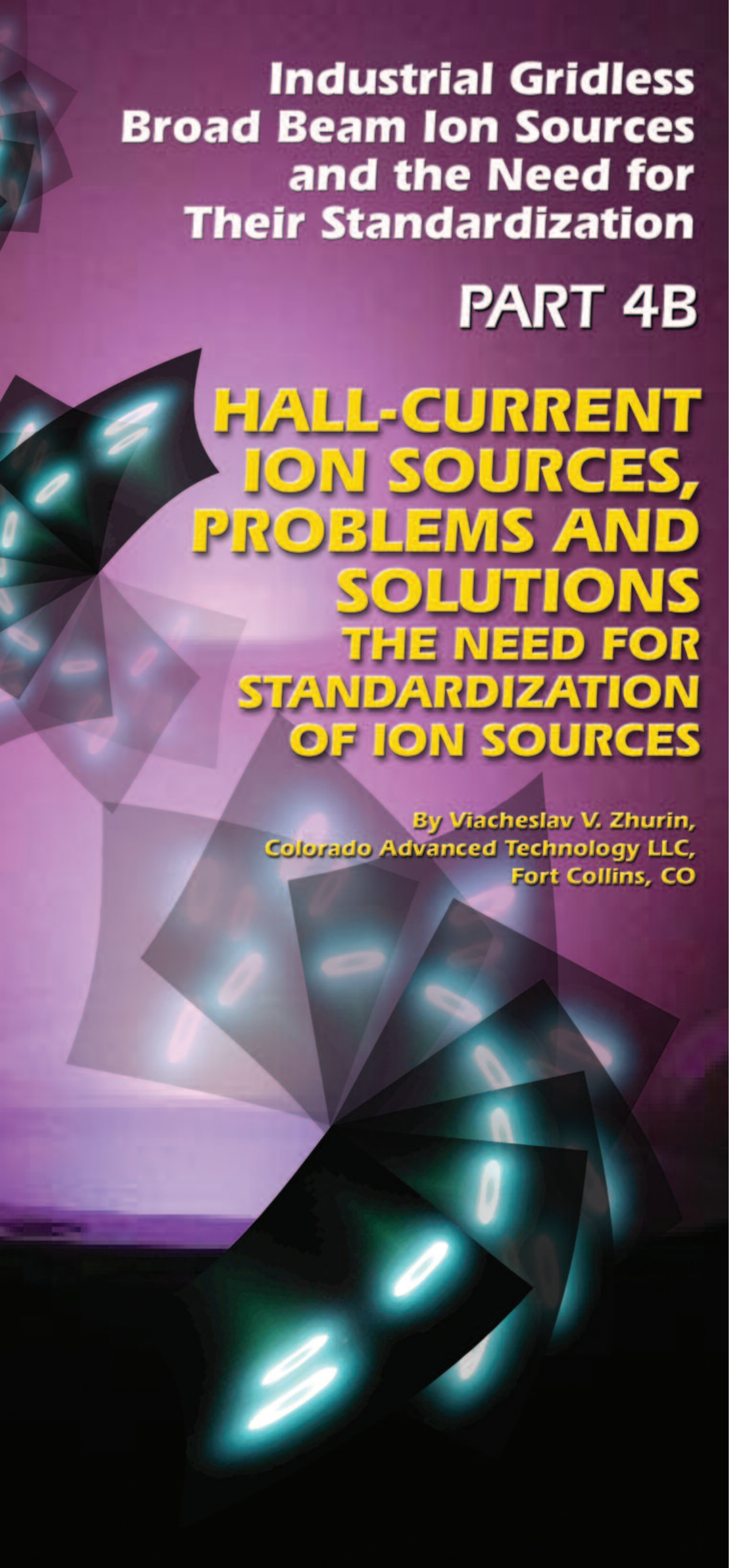

Industrial Gridless Broad Beam Ion Sources and the Need for Their Standardization

PART 4B

HALL-CURRENT ION SOURCES, PROBLEMS AND SOLUTIONS

THE NEED FOR STANDARDIZATION OF ION SOURCES

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This article “Industrial Gridles Broad Beam Ion Sources ...” consists of 4 parts. Part 1, published in the April 2009 issue of *VT&C* consisted of the “Introduction” and “Closed Drift Ion Sources. Part 2 published in the May 2009 issue is "End-Hall Ion Sources”. Part 3A published in August 2009 issue is “Non-Traditional Ion Sources”. Part 3B published in September 2009 issue is “Linear Broad Beam Ion Sources”. Part 4A published in October 2009 issue is “Hall-Current Ion Sources Basic Problems, Solutions”. And Part 4B of this November issue covers the rest of”Hall-Current Ion Sources Basic Problems and Solutions” and “The Need for Standardization of Ion Sources”.

6. Ion beam is quite divergent.

Ion beam is quite divergent for the end-Hall type ion sources with the angle of about 60°; for the Closed Drift ion sources with a cathode-neutralizer it is about 40° [*Since there are not so many known Closed Drift ion sources, but there is quite a number of universities and companies working with closed drift thrusters; the closed drift thrusters divergence was studied in details with many particular designs.].

For the end-Hall ion source, the ion beam divergence depends on the conical anode angle, the external magnetic pole placement, the magnetic field values and configuration in the discharge channel, which are quite similar for most existing designs, except the hybrid end-Hall [34], the working gas ionization potential and its mass, the discharge conditions. The ion beam divergence is determined by efficiency of ions acceleration in the discharge channel; such efficiency is determined by a variety of factors, some of which were discussed in [56] and these and other factors are presented in **Table 6.3.**

For those who are interested in practical modifications of a quite divergent ion beam coming from Hall-current ion sources, especially from end-Hall type, it is necessary to inform that there are known and tested ways how to provide ion sources

Table 6.3. Factors reducing efficiency of ions acceleration, influence on ion beam divergence.

