1 Hall-Current Ion Sources

1.1 Introduction

Ion sources and the development of ion beams are produced by the creation of strong electrostatic fields in plasma. For quite a long period of time, before the 1950s, electrical discharges were studied without magnetic fields. It was believed that strong electrostatic fields in a plasma volume were impossible to develop. At that time, it was experimentally found that strong electric fields could be observed only in thin layers of Debye-layer scale near electrodes, in places where quasineutrality is broken.

Then, in the 1950s, successful experiments confirmed the theoretical possibility of magnetic field utilization providing magnetization of electrons, which sharply helped to increase plasma electrical resistance and to obtain large electric fields with the development of Hall currents in crossed electric and magnetic fields in a plasma volume.

The Hall-current ion source operation is based on the physical principles of electron magnetization and on the increase of plasma resistance and electron lifetime, during which electrons can interact with neutral particles and ionize them. This concept was implemented in the development of modern electric propulsion devices for space apparatuses, which were later transformed and are now used as ion sources.

In the ion source discharge channel, the electrons are magnetized, if $\omega_e \tau \gg 1$ (ω_e is the electron cyclotron frequency in a magnetic field; τ is the average time between electron collisions with other particles and the discharge channel walls). The ions are usually not magnetized, $\omega_i \tau \ll 1$ (ω_i is the ion cyclotron frequency in a magnetic field; τ is the average time between ion collisions with other particles and discharge channel walls) and move under the applied electrical field between the anode and the cathode. During discharge in the magnetic field, electrons move to the anode not in straight lines, but rather in circles in crossed magnetic and electric fields; they experience collisions with working gas molecules, ions, discharge channel walls, and also due to oscillations. Ions are not influenced by the magnetic field, but move from their places of origin, usually near to the anode into the cathode direction along the electric field. Moving from the ion source, an ion flow captures the necessary number of electrons for neutralization and develops what is called an ion beam, though the

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ions are accompanied, in general, by electrons. Electrons drifting in the azimuth direction neutralize the space charge of ions in the discharge channel. Due to this physical fact, in Hall-current ion sources (contrary to gridded ion sources) there is no limit for an ion beam current that exists in gridded ion sources caused by a space charge of ions. Because electrons move in circles in crossed magnetic and electric fields, the ion sources and thrusters use a principle known as ion source-thrusters with closed electron drift.

Part of the regular operation of Hall-current ion sources is the existence of a variety of oscillations of discharge current and voltage in a certain range of values, especially at low and high values. Operating magnetic fields depend on ion source dimensions, but as a rule, magnetic fields in a discharge channel of the cylindrical ion sources are not very high: from about 100 G to a maximum of 500 G. It is necessary to note that linear ion sources with closed electron drift, which will also be discussed in the book, can have substantially higher magnetic fields, sometimes over 1000 G.

In the following sections, existing gridless ion sources and their designing features and differences will be described, followed by a discussion of the main physical characteristics of such ion sources.

1.2
Closed Drift Ion Sources

Closed drift ion sources (CDIS) were developed to a very high degree of efficiency as thrusters in the 1960s; then in 1972, Russian scientists launched a "Meteor" satellite with the thruster based on the closed electron drift principle.

Currently, every third Russian satellite is equipped with a closed electron drift thruster. There are already over 200 thrusters in space; many CDIS are on American satellites too.

Besides the magnetization of electrons, one of the basic ideas in the successful operation of CDIS for a broad range of discharge voltages, currents, and a variety of gases is that the magnetic field in a discharge channel increases from the anode to an ion source exit. In other words, *CDIS is an ion source with a positive magnetic gradient in a discharge channel*. The main "operating" magnetic field is a radial component. The discharge channel has an annular form.

In general, there are two types of CDIS: magnetic layer ion source (MLIS) (Figure 1.1) and two modifications of anode layer ion source (ALIS), shown in Figure 1.2a and b [1, 2] as schematics and three-dimensional pictures. The main parts of CDIS – anode, magnetic poles, and magnetic coils developing the magnetic field – are shown in these figures. Cathode neutralizers are not shown.

In Figure 1.2a and b, ALIS have a different placement of anode: in Figure 1.2a, it is inside the discharge channel; and in Figure 1.2b, some of the anode's surface is extended outside the magnetic poles.

Such an extended anode provides a slightly narrower range of operational discharge voltages, but it has the advantage of sharply reducing the erosion of magnetic poles in comparison with regular ALIS anode placement (Figure 1.2a.)

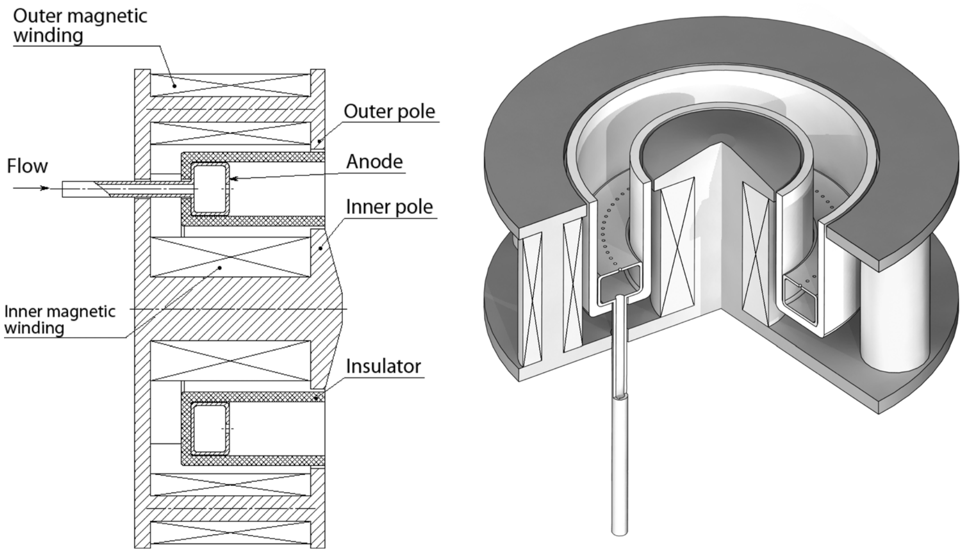

Figure 1.1 Magnetic layer closed drift ion source.

The dimensions of a cylindrical form CDIS are from about 20 mm of the exit-plane diameter up to 290 mm (recent thruster design). As ion sources, CDIS are used from about 50 to 100 mm of exit diameter. Working gases are Ar, Xe, O_2, N_2, H_2, CH_4, and others.

The range of operation for discharge voltages is $V_d \approx 80$–1000 V; for discharge currents, it is $I_d \approx 0.1$–15 A. The mean ion beam energies are about $E_i \approx 0.7\,eV_d$ (in eV); the ion beam current is about $I_i \approx (0.7$–$0.8)\ I_d$. The erosion rate of the anode is negligible; the erosion rate of magnetic poles is substantial, though for ALIS, the erosion rate of poles with an extended anode area outside the discharge channel [2] is negligible. The ion beam divergence for MLIS is about 20° (for 70–80%) of ion beam flow; for ALIS, it is about 15–20° [1]. The hollow cathode (HC) is utilized as a source of electrons for ion beam neutralization and ionization of neutral atoms; HC erosion is negligible.

In thin film technology, cylindrical CDIS are not widely utilized. However, Diamonex [3, 4] use cylindrical MLIS for DLC coating. Russian companies, Platar and MIREA use cylindrical MLIS for a variety of thin film tasks (etching, sputtering, ion beam assistance). ALIS modification without an external source of electrons is utilized extensively by many companies, mainly in the form of linear ion sources of different dimensions (up to 300 cm long).

CDIS advantages:

1) High transformation of a discharge current I_d into an ion beam current I_i, $I_i/I_d \approx 0.7$–0.8, with utilization of an external source of electrons and with adequate magnetic field optimization.

