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E-MEVVA - source of high charged ions. Initial data in the light of new measurements results

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E-MEVVA – SOURCE OF HIGH CHARGED IONS. INITIAL DATA IN THE LIGHT OF NEW MEASUREMENTS RESULTS: Preprint ITEP 9 – 02/

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Comparison results of the basic measurements data, carried out on the E-MEVVA ion source, created in ITEP in 1991 - 1994, with the data obtained on two new variants of the source are brought. Two new variants were developed in High Current Electronics Institute of Siberian branch of RAN in Tomsk and in ITEP in 2001. The comparison actually confirms reliability of conclusions, which were made on the basis of the first measurement results.

E-MEVVA - ИСТОЧНИК ВЫСОКОЗАРЯДНЫХ ИОНОВ. ИСХОДНЫЕ ДАННЫЕ В СВЕТЕ НОВЫХ ИЗМЕРЕНИЙ: Препринт ИТЭФ 9-02/

В.А. Баталин – М. , 2002 – 12 с.

Приводятся результаты сравнения данных основополагающих измерений, выполненных на источнике E-MEVVA, созданном в ИТЭФ в 1991 – 1994 годах, с данными, полученными на двух новых вариантах источника E-MEVVA, разработанных в Институте Сильноточной Электроники Сибирского отделения РАН в Томске и в ИТЭФ в 2001 году. Сравнение фактически подтверждает достоверность выводов сделанных на основании результатов первых измерений.

Fig. – 8, refs – 7 naims.

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To the end of 2001year the long stage of tests of the ion source E-MEVVA was finished. It was begun in 1995. E-MEVVA - the metal-vapor vacuum-arc source of high charged ions with an external electron beam and drift channel - was created in ITEP and for the first time was tested in 1992 with the copper cathode [1]. The study of its characteristics was continued in ITEP in 1993 - 1995 with the uranium cathode [2]. Since then the work on its improvement continued in ITEP, in USA (Berkeley, Brookhaven,), and since 1999, in the Institute of High Currents Electrons in Tomsk. The last development 2000 - 2001 gave new results, to which we'll come back later. And now we would like to say a few words about the initial components of all this work, how it began. On the schematic view fig.1 original components of E-MEVVA creation are shown.

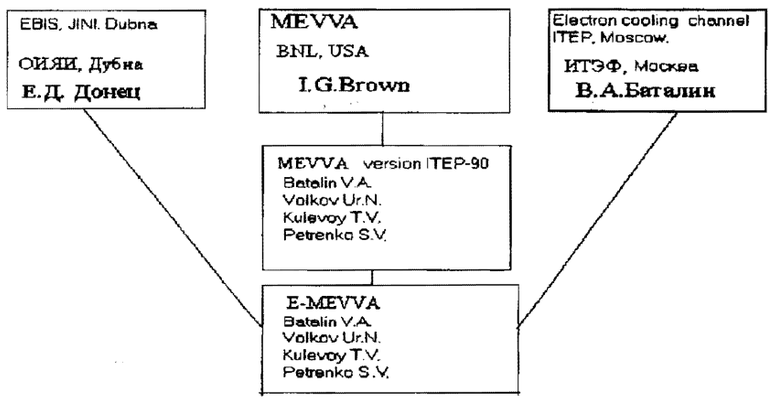

Fig.1. Schematic view of E-MEVVA original components.

First of them, the electron beam method of ionization, was offered in 1967 by E. D. Donets. [3]. It is carried out in to Laboratory High Energy in Dubna 1980 by creation of the EBIS. Idea of this method consists in following. The ions, saved in ions trap, are exposed to ionization by electron impact and are operated through a series of potentials distributions on section of the particles drift channel.

The beam of energetic electrons, which are necessary for stepwise ionization of stored ions, forms by an external electron gun. Calculate-theoretical and the experimental data on the stepwise ionization parameters (the Donets plot - dependence of the ionization factor on energy electrons and type of ions) underlie in a base of the calculation of ions ionization efficiency in the E-MEVVA drift channel.

