# NON-PROPULSIVE APPLICATION OF THE TAL TECHNOLOGY

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## ABSTRACT

The range of operating parameters and the various modes of operation of the ion sources created on the basis of accelerators with an anode layer are considered. The design of sources generating axial and radial beams of ions with energy between 100-3000 V are described. An application of devices with "vacuum" anode layer are discussed. The method of thin film deposition from low-energy ion-beams in retarding anode layer is offered.

## INTRODUCTION

One of the major "spin-off" results, accompanying the development of Electric Propulsion, is the creation of plasma accelerators and ion sources for application in industrial technological processes and other areas of engineering.

Since the early 60's sources of ions and plasmas were successfully applied for ion beam sputtering of materials with the purpose of drawing coverings, ion etching and clearing of surfaces, ion placing in process of thin film deposition, plasmachemical synthesis of complex structure, ion implantation etc. [1-3].

The technology of accelerators with an anode layer, actively developed in TSNIIMASH for use in advanced electric propulsion systems [4,5], has a lot of specific peculiarities, which make its rather attractive for non-propulsive applications also.

The most obvious field of application, which accelerators with anode layer can find besides propulsion systems is ion-beam technology.

The list of the typical requirements for application of ion sources in industrial processes can be formulated as follows: adjustable energy of ions in a range $10^1$-$10^3$ V; ion current density on a target from 0.1 up to 20 mA/cm$^2$; an opportunity of uniform processing of surfaces up to 100 cm$^2$; high cleanliness (absence of impurities) of ion beam, rather small mass flow rates of working substance, caused by low pumping speed of usual technological facilities, etc.

In comparison with electrostatic ion sources, generating broad high-energy beams of low density [6], it is possible to create, using Hall-current accelerators, much more dense ion flows at rather low energy of particles on a target.

We shall note, that as well as in ion electrostatic sources in ion sources with anode layer, various working substances - evaporated metals, inert gases [7-9], chemically active substances can be applied . A list of propellants that were practically tested includes H2, He, Li, N2, O2, Ne, Ar, Kr, Xe, Cs, Ba, Cd, Tl, Pb, Bi, CH4, SiH4, mixes of various gases with air, and others.

As the formation of an ion beam in ion sources with an anode layer comes true in a short accelerating gap, the ion sputtering of walls of the discharge chamber is rather unsignificant, that allows to lower to a minimum quantity of impurities in a beam. The new opportunities on creation of beams of high cleanliness are opened with use in technological processes of microaccelerators with an external anode layer [10], where the direct interaction of ions with elements of a design is practically excluded.

In a general case for creation of ion sources., a design approach repeating a number of characteristic features inherent to the TAL engine can be used.

However, the specified limit on pumping speed in technological facilities limits the application of sources with habitual "propulsive" configuration to devices of very small size. Proceeding from a reasonable value of neutral density , which is necessary to ensure effective ionization of the working substance, as argon,

in the discharge chamber of a Hall ion source, its size should not exceed 20-40 mm.

## ION SOURCES WITH ANODE LAYER

The single-stage ion source T-27, created in TSNIIMASH for ion assisting during drawing optical layers, has an average diameter of the working channel of 27 mm.

The ion source operates with inert gases consuming the mass flow rates of 0.5-2 mg/s at discharge voltages of 100 - 400 V (for Xenon - up to 600 V). This source allows ion beams with currents up to 0,5 - 1 A at the distance of 20 cm from a source exit plane. Research efforts that were made to operate the T-27 on a argon-xenon mixture and air-xenon mixture at the volumetric xenon content of 15-25 %, are partially submitted in paper [7]. Small impurityes of rather easily ionized xenon to relatively hard ionized gases allow appreciably to increase efficiency of ionization in a source and to form beams with the 70 % content of the basic substance ions.