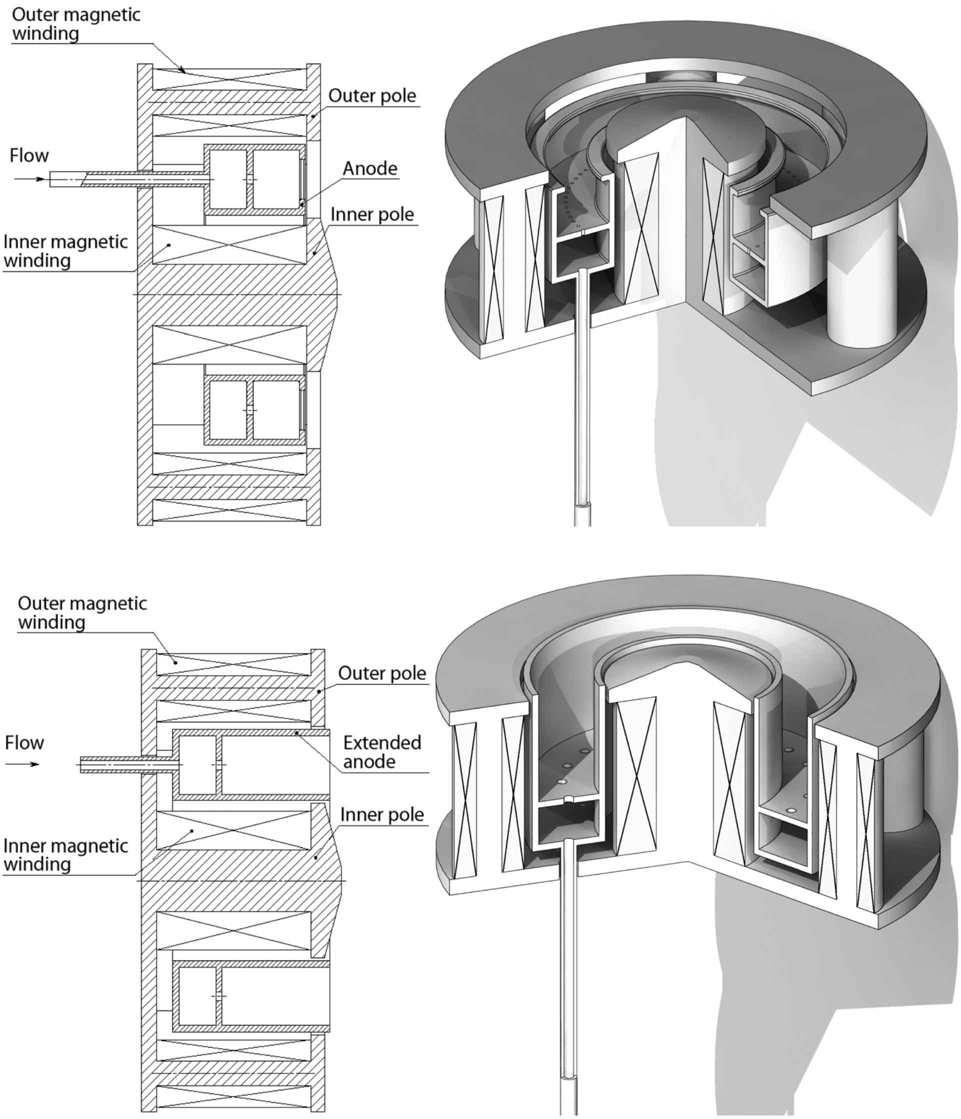

Figure 1.2 (a) Regular anode layer closed drift ion source. (b) Anode layer closed drift ion source with extended anode to reduce sputtering of magnetic poles.

2) Wide range of discharge voltages (ion beam mean energies), from about $V_d \approx 80$–1000 V, $E_i = 55$–700 eV.
3) Optimum magnetic fields for cylindrical CDIS are in the range of 100 G to 600 G; for linear ALIS, the magnetic fields are usually substantially higher, over 1000 G.
4) Because of good magnetic field optimization, the cylindrical CDIS can operate up to about 1.5 kW of applied power without a water-cooled anode. Hot discharge

plasma with an optimized magnetic field is well separated from the discharge channel walls and anode.

Shortcomings:

1) Need for a variety of operating conditions in magnetic field optimization. The ratio of the ion beam current to the discharge current $I_i/I_d = f(H_{max})$ is not a linear function of the magnetic field, and the maximum depends on the working gas, discharge voltage, and current. Optimization is provided by magnetic coils with variable magnetic fields. Permanent magnets can only be used for a specific selected range of V_d and I_d and a working gas. In practice, not many users want to perform such optimization.
2) Operation of CDIS without an external source of electrons in the so-called self-sustained discharge [5] (discussed in subsequent chapters) produces low transformation of the discharge current into an ion beam current $I_i \approx (0.05–0.1)\ I_d$ and high spread of ion beam mean energies $E_i \approx (0.4–0.5)\ eV_d$ (eV); and in the ion beam energy distribution, there are ions with low (from several eV) and high (up to twice eV_d) distribution. The length of ALIS is usually in the range 15–20 to 100, 200, and even 300 cm.

1.3 End-Hall Ion Sources

The discharge channel has a cylindrical form with a massive hollow conical anode. The cathode, serving as a source of electrons, is usually in the form of a hot filament (HF) or HC. Generally, electrons are only magnetized at the exit part, where the magnetic field has a radial component connecting to the external magnetic pole. Also at the exit, the magnetic field is quite low because the end-Hall ion source utilizes the permanent magnet's magnetic field, which decreases from the place under the anode where a gas distributing system is usually located. The magnetic-field value on the permanent magnet top (or on electromagnet) is about 1–2 kG; at the ion source exit (front flange), this magnetic field is reduced to about 50–100 G. Due to this, the *end-Hall ion source can be considered as a source with a negative gradient of magnetic field.*

The next series of figures show a variety of end-Hall-type ion sources with the following main parts labeled: anode, insulators, body (magnetic path), reflector-gas distributor, working gas, permanent magnet, magnetic coil, magnetically soft iron, and conical insert. The cathode is not shown; it is either HF or HC. (Cathodes are discussed later in Chapter 5.)

Information about one of the first end-Hall-type ion sources was published in 1973 [6]. Figure 1.3 presents a schematic drawing and three-dimensional picture of the Hall-current ion source for the development of low-energy ions, indicating an exit area for the neutralized ion beam; a front flange; a discharge channel made of dielectric material; an anode connected to a power supply (not shown); a back flange; a cathode as an HF; a working gas; and a system of electromagnetic coils providing a non-uniform axial symmetric magnetic field distribution in a discharge channel. A magnetic field in the discharge channel is sufficient for magnetization of electrons

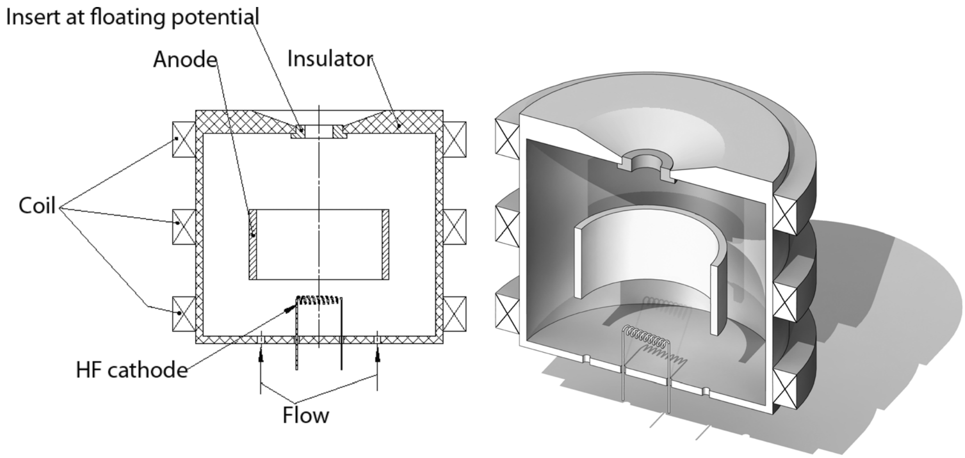

Figure 1.3 One of the first Hall-current low-energy ion sources [5]. HF cathode is in the discharge channel.

($\omega_e \tau_e \gg 1$). At the same time, ions are not magnetized ($\omega_i \tau_i < 1$) in the same way as closed drift ion sources-thrusters. The ion source was operated in stable conditions with several working gases, such as hydrogen (H_2), nitrogen (N_2) and argon (Ar), at discharge voltages $V_d = 150–600$ V and with discharge currents $I_d = 0.15–1.0$ A. Also, it was reported that the ion beam angular divergence was 16° and the ion beam energy was close to the discharge voltage in eV.

The distinctive feature of this ion source is the presence of the cathode neutralizer inside the discharge channel. In all further designs, the cathode neutralizer is outside the discharge channel. The front flange, which has a small conical opening, does not allow the extraction of high ion beam currents. With the discharge currents $I_d = 0.15–1.0$ A, the ion beam currents were $I_i = 0.4–30$ mA. In other words, the discharge current conversion into the ion beam was quite low.

The main design of an end-Hall ion source, which is still used by most producers, is presented in Figure 1.4. As shown, a hollow cone-shaped anode and a magnetic

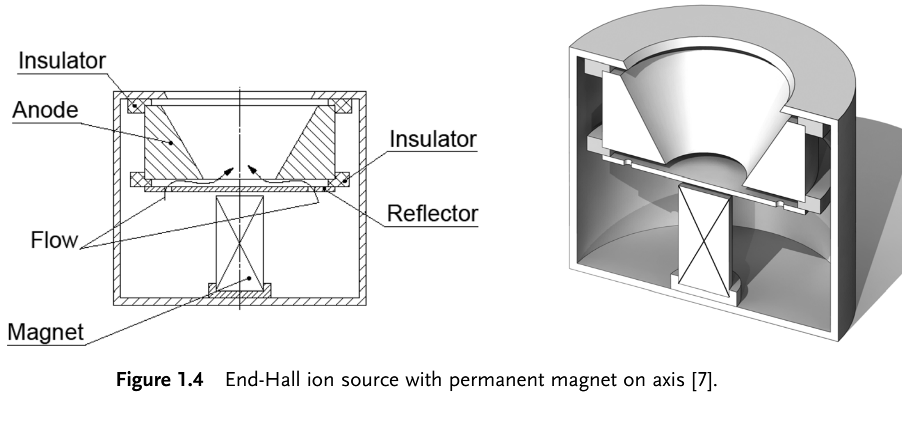

Figure 1.4 End-Hall ion source with permanent magnet on axis [7].

field made by one or several permanent magnets are placed on the source's axis under the reflector. The permanent magnet is usually fabricated from Alnico, either 5 or 8; Alnico magnets are good for sustaining high temperatures up to about 540 °C. This design was suggested in *End-Hall Ion Source*, by H.R. Kaufman and R.S. Robinson [7]. It was developed and extensively studied at Kaufman & Robinson Inc. (K&R), with at least three different dimensions (Mark I, Mark II, Mark III) and discharge currents from under 1 A up to about 15 A and discharge voltages from about 50 V up to 300 V with various working gases. After its patenting in 1989, it was produced by Commonwealth Scientific Corporation (CSC) for about 10 years, and later in 1999 by Consolidated Vacuum Corporation (CVC) and in early 2000 by Veeco Instruments. It is necessary to note that Veeco and K&R continue to provide improvements to this design, which will be discussed later. The main design creates a simple and reliable device. Many foreign ion source producers, especially Chinese and S. Korean companies, made similar designs.

