almost exclusively by small loops of tungsten or tantalum wires, which were heated by an external power supply (see e.g. [3]). This method has the advantage of a relatively easy construction, smallness and inexpensiveness. However, to achieve high emission currents, the loop has to be heated strongly so that the danger of melting is immanent and therefore the lifetime is restricted, which in a magnetic field is enhanced by the Lorentz force trying to twist the wire loop through which the heating current is flowing. In addition, the external power supply presents a high capacity which limits the frequency response of such a probe.

We have developed a method to heat small pieces of lanthanum hexaboride or graphite by an infrared laser beam until the material becomes emissive. Mounted on a ceramic tube, with the necessary electrical connection, a laser-heated emissive probe can be constructed. Since neither of these materials can melt (however, sublimate), the lifetime of such a probe is much longer and it can be heated to much higher temperatures so that also its emission is stronger, making it suitable for hotter and denser plasmas. Since no external power supply is needed, also the upper cut-off frequency of such a probe is higher so that plasma potential fluctuations over a wider range can be registered. Lasers have up to now only been used once for heating an emissive probe [7].

2. Experimental set-up

The experiments were performed first in a test device and then in the VINETA machine at the Max-Planck-Institute for Plasma Physics in Greifswald, Germany [8]. In the test device (20 cm length and 14 cm diameter) temperature measurements of the probe tip and of the current to the wall for different background pressures and heating times were carried out. The experimental set-up and the probe are shown in Fig. 1.

Small cylindrical pieces of 2 mm diameter and heights of about 4 mm of LaB_6 or graphite were used as probe tips. The mechanical and electrical connection was made with a Mo-wire of 0.2 mm diameter that was wound around the probe tip and inserted into a ceramic tube of 3 mm inner and 4 mm outer diameter (see insert of Fig. 1). The reasons for the choice of

LaB_6 and graphite as probe materials were twofold [9]: On one side, the work function of LaB_6 is low and therefore we get a high electron yield even for low temperatures. Graphite, on the other hand, has a higher work function, but its absorption coefficient is very high, wherefore it absorbs the laser light much better. Thus it attains higher temperatures for lower laser powers also producing high electron emission.

In both experimental set-ups, the test chamber and VINETA, the probe tips were heated from the front side through a quartz-glass window by an infrared high-power diode laser JenLas HDL50F from JenOptik, Jena, Germany, with a maximum laser power of 50 W at a wavelength of 808 nm. The laser beam is coupled into a fibre cable of 3 m length terminating in an output head, with which a focal spot of 0.6 mm diameter is produced in a distance of 20 cm. The temperature of the probe tips was measured by means of a PV11 Mycro-Pyrometer and a thermo graphic camera.

2. Experimental considerations and results

The temperature distribution along the shaft of the probe is shown in Fig. 2. In this case the laser heating power was 15 W. The temperature is highest on the tip of the probe, where it reaches almost 1300°C, and along the tube it decreases. Figs. 3a and 4a show the temperatures of the LaB_6 tip and graphite tip, respectively, versus the laser power, corrected for the different emissivity of the materials. As we see, the highest temperature was achieved by the LaB_6-tip for a laser power of 40 W, namely about 1300°C. However, the maximum achievable temperature for LaB_6 is around $T_{\mathrm{LaB}_6} \cong 2500$ K. At this temperature LaB_6, with a work function of $W_{\mathrm{LaB}_6} = 2.7$ eV and a Richardson constant of $R^*_{\mathrm{LaB}_6} = 30\times10^4$ A/K^{2}m^2 [10], emits an electron current density of $j_{em} \cong 1.4\times10^6$ A/m^2. This has to be compared to the average electron current density in the edge region of a tokamak such as ASDEX Upgrade where we have to expect an electron density of $n_e \cong 5\times10^{18}$ m^{-3} and an electron temperature of $T_e \cong 20$ eV. With these values we obtain an average electron current density in the plasma of $j_e \cong 1.1\times10^6$ A/m^2. Thus, with such a probe it would be possible to measure the plasma potential, including its fluctuations, directly in the edge plasma of even a large tokamak like ASDEX Upgrade.