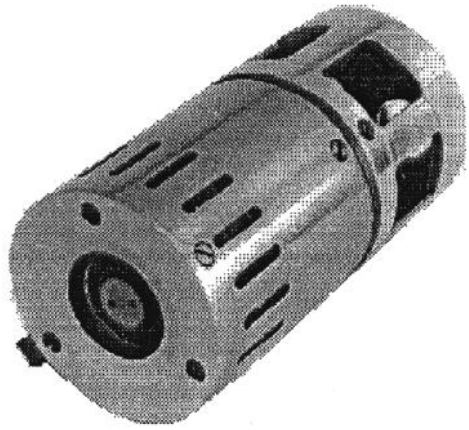


Fig.1. Ion Accelerater D-20

In Fig. 1 the other ion source created in TSNIIMASH on the basis of the accelerator D-20 (average diameter of the channel about 20 mm) is represented.Range of working parameters of this device operated with xenon or argon is illustrated on Fig.2. The operation of this source with one-stage, or two-stage circuits of the power supply is allowed.

The size and weight of a 3-cm electrostatic ion source manufactured by the Commonwelth Scientific Corporation [11,12] were taken as a targeted mass-dimensional parameters for designing the D-20. The comparative analysis of working parameters of these two devices, that have identical geometrical sizes, shows on identical range of ion energy and beam current in D-20, and accordingly, a ion current density on a target surface can be increased by the order of magnitude.

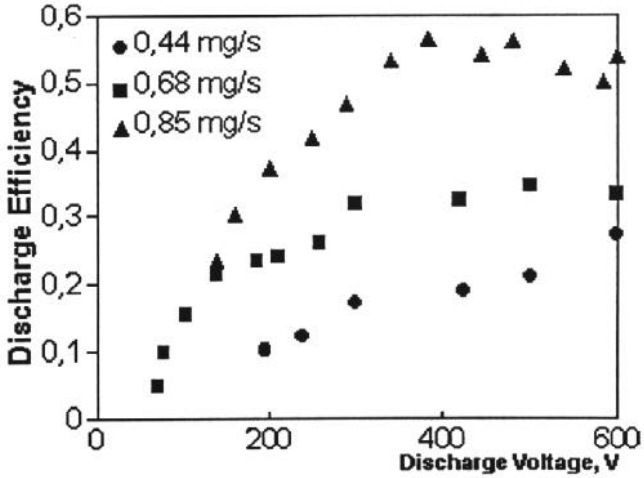



Fig.2. Discharge Efficiency of the D-20 vs Discharge Voltage

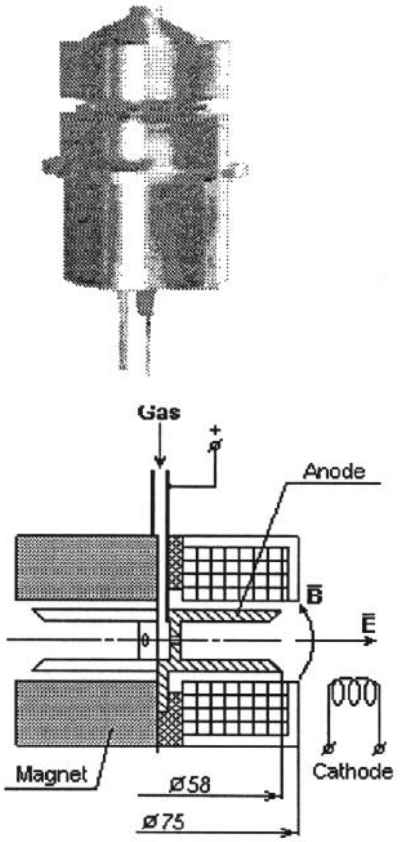
It is characteristic, that even at a discharge current of 0.3 A, the discharge thrust efficiency of a source is more than 30 %. That confirms the high degree of ionization and acceleration efficiency. The gas mass flow rate through. (The cathode was not taken into account). For technological processes, the duration of which does not exceed several tens of hours a very simple design of hollow cathode with a replaceable $LaB_6$ insert was developed. Thus the characteristic mass flow rate of gas (Xe) through the cathode does not exceed 0.1 mg/s. The D-20 has a completely radiative cooled design. If necessary it can be easily installed on water-cooled assembly flange.

In a general case the configuration of ion sources with anode layer can be various. The Hall drift current can be closed as around a direction of acceleration of ions, and around a direction of a magnetic field.

