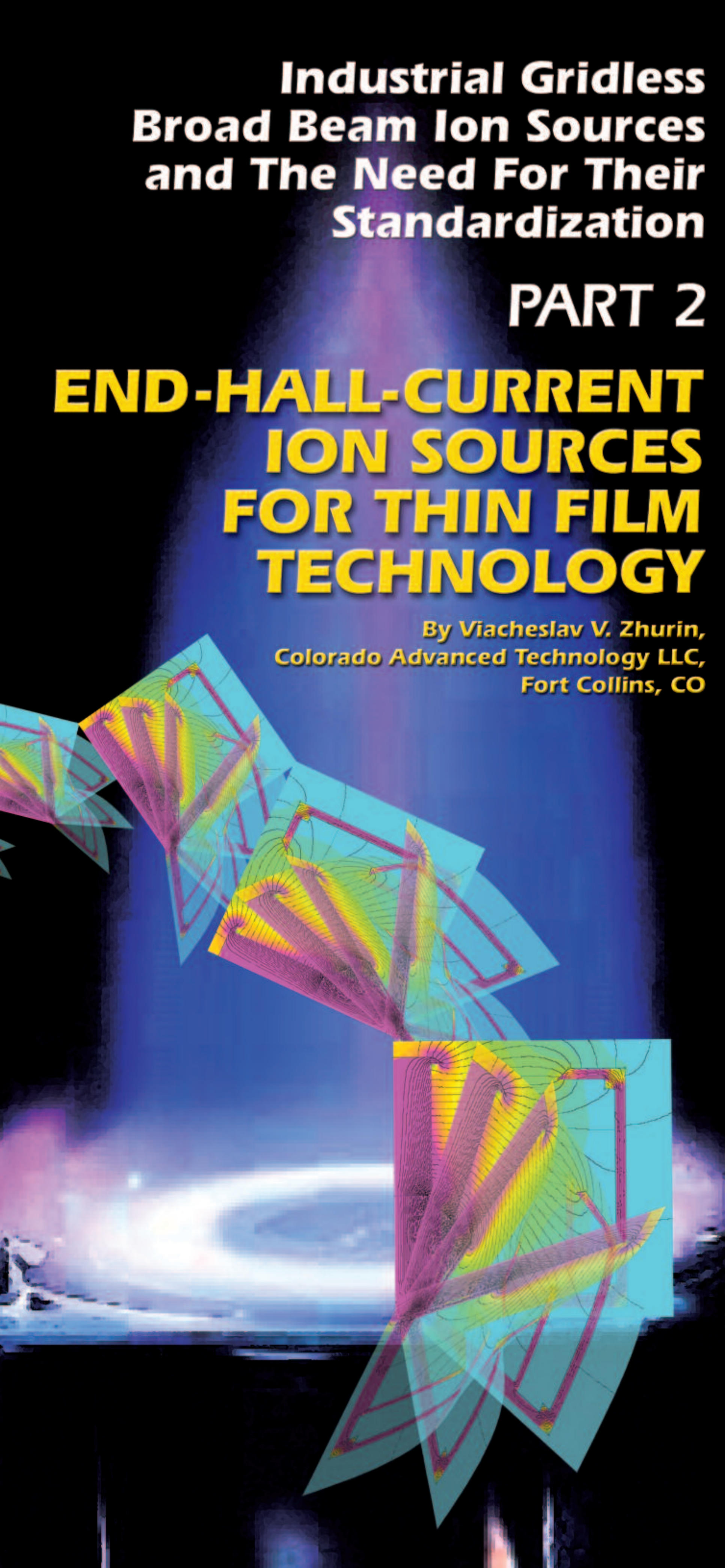
Industrial Gridless Broad Beam Ion Sources and The Need For Their Standardization

PART 2

END-HALL-CURRENT ION SOURCES FOR THIN FILM TECHNOLOGY

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



This article "Industrial Gridles Broad Beam Ion Sources ..." consists of 4 parts. Part 1, published in the April 2009 issue of *VT&C* consisted of the "Introduction" and "Closed Drift Ion Sources. Part 2 is "End-Hall Ion Sources". Part 3 will cover "Non-Traditional Ion Sources" and "Linear Ion Sources". And, Part 4 will cover "Hall-Current Ion Sources Basic Operation Parameters Problems and Solutions" and "The Need for Standardization of Ion Sources".

Another variety of Hall-current ion sources, the so-called end-Hall ion source became more known and utilized in the low-energy thin film technology than the closed drift ion sources that were investigated experimentally and theoretically as thrusters for Electric Propulsion in space. For the end-Hall ion sources there was given the information about operation of such ion sources providing the range of discharge currents, voltages, mass flows for various working gases. This type of broad beam ion sources needs to continue to study physical phenomena taking place in them, with explanations about limits of operation and processes that influence on such limits.

Almost from the beginning of working with closed drift thrusters-ion sources it was discovered that there could be developed plasma oscillations and instabilities [13] caused by the anomalous high mobility of electrons across magnetic field and leading to the destruction of electric field.

In order to suppress oscillations and instabilities in the thrusters-ion sources with the closed electron drift of Magnetic and Anode Layer types, the increasing magnetic field in the direction of electric field is realized, in other words, with the positive gradient of magnetic field from anode to cathode.