This and other varieties of end-Hall ion sources are characterized by the following features:

1) Overall dimension of the outer flange for the exit of an ion beam. Depending on the geometry and outer flange, end-Halls are designed for application of a certain working gas mass flow, which translates into a discharge current and then into an ion beam current. The external flange, as a rule, is made of a soft magnetic iron and is part of a magnetic circuit–magnetic pole; the external shell of the ion source is also fabricated of a soft iron.
2) Geometrical dimension of the anode, which is usually several centimeters in length and diameter. Anodes can be made of a variety of materials that determine the electrical conductivity, its participation in a thin film process (as a contaminant, or chemical element that can be a part of a thin film), and in some cases, possible resistance to anode "poisoning." Anode "poisoning" is usually a deposition of thin films of reactive gas compositions with the anode, discharge channel, and vacuum chamber materials. These dielectric depositions drastically change the operational characteristics of the ion source, decreasing major parameters such as the ion beam current, and mean energy. This unpleasant feature will be discussed in detail in Chapter 6.
3) Design of a working gas introduction into a gas discharge channel, in particular, how a working gas is applied; how the area under the anode is designed; how well mixed a working gas is when applied into the anode area; if any working gas has a possibility to escape from a discharge channel before being ionized by an applied electric potential; how the electrical conductive plate (sometimes called as a reflector) between the anode area and magnet–magnetic pole (where a working gas usually is applied) is affected by an ion beam that (in many cases of end-Hall ion sources) has a component directed into the side of a reflector causing sputtering, producing damage, and contaminating an ion beam with the reflector material.
4) Magnetic field value in a discharge channel and how magnetic field lines are directed; is a magnetic field gradient positive (in certain cases, an end-Hall ion

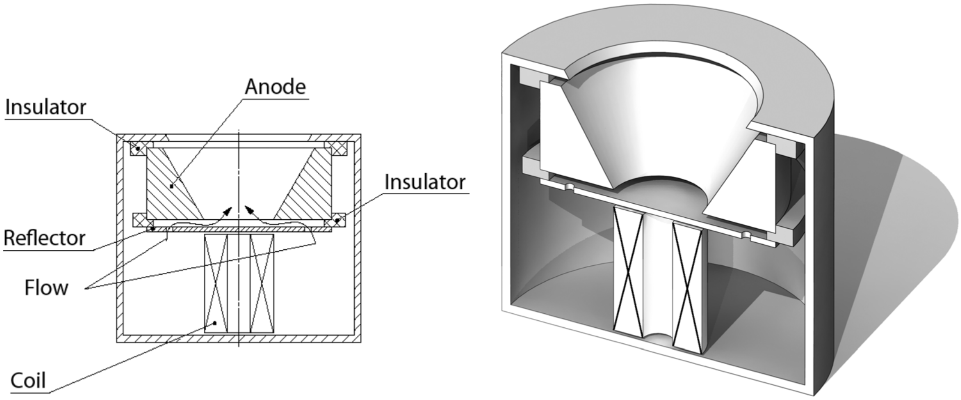

Figure 1.5 End-Hall ion source with magnetic coil on axis [7].

source can be designed with a positive magnetic field gradient) or negative; how permanent magnets or magnetic coils are placed; what kind of material permanent magnets are made of because it is important not to apply high levels of heat to magnets due to the possible threat of being demagnetized.

5) In almost all plasmadynamic systems in which discharge takes place in electric and magnetic fields, and especially in the presence of crossed electric and magnetic fields, there are various types of oscillations and instabilities of main discharge values: discharge current and voltage. The analysis of plasma parameters in ion sources shows that the ion beam energy spread is determined by the extended region of ionization and oscillations of electrical potential in a discharge channel. Development of ions with energy exceeding eV_d shows that oscillations play an important role and produce a significant impact on the ion beam current and the energy of ions. Detailed description of various types of oscillations and instabilities will be presented in Chapter 3.

Figure 1.5 shows the same design as Figure 1.4, where a magnetic coil [7] is utilized instead of a permanent magnet. A magnetic coil requires a separate power supply, but it allows changing magnetic field values in the discharge channel over a broader range. For those who want to use a magnetic coil, it is necessary to note that the magnetic field distributions provided by a permanent magnet and a magnetic coil are slightly different, and the discharge behavior is slightly different as well. Only scrupulous investigations show a different behavior of ion beam parameters.

Figure 1.6 shows an end-Hall of the S. Korean company, VTC-Korea [8]. In this design, a soft iron cylinder is inserted to continue a magnetic path close to a gas distributor reflector in order to reduce the high-temperature impact on a permanent magnet.

The reason for inserting such a soft iron cylinder is the fact that many producers are trying not to use Alnico permanent magnets because they can get much higher magnetic field values with, for example, Nd-Fe-B magnets.

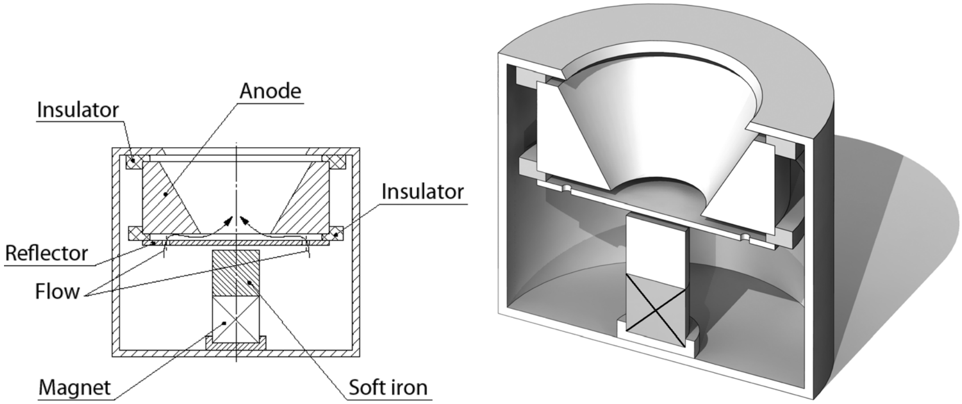

Figure 1.6 End-Hall with soft iron on top of permanent magnet to reduce temperature impact on magnet [8].

However, Nd-Fe-B magnets are significantly more sensitive to high temperatures and their maximum operational temperature is about 150–200 °C, depending on the magnet's quality.

As shown in Figure 1.7, magnets are placed at the base of an ion source body [9]; a soft iron cylinder is placed where the permanent magnet is usually located on the ion source axis, similar to Figure 1.4. This company [9] also utilizes regular placement of a permanent magnet at the ion source base. This end-Hall ion source design is also equipped with a water-cooled anode and water-cooled magnet assembly.

Utilization of a soft-iron cylinder has another advantage: if an ion beam would penetrate a reflector (and this happens quite frequently), it would not harm a magnet.

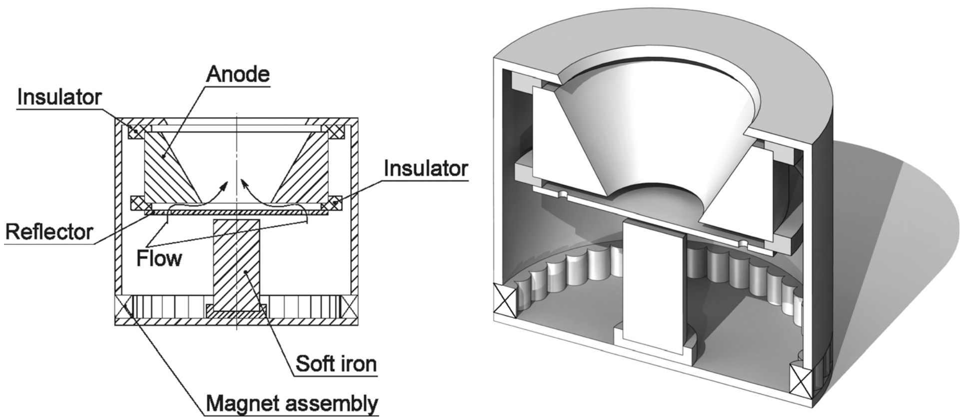

Figure 1.7 End-Hall with magnets at base; soft iron is used instead of magnet; design reduces temperature impact on magnets [9].

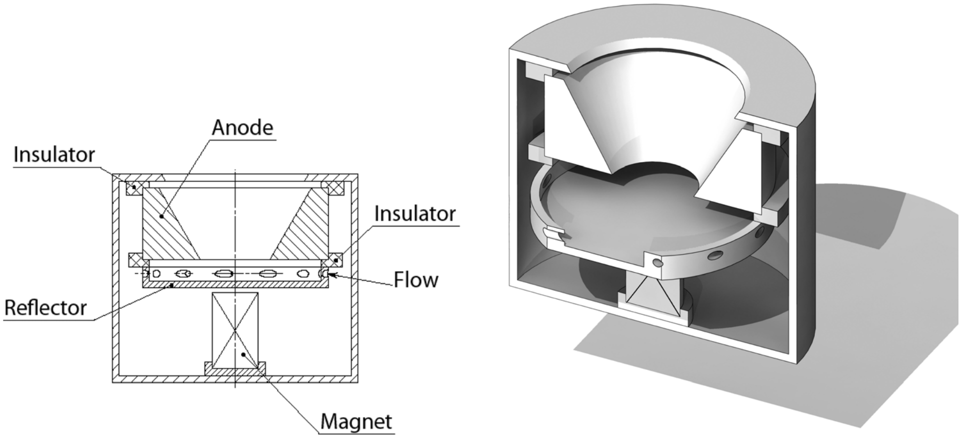

Figure 1.8 End-Hall with buffer area for improved gas distribution [10].

As shown in Figure 1.8, the gas distribution area is substantially increased. Working gas is applied through holes that have a certain angle to provide a gas vortex flow for better working gas distribution [10]. This distribution increases the ion beam current in comparison with the regular end-Hall design (Figure 1.4), which translates to improved conditions for working gas ionization and, correspondingly, to a higher ion beam current than in a regular end-Hall.

