Plasma Immersion Ion Charge State and Mass Spectrometer

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Abstract – The work is devoted to the development and investigation of a new spectrometer for the measurement of ion charge state and mass composition of a plasma based on the combination of two methods – plasma immersion ion acceleration and time-of-flight ion separation.

Ion acceleration in the spectrometer is carried out in the short-pulse mode by applying a negative bias potential to the plasma immersed drift tube. The measurement of the ion current at the end of the tube using time-of-flight ions separation must be done after the bias potential pulse termination.

The investigations of the ion charge state were carried out using a DC vacuum-arc Ti metal plasma.

It is experimentally shown that the application of a negative bias potential with a pulse amplitude of more than 1.5 kV and duration in the range from 50 to 1000 ns allows measuring the spectra with good charge state and mass resolution for various plasma concentrations and drift tube lengths from 0.5 to 0.9 m.

The spectrometer is noted for the design simplicity and compactness. It can be used for ion charge state and mass composition investigation in the wide range of concentration of most periodic table metal element plasmas.

1. Introduction

Numerous recent investigations showed, that for technological use of plasma streams and ion beams generated using these streams it is necessary to know not only their traditional parameters (namely density, average energy), but also specific ones, which contribute to the interaction of the stream with the target.

There exist various methods of defining the charge state, such as time-of-flight method, based on the tangential ions deflection [1]; single pole magnetic spectrometer [2]; the method of inhibit grids [3]; Thomson spectrometer [3].

In this work the new approach to the time-of-flight method is described, which is based on the plasma immersion ions acceleration in the quasi planar plasma filled diode in the longitudinal direction and their consequent registration with a Faraday cup, placed at a certain distance from the diode gap. In this paper the spectrometer operation principle, several conditions influence on the spectrometer resolution and some experimental results, obtained with generated by DC vacuum arc plasma are presented.

2. Spectrometer operation principle

The spectrometer can be used for measuring ion charge state and mass structure in different kinds of plasmas, both gas plasma obtained by gas discharge (glow discharge, arc discharge with heated cathode, RF and microwave discharge, *etc.*) and metal plasma, obtained by spark or arc discharge, or target surface ablation under the impact of laser radiation or high-current ion and electron beams.

Let us consider the dc vacuum arc plasma as an example of analyzed medium to illustrate the spectrometer operation principle. As shown in Fig. 1, the vacuum arc plasma generator provided with the filter to remove microdroplets is installed coaxially with the spectrometer drift tube. The vacuum arc evaporator generates the metal plasma stream, which is directed towards the spectrometer axis. The drift tube of diameter D and length L is closed at both ends by the fine-structure metal grid. At the exit of the drift tube, with a vacuum gap, the Faraday cup registering the ion current is installed. At the entrance into the drift tube, at the distance d, an additional grounded grid is placed.

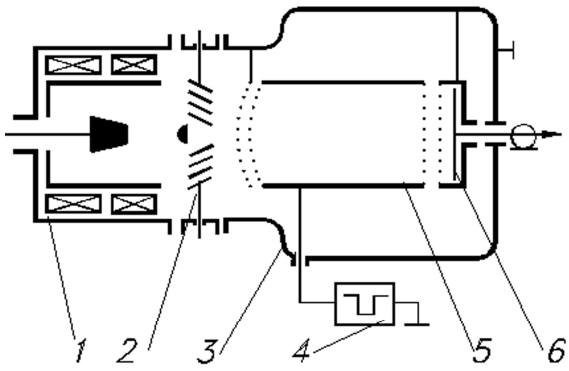

Fig. 1. The schematic of the time-of-flight spectrometer: 1 – Vacuum arc plasma generator, 2– Plasma filter, 3 – Vacuum chamber, 4– pulse generator, 5 – drift tube, 6 – Faraday cup

In case of dc vacuum arc discharge, the drift tube, initially, is immersed into the plasma. When a negative bias voltage pulse is applied to the drift tube, the accelerating gap formation near the grid installed at the tube input begins. It is possible to divide this process into the two time stages.

At the first stage, the accelerating gap formation occurs due to fast leaving of plasma electrons that creates the double layer screening the negative potential of the grid. The time of the double layer formation is determined by the plasma electron frequency and does not exceed a nanosecond. At the initial moment, ions in the gap are distributed uniformly over its length. This means that crossing the accelerating gap, ions gain different energies depending on their initial position within the gap. During ion acceleration, the profile of their concentration across the gap changes, and the gap widens. Since the accelerating gap widening is a dynamical process, ever increasing numbers of plasma ions turn out under such conditions that the energy they gain approaching the grid of the drift tube is $W<ZeU$. Thus, till the moment of spatial stabilization of the plasma emissive boundary, a polyenergetic ion flow will be formed at the entrance into the drift tube, with energies ranged from the initial ions energy T_i to $W=ZeU$. Stabilization of the plasma emissive boundary is achieved in two ways.

In the absence of the additional electrode near the input grid of the drift tube as well as in the case of the distance between the grids is greater than the gap formed, the location of the emissive boundary is determined from Child-Langmuir law accounting for partial compensation of the ion space charge by secondary electrons. The secondary electrons are emitted from the end grid as a result of ion-electron emission. If the grounded grid near the end grid of the drift tube is present, and the distance between the grids is less than the accelerating gap determined from Child-Langmuir condition, then stabilization of the plasma emissive boundary occurs earlier in time and is determined by the distance between the grids. This case allows for a partial decrease in the non-monoenergetic portion of ions at the entrance into the drift tube.

After that, all plasma ions will cross the entire accelerating gap and gain the energy $W=ZeU$.

When the ion beam has gone through the entrance grid, it drifts within the equipotential space of the tube. The drift tube is filled with the plasma propagating along its axis. This plasma provides neutralization of the beam space charge, thereby eliminating the energy spread of ions due to the axial space charge depression in the ion beam.

Going along the drift tube of the length L, the ion beam is separated depending on charge state and mass of ions. The time of flight for the ion with the charge state Z_i and mass m_i is:

$$t_i = \frac{L \cdot m_i^{1/2}}{(2Z_i eU)^{1/2} + m_i^{1/2} V_i}, \qquad (1)$$

where V_i is the initial velocity of the ion in the vacuum arc plasma, U is the accelerating voltage at the spectrometer, and e is the electron charge.

For a normal operation of the spectrometer, it is necessary to eliminate deceleration of ions having passed the drift tube in the gap between the Faraday cup and the drift tube exit grid. It means that parameters of the spectrometer should be chosen in such a way that its accelerating voltage pulse duration would be less than the time of flight for fastest beam ions. The issues of optimization of the spectrometer parameters will be considered along with the discussion of experimental results.

3. Experimental results and discussion

A schematic of the experimental setup is presented in Fig. 1. For ion acceleration we used a highly stable generator with the following parameters: the output voltage amplitude can be varied from 0 to −2 kV, output pulse duration – from 50 ns to 2 μs, repetition rate – up to 50 Hz. The pulse leading-edge time did not exceed 10 ns.

In different experiments, the length of the drift tube was 0.58 and 0.89 m. The ion species was determined by the material of the cathode of the vacuum arc evaporator operating in dc mode of plasma generation. The pressure in the vacuum chamber and, correspondingly, in the spectrometer drift tube was $(3–7)\cdot10^{-3}$ Pa. The ion beam current measured by the Faraday cup was averaged over 500 pulses. For registration, the oscilloscope Le Croy Wave Runner 6050A was used.

In Fig. 2, oscilloscope traces are presented for the ion current at the exit of the 0,89 m drift tube that were obtained for 400 ns accelerating voltage pulses of different voltage magnitudes. The comparison of the oscilloscope traces shows that with increasing voltage from 300 up to 1500 V, the FWHM of current pulses corresponding to ions with the same charge state gradually decreases. This evidences that the ion spectrum is influenced by scattering on residual gas atoms. At the accelerating voltage exceeding 1.5 kV, the residual gas influence is insignificant (curves 4 and 5 in Fig. 2).

Fig. 3 demonstrates the influence of the accelerating voltage pulse duration on the ion energy distribution in the spectrometer. It follows from the data of Fig. 3 that at short pulse durations, 50–150 ns, there are no ions of energy corresponding to ZeU in the spectrum. It means that the formation time for the accelerating gap with the fixed boundary of ion emission is greater than 200 ns. It is important to note that traces of current pulses for ions corresponding to low-energetic part of the spectrum coincide. This fact allowed for much better resolution of the spectrometer in two ways. In Fig. 4, *a*, oscilloscope traces of the Ti ion current obtained for two pulse durations (300 and 325 ns) are presented. The resulting curve trace is obtained by means of subtracting the ion current trace at 300 ns from the ion current trace at

325 ns. The result demonstrates the total absence of low-energetic tails in the ion spectrum and a substantial reduction of the peaks' half-width.

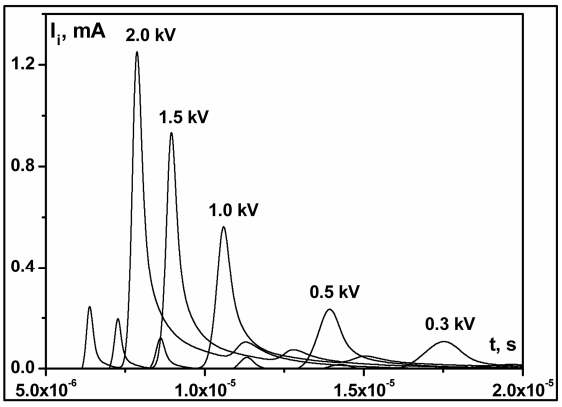

Fig. 2. The ion current for the different accelerating voltage amplitudes

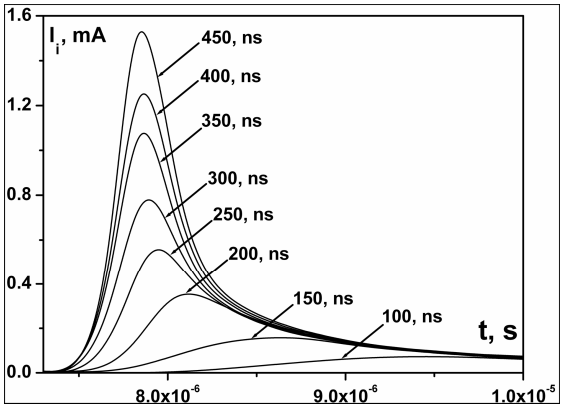

Fig. 3. The twice Ti ion charge state current peak for the different accelerating voltage pulse durations

The best results for the resolution of the time-of-flight plasma immersion ion charge state and mass spectrometer are obtained by eliminating the inductive-resistive influence of the plasma separating the drift tube entrance grid and grounded body of the vacuum installation. For that, the additional grounded grid was installed at 3 mm distance from the drift tube input grid. Dynamical variations of the accelerating gap in this case took place only before the plasma emissive boundary displaced to the grounded grid. If the accelerating voltage pulse duration was greater than the time of gap widening up to the fixed value determined by the distance between the grids, then, even at short pulse durations, the ions passing the entire potential difference and gaining the maximum energy ZeU appeared in the energetic spectrum. The ion current at the spectrometer exit obtained by the method of subtraction of pulses corresponding to 300 and 325 ns durations of the accelerating voltage is presented in Fig. 4, *c*. It follows from the data of Fig. 4, *c* that, e.g., for ions with the charge state Z=2, the current pulse FWHM is 170 ns. Taking into account the expression (1) it means that in the spectrometer, high resolution can be achieved providing the temporal resolution for the most of elements of the periodic table. In the case of gas discharge plasma, or alkaline metal plasma, the process of ion flow formation in the spectrometer will be similar. The only difference is in smaller initial energy spread of plasma ions that would even improve, possibly, the spectrometer resolution.

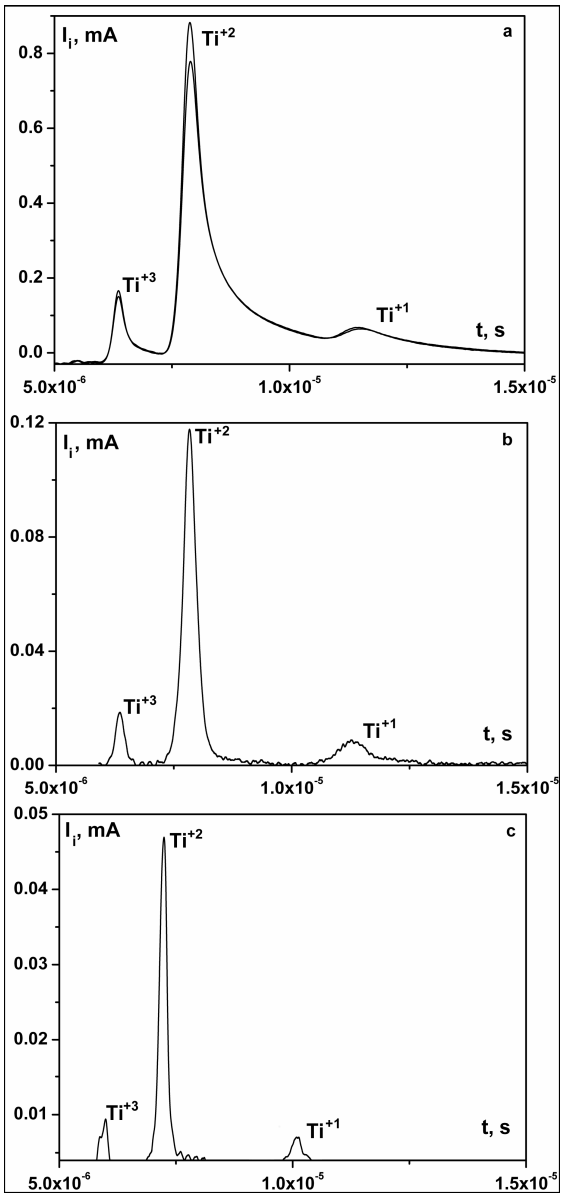

Fig. 4. The ion current for 300 (lower waveform) and 325 (upper waveform) ns accelerating pulse durations (a), and difference signals without additional grid at tube entrance (b) and for the tube with the limiting grid (c)

4. Spectrometer resolution

Spectrometer resolution is its most important characteristic and determines the area of its practical application.

Taking into consideration specific features of any spectrometer, one can distinguish a number of factors affecting the spectrometer resolution of ion charges and masses.

Let us consider different factors one after another, along with possible approaches to reducing their influence worsening the spectrometer resolution.

If the spectrometer is used for measuring charge state and mass composition of the vacuum arc plasma, whose parameters are unstable in time, it is necessary to have enough statistics of registered pulses and make quantitative estimations from averaged values in order to obtain reliable data. In this case, the half width of the resulting energy spectrum of ions will be affected by the statistical spread of the spectrometer accelerating voltage amplitude including pulse-to-pulse variations of the generator ion loading. To eliminate such influence in the spectrometer, it is necessary to employ a pulsed voltage generator with high stability and weak dependence of output voltage on the current of ion loading. In other words, the generator should be designed for a current considerably exceeding the spectrometer ion currents.

An important factor influencing on the spectrometer resolution is also the residual pressure in the vacuum chamber. Residual or reactive gas used in technologies affects ions scattering at their transportation in the spectrometer drift tube that finally results in widening peaks of the current oscilloscope traces registered by the Faraday cup. The experimental data obtained for different vacuum conditions ($7 \cdot 10^{-3}$ and $3 \cdot 10^{-3}$ Pa) show, that the ion signal FWHM decreases from 750 to 600 ns. This fact indicates the improvement of the spectrometer resolution with decreasing residual gas pressure.

So, if the spectrometer is employed for measuring the charge state and mass composition of plasmas produced by various methods, the possibility of improving the vacuum conditions in the spectrometer drift tube, e.g., by means of additional pumping, should be provided.

Evidently, the final resolution of the spectrometer depends also on the initial energy spread of ions in plasma. For instance, when analyzing the vacuum arc plasma propagating along the spectrometer axis, one should take into account that the ions' energy spread in the plasma is several tens eV [2]. In order to reduce the influence of the initial energy spread of ions on the spectrometer resolution, the accelerating voltage $U >> \bar{W}/Ze$ should be used, where $\bar{W}$ is the mean energy of the directed motion of ions in the vacuum arc plasma. In fact, that means the bias potential $U < -1$ kV is required to be applied to the drift tube.

It is important to take into account the possibility of one more factor's influence on the spectrometer resolution. The energy spectrum can change during the high current ion beam transport in the drift tube due to the influence of the longitudinal beam self space charge fields. In case of revealing the influence of this factor on the spectrometer resolution, it is necessary to use additionally a system of ion beam charge neutralization in the drift tube (for example – heated wires), or decrease the ion beam current at the drift tube entrance down to the value, at which the ion beam self space charge electric fields do not produce longitudinal drop potentials comparable to the ion accelerating potential.

At last, for optimization of the spectrometer resolution, it is important to account for the system geometry. At the drift tube of length L and the entrance grid of diameter D, the ions energy spectrum at the drift tube exit will spread to about $D/L \cdot 100$ %. It is conditioned by the fact that ion optics allows for ion motion in the drift tube both parallel to the axis and at the angle $\alpha \approx D/L$. The influence of this factor can be reduced by means of the beam collimation or the increase of the bias potential applied to the drift tube.

5. Conclusion

The time-of-flight plasma immersion ion charge state and mass spectrometer features simple design and high reliability and allows for high resolution in charge state and mass structure of any plasma.

References

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