acta physica slovaca vol. 55 No. 6, 521 – 529 December 2005

PLASMA DENSITY MEASUREMENT USING ION PROBES[1]

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Received 18 April 2005, in final form 18 July 2005, accepted 21 July 2005

The study reports the plasma density measurement employing simple ion probes. Ion flux probes are used to determine if the extraction process of an electron beam is source limited in a cold cathode e-beam source. The probes indicate the approximate order in the magnitude of plasma density. However, in spite of this indication, there is a variation of the measured plasma density from a shot-to-shot. The simple ion probes offer a quick evaluation of the plasma gun when a plasma density in the order of 10^{13} cm^{-3} at the anode-cathode gap region is anticipated. The velocities of plasma maxima were found to be approximately 1.4 to 5 cm/μs.

PACS: 29.25.Bx, 29.25.Lg, 29.25.Ni, 41.75.-i

1 Introduction

There are various kinds of electron beam sources, like thermionic emitters, cold cathode emitters, plasma cathode e-guns, grid controlled plasma cathodes, photoemissive cathodes and ferroelectric electron beam sources. A high electron beam density is a requirement in all these types of devices. In addition a well-collimated electron beam, obtained from the plasma, is expected. Many are dependent on the quality of plasma. Cold field-enhanced emitters normally lead to a fast plasma closure (typically less than 1 μs), but a high brightness electron beam is obtained. Plasma cathode electron sources have a plasma discharge in a magnetic field. The intense electron beam is generated by applying a potential difference in the vacuum diode between an anode and cathode. The Plasma Edge Cathode promises to overcome the limitation of conventional cold cathode sources [1-8]. To obtain a well behaved electron beam, the change in plasma density versus time was measured using simply designed ion probes.

[1]Presented at Joint 15th Symposium on Applications of Plasma Processes (SAPP) and 3rd EU-Japan Symposium on Plasma Processing, Podbanské (Slovakia), 15 – 20 January 2005.

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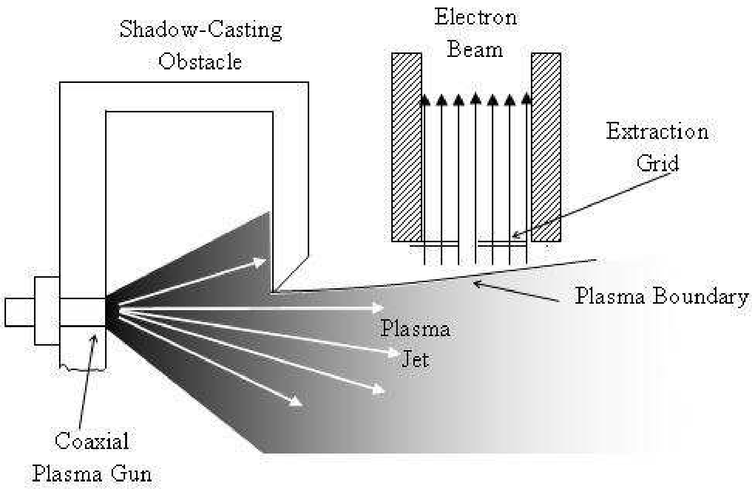

Fig. 1. Concept of Electron Beam Generation (Plasma Edge Cathode). Extraction grid - anode, Plasma boundary - cathode, anode-cathode gap potential = 30 kV, Plasma gun = ceramic surface flashover.

2 Cold-cathode e-beam source

The plasma density probes were used to optimize the cold-cathode e-beam source called "Plasma Edge Cathode" [1-8]. Studies of the electron beam generation were presented earlier [1-3,5-8]. Figure 1 shows a concept of an electron beam generation. The plasma expands from a localized surface flashover. Next, an obstacle intercepts the expanding plasma and causes a stationary transverse plasma boundary. If an extraction potential is applied between an anode parallel to the plasma edge and the plasma boundary, electrons are then pulled off the plasma and an electron beam is generated.