Figure 1.9 shows another version of a gas distribution area with a straight-through working gas flow. According to Svirin and Stogny [11], in this design the gas distribution is arranged by the conical inserts and the hole. Here, the electromagnet is utilized for finding the optimum magnetic field, and it is claimed that such a design provides a higher ion beam current than in the regular end-Hall (Figure 1.4).

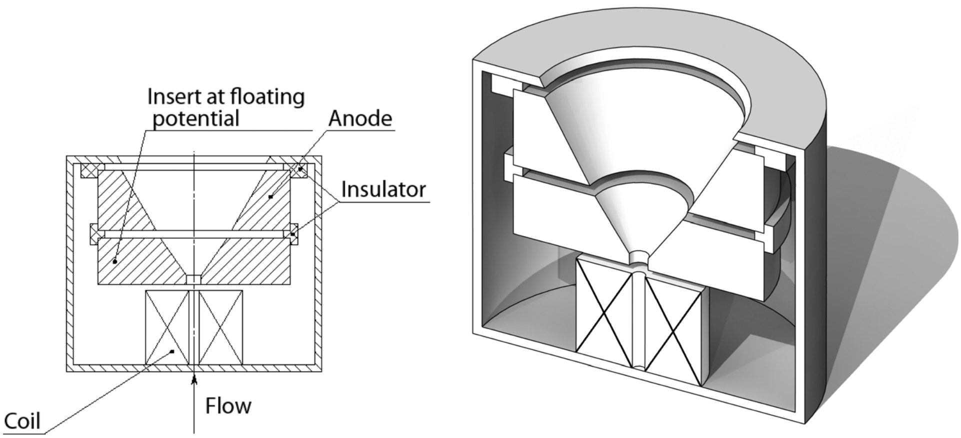

Figure 1.9 End-Hall with hollow insert under anode reduces insert's sputtering [11].

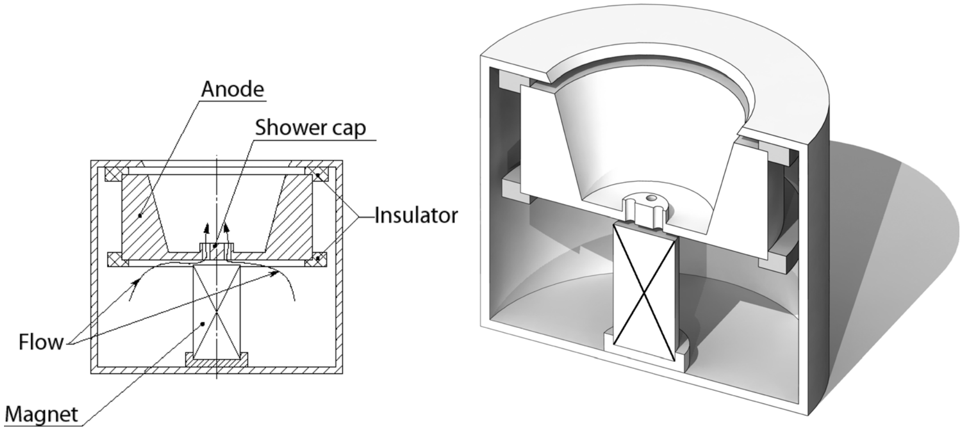

Figure 1.10 End-Hall with connected anode and reflector; working gas distributed through a "shower cap" [12].

Figure 1.10 shows an end-Hall ion source with a discharge channel that is under the anode potential, including a gas distributing area-reflector [12]. Our experiments with a similar design showed the following features of such a design:

1) Reflector connected to the anode operates as the anode itself. An electron current delivered by an external source of electrons (neutralizer) becomes attracted to the central part of a reflector; mainly a longitudinal magnetic field provides confinement of a discharge area and directs straight to the center of a reflector anode.
2) Such a design reduces the ion beam current compared to a reflector, which is under a floating potential. For example, for argon working gas, a discharge voltage $V_d = 50$ V and discharge current $I_d = 5$ A, and an ion beam current for end-Hall with a floating potential $I_i = 0.8$ A; for the end-Hall ion source with a reflector connected with anode, this value $I_i = 0.4$ A. For $V_d = 100$ V, $I_d = 5$ A, an ion beam current for a floating potential design $I_i \approx 1.2$ A and for a reflector connected with an anode $I_i \approx 0.6$ A.

In many cases, producers of end-Hall ion sources make the anode and reflector from various materials, but mainly of stainless steel.

Here are some considerations about the utilization of the reflector and anode made of stainless steel. The application of high currents and voltages leads to the stainless sputtering and development of magnetized flakes adjusted to a reflector and standing on its top. Some flakes are several millimeters in length and can create an electrical connection between a reflector and an anode. In this case and as noted above, an ion beam current will be reduced substantially. A reflector will be damaged faster and an ion beam will be "dirtier" (more sputtering erosion of a reflector area). To avoid such a situation, it is necessary to frequently inspect an ion source discharge channel, and the reflector and anode must be cleaned regularly. Utilization of other materials, like Ta, Ti, Hf, and Mo, can be a good substitution

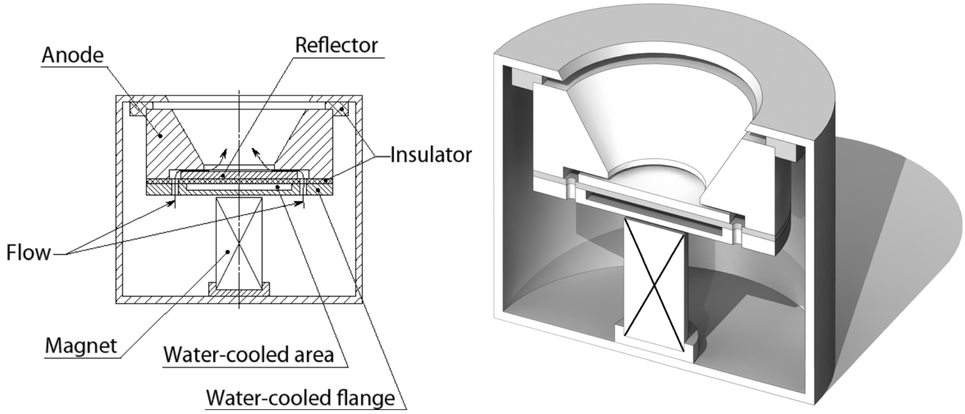

Figure 1.11 End-Hall with water-cooled anode through a dielectric plate; such design helps fast assembly [13].

for stainless steel. They are sputtered less and their components can participate in certain depositions of these materials.

Figure 1.11 shows an end-Hall design with the indirect water-cooled anode through a dielectric plate [13]. In order to have high ion discharge currents and voltages (higher ion beam currents and energies) with high electric powers released into a discharge channel, and not to overheat the main part of a discharge channel anode, it is necessary to water cool the anode because end-Hall-type ion sources have a low efficiency of transformation of the discharge current into the ion beam current. Water-cooled anode designs have been practically developed from the beginning of the end-Hall ion source introduction. In general, it is a water flow in the anode that has a cavity with electrical separation of the anode potential through the insulators. The insulators must be clean, and the water should have no contaminating particles. That is why purified water is sometimes utilized, and from time to time the insulators must be cleaned of any contaminating residue.

Water-cooled anodes make it possible to apply at least twice as much electric power compared to radiation-cooled anodes.

Figure 1.11 [13] shows a schematic design of an unconventional anode-cooling system where the anode is cooled through a dielectric plate. Water flows in a cavity of a copper plate under a dielectric plate. The anode, in such a case, is not directly cooled, but through the dielectric plate and at high applied electric powers of about 3 kW ($V_d = 200$ V, $I_d = 15$ A), it can be heated to very high temperatures of about 1070 °C. With the direct water-cooled anode, it is heated to 500 °C; at the same time, the gas distributor reflector has decreased its temperature from 1050 °C (direct water cooling) to 630 °C. In a vacuum of about 10^{-5} – 10^{-3} Torr, the mean free path of particles is substantially longer than the dimensions of an ion source and there is no convectional heat transfer. In the points of connection of any solid material, there are very limited areas of a contact. In such a case, the main heat transfer is realized by radiation only.

However, such a design has certain advantages in comparison with the direct water-cooled anode:

1) Because the anode is not connected with a water flow, the whole design is very simple. The discharge channel and anode can be assembled–disassembled in a few minutes if the source is cooled off.
2) In the problem of so-called anode "poisoning" [14] (discussed in Chapter 7), the radiation-cooled anodes and the anode design (Figure 1.11) in some dielectric and insulating depositions do not stick like a water-cooled anode surface due to the high heated anode surface. Such end-Hall ion sources can operate longer in conditions of anode bombardment by dielectric and insulating particles.

However, the anode surface with indirect cooling must be carefully monitored and not exposed to temperatures at which the anode surface could melt. Also, a sputtering effect that continuously takes place by electrons increases with a surface's temperature.

This design showed slightly better performance than a regular end-Hall design with the discharge current transformation into the ion beam current with $I_i \approx 0.3\ I_d$.

Figure 1.12 presents an end-Hall ion source with not only a water-cooled anode, but with water-cooled magnets. For certain technological processes that are highly sensitive to change of temperature regimes in the discharge channel, such a design serves very well. A soft iron cylinder completely substituted a permanent magnet with a series of smaller dimension magnets placed at the lower flange base. As a result, such a design can operate at a high applied electric powers of about 3 kW. Also, this design showed a very low sputtering rate of the gas distributor reflector.