Factors reducing efficiency of ions acceleration	Caused by	Leads to
1. Ions azimuthal rotation	Non-uniformity of radial magnetic field lines; light working materials; low velocities (energies)	Ion beam divergence for certain angle
2. Ion-optical aberrations	Imperfectness of BE-layer focusing	Defocusing of ion beam
3. Edge effects on ion beam boundary	Jumps of electric potential	Ion beam divergence Transitions from regular to vacuum regime for ALIS
4. Azimuthal non-uniformity of BE-discharge	Non-uniform working gas supply, ion beam current fluctuations; magnetic field azimuthal non-uniformity	Wide spread of ion beam energy
5. Non-uniformity of ion generation Over BE-layer length	Discharge channel finite length	Wide spread of ion beam energy distribution.
6. Reversed electron current	Plasma instabilities, anomalous electrical conductivity	Excessive erosion of gas distributor - reflector

with the certain plasma optical devices that are capable to focus, or defocus an ion beam coming out ion source and apply controlled ion beam over small (few square millimeters) and large areas (over a thousand square centimeters). Description of a simple plasma optical system that can be very useful for control of ion beam divergence was published in several articles by well-known Russian scientist A.I. Morozov, a father of a Closed Drift Thruster-Ion Source concept with a positive mag- netic gradient [76].

In fact, an ion beam from end-Hall of Mark-2 dimensions can be focused by a magnetic coil of moderate dimensions. An electric potential from about 10 to 100 V have to be applied to a coil's electrically conductive body and ion beam of 100 mm diameter becomes focused to about 1-2 mm diameter. The plasma lens' focusing distance can be just few centimeters, and in comparison with a regular electrostatic lens it is about 100 times shorter. In **Figure 36** [76] there is shown a concept for utilization of an electrostatic plasma lens that was successfully tested in experiments [77]. [*The plasma optical methods for ion beam control will be discussed in details in one of our further publications in *VT&C*.] In other words, it is possible to control an ion beam current density over investigated area. The only problem is it necessary to use any efforts in complication with additional coil, and applied electrical potential. However, all these additions such as magnetic coil and power supplies are quite simple and inexpensive.

7. Ion beam contamination produced by a neutralizer.

The major cathode-neutralizer with Hall-current ion sources of cylindrical geometry is a Hot Filament (HF). Ion beam coming out of the end-Hall ion source using a Tungsten HF neutralizer contains a certain amount of Tungsten particles, because it evaporates due to high temperature, and due to its ion bombardment. In the case of the requirement for high ion beam purity, it is necessary to undertake specific measures for preventing such contamination. The methods for reducing ion beam contamination from a HF material include:

a) finding optimum placement (distance) of a HF from an ion source's exit flange with minimum HF wire sputtering by ion beam;

b) finding an ion source's optimum operation conditions (if these conditions will be also acceptable for the process) with minimum erosion of a HF wire;

c) proper screening of a HF radiation from a target [*The HF configurations will be discussed in our further publications, in particular with "Cathodes Neutralizers for Ion Sources], and finally,

d) utilization of a Hollow Cathode (HC) that produces less contaminating particles than a HF by the order of value at the same ion source operation conditions.

8. Excessive radiation power from a Hot Filament.

Another shortcoming associated with the HF utilization is, for certain processes, an excessive radiation power coming from a HF, besides the ion beam radiation itself. Here are some estimations. The typical discharge current of a HF is about 20-25 A with the discharge voltage of 20-25 V. Thus, the additional radiation power coming from an ion source into a target or substrate is increased by about 400-600 W, which is too high in comparison with a HC (at $I_d \approx 5$-7 A maximum and $V_d \approx 20$-25 V) of about 100-125 W. So, if an ion source operates at the discharge current of about $I_d \approx 5$ A and the discharge voltage of about $V_d \approx 100$-150 V (typical optimum operation

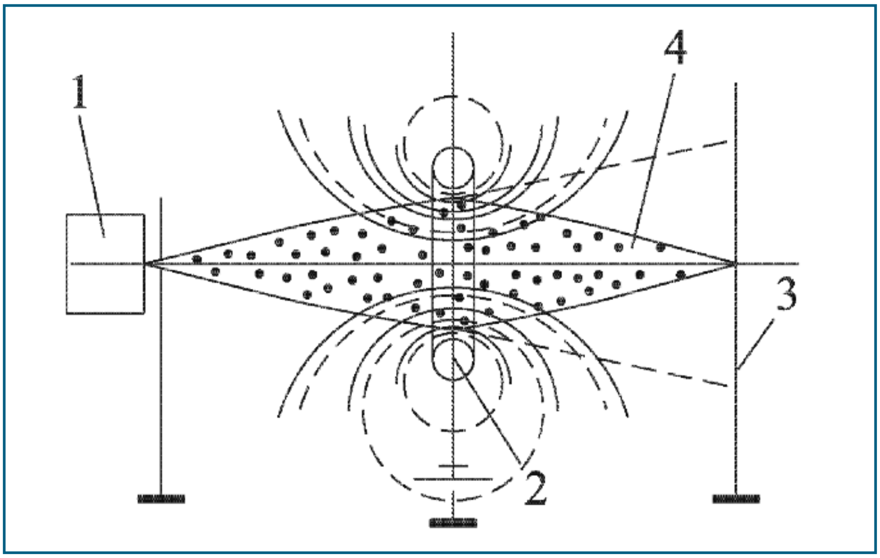

Figure 36. Electrostatic plasma lens: 1 – ion source with neutralized ion beam; 2 – magnetic coil combined with electrode; 3 – target; 4 – focused ion beam.

characteristics of the end-Hall ion sources), the electric power applied into discharge is about 500-750 W. It means that a power applied into a HF can be comparable with a power applied into the discharge channel. In such a case, for some sensitive to the radiation heat thin film depositions it is necessary to place an ion source at the distance that would be not harmful for a processing object. And moving a target from an ion source reduces an ion beam current that, in general, decreases from an ion source as square of a distance, or $I_i = I_o r_o^2/r^2$ (where I_o is ion beam current at an ion source's exit plane) and most thin film processes need a high ion beam current possible to provide necessary effect. It means that the radiation and the proper ion beam current must be optimized for each particular thin film deposition tasks where the targets or substrates are sensitive to excessive radiation.