(Ionization factor $j\tau = nv\tau = \frac{N_\tau}{\langle\sigma\rangle}$ - number of collisions in τ seconds /scattering cross section.)

Such estimations have shown that at rather high density of an electron beam current, it is possible to give satisfactory high charged ions generation without accumulation of ions in the drift channel.

One more component on E-MEVVA creation is the method of overlapping of an electron beam with ions. By the initial purpose of development of the device for such overlapping was the studying of an opportunity of a construction of the channel for linear electron cooling of a proton beam, for injection in the linear accelerator. The circuit of such channel was offered in ITEP in 1977 [4]. The experimental research of the channel was carried out in ITEP with 1985 till 1987. In experimental installation, created in ITEP for study characteristics of the channel model for the linear electron cooling, was used the gas discharge ion source - duoplasmatron - with two pulsing valves.

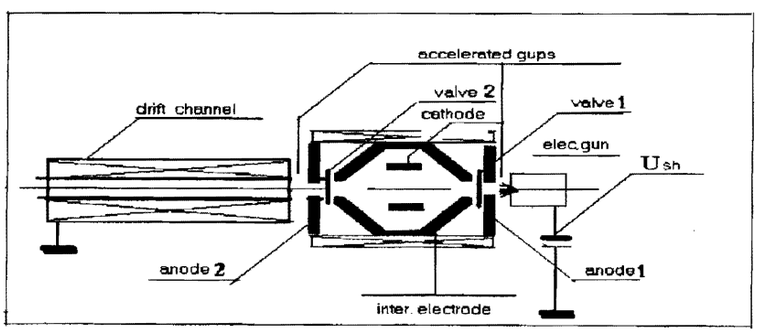

Fig.2 ITEP channel for electron cooling.

The device (fig.2) include an electron gun (EG), ion source (IS) and channel for beams overlapping, or drift channel (DCh). Thus the axis EG coincided with IS axis and DCh axis. The IS was designed in such a manner that its cathode, anode and other electrodes had axial apertures, through which it was possible to pass an

electron beam, focused and accelerated in an electron gun, supplied with the appropriate optics. By the work of such device the longitudinal average speeds of each of beams in DCh can be made equal, or distinguished on given magnitude, by suitable choice of the negative potential EG (- U_{sh}), as electrons in this device are decelerated, flying by the gap, in which ions are accelerated. If to use a gas discharge IS, an input at IS and output from the IS is necessary to supply with pulsing valves, opening only for passing both electron and ion beams, to protect EG from too high gas flow from the IS.

The rather bad propagation the EB through the DCh obtained on experience (2.5 mA from 180 mA) in our circuit was mainly connected to application of a discharge ion source. It was necessary to use two pulsing valves, (double collimate EB), and also it was a gas flow, which scatter electrons. This situation can essentially be change, if to use MEVVA - ion source, as he operates at high vacuum (without an external flow of a working gas). Thus a scattering of electrons on residual gas become much less, necessity in valves go away and appear the new opportunities for study of influence of a more intensive beam of electrons on the processes of ionization in DCh. Thus, the third component of all work on creation of the E-MEVVA source has become a metal-vapor vacuum arc (MEVVA) ion source, which was developed in 1980 in Berkeley by J. Brown. MEVVA sources successfully developed in ITEP by several groups (L. Kondratiev and M. Kaz, A. Vasiliev and the group of linear accelerators laboratory). For E-MEVVA creation the most suitable has occurred the MEVVA version ITEP-90. It was developed for the linear accelerator of heavy ions TIPr-1. In this version the ring cathode from metal was applied. For application of an external electron gun it was enough to do an axial aperture in the cathode flange of the MEVVA. On fig. 3 the schematic view of the first variant of E-MEVVA is shown.