If this extraction is space charge limited, there is minimal electric field intensity at the surface of the plasma and no additional forces should be acting on the particles at the plasma boundary. This suggests that the plasma boundary stays stationary even under electron extraction which is true as long as the plasma density and plasma temperature are sufficient. The aim of the study is to resupply electrons from inside the plasma to its surface by a thermal motion for an extracted current density. The plasma density of the emission layer should not be smaller than the minimum density of $n_e = 4 \times 10^{13}$ cm^{-3} for the 100 A/cm^2 electron beam [1]. If the plasma density is smaller than the minimum density of the emission layer, the electron beam is not space charge limited. Thus, the electric field will penetrate into the plasma and pull the electrons from the plasma while exposing the ions to the electric field.

3 Experimental set up for the plasma density measurement

Figure 2 shows plasma density measurement. The plasma density experimental set up presented in this work consists of a plasma gun drive, plasma source, vacuum chamber, and ion probes. The anode is removed from the chamber and replaced with the first ion probe. The plasma gun

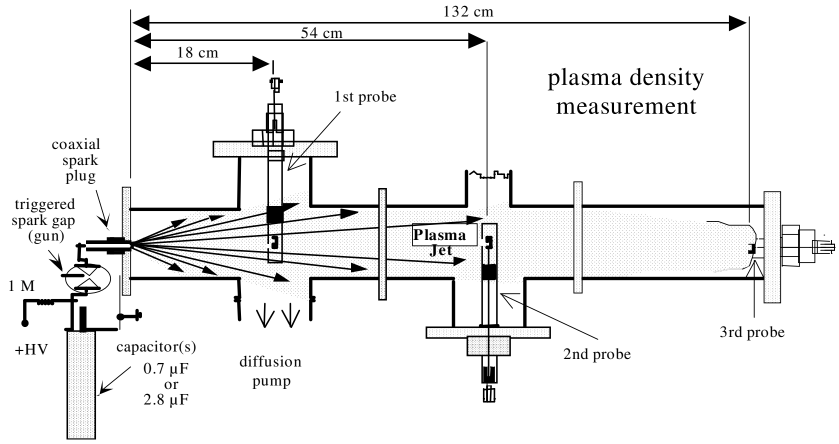

Fig. 2. Plasma density experimental setup using three ion probes, placed at 18 cm, 54 cm, and 71 or 132 cm from the plasma gun.

drive consists of six ceramic type capacitors with 0.3 μF capacitance, one or two S-type 0.7 μF Maxwell capacitors, and one or two S-type 2.4 μF Maxwell capacitors [5-8]. A maximum energy stored in these three types of gun drives is approximately 0.1 kJ, 0.4 kJ, and 2 kJ respectively. A plasma source inside the vacuum chamber is a surface flashover over a 5 mm diameter ceramic disk. A vacuum of less than 1.33×10^{-4} Pa (10^{-6} Torr) is reached in the Pyrex vacuum chamber evacuated by a diffusion pump. The chamber allows a measurement of the plasma drift up to 133 cm. The plasma density is measured by using ion-flux probes.

Three ion probes are positioned downstream at 18 cm, 54 cm, and 71 or 132 cm from the plasma source, Fig. 2. The probes are made of a 1/2 inch copper tube with a calibrated hole and the aluminum ion collector inside, as shown in Fig. 3. The ions pass through the calibrated hole in the probe casing before reaching the collector. The ion flux hitting the collector acts like a current source in the plasma density measurement circuit shown in Fig. 4. The probes are negatively biased to insure that they reject plasma electrons and the secondary electrons from the collector. Each probe is DC isolated using a 1.5 μF capacitor from a 50 Ω scope. The ion/electron current density is written as the total current, I, passing through a known ion probe area, A. This current density is equal to the total charge delivered to the Faraday cup per second, and be calculated using the following equation:

$$j = \frac{I}{A} = n\, e\, v_{pl}, \tag{1}$$

where j is the ion/electron current density, n is the plasma density, e is the electron charge, and v_{pl} is the plasma velocity calculated from two peaks detected by two downstream probes 36 cm apart shown in Fig. 2.