Obviously, alongside with devices, generating tubular or converging axial beams, ion sources such as "ion magnetron" can be created with a beam, radially expanding in an angle of 2 $\pi$. Similar sources can be applied, for example, to uniform processing of internal cylindrical surfaces, details as a tape, etc. By installation around a source of the screen with diaphragm of necessary form it is possible to receive one or several wedge-similar beams.

The examples of radial ion sources created and tested in TSNIIMASH are shown in Fig.3 and 4.

The single-stage radial accelerator shown in Fig.3 has an independent magnetic system, with




hollow anode installed inside it.

Fig.3. Single-stage radial Ion sourse

Ion source generates radial beams of ions of inert gases with currents up to 3,5A in a range of a applied voltage of 200 - 400 V.

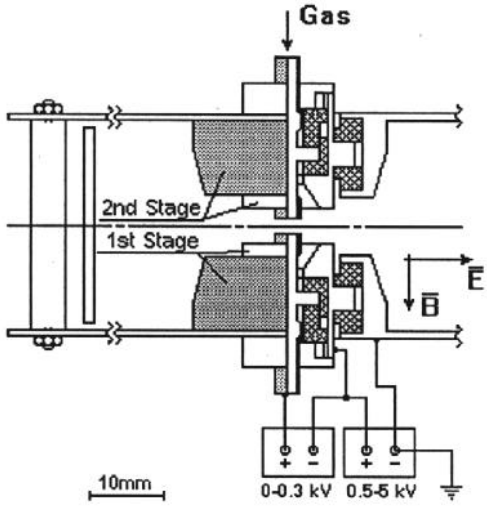



Fig.4. Two-stage radial Ion sourse

The two-stage ion source, shown on Fig. 4 is intended for use in the vacuum chamber, supplied with external magnetic system from permanent magnets or Helmholtz coils ensuring strong magnetic field along it axis . (Similar configuration of the device was used in early works performed by Yerofeev and Lyapin for study of ion generation in the anode layer, however bismuth was used as working substance [13].

At xenon mass flow rates of 0.3 - 0.7 mg/s the source provides ion beam current in a range 0,2-0,6 A with ions energy from 1 up to 3,5 keV. I-V curves obtained for this device, distribution of a ion current on height of a beam and also the ion energy distribution obtained at a distance (radius) 20 sm are presented on Fig. 5 and 6.

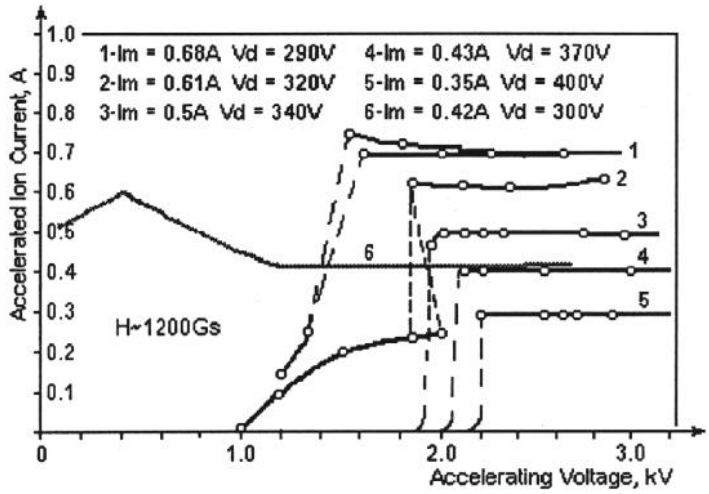



Fig.5 CV curves of two-stage radial ion sourse

At accelerating voltages higher than 1,5 kV operation without a cathode is possible. The space charge compensation occurs automatically at the expense of ionization of residual gas in the chamber or electron emission from walls.