Figure 1.13 presents the unconventional gas application into the discharge channel with a regular type end-Hall ion source, similar to that shown in Figure 1.4. It did not

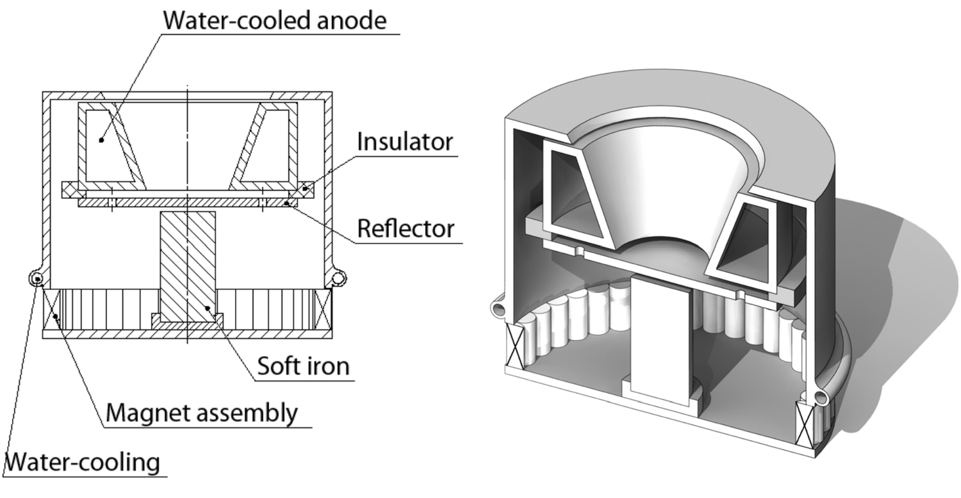

Figure 1.12 End-Hall with water-cooled anode and magnets helping stabilizing operating parameters [15].

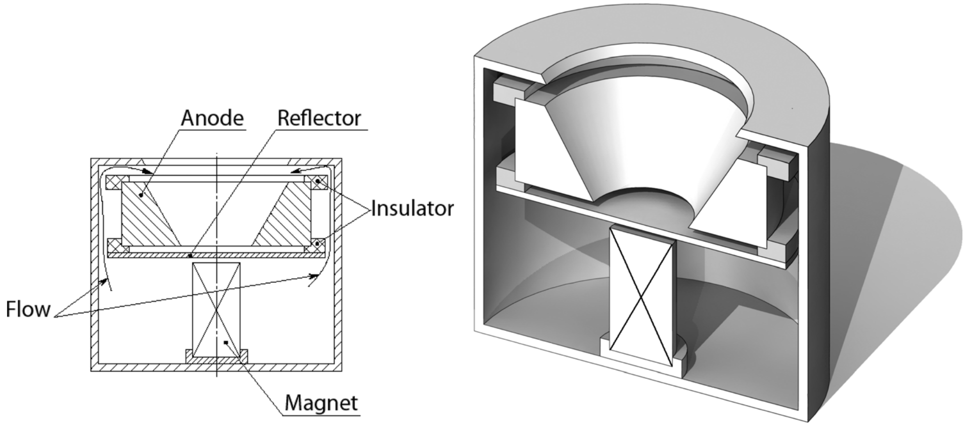

Figure 1.13 End-Hall with working gas applied from top, between anode and upper flange; low reflector's sputtering.

show any advantage in the discharge current transformation; it gave $I_i \approx 0.2\ I_d$. However, a sputtering erosion of the reflector is substantially lower than for a regular gas application (Figure 1.4).

Figure 1.14 shows a working gas application through the anode. Despite the complexity, this gas introduction has certain advantages, such as improved ion beam energy distribution, which is substantially narrower than with a regular gas application (Figure 1.4). A protective cap placed on a permanent magnet gives a signal when an ion beam goes through the reflector [10]. Also, in such a case, the gas distributor reflector experiences significantly less sputtering – about half as much as the regular one.

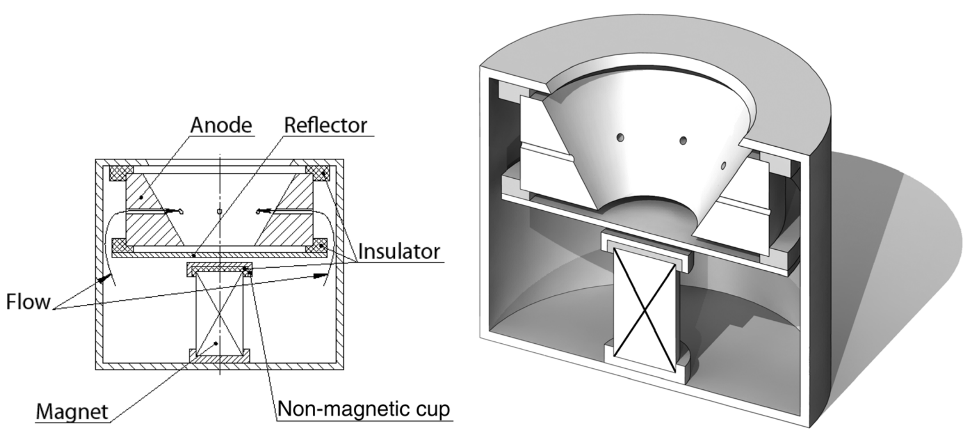

Figure 1.14 End-Hall with working gas through anode; protective cap over a magnet gives signal when ion beam goes through reflector [10].

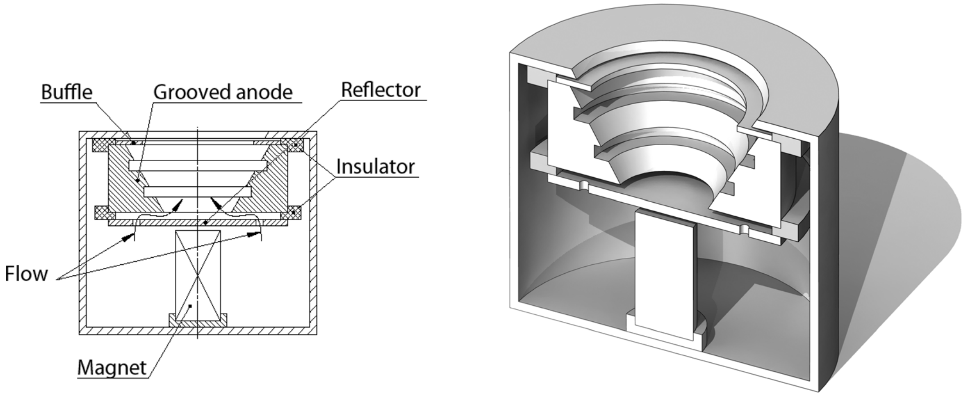

Figure 1.15 End-Hall with grooved anode and baffle to reduce anode "poisoning" [16].

Figure 1.15 [16] shows a special end-Hall design with a grooved anode and placement of the baffle in the presence of reactive gases that "poison" the anode, or at least substantially increase the operating time of the anode. The grooves have sides that do not receive depositions of dielectric or insulating particles. These sides are in the shadow groove parts because in the ion source pressure operating conditions with the long mean free path of particles, the particles propagate along straight lines from their points of origin without collisions with other particles. Thus, a certain part of the anode remains without deposition from contaminating particles returning back into the ion source discharge channel from a target-substrate or vacuum chamber parts. These parts without depositions gradually become deposited, but it can take tens, even hundreds of hours. The non-deposited parts of the grooved anode operate for quite a long time with nominal parameters.

In this work, a metal baffle placed between the anode and the front flange was also utilized. The baffle serves as a shadow for the anode's parts. In this case, the anode operates with reactive gases even longer than with the grooved anode, even though the ion beam current is reduced by a factor of about 0.25 in comparison with the nominal. For processes with ion beam currents that are not high, the increase in the discharge current with the additional baffle can be very helpful in working with reactive gases for longer periods of time without cleaning the ion source anode.

For a period of time, the end-Hall design was investigated as a thruster for electric propulsion technology. Detailed tests of the end-Hall design as a thruster revealed a low thrust efficiency compared with the closed electron drift thrusters, and it was not seriously considered as an electric propulsion device. The problem is that the end-Hall ion source thruster has a negative magnetic field gradient in the discharge channel, and this leads to the development of various oscillations of discharge parameters and low ionization transformation of a working gas [17]. However, due to the simplicity of the concept, several hybrid designs were developed with the end-Hall and closed drift properties for use as a thruster (Figure 1.16) [18] and an ion source (Figure 1.17) [19].

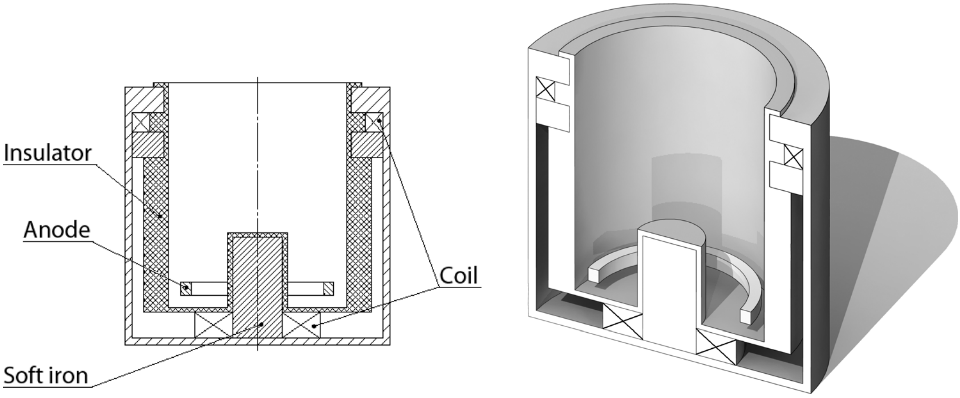

Figure 1.16 Hybrid end-Hall and closed drift ion source-thruster with electromagnets for magnetic field [18].

Figure 1.16 shows a hybrid ion source-thruster suggested in *Cylindrical Geometry Hall Thruster* by Raitses and Fisch [18]. As one can see, this device is similar to a closed electron drift thruster in which the central internal magnetic pole is substantially shorter. The magnetic-field gradient is provided by two electromagnetic coils. The thruster showed quite good efficiency, though it is still less than a regular closed electron drift thruster.

