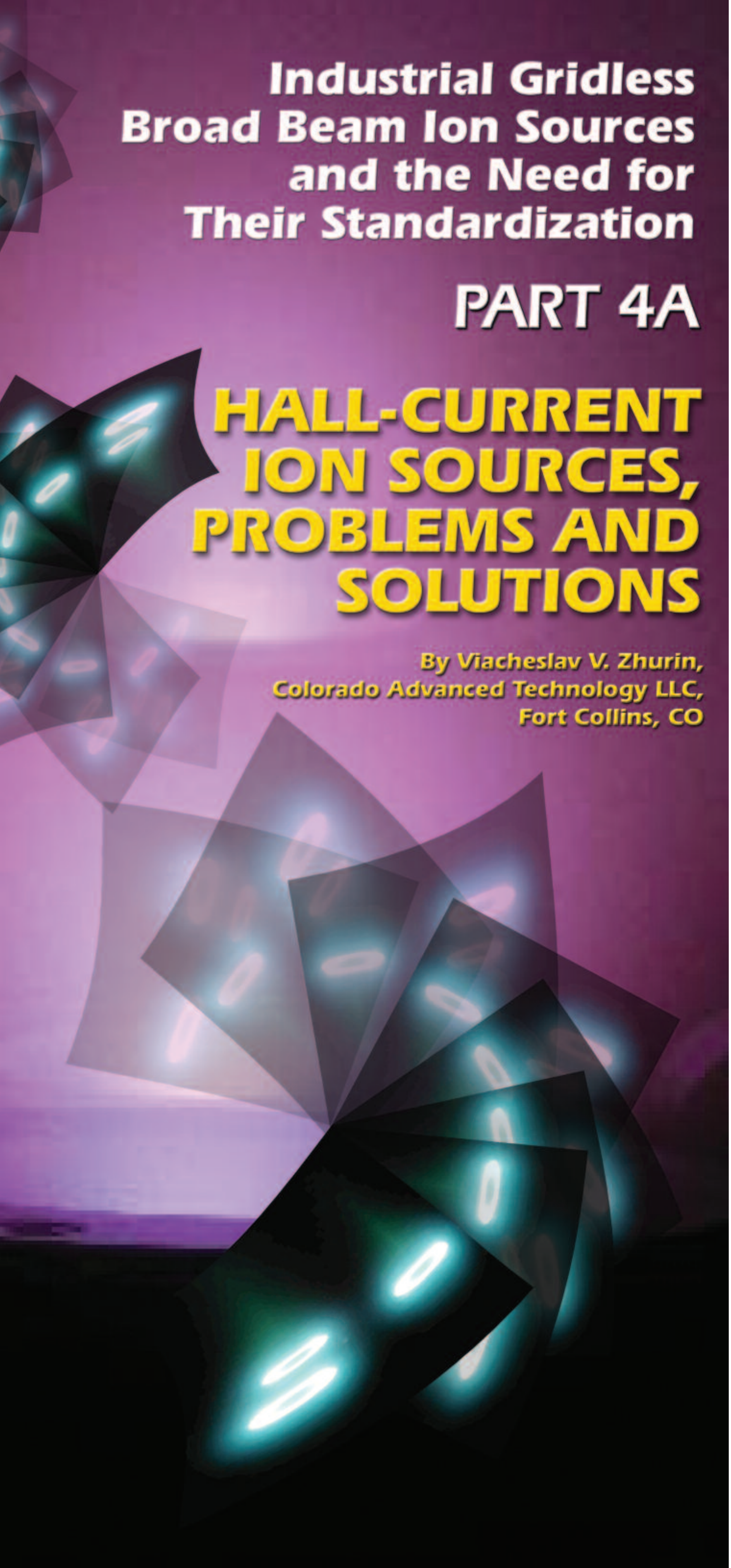

Industrial Gridless Broad Beam Ion Sources and the Need for Their Standardization

PART 4A

HALL-CURRENT ION SOURCES, PROBLEMS AND SOLUTIONS

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This article "Industrial Gridles Broad Beam Ion Sources ..." consists of 4 parts. Part I, 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 3 of August issue covered "Non-Traditional Ion Sources" and Part 3B of September issued covered "Linear Broad Beam Ion Sources". And, Part 4 covers "Hall-Current Ion Sources Basic Operation Parameters Problems and Solutions" and "The Need for Standardization of Ion Sources".

The advantage of ion-plasma thin film deposition in comparison with other types of depositions is determined by the following features:

- thin films obtained by ion-plasma beams have better adhesion than thin films produced by other methods due to high energy of sputtered particles coming to a substrate; high energy of sputtered particles reduces a minimum temperature of epitaxial grows of films and also provides films of higher density:
- deposition of films of metals and dielectrics, alloys and composite materials takes place without change of a stoichiometric composition, if temperatures of a sputtered target and a substrate remain sufficiently low;
- since sputtering process does not need melting of a target material, it is possible to obtain films of refractory materials and also of non-melting materials;
- by regulation of energetic ions composition and surrounding gas media, it is possible to change properties of obtained films, to control and regulate its stoichiometry;
- a substrate and growing film can be cleaned before, during and after the deposition process by ion bombardment; the energy of ion bombardment can be regulated in order to find the most desirable properties.

Thin films of necessary composition are obtained either by sputtering of corresponding composition target, or by simultaneous sputtering of a series of targets of different materials, or by utilization of various working gases. In this case, a sputtering efficiency can be regulated by the ion beam current and energy of bombarded ions. A sputtered target dimension can be selected according to dimensions of a substrate, so the area of uniform deposition on a substrate will depend on ion source size and target dimensions.

The rates of low energy ion-plasma deposition, in general, are lower than the rates of physical vapor (PVD), or magnetron depositions. However, this shortcoming can be overcome by utilization of high ion beam currents that recently developed Hall-current ion sources can deliver.

Early developed ion sources could not provide sufficiently pure depositions because ion sources operated at high working pressures and low ion beam currents. New generation of ion sources that came from electric propulsion can operate at pressures of 10^{-5}-10^{-4} Torr that significantly reduce contamination of thin films.

Basic parameter of ion-plasma deposition is a distributions rate, ξ_d determined by formula:

$$\xi_d = (\xi_s \alpha_{ad}/s) \cdot \int \beta ds, \qquad \textbf{(4.1)}$$

where ξ_s is a sputtering rate, nm/sec; α_{ad} is an adhesion coefficient of sputtered particles to a substrate; β is a probability of appearance of sputtered particles from a target element ds into a substrate; s is area of a sputtered target.

A sputtering rate, ξ_s is quite complex function of energy and energy distribution of bombarding ions:

$$\xi_s \sim \int S(E) j(E) dE, \qquad \textbf{(4.2)}$$

where S(E) is a sputtering coefficient, atom/ion; j(E)dE is an ion current density distribution of ions bombarding target.

In a simple approach, a sputtering coefficient characterizes a number of sputtered atoms N_n for one incident ion N_p is expressed by a simple looking formula:

$$S(E) = N_n/N_p. \qquad \textbf{(4.3)}$$

The typical form of S(E) dependence is presented schematically at **Figire 32** [71]. Here one can see five regions of ion beams different energies that can be applied to a target. In the region I there is practically no sputtering. The region II is area of a sputtering threshold with $\varepsilon^* \sim$ 20-30 eV [*There are different opinions whether a sputtering threshold value is exact number for different materials. Majority of experiments show that it is not exact number, and it rather has a quite broad distribution that depends on various experimental conditions, such as surrounding pressure and a target's temperature.]. In the region III the coefficient S with quite a good degree of accuracy increases linearly, and the characteristic values $\varepsilon_1 \sim$ (30-50) eV, $\varepsilon_2 \sim$ 500-600 eV. Then the growth decreases, passes through the maximum in the region IV and in the region V one can see sharp decline of the sputtering coefficient. This behavior of sputtering coefficient is very similar for majority of materials.

These expressions together give a following equation for a deposition rate:

$$\xi_d \sim (\alpha_{ad}/s) \int\int \beta S(E) j(E) dE ds. \quad \textbf{(4.4)}$$

From the above given expression (4.4) one can see that the efficiency of ion-plasma deposition is determined by three factors: 1. sputtering defined by the parameter ξ_s, 2. transfer of particles defined by the parameter β, and 3. condensation of particles defined by the parameter α_{ad}. As formula (4.2) shows, the parameter ξ_s depends on the ion current density j and energy E. All these parameters determine the total rate of ion-plasma deposition. Also, these parameters influence on the quality of obtained thin films.

In every sputtering-deposition process by an ion-plasma beam it is necessary to know the ion beam current density and the mean ion energy of ions bombarding sputtering target. At pressures higher than 10^{-1} Pa (7.5×10^{-3} Torr) there is a high probability of collisions between ions and atoms of surrounding gas; there is a quite aggressive phenomenon of a charge exchange during an ion motion to a target. In such a case, an ion loses its charge and bombards a target as a neutral particle that preserved its kinetic energy acquired earlier. As it was discussed in our previous publication in *VT&C* [25], the effective cross section for a charge exchange, for example, for Argon ions in a reaction $Ar^+ + Ar \rightarrow Ar + Ar^+$ has a very high value of about 10^{-15} cm^2. That is why for having a pure ion beam, besides of a purity of gas composition, it is desirable to operate with ion beams at low pressures of 10^{-4}-10^{-5} Torr .

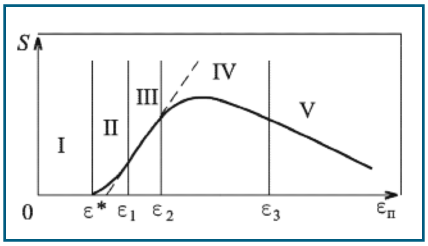

Figure 32. Sputtering coefficient S(E) as function of ion beam energy

As one can see in a **Figure 32**, the most optimum sputtering coefficient as function of energy is a range of energies from about 100 eV to about 600 eV. In order to increase the efficiency of sputtering it is better to increase particles power through the increase of an ion current density (which is proportional to a discharge current), but not ion energy.

Ion beam deposition of thin films are utilized in cases, when it is necessary to produce very thin films (from several Angstroms to over 1000 A) of complex stoichiometric composition that will be impossible to obtain by a PVD or by a magnetron deposition.

Work with Hall-current ion sources can include various new approaches in thin film depositions that are necessary in development of advanced optical systems. The examples of the new ways to make optical structures with improved properties of deposited materials are: **a**) a biased target deposition and **b**) an ion assisted magnetron deposition with magnetron's electrons utilized for the ion source ionization and the ion beam neutralization [*These two new methods will be discussed in our further publications in *VT&C*].

I. BASIC PARAMETERS, PROBLEM, SOLUTIONS

There are several problems accompanying existing broad beam gridless Hall-current ion sources. Some problems are serious, some not. Some problems can be ignored completely at certain situations, some must be looked deeply, estimated, and, if necessary, taken into account, or solved. Also, since the majority of industrial ion sources at this time are the end-Halls, there will be most discussed basic parameters of the end-Halls and less information will be presented below about the Closed Drift Cylindrical Ion Sources. For some cases there will be given comparisons of end-Halls with Closed Drift Cylindrical ion sources, Linear end-Halls and Anode Layer Linear Ion Sources. Presented in Part3 [77] some ion sources (Denton, DynaVac) can be related to a certain degree as end-Halls. However, the hybrid ion source [34] can be called as an end-Hall-Closed Drift ion source, because the magnetic field in it has a positive gradient.

Here are considerations about the main important characteristics of industrial gridless ion sources and what kind of job they are designed to do.

1. Ion beam energy E_i does not equal exactly to the discharge voltage eV_d

Because ions are developed in a certain volume with a certain dimensions and the applied discharge potential is usually distributed over these dimensions, ions are materialized with different energies in different points of a discharge channel. It means that an ion beam coming out of a gridless ion source has quite a broad energy distribution.

Figure 33a shows quite a broad ion beam energy distribution for the end-Hall type ion source with the discharge voltage $V_d = 150$ V, discharge current $I_d = 5$ A and two emission currents $I_{em} = 5$ A and $I_{em} = 10$ A; working gas Argon. Some works [23] explained the hump for $I_{em} \approx I_d = 5$ A by appearance of charge exchange particles at an ion source's exit. As one can see, with the emission current that is higher than the discharge current helps this low-energy humps at low energies between 20 and 50 eV to disappears.