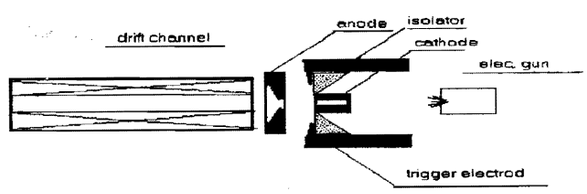

Fig.3 Schematic view of the first variant of E-MEVVA.

Here the focused and accelerated EB goes through in the cathode MEVVA aperture, goes through the ion source area and further the drift channel, where there is its the interaction with MEVVA plasma. As a result in the drift channel there are the conditions for process of stepwise ionization and by that increases the charge of

ions. The comparison fig.2 and 3 shows that the E-MEVVA circuit repeats actually the schema of the electron cooling channel.

The basic critical element of the whole of composition, which determined the success of the work, on increase ion beam charge in DCh, was the electron gun, and the main its parameter – the density of EB current. The measurements with the first electron gun, with the heated cathode and pulsing anode voltage, have shown absence of noticeable effect. Charge state distribution (CSD) of an ion beam at the of the injector output of the accelerator TIPr-1, on which measurements were carried out, did not practically depends on presence of the EB. The success has come after introduction in work so-called of the micro-plasma cathode (is offered by S.V. Petrenko) based on the semi-conductor diode (fig.4). The semi-conductor cathode, used in a source, represented the silicon diode with destroyed p/n transition, which leaving on a surface of the crystal.

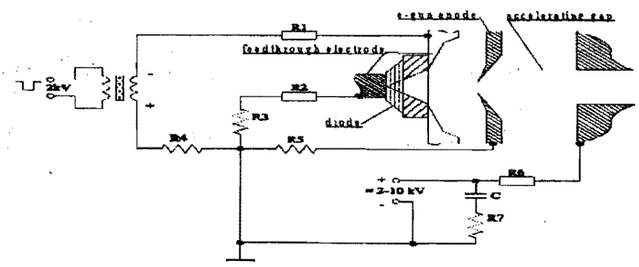

Fig.4 Electron gun with semi-conductor cathode.

Let us discuss the influence of using the semi-conductor cathode in EG fig. 5 on the E-MEVVA work.

A. Influence of an electron current on the form of the ion current pulse at the injector output

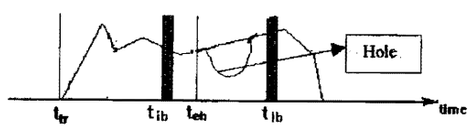

Fig.5 Ion beam current pulse at the injector output.

On fig.5 an ion beam current pulse at the injector output is shown. The time marks show possible moments for start of short ion beam for a TOF measurement and moment of the start of EB. The main effect of switching on EB consists in the appearance of **a hole** in the pulse of a total ion beam current. The duration of the hole is defined by EB duration, and the depth depends on value of the electron

current. When the electron beam goes to the drift channel he goes through the focusing system of IS. There the EB becomes decelerated and can landed on electrodes in the field of formation of an ion beam. Evidently, at a rather big EB current, the condition of optimum formation of the ion beam can be broken and the current of the beam becomes reduced, and sometimes appears the complete disappearance of all ion current at the injector output.

Б. Change in TOF spectrum.

By work of the E-MEVVA source without EB the CSD at the injector output not strongly differs from ions spectrum generated by a usual MEVVA ion source. At switching on an electron beam in ions spectrum on specific charge (or specific mass) (CSD with EB) appears the fundamental changes in TOF (time-of-flight) spectrum of a beam at the injector output. The changed spectrum occurs in the time at once after of the hole. The time of its existence is close to the time of a pulse EB. (We should like to note that to the end of an ion current pulse, the spectrum becomes restored in the initial kind, i.e. as CSD without EB). In particular, for ions of uranium these changes consist in following (fig.6).

1. Low charged ions peaks of uranium (1+, 2+, 3+) in a spectrum, disappeared or considerably decreased.

2.The additional intensive peaks in the range of specific mass (5, ...8); (10, ...15); (20, ...35) appear. It was supposed, that this effect was a result of the stepwise ionization of low charged ions, including of uranium ions, by fast electron in the drift channel and, hence, transition low charged ions in a more high charged condition.