Of course, the best solution for reducing excessive radiation from a HF is the utilization of a Hollow Cathode neutralizer. Unfortunately, the Hollow Cathodes do not have such wide utilization as Hot Filaments, because of the HC complexity and the need to have a more complex Power Supply. Also, the HC for some users is not only complex and capricious, but expensive.

9. Erosion of end-Hall discharge channel and other parts.

In most end-Hall ion sources designs the working gas is applied into a discharge channel through the holes in a gas distributor-reflector under a conical hollow anode bottom part (see **Part 2**, **Figure 6b**). The reflector is placed between anode and a permanent magnet (in **Figure 7a** of **Part 2** one can see the reflector 216 and the magnet 204) and it also serves as a shield between hot ionized plasma consisting of high energy ions and low energy electrons supplied by a cathode made of a Hot Filament, or a Hollow Cathode. The reflector-shield protects the permanent magnet from over-heating and direct impact from plasma. The developed in a discharge channel an ion beam is "supposed" to be propagating to an ion source's exit, but a certain part of an ion beam flows into the opposite direction, into the reflector's surface.

Reflector usually after about 20-25 hours of operation at moderate discharge currents of about 4-5 A and over and at regularly used "optimum discharge voltages" (providing high ion beam current) of $V_d = 100$-150 V [*End-Hall Mark-II and EH-1000, the major "work-horses" of industrial ion sources, have a maximum ion beam current value at about 100-125 V, and Oxygen ion beam current for these ion sources is higher than Argon's ion beam current by about 15-20% at the same discharge current and voltage.] becomes sputtered in its central part and eventually eroded through into a quite substantial hole of several millimeters diameter, so it is necessary to substitute such reflector with a new one.

In all well developed end-Hall ion sources the reflector is under a floating potential, because as theoretical estimations and experiments have shown, if the reflector is at anode potential, the reflector's erosion is substantially higher than with the floating one. During the ion source operation a floating reflector becomes positively charged at about $0.5V_d$ (depending on distance between anode and reflector). And it is certainly not supposed to be connected to the ground as some developers do, because, in such a case, discharge would have a short way from anode to the ground.

Some users of end-Hall ion sources that experience the problem of reflector's sputtering are trying to reduce the reflector's damage with theirs own means (special reflector's design), or to make reflector's eroded parts easier and convenient to replace. One of users even received a US patent [69], in which it is described (**Figure 37**) the substitution of a reflector's 32 eroded part 36 with an insert 34 of about 1.8 cm in diameter that can be placed in a reflector's central part.

After a certain time of operation, and a visible inspection, this insert during a vacuum chamber opening is substituted for a new one through an ion source opened top with tweezers, or a similar instrument. Such substitution certainly makes sense, especially if one wants to utilize a reflector's central eroded part with an expensive material like Tantalum, or Molybdenum-Rhenium alloy, Hafnium, etc that could be compatible with the thin film deposition process (for example, obtaining Ti_2O_5 thin film depositions).

This patent also shows how serious the problem with the reflector's erosion. However, the manipulation with the reflector's part described in the patent does not reduce the reflector's erosion, and this problem remains unsolved.

For those users who need comparatively "clean" ion beam of a working gas here are some numbers obtained from experiments about the quantitative values of erosion of a HF, reflector and other ion source's parts impact on ion beam purity. A HF evapo-

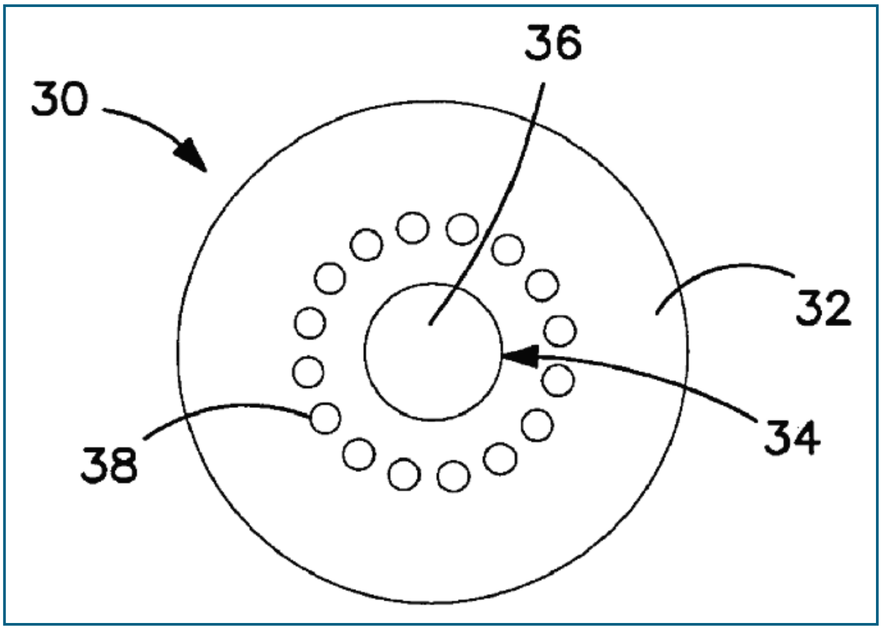

Figure 37. Typical reflector of end-Hall Mark-2 [69]: 30 – general view; 32 – reflector's surface; 34 – groove for substitution of the central part 36; 38 – gas distributor's holes