Figure 1.17 shows the schematic design of a similar hybrid ion source; in this case, a permanent magnet is utilized [19]. A soft-iron cylinder is placed in front of the magnet to reduce possible thermal stress on the magnet at highly applied electric powers. The positive magnetic field gradient is provided by two magnetic shunts. Similar to a regular closed drift thruster, this design is quite sensitive to the rate of a magnetic field gradient and to the ratio of the magnetic shunt lengths, which are important as the additional coefficient influencing the operating parameters. It also has a good discharge current into an ion beam current transformation rate, $I_i/I_d \approx 0.7–0.8$. This design still needs further detailed experimental work.

Figure 1.18 shows the end-Hall ion source with a magnetron HC discharge [20]. This recently developed ion source is based on the concept of a closed drift thruster

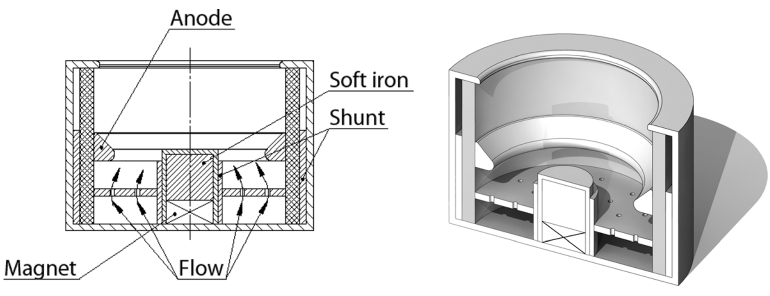

Figure 1.17 Hybrid end-Hall and Closed Drift ion source-thruster with permanent magnet soft iron and shunts for positive magnetic field gradient [19].

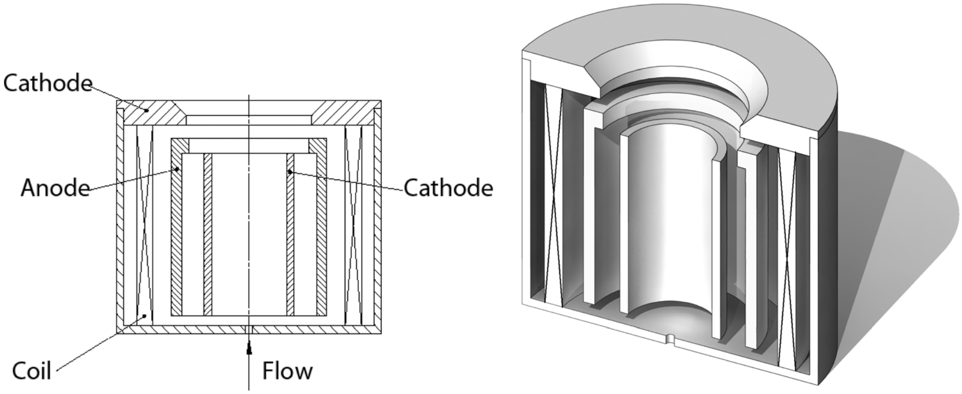

Figure 1.18 Hybrid end-Hall with anode layer ion source without external source of electrons [20].

with the anode layer. It mainly consists of an annular anode and a cylindrical HC enclosed by magnetic poles and an inner shield. The magnetic field in the discharge channel is produced by a SmCo permanent magnet on Fig. 1.18 it is shown with a magnetic coil, back shunt, and inner and outer magnetic poles. A cylindrical magnetic ring is shortened and centrally inserted as an inner magnetic pole. The cylindrical magnetic permeability tube strengthens the magnetic field close to the annular anode in the discharge channel. The working gas is introduced into the HC region via an inlet in the gas distributor. There is no external emissive element utilized with this ion source.

Here are some considerations about this design. This ion source discharge operates in a self-sustained modification at the discharge voltages (discussed in Chapter 4) from $V_d = 300\,\text{V}$ and up to 450 V, with the discharge currents from $I_d = 1$ A up to 4 A. Because it operates with discharge in a self-sustained regime, no external source of electrons is utilized. Instead, the external magnetic pole and internal magnetic pole are utilized as cold cathodes to produce secondary electrons for ion beam neutralization. This ion source is typical of the ALIS (Figure 1.2a) utilized by many companies for cleaning and sputtering without an external source of electrons, with a broad ion beam energy distribution, a low ion beam current, and a low mean ion beam energy value ratio to a discharge voltage. This ion source was referred to as end-Hall by the authors, but we would classify it as a hybrid between a closed drift and end-Hall ion source. For certain technological tasks (cleaning, sputtering), this ion source can be a very suitable device. It needs to be qualified with various working gases, and cold cathode sputtering rates should be measured to estimate an ion beam purity.

Also, it needs to be checked for the proper ion beam neutralization, with targets placed at different distances from the ion source.

Figure 1.19 shows an end-Hall ion source design with the gas distributor reflector having additional material on the reflector's top. The additional piece of material increases the reflector's thickness and its lifetime, which was previously reduced by an ion beam sputtering (discussed above). This reflector can be made sectional, with the central part made of a specific material that can be part of the thin film deposition

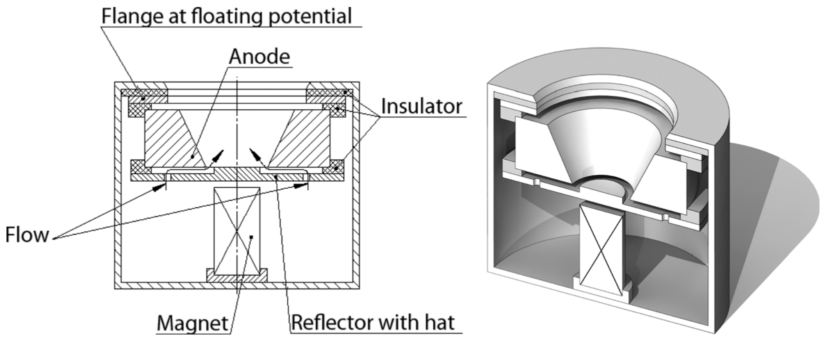

Figure 1.19 End-Hall with improved features: reflector with "hat"; floating potential flange to reduce ion beam spread.

process (for example, with the tantalum, or titanium material during obtaining these elements oxides, etc.).

Also in this design, the exit flange-external pole is made of sections. The lower part is separated by a dielectric piece, and the lower flange part is under a floating potential. The electric potential induced during an ion source operation by reflecting with its potential (usually of about $0.5\,V_{\mathrm{d}}$) helps in reducing the ion beam divergence.

Figure 1.20 shows a new design of an end-Hall ion source with a two-chamber anode and a working gas introduced through the anode [21]. Such a design provides a very uniform working gas distribution and has proved to be more efficient than regular designs. Working gas introduction in the anode area accomplishes the ionization process in a shorter distance at the anode by applying electric potential only in a narrow region, leading to a high ratio of the mean ion beam energy to the discharge voltage times electron charge. In regular end-Hall ion sources, $E_{\mathrm{i}}/eV_{\mathrm{d}} \approx$ 0.6–0.7. In this new end-Hall design with a two-chamber working gas introduction, this ratio $E_{\mathrm{i}}/eV_{\mathrm{d}} \approx 0.9$. This design will be discussed in detail in Chapters 5 and 9.

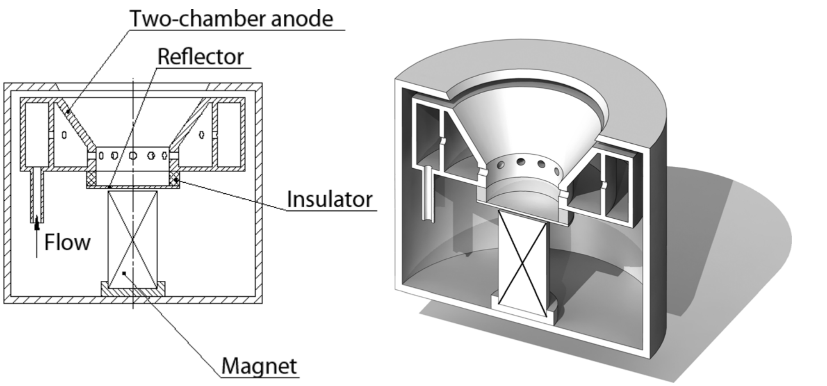

Figure 1.20 End-Hall with double-chamber anode and working gas through anode to improve ion beam energy distribution [21].

1.4
Electric Discharge and Ion Beam Volt–Ampere Characteristics

Electric discharge in a gas is the method of obtaining ions in an ion source. In over 100 years of electrical discharge studies, and especially in devices designed for obtaining controlled flows of ions and electrons, it was found that in the particular range of pressures of 10^{-5} – (1–2) $\times 10^{-3}$ Torr of working gases when an ion beam satisfies the conditions for thin film technology, electric discharge exists in various modifications.

There are two main regimes of discharge in the ion sources: (1) a nonself-sustained regime and (2) a self-sustained regime. A nonself-sustained regime requires a cathode emitting electrons for discharge ignition and its maintenance. A self-sustained regime does not need an external source of electrons. After ignition, a self-sustained discharge maintains its existence by a sufficient electric potential ($V_d = 300$–350 V and above) applied between the anode and any conductors in a discharge channel (walls, flange) that can serve as cathodes with ions and electron collisions with such conductors (high potentials, in principle, can generate electrons with dielectric and insulators surfaces, but with less probability than with conductors).

This discharge produces a sufficient number of secondary electrons from ion bombardment of the discharge channel and parts.

The characteristics of a self-sustained discharge ignition and its extinction depend on several factors: (1) pressure condition in a discharge channel; (2) gas type, especially its ionization potential; (3) means of gas introduction into a discharge channel: uniformity, through one or a series of holes, slits, mixing; (4) geometry of the anode and its relative placement cathode serving parts; and (5) magnetic field value and its distribution.