3. Existence of the dependence the ion CSD with EB from the energy of electrons. In particular, the special interest has the value of electron energy, at which the effect of the ions spectrum "with EB" disappears. Measurements have shown, that the energy of disappearance of the effect has different magnitude for ions copper and ions of uranium. Though a change of electron energy can cause the change the EB current and its density and thus to create dependence of a CSD from energy, this effect gives the additional information, useful to an estimation of the effective EB density in DCh with the help of Donets plot.

We shall address now toward the configuration of new peaks in an ion spectrum on specific mass, with EB.

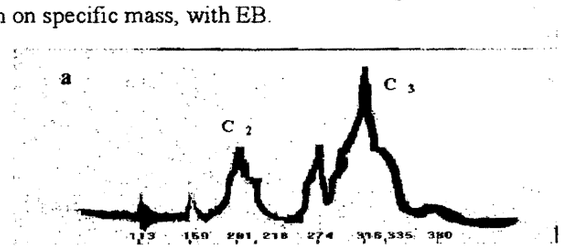

Fig.6 The part of TOF ions spectrum at the injector output.

On fig. 6 a part of TOF ions spectrum at the injector output is shown. The letter C3 designates peak, arising at switching on EB. He extend for meanings of specific mass from 20 up to 35. Here, essentially, there are the missing peaks of uranium ions (with charge 1+, 2+, 3+), which have turned into ions of uranium with charges 7+ ... 12+ (specific mass: 34, ...19,8). At the same time the resolution of TOF method, which used on the accelerator TIPr-1, does not allow to see it, as the peaks merge into one.

Thus, these results are looking insufficiently convincingly. If to suppose, that the combine peaks are ions of uranium and to estimate, with the help Donets plot, density of the EB current, capable to create ions such charge, we shall obtain value about 500 A/cm^2. Taking into account the fact, that in structure used by us for injection EB in the ion source (fig.4), the calculated density of EB current (limited by the volume charge) is very far from such value it is necessary to assume, that at the input in the IS there were the conditions for neutralization of the EB charge. Though the factor of ionization is determined by acting density of the EB current inside of the drift channel, instead of current density at the input IS, this circumstance did not add conviction to our 1994 results. Thus, as two purposes of the further activity we have directed towards the following work. First, to improve measurements of a high charged ions spectrum, namely, we have decided add to TOF measurements of an ions spectrum the magnetic its analysis and, secondly, to try to create more reliable system of an EB diagnostics.

The first magnetic analysis of the ions spectrum at the injector output (1995)

For the first attempt to carry out the magnetic analysis at the injector output the magnet analyzer was established (the parameters in table1). It was borrowed (on the short time) from the proton accelerator ISTRA-36.

Table 1. Parameters of the magnet analyzer 1995

Bending angle	60°
Bending radius	0.35 m
Entrance aperture	20 x 48 mm
Value of magnetic field range	0.006 - 1.1 T
Current range	1 - 26 A

The results of these magnetic measurements [5] unfortunately, have also appeared incomplete convincing. The comparison of spectra, obtained at the magnetic analysis in these measurements, with the former TOF measurement spectra, is given by the following results.

A) The group of combined peaks (fig.6) "C3" (20, ...35) in a TOF-spectrum degenerates in two peaks (27 - 30) and (32 -34), i.e. practically is away in the MA-spectrum.

B) But there are two groups of MA-peaks, "D" (49, ...58) and "E" and (63, ...66) [5], which never appear in TOF-spectra.

Satisfactory explanation in this case can be such fact, that in the DCh goes the process of a damage of high charged ions in the measuring channel of the magnet analyzer. The loss of high charged ions have a place as a result of recombination of these ions during passage of the measuring channel with rather bad vacuum (worse on the order than in column). In this case, because of processes of recombination, ions from group "C3", in a result of capture several electrons, pass into the groups "D" and "E". For TOF method such change in a spectrum undetectably so, as in this case, because of processes of recombination, ions from group "C3", in a result of capture several electrons, pass in the groups "D" and "E".