rates during the operation at the end-Hall ion source optimum parameters ($I_d \approx$ 5-7 A, $V_d \approx$ 100-150 V) and applied powers of about 700-1000 W with the rate of about $\xi = (2\text{-}3) \cdot 10^{-5}$ g/s; at the same time the stainless steel reflector's erosion exceeds this number by a factor of 5-10, or $\xi = (1\text{-}3) \cdot 10^{-4}$ g/s. The reflectors made of graphite erode less than stainless steel by a factor of 3, or $\xi = (3\text{-}6) \cdot 10^{-5}$ g/s. Unfortunately, the graphite reflectors can be used only with the noble gases. These numbers are not exact values for every end-Hall; they give rather relative values depending on each particular design and operational conditions (I_d, V_d, working gas, magnetic system, discharge channel design, etc).

About having "clean" ion beam without contaminations. There are no such ion sources that can deliver an ion beam free of contaminations. However, it is possible to reduce such contaminations by using optimized designs of ion sources and operational conditions. In **Table 6.4** there are given major sources of an ion beam contamination.

The reflector's erosion problem became quite known to many users, because of not only ion beam contamination (some processes tolerate such contaminations), but the reflector's erosion sometime leads to an ion beam complete penetration through the reflector and it erodes and ruins the magnet. In some cases, it is necessary to stop the process, to disassemble the ion source and to substitute for the new reflector.

Erosion of a Hollow Cathode keeper aperture brings another source of ion beam contamination. However, according to work [70] with hollow cathodes for the Stationary Plasma Thrusters (SPT) (also used in ion sources as magnetic layer Closed Drift devices) the erosion of the Molybdenum keeper is about $\xi = (2.5\text{-}3) \cdot 10^{-8}$ g/s (spectroscopic and mass loss measurements) for the discharge current I_d = 10 A, and is $\xi = (1.5\text{-}1.6) \cdot 10^{-7}$ g/s for the discharge current I_d = 25 A; working gas Xenon. There also exists a certain erosion of the HC emission material. But, its loss is much lower than for the Molybdenum keeper. In other words, the Hollow Cathode erosion is significantly lower than those of the reflector and the Hot Filament.

Erosions of anode and of external magnetic pole-exit flange are quite high and hard to minimize. However, for each technological process it is possible to find certain optimum conditions for the discharge voltage and current, placement of a Hot Filament and a magnetic field value in the discharge channel that produce a least sputtering of all these ion source' parts leading to ion beam contamination.

10. Contamination of ion beam from sputtering of ion source magnetic poles and from anode.

Since magnetic poles (for end-Hall ion source only the external flange will be sputtered; the internal pole is protected by the reflector) and anode in general have a quite a large surface area in comparison with the reflector and Hot Filament, the erosion of poles and anode is not so much noticeable and there is no published data about end-Hall erosion of poles and anode, but it is significant and can be estimated as about $\xi \approx 10^{-4}$ g/s. The extensive work with closed drift thrusters for electric propulsion in space in Russia, US, Europe and Japan laboratories gives good information about such erosion.

Table 6.4 End-Hall ion source parts, HF and HC erosion (sputtering) rates

Part	Sputtering rate, ξ, g/s	Possible means to reduce sputtering/contamination
1. External pole (flange)	$(1\text{-}5) \cdot 10^{-4}$	Magnetic field optimization, lower applied power
2. Anode	$(1\text{-}5) \cdot 10^{-4}$	Magnetic field optimization, lower applied power
3. Reflector, Stainless Graphite	$(1\text{-}3) \cdot 10^{-4}$ $(3\text{-}6) \cdot 10^{-5}$	Magnetic field optimization, lower applied power
4. Hot Filament	$(2\text{-}3) \cdot 10^{-5}$	Lower applied power, HF placement optimization
5. Hollow Cathode		
a) Keeper's hole	$(2.5\text{-}3) \cdot 10^{-8}$	Lower applied power, gas flow optimization
b) Cathode's exit hole	$(1\text{-}3) \cdot 10^{-9}$	Lower applied power, gas flow optimization
c) Emissive element	$(1\text{-}2) \cdot 10^{-9}$	Lower applied power, gas flow optimization
6. Vacuum chamber, Parts of targets frames, etc	$(1\text{-}3) \cdot 10^{-9}$	Lower applied power, gas flow optimization Optimum design with minimum sputtered parts

For example, there are detailed studies of erosion of the front flanges of CDIS-thrusters. They have been tested during quite a long time periods up to several thousand operating hours. Such observations are very useful, because they show tendencies and give information how to reduce such erosion caused by ion beam sputtering.

In ion sources utilized for thin film technology or similar tasks there are no thousands of hours of continuous operation, because it is not difficult to substitute eroded parts after visible detection.

The linear Anode Layer Ion Sources operating without the external electrons producing cathode-neutralizer experience much higher erosion than end-Halls and Closed Drift ion sources with external cathodes neutralizers (HFs, HCs, etc).

11. Problem of the double ionized particles.

It is necessary to note about recently improved designs of main producers of ion sources. The latest models became smaller in dimension. At the same time they have higher major operational parameters than previous models, like Mark-I and Mark-II. There is not much new in designs of the magnetic field configuration, or magnetic field strength, but the applied electrical power now is in smaller volume. In result, the higher energy release in a smaller volume leads to higher ionization probability and to a certain increase of the double ionized particles. As it was indicated in our previous publication [25] the presence of double charged ions even in the amount of 10^{-4}-10^{-3} ratio to single charged particles can substantially influence the sputtering process by an ion beam. Even that operating at much lower discharge voltage (energies) in Hollow Cathodes with $V_d \leq 30$ V, I_d = 1-10 A than in ion sources with V_d = 50-300 V, I_d = 1-10 A, a presence of double ionized particles is one of the reasons for erosion of Hollow Cathode vital parts [70] at low discharge voltages. However, this remark is important only for the very sensitive to a low contamination ion beam cases in thin film deposition processes.

12. Anode "poisoning" problem.

One of important and not completely

solved problem is the so-called anode "poisoning" during operation of Hall-current ion sources with reactive gases such as Oxygen, Nitrogen, Hydrogen, etc. During such operations reactive gases produce thin film depositions on the discharge channel, targets, vacuum chamber and especially on the anode.

Anode covered with dielectric or insulating thin films gradually loses its electrical conductivity and makes shift from established operational parameters to the new ones that also are gradually changing. The discharge voltage increases significantly at the constant discharge current, and the discharge current decreases, if a Power Supply works at the constant discharge voltage. In the case, if a Power Supply works at the constant discharge voltage, the discharge current begins increasing significantly to maintain discharge. In both cases, it is necessary to stop the process and either to clean the anode, or substitute for a new one.

The means for attempts for solving this problem are known [21] and shown in **Figure 38a.** It is a design of Hall-current ion sources with grooved anode that makes some anode areas "invisible" for returned back to anode oxides or other deposits, or other devices that protect anode from particles returned back to anode from the process. *[*Detailed discussion of such methods will be in one of our next publications in **VT&C**.]*

Another way to reduce significantly the oxide and other insulating particles from target is placement of a protective shield in the ion source discharge channel, as it is shown in **Figure 38b.**

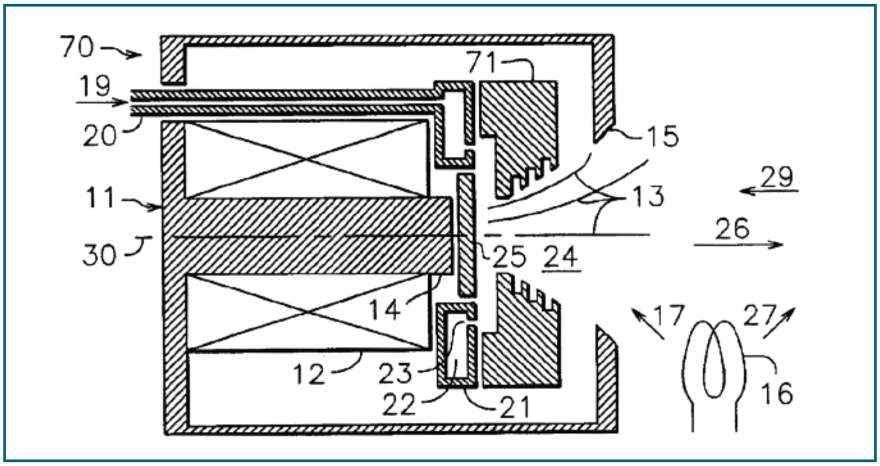

Figure 38a. Grooved anode 71 with hidden surfaces "invisible" for reflected oxide particles from vacuum chamber.

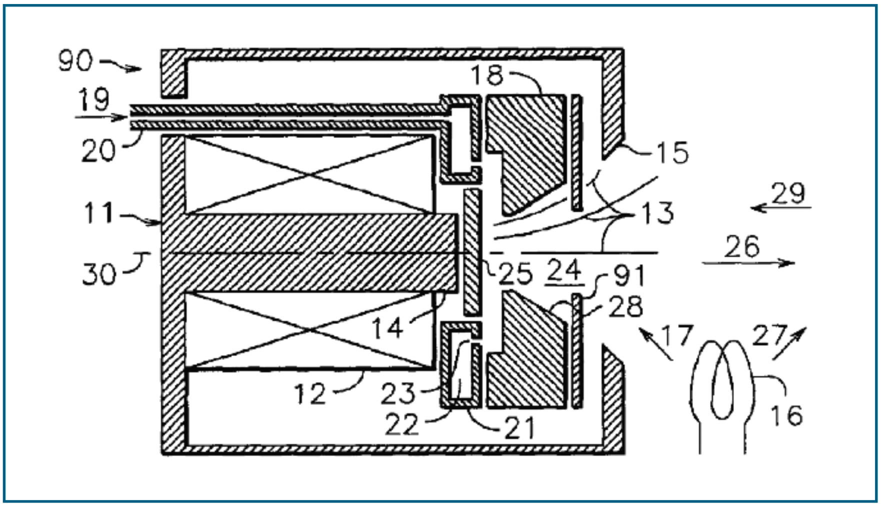

Figure 38b. Protective shield 28, regular anode 18 in end-Hall discharge channel

Such type of arrangement works even better than a grooved anode, though it reduces the ion beam current by about 15-20% with the same discharge parameters.

13. Problems with reliable operation of cathodes-neutralizers such as Hot Filaments, Hollow Cathodes and others.

There is no secret that majority of Hall-current ion sources users have Hot Filaments as cathodes-neutralizers because they are simple, cheap and quite reliable, if there is no need in long operation lifetime of more than 10-20 hours. However, some users have Hollow Cathodes that allow working for hundreds of hours with certain knowledge of such a device.

Hot Filaments for each ion source must be selected carefully with correct thickness and length, with needed applied heating current, placed at optimum distance from ion source's front plate to reduce sputtering from ions leading to Tungsten wire break. A power supply to a Hot Filament should be with ac current, not a dc. Because an alternative current provides a HF lifetime longer in about two times than a direct current. *[*Detailed discussion of various Cathodes-Neutralizers will be after this article in **VT&C**.]*

14. Conclusion to Basic Problems, Solutions

For developers and users of broad beam gridless ion sources it is necessary to emphasize how it is important to have a neutralized ion beam and how underneutralized beam can change drastically major operating parameters. As examples, in **Figure 39** there are presented typical energy distributions for a new end-Hall type ion source [72] with comparatively monoenergetic ion beam. As one can see, an ion beam with emission current $I_{em} > I_d$, or so called "over-neutralized" beam has the most narrow energy distribution with the ratio of $E_i/eV_d \approx 0.94$; for $I_{em} \approx$ Id the ratio $E_i/eV_d \approx 0.86$; for $I_{em} < I_d$ the ratio $E_i/eV_d \approx 0.76$. Regular end-Hall ion sources, as it was shown in this article **Part 4A** have $E_i/eV_d \approx 0.6\text{-}0.7$. Regular end-Hall ion sources with underneutralized ion beam have the ratio E_i/eV_d substantially lower than 0.6.

In **Figure 40** there are presented Volt-Mass flow Characteristics $V_d = f(\dot{m}_a)$ for Id = 1 A, for different ratios of emission and discharge currents: $I_{em} < I_d$, $I_{em} \approx I_d$ (in fact, $I_{em} \approx 1.1 \cdot I_d$), and $I_{em} > I_d$, working gas

Argon. There are several advantages operating with excessive electron emission in comparison with $I_{em} \approx I_d$, which are seen in **Figure 39** and **Figure 40**: 1. an ion beam has a narrow energy distribution; 2. the same discharge voltage with excessive emission needs less working gas mass flow. However, there is a disadvantage: to have a higher electron emission: it is necessary to apply substantially higher heater current to a neutralizer, which means a shorter lifetime of a cathode-neutralizer.

The situation with the ion beam current is very similar to ion beam energy distribution: higher emission and emission equal to discharge current provide higher ion beam current (this is clearly shown in **Figure 35b** of **Part 4A**, on which an ion beam current is shown by numbers 3 for $I_{em} > I_d$ and 4 for $I_{em} \approx I_d$); under-neutralized ion beam has lower ion beam current and ion beam is more divergent than in two other cases, and it is not shown in **Figure 35b**.

Also, it is necessary to remind that all these considerations are for the ion sources operating in a non-self sustained regime of discharge, i.e. about under V_d = 250-300 V. But the industrial gridless Hall-current ion sources have the optimum discharge voltage in area of V_d = 90-150 V. That means that experimental facts presented above are very important and must be taken into account.

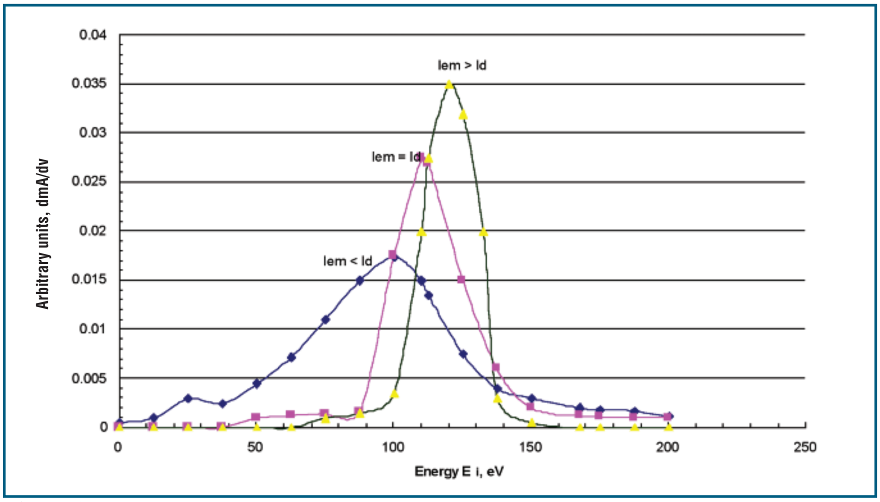

Figure 39. End-Hall new design [72], Ion beam Energy distribution for different neutralization ratios: $I_{em} < I_d$ (I_{em} = 3.8 A), $I_{em} = I_d$ (I_{em} = 4 A), I_{em} > Id (I_{em} = 6 A) ; V_d = 130 V; I_d = 4 A; Noble gas.

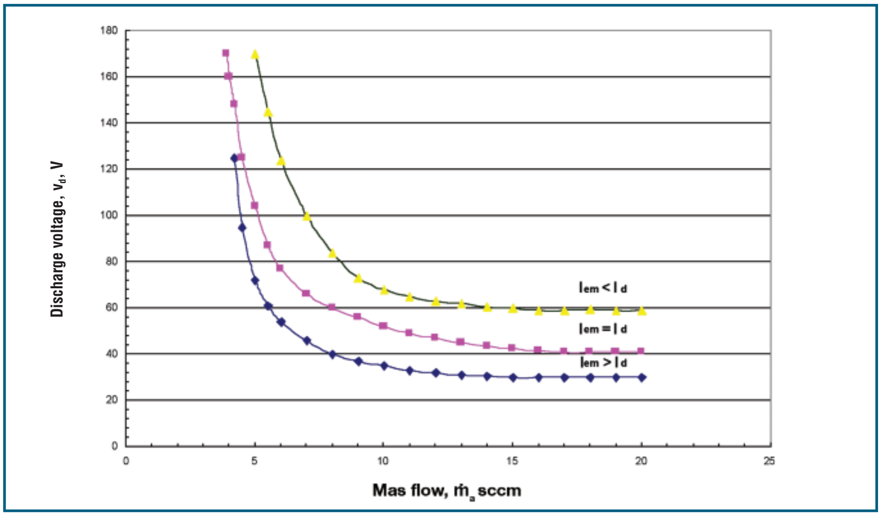

Figure 40. End-Hall ion source old design: Volt-Mass flow Characteristic $V_d = f(\dot{m}_a)$ for I_d = 1 A, for different ratios of emission and discharge currents; Argon.

II. THE NEED FOR STANDARDIZATION OF ION SOURCES

Because there is a quite big number of companies producers of ion sources of varieties of gridless types and these companies have practically no exchange of information, except finding opponents rarely published articles, in which ion sources are utilized for certain thin film tasks, finding and examining the manuals from customers, advertising literature, it is necessary to apply certain criteria for comparison of operational parameters of ion sources producers, to make users work easier.

Here is the example, what is going on with the modern ion sources utilized for certain physical thin film technology tasks. The ion beam sputtering of the same material with the same ion beam mean energies and ion beam currents for ion sources made by different poducers showed in some cases different results. An ion beam of Argon ions with the mean energy of 100 eV and with the ion beam current density of 1 mA/cm^2 delivered by various ion sources made by different companies show in many cases quite different experimental results, because these experiments were provided in different vacuum chambers with different pumping, with different ion sources, with different means and methods for an ion beam neutralization and different methods for measurements or estimations of the ion beams mean energies and currents.

Another example of a wide-spread misunderstanding. It is the name of ion sources, because some producers call any Hall-current broad beam ion sources as Closed Drift ion sources, some producers call them as end-Hall ion sources.

The widespread adoption of major types of advanced ion sources recently have been introduced into an ion source market mainly by Chinese and South Korean companies with the possibility of increasing users knowledge and confidence in this challenging technology, by fully characterizing and testing ion sources in the most representative and proper typical conditions close to utilized in practice during the thin film operations. However, some recently developed ion sources have no substantial scientific basis and adequate tests that are necessary for reliable predictable operational characteristics. [*Any developments of new ion sources take at least one year of regular everyday experiments to obtain optimum operation characteristics.]

Extensive qualification tests of ion sources by independent laboratories would allow the ion sources producers to fully and better understand the behavior of ion sources in the most diverse conditions, similar to the operation in the thin film technologies, to identify, investigate and eliminate potential failure modes. Independent extensive test database of various ion sources types and dimensions can provide users with the best information and confidence that the ion sources they selected will perform in their special conditions and will help to fulfill the required tasks.

In order to provide users with the best information and confidence in the selected ion sources, it is necessary to use the instruments and techniques needed to completely characterize ion sources. Those instruments and techniques are generally known to major ion sources producers and also to several American and Russian universities working for quite a long time with the electric propulsion thrusters and ion sources. There are several techniques for measurements of ion beam parameters such as an ion beam current, an ion beam mean energy, an ion beam spread angle, a number of double ionized particles, a number and influence of charge-exchange particles on ion beam current, energy and efficiency, influence of reactive gases depositions poisoning discharge channel and changing operational characteristics leading to oscillations, instabilities, etc.

Possible sources of misunderstanding and wrong selection of standard procedures should be identified and resolved. The users are not supposed to be confused with the basic important parameters they need for the technological process. They should know what is difference between discharge current and ion beam current, the difference between discharge voltage and ion beam mean energy, how charge-exchange and double ionized particles can impact on ion beam performance, and how the changes in these parameters and different working gases can influence the technological processes.

Besides the major mistakes about the above mentioned discharge I_d and ion beam I_i currents, the discharge voltage V_d and the ion beam mean energy E_i [*As it was discussed earlier $I_i \approx (0.2\text{-}0.25)\cdot I_d$ and $E_i \approx (0.6\text{-}0.7)\cdot eV_d$ for end-Hall ion sources, and $I_i \approx (0.7\text{-}0.8)\cdot I_d$, for closed drift ion sources with external source of neutralizing electrons, for ALIS linear ion sources without external source of neutralizing electrons $I_i \approx 0.1\cdot I_d$ and $E_i \approx (0.1\text{-}0.5)\cdot eV_d$], there is another very important point of misunderstanding. It is about ion beam neutralization and what particular value of the electron emission current I_{em} must be selected for the operating discharge current I_i and discharge voltage V_d.

Unfortunately, many Hall-current users following some publications sometime apply simply a high heating current I_h for the Hot Filament that, in some cases, makes no harm to the thin film technological process; and in some other cases, the users change the Hot Filament's I_h when the visible sparks would subside and this is considered a point of ion beam neutralization, instead of direct measurements of electric potential in beam, or target.

At the same time, all, especially new developed Hall-current ion sources (including the so-called non-traditional ion sources) must be qualified not only for the ranges of working gas mass flows and discharge voltages, but they must be measured for the ion beam current by the Faraday probe and for the mean ion beam energy and its distribution by the retarded potential screened probe.

Users should know that the ion sources can operate sometime without oscillations, and, in some cases, only with the oscillation of main parameters, such as the discharge voltage and current, and still can deliver the necessary ion beams energies and currents for thin film tasks.

These efforts would save useful resources that users spend for checking of various ion sources at theirs conditions. Preliminary tests that can be provided by independent universities laboratories would guarantee the ion sources quality and the operational characteristics claimed by producers.

Because of the challenge of certain ion sources testing, only a small number of highly qualified centers of low energy plasma can be attracted for such a purpose. We would recommend using services of several independent well-known plasma centers such as: University of Michigan Plasma Dynamics and Electric Propulsion Laboratory, Texas Tech University Pulsed Power Laboratory, Scientific Technical Center of Plasma Physics at Moscow Institute of Radioelectronics, Plasma Laboratory at Bauman Technical University (Moscow, Russia). These laboratories already worked for many years with ion sources and electric propulsion devices that require practically the same types of instrumentation and vacuum facilities. They have qualified personnel and can compare and provide ion sources users with the high quality operational data. It is not necessary to have a significant investment level to cover the whole range of different requirements for the standardization work, because these laboratories already have all the measurements methods and skillful personnel.

These independent plasma physics centers, in general, will be not involved in the development and qualification tests. They can be used mainly for the acceptance tests.

From the user's position, after the development, qualification and acceptance tests the ion source final operation conditions must be with the required parameters in operating environment as at users "home".

Some users may want to change the operation conditions and parameters in comparison with the producer's. For example, ion source producers provide the manuals with main data for most common working gases like Oxygen and Argon at certain range of discharge voltages (ion energies) and currents (ion beam currents). However, some users would like to have data for different working gases, like Nitrogen, Methane, Hydrogen, etc, or to have the operating discharge voltage and currents not in the known and established ranges, for example, the end-Hall ion sources can be operating at low (10-20 eV) and high energies (300-500 eV) and high ion beam currents (> 10 A). In such cases, if necessary, the selected independent plasma centers testing ion sources can provide the services of ion sources tests with various working gases, in large and small vacuum chambers and with different pumping means. All such works can be done at well-known plasma laboratories by very qualified people with minimum investment, time and labor expenses.

The comparison of actual operational characteristics with the previous versions, or the existing standard ion sources can be the typical objective of the acceptance tests. In some cases, it may be more important to indicate the deviation from the existing "standard" ion sources parameters, to show the most desirable mode of operation for the users needs.

The standardization of ion sources will require the tests with the following main objectives:

- identification of test conditions, measurement methods and instrumentation that allow the characterization of ion sources with the operating parameters similar as the customer's. In particular, the Faraday cups and retarding potential probe must be tested by several laboratories and accepted for standard measurements.
- understanding of quantitative dependency of the operating parameters on test conditions and equipment, such as vacuum chamber dimensions, pumping abilities, measurements of main parameters at different distances from an ion source.

CONCLUSION

Most well-known Hall-current ion sources, especially end-Hall type, made by world producers are presented and analyzed. There are discussed major advantages and shortcomings of existing models. Some problems accompanying operation of ion sources are described. There is expressed a concern that some producers of ion sources do not present well qualified and tested ion sources. In fact, since there are no existing standards for ion sources as products, only few well-known companies producers provide good experimental data with adequate explanation of physical phenomena taking place in ion sources and interaction of ion beams with targets, substrates, vacuum chamber parts, etc. Because some producers of ion sources do not present well tested ion sources and give sometime contradictory information. In other words, the majority of produced ion sources can be seen as a chaotic array of fine instruments without provided necessary justification of all important characteristics of such ion sources.

Industrial Hall-current gridless ion sources should satisfy several crucial conditions for their satisfactory operation that include:

1. Ion beam must be always well neutralized.
2. Stable operation in the whole range of discharge voltages: for end-Hall ion sources this range usually is from about $V_d \approx$ 50-80 V and up to 300 V. However, most ion sources operate in quite narrow range of $V_d \approx$ 90-125 V for most working gases.
3. Stable operation in the whole range of discharge currents: for end-Hall ion sources this range usually is from about $I_d \approx$ 0.5 A to 5 A.
4. High ion beam current. It is desirable that end-Hall type ion source could provide an ion bean current at least as $I_i \approx (0.2\text{-}0.3) \cdot I_d$.
5. An ion beam mean energy should be at least as $E_i \approx (0.6\text{-}0.7) \cdot eV_d$. Also, it is desirable that an ion beam energy distribution will be not "smeared" all over large energy range, but it will be in a possibly narrow energy range of $E_i = \pm$ 50 eV (**Figure 34a**).
6. Operation of discharge voltage and current should be with low level of oscillations. Though, for $V_d >$ 250 V in most cases it is impossible to have an ion source operating without oscillations. In such cases, it is necessary to provide reliable measurements of ion beam current and energy at high V_d.
7. Ion beam should be not very divergent.
8. Ion beam should be with low contamination level.
9. In order to have "clean, pure" ion beam operation is better to be at low pressures in vacuum chamber, from 10^{-5}- $(1\text{-}2) \cdot 10^{-3}$ Torr to reduce charge exchange particles.
10. Ion beam should have low number of double ionized particles (double energy).
11. Those who work on the same conditions with ion energy and current can always find optimum with placement of neutralizing means, reflector, working gas mass flow that reduce contamination, a beam divergence.
12. Permanent magnets must be checked regularly at the reflector's surface by a transversal magnetic probe. Magnets lose magnetism gradually, especially, if end-Hall ion source can be overheated. One of the first patterns of low magnetic field is a reduced discharge voltage from a high voltage side, when discharge voltage can not achieve V_d = 200-250 V and high discharge currents I_d = 5-7 A.

More details on other physical phenomena of ion sources behavior such as operation with reactive gases, strong oscillations and instabilities of discharge current and voltage, Hot Filaments and Hollow Cathodes already have been published in *VT&C* and will be presented in our further publications.

ABOUT OUR FURTHER *VT&C* PUBLICATIONS

We are planning to continue publishing articles in *VT&C* about different aspects of physical phenomena and operation of Broad Beam Hall-Current Gridless Ion Sources. Next themes for publication will include:

1. Cathodes for Industrial Ion Sources. Various types of cathodes will be described in detail: Hot Filaments, Hollow Cathodes, Plasma Bridge, RF-neutralizers, Cold Cathodes and others.
2. Operation of Industrial Ion Sources with Reactive Gases. This subject will include various methods of avoiding anode "poisoning" (contamination mainly from oxides) including different designs of anodes and discharge channels.
3. Hall-Current Ion Sources. Perspectives. There will be presented analysis of existing and possible future designs.
4. Plasma optics. There will be shown certain simple methods of focusing-defocusing of Ion Sources plasma beams.
5. Radiation from Ion Sources, its impact, possible methods for optimization.
6. Measurements of energy, ion beam current and other parameters in Ion Sources.

7. Ion Sources and novel methods in thin film deposition, including a so-called biased target deposition, an ion assisted magnetron deposition.
8. Application of Ion Sources for unconventional applications: vacuum pumping, mass separation, switching.
9. Ion Sources and Electric Propulsion.

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