For comparison, the highest emission current from a conventional emissive wire probe of tungsten with a Richardson constant of $R^*_\mathrm{W} = 74\times10^4$ A/K^{2}m^2 and a work function of W_W = 4,55 eV, heated to a temperature of 3000 K, is about 1.5×10^5 A/m^2, thus one order of magnitude less than the value mentioned above. With a melting point of 3574 K for tungsten, 3000 K is about the maximum temperature a W-wire can be electrically heated before it becomes mechanically too weak, in particular in a magnetic field where the Lorentz force tries to twist the wire, in whatever direction the probe is inserted.

With a Richardson constant of $R^*_\mathrm{C} \cong 48\times10^4$ A/K^{2}m^2 and a work function of $W_\mathrm{C} \cong$ 4,8 eV [7], the emission of graphite is comparable to that of tungsten. On the other hand, graphite can be heated much higher than tungsten so that with sufficient laser heating power also a very high electron emission can be achieved. With the sublimation temperature of graphite being around 4000 K, it could be heated to about 3600 K, in which case the emission current density is around 1.2×10^6 A/m^2.

The temporal evolution of the emission current to the test chamber wall has been measured for different laser heating powers. The results are presented in Figs. 3b and 4b. Since no plasma was produced in this chamber, we emphasise that the figures just show the space charge limited currents between the negatively biased emissive probe and the chamber wall. In all cases, the emission current increases rapidly and reaches saturation after about 15 s, but this refers only to the probe tip for short heating times. If the probe is heated constantly, about 5 min are needed to establish a thermal equilibrium of the entire probe, in particular of the ceramic tube.

In general we have observed that the emission current of the graphite probe is lower than that of the LaB_6 probe for the same laser power and the same bias, but it is more stable. This is also obvious from a comparison of Figs. 3b and 4b, where in the former case the vertical spread of the curves is considerably smaller. For short heating times the emission current was usually not so stable, but after some minutes of heating a good stability was obtained.

This fact was confirmed also by the emissive probe characteristics (Fig. 5), recorded in the edge region of the VINETA plasma column in the helicon regime at an argon pressure of 0.22 Pa. Also in this case the electron saturation current shows big fluctuations for short heating times (Fig. 5a), but becomes more stable after long heating times (Fig. 5b). In the latter case, the LaB_6 probe tip was heated for several hours at full laser power without showing any sign of evaporation from its surface.

In the same position of the probe, we have also verified that the laser heated probe is able to show temporal oscillations of the plasma potential (Fig. 6). The time series show that the oscillations occur between about –0.5 V and +1.0 V, having a typical frequency of 9 kHz. Thus the amplitude was 0.75 V approximately. Most probably this instability is a drift type one, driven by the density gradient in the edge region as it was often observed and investigated thoroughly in such types of cylindrical magnetised plasmas (see e.g. [11]).

3. Conclusion

We have succeeded to construct robust laser-heated electron-emissive probes of lanthanum hexaboride or graphite which can produce a higher emission current than a conventional emissive wire probe. Therefore such a probe is more suitable for denser and hotter plasmas than a conventional emissive wire probe.

We have observed stabler currents in case of a graphite probe tip than in the case of a LaB_6 one. In general graphite turns out to be stabler even at higher biases and for different pressures. This fact allows us to conclude that graphite is more suitable than LaB_6 for a laser heated emissive probe. In addition graphite is better suited for the use in experimental fusion machines, where low-Z_{eff} materials are preferable to reduce bremsstrahlung losses.

One problem is, as also shown in our experiments (Figs. 3b and 4b), that the electron emission of graphite is obviously considerably lower than of LaB_6, due to the higher work function of the former material. On the other hand with a stronger laser the emission from graphite can be further increased to values comparable to that of LaB_6.

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Figure captions

Fig. 1: Experimental set-up of the laser-heated probe in the test chamber. The insert shows the construction of the probe tip.