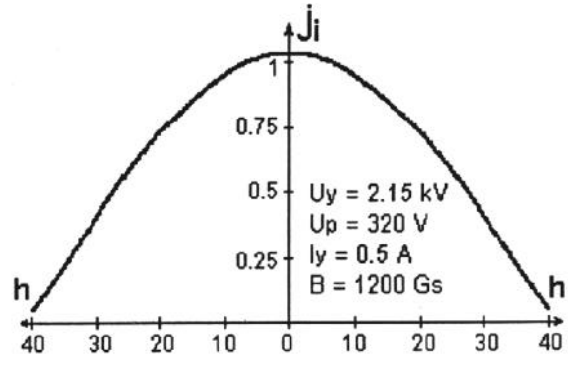



Fig.6. Ion current density distribution

At a value of magnetic field of 1 kGs the discharge voltage required for efficient ionization in the first step of a source shown in Fig. 4 makes about 300 V. Initial disorder of ions energy in the first stage determines final homogenity of the beam.

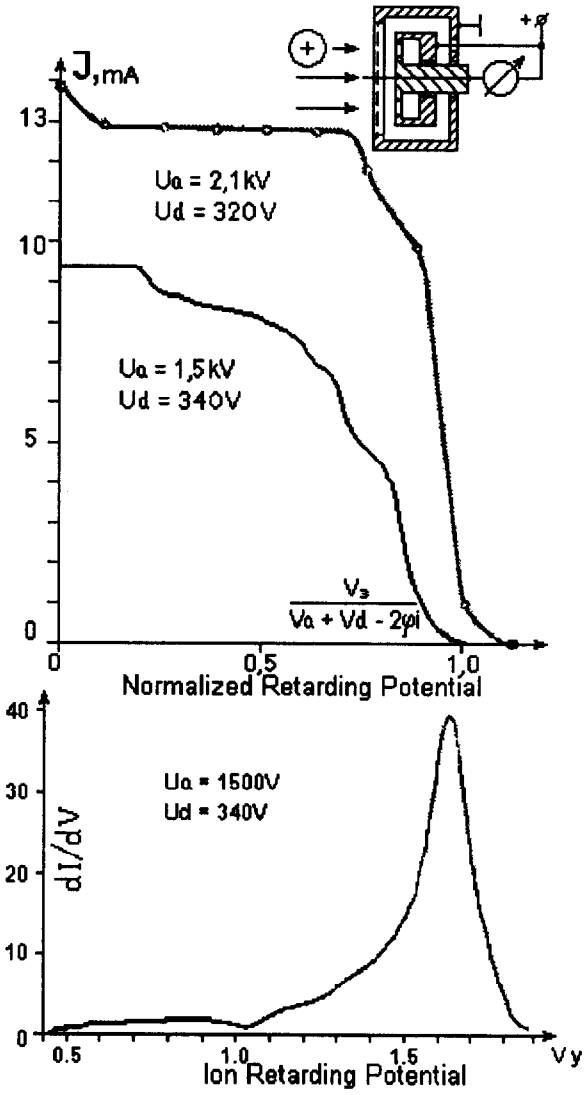



Fig.7. Parameters of the Two-stage Ion Sourse Beam

It is necessary to note, that the specified design of the two-stage accelerator allows the use other types of discharges for preliminary generation of ions. The presence of an external magnetic field, allows the opportunity to incorporate naturally into the first stage a UHF ECR discharge.

## "VACUUM MODE" OF ExH DISCHARGE WITH ANODE LAYER

The "anode layer", used in TAL for acceleration of ions, is the natural form of the gas discharge arising in crossed ExH fields near to a positive electrode at presence of azimuthally-homogeneous conditions in a direction of drift current. Along a magnetic field the discharge is usually bounded by surfaces under the cathode potential. At gas pressure of $10^{-9}$ - $10^{-3}$ Torr, magnetic field about 1 kGs and voltage more than 1 kV in the specified conditions a so-called "vacuum mode" of the discharge with closed Hall current [14] is realized which also sometimes has name of Penning discharge with the cold cathode. The discharge current is proportional to pressure (this law is already used in vacuum gauges of pressure) and grows voltage and magnetic field. Density of ions in such devices is much less than density of electrons.
So, this mode differs from quasineutral mode of Hall current devices operation [15].

