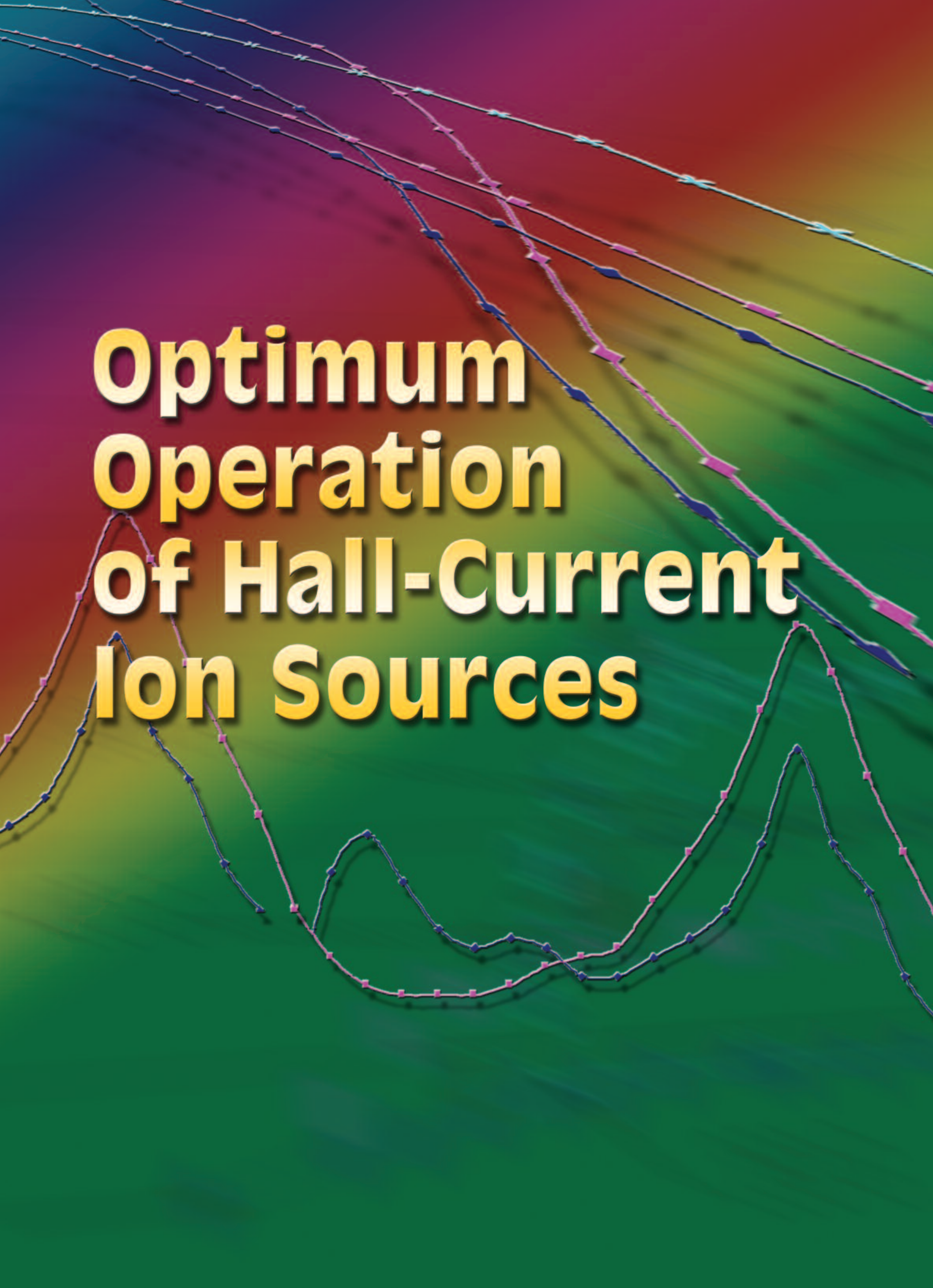
Optimum Operation of Hall-Current Ion Sources



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Broad -beam ion sources, in general, are of two substantially different classes: gridded and gridless. Gridded multi-aperture ion source using electron bombardment for ionizing working gas was introduced as space thruster in 1961. Later in 1970-1980's began intensive utilization of this type ion source for thin film technology. Gridded ion sources, in general, are high voltage, high energy devices typically from about 100 to about 1000 V. They are quite monoenergetic (with energy spread about 10 eV), discharge voltage corresponds to energy of ions; they can be well collimated over large areas. However, they suffer from a series of shortcomings such as: complexity of design, tough restrictions on grids and materials, theirs ion beam current is determined by a Child-Langmuir Law or the Three-Halves Power Law, which states that the space charge limited current in a plane-parallel diode varies directly as the three-halves power of the anode voltage V_a and inversely as the square of the distance d separating the cathode and the anode, or with this formula: $I_i \sim V^{3/2}/d^2$; and because gridded ion sources have a space-charge limit they can not deliver adequate ion beam current density at low discharge voltages (energies). An example: gridded ion source while providing an ion beam current equal $j = 1.0$ mA/cm^2 at $V_d = 1000$ V, or equivalent of 1000 eV, and at $V_d = 100$ V (100 eV) the ion beam current due to a Child-Langmuir law will be $j = 0.01$ mA/cm^2.

After development of gridded ion sources and their utilization in thin film technology there were appeared new scientific-technical tasks that required low energies and higher ion beam currents. An example: for ion assisted deposition, one ion source is a main sputtering ion source, which can be either gridded, or gridless and directed to a target, and another one that is directed to a substrate for improvement of substrate properties; in this case, it is desirable to have ion assisting source with ion beam energy under a substrate's sputtering energy threshold. In 1980es there were invented new types of ion sources-gridless. They became so efficient for many thin film deposition tasks that after about year 2000 some companies producers of ion sources practically stopped making gridded ion sources and now produce varieties of gridless ion sources.

Gridless ion sources do not have space-charge limit, because ions are accelerated together with electrons and there is no limit on ion beam current in such type of ion sources. They found wide application in thin film deposition technology and, in general, operate at low discharge voltages, from about 50-80 V to 300-500 V; their typical, most optimum range of discharge voltages are from about 90 to 150 V with the peak performance (highest ion beam current) at 100-125 V. They are rigid, easy to assemble-disassemble, parts are comparatively inexpensive, but theirs ion beam is quite divergent, an ion beam energy is usually is about 60-70% of discharge voltage. However, they can deliver ion beam currents from low to 1-5 A, or about 5-10 mA/cm^2 of ion beam current density, or in hundreds times higher than gridded ion sources at low energy of about 100 eV.

Gridless ion sources utilized for industrial application, in geeral, are of two common types. Both called as Hall current ion sources: a closed electron drift ion source with annular discharge chamber and an end-Hall ion source with a circular discharge chamber

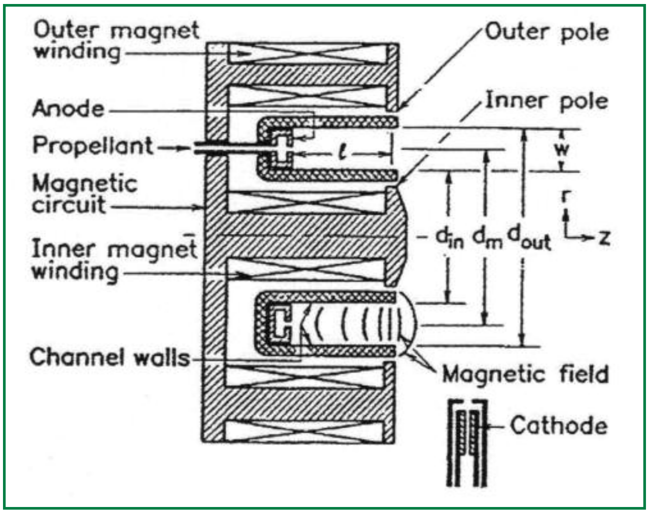

Figure 1. Closed drift ion source. Closed drift thruster of the magnetic layer type.

occupied mainly by a hollow anode of a conical shape. Both types utilize a Hall effect that is playing a major role in acceleration of ions. All these ion sources also, as gridded sources, are a spin-off from electric propulsion space programs. As thrusters they were planned to be utilized for movement of space satellites: changing and maintaining orbits.

Ion sources with closed electron drift have been utilized as thrusters from early seventies, since appearance in space in 1972 of first Russian electric propulsion thrusters utilizing a closed electron drift effect. To this time over 200 thrusters on a closed drift effect have been flown on various satellites, mainly in Russia, some of them – in USA and Europe. End-Hall thrusters have been planned for space satellites in the USA, but low efficiency was main obstacle for their implementation.

Closed drift Hall current ion sources operate in the following way (**Figure 1**) [3]. Working gas supplied into a discharge channel close to anode, or through anode is ionized by electrons moving under impact of electric field from cathode to anode in magnetic field. In a traditional performance, an ion source consists of anode, cathode (in **Figure 1**, it is a hollow cathode), a discharge chamber with accelerating channel, a magnetic system with magnetic poles, a magnetic field provided by electromagnetic coils, or permanent magnets, a central core, and a magnetic path. Closed drift magnetic system is designed in a way that a radial magnetic field is realized in an annular accelerating channel, usually made of dielectric material. Magnetic poles are quite close to each other. Magnetic field is at minimum (about zero Gauss) in anode area and gradually is increasing to exit area. An electric potential is applied between anode and cathode, and an electric field in a discharge channel is directed approximately parallel to an ion source axis.

End-Hall ion source (**Figure 2**) [1, 2] operates in a very similar way as a closed drift ion source and it has mainly an axial component of magnetic field in a discharge channel and only at exit area there is a radial component ending at an external magnetic pole. Magnetic poles are separated by a substantial distance. Magnetic field, in this case, is at maximum in anode area and decreasing approximately as $1/r^2$ to exit of a discharge channel. Working gas is applied through a separate gas distributor (called sometime, reflector) placed under an anode area, and from there is directed into an anode area.

An end-Hall ion source shown in **Figure 2** consists of a cathode 12, a hollow conical anode 13, magnetic system 14 (shown only the upper part of the magnetic system). Magnetic system 14 usually consists of a magnetic path with a pole 19, a magnet 16 that can be a permanent magnet or electromagnet. Magnetic field from magnet 16 decreases in a discharge channel 37 from a gas distributor (sometime called as reflector) 15 to a discharge channel exit 38, producing, in general, in a discharge channel 37-38 a magnetic field distribution a magnetic field with a negative gradient.

Anode 13 made of a non-magnetic material but of good electric conductivity; it has a hollow conical shape and connected through a conducting plate 30 with anode power supply (not shown). Working gases such as Argon, other noble or reactive gases (Oxygen, Nitrogen) are applied in to anode area 37 through a gas distributor/reflector 15 with holes 17.

Hot filament (usually a Tungsten or Tantalum wire) cathode 12 is placed between two cathode supports 18 and electrically isolated from the outer pole piece 19. Cathode supports 18 are connected by a solid insulated wiring (not shown on this figure) through an ion source' body 10 to a cathode power supply (not shown). A cathode wiring can be placed outside of a main body of an ion source. In some cases, instead of a hot filament there is utilized a hollow cathode, which in design is not so simple as a hot filament, but can provide higher emission currents and much longer operation lifetime.

For end-Hall ion source, hot filament cathodes of Tungsten (Tantalum has unpleasant property of being sagged after short operation time, and because of this, it is used quite rare and at low emission currents) of 0.020" (about 0.5 mm) thickness at discharge currents, I_d of about 5 A and discharge voltage, V_d of 150 V (or 750 W, which is about maximum power that can be applied into end-Hall with radiation cooled anode without overheating the magnet) can operate from 4 to 6 hours with Argon, from 6 to 8 hours with Oxygen, and from 8 to 14 hours with Nitrogen as working gases.

A hollow cathode with the same discharge parameters (I_d = 5 A, V_d = 150 V) usually operates with noble gases such as Argon (in technology), Xenon (for space thrusters) and can serve 100-200 hours with Argon utilized in anode and hollow cathode and with good accurate precautions, keeping gas supply clean, without contaminated gas lines. However, when a hollow cathode (with, for example, Argon as working gas) is utilized with reactive gases, such as Oxygen supplied into anode area, its lifetime becomes shorter due to penetration of reactive gas into internal parts of a hollow cathode; it becomes so-called "poisoned" (oxidized) [*This phenomenon and how it influences on performance of hollow cathode, discharge channel, anode and what to do with it will be discussed later in further publications]. Reactive gases sharply reduce emissive ability of a hollow cathode, usually made of Tantalum foil or other emissive materials. Lifetime of hollow cathodes with reactive gases in anode area is usually about halftime of operation time with noble gases.

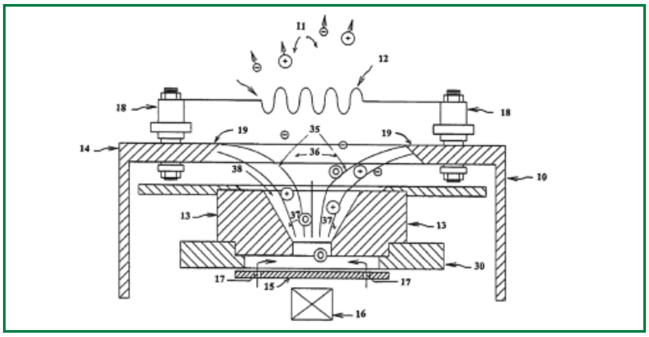

Figure 2. End-Hall ion source schematic: 10 - ion source; 11 - ion beam; 12 - Hot Filament cathode; 13 - anode; 14 - magnetic system; 15 - gas distributor - reflector; 16 - magnet; 17 - holes for working gas supply; 18 - cathode supports; 19 - magnetic pole; 30 - dielectric separarting plate; 35 - magnetic field lines; 36-37 - discharge channel.

An ion beam is developed in area between an anode 13 and cathode 12. Electrons (shown in **Figure 2** as circles with a sign -) supplied by a cathode are used for ionization of working gas neutral particles (shown as circles with a sign o) and for neutralization of developed ions (shown as circles with sign +). In result, neutralized plasma flow 11 exits from an ion source.

As it was mentioned earlier due to existence of mainly longitudinal magnetic field lines in end-Hall discharge channel, there is a negative aspect of end-Hall performance. It is existence of a strong plasma flow not only into an ion source direction, but also into opposite direction, into a gas distributor/reflector 15. Such strong plasma flow leads into a severe damage of a gas distributor/reflector 15, reducing its lifetime significantly. Besides a gas distributor/reflector damage, its sputtered particles fly back into a discharge channel's exit, into a vacuum chamber area leading to contamination of sputtering/deposition, ion assist process involving ion source.

In Hall current ion sources a magnetic field value in a discharge channel is selected in such a way that Larmour radii for electrons r_{Le} and ions r_{Li} calculated through energy corresponding to applied potential difference satisfy to the condition: $r_{Le} << L << r_{Li}$, where L is a characteristic dimension of an acceleration region in an ion source's discharge channel. In Hall current ion sources a cyclotron frequency of electrons ω_e must be greater than a frequency of electron collisions υ with other particles and discharge channel walls, i.e. $\omega_e >> \upsilon = 1/\tau_e$, where τ_e is an average time between electron collisions with other particles and discharge channel walls. That is why a so-called Hall parameter $\omega e \tau e$ that is utilized for electron magnetization is $\omega e^{\tau} e >> 1$.

The condition for magnetization of electron component in plasma ($\omega_e \tau_e >> 1$), and, at the same time, an ion component is not magnetized ($\omega_i \tau_l << 1$) means that a determining process in closed drift ion sources is an ion current motion in a discharge region, and an electric field is "suspended" on a magnetized electron component. In end-Hall ion source and some other type of ion sources, electrons in certain areas of a discharge channel occupied by plasma (at exit in end-Hall ion sources) can be only partially magnetized.

End-Hall ion source shown in **Figure 2** was first described in a patent [1] and an article [2], and later, in various patents and articles [1, 2, 7, 8, 9]. Closed drift thrusters-ion sources were described in large amount of literature, especially, in Russian publications. In the last 10 years there was also quite a boon with publications in American scientific literature, mainly as thrusters. One of our publications [3] gives a review of Russian works and basic physics of closed electron drift thrusters-ion source.

Despite that closed electron drift ion sources are more efficient than end-Hall ion sources, the simplicity of design and operation of end-Hall ion sources made them a major workhorse in the thin film technology and many other applications.

Recently, in the thin film technology, there was developed interest for the high ion beam currents with low ion beam energy for various new approaches in physical-chemical processes such as an ion assisted deposition, a biased target deposition, a magnetron with ion assisted deposition and other new techniques with one of accompanied problems is how to obtain low energy ion beams with high current. In many practical tasks it became important to have high current ion beams with low energies under a sputtering threshold that is about 15-30 eV for most materials utilized in the thin film technology.

In some recently published works a low energy ion beam was achieved with utilization of high mass flow of working gas (about 80 sccm for Argon) and comparatively high pressures in a vacuum chamber of $(1\text{-}2) \cdot 10^{-3}$ Torr [4].

Discussing broad-beam gridless ion sources it is necessary to emphasize, what are the most important characteristics in ion sources that users need to know and what kind of optimization can be done with end-Hall ion sources:

1. The range of energies which is a function of discharge voltage range of operation. End-Halls usually have the discharge voltage range from about 50 V to maximum 300 V for Argon and Xenon, for reactive gases Oxygen and Nitrogen the discharge voltages usually are from 80-100 V and up to 300 V. Note, that these ranges are for ion sources made by Veeco Instruments (Mark-2 and Mark-2+) and Kaufman & Robinson Inc. (K&R) (EH-1000, EH-2000). Other makers of end-Halls (Sainty's [9], several Chinese and South Korean companies) have slightly narrower range of discharge voltages V_d (and, therefore, energies). As a rule, ion beam energy in end-Halls is about $E_i \approx 0.6 \cdot V_d$, closed drift ion sources have $E_i \approx (0.7\text{-}0.8) \cdot V_d$. Ion beam energy is not so monoenergetic as in gridded ion sources, it has quite a broad distribution with the maximum at the operating Vd.
2. Range of ion beam ion currents. For above mentioned end-Halls (Veeco's and K&R the ion beam current I_i is generally $I_i \approx (0.2\text{-}0.25) \cdot I_d$. As it was indicated above end-Halls can deliver ion beam currents up to 1-2 A. Well regulated necessary ion beam current with the certain energy of ions, because the ion beam current density (the number of energetic ions in the unit of area in unit of time) produces necessary work on a target (targets), the ion energy also works on a target, knocking out necessary number of atoms per applied ion from a target. So, in general, higher the ion energy, higher is the sputtering rate (up to a certain level, of about 500 eV, when a number of emitted sputtered atoms for each incident ion starts to decrease (they go deeper inside, becoming implanted); so, for regular material processing tasks, it is not necessary to have ion beams with

energies higher than 500 eV). In industry, the higher ion beam current density and the higher ion beam energy produces faster processing of materials.

3. Simplicity in design and operation, easy to assemble and disassemble; all its parts must be inexpensive to make and substitute, easy to control electric and magnetic fields; easy operate with available Power Supplies.
4. Like many other physical devices, with a series independent variables, which include ion source dimensions that usually determine what kind of electric power can be applied into such device without hurting some parts, like magnet, or anode, or this device can produce unnecessary number of double ionized particles, or too much erosion from heated parts and bombarded by ion beam, or it would consume too much of working gas with low transformation into ion beam; all these factor should be taken into account.
5. Stability of operation; at certain operating conditions, such as high discharge voltages, high pressure in vacuum chamber, etc, ion source can become unstable with high level of discharge current and voltage oscillations; these oscillations can be caused by various reasons, some of them are discussed below;
6. "Poisoning" of anode and discharge channel with oxides and other deposits that can lead to gradual increasing of discharge voltage at constant discharge current and gradual decreasing of discharge current at constant discharge voltage.

REGIME OF NON-SELF-SUSTAINED DISCHARGE

Volt-Ampere Characteristics of Discharge

The experiments presented in this article were conducted with the improved performance end-Hall ion source described in [7]. In order to analyze the experimental results with a so-called non-self-sustained discharge and its role in Hall-current ion sources, it is best way to start with the analysis of Volt-Ampere (V-A) characteristics of discharge in Hall-current ion sources. In general, V-A characteristics for both types of ion sources demonstrate very similar behavior.

In **Figure 3** upper curves **1** and **2** show typical Volt-Ampere (V-A) characteristics of high current intense discharge of end-Hall type ion source for discharge current I_d = 5 A as function of discharge voltage V_d. Working gas is Argon, pressure in vacuum chamber is between 5×10^{-5} and $(1\text{-}2)\times10^{-3}$ Torr. Lower curves **3** and **4** present an ion beam current I_i as a function of discharge voltage, $I_i = f(V_d)$. Discharge between anode and cathode is maintained by electron emission provided by a cathode. Two different electron emission currents are utilized in this figure $I_{em} \approx I_d$ = 5.0 A (curves 2 and 4) and I_d = 5.0 A with I_{em} = 10 A (curves **1** and **3**).

Source of electrons is either a Hot Filament (HF), or a Hollow Cathode (HC). For the conditions in end-Hall ion source a magnetic field value of a permanent magnet, or electromagnet is, in general, between about 500 G and 1500 G (depending on ion source's dimensions) that is maximum value at the top of a gas distributor/reflector. For a closed electron drift ion source a magnetic field of a permanent magnet or electromagnet is between 100 G and 500 G that is a maximum value, which is usually at exit flange (depending on working gas and ion source dimensions).

High current electrical discharge in Hall current ion sources represented in **Figure 3** is of two types: a *non-self-sustained and a self-sustained discharge*. A non-self-sustained discharge takes place for discharge voltages from about $V_d \approx$ 50-60 V for an end-Hall, and from about $V_d \approx$ 80-100 V for a closed electron drift and up to about 360-370 V for both ion sources it can exist and maintained only due to a continuous development of charged particles provided by a source of electrons. In practice, a non-self sustained discharge is realized with help of a hollow cathode (HC), or a hot filament (HF), or other source of electrons.

Due to different placements of magnetic fields, a closed electron drift ion source has magnetic field maximum at the exit of discharge channel and is considered as a source with a positive gradient of magnetic field, and an end-Hall has a magnetic field minimum at the discharge channel exit and maximum magnetic field at a basement of a gas distributing system and is considered as a source with a negative gradient of magnetic field. With Xenon as working gas, discharge can be ignited by about 15-20 Volts lower for both ion sources. This discharge voltage ignition values given above are for approximate equality of discharge and emission currents. Various ignition discharge voltages can be explained by the fact that a closed drift ion source has mainly a radial magnetic field component in the whole discharge channel, and end-Hall has a radial magnetic field component at exit from an ion source. So, for electrons generated outside the ion source discharge channel it is more difficult to go through a higher radial magnetic component in a closed drift source than in an end-Hall source.

Operation of End-Hall Ion Source with Excessive Electron Emission

If the emission current is higher than the discharge current, the situation with the ignition of ion source and ion beam current value is changed substantially. The curves **1** and **3** of **Figure 3** represent Volt-Ampere characteristics for emission current higher than discharge current, and, in this particular case, for I_{em} = 10 A.

In practice, there is always utilized approximate equality of discharge and emission currents $I_d \approx I_{em}$, and the producers of ion

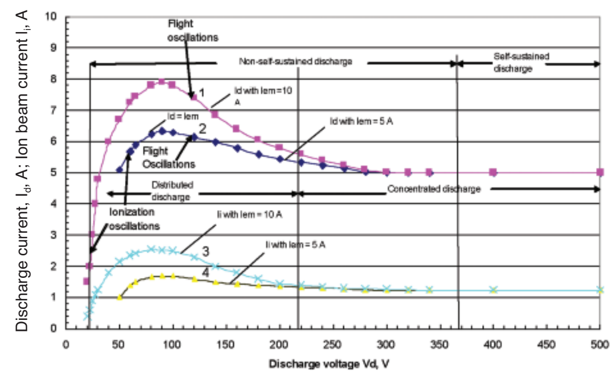

Figure 3. V-A Characteristics for end-Hall ion source with I_d and I_i as functions of V_d for $I_d = I_{em}$ = 5A, and I_{em} = 10A, working gas Argon.

sources encourage users to apply slightly higher emission current by about 5-10% over a discharge current value. What is called here as emission current is simply a cathode current (of a hollow cathode (HC), or a hot filament (HF)). In absence of electromotive force (EMF) between a cathode and vacuum chamber a cathode current is equal to a discharge current. Discharge current is equal to a sum of ion current and electron current through an ion source. In such a regime of operation a cathode potential relative to a vacuum chamber walls is usually negative. However, when a source of EMF exists, a cathode current can be higher than a discharge current by a value of an electron current to vacuum chamber walls, which can be regulated by a cathode's EMF. Correspondingly, a cathode potential and plasma at an ion source exit will be changed. These changes depend also on version of connection of polarity of a cathode source of EMF.

During increasing of a cathode current relative to a discharge current the changes of a gas discharge chamber parameters reduce the discharge ignition voltage and expand the range of ion source operation in to the side of low discharge voltages and higher ion beam currents. From **Figure 3** one can see that the ratio of an ion beam current to a discharge current is increased also substantially, $I_{i,Iem=10A}/I_{i,Iem=5A} \approx 1.56$.

1. The curves **1** and **3** of V-A characteristics show importance of a high emission current for maintaining gas discharge at low discharge voltages and providing an ion beam current higher than at usually accepted conditions of equal emission and discharge currents. The discharge currents curves at I_{em} = 10 A and I_{em} = 5 A, and also the ion beam current curves at I_{em} = 10 A and I_{em} = 5 A practically coincide with each other at discharge voltages of $V_d \approx 200$ V and higher. At discharge voltages over about 300 V discharge current practically does not depend on a discharge voltage, because at $V_d \geq 300$ V neutral atoms are practically all completely ionized and discharge current value becomes saturated.

Volt-Ampere characteristics for other gases such as Xe, or O_2 and N_2 are similar as for Ar. Heavy gas Xe with its low first ionization potential (E_{ion} = 12.13 eV) has ignition discharge voltages lower than Ar (E_{ion} = 15.76 eV), down to about 15-20 V, but O_2 and N_2 start discharge at voltages about 70-80 V and up. However, the additional emission helps to reduce the discharge voltage ignition for all gases by 10-20 V.

Another feature of the discharge with emission higher than the discharge current is that after beginning discharge with the above particular parameters (for example: Ar, I_d = 5 A, I_{em} = 10 A, $V_{d,ign} \approx 30$ V) discharge will be extinguished at lower discharge voltage value of $V_{d,ext} \approx 20$-25 V, where $V_{d,ign}$, and $V_{d,ext}$ are an ignition and extinguishing discharge voltage values.

In practice, in order to have conditions of low voltage discharge (low ion beam energies), it is advisable to start discharge at higher discharge voltage, like V_d = 100 V with $I_{em} \approx I_d$, or at $V_d \approx 60$-70 V with $I_{em} > I_d$, and then gradually decrease discharge voltage value by a Power Supply to a required lower value. Xenon's low first ionization potential allows ion source' starting with voltages of 40-50 V and lower with $I_{em} \approx I_d$, and at about 15-20 V at $I_{em} > I_d$. These numbers are for end-Hall type ion sources; for closed electron drift ion sources ignition voltages are higher by 20-30 V.

As was above noted, a high current discharge in ion sources with a discharge voltage over $V_d \approx 370$-380 V presents itself a *self-sustained discharge* when it is not necessary to supply electrons from a cathode-neutralizer for neutralization of ions. After discharge is initiated, a high voltage discharge produces sparks creating electrons in discharge channel and outside of an ion source, in vacuum chamber walls.

Also, discharge at low discharge voltages and up to about V_d = 215 V presents itself a mode that called a *distributed discharge*. A discharge at higher discharge voltage over 215 V presents itself another modification called a *concentrated discharge*. These modifications received such names because they are observed from outside of a vacuum chamber as distributed and concentrated forms of discharge, meaning that a distributed discharge is really uniformly distributed over a discharge channel area, and a concentrated discharge can be seen in a form of plurality of pinched plasma flows, and at high currents of 10 A and higher as one pinched discharge surrounded by a glow.

As it was noted in [5], both kinds of intensive discharge such as a non-self-sustained (in a distributed mode) and a self-sustained (in a concentrated mode) significantly different in their physical processes. The processes taking place in a distributed discharge are more complex and less investigated. In particular, for propagation of electron current from cathode to anode it is necessary to have a presence of excessive plasma conductivity, which at certain conditions can be caused by development of oscillations of current and voltage. At the same time, the total relative amplitude of ion beam current oscillations in a distributed mode is substantially lower than in a concentrated discharge.

In one of publications about closed drift anode layer type ion sources/thrusters [6] there are presented experimental results with discharge, where the working gas was Bismuth. In the anode layer ion source/thruster having dimensions of exit discharge channel diameter is 80 mm the discharge's distributed mode was at discharge voltages of less than 250 V. It was noted that at a distributed form of discharge the ion flow parameters at the source's exit are more uniform that at a concentrated modification. Also, an ion beam focusing quality of a distributed mode is better than in a concentrated modification. The exact values of discharge voltage for transition from one form into another depend on: dimensions and geometry of discharge channel, discharge current, working gas mass flow and magnetic field in a discharge channel.

It is necessary to note that the behavior of curves such as initial discharge voltage (discharge ignition), an ion beam current value, the ranges of various discharge types and modes depend not only on the emission current value, but also on the following factors:

2. Mass flow of working gas applied into a discharge channel and pressure in vacuum chamber: higher the mass flow, lower the discharge voltage ignition;

3. Dimensions and shape of an ion source's discharge channel;

4. Magnetic field value and ion source' magnetic circuit configuration;

5. Gas distributing system; how working gas is applied into anode region; how working gas is distributed in discharge channel, whether it comes from area under anode (could be applied first into a so-called buffer area) and well distributed there, or applied through small jets from gas supply holes, or from anode itself;

6. Emission current value supplied by HF, HC, or by other means; how emission provides a flow of electrons into a discharge channel; how HF, HC are placed and at what distance from exit flange of ion source;
7. Kind of working gas: low, high atomic mass, ionization potential.

ION BEAM ENERGY OF END-HALL ION SOURCE

As it was above mentioned noted, one of the most important characteristics of ion source is ion beam mean energy values and how this energy is distributed, is it a monoenergetic beam, or distributed over certain range of energies, what is real ion beam mean energy, how to estimate it.

In **Figure 4** there is presented the retarding potential energy analysis for end-Hall ion source described in [7] operating at discharge current $I_d = 5$ A and discharge voltage $V_d = 90$ V with two different emission currents, $I_{em} = 5.0$ A and $I_{em} = 10$ A; working gas is Argon.

An ion beam probe using retarding potential is at distance of 30 cm from end-Hall ion source exit (front flange). These profiles show measured various ion beam currents with variable potentials applied to a probe's grid. As one can see, the probe's plot for higher emission with $I_{em} = 10$ A is on the top of a regular curve with $I_d = I_{em} = 5$ A. It also since area for curve with $I_{em} = 10$ A includes the area with $I_{em} = 5$ A, it means that energy volume for $I_{em} = 10$ A is larger than for $I_{em} = 5$ A. The real ion beam energy distributions are obtained after differentiation of both curves.

Such differentiation with assumption for presence of only singly charged ions is performed in **Figure 5.** where the median energy of ions presented in electron-Volts, which correspond to the retarding potential in Volts. In **Figure 5** one can see two energy distributions for regular and higher than discharge current emissions.

Figure 5, for the case $I_d = I_{em} = 5$ A, shows quite a good number of ions with mean energy of about 25-30 eV and 90 eV with much less ions between these energies. For the case of $I_d = 5$ A and $I_{em} = 10$ A the energy analysis indicates that most ions are distributed with energy mostly around 90 eV and with very low percentage of other energies.

Very similar results for ion beam energy analysis shown in **Figure 6** and **Figure 7** were obtained for the cases with discharge current $I_d = 5$ A at higher discharge voltage of $V_d = 150$ V, $I_d = I_{em} = 5$ A, and $I_d = 5$ A and $I_{em} = 10$ A. Again, for $I_d = I_{em} = 5$ A a certain number of ions are distributed around 30 eV, with the most part around 150 eV. The energy distribution for higher emission current $I_{em} = 10$ A is mainly around 150 eV.

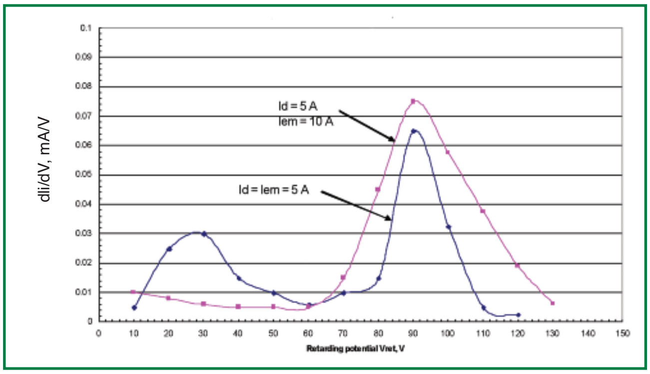

Figure 5. Energy analysis, end-Hall ion source, HF, Ar, $V_d = 90$ V, $I_d = I_{em} = 5$A, and $I_d = 5$A, $I_{em} = 10$A, probe at 30 cm from ion source; dl i/dV, mA/V as function of retarding potential, V_{ret}, V.

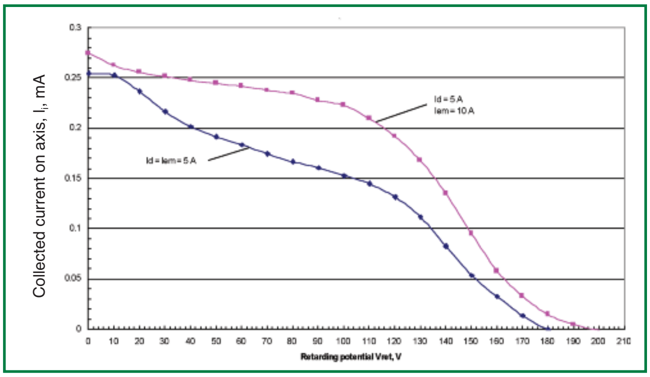

Figure 6. Energy analysis, end-Hall ion source, HF, Ar, I_i as function of V_{ret}, $V_d = 150$A, $I_d = I_{em} = 5$A, and $I_d = 5$A, $I_{em} = 10$A, probe at 30 cm from ion source.

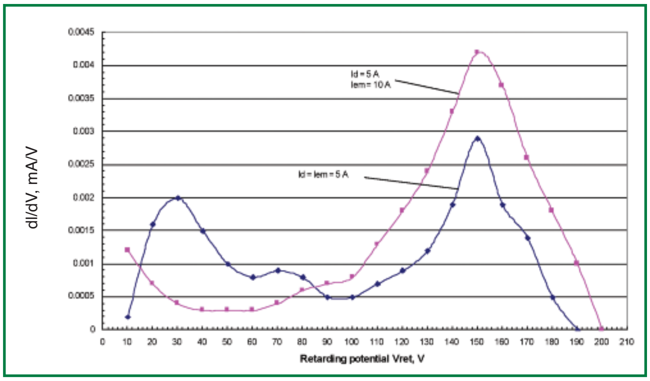

Figure 7. Energy analysis, end-Hall ion source, HF, Ar, $V_d = 150$V, $I_d = I_{em} = 5$A, and $I_d = 5$A, $I_{em} = 10$A, probe at 30 cm form ion source. dli/dV, mA/V as function of retarding potential, V_{ret}, V.

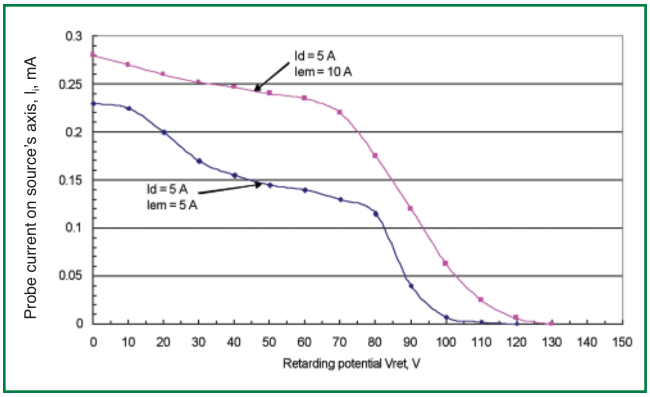

Figure 4. Energy analysis, end-Hall ion source, HF, Ar, I_i as function of V_{ret}, $V_d = 90$V, $I_d = I_{em} = 5$A, and $I_d = 5$A, $I_{em} = 10$A, probe at 30 cm from ion source.

Our estimation of energy distributions for the cases with equal discharge current and emission current and for emission current higher than discharge current indicates that plasma parameters in end-Hall ion source are determined mainly by developing in the charge channel oscillations. The “smearing” ion energy spectrum is caused by two main factors: 1. extended region of ionization due to comparatively long discharge channel, and 2. oscillations of potential.

The range of ion energies can be seen on **Figure 5** and **Figure 7** where there are ions with energy exceeding eV_d. In **Figure 5** at $V_d = 90$ V, there are ions with energies higher than 90 eV, and in **Figure 7** at $V_d = 150$ V, there are ions with energy up to 200 eV.

In recently published work [4] the experimental results for low-energy ion beam from end-Hall ion source utilized for etching of different materials are presented. There are shown the ion beam characteristics performed with the help of a retarding potential analysis for discharge voltage $V_d = 150$ V and discharge current $I_d = 5.7$ A (it is not mentioned, but is assumed that $I_{em} \approx I_d$); working gas Argon. The analysis after differentiation of a probe’s ion current versus a retarding potential shows two typical “humps”, one is of low energies of about 25 eV and another one at about 150 eV. Low energy “hump” is attributed to mostly charge-exchange ions that take place during propagation of ion beam originated in an ion source’s discharge channel through background neutrals. However, there is given the consideration that an ion source operation and an ion source design may produce those low energy ions.

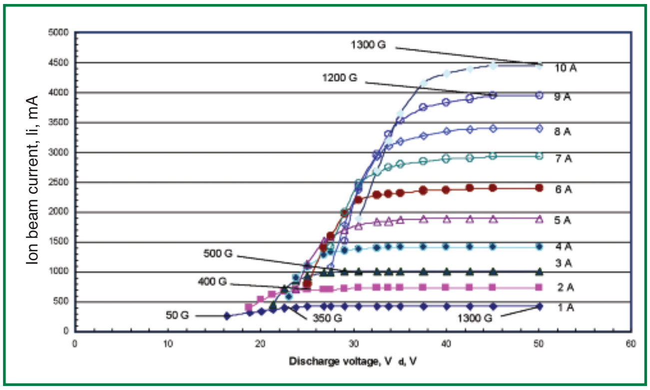

Figure 8a. End-Hall ion source ion beam current as function of discharge voltage at high emission I_{em}=15A for discharge currents I_d = 1, 2, 3, 4, 5, 6, 7, 8, 9,10A with various mangetic fields from 50 to 1300 G at reflector, Ar.

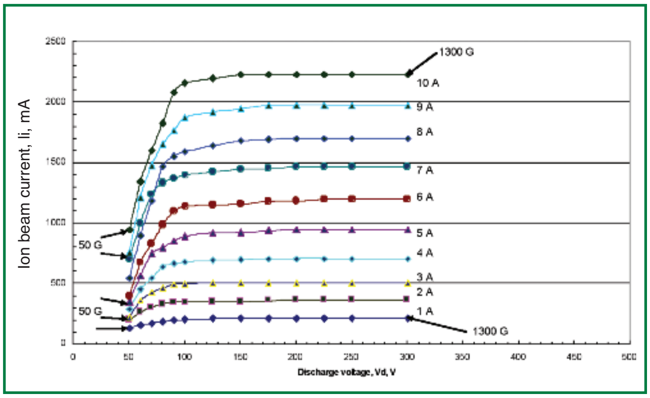

Figure 8b. End-Hall ion beam current as function of discharge voltage for regular emission current Id=I_{em} for discharge currents I_d = 1, 2, 3, 4, 5, 6, 7, 8, 9,10A with various mangetic fields from 50 to 1300 G at reflector, Ar.

END-HALL ION SOURCE OPTIMUM MAGNETIC FIELD

Ion Beam Current

In **Figure 8** there are presented experimental results of a measured ion beam current, I_i as a function of discharge voltage V_d. with various magnetic field values at the gas distributing system (reflector) for discharge currents I_d = 1, 2 , 3, 4, 5, 6, 7, 8, 9, 10 A and the emission current I_{em} = 15 A. The magnetic field values were varied from 50 G to 1300 G. These profiles show that for each discharge current there is an optimum effective magnetic field that provides a maximum ion beam current. At optimum magnetic fields and utilized high emission current I_{em} = 15 A the ion beam currents are from about $I_i = (0.325\text{-}0.4) \cdot I_d$ for I_d = 1-4 A, and about $I_i = (0.44\text{-}0.56) \cdot I_d$ for I_d = 5-10 A. For such high emission current the discharge voltages were in the range from about 20 V for low discharge currents, and up to measured 50 V. These discharge voltages correspond to ion beam mean energies to from about 15 eV and up to about 35 eV. For V_d = (20-30) V, ion beam mean energies correspond to about $E_i \approx (0.6\text{-}0.7) \cdot V_d$, and for V_d = (40-150) V one can have $E_i \approx (0.7\text{-}0.9) \cdot V_d$ in comparison with $E_i \approx 0.6 \cdot V_d$ for a case with $I_d = I_{em}$. The ion beam current values are, in general, substantially higher than for the case $I_d = I_{em}$, because for equal discharge and emission currents an ion beam current for such ion sources like Mark-2 (Veeco), EH-1000 (K&R), Sainty’s an ion beam current is $I_i \approx (0.2\text{-}0.25) \cdot I_d$.

Also, in **Figure 8** there are indicated the magnetic field values at a gas distributor-reflector, where experimental points give ion beam current values through each 50-100 G. These values show that for low discharge currents it is not necessary to use high magnetic fields, however, for the discharge currents of about 9-10 A it is very important to have high magnetic field values, or for such currents there will be difficult to obtain high ion beam currents.

Note that for the cases with equal discharge and emission currents the ion beam current dependence on discharge voltage is very similar to that with the high emission current, except that the ion beam currents are lower, though the magnetic field values behave in the same way: if one wants to have high ion beam currents at high discharge currents over 5 A, the magnetic fields should be at least over 1000 G on the reflector.

In practice, most commercial end-Hall ion sources utilize a permanent magnet placed under a gas distributing system with the magnetic field value of about 1000-1200 G at a gas distributor-reflector. It means that ion sources equipped with high magnetic field values can be good with high electron emission for obtaining high ion beam currents, however, with time magnetic field usually gradually deteriorates due to various reasons (overheating, careless treatment, etc). For those who want to have low ion beam energies and an ion beam current is not so important, it is advisable to use low magnetic fields.

In **Figure 9** there are presented Volt-Ampere emission characteristics for discharge currents operating at I_d = 1 A, 2 A, 5 A and emission currents I_{em} change from 2 A to 15 A. Magnetic field value B = 200 G, Argon. Also **Figure 9** shows that in order to obtain the effect of high emission current at low discharge currents, it is not necessary to increase substantially the emission current.

In **Figure 10** there are presented Volt-Ampere emission characteristics for discharge currents operating at I_d = 2 A, 5 A, 10 A and emission currents I_{em} change from 2 A to 20 A. Higher magnetic field value B = 700 G, Argon. As in **Figure 7**, the effect of higher emission current on discharge voltage (ion beam energy) than the discharge current also is not so prominent at high discharge currents.

In **Figure 11** there is given the comparison of behavior of the discharge voltage as function of the emission current for the discharge currents of 2 A and 5 A and magnetic fields at reflector's place of 200 G and 700 G

As one can see, if one would want to have low discharge voltages (low energies), it's easier to get them with lower magnetic field. However, an ion beam current will be higher at higher magnetic fields.

There is another aspect of utilization of high emission current in comparison with equal to discharge current. In **Figure 12** there is shown a discharge voltage as function of mass flow applied into discharge channel for discharge current I_d = 1 A for three different emission currents I_{em} = 1, 3, 5 A. As one can see, the utilization of higher emission current not only reduces discharge voltage (and ion beam energy), but for the same discharge voltage one can apply substantially lower mass flow. Lower mass flow keeps pressure in vacuum chamber lower, and "cleaner" plasma flow with less charge-exchange particles.

Ion beam energy

In **Figure 13** there are presented the ion beam mean energies as function of angle from end-Hall ion source axis for the discharge current of I_d = 1 A, discharge voltage V_d = 50 V and various emission currents of I_{em} = 1, 2, 3, 5 A; ion probe is at distance of 30 cm from the end-Hall front flange. As one can see, at the emission current of $I_{em} \approx I_d$ = 1 A the mean energy is about

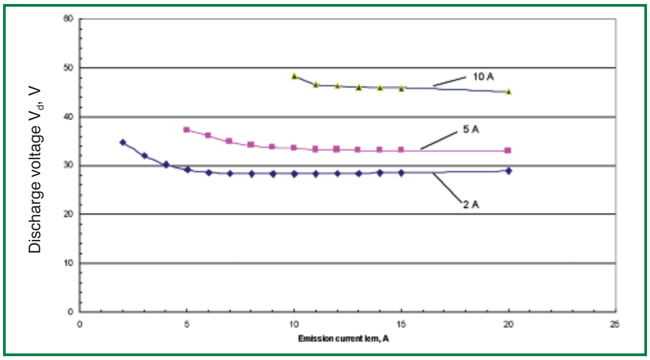

Figure 10. End-Hall. Discharge voltage V_d as function of emission current I_{em} for different discharge currents I_d = 2A, 5A, 10A; Argon, B = 700 G.

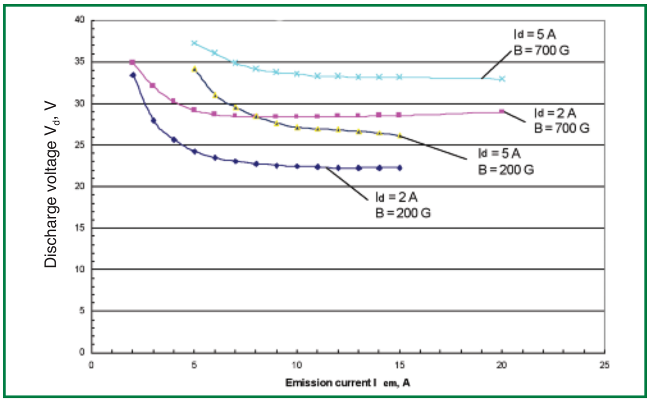

Figure 11. End-Hall, Argon, V_d as function of I_{em} for I_d = 2A and 5A with B = 200 G and B = 700 G.

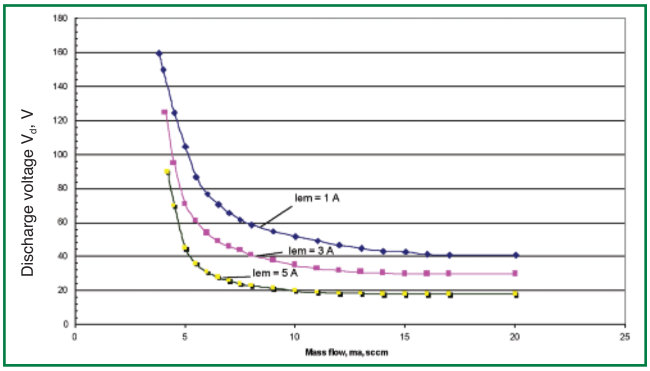

Figure 12. End-Hall, Discharge voltage V_d as function of mass flow for I_d = 1A and different emission currents I_{em} = 1, 3, 5A, Argon.

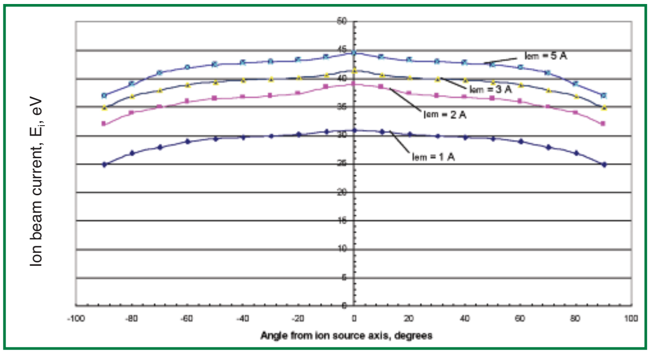

Figure 13. End-Hall, Ion beam energy E_i as function of angle from ion source axis, I_d = 1A, V_d = 50 V, emmision currents I_{em} = 1, 2, 3, 5A, Argon, ion probe at L = 30 cm form ion source exit plane.

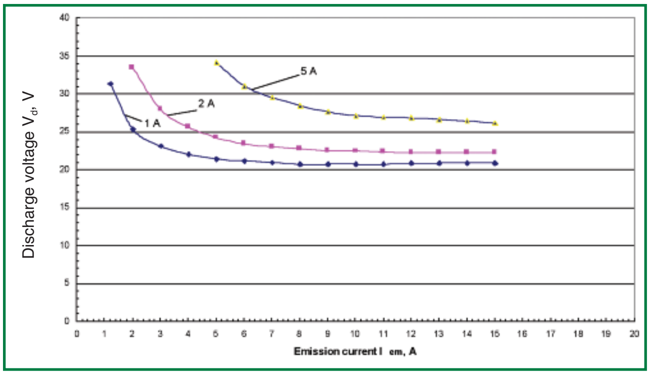

Figure 9. End-Hall ion source, Discharge voltage V_d as function of emission current I_{em} for discharge currents I_d = 1A, 2A, 5A, Argon, B = 200 G.

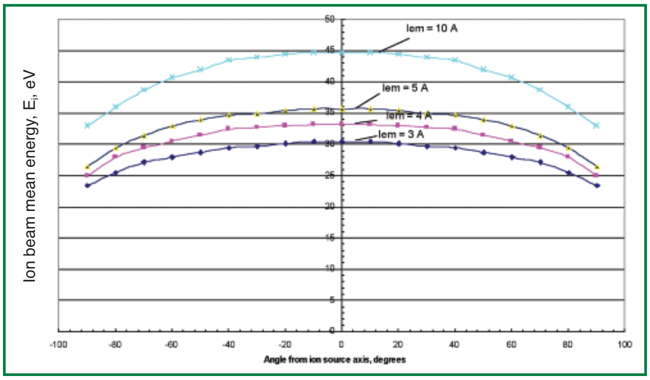

Figure 14. End-Hall ion source. Ion beam mean energy E_i as function of angle from ion source axis, V_d = 100V, I_d = 3A, L = 30 cm with various emission currents $I_{em,}$ = 3, 4, 5, 10A.

$E_i \approx 0.6 \cdot V_d$, as in most end-Hall ion sources [1, 2]. For comparison, in ion sources/thrusters with closed electron drift the ion mean energy is about (0.7-0.85) $\cdot V_d$. This is explained by the fact that the efficiency of ion beam generation in closed drift ion sources/thrusters is substantially higher than in end-Hall ion sources. However, as one can see, with the increasing electron emission current up to I_{em} = 5 A the mean ion beam energy increases to about $E_i \approx 0.9 \cdot V_d$ on an ion source axis

In **Figure 14** one can see the ion beam mean energies as function of angle from end-Hall ion source axis for the discharge current of I_d = 3 A, discharge voltage V_d = 100 V (one of the most "popular' discharge voltages used in practice of thin film deposition) and various emission currents of I_{em} = 3, 4, 5, 10 A; ion probe is at distance of 30 cm from the end-Hall front flange.

With the emission current increase up to I_{em} = 5-10 A the mean ion energy becomes $E_i \approx 0.9 \cdot$ Vd. However, with the decrease of discharge voltage to $V_d \approx 20$ V the mean ion energy decreases to about $E_i \approx (0.55\text{-}0.7) \cdot V_d$ and with the increase of discharge currents over 7-10 A this effect is not so prominent. We are planning to provide more experiments with high emission currents and high discharge currents. One of assumptions is that at higher discharge currents over 7-10 A a distributed mode of discharge makes transition into a concentrated mode.

It is necessary to note that higher than regular electron emission ($I_{em} > I_d$) strongly influences on the ion beam current, the mean ion energy, discharge behavior at low discharge currents (under about 5-7 A) and discharge voltages (under about 220 V) that are in the operation range in the distributed mode of the non-self-sustained discharge.

Conclusion

Here are some conclusions from the presented experimental results with end-Hall type ion sources. The end-Hall ion source efficiency can be improved in several ways, which include:

1. Operation with discharge in the non-self-sustained regime in a distributed mode.
2. Ion source efficiency, its ion beam current and beam mean ion energy can be substantially enhanced utilizing excessive electron emission from a Hot Filament or Hollow Cathode source of electrons.
3. Operation with high electron emission and low magnetic field can provide ion beams with low energy under 20 eV for most working gases with reasonable values of ion beam currents.
4. For each end-Hall ion source the magnetic field should be optimized depending on particular task for this ion source whether it could be with low or high ion beam energy.

In our next publications we are going to discuss the following important topics for end-Hall ion sources adequate operation:

1. Oscillations and instabilities in Hall-current ion sources and what to do with such oscillations and instabilities.
2. Double ionized particles, theirs role and how to eliminate them in operation and design.
3. Standardization of ion sources, interaction of ion source with vacuum chamber. "Poisoning" of anode and how to operate ion source in the conditions of anode oxidation.
4. Facility effects on operation of ion sources. Heating effects from ion sources
5. Charge-exchange particles, theirs role. Ion beam and target neutralization.

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