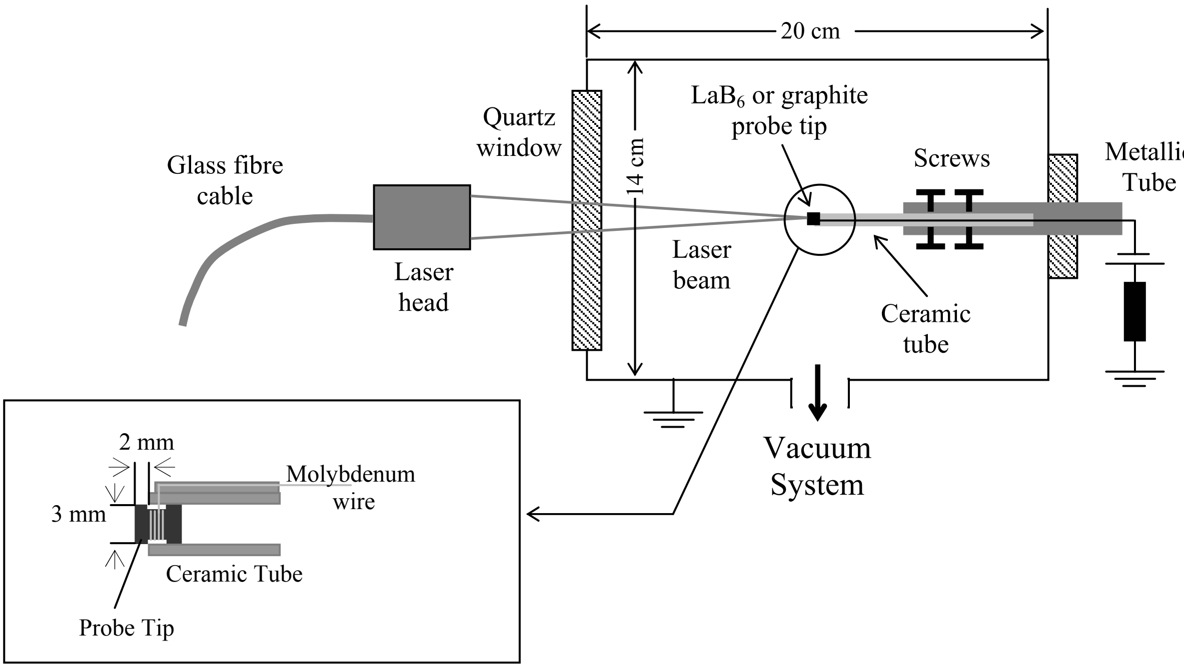
Fig. 2: Temperature distribution along the probe shaft; the LaB_6 probe tip is on the right-hand side. The laser beam comes from the right.

Fig. 3: (a) Temperature vs. laser power for the LaB_6 probe tip. (b) Space charge limited current (without plasma) to test chamber wall vs. time for different laser power for LaB_6 laser heated emissive probe. The exposure time (heating time) was 60 seconds and the applied potential on the probe was $V = -20$ V.

Fig. 4: (a) Temperature vs. laser heating power for the graphite probe tip. (b) Space charge limited current (without plasma) to test chamber wall vs. time for different laser powers for the graphite probe tip. The exposure time was 60 s and the applied potential on the probe was $V = -20$ V.

Fig. 5: (a) Typical current voltage characteristics for short-time heating (30 s) at low plasma density. (b) Typical current voltage characteristics for long-time heating at high plasma density (the saturation of the emission current on the left side at 1 A is due to the multimeter).

Fig. 6: Typical plasma potential fluctuations in the edge region of the VINETA plasma column, which is a drift instability with a frequency of 9 kHz.