Despite low probability of ionization a vacuum discharge with anode layer can be used for generation of rather intensive beams.
Yet in the 70's in in the former USSR under the management of Prof.Yu. Maishev the ion-beam sources of a "Radikal", "Louch", "Kholodock"[16-18], distinguished only by a configuration of the discharge chamber and style of electron current drift closing, were created on these principles. In these sources for increase of probability of ionization of working substance, special measures on increase of neutral density directly in a zone of the ExH discharge are undertaken. The submission of working substance from the anode, as a rule, is not applied. During ion source operation a great portion of working substance due to a gas back flow from the vacuum chamber is actively used.
According to the theory developed for TAL the average energy of ions in such conditions makes about 30 % from an applied voltage and the disorder of ions energy in a beam is rather significant [19].
Nevertheless at voltage range of 1 - 7 eV it is possible to obtain density of ion current up to 5 -10 mA/sm$^2$. The sources of the specified type, despite rather low gas utilization efficiency and low power efficiency, are successfully applied for sputtering of conducting and dielectric surfaces, homogeneous (95-98 %) ion etching of

semi-conductor structures and elements of integrated optics [18].

For increases of average energy of ions of hard-ionized gases in a beam it is possible to use in accelerator with anode layer, operated in vacuum mode, additional stage for preliminary ionization of working substance and to submit gas from the anode. At limited pumping speed in the vacuum chamber, applying of pulsing feed system of the gas submission can help to achieve increases of neutral density in the E×H discharge. Such a two-stage accelerator with anode layer with pulsing gas feed system was applied, for example, to creation of quasystationary flows of a helium and argon in experiments on imitation of interaction of plasma thermonuclear fusion reactor with materials of the first wall [20].

Finishing this section it is necessary to tell about the accelerator with a vacuum Hall current, created by Prof. A.V. Zharinov in the early 60's for acceleration of wedge-similar ion beams.

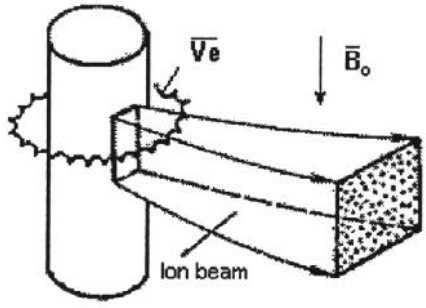



Fig.8. Accelerator with "vacuum detour"

In Fig. 8, taken from Ref. 21, scheme of acceleration of a limited ion beam extracted from a slot discharge source by an electrical field of the vacuum anode layer, non-uniform in drift direction, is shown.

At accelerating voltage more than 10 kV and magnetic field close to 1kGs it was possible to form beams of heavy ions with density of ion current up to 100 mA/sm$^2$ [21].

## ION BEAMS BRAKING IN ANODE LAYER

It is known, that the density of thin film deposited directly from accelerated ion flows has a maximum, coming nearer or superior parameters of firm substance only at certain values of the ion energy $\varepsilon_i$ (50-70 eV for $Pb^+$, 48 eV for $Mg^+$, etc.) [3,22]. Excess of this limit results in growth of the contents in a less dense phase because of accumulation of vacancies in an irradiated material. Therefore the development of methods of ion deposition with energy $10 < \varepsilon_i < 100$ eV from beams of high density $j > 10$ mA/cm$^2$ is desived.

The jump of potential, concentrated in an anode layer can be used for acceleration by an electrical field of ions, moving from high-voltage border of a layer and for braking of ions, coming with the return side.

The external ion beam, directed on some surface, surrounded by vacuum anode layer will be slowed down by a counter electrical field.

Thus, it is not required to carry out preliminary division of electric charges. As is shown in [23], the systems with a retarding anode layer can be used, for example, for recuperation of energy of the ion beams generated by electric propulsion. The energy of ions overcoming a potential barrier, should accordingly decrease on value of $e\varphi$, where $\varphi$ is potential of a surface perceiving a beam.

Thus, it is possible to adjust energy of ions, changing the voltage of the vacuum discharge with anode layer.

