Industrial Gridless Broad Beam Ion Sources and The Need For Their Standardization

PART 1

By Viacheslav V. Zhurin,
Colorado Advanced Technology LLC,
Fort Collins, CO

Recently beam industrial ion sources became extremely valuable in applications of many important fields, especially in the thin film technology. From just few experimental samples of ion sources made in American and Russian laboratories in 1970es there are now so many producers in several countries that it is necessary to look at latest achievements and compare. Here is a short review of known ion source producers with description of the most distinctive features of the gridless ion sources obtained from available information and from our analysis. Since our previous publications [1, 2], where there were discussed mainly the optimization conditions and oscillations and instabilities of gridless Hall-current ion sources operation. In this article there is presented the estimation of major gridless broad beam ion sources and theirs modifications, theirs advantages, shortcomings and possible improvements.

In the last 30 years the utilization of ion sources and ion beams became broader with each year. Ion and plasma sources are used in many very fine physical processes at atomic level for sputtering and ion assisting applications. Ion sources with varieties of ion beams of different energies and currents allowed having thin film depositions that was impossible to make by any other means. The quality and purity of depositions of various materials that before the utilization of ion sources was impossible to do, now is easy to implement with different ratios between materials making possible to obtain new often unpredictable great properties. The ion sources technique in general is improved substantially, though major principles of development and operation of new ion sources did not change much. Some of those principles include electric discharge in ionizing gas or gases; this electric discharge takes place between anode and cathode with applied between them magnetic field that usually extends the length and life of electrons, forcing electrons move in the crossed magnetic and electric fields. Longer life of electrons permits to provide necessary ionization with development of ions and neutralization of ion beam.

Below there is presented analysis of major ion sources and some of theirs specific features distinguishing them.

Ion sources utilized for the thin film technology were developed from the Electric Propulsion technology. And the first available as ion sources were so-called gridded ion thrusters-sources. The ion sources are materialized from varieties of the electrostatic thrusters. The main feature of electrostatic thrusters in comparison with other types of thrusters, that acceleration of charged particles is realized in a constant electric field provided by external sources in the conditions of impact of a space charge of accelerated particles. Because of this fact, in the electrostatic, sometime called as gridded thrusters, the ion beam current is limited and its maximum value is determined by the well-known Langmuir-Child law (so-called "three second" law), or

$$j_i = (4/9)\varepsilon_o(2e/M)^{1/2}V^{3/2}L^{-2},$$

where j is an ion current density, ε_o is a dielectric constant, e and M are particle's charge and mass, V is an accelerating potential; L is a length of accelerating distance between anode and cathode.

Detailed analysis of gridded ion sources can be found in [3].

World Producers of Ion Sources

In **Table 1** titled "Producers of Ion Sources Types, R&D, Repair"there is presented a list of known to us producers of mostly gridless ion sources of companies, university laboratories, small and big R&D companies involved in tests and various experiments with ion sources, electric propulsion thrusters, thin film technologies. In the Table there are also indicated the types of ion sources and techniques the companies are working.

The biggest producer of various types of ion sources (end-Halls, gridded, anode layer, etc) is Veeco Instruments (USA): more than several hundred ion sources per year. Besides high quality ion sources, Veeco has developed good screen-touch Power Supplies for easy, convenient and reliable operation. Veeco has a group of scientists and engineers that constantly work on improvement of their products.

The next well-known producer is Kaufman & Robinson Inc. (USA) that makes about 30-40 ion sources per year. Despite the largest number of patents about gridded and gridless ion sources, several years ago they switched most of production and R&D to the varieties of end-Hall ion sources. Their new series of small size end-Halls can be very useful for universities and small companies working on thin film problems and a good substitution of linear end-Hall ion sources. However, they do not make their own Power Supplies. This company is not only inventor of major ion sources concepts, but it also came to the several new approaches with improvements in thin film technology such as a biased target deposition, a magnetron ion assisted deposition, where the end-Hall ion source operates without either a Hot Filament, or Hollow Cathode using electrons from a magnetron for an ion beam neutralization and ionization, development and utilization of low-energy ion beams of the assisting end-Hall ion source.

Both companies have the means for measurement of the ion beam current and energy, various thin film depositions tests, and can work with companies that are looking for new fine thin film depositions. In the last several years, both companies substantially changed the line of the end-Halls and introduced new models that easy to assemble/disassemble and improved theirs operational characteristics.

Veeco with its new line of Mark-1+ and Mark-2+ end-Halls in order to disconnect anode from a water cooling line, instead of a direct anode cooling, introduced the dielectric plate that separates anode from a water-cooled plate under the anode. Anode cooling is not provided directly and efficiently as it in the regular Mark-2 water-cooled anode. It becomes more heated than in the previous model. But there is an advantage of such a "hot anode" for the processes involving Oxygen and other reactive gases. With a "cold anode" (water-cooled) the oxides usually easily deposit on anode (so-called anode "poisoning") and sometime substantially disrupt regular operation with sharp increasing of a discharge voltage, or decreasing an anode current, depending on the Power Supply mode. Now with the indirect anode heating the anode becomes quite hot and the oxides do not stick with such a rate that is with a direct cooled anode, reducing anode "poisoning" (unfortunately, there were no publications about the difference of operation with reactive gases of previous Mark-1 and Mark-2 models with new Mark-1+ and Mark-2+). With such arrangement the magnet is not heated, it is protected by a gas distribution system and a separating dielectric plate, and it allows disassembling anode in a matter of minutes in comparison with the previous Mark type end-Halls. However, the heated anode should be watched during the high applied electric powers (2-3 kW). Because at high applied powers into a smaller volume and with a heated anode, there are some problems occur for certain sensitive thin film depositions that can not withstand energy of double ionized particles (with doubled ion energy) and a high radiation flux coming out a discharge channel into a thin film deposition area.

Also, it seems that only these two companies can make industrial Hollow Cathodes (HC) for working gas ionization and neutralization of ion beam charge and current, and successfully use them with the ion sources. All K&R end-Hall ion sources EH-200, EH-400, EH-1000 and EH-2000 are of a modular design with anode assembly easily separated from the rest of the discharge chamber (magnetic system, magnet, gas distributing system.

Another known producer of the end-Halls is Saintech Ltd (Australia) with several patents in this field; it makes about 30 ion sources per year. The placement of gas distributor-reflector at the anode potential does not make end-Halls of this company efficient in the ion beam current value, and theirs discharge voltages (energies are about 0.6 of discharge voltage) are under 225 V (meaning that theirs maximum ion beam mean energy is about 135 eV). Saintech's ion sources are simple and easy to assemble-disassemble. The source of electrons is a Hot Filament.

There is a group of Russian Research Institutes and company called Fakel, major producer of closed drift thrusters in the world. This company is well-known in USA and Europe with its thrusters and more than 200 of them flown into space. Fakel developed several types of ion sources based on magnetic layer closed drift thrusters [4] and makes several hundred thrusters per year. Fakel has several Russian and US patents in this field; it also makes good Hollow Cathodes, but they are expensive and very hard to make and they

Table 1. Producers of Ion Sources Types, R&D, Repair

Company	End-Halls	Hot Filament	Hollow Cathode	Anode Layer	Magnetic Layer	RF	Gridded Sources	R&D	Repair
1. Veeco Instruments (USA)	+	+	+	+		+	+	+	+
2. Kaufman & Robinson (USA)	+	+	+		+	+	+	+	+
3. Advanced Energy (USA)*				+					
4. Denton Vacuum (USA)	+	+							
5. Dymonex (USA)		+			+				
6. Plasma Processing Group (USA)							+	+	+
7. CATech (Colorado Advanced Technology, USA)**	+	+	+			+		+	+
8. General Plasma (USA)				+					+
9. Kurt Lesker Co (USA)							+	+	
10. Dynavac (USA)	+	+							
11. SPECS Technologies Corporation (USA)						+	+	+	
12. 4-Wave (USA)	+	+	+					+	+
13. Vecor (USA)	+	+		+					
14. Fil-Tech (USA)	+	+							+
15. Plasma Controls (USA)			+				+	+	
16. Intlvac (Canada)	+	+	+					+	
17. Platar (Russia)		+			+		+	+	+
18. "Luch" (Russia)	+	+							
19. "Applied Electronics" Tomsk High Current Institute, Russia	+	+				+	+		
20. Fakel Enterprise Kaliningrad, Russia	+	+	+		+			+	+
21. Moscow Institute of Radio-Electronics, Russia		+	+		+			+	+
22. Plasma Lab, Moscow Bauman Technical University, Russia				+				+	+
23. Saintech (Australia)	+	+						+	+
24. Beijing Oriental An	+	+					+	+	
25. Taike High-Tech Co., Ltd. (Beijing)	+	+							
26. Beijing Teng-Vacuum Technology	+	+							
27. Zhaoqinq Technology Development (Beijing)	+	+							
28. Chi-kwong Technology (Shanghai)	+	+							
29. Shanghai NanoVac Technology	+	+		+				+	
30. Zhenjiang 3Y Vacuum Optical Co	+	+							
31. Plasma Technology Ltd (Hong Kong)	+			+					
32. Korea Vac-Tec(S.Korea)	+	+		+			+	+	+
33. Hanil Vacuum Machine (S.Korea)	+	+							
34. Univac S. Korea	+	+							
35. S. Korea Institute of Science & Technology	+	+							
36. Protech S. Korea Co.	+	+							
37. INTEC Inc S. Korea	+	+							
38. Gencoa Ltd (England)				+			+		
39. JENION (Germany)							+		
40. Ion Beam Scientific (England)	+	+	+				+	+	
41. BeamTec (Germany)	+	+	+				+	+	
42. Nordiko (England)						+	+		
43. Mantis Deposition Ltd (England)						+	+		
44. Oxford Applied Research (England)						+	+	+	
45. Roth & Rau AG (Germany)						+	+	+	
46. Belarus State University	+	+			+			+	+
47. ULVAC (Japan)				+			+	+	
48. LJ-UHV Technology (Taiwan)					+				
49. National Research Center, Ukraine	+	+		+	+			+	

* Advanced Energy Ion Source Products was acquired by General Plasma in 2008 **CATech provides consulting, R&D and repair

are used, in general, for space thrusters of a closed drift type.