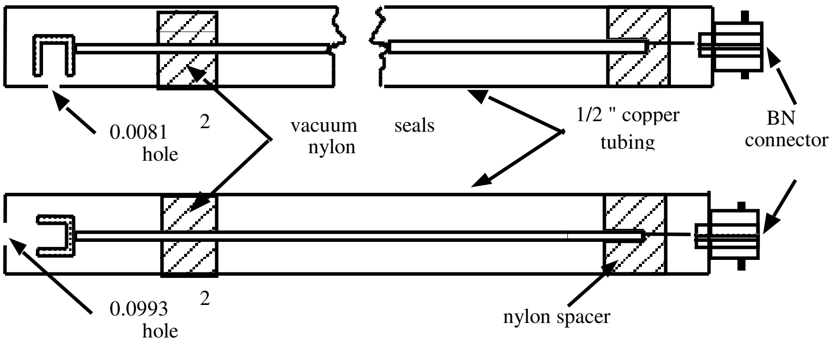

Fig. 3. Ion flux probes, made 1/2 inch copper tube with the 0.0081 cm^2 calibrated hole (#1 and #2 positioned probes) and the 0.0993 cm^2 calibrated hole (#3 probe), aluminum Faraday cup (ion collector).

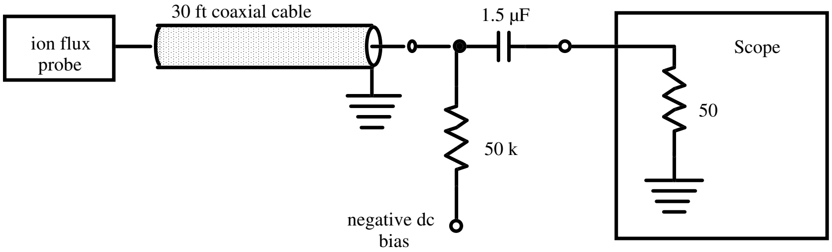

Fig. 4. Ion flux probe circuitry, 1.5 μF bias capacitor, -50 to -75 V negative bias charge, 50 ohm oscilloscope termination, the screen room located about 30 ft from the experiment.

4 Experimental data obtained from ion probes

The electron beam effective area, electron beam duration and electron beam density are correlated to each other. Using the larger anode area (42.4 cm^2) causes more rapid plasma closure of the anode-cathode (A-K) diode which shortens the electron beam duration. A smaller area anode (4.71 cm^2) may obtain a larger electron beam density. The plasma boundary (the cathode plasma layer) should have enough electrons to accommodate a denser electron beam.

It takes about 2 μs for a proper cold-cathode-layer to develop when the plasma gun fires. The plasma arrives below the anode and forms the stable cathode layer. The ion probes placed in the plasma steam respond to the plasma arrival and indicate the plasma density. The ion probe indication is crucial to determine the correct time delay between firing the plasma gun and beam extraction. The ion probes respond when the plasma disappears from the active region. The electron beam duration was about 2.5 μs. A total short of the A-K gap appeared in 4 to 5 μs. The first probe indicated the first peak of the fast plasma component (shown later in Fig. 7). The oscilloscope trace of the first probe shows that there is still plasma entering the extraction region from the plasma gun after the diode short.

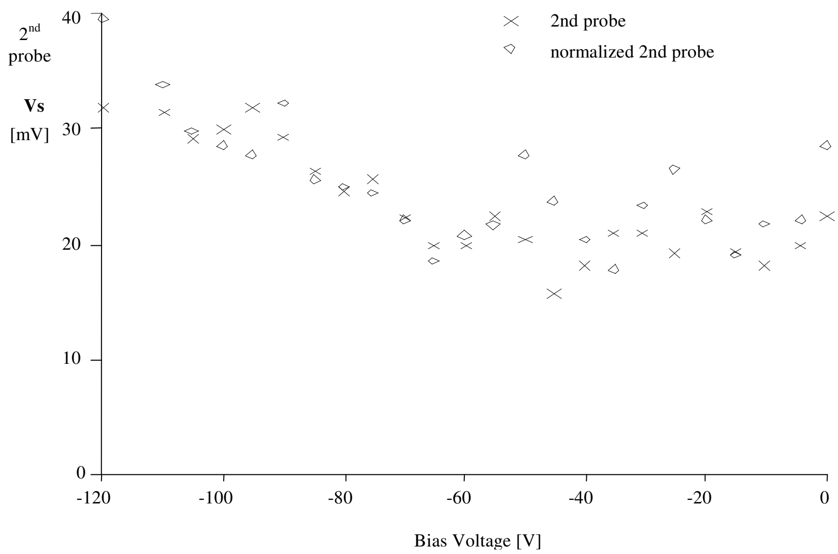

Fig. 5. Ion-flux-probe signal response [mV] versus the Faraday-cup bias-voltage [V], (2nd position inside the chamber), measured plasma density is calculated as $n = 1.1009 \times 10^{13} \times$ Vprobe [cm^{-3}].

4.1 Ion probes plasma measurement using the 0.1 kJ gun drive

The 0.1 kJ gun drive is used with the large-area anode (42.7 cm^2) for e-beam generation [7,8]. The gun drive is charged at 25 kV. The three ion probes at 18 cm, 54 cm, and 71 cm from the plasma source are used to measure the last plasma maximum called the slow component [2,3,4]. Due to a variation of the plasma signal from shot-to-shot, the third probe response is used to normalize the signals from the 1$^{\rm st}$ and 2$^{\rm nd}$ probes. The third probe is kept constant at the -75.5 V bias potential as a reference. The bias voltage of the first and the second probe is changed from 0 V to -120 V by -5 V increments for each group of eight measurements.

Figure 5 shows the ion probe signal response. The second probe starts to short out at approximately -105 V of the bias voltage. In the ion probe measurement, one should be able to find a region where the probe response is independent of the bias voltage. The measurement where the bias voltage is less negative should have a lower probe response because of the possibility that electrons in the plasma enter the probe collector and counteract with the ions. When the bias voltage is more negative, one should consider that electrons do not enter the probe. However, secondary effects may become dominant. For example, a bias size could affect finite plasma conductivity across the A-K gap (several mm wide) inside the ion probe. The ion probe should operate in a range where the probe response does not depend on negative bias voltage. The first probe, positioned 18 cm from the plasma source, is reacting on plasma pressure waves too close to the plasma source and its readings are affected from this plasma turbulence. Furthermore, radiation from the arc may be dominant. The second probe's normalized response shows the "plateau" in a range of -30 V to -50 V of bias voltage where one should expect the maximum reliability.

In the experimental work, the -50 V bias is found to be in the correct range. The plasma density is calculated from the oscilloscope reading using equation (1) as follows:

$$n = \frac{I}{A\,e\,v_{pl}}, \tag{2}$$

where the total current, I, causes a voltage drop, V_S, across the 50 Ω oscilloscope termination. One can re-write the density equation using Ohms Law and substitute the first and second probe input parameters. An example of the slow component electron density calculation is:

$$n = \frac{V_S}{R_S\,A\,e\,v_{pl}} = \frac{V_S}{50 \times 0.0081 \times 1.602 \times 10^{-19} \times 1.4 \times 10^6} = 1.1009 \times 10^{13}\,V_S \quad [1/\mathrm{cm}^3], \tag{3}$$

where using the known ion-probe hole-area of 0.0081 cm^2, plasma velocity of the slow component of 1.4 cm/μs, and where V_s is the slow component peak in volts from the oscilloscope trace.

This measurement indicates an order of plasma density of 10^{12} cm^{-3} at the extraction region 18 cm from the plasma gun, and plasma density of 10^{11} cm^{-3} at 54 cm from the plasma source. The plasma velocity of the slow-component peak was calculated using the location of all three probes. The calculated plasma velocity of the slow component was averaged over all measurements and is 1.40 cm/μs. The third probe, located at 71 cm from the plasma gun, began to respond to the arriving plasma in 6 μs (repeatedly). The second probe began to respond 1 μs earlier. Both probes often show two peaks at the fast component location.

The previous investigator [3, page 32] measured velocities of the slow component as 1.18 cm/μs and of the fast component as 5.3 cm/μs. An additional work [4, page 30] found that the first peak traveled at 10 cm/μs and the second peak at 5 cm/μs (,) but this study was done for larger vacuum-chamber geometry. The ion probe response to plasma is simulated using a computer. The ion-probe bias circuit with its 30 ft transmission line is simulated by PSpice. The ion probe collector is modeled as an ideal current source with a piece-wise linear waveform. The simulated waveforms at the probe's side and the scope's side generally agree when using a 1.5 μF bias capacitor. An experimental value of a 2 nF bias capacitor reported in [3, page 25] is not a good choice and leads to incorrect data.

The plasma density measurement indicates the correct order of magnitude based on the probe's response. However, there might be questions about the second probe reading at a bias voltage of 0 V. There should not be a current across the A-K gap of the ion probe at this potential because the plasma is expected to be a neutral gas and one should expect a zero response from the probe. Furthermore, the probes are cleaned with an acid solution and no difference is found in their behavior. When the probes are oriented in the opposite direction, or covered with a piece of Mylar, they show zero response. Figure 6 shows the third probe response of the slow component peak. The bias voltage is kept at -75.5 volts. The data shown in the graph are split into 24 groups of approximately 8 shots each. The average value of the 24 groups is 111.5 mV ± 23 %. The calculated plasma density from the 3rd probe geometry is as follows: $n = 8.76 \times 10^{11}$ $V_s = 9.8 \times 10^{10}$ cm^{-3} at 71 cm from the plasma source.

It is possible that this shot-to-shot signal variation indicates a plasma propagation with turbulence from the source. This "one dimensional" plasma drift might be caused by a pressure gradient build up at the plasma source region during the gun discharge. From there, the plasma

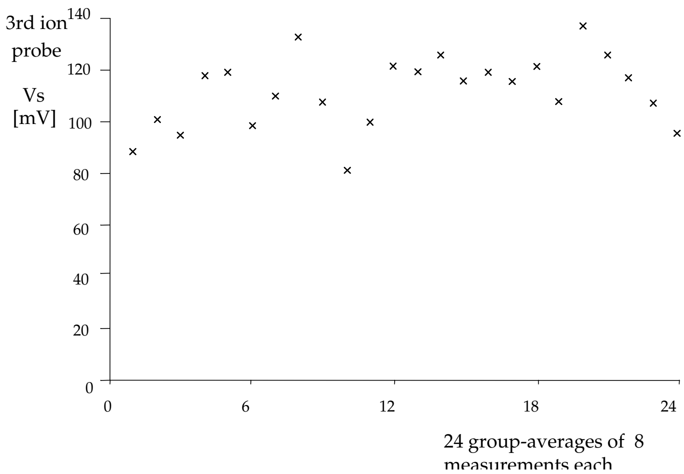

Fig. 6. Third probe at constant bias voltage of -75.5 volts, located at 71 cm from the plasma source, measured plasma density is $n = 8.76 \times 10^{11} \times \mathrm{Vprobe} = 9.8 \times 10^{10}$ [cm^{-3}].

is pushed through the cylindrical chamber. The measurements support this assumption in experimental work with the anode in place. An electron beam is generated [7,8] if the extraction potential is applied in 2 to 4 μs after the gun fired. Using longer delays (over 4 μs) rapidly leads to a short of the diode, that indicates a plasma movement in directions other than the "one -dimensional" plasma drift along the cylindrical chamber. The cold cathode plasma boundary becomes stationary in space for microseconds until more plasma arrives in the cold cathode region.

4.2 Ion probes response using the 2 kJ plasma gun

The 2 kJ capacitor gun drive is used in the 4.71 cm^2 e-beam generation (anode size) [5]. Figure 7 shows a typical response of the three ion probes using the $2 \times 2.4\mu$F gun at 14.5 kV charging voltage. The three probes were positioned at the 18 cm, 54 cm, and 132 cm distance from the plasma gun. The first probe reading is the plasma density at the extraction region, 18 cm from the source. The plasma velocity was about 4.9 cm/μs for the fast component and 1.8 cm/μs for the slow component. It was difficult to recognize the fast component on the first probe trace because the positive reading at the beginning of the trace is probably caused by a trigger noise and/or radiation from the vacuum arc hitting the Faraday cup of the probe.