In the gridless ion sources, because they have a broad energy distribution, an ion beam energy is usually estimated by the mean ion energy which is the total integral energy of ions distribution divided by the ion beam current. In the most well-known cylindrical Closed Drift and end-Halls ion sources (studied by Fakel, MIREA, Veeco, K&R) the ion beam energy was measured with the retarding potential probe [71] and gave the mean value $E_i \approx (0.6\text{-}0.7) \cdot eV_d$; for the linear ion sources $E_i \approx 0.5 \cdot$ eVd with a cathode-neutralizer; without a cathode-neutralizer it can be down to $E_i \approx (0.1\text{-}0.5) \cdot eV_d$. As one can see, the end-Hall ion source ion beam energy is not a monoenergetic, but represents a broad energy distribution, as it is shown in **Figure 33a** [1].

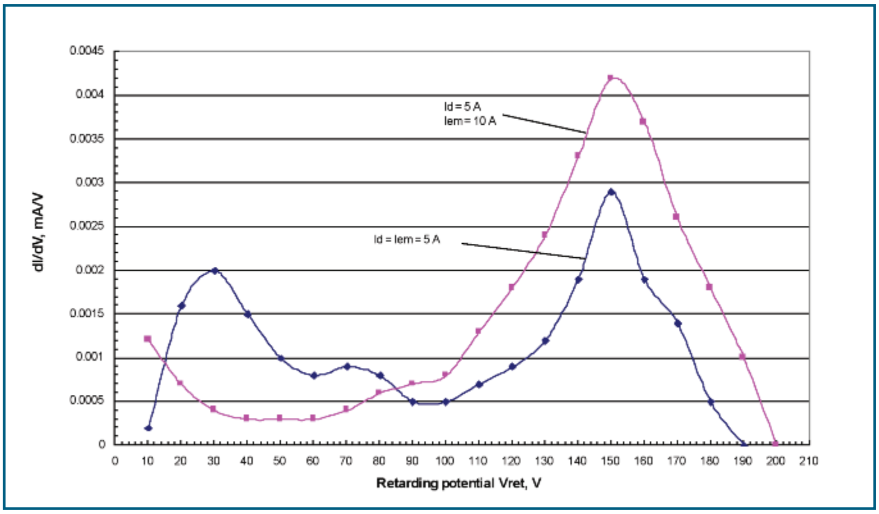

Figure 33a. Ion beam energy distribution in end-Hall ion source for discharge voltage $V_d = 150$ V, discharge current $I_d = 5$ A and two emission currents $I_{em} = 5$ A and $I_{em} = 10$ A; working gas Argon

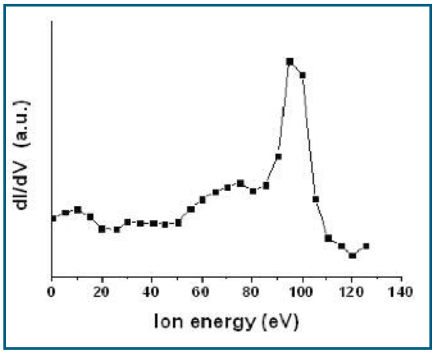

Figure 33b. End-Hall ion energy profile for Oxygen; discharge voltage $V_d = 125$ V; gas flow $\dot{m}a = 20$ sccm [29].

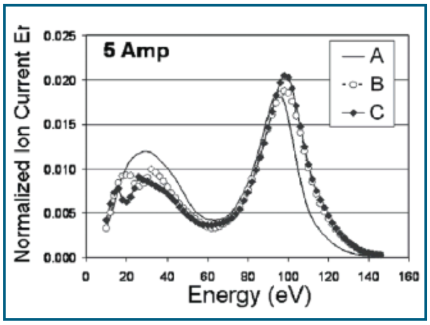

Figure 33c. Ion energy distributions for Mark-II with HF (A), Mark-II$^+$ with HF (B), and Mark-II$^+$ with HC (C); $V_d = 100$ V, $I_d = 5$ A, working gas Argon.

Some other ion beam energy measurements showed that for some end-Hall designs an ion beam energy distribution can have even a broader distribution than shown in **Figure 33a**.

For example, in **Figure 33b** there is presented even a wider energy distribution with a quite fuzzy energy distribution from about 0 to 80 eV with a maximum energy of about 95 eV and the discharge voltage of $V_d = 125$ V; working gas is Oxygen.

In one of latest Veeco works [23, 23b] there are presented quite meticulous measurements of ion beam energy distribution for new end-Halls of Mark-I$^+$ and II$^+$ generation and comparisons with the old Mark end-Halls.

In **Figure 33c** one can see the ion beam energy distribution has two distinctive peaks; one is at about 30 eV and another is at about 100 eV.

Recent work with end-Hall various types of magnetic systems, working gas application into a discharge channel in anode area [72] with a quite advanced retarding potential system [73]. In the pictures made by Kljuev [72] and shown in **Figure 34a** there are presented the ion beam energy distributions that show substantially improved an ion energy monochromaticity.

The ion beam distribution shown in **Figure 34a** and **34b** the discharge voltage $V_d = 130$ V, and the discharge current $I_d = 4$ A. The mean ion beam energy $E_i = 114$ eV, or $E_i/eV_d \approx 0.88$ that is significantly higher of 0.6-0.7 in regular end-Halls [1]. Also, there is no low-energy hump, at least

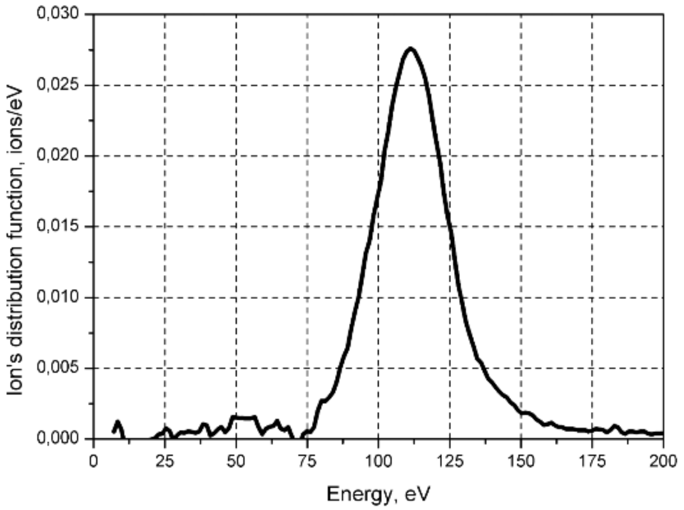

Figure 34a. End-Hall ion energy distribution for Oxygen-Xenon mixture, anode voltage V_d = 130 V, I_d = 4 A; gas flow: $\dot{m}_a$ = 22.7 sccm O_2 and $\dot{m}_a$ = 3.6 sccm Xe [72, 73]; $E_i \approx$ 114 eV.

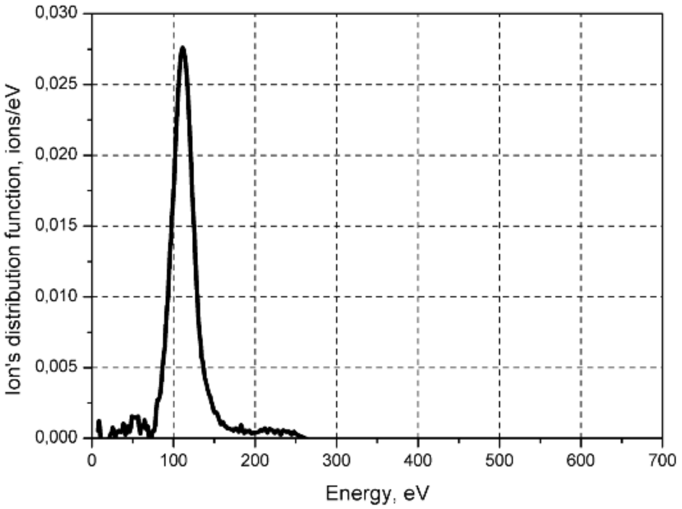

Figure 34b. End-Hall ion source ion energy distribution for Oxygen-Xenon mixture, anode voltage V_d = 130 V, I_d = 4 A; gas flow: $\dot{m}_a$ = 22.7 sccm O_2 and $\dot{m}_a$ = 3.6 sccm Xe [72, 73]; $E_i \approx$ 114 eV.

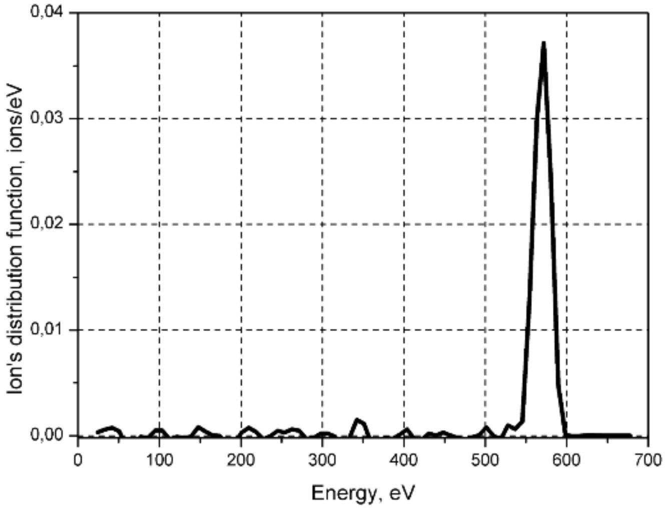

Figure 34c. Gridded ion source, ion beam energy distribution; V = 600V, I_d = 100 mA; working gas Argon [73].

in such a large scale as it shown in **Figure 33a** ($I_{em} \approx I_d$ = 5 A) and in **Figure 33c.**

In **Figure 34b** there are the same discharge parameters as in **Figure 34a**, except it is in a different scale with energy up to 700 eV. This figure is made with purpose of comparing with the typical gridded ion source energy distribution measurement.

For those who is interested how monochromatic ion beam coming out of gridded ion sources. In the gridded ion sources the ion beam energy in practice always is considered equal to the discharge voltage, or $E_i \approx eV_d$.

The measurements with a multigrid retarding potential probe [73] showed that in the gridded ion sources there is also an ion beam energy distribution-deviation from the monochromatic one. For example, for the gridded ion source made by Platar Ltd [74] (Klan-103, Ion beam current: I_i =50 – 200 mA, Accelerating voltage: V=200-1500V, Grid aperture: D_0=∅100mm, accelerating voltage: V_d=40V, Discharge current: I_d=0,1-1,5A) and shown in **Figure 34c**, the discharge voltage U_d = 600 V, the ion beam current I_i = 100 mA, the mean ion beam energy is E_i = 575 ± 25 V, or $E_i/eV_d \approx 0.96$.

The comparison of **Figure 34a, b** and **Figure 34c** made at the same scale shows that the end-Hall ion source of an improved design [72] has a comparatively monochromatic ion beam energy with very close energy distribution spread similar to a gridded ion source.

The ion beam monochromaticity is very important factor in the problems of a supermultilayer coating and materials (SMM) with a periodic structure with each layer thickness less than 25 nm and total number of layers over 10000 [73b]. Because during deposition of such small thin layers a large spread of ion beam energies can be crucial and will be not able performing a designed structure.

2. Ion beam current I_i is a certain part of the discharge current I_d

It is known that the ion beam current I_i, as the ion beam energy, being also a very important characteristic of any ion beam source, is not equal to the discharge current I_d, or $I_i \neq I_d$. This is simply means that at most regimes of ion source operation the working gas is not completely ionized or some parts of it escape from impact of electrical discharge. Usually, the ion source and its efficiency of transformation of working gas into an ion beam are characterized by the ion beam current I_i, and the so-called equivalent ion beam current $I_{\dot m}$ obtained during operation, which is determined by formula:

$$I_{\dot m} = \dot m_a e/M, \tag{4.5}$$

where $\dot m_a$ is a working gas flow; e is electron charge; M is a working gas atomic mass.

It is prudent to estimate an equivalent of 1 sccm of working gas in the following way:

$$1 \text{ sccm} = 4.48 \cdot 10^{17} \cdot 1.6 \cdot 10^{-19} = 7.17 \cdot 10^{-2} \text{ A},$$

or

$$[\text{sccm}] = [\text{atoms/s}] \cdot [\text{Coulombs/charge}] = [\text{equivalent Amperes}].$$

In other words, if a working gas will be completely ionized and therefore transformed into ion beam, one Ampere of ion beam needs about 14 sccm, or 1 A ≈ 13.95 sccm. For most known in thin film technology working gases this equivalent relationship is correct with quite a good accuracy. In some cases, it is necessary to have a correction for a gas compressibility at standard temperature and pressure that can change a mass flow rate very insignificantly. For Xe with the correction factor, 1 A ≈ 13.85 sccm. In practice, one can consider that in order to have a high ion beam current from 1 to 5 A, it is necessary to have a working gas mass flow from about 14 sccm to about 70 sccm.

However, because the working gas is not completely ionized, and most of time it is partially ionized due to various reasons, such as inefficient discharge, low discharge voltage, working gas with high first ionization potential and inefficient magnetic system that do not permit complete ionization, to have a reasonable ion beam current at applied discharge currents from 1 to 5 A, one has to supply a substantially higher mass flow of a working gas (in 2-3 times higher than 14-70 sccm).

Because the ionization process in end-Hall ion sources is not very effective, for the end-Halls the ion beam current, in general, is about $I_i \approx (0.2\text{-}0.25) \cdot I_d$. For new Veeco's Mark$^+$ and for K&R EH series $I_i \approx (0.25\text{-}0.3) \cdot I_d$; in some cases $I_i \approx 0.35 \cdot I_d$ (Veeco's Mark-II$^+$ [23]). For the Hall-current ion source with the additional area for generation of ions developed by Belorussian scientists $I_i \approx (0.25\text{-}0.3) \cdot I_d$ [32]; for the end-Halls with high electron emission [1] $I_i \approx 0.4 \cdot I_d$; for the hybrid type end-Hall-closed drift ion source [34, 68] the higher ratio of the ion beam current to the discharge current is $I_i \approx (0.7\text{-}0.8) \cdot I_d$. For the closed electron drift ion sources, the ion beam current can be $I_i \approx (0.8\text{-}0.9) \cdot I_d$ [34, 68].

The closed drift ion sources of Magnetic, or Anode Layer types, in the case of working without the external source of electrons (Hot Filament, Hollow Cathode, or others) operating in the so-called self-sustained regime [1], when discharge develops sparks producing neutralizing electrons, and are maintaining discharge at higher discharge voltages from about 250 V and higher, up to 3000 V. [*Discharge voltage range for existence of either a non-self-sustained, or a self-sustained regime depends on a working gas pressure, its first ionization potential, the discharge current, the magnetic field value, and some other factors, such as a vacuum chamber dimensions and geometry.] This regime of operation without external source of electrons does not deliver substantial ion beam current, and the ion beam current is usually $I_i \approx 0.1 \cdot I_d$, or less.

For the thin film tasks, where there is a need for higher energies and there are problems with a HF (most frequently utilized cathode-neutralizer in practice) lifetime, this can be a good solution.

However, since an ion beam is not completely neutralized, it contains a high positive charge that is applied to a target, or a substrate. Such an under-neutralized positively charged ion beam can be a problem for certain thin film depositions. Some producers of Hall-current ion sources do not give correct evaluation of the ion beam currents and their mean energies.

Both values of the ion beam mean energy E_i and the ion beam current I_i are not shown on the power supplies and need to be measured with the probes. For developers of the ion sources working together with the power supplies makers, one of the future tasks will be is the calibration of a Hall-current ion source and its Power Supply for each specific gas and distance, and to show the ion beam current value and the mean energy on a power supply front panel as a function of distance from an ion source. Such arrangement can resolve a long standing problem of correct determination of the ion beam current and the ion beam energy that users can utilize in the scientific-engineering estimations of physical processes.

3. Ion beam neutralization

As a rule, an ion beam should be neutralized. [*This problem will be discussed

Table 6.1 Basic Parameters of Traditional Gridless Hall-Current Ion Sources
Working gases: Ar, Xe, O_2, N_2

Ion Source	I_d, A	I_i, A	I_i/I_d	V_d, V	E_i, eV	E_i/eV_d
1. End-Hall*						
Mark-I, II	1- 5	0.2-1.0	0.2	50-300	30-180	0.6
Mark-I$^+$, II$^+$	1-15	0.25-5	0.25-0.35	60-300	40-210	0.65-0.7
EH-200-2000	1-10	0.25-2.5	0.25	60-300	40-210	0.65-0.7
Svirin [32]	1-2.5	0.25-0.75	0.25-0.3	80-250	55-180	0.7
Kljuev**[73]	1-5	0.25-1.5	0.25-0.3	100-400	55-360	0.55-0.9**
Hybrid [34]	1-5	0.8-4.0	0.8	50-600	35-420	0.7
2. CDIS						
Platar	1-5	0.3-3	0.6	100-600	50-480	0.5-0.8
3. Linear sources						
End-Hall***	1-10	0.2-2.0	0.2	40-200	25-120	0.6
MLIS	1-5	0.4-4.0	0.8	100-600	70-360	0.7
ALIS****	0.5-5	0.1-2.0	0.1-0.2	500-3000	150-1000	0.1-0.4

* End-Halls Mark-I, II, I$^+$, II$^+$ produced by Veeco; End-Halls EH-200-2000 produced by K&R.

** In Kljuev et al [73] end-Hall maximum ratio $E_i/eV_d = 0.9$ was measured; this result and this particular end-Hall design will be discussed in one of our next publications in *VT&C*. Also in this work working gases besides "tradistional" Ar, O_2 were Xe, Kr and mixtures.

***Linear end-Hall with a Hollow Cathode produced now by Veeco.

****ALIS Anode Layer Ion Sources made by many producers including Veeco, General Plasma Inc., ULVAC, several Russian, Chinese and Korean companies.

in one of our following articles in *VT&C* about the ion beam neutralization and the sources of electrons that can be utilized for this purpose] Many ion sources users do not establish correct value of the emission current through the cathode-neutralizer. As it was above mentioned, the insufficient neutralization develops a positive electrical charge on a target, a substrate, leads to additional beam divergence and appearance of undesirable oscillations and instabilities of the main ion source' operational parameters V_d and I_d, and, as a consequence, makes a negative impact on E_i and I_i. For those who work on specific thin film processes, it is recommended to calibrate an ion source measuring the electrical potential on the target for the operational conditions ($\dot{m}a$, V_d, I_d, working gas type). [*Magnetic field is supposed to be constant in such measurements.] It is desirable that the electric potential measurements will be on a probe with area close to the utilized in practice and, certainly, a positive electric potential should be reduced to a zero value.

It is important to note that an under-neutralized ion beam even of few volts can produce neutralizing sparks that can be detrimental for fine thin film process [12]. However, an extra negative potential to a target caused by excess of electrons does not produce any noticeable sparks at moderate negative potentials of ≤ 15-20 V, because electrons due to their high mobility dissipate fast into a surrounding vacuum chamber.

4. Oscillations and instabilities of discharge current I_d and voltage V_d

As it was described in our previous publication [2], the oscillations of main operational parameters of Hall current ion sources exist in most ranges of discharge voltages and currents.

In some ranges an ion source even can not operate without oscillations. But these oscillations must not experience transition in to instabilities that can change drastically operation parameters leading to deviation from the nominal operation regimes and with big probability to complete extinguishing of discharge and, correspondingly, to interruption of the technological process.

In **Table 6.2** there are presented various types of oscillations that can be a part of regular operation, if their amplitudes do not exceed certain levels and they do not lead to instabilities that can interrupt normal discharge, ionization and acceleration of developed ions.

In **Figure 35b** of a Hall-current ion source Volt-Ampere Characteristics (VAC) there also are shown the areas of presence of main oscillation types [1] Here are the distinctions of the discharge voltage and current oscillations between end-Halls and Closed Drift type ion sources.

Because, in general, the end-Halls are the ion sources with the magnetic field negative gradient and the Closed Drift ion sources are with a positive magnetic gradient in the discharge channel, the Closed Drift ion sources do not have such large discharge voltage and current oscillations at $V_d \geq 200$ V, as end-Halls do, and can operate practically up to $V_d = 800\text{-}1000$ V.

End-Hall ion sources, in order to operate at $V_d \geq 300$ V need special filtering circuit placed between the anode and the Power Supply [1, 28]. [*Closed Drift Thrusters, despite of having lower level of the discharge voltage and current oscillations than the end-Hall ion sources, are always using in practice various filtering devices since early 1970ies.]

In **Figure 35a** there are presented V-A characteristics for end-Hall type ion source similar to presented in **Figure 35b** and the dependence of an amplitude of discharge

Table 6.2 Discharge Voltage and Current Oscillations and Instabilities

Type of oscillations	Range of frequencies	Possible means to reduce impact
1. Ionization	10 kHz – 3 MHz	Increase discharge voltage V_d
2. Flight	100 kHz – 10 MHz	Ion source can operate with such oscillations safely
3. Contour	1-30 kHz	Utilize filtering circuit between Anode and Power Supply
4. Hybrid azimuthal waves	1-100 MHz	Optimize magnetic field in end-Hall discharge channel. Reduce V_d
5. Caused by high pressure in vacuum chamber	Chaotic in all frequencies	Operate at nominal pressures in vacuum chamber $\geq 10^{-5}$- $\leq 2\cdot 10^{-3}$ Torr
6. Caused by under-neutralization	Chaotic in all frequencies	Use proper neutralizing current, always have $I_{em} \geq I_d$
7. Caused by water vapors release	Chaotic in all frequencies	Pump out water vapors before starting discharge at least 20 min
8. Caused by wrongful operation	Chaotic in all frequencies	Check mass flow meter; check dielectric, or insulating depositions on anode, discharge channel

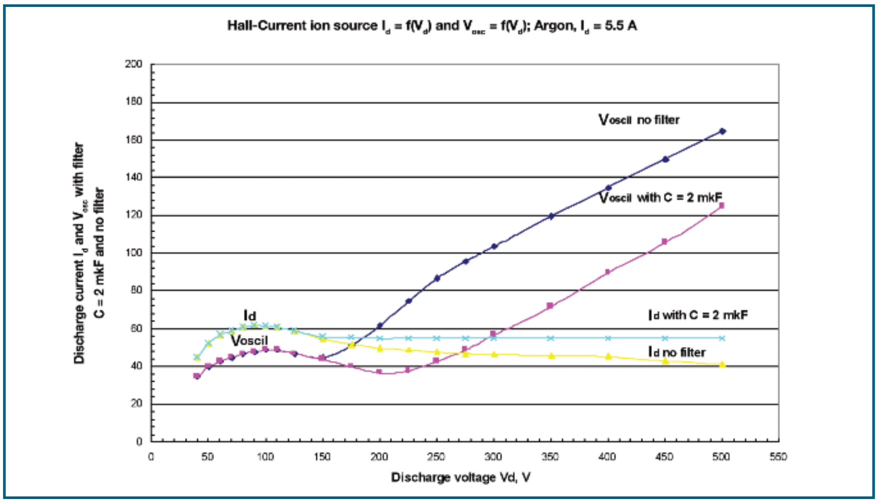

Figure 35a. Discharge current I_d and discharge voltage oscillation amplitudes V_{oscil} as function of discharge voltage V_d of end-Hall ion source with filter C = 2 mkF and without filter; working gas Argon; discharge current $I_d = 5.5$ A; Discharge current scale must be divided by 10

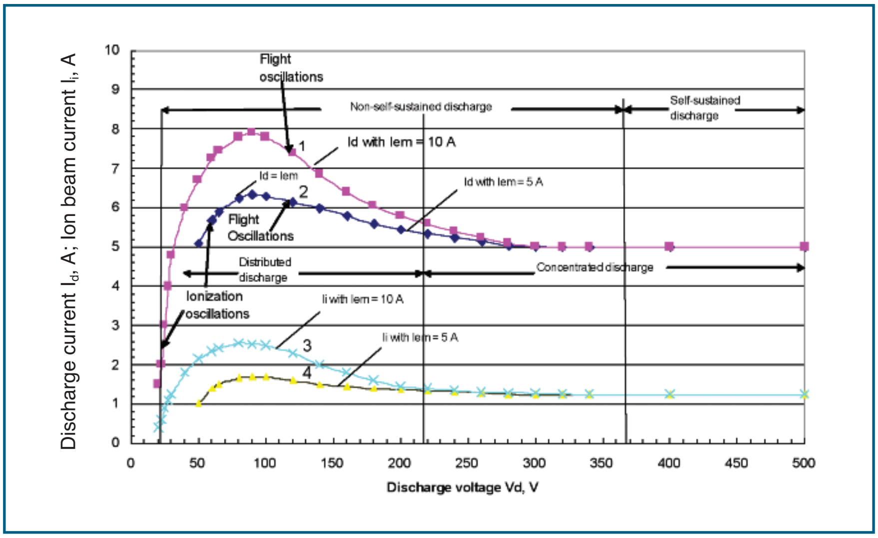

Figure 35b. Volt-Ampere Characteristics of a Hall-Current Ion Source; two cases: $I_d \approx I_{em} = 5$ A, and $I_d = 5$ A, $I_{em} = 10$ A; working gas Argon

voltage oscillation amplitudes V_{oscil}, and a discharge current I_d with presence of a filtering device (C = 2 mkF) and without such a device (C = 0). These experiments were possible to carry out with $I_{em} \approx I_d$ for filter with C = 2 mkF, and with $I_{em} > I_d$ without filter, because at high discharge voltages and $I_{em} \approx I_d$ the oscillations were too high to maintain discharge and make any reasonable measurements. However, with $I_{em} > I_d$ the oscillation level was measurable, though still higher than with a filter.