In order to discuss a nonself-sustained discharge and its role in Hall-current ion sources, it is best to start with the analysis of the Volt–Ampere (V–A) characteristics of discharge in the Hall-current ion sources, although in general, V–A characteristics for both types of ion sources (CDIS and end-Hall) demonstrate a similar behavior.

In Figure 1.21, the upper curve **1** shows typical V–A characteristics of high current intense discharge of an end-Hall type ion source for discharge current $I_d = 5$ A as a function of discharge voltage, $I_d = f(V_d)$; a discharge current constancy is regulated by a working gas mass flow that is substantially changing from high to low while moving with discharge voltages from low to high values. The working gas is argon, and the pressure in the vacuum chamber is between 5×10^{-5} and (1–2) $\times 10^{-3}$ Torr. The lower curve **2** presents an ion beam current I_i as a function of discharge voltage, $I_i = f(V_d)$. The discharge between the anode and the cathode is maintained by electron emission provided by a cathode placed outside of the ion source.

The source of electrons is either HF or HC. For the conditions in the end-Hall ion source, a magnetic field of a permanent magnet or electromagnet is, in general, between about 500 and 1300 G (depending on ion source dimensions), which has a maximum value at the top of a gas distributor-reflector. This means that a magnetic-field value is 300–500 G higher on a magnet's top [It is agreed by most producers that

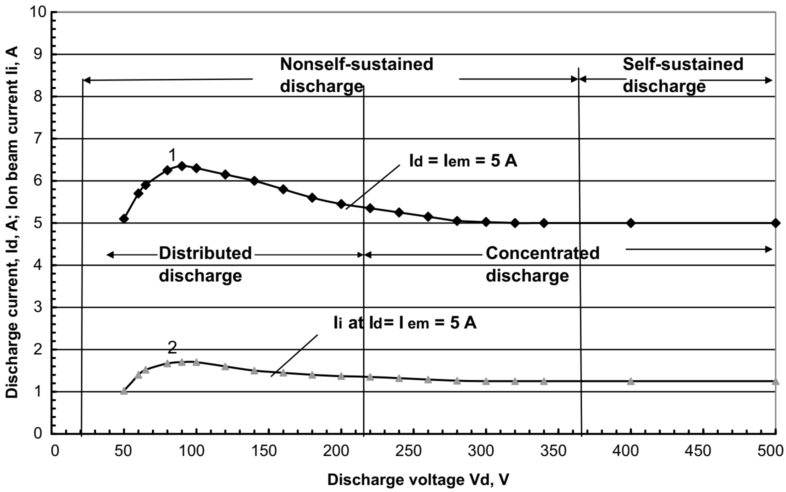

Figure 1.21 V–A characteristics, regimes, and modes for end-Hall ion source with discharge I_d and ion beam current I_i as functions of discharge voltage V_d for $I_d = I_{em} = 5$ A; working gas argon.

the top of a permanent magnet looking to a gas distributor will be a North pole.], or 1000–1800 G. Variations in low and high values are acceptable, depending on a particular ion source task. For comparison, in a closed electron drift ion source, a magnetic field of a permanent magnet or electromagnet is between 100 and 500 G of the maximum value, which is usually at the exit flange (depending on working gas and ion source dimensions).

High current electrical discharge in Hall-current ion sources (Figure 1.21) consists of two types: a *nonself-sustained* and a *self-sustained discharge* [22]. *A nonself-sustained discharge* takes place for discharge voltages from about $V_d \approx 50$–60 V for an end-Hall operating with argon working gas and other noble gases; from about $V_d \approx 80$–90 V with reactive gases such as oxygen and nitrogen; and from about $V_d \approx 80$–100 V for a closed electron drift with noble gases and up to about 360–370 V for both ion sources. It can only exist and be maintained due to a continuous development of charged particles provided by a source of electrons.

With xenon as the working gas, discharge can be ignited by about 15–20 V lower for both ion sources. The discharge voltage ignition values given above are for approximate equality of discharge and emission currents. For emission currents that substantially exceed the discharge current (discussed in Chapter 4), the ignition voltage can be 20–30 V lower. CDIS have, as a rule, higher ignition voltages than end-Hall ion sources. Various ignition discharge voltages can be explained by the fact that a CDIS mainly has a radial magnetic field component in the whole discharge channel, and end-Hall has a radial magnetic field component only at the 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 field component in a closed drift source than in an end-Hall source.

As noted above, a high current discharge in ion sources with a discharge voltage over $V_d \approx 370–380\,V$ presents itself as 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 the discharge channel and outside of an ion source in the vacuum chamber walls.

Also, discharge at low discharge voltages and up to about $V_d = 200–220\,V$ (argon) presents itself as a modification that is a *distributed discharge*. Discharge at higher discharge voltages (above about 220 V) presents itself as a modification called a *concentrated discharge*. These modifications received such names because they are observed from outside 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 the form of plurality of pinched plasma flows, and at high currents of 10 A and above as one pinched discharge surrounded by a glow.

Both kinds of intensive discharge, nonself-sustained (in a distributed mode) and self-sustained (in a concentrated mode), are significantly different in their physical processes. The processes taking place in a distributed discharge are more complex and have been less investigated. In particular, for propagation of electron current from the cathode to the anode, it is necessary to have excessive plasma conductivity, which under certain conditions can be caused by the 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 the publications about closed drift anode layer type ion sources-thrusters [23], experimental results with discharge are presented where the working gas was xenon. In the anode layer, an ion source thruster having dimensions of exit discharge channel diameter of 80 mm, the discharge 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 exit are more uniform than at a concentrated modification. Also, an ion beam focusing quality on 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: (1) dimensions and geometry of the discharge channel, (2) discharge current, (3) working gas mass flow, and (4) magnetic field components and their values in a discharge channel.

Besides V–A characteristics (Figure 1.21), which are not easy to properly investigate for regular ion source users, there is another important characteristic: the discharge voltage as a function of the working gas mass flow $V_d = f(\dot{m}_a)$ at constant discharge currents, $I_d = 1, 2, 3, 4, 5...10$ A. Typical characteristics of $V_d = f(\dot{m}_a)$ and $I_d = 1, 3, 5$ A for oxygen, argon, and krypton for new end-Hall ion sources with a multichamber anode [21] are given in Figure 1.22.

A well-tuned ion source always shows smooth curves for $V_d = f(\dot{m}_a)$. Usually, such curves begin showing erratic behavior at low and high discharge voltages, when discharge experiences various oscillations. In addition, many producers of

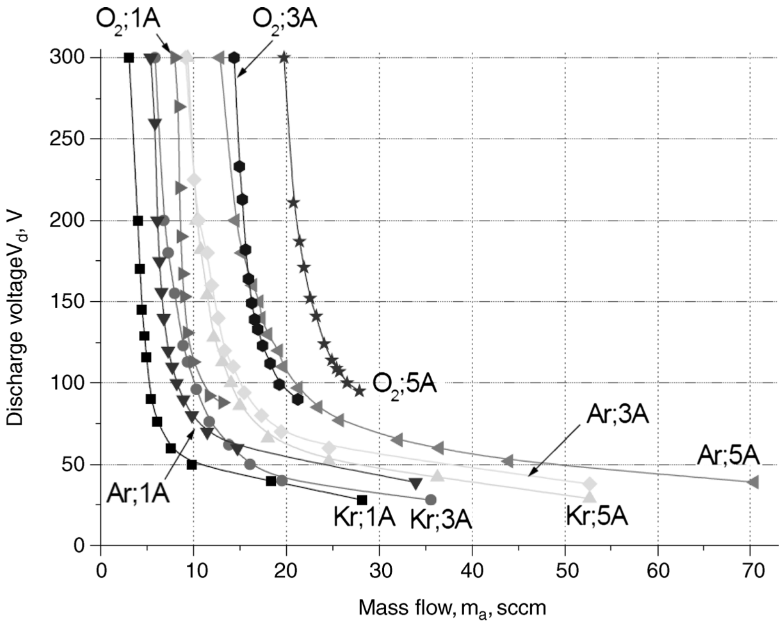

Figure 1.22 End-Hall ion source [21] discharge voltage as function of a working gas mass flow $V_d = f(\dot{m}_a)$ at constant discharge currents $I_d = 1, 3, 5$ A for oxygen, argon and krypton.

ion sources with a narrow range of operating discharge voltages could not find a proper optimum magnetic field in a discharge channel. Also, tested curves of $V_d = f(\dot{m}_a)$ become quite narrow. For example, one can see (Figure 1.22) that for oxygen (nitrogen behaves in similar way), the discharge voltage at its low value does not go lower than about $V_d = 80$–90 V. However, by regulation of a permanent magnet's magnetic field, it is possible to have oxygen with a discharge voltage of $V_d = 40$–50 V.

Figure 1.22 presents experimental data for a recently developed new end-Hall ion source [21] for the discharge voltage as a function of a working gas mass flow $V_d = f(\dot{m}_a)$ for constant discharge currents $I_d = 1, 3, 5$ A for oxygen, argon, and krypton. As one can see, at high discharge voltages a working gas mass flow is quite low; for most gases it is under 5–10 sccm for low discharge currents and, especially, for krypton. A working gas mass flow is influenced by the ionization potential (low first ionization potential gases have higher ionization cross section) and atomic or molecular weight. Also, the vacuum chamber size, its pumping means, and the dimensions of an ion source opening diameter have an influence on the applied working gas mass flow. In general, the larger a vacuum chamber, the bigger the ion source dimensions, the higher is the mass flow of a working gas required.