However, the systems with the increasing magnetic field are not always conven-

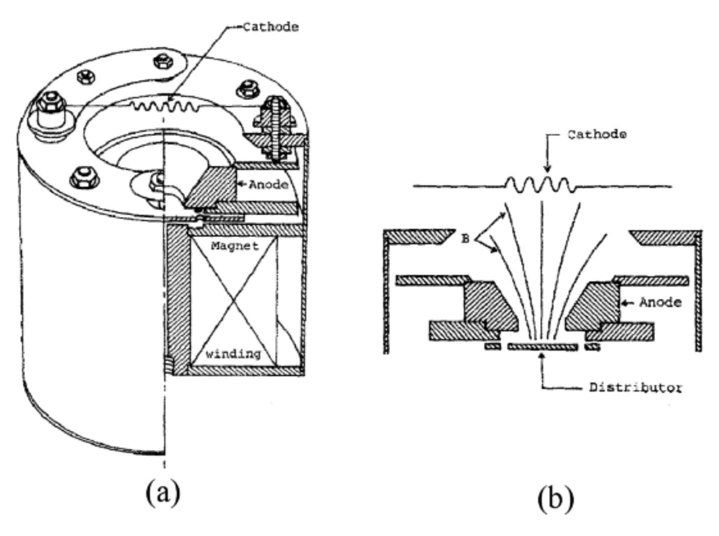


Figure 6. Schematic of an end-Hall ion source (**a**) overall (**b**) discharge region with magnietic field lines

ient in the design and applications. There are several good examples, when a negative magnetic gradient is convenient for certain physical tasks. For example, in the new approach for the plasma optics suggested and developed by A.I.Morozov and his collaborators [14, 15], in the simple and the most important part – the axial lens, it is necessary to have a decreasing magnetic field focusing in the direction of electric field.

In a series of works [16, 17, 18] there are considered schematics of ion sources with the negative magnetic gradient and in [16] there is given the criterion for suppression of low-scale disturbances for such a case. It is shown that if magnetic field decreases in the direction of electrical field faster than the electron concentration, it is possible to find certain conditions, when the instability will be suppressed for all wave numbers. Experiments also confirm such results. However, the conditions that utilized in [16, 17, 18] are for comparatively low discharge and ion beam currents of not higher than 20 mA and discharge voltages from 1 to 5 kV for various working gases. Those who work in the thin film technology can see that such range of ion beam currents and energies are hardly acceptable, especially, for the industrial usage.

The good alternative for the thin film technology in the last 20 years became the another type of Hall-current ion source frequently called as an end-Hall ion source [19], with the high discharge currents (1-15 A) and correspondingly ion beam currents (0.2-3 A) with a very reasonable range of discharge voltages (50-300 V) and comparatively low mean ion beam energies (30-180 eV) for most known working gases (O_2, N_2, Ar, Xe, etc). Below there is presented a short review of known end-Hall models and theirs modifications.

In **Figure 6** there is shown a schematic drawing of the original end-Hall design [19, 20]. It shows the anode and magnet placement that still is used in Veeco, K&R and many other producers of ion sources. The magnet is under the gas distributor-reflector is actually protected by the gas distributor-reflector from a high-temperature and the direct impact from an ion beam propagating not only to the exit, but also into an opposite side into the reflector. Anode can be a radiation or water cooled, or cooled through a dielectric plate (latest Veeco design). In latest models, end-Halls have a modular design with the anode assembly that can be removed from the whole ion source assembly in a matter of few minutes.

The cathodes of these end-Hall designs utilize either a Hot Filament (HF), or a Hollow Cathode (HC), or other means for producing electrons for working gas ionization and ion beam neutralization [* Also used: Plasma Bridge Neutralizer (PBN), Radio-Frequency Neutralizer (RFN), etc.]. Major end-Hall makers have good measuring techniques for the ion beam currents, energy and sputtering ability of ion beams.

An ion source has a magnetic system (for simplicity shown only an upper part in **Figure 6b**) consisting of several parts such as: an electromagnet, or permanent magnet (on **Figure 6a** electromagnet is shown not in dimension; permanent magnet usually is of a cylindrical form about 50-80 mm long depending on an ion source size with the diameter of 12-20 mm, if Alnico-5 magnets are used) representing an internal magnetic pole, magnetically permeable shell with the ion source's exit flange as an external magnetic pole.

In end-Hall ion source (**Figure 6**) there is no positive magnetic gradient from anode to a source's exit. The magnetic field decreases from the internal magnetic pole that usually is placed under a gas distributor-reflector. In other words, the end-Hall is an ion source with a negative magnetic gradient with all the consequences, which are:

- Reduced ionization ability in discharge channel leading to lower rates of an ion beam current to discharge current I_i/I_d = 0.2-0.25, instead of 0.7-0.9 for the closed drift source.
- Increased oscillations and instabilities leading to difficulties to maintain discharge at discharge voltages higher than V_d = 250-300 V.
- Increased ion beam expansion angle leading to higher erosion rates for the discharge channel, the external magnetic pole, increased ion beam penetration into a gas distributor-reflector and its intensive erosion.

However, the concept of the closed drift ion source did not find its broad utilization in the thin film deposition market in comparison with the end-Hall source concept. Here are several reