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Losses of ion energy in the multicomponent beam

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Abstract. Energy losses of near axis ions and decreases in ion current density in the center of a beam were observed in a liquid metal source operating under a charged nanodroplets (In, Sn, Au, Ge) generation regime. In experiments, nanodroplets with the sizes of 2–20 nanometers and a characteristic specific charge of 5×10^4 C/kg were revealed. Energy spectra of ions were defined by means of the filter of speeds with cross-section static electromagnetic fields. A reduction of 4% of the In^+ ions energy was observed under the conditions of the curried out measurements. The stream of nanoparticles, in contrast to an ion beam, has a small radial divergence; outside of this stream, change of ion speeds is not observed. Energy losses of ions occur during their flight through small nanoparticles. Penetration depth of the accelerated ions in liquid indium is estimated within the framework of the Lindhard-Scharff-Schiott model. Similar interaction between components occurs in ion-beam systems of complex composition where there is a relative movement of various charged particles.

1 Introduction

Energy losses of the accelerated ions occur, for example, during the interaction of beams with plasma and with a solid state surface. In the case of plasma, the model of Coulomb collisions is applied to the definition of energy losses [1]. The results of these calculations correspond well to experimental results. At movement of the accelerated ions through the condensed substance, their non-elastic collisions with electrons and elastic collisions with nuclei of atoms [2] are considered. At low ion energy, their penetration depth in substance up to a complete stop is determined mainly by interaction with the nuclei. Evolution of distribution function of ions also occurs inside beams with a high concentration of particles. Cross-section scattering of ion energy grows under action of fluctuated electric fields and as a consequence, brightness of beams decreases [3]. It is observed in experiments that Coulomb collisions between negative hydrogen ions result in loss of a part of a beam current [4].

Collisions can occur between various fragments of the beam at their relative movement also. A similar situation applies to various types of mass – analyzers during separation of ion beams of complex composition. Energy losses of ions in the liquid metal ion source in the present work are considered. Under certain conditions in such sources, ions and charged nanodroplets are generated which can be deposited on a solid surface. This is of interest for the formation various quantum structures.

2 Experiment

The compact ion source of container type (Fig. 1) was used for creation of the beams [5]. The working substance (Sn, In, Au, Ge, eutectics BNiAl) with the moistened needle (W, Fe, Ni) was located in the graphite container which was warmed up from the rear by electron bombardment up to melting temperature of the working substance. The ion accelerating voltage was measured directly between a needle and an extractor, i.e. after limiting resistance. The beam composition and energy spectra of ions were defined by means of the analyzer with crossed fields (such as the Vine's filter of velocities). The mass-analyzer could be moved with respect to a beam axis on two cross-section coordinates by means of micrometric screws without infringement of vacuum. Spectra of oscillations of a beam current were registered by analyzer S4-25 with a range of frequencies up to 60 MHs. Distribution of an ion current density on a beam radius was defined with the help a small size multichannel probe. The measuring system was calibrated with the help of standard devices, and physical measurements repeated for the accumulation of the statistical data.

The experimental system was mounted on the basis of vacuum installation A 700-Q Leybold-Heraeus with limiting vacuum of 5×10^{-6} Torr.

3 Results and discussion

It is known that at small ion currents, an emission from the liquid metal ion sources is stable. At a certain threshold

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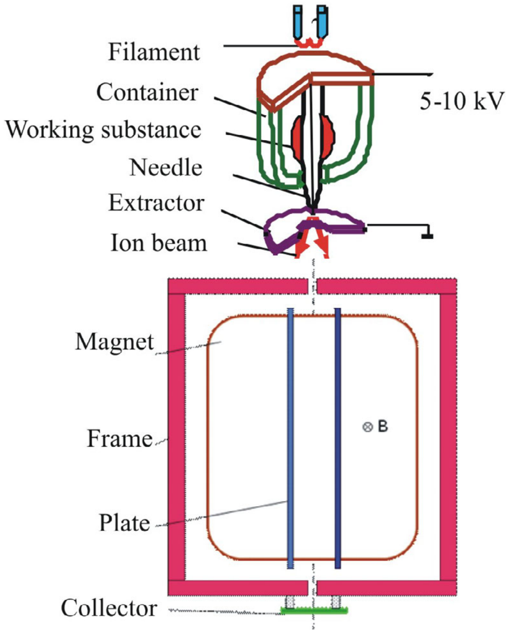

Fig. 1. The schema of experiments with liquid metal source and the filter of ion's velocities.

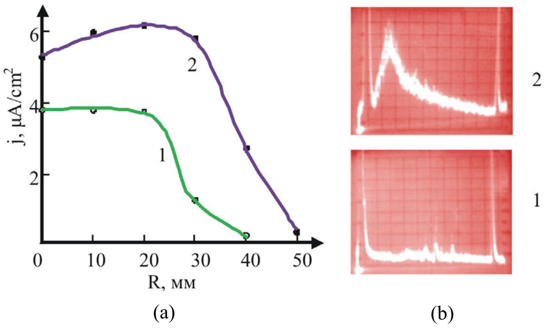

Fig. 2. (a) Radial distribution of the ion current density; (b) oscillograms of beam current fluctuations; 1 – beam current $I_b = 38$ μA, 2 – $I_b = 65$ μA.

current of a beam (about 40 μA), high-frequency oscillations are excited that is accompanied by the generation of charged nanodroplets of size 2–20 nanometers and a specific charge $q/m = 5 \times 10^4$ C/kg (In, Sn) [5,6]. The distribution of nanodroplets in the sizes is described by decreasing exponential function; the quantity of particles of the minimal size exceeds on 3 orders of magnitude the number of particles of the maximal size. Estimations show, that on average one elementary charge is necessary for 16 atoms of nanodroplet.

Oscillations of a beam current are caused by development of capillary instability of a Taylor cone on whose surface the system of standing waves is established. The discrete form of a spectrum of oscillations is caused by it. In experiments it was revealed that during excitation of the emitter instability, the ion current density in the beam center is a slightly reduced in comparison with periphery of a beam (Fig. 2). Energy spectra of ions, which were reproduced at retention of experimental conditions, were measured in the beam center (Fig. 3a) and outside of its axis (Fig. 3b). The last was achieved by moving of the mass – analyzer across a beam axis. Spectra are obtained in two regimes: without and with nanoparticle generation (curve 1, $I_b = 30$ μA and curve 2, $I_b = 50$ μA, respectively). Electric field intensity in the analyzer of 140.5 V/cm corresponds to ions with an energy of 6 keV.

It is necessary to note, that the position of an entrance crack of the analyzer concerning a beam axis was adjusted so that the maximum of a passing current was reached at a potential difference between the plates, equal to the calculated value. The position of the analyzer did not vary with the observation of charged nanodroplets. Also the spectrum of energy of two-atom ions In_2^+ in a regime of nanoparticle generation (Fig. 3c) was observed. Apparently on Figure 3, with the generation of nanoparticles, a maximum of a spectrum in the beam center shift aside smaller energy on 250 eV and outside of a beam axis, maximum shift aside the greater energy. The last shows that for increase in a beam current, U_b extraction voltage increase is necessary. It is known, that charged nanoparticles in liquid metal ion sources extend in the form of a beam with a divergence angle of only 3–4° (divergence of an ion beam is up to 90°) [7]. An absence of delay of the ions moving outside of a beam axis (Fig. 3b) indicates that reduction of energy of ions occurs due to them interacting with charged nanodroplets during extending along a system axis. The relative velocity of ions and nanodroplets is equal to $0.75v_i$, where v_i – velocity of ions, under the conditions of our experiments. Interaction of ions with nanodroplets occurs at between a needle and the entrance to the mass – analyzer (a distance of about 10 mm). Further, the magnetic field of the analyzer separates various components of a beam.

At field emission of ions, Raleigh instability of the extended liquid jet is excited which ends with a separation of nanodroplets [8]. Duration of instability development is defined by expression

$$t = \frac{1}{2\gamma_m}\left(\ln\frac{\sigma}{Tk_{\min}} + 2\ln\frac{\upsilon k_{\min}^2}{\gamma_m}\right), \tag{1}$$

where σ is the factor of surface tension; γ_m is the maximal increment of the linear theory; T is the temperature of a liquid; $k_{\min}$ is the wave number corresponding to a increment maximum; υ is factor of kinematic viscosity. Calculations of disrupter time under this formula give a value of about $t = 10^{-10}$ s. During this time an early formed nanoparticle will travel a distance of 2.45 μm. Then for the total number of nanoparticles in a stream on which the ion dissipates during flight up to an entrance in the analyzer, we shall obtain a value near $N = 10^4$ particles in a cylinder with a radius of 130 μm and a height of 10 mm.

Penetration depth of the accelerated ions in the condensed substance is considered in the theory of Coulomb collisions with electrons and nuclei of atoms [2]. At low energy of ions their stopping is determined by elastic interaction with nuclei, and penetration depth in substance

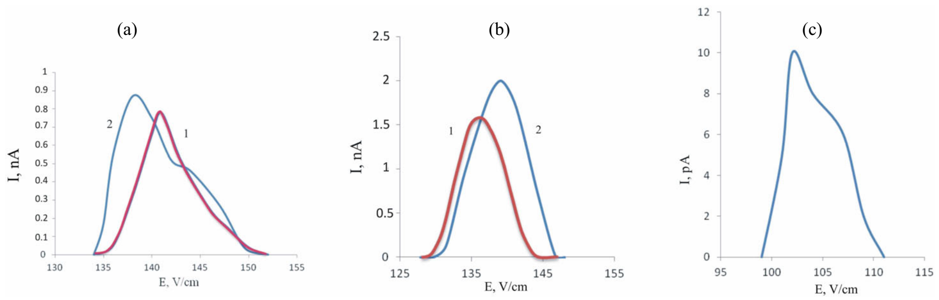

Fig. 3. Ion current through the filter of velocities as function an electric field intensity: In_1^+: $1 - I_b = 30\ \mu$A, $U = 6$ kV; $2 - I_b = 50\ \mu$A, $U = 6.2$ kV. (a) In the beam center; (b) Outside of a beam axis; (c) In_2^+: $I_b = 50\ \mu$A, $U = 6.2$ kV; in the beam center.

is estimated from expression

$$R_n = 2kE_0, \tag{2}$$

where

$$k = \frac{1.8\left(Z_1^{2/3} + Z_2^{2/3}\right)^{1/2}}{NZ_1Z_2}\frac{M_1 + M_2}{M_2}\ \mathrm{nm}\ (\mathrm{eV})^{-1};$$

Z_1, M_1 and Z_2, M_2 are the nuclear numbers and mass of a primary ion and atoms of substance accordingly; N is the concentration of atoms nm^{-3}. At $E_0 = 3.38$ keV, corresponding to relative speed of an ion for both nanoparticle $v_i - v_{np}$, and $N = 34.1\ \mathrm{nm}^{-3}$ for liquid indium, expression (2) gives a value $R_n = 1.54$ nm. Penetration depth of ions is less than the observed minimal size $d_{np} = 2$ nm of nanodroplets, therefore ions should lose all energy. However it is necessary to mean, that the probability of ion flight along diameter of a drop is much less, than along all shorter pieces.

It is known, that charged nanodroplets and clusters, incorporating up to 30 atoms, are intensively generated in liquid metal sources [9]. The size of such clusters (about 1 nanometer) is less than the calculated penetration depth of ions $R_n = 1.54$ nm in our conditions. Most likely, in order to observe of such small particles the resolution of electron microscope Tesla that we used [5] was insufficiently. Hence, ions are losing a part of their energy during passage through small nanodroplets and leave them in a initial direction.

The charging state of the fast ion past through nanodroplet, demands separate consideration. Experiments, in which the stream of the fast neutral atoms extending along an axis of a beam [10] was observed, are known. A spectrum of energy of these atoms is wide enough. It is natural to assume, that the part of near axis ions will be neutralized during flight through small nanodroplets.

Apparently on Figure 3a (curve 2), a portion of ions which posses rather high energy is present. Most likely, this group of ions was extended outside of a nanoparticle beam and did not interact with it. The similar form of a peak in an energy spectrum is observed and for two-atom ions (Fig. 3c), that testifies as to their participation in the specified processes alongside single-atom ions.

Absorption of a part of near axis ions and loss of a charge by them as a result of collisions with nanodroplets proves a reduction of a current density in the beam center (Fig. 2) [11].

4 Conclusion

In a liquid metal source there is a penetration of fast near axis ions in charged heavy nanoparticles, resulting in appreciable loss of ion energy (250 eV at initial energy of ions 6 keV). Similar processes are necessary for taking into account at precision focusing of ion beams and separation of ions in mass and energy analyzers. Measurement of spectra is necessary by means of energy analyzer and the sizes of nanoparticles by means of an electron microscope with high resolutions for correct quantitative estimations.

I.S. Gasanov has carried out a formulation of a task, the organization and participation in experiments and the spelling of the article. I.I. Gurbanov has developed and has prepared a measuring system and participated in preventive maintenance of an ion source and experiments. E.M. Akbarov participated in calibration of measuring devices, carrying out of experiments, and arrangement of measurement results.

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