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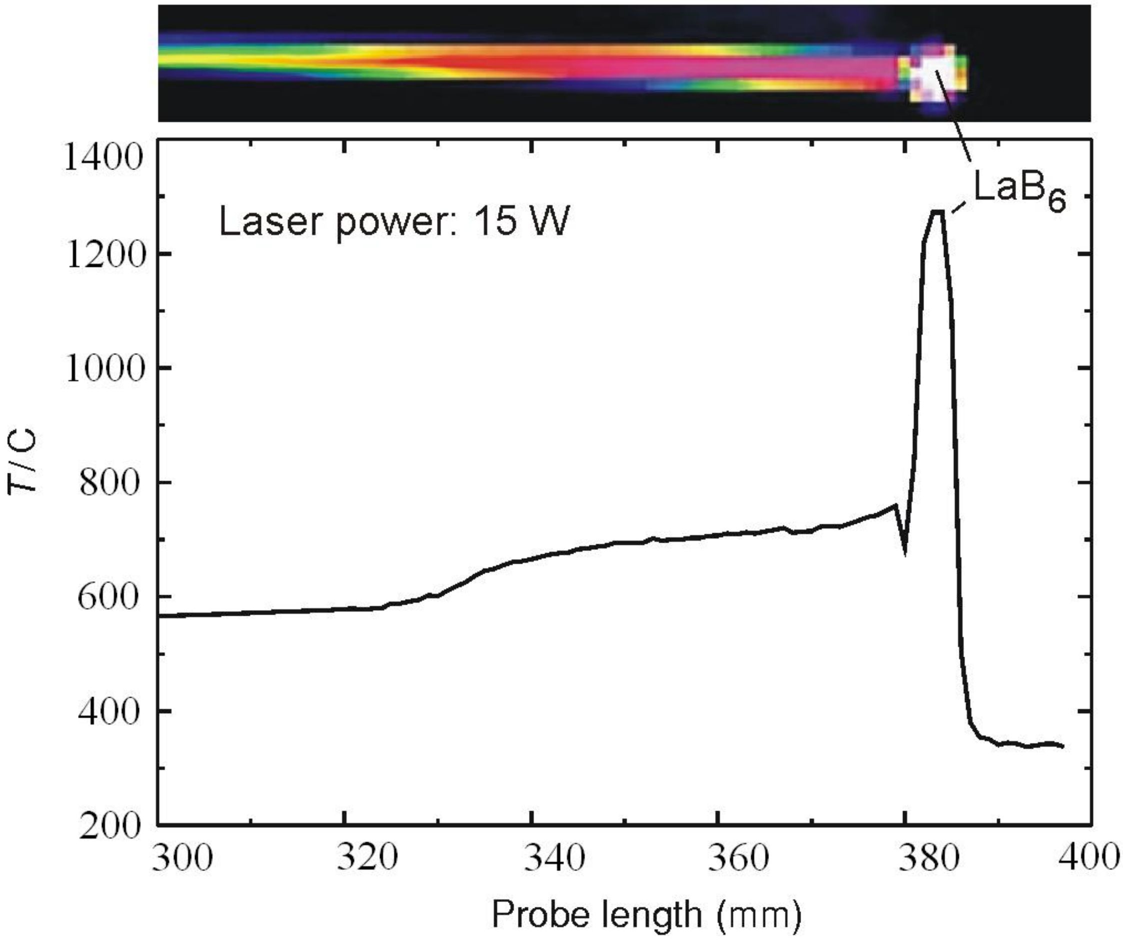
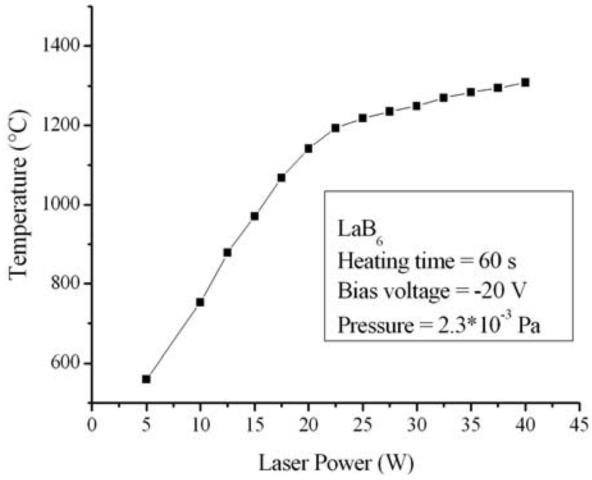
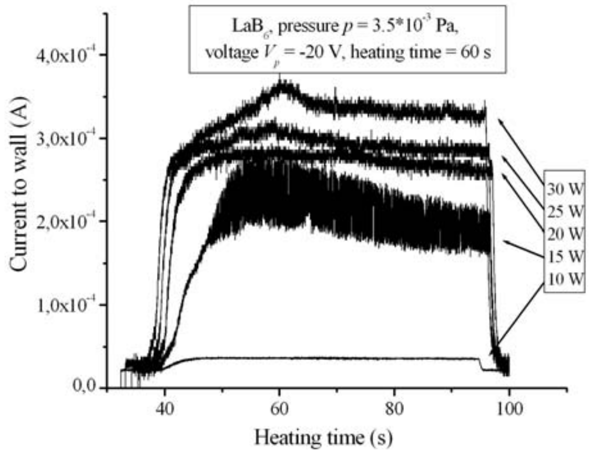


Fig. 2: Temperature distribution (in °C) along the probe shaft when the probe tip is heated with 15 W laser power; the LaB_6 probe tip is on the right-hand side. The laser beam comes from the right.





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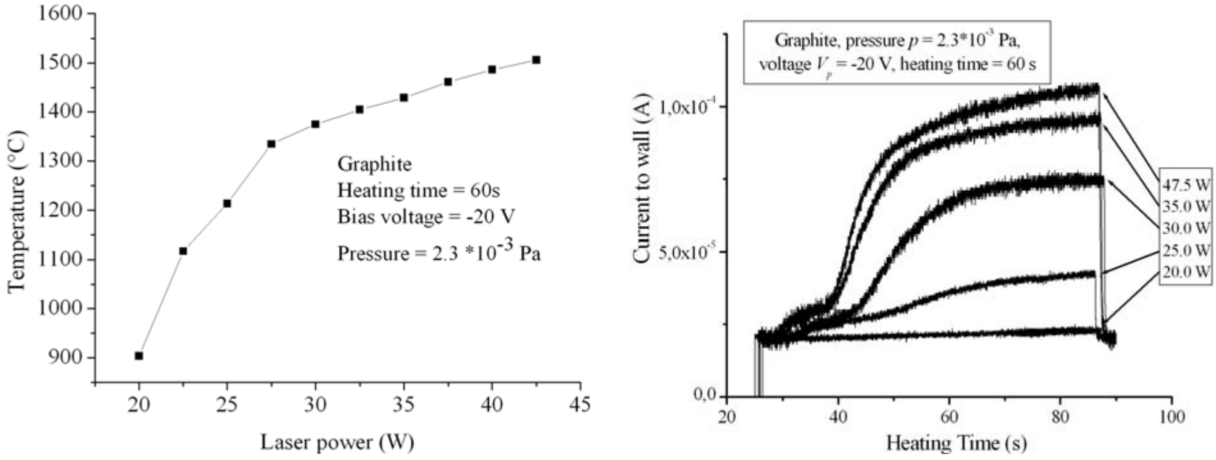

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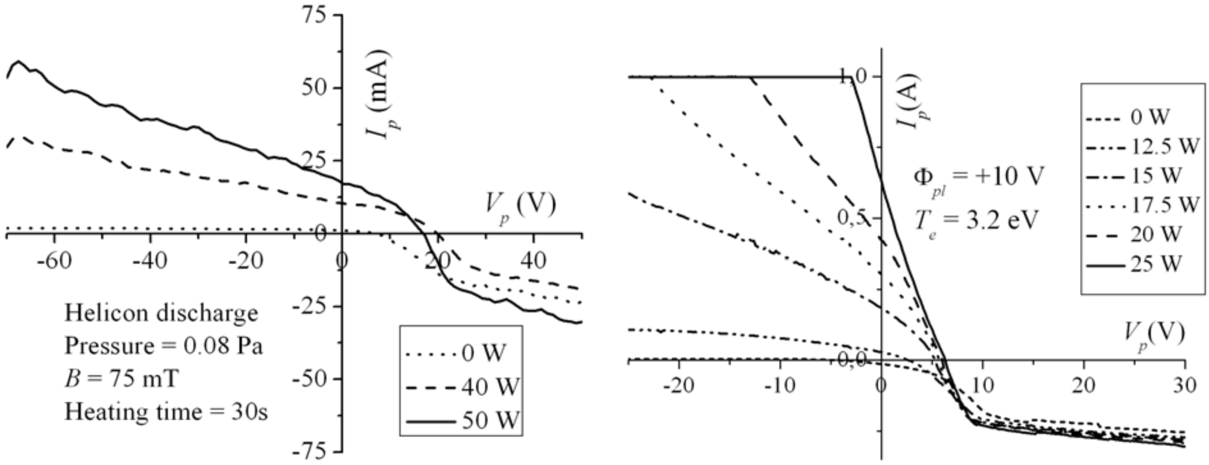