Table 2. Parameters of magnet analyzer 1998

Bending angle	60°
Bending radius	0.3 m
Entrance aperture	20 x 48 mm
Value of magnetic field range	0.1 - 1.3 T
Step of measurements	3.10^{-4} T

The following cycle of magnetic measurements of ions spectrum was made with another magnet analyzer established on the injector output in 1998. The spectrum on specific charge of the ion beam was this time measured with the help of the magnet analyzer, the parameters of which are given in table 2. At the input of the magnet analyzer the pair of vertical slits with width of 2 mm and distance between them 180 mm were established. Taking into account experience of the previous measurements, we have supplied this magnet analyzer with the own high vacuum pump. The measurements of ions spectra of usual MEVVA have shown very good resolution of the spectrometer (so, were separated the copper isotopes). It is necessary to note that was the satisfactory vacuum in the chamber of the magnet. So only a few re-charged ions in spectra were detected. Unfortunately, this magnet analyzer has not enough good sensitivity, so makes the data, which we have obtained a few poor. In particular, for this reason detailed measurements of the ion spectrum for the original variant of E-MEVVA were not made. We consider this circumstance as the miscalculation in our work.

Improvement of the electron gun design and development of methods of EB diagnostics

The least stable unit of the first design E-MEVVA was the electron gun, its cathode is more correctly. The cathode, chiefly, responsible for a instability of the work of the whole device. Except instability, us oppressed the unpredictability of properties of the cathode, as at replacement of one cathode on to other, and at the operation of each of them. Therefore during the improvement design of E- MEVVA,as soon as

the work of the electron gun was started, the first work was the study of properties of cathodes. For study EB parameters was built the test bench, the circuit is at fig.7.

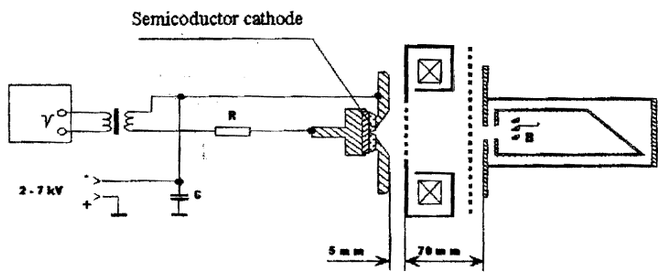

Fig.7. The circuit of the test bench for study of EB parameters.

The measurements were carried out at rather high vacuum, so gas focusing was not be able, i.e. the opportunity of neutralization of an electron flow by ions in result of ionization of gas, was excluded.

In table 3 are parameters of an electron gun with the semi-conductor cathode and basic characteristics EB at the best case, i.e. for exemplars of the cathode which show efficient work. We pay attention to the small diameter of the aperture in the anode, it prove the rather high density of the beam current at the output of the anode. However, the unpredictable properties of the cathode of this type is not resolved up to now.

Table 3. Parameters of an electron gun with the semi-conductor cathode and basic characteristics EB

Parameters	Range of values	Optimal value
Geometrical parameters		
Semiconductor hole diameter	0,1 - 1 mm	
Gap semiconductor-anode (mm)	2-4	2
Anode aperture (mm)	1-2	1
Extractor aperture (mm)	2	
Accelerating gap (mm)	30	
Cathode flange hole diameter (mm)	20	
Power supply of cathode block		
Voltage (V)	300-1000	300
Current (A) Duration (μsec)	5 - 100 10	5
Electron beam parameters		
Current (A)	2 - 30	
Accelerating potential (-kV)	2 - 15	5-7
Duration of beam pulse (μsec)	10	

Except the semi-conductor cathode, the cathode of plasma and the fiber cathodes both were tested. The quite satisfactory results, as the stability of work, so and the predictability of properties, were obtained for the plasma cathodes.

On fig. 8 is shown an electron gun with the plasma cathode. The discharge is between the metal electrode and expander and is supported by the discharge on the anode, how it takes place in a source MEVVA. Detailed measurements of an ion spectrum for E-MEVVA with such gun was not made. We shall note only the fact that the very important effect -the hole in an ion current at the injector output - was observed during work of the injector with this type of cathode.

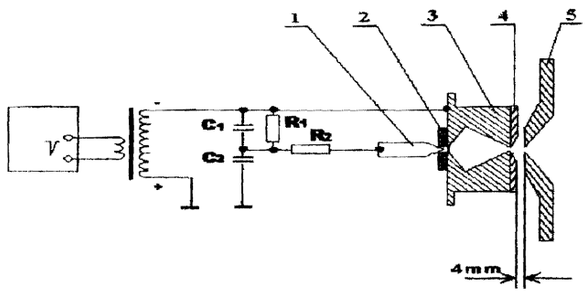

Fig.8 Electron gun with plasma cathode. 1-metallic electrode, 2- isolator, 3-expander, 4- diaphragm, 5-anode.

We shall address now to results of development of methods the diagnostics EB. We note, that the size and the form of the hole (fig.5) are the indirect certificate about parameters EB. The total EB current from the electron gun was measured by three ways: (1) By a Rogovsky belt in a circuit of the accelerating voltage supply. (2) E-current collector as the Faraday cup. (3) With the help of the time of the discharge from the storage capacitor, which are feeding the accelerating voltage. The reliable agreement between the results of these methods of measurement at the test bench is not fixed. It is necessary to consider the third method as the preferable to the checking of the E-MEVVA work. This method, except measurement of a current, more than others, gives the additional information. So, on the experience, at the injector, three types of the storage capacitor discharge were observed.

A) The duration of the discharge of the capacitor is 1-2 μs and does not depend on a EB current. Breakdown of the gap.

B) The duration of the discharge of the capacitor exceeds considerably duration of the EB current. It means, that the EB current is accompanied by the dependent gas discharge. In this case the gas focusing EB is possible.

C) The duration of the discharge of capacity corresponds to duration of the EB current. Gas focusing is not present.

The additional information on EB parameters is given by measurement of a EB current at the injector output for two cases: (1) MEVVA - is switched on, and (2) MEVVA - is switched off. The substantial growth of the EB current at MEVVA switching on was proved about the focusing of an e-beam in the drift channel.

New variant of E-MEVVA design

The main defects of the first design of E-MEVVA [1] was recognized the following parameters: (a) large distance from the anode of the electron gun up to the input in the axial MEVVA aperture (>10см); (b) the magnetic field in DCh is not big enough. Besides it was recognized useful to have an external magnetic field in the MEVVA area. In the new design the electron gun come nearer to the input MEVVA, so the its distance now is 4 cm.

In comparison with former, the new structure of the generator of plasma (MEVVA) is here applied. The new solenoid of the drift channel (SDC) in a pulsing mode is capable to give the induction of a magnetic field along an axis of the drift channel up to 1,3 T. The solenoid E-MEVVA (SeM), which create an axial magnetic field in area of the generator of plasma (induction up to 0,4 T) is established also.

We shall come back later to work of ITEP group and now a few words about achievement on development of the E-MEVVA method in other laboratories. Very successfully and very hopeful for future development of the method were works on creation of the source Z-MEVVA in BNL under management of A.Hershcovitch. Just of his energy and enthusiasm we are obliged to interaction of three laboratories and, in as a result, successful result of this stage of work on E-MEVVA. One more group, under management of E.Oks, was studying opportunities of the method in High Current Electronics Institute, in Tomsk. The measurements in Tomsk, carried out on the developed there variant E-MEVVA, have much add to the results obtained in ITEP and besides have added reliability to all the results on the source of high charged ions, E-MEVVA [6].

The variant E-MEVVA, developed in Tomsk [7] in comparison with first ITEP variant differs by a more powerful electron gun with the plasma cathode. (Current EB - up to 100 A, anode voltage - up to 20 kV, duration of the pulse - 200 ms). In this design there is not a separate channel of drift. The drift of plasma occurs inside the anode MEVVA in length of 40 cm. The measurements were carried out on specially for this purpose created the test bench, which was supplied by the equipment for TOF measurements with high resolution. The effect of appreciable influence EB on ion spectral structure of a beam was obtained after careful vacuum training, at a current EB about 40 A. And the results consist in following:

1.The analysis of their data shows us, that as well as in ITEP, the effect of inclusion EB **appear of the hole** in a pulse the total ion beam current. The duration of the hole corresponds to duration of the EB, and the depth depends on the magnitude of an electron current.

2. There are the changes in TOF ions spectrum. The work of the source without EB give the spectrum at the source output not strongly differs from ions spectrum generated

by a usual source MEVVA. With EB in ions spectrum on specific charge (or specific mass) appear the essential changes in TOF spectrum of a beam on the source output.

The changed spectrum occurs in time after hole. The time of its existence is close time of a pulse EB. In a spectrum disappear or considerably reduce peaks, appropriate the most-low charged ions of metal used in MEVVA. There are the additional intensive peaks in area higher charged ions. Besides, influence neutralization of EB is noticeable, without which it is impossible to explain magnitude of obtained density of a EB current.

We see almost exact confirmation of characteristics of the effect with EB for the variant E-MEVVA in Tomsk with the ITEP variant E-MEVVA, with one, very essential addition. Before, it was possible only, to assume, hat the effect of occurrence of new peaks was a consequence of the stepwise ionization low charged of ions of metal by fast electrons in the channel of drift and, hence, transition low charged ions in more high charged condition. In Tomsk, the additional peaks in TOF ion spectrum of a beam were well permitted, and they have no doubt is more high charged ions of the given metal.

In Tomsk the ion spectrum of lead was obtained by work of the stand without EB and with EB. We see for a case with EB essential reduction of intensity of peaks (1+, 2+) and occurrence of new peaks (3+, 4+, 5+, 6+, 7+). The measurements in Tomsk were made yet for ions of the following metals: Bi, Sm, Sn, In and Cd.

The results are given in tab. 4.

Table 4

The source		E- MEVVA								MEVVA				
	z	1	2	3	4	5	6	7	Q	1	2	3	Q	Coef..
Cd	48	20	42	24	11	2			2.32	44	56		1.6	1.5
In	49	22	39	25	11	<1			2.31	42	56	2.3	1.4	1.44
Sn	50	5	52	21	16	5	<1		2.65	19	76	5.1	1.4	1.42
Sm	62	0	45	49	12	3			2.74	0	67	33	1.2	1.18
Pb	82	11	18	23	28	14	5	2.5	3.40	19	81		1.8	1.88
Bi	83	1.5	21	35	25	11	4	1.5	3.44	58	42		1.4	2.42

The following step was made already in ITEP. It consists in measurement of the ions spectrum of the lead ions on the magnet analyzer for the combination: the Tomsk electron gun and new ITEP source MEVVA with the new drift channel, for work injector with EB and without EB. Unfortunately, for detection of an effect of charge increasing, it was necessary to have high resolution of spectrometer. The result is shown on fig. 12, where we see almost complete disappearance of peak 2+ and obvious appearance of rather effective peak 4+ during the work of EB. We shall note, that the maximum charge 4+, against 7+ in Tomsk, is connected with the fact that current EB here was 20 A, while in Tomsk it was 40 A. Such reduction maximum charge corresponds to change of the factor of ionization. Thus the opportunity of generation high charged ions of metal on the device similar E-MEVVA is proved, as by TOF measurement, so and by magnetic analysis of ions spectrum.

Conclusion

As any ion source, E-MEVVA is intended for work on accelerators, or on installations for implantation of ions, or for other applications. The given condition of this device not yet allows using he for such purposes. Constructive defects don't allow the unreliable and stable its work. We see the problem in creation of the reliable, operational variant of E-MEVVA.

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