As discussed at the beginning of this book, the most important characteristic values of any industrial ion source are: an ion beam current value I_i, and a mean ion beam energy E_i. Both values are not given on power supplies and are not easy to measure; there are special probes for this purpose(discussed in Chapter 9). The

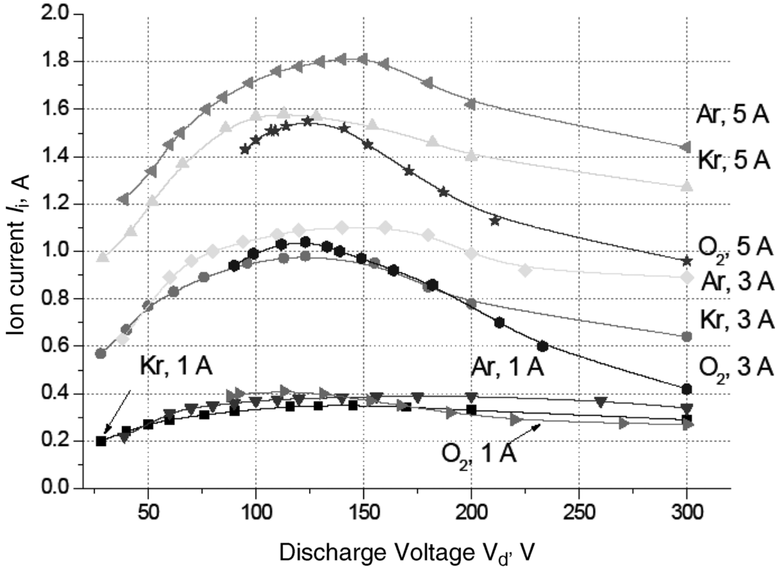

Figure 1.23 End-Hall ion source [21], ion beam current as function of discharge voltage $I_i = f(V_d)$ at constant discharge currents $I_d = 1, 3, 5$ A for oxygen, argon and krypton.

results of an ion beam current as a function of discharge voltage $I_i = f(V_d)$ at constant discharge currents $I_d = 1, 3, 5$ A for oxygen, argon, and krypton for a new end-Hall ion source with a multichamber anode are presented in Figure 1.23.

Comparing this figure's curves with Figure 1.21, there are definite similarities in the behavior of the curves for an ion beam current for all tested gases. All experimental curves are taken with an external cathode in the form of HF, with discharge current and neutralization currents approximately equal to each other, or $I_d \approx I_{em}$. All curves show a typical nonself-sustained discharge with a maximum ion beam current in the range of discharge voltages from about $V_d = 100$–150 V at all discharge currents and for all working gases.

The above discussions of various V–A characteristics, regimes, and modes for end-Hall ion sources are due to the fact that for most of the time, end-Hall ion sources are utilized in the range of discharge voltages from about $V_d = 50$–80 V (if possible) and up to about 150–175 V. However, in practice, $V_d = 100$ V is the most probable experimental value with $I_d = 1$–5 A.

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

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

2) Dimensions and shape of an ion source discharge channel.
3) Magnetic field value and ion source magnetic circuit configuration.
4) Gas distributing system; how the working gas is applied into the anode region; how the working gas is distributed in the discharge channel, whether it comes from an area under the anode (could be applied first into a so-called buffer area) and well distributed there, applied through small jets from gas-supply holes, or from the anode itself.
5) Emission current value supplied by an HF, HC, or other means; how emission provides a flow of electrons into a discharge channel; how the electron sources are placed and at what distance from the exit flange of the ion source.
6) Type of working gas: low or high atomic mass, ionization potential.

1.5
Operating Parameters Characterizing Ion Source

The cylindrical Hall-current ion sources can operate with many different working gases. However, a majority of work in industrial utilization of ion sources is with gases such as oxygen, nitrogen, argon, other noble gases (xenon, krypton), methane, and hydrogen. The most important operation characterizing parameters of cylindrical Hall-current ion sources are:

1) **Range of Discharge Voltages, $\mathbf{V_d}$**: Hall-current ion sources can usually operate from about $V_d = 50$–80 V to about $V_d = 1000$ V. The range of discharge voltages translates into an ion beam energy (ions born in electric discharge are accelerated by applied electric potential between the anode and the cathode). Most closed drift and end-Hall ion sources have a very broad ion beam energy distribution with a mean ion energy $E_i = (0.6$–$0.7)\ eV_d$, though recently developed new ion sources are capable of having a narrow ion beam energy distribution with a mean energy $E_i = (0.8$–$0.9)\ eV_d$. This is for properly neutralized ion sources. In these cases, when an ion beam is not neutralized by an external source of electrons, or underneutralized with the emission current lower than the discharge current, a mean ion energy $E_i = (0.1$–$0.5)\ eV_d$. In academic studies of Hall-current ion sources [1], this feature of a discharge voltage conversion into an ion beam mean energy is characterized by *the coefficient of the ion beam energy transformation*, or the ratio of a mean ion beam energy to the applied electric potential to anode times the electron charge:

$$k_1 = k_E = E_i/eV_d \tag{1.1}$$

Most ion source users do not pay much attention to this coefficient; however, we are going to show later that this value is important in many thin film deposition tasks.

2) **Range of Discharge Currents, $\mathbf{I_d}$**: Hall-current ion sources can usually operate from about $I_d = 1$–2 A to $I_d = 10$–15 A. In principle, it is possible to design ion sources with substantially higher discharge currents of up to $I_d = 50$–100 A.

However, such high discharge currents would need a large-diameter discharge channel with high working gas mass flows that must be pumped from a vacuum chamber and big power supplies. This requires high-production vacuum pumps, a lot of energy, and big financial expenditures. Also, such high discharge currents may not be necessary for most designed technical tasks. Only in special occasions such discharge currents can be justified.

The range of discharge currents translates into an ion beam current, or how efficient the design for an ion source is for a discharge current transformation into an ion beam current. This feature is usually characterized by *the coefficient of the discharge current transformation into the ion current*:

$$k_2 = k_\mathrm{i} = I_\mathrm{i}/I_\mathrm{d} = \dot{\mathrm{m}}_\mathrm{a} e/(M I_\mathrm{d}) \tag{1.2}$$

where $\dot{\mathrm{m}}_\mathrm{a}$ is a working gas mass flow, e is the electron charge, and M is a working gas atomic mass. The coefficient k_i for ALIS and MLIS is 0.8–0.9 in optimum regimes with correctly used magnetic field and with the external source of electrons for ion beam neutralization. For end-Hall ion sources, this coefficient is usually 0.2–0.25.

3) **Relative Monoenergeticity of an Ion Source's Ion Beam Energy**: This feature is characterized by the coefficient determining the ratio of a certain range of energies around the mean ion beam energy (for example, a 90% from the total ion beam energy distribution) to the electron charge times the discharge voltage, or:

$$k_3 = k_{\Delta E} = M\langle v_\mathrm{i}^2\rangle/(2\,eV_\mathrm{d}) \tag{1.3}$$

4) **Ion Beam Divergence**: At the ion source exit, which is determined by a certain percentage (70–80%) of a total ion beam current density j_i passing from an ion source axis through a conical surface with an opening half-angle α of 10–15° (ALIS with proper ion beam neutralization), 20° (MLIS with proper ion beam neutralization), and 40–60° (end-Hall ion source with proper ion beam neutralization). *The coefficient determining impact of an ion beam flow divergence* can be determined as:

$$k_4 = k_\alpha = \langle v_\mathrm{iz}\rangle^2/\langle v_\mathrm{i}^2\rangle \tag{1.4}$$

where $v_{\mathrm{i}z}$ and v_i are ion particles velocity in the z-direction, and total ion flow.

5) **The Coefficient of the Working Material Utilization**:

$$k_5 = k_{\dot{\mathrm{m}}_\mathrm{a}} = \dot{\mathrm{m}}_\mathrm{i}/\dot{\mathrm{m}}_\mathrm{a} \tag{1.5}$$

This coefficient $k_{\dot{\mathrm{m}}_\mathrm{a}}$ together with k_i coefficient shows how efficient the particular ion source is in transformation of a working material into an ion beam flow.

6) In some cases, it is necessary to take into account *the coefficient determining a number of doubly ionized particles*, or a current of the working gas and their ratio to a number of singly ionized particles, or a current with:

$$k_6 = k_{z++} = I_{\mathrm{i},z++}/I_{\mathrm{i},z+} \tag{1.6}$$

This coefficient can be from 10^{-4} for low ion beam mean energies, up to 10^{-1} at moderate energies of about 300 eV, and up to 0.5 and more at higher energies of above 500–800 eV. Coefficient k_{z++} also depends not only on ion beam energies, but on a working gas first ionization potential and a gas pressure. In some cases, even a small coefficient k_{z++} can have a great impact on certain thin film processes, because the doubly ionized particles possess double ion energy that can cause substantial sputtering of materials. This coefficient, along with some specific operations of ion sources, will be discussed in another chapter.

7) *Coefficient determining the ratio of ionized particles flying into the direction of an ion beam exit $I_{i,direct}$ and a number of ions, or a current flowing into the opposite direction $I_{i,reverse}$,* into a reflector, the place where a gas distributor is located:

$$k_7 = k_{\text{rev}} = I_{\text{i,reverse}}/I_{\text{i,direct}} \tag{1.7}$$

This coefficient is especially important for end-Hall ion sources in which a substantial flow of ions is directed into a gas distributor-reflector in the opposite direction of the exit plane. This flow of ions falls on a reflector's surface, sputters it, reflects back to the exit plane, and makes an ion beam contaminated with a reflector's material. In some cases, the coefficient k_{rev} can be from 10^{-4} to 10^{-2}, which is quite a large number. This reverse flow produces substantial damage to a gas distributing system-reflector, and the reflector must be substituted for a new one within 15–20 h of operation at $I_d = 5$ A and $V_d = 100$–150 V.

Appendix 1.A: Web Addresses

http://www.orc.ru/~platar/P6E.html.
http://www.mirea.ru/science/priority/plazm.html.
http://www.veeco.com/linear-anode-layer-ion-sources/index.aspx.
http://generalplasma.com/products/ion-sources/ppals-ion-source.
http://glass-coatings.narod.ru/ionsource_ru.htm.

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