The calculated electron plasma densities of the first, second, and third ion probe are 1.35×10^{13} cm^{-3}, 2.43×10^{12} cm^{-3}, and 2.89×10^{11} cm^{-3} of the fast component. The slow component calculated densities are 1.59×10^{13} cm^{-3}, 4.81×10^{12} cm^{-3}, and 2.66×10^{11} cm^3. These are the highest plasma densities measured using the 2 kJ gun drive. There is a material structural limit of the vacuum arc (2 kJ gun at 14.5 kV) and consequently the plasma density limit. That power setting was the plasma generation system maximum without causing unnecessary erosion. The 4.71 cm^2 -area anode [5] worked best with a 2 μs delay between firing the plasma gun and the extraction. The electron beam duration was about 2.5 μs. Allowing 300 ns for the system

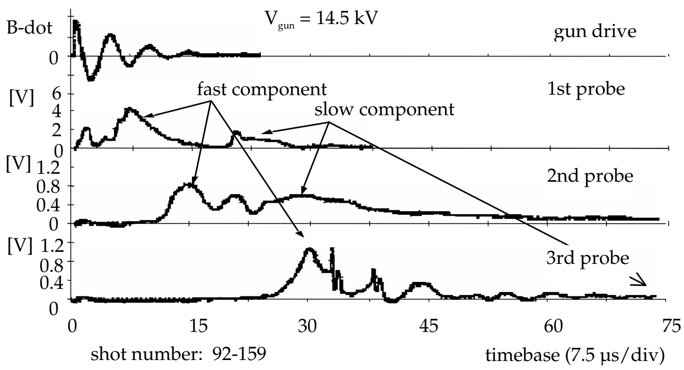

Fig. 7. Ion-flux-probe plasma-density measurement, 2 kJ capacitor gun drive, 14.5 kV charging voltage, plasma densities of fast and slow component at the plasma cathode layer were 1.35×10^{13} cm^{-3} and 1.59×10^{13} cm^{-3} . Top trace: B-dot sensor (loop sensor) that measures the time rate-of-change of a magnetic field generated by the plasma-gun-discharge-current.

delay, a short of the A-K gap appeared in 4 to 5 μs after firing the plasma gun. The first probe at that moment indicated the first peak of the fast plasma component (shown in Fig. 7). The oscilloscope trace of the first probe shows that there is still plasma entering the extraction region from the plasma gun after the diode short.

It should be possible to increase the electron beam duration if the A-K gap short is avoided. However, the technical problems of the effect of chamber walls and an innovative design of the collimator should be solved. Those changes could possibly improve the longitudinal drift of the plasma and the stationarity in space when no electric field is present in the cold cathode layer. These simple ion probes would provide a correct indication of experimental trend.

5 Conclusion

This research investigation presents a plasma density and plasma velocity measurement using plasma ion probes. The new data were taken, for the first time, with the 2 kJ plasma gun drive. The surface-flashover plasma source produces a plasma cathode layer with an electron density of the order of 10^{13} cm^{-3}. This plasma density is needed for a 100 A/cm^2 electron beam of 4.71 cm^2. Larger area electron beams (42.7 cm^2) encounters more significant experimental obstacles. For example, the cathode plasma layer would close faster under electron extraction (electric field). Experiments found that the 0.1 kJ plasma gun drive produces sufficient dense (and stable) plasma of the order of 10^{12} cm^{-3}.

The velocities of plasma peaks are found to be approximately 1.4 to 5 cm/μs. The ion probes indicate a signal variance from shot-to-shot possibly due to several factors: for example, a wall effect due to small chamber geometry, or a changing current - changing surface flashover of the plasma gun. These plasma probes readings are crucial for future design improvements. These simple ion-probes are possible tools for plasma diagnostics in the vacuum system.

Acknowledgement: The research investigation has been conducted at the Pulsed Power &

Plasma Emission Laboratory in Lubbock and supported by the US Air Force Office of Scientific Research under contract No. AFOSR-87-0154, PI - Klaus W. Zieher.

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