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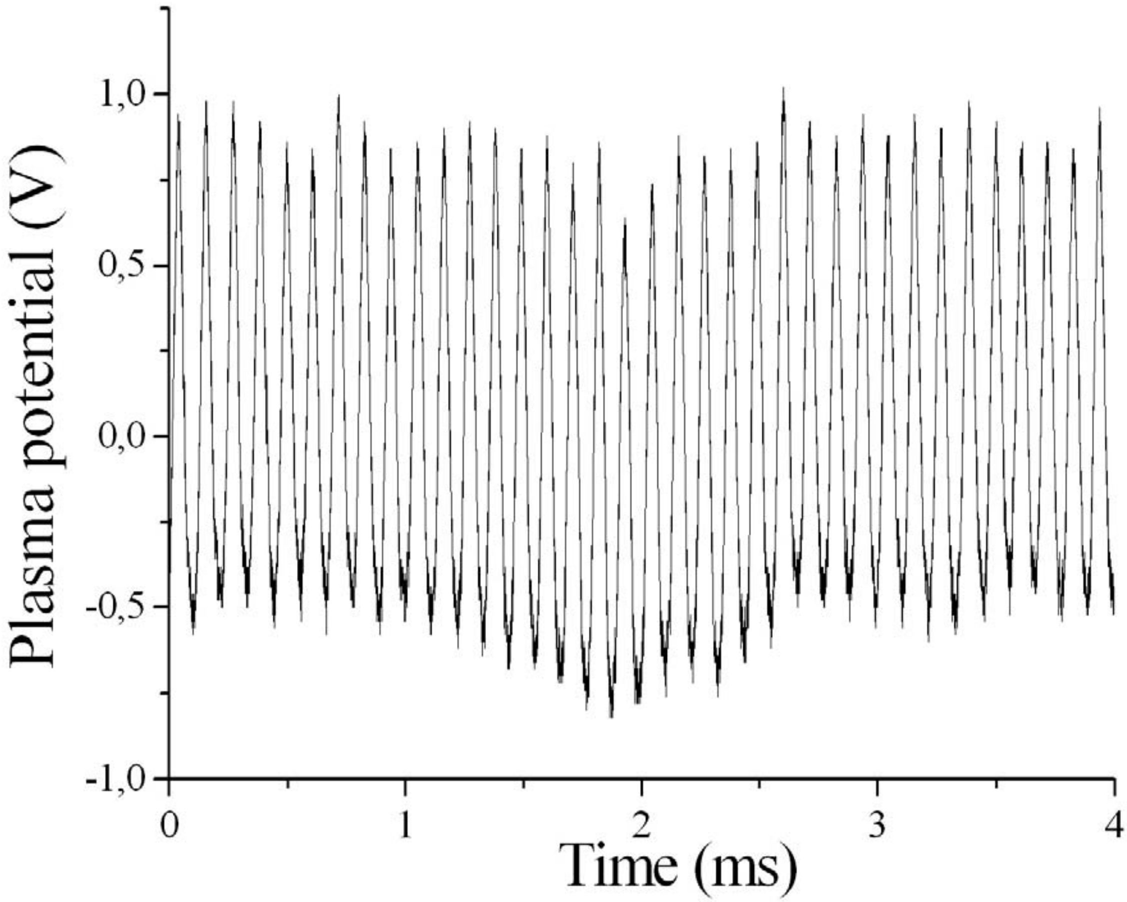

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