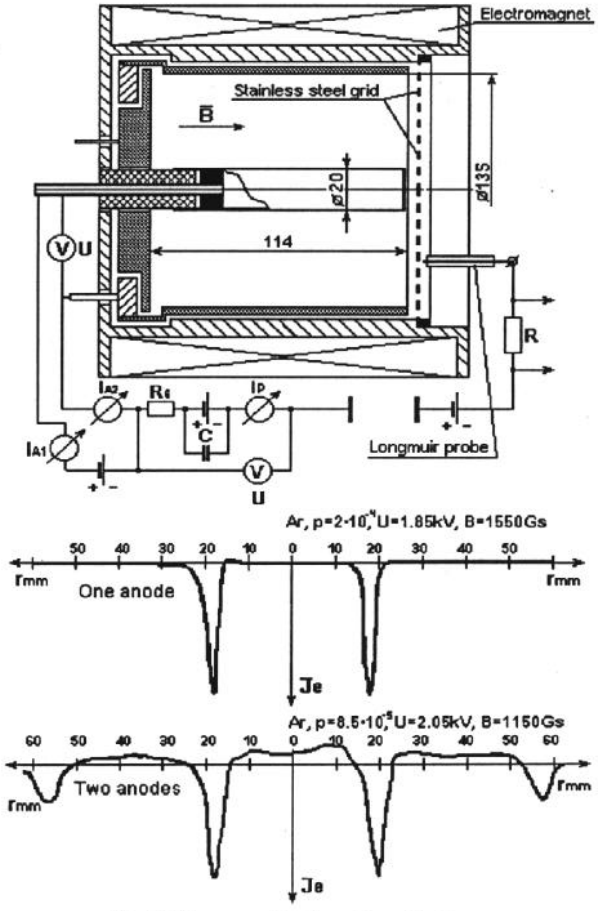



Fig.9. Two anode Penning device

On the specified principle the device for thin film deposition from low-energy ion beams can be also constructed.

In the first approximation, maximum density of an ion flow in a retarding anode layer can be expressed as

$$j_i \le 2\pi e(j_{i2}/\nu_i)^2 / MiVi$$

where $j_{i2}$ - density of secondary ions, formed in the anode layer itself at the expense of ionisation collisions of electrons with atoms of residial gas with frequency $\nu_i$.

If desired the processes of formation and braking of an ion beam can be combined in one device. In Fig.10 a configuration of the device with two coaxial anodes is shown, the surfaces of which are oriented precisely along a strong magnetic field, created by an external solenoid. At pressures less $10^{-4}$ Torr, and magnetic field about 1 kGs there are two independent anode layers, divided by an ion-drift space. The border of location of an anode layers can conditionally be identified with peaks in distribution of a longitudinal electron current, on disks with cathode potential (Fig.9). One of disks is made of a grid from stainless steel. The electron current was measured by Langmuir probe, located near the grid and moving on radius of the device.

To replace the internal anode of the device, shown on Fig. 9 with an radial ion source as shown in Fig.4, it is possible, to carry out acceleration and braking of ions in a uniform system with a cross magnetic field.

The possible resulting configuration of the device for thin film deposition from beams with controlled ion energy is shown on Fig.10. Also other constructive decisions are essentially possible.

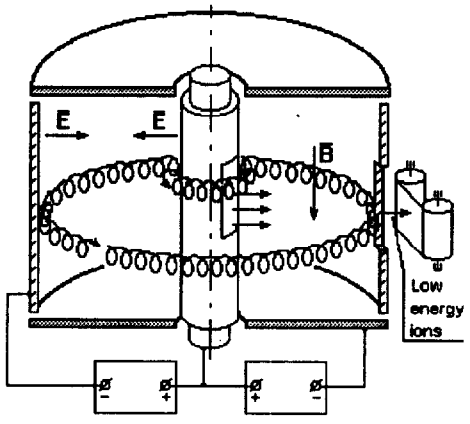



Fig.10. Device for low energy ion beam forming

## THE CONCLUSION

The various updatings of ion sources on the basis of accelerators with an anode layer give rather ample opportunities at the choice of working parameters: ion current density, energy of ions, working substance and configuration of ion beams. The development of ion sources for industrial application can be carried out by use of uniform physical representations about properties of the ExH discharge with anode layer.

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