From a certain discharge voltage, which for Argon is about $V_d \approx 150\text{-}160$ V (a splitting point), and for Oxygen at about $V_d \approx 190\text{-}200$ V, there are observed substantial discharge voltage oscillations V_{oscil} as function of applied discharge voltage V_d. Discharge current oscillations are usually have lower oscillation amplitudes and are not shown in **Figure 35a.** Very similar behavior experiences a Closed Drift ion source-thruster, however, with smaller amplitudes of discharge voltages and currents [75].

It is necessary to note that different modifications of end-Hall ion sources behave in a similar way, and the discharge voltage and current experience high oscillations of discharge voltage and current, however, a splitting point and maximum oscillation amplitudes depend on many factors, such as a discharge channel geometry and dimension, magnetic field values in a discharge channel, discharge current value, working gas and pressure in a vacuum chamber.

5. Volt-Ampere Characteristics V_d-I_d, various operational conditions

As it was discussed above and in our previous publications [2], in the Hall-current ion sources at certain range of discharge voltages and currents there are various types of oscillations and instabilities that limit the range of operational parameters. Usually, for the end-Hall ion sources the range of operational discharge voltages is from about 50-80 V and up to maximum about 300 V. Each and every new ion source should be tested for the Volt-Ampere Characteristics (VAC). These VACs (the example is shown in **Figure 35**) are regulated by various working gas mass flows $\dot{m}$a and correspond to certain discharge currents I_d. The VAC characteristics

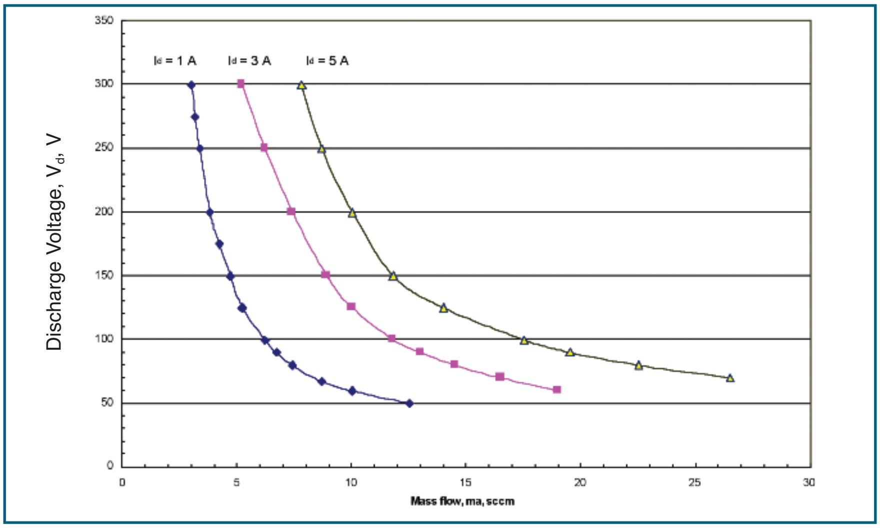

Figure 35c. End-Hall ion source; discharge voltage V_d as a function of working gas mass flow for different discharge currents, $I_d = 1, 3, 5$ A; $I_{em} \approx I_d$; working gas Argon

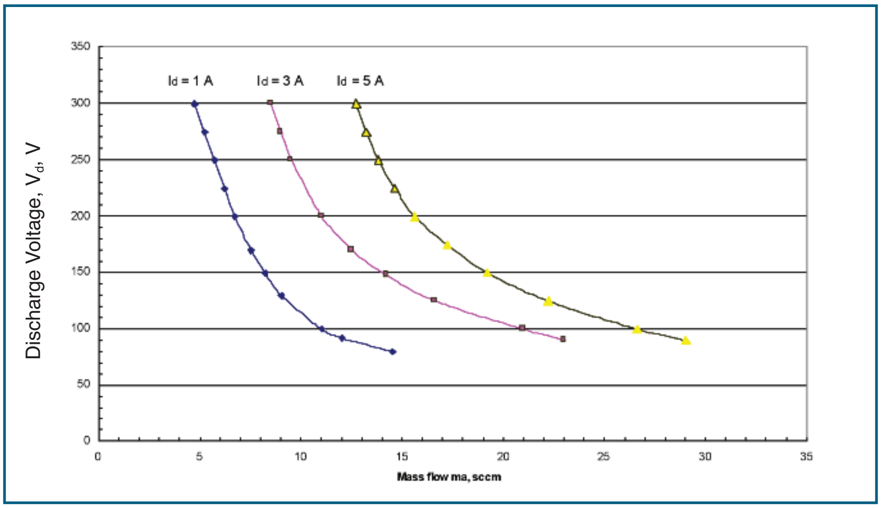

Figure 35d. End-Hall ion source; discharge voltage V_d as a function of working gas mass flow for different discharge currents, $I_d = 1, 3, 5$ A; $I_{em} \approx I_d$; working gas Oxygen

show important phases of an ion source behavior, from low and up to high discharge voltages. In **Figure 35b** there are shown several modes of discharge that are parts of regular operation. They have shown with the emission current approximately equal to the discharge current ($I_{em} \approx I_d = 5$ A) and with the higher emission than regular equal to discharge current ($I_{em} > I_d$).

Another way of indication of an ion source correct operation is obtaining the dependencies of the applied working gas mass flow (frequently called as anode mass flow) as functions of the discharge voltages such as $\dot{m}a = f(V_d)$ for a series of constant discharge currents I_d = const.

Such mass flows – Volt discharge characteristics at constant discharge currents are shown in **Figure 35c** and **Figure 35d.** They are quite easy to obtain. Please use always very similar ratios between the discharge current Id and the electron emission current I_{em}, or $I_{em} \geq I_d$. In practice, they are recommended in the manuals quite close to each other, with the electron emission current that should be slightly higher than the discharge current by about 5%. If you use the electron emission higher than the discharge current by about 10%, there is no problem. The problem is, if the electron emission is lower than the discharge current!

It is certainly necessary for each new developed ion source to measure the most important parameters, such as an ion beam current I_i, an ion beam mean energy E_i and energy distribution by a retarding potential probe. For the ion sources users, if the I_i and E_i measurements are impossible to provide, the $\dot{m}a = f(V_d)$ curves can be a good indicator, how an ion source operates.

In general, reactive gases (O_2, N_2) have narrow range of operating discharge voltages V_d than noble gases. Also oscillations with ractive gases begin at aboiut 220-250 V in comparison with $V_d \approx 300$ V for Ar, Xe. And these data, of course, are with good preliminary pumping.

General remarks to users who would want to check the nominal operation characteristics without exact measurements of the ion beam currents and mean energies. The curves like shown in **Figure 33c** and **Figure 33d** must be smooth, without any drastic turns, especially at the very low working gas mass flows; sometime it can happen at high mass flows. Unusual behavior of such curves at low and high V_d indicates presence of various oscillations that were described above.

End-Hall ion sources usually operate at narrower range of discharge voltages than Closed Drift ion sources. However, end-Hall ion sources can operate at low discharge voltages at $V_d \approx 50\text{-}60$ V with Ar and $V_d \approx 30\text{-}40$ V with Xe, and at $V_d \approx 80\text{-}100$ V with O_2 and N_2. Closed Drift ion sources have discharge voltages for all above mentioned working gases by 20-30 V higher. This is explained by presence of a strong longitudinal magnetic field component in the end-Halls anode area (electrons move easier along a longitudinal magnetic component that exists mainly in end-Hall ion sources, and slower through a radial magnetic component that exists mainly in Closed Drift ion sources). At the same time, Closed Drift ion sources have magnetic field component practically equal to zero in the anode area.

It is necessary to note that the VACs for different gases are different, but general tendencies in the discharge mode types, their range of existence (of non-self-sustained, self-sustained, distributed and concentrated) and various types of oscillations are very similar.

The curves $V_d = f(\dot{m}a)$ for $I_d = 1, 2, 3, \ldots 10$ A must be taken for the same ratio of I_{em}/I_d. For example, $I_{em} = 1.1 \cdot I_d$, or $1.05 \cdot I_d$. In some cases, drastic change in I_{em}, like $I_{em} = (1.5\text{-}2.0) \cdot I_d$, or $I_{em} = 0.9 \cdot I_d$ can change significantly the behavior of the curve $V_d = f(\dot{m}a)$. It is necessary to note about very important relationship here between the discharge current I_d and emission current I_{em}. An extra emission current from a Hot Filament, Hollow Cathode, or other variety of heated cathodes would not produce any "harm" to the operation.

The discharge voltage V_d will be decreased to a certain extent in comparison with $I_{em} \approx I_d$, the change from $I_{em} \approx I_d$ to $I_{em} = (1.5\text{-}2.0) \cdot I_d$ can be 15-20% reducing discharge voltage. For example, at $I_{em} \approx I_d$ $V_d = 100$ V, and at $I_{em} = (1.5\text{-}2.0) \cdot I_d$ V_d will be $V_d \approx 80$ V practically for all utilized in industry working gases; however, at $I_{em} = 0.9 \cdot I_d$ V_d will be 110-120 V. But a lower or insufficient number of neutralizing electrons can be quite "harmful" for the technological process, because insufficient neutralization can increase the discharge voltage and produce some undesirable sparks leading to development of necessary for ion beam neutralization electrons. Extra electrons that present during excessive electron emission usually help to reduce discharge voltage, increasing ionization process in a discharge channel and "unnecessary" electrons diffuse in a vacuum chamber.

As one can notice this relationship between discharge and emission currents ($I_{em} \approx I_d$) are most important in the Volt-Ampere Characteristics in the region of a non-self-sustained discharge. In **Figure 35b** this region is from about 20 V (with high emission) – 40 V ($I_{em} \approx I_d$) to about 370 V. In practice, the end-Hall ion sources operate at the optimum discharge voltages from about 90 V to about 150 V, and this range of discharge voltages is very sensitive to the ratio between I_{em} and I_d.

As it was mentioned in this article in Part 3, especially about Anode Layer ion sources, linear and cylindrical that operate in the region of a self-sustained discharge, from about 350 V and up to 3000 V, when necessary ion beam neutralization can be provided by sparks in an ion source discharge channel, or in vacuum chamber, or on a target, it is still necessary to have an ion beam neutralized with the external source of electrons. Otherwise, an ion beam current is much lower ($I_i \approx 0.1 I_d$ or less), and ion beam energy is very spread and fuzzy ion beam mean energy ($E_i \approx (0.4\text{-}0.5) eV_d$) than in the case with applied external source of electrons.

Also, the magnetic field at a permanent magnet should remain constant. Some end-Hall producers use magnets of rare-Earth elements that can lose their magnetism quite fast under impact of high temperatures. Alnico magnets are the best choice for end-Halls. However, look at particular Alnico types that require the ratio of magnet's length to diameter (Alnico-5 needs $l/_d = 4$). Alnico magnets can be too expensive for some producers of ion sources. [*Information for those who is trying developing own end-Hall ion sources. Alnico Rod magnets are utilized in both Grade 5 and Grade 8. Alnico 8 magnets have a lower remanence (magnetization left behind in a medium after an external magnetic field is removed), but a higher coercivity (coercivity measures the resistance of a ferromagnetic material to becoming demagnetized) than Alnico 5 magnets. This means that Alnico 5, though stronger, is easier to demagnetize. Alnico 5 rod magnets should have a length to diameter ratio of about 4 to 1 in order to avoid self-demagnetization.]

For those who design and test new variants of end-Halls, the discharge voltage-mass flow $V_d = f(\dot{m}a)$ characteristics for various discharge currents $I_d = 1, 3, 5$ A shown in **Figure 33b** and **Figure 33c** are good examples of an ion source main parameters behavior. It should be remembered that the curves $V_d = f(\dot{m}_a)$ must be smooth, no breaks. Because the breaks show that an ion source experiences oscillations with transitions in to instabilities, which can either stop discharge, or make major parameters unstable and unpredictable.

One of methods that helps improving VACa characteristics of end-Hall ion sources, as it was described in one of our publications [28], is utilization of a filtering device between end-Hall's anode and a Power Supply.

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