Similar estimation goes for Institute of Radioelectronics in Moscow, maker and inventor of varieties of magnetic layer closed drift thrusters and ion sources (except, they do not make many thrusters, and mostly do R&D with thrusters and ion sources), and Moscow Bauman Technical University that makes good reliable anode layer ion sources. Russian company “Platar” affiliated with Moscow Aviation Institute makes quite a large number of various ion sources (gridded and gridless of magnetic layer closed drift type). Russian company “Applied Electronics” in Tomsk at High Current Research Institute of Russian Academy of Sciences makes several types and dimensions of anode layer ion sources. Russian company “Luch” (Podol’sk, near Moscow) makes the end-Halls with separately water cooled anode and magnets for the optical coating tasks. Belarusian State University has a Department known for development of various ion sources of closed drift and end-Hall types.

All Russian Institutes and R&D centers have very highly qualified scientists and engineers that can accommodate practically any need for most complex thin film tasks. However, absence of good marketing, limiting use of end-Hall type ion source, broad utilization of closed drift ion sources with more complex design than end-Hall source, does not make theirs products popular yet. And this is despite of the fact that the magnetic layer closed drift sources have significantly higher efficiency and broader range of operation discharge voltages (energies) than end-Halls. Almost all Russian groups have Hollow Cathodes, but they are quite complex in design, made for space applications, expensive and hard to repair for customers. They are capable to make cheap, simple Hollow Cathodes and already are working on them.

There is a quite big group of Chinese companies and research institutes (8), mainly makers of the end-Halls. The same goes for the South Korean companies (6). There is not much of information about theirs design and operation parameters and how many units per year they produce. However, there are some end-Halls that have a high power up to 4 kW and most of them have a water cooled anode. This indicates about sophistication of the designs and high discharge current (up to 5-10 A) and most of them operate from about 80 to 250 V of discharge voltage with various working gases.

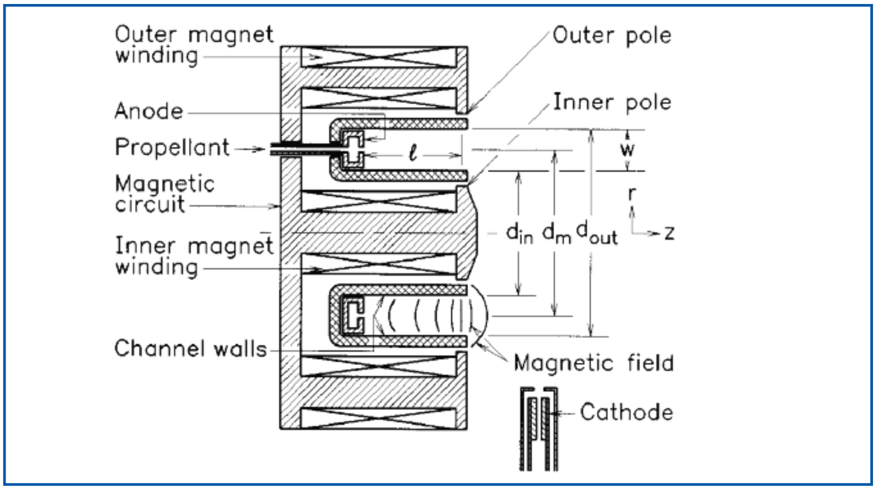

Figure 1. Closed drift Hall-current ion sources-thrusters of magnetic layer type

Surprisingly, there are practically no well-known producers of ion sources in Japan, except ULVAC (that makes several Linear Anode Layer ion sources), and a limited number is in Europe, which mainly make gridded ion sources.

The assessment of ion sources producers shows that more than 40 companies in the world that make, repair, or enhance ion sources operation, sell them, for example, as end-Halls of various capabilities. Unfortunately, some companies claim certain ion beam parameters such, as an ion beam current value, an ion beam energy range, etc without really measuring these values. In many cases (except Veeco, K&R, Russian companies and few others), there are producers and users that are confused about the discharge current and the ion beam current, the discharge voltage and the ion beam energy; and they do not distinguish them. Some companies and users claim that the discharge current is equal to the ion beam current and the discharge voltage is equal to the ion beam energy. Some companies do not provide the information about the optimum placement of ion beam sources, targets and substrates in vacuum chambers, the distances between ion sources and targets, the proper neutralization of ion beams, the possible influence of entrained working gas, charge-exchange particles, double ionized particles, oscillations etc. that impact on the operating characteristics.

Hall-Current Closed Drift Ion Sources

Ion sources with Hall current and closed electron drift operate as follows.

In **Figure 1** there is presented the schematic picture of the closed drift thruster – ion source of so-called magnetic layer type [4].

In the area between anode and cathode a magnetic field is developed with the help of the sources of magnetic field: electromagnets, or permanent magnets [*Own magnetic field produced by a discharge current, in general, in industrial ion sources is negligible and does not influence on the discharge]. With a supply of working gas (any inert gas like Argon, Xenon and others, or reactive gases: Oxygen, Nitrogen; in some cases, gases containing hydrocarbons) and preliminary turned on a heated emissive cathode, an electric discharge is ignited between anode and cathode by increasing a discharge voltage V_d at a certain discharge current I_d.

The magnetic field value in a discharge channel is selected in such a way that electrons emitted by a cathode are magnetized, or an electron Larmour radius, R_{Le} is much smaller than a discharge channel’s length, L_{ch} and a discharge channel’s width w_{ch}:

$$R_{Le} << l_{ch},\ R_{Le} << w_{ch}. \qquad \textbf{(1)}$$

At the same time, ions are not magnetized, or ion Larmour radius, R_{Li} is large, or comparable with a discharge channel length and width:

$$R_{Li} >> l_{ch},\ R_{Li} >> w_{ch}. \qquad \textbf{(2)}$$

It is known [8] that for obtaining strong stationary electric fields in a collision-free, or weakly collision-free plasma it is necessary that the electron component will be magnetized. In modern thrusters-ion sources electrons can be magnetized [*The magnetization condition of plasma is determined by the Hall parameter for electrons $\beta_e = \omega_e\tau_e$ and for ions $\beta_i = \omega_i\tau_I$, where ω is the angular cyclotron frequency, τ is the mean time between collisions and the subscripts e and i indicate electrons and ions.] at comparatively low values of magnetic field from about 100 to 1000 G. However, the electron component's magnetization relative to the collisional processes does not provide existence of volumetric electric fields in plasma.

In other words, ions in a discharge channel are moving mainly under influence of electric field, and electrons are drifting along azimuth in crossed electric and magnetic fields.

Neutral atoms of working gas coming from a gas-distributor collide with electrons and become ionized in a cloud of electrons rotating under influence of crossed electric and magnetic fields. Developed ions are captured by electric field, accelerated in it and leave a discharge channel with electrons created during ionization, and a certain amount of electrons are returning to anode. A charge of electrons coming into anode is transmitted through an electric supplying line into a cathode, from where electrons are emitted; those electrons neutralize a flow of accelerated ions. In the result of this process, ions and electrons leave an ion source channel. Because an ion acceleration in ion source takes place in an electron cloud, which neutralize an ion volumetric charge, there is no limitation for ion beam current caused by a volumetric charge of accelerated ion flow (in comparison with the gridded ion sources).

One of the most important ideas in Hall-current ion sources is the development in the discharge channel of a certain configuration of electric potential. Electric field must satisfy as minimum to the following conditions: 1) it must be macro-stable, and 2) magnetic field equipotentials (magnetic field lines of the same potential) must be convex into the anode side. In this case, a "focusing" ion flow will be provided, i.e. a compression of accelerated ions from the discharge chamber walls into the channel's center (median surface). An electric field macrostability is provided by the development of a magnetic field increasing from anode to the exit channel's side and by an electric conductivity of electrons developed during ionization. Such conductivity is provided by different mechanisms: a classic electric conductivity, a near-wall conductivity and high-frequency oscillations.

A possibility for development of electric field convex to the anode side and focusing ions into a channel's median surface is caused by the equipotentialization of magnetic field lines. The idea of this process is in the fact that for the ion sources with closed electron drift the equation of electron's motion (dissipationless Ohm law) has the following form:

$$\nabla p_e/en + \mathbf{E} + (1/c)[v_e, H] = 0, \qquad \textbf{(3)}$$

where ∇p_e is a gradient of electron pressure; e is an electron charge; E is an electric field strength; and E = -gradΦ; v_e is an electron velocity, H is a magnetic field strength; Φ is an electric field potential.

The integration of equation (1) along a magnetic field line gives the following expression:

$$\Phi^*(\gamma) = \Phi - kT_e(\gamma)\ln[n_e/n_e(\gamma)], \qquad \textbf{(4)}$$

where $\Phi^*(\gamma)$ is a constant value of a potential along a magnetic field line, called a thermalized potential; T_e is an electron temperature; k is Boltzmann constant; n_e is an electron density in discharge; $n_e(\gamma)$ is a characteristic electron density on this magnetic field line (normalizing value).

From equation (4) one can see that magnetic field lines are the equipotential lines, if $T_e \rightarrow 0$, or $n_e = n(\gamma)$; in other words, $\Phi \approx \Phi^*(\gamma)$. If these conditions are performed, it is sufficient to create the magnetic field lines of convex form into the anode side in order to obtain a necessary geometry of electric field equipotentials. Therefore, for development of an ion source with high performing characteristics the following conditions must take place:

- A uniform density of ion flow (and, correspondingly, neutral particles) near anode; this eases an impact of a component ∇p_e;
- Geometry of magnetic field lines should be convex into anode;
- It is especially important to provide necessary ion focusing in the ionization region, where an ion's velocity is small. It is easy to do by designing around anode a magnetic field with a zero value of a magnetic induction and before entering into a discharge channel to make a buffer volume with a working gas applied from a gas-distributor. The utilization of these elements develops necessary conditions for separation of ion flow from channel's walls in the acceleration region.
- Utilization of a buffer chamber makes possible to obtain a uniform working gas flow (neutral particles) into a discharge channel, and, correspondingly, a uniform ion flow. [This trend with a buffer chamber is comparatively new, and also, the first closed drift thrusters-ion sources did not have such a buffer chamber and still could operate quite efficiently.]
- Besides magnetic field geometry, its strength must have a positive gradient. A positive gradient of magnetic field has an optimum value for different dimensions of discharge chamber and probably for different gases. [*For Argon and Xenon, the optimum magnetic field differs by at least two times; for example, for closed drift ion sources with extended acceleration zone, the optimum maximum value of magnetic field for xenon is about 300 G, and for argon, it is about 150 G. These numbers are for the magnetic layer type and depend on the closed drift device dimensions.]

Three different sizes of the closed drift thrusters that can be utilized as the ion source of a magnetic layer type SPT-70, SPT-100 and SPT-200 (the numbers 70, 100 and 200 correspond to the exit diameter in millimeters) produced by "Fakel" Enterprise [5] are shown in **Figure 2a**, and in the operation is in **Figure 2b**, where one can see a plasma flow coming out of annular discharge channel and neutralized by a Hollow Cathode. In **Figure 2b** is shown SPT-100, Stationary Plasma Thruster magnetic layer type that was flown on more than 50 space satellites with total number of thrusters over 200 [*Each third Russian satellite now has the SPT thruster.] Hollow Cathodes are seen on the top of the

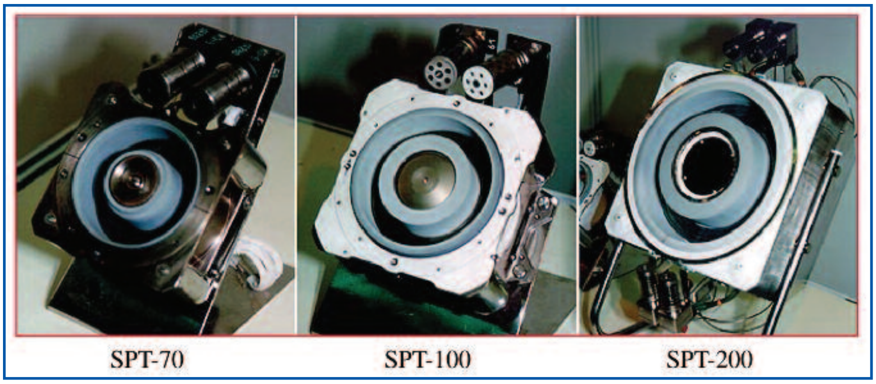

Figure 2a. Pictures of magnetic layer closed drift thrusters-ion sources SPT produced by Fakel Enterprise [5]; SPT-70, SPT-100 and APT-200 have two HCs for redundancy; at the time of operation only one HC is on

Figure 2b. Plasma flow coming from the closed drift ion source of magnetic layer type SPT-100. Hollow Cathode neutralizer is on the top.

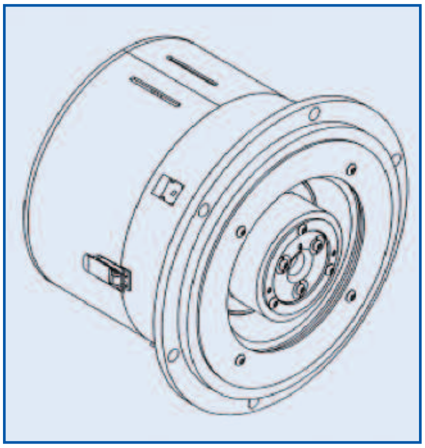

Figure 2c. Diamonex magnetic layer closed drift ion source utilized for DLC coating [6]; HC is placed on the source's axis

thrusters, and, as one can see, there are two of them, in the case, if one would be out; though Hollow Cathodes (HC) lifetime is about 8000-10000 hours each.

The well optimized magnetic layer closed drift ion sources can have a very high efficiency and high rate of the discharge current transformation into the ion current of about $I_i/I_d \approx 0.8\text{-}0.9$.

In **Figure 2c** one can see a Diamonex magnetic layer closed drift ion source that was utilized successfully for obtaining diamond like carbide coatings [6]. Its optimum range of discharge voltages and current for a DLC depositions is $V_d = 80\text{-}120$ V and $I_d = 6\text{-}10$ A [7]

If magnetic field is uniform, or decreases from anode, then the region of excessive electric fields, ionization and electron temperature is adjusted (become closer) to anode surface. This is true for all types of closed drift ion sources. By making a necessary profile of a magnetic field, it is possible to localize a region of strong electric field in any place of a discharge chamber. That was established empirically in closed drift ion sources of different types during optimization of their parameters.

For those who are trying developing one of new types of closed drift ion sources for certain particular tasks, such as operation with low discharge voltages (energies), or with high discharge voltages and high currents (high powers), it is necessary to provide a proper source's optimization for a magnetic field. It means that at fixed values of the discharge voltage V_d and the anode mass flow $\dot{m}_a$ there is the optimum value of magnetic field B_r at which there is achieved the optimum efficiency of an ion source. In this case, the discharge current I_d is at minimum.

In **Figure 3** there is presented the dependence of discharge current of a maximum radial component of magnetic field value achieved in the discharge channel. For the case shown in **Figure 3** the optimum magnetic field value is about 160 G for Xenon. For Argon the optimum magnetic field is about 50-80 G. Those values depend on the ion source's dimensions. Such discrepancy is easy explained by the difference in Xenon-Argon atomic masses ($131.3/40 \approx 3$).

In **Figure 4** there is presented the ratio of an ion beam current to a discharge current as a function of a radial magnetic field in the anode layer closed drift thruster-ion source, $I_i/I_d = f(B_r)$ for a two different gases at comparable conditions with the **Figure 3** for a Magnetic Layer closed drift thruster-ion source: $V_d = 300$ V. It is necessary to note that the optimum magnetic field for the Anode Layer source are higher by about a factor 2.0-2.5 than for the Magnetic Layer; however, the optimum values of I_i/I_d are close to each other (about 0.8)

It is important to remember that **Figure 3** and **Figure 4** correspond to some specific dimensions of MLIS and ALIS. They show rather tendencies (these two figures are for the SPT-70 dimensions) and can not be taken as the standard values.

In **Figure 5a** there is shown the anode layer closed drift ion source [4]. It has major similarities with the magnetic layer type, except that it has a substantially shorter electrically conductive discharge channel (magnetic layer has, in general, dielectric walls, though there are some designs with conductive walls); it has a slightly higher magnetic field than the magnetic layer (about twice as the magnetic layer's of the same dimension).

It discharge voltages are also higher and

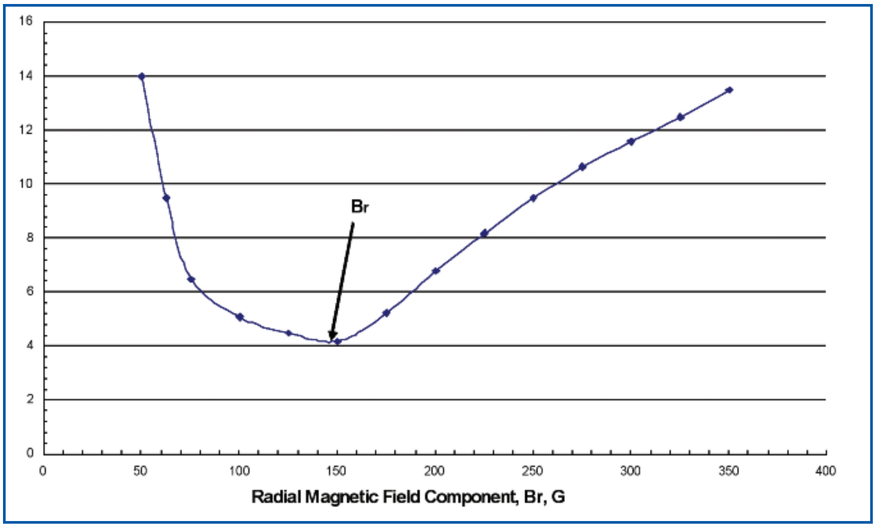

Figure 3. Dependence of discharge current I_d of magnetic field in closed drift thrusters-ion sources [8]; optimum magnetic field value is at the discharge current minimum; working gas Xenon, V_d = 300 V; HC is source of electrons

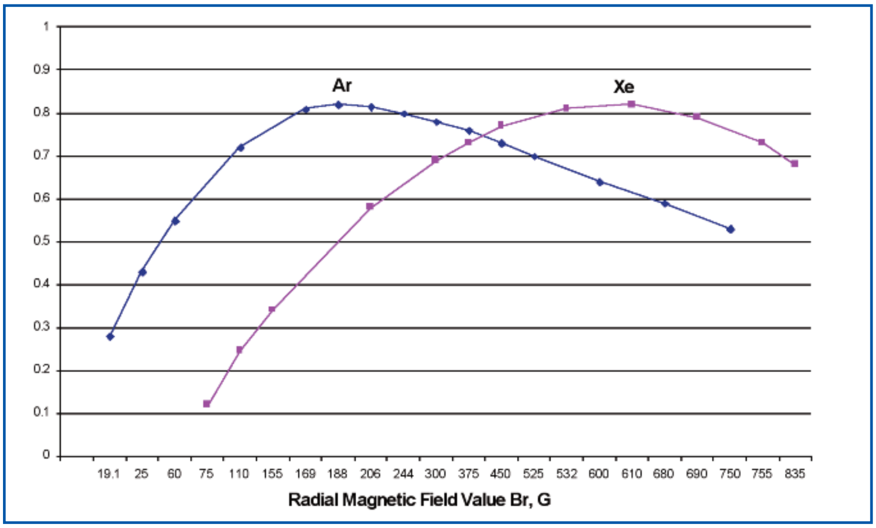

Figure 4. Optimum ratio of ion beam current to discharge current I_i/I_d as function of radial magnetic field value B_r in Anode Layer Closed Drift Thruster-Ion Source for Ar and Xe [8]; V_d = 300 V; HC is source of electrons

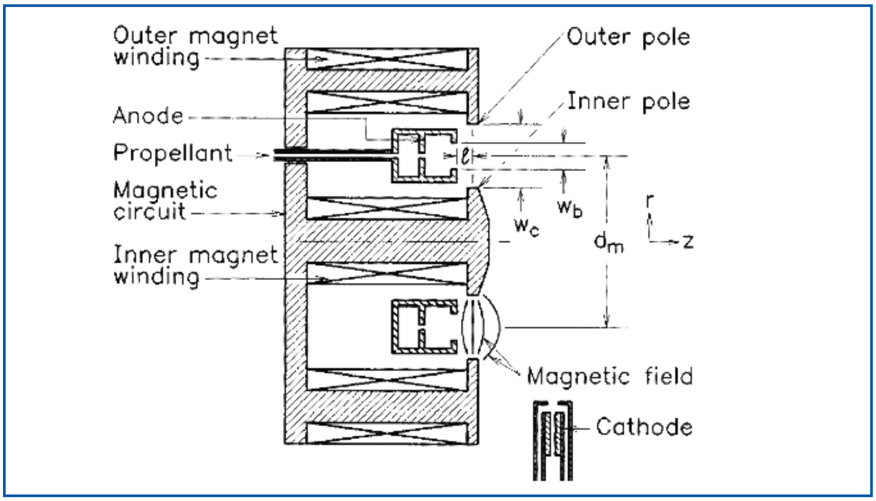

Figure 5a. Anode layer closed drift ion source with the Hollow Cathode [4]

with the HF or HC discharge voltages start from about 100 V with noble and reactive gases. The version with the Hollow Cathode electron source (**Figure 5a**) has operational characteristics similar to the magnetic layer type (**Figure 3b**). It has high ion beam current to discharge current ratio I_i/I_d = 0.7-0.8 and ion beam mean energy is about $E_i = (0.7\text{-}0.8)\times V_d$.

For those who are trying to obtain an ion beam without impurities that usually caused by erosion of anode layer ion source magnetic poles there is interesting approach [9] with the hollow anode placed at the exit plane (**Figure 5b**). The anode layer becomes completely moved out of the thruster-source's exit. In this case, the source's characteristics are practically the same as with the anode placed inside of discharge channel. However, in general, the discharge current is happened to be lower by about 5-10%, and the range of stable operation become slightly narrow at low discharge voltages (at V_d < 100 V) in comparison with the discharge channel depth of about 7.5 mm. The advantage of such a source is in a sharp reduction of erosion of magnetic poles and other parts of ion source by an ion beam coming out of discharge channel.

In thin film technology the anode layer ion source, as a rule, is used without a cathode neutralizer, in other words, it operates in discharge of a self-sustained type [1, 10] at discharge voltages from 300-400 V and up. In [11] there are presented experimental results of the ion source with anode layer type with a Hot Filament as a cathode, and without Hot Filament (without a source of electrons). Working gas is Bismuth. The source's discharge voltages were from about 125 V to about 500 V (Note: Comparatively low discharge voltages are explained by a Bismuth low ionization potential). As it was discussed in our previous publication [1] discharge in ion sources exists in two main types: a non-self-sustained and a self-sustained with the modifications: a) is a distributed discharge ($V_d \leq 250$ V), and b) is a concentrated discharge ($V_d \geq 250$ V). [*Those values depend on the kind of gas and are given for Argon. For other gases, the ionization potential and atom mass are main factors for the non-self-sustained and self-sustained types, distributed and concentra-

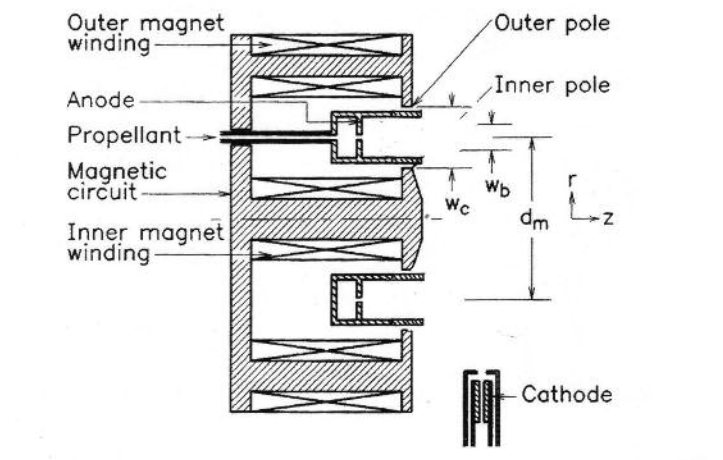

Figure 5b. Anode layer ion source with extended anode length up to exit plane leading to anode layer moving outside of magnetic poles plane [9]

tion modes boundaries.] The utilization of a Hot Filament or a Hollow Cathode as the cathode changes discharge structure and indicates increase of ionization in the discharge channel. In the whole range of studied discharge voltages (125-500 V) the ion beam current was higher with a Hot Filament or a Hollow Cathode than without cathodes providing electrons for ionization and neutralization by a factor 1.4-1.5 in comparison with the ion sources operating without cathodes supplying electrons.

It is very convenient to operate ion source without a cathode neutralizer, because there is no need in additional problem caused by the extra power supply and by the easily destroyed Hot Filament, or by the capricious Hollow Cathode, which is itself a miniature electron-ion source. However, not every thin film physical process can tolerate high voltages in plasma applied to targets, or substrates and multiple sparks generating neutralizing electrons. There are some ion beam etchings processes, when an ion beam directed on the electrically isolated target, and with insufficient neutralization there are observed neutralizing sparks produced by positive potentials as low as 6.4 V, which were able to cause damage [12]. Though, there are many other thin film tasks, where anode layer ion sources without complete ion beam neutralization are very convenient for etching, sputtering, etc.

The ion source of closed drift type with anode layer working with Argon, Xenon and other noble gases, and Oxygen, Nitrogen has two most useful regimes of operation: a high-voltage (Vd =1000-3500 V), the so-called "vacuum regime" with a collimated beam, and a comparatively moderate voltage (Vd = 500-1000 V), the regular regime with a broad divergent beam. The regime of operation with a collimated beam is usually utilized as the main type of operation for anode layer ion sources; it exists at low pressures of a working gas. In this mode the discharge current is proportional to the discharge voltage. Increasing pressure, it is possible to make transformation into the regime with the divergent beam and substantially higher discharge current operating at almost constant discharge voltage.

In the "vacuum regime" of the anode layer discharge channel there is no equality between electron and ion densities, or $n_e \neq n_i$. The Hall current increases with increase of discharge voltage, leading to the increase of a number of ionizing collisions and increase of the discharge current. With increase of pressure the condition $n_e = n_i$ begins to be performed, and the generation of ions takes place with the higher rate than their removal. In the regime with the divergent ion beam an ion current is not limited by the space charge and can be in 10 times larger than in the regime with the collimated ion beam. But, in this case, there is no control of the ion beam energy and its direction. Anode layer type ion sources are easy in operation and can work with most inert and reactive gases without external heated cathode, which is great advantage. Anode layer ion sources are high-voltage (high energy) sources and recent tendencies in thin film technology are the utilization of low voltage (low energy) ion beams that do not produce much damage to substrates during the ion assist tasks.

References

1. V.V.Zhurin, "Optimum Operation of Hall-Current Ion Sources", Vacuum Technology and Coating, November 2008, p 59-67.
2. V.V.Zhurin, "Oscillations and Instabilities in Hall-Current Ion Sources", Vacuum Technology and Coating, December 2008, p 55-60.
3. H.R.Kaufman, R.S.Robinson, "Operation of Broad Beam Sources", Commonwealth Scientific Corporation, Alexandria, VA, 1984.
4. V.V.Zhurin, H.R.Kaufman, R.S.Robinson, "Physics of Closed Drift Thrusters", Plasma Sources Science and Technology, 8, 1999, p R1-R20.
5. O.Gorshkov, "Russian Electric Propulsion Thrusters Today", www.videocosmos.com
6. F.Kimock, S.Finke, D.Brown, E.Thear, "The Evolution of Ion-Beam Diamond-like-Carbon Technology into Data Storage: Space Propulsion, Sunglasses, Slides, and New Disks", DataTech Magazine, 1999 Second Edition, p 69-77.
7. B.Knapp, S.Finke, "Direct Ion Beam Chemical Vapor Deposition of SiO2-Like Materials Using a Closed-Drift Ion Source", Society of Vacuum Coaters, 46th Annual Technical Conference Proceedings, 2003.
8. N.V.Belan, V.P.Kim, A.I.Oransky, V.B.Tikhonov, "Stationary Plasma Thrusters', Kharkov, 1989 (in Russian).
9. E.A.Liapin, A.V.Semenkin, "Accelerator with Anode Layer Moved Out of Discharge Channel", VII All-Union Conference on Plasma Accelerators and Ion Injectors, Kharkov, 26-28 September, 1989, p 210-211 (in Russian)
10. E.A.Liapin, A.V.Semenkin, "Modern State of Investigations of Accelerators with Anode Layer", in "Ion Injectors and Plasma Accelerators", edited by A.I.Morozov and N.N.Semashko, Moscow, Energoatomizdat, 1990, p 20-33 (in Russian)
11. V.S.Erofeev, E.A.Liapin, "Discharge Modifications in the Source of Ions of Hall Accelerator with Anode Layer", Proceedings of II All-Union Conference on Plasma Accelerators, Minsk, 2-5 October, 1973, p 136-137 (in Russian).
12. D.H.Olson, "Ion Milling Induced ESD Damage During MR Head Fabrication", EOS/ESD Symposium 98-332, p 4B.2.1-4B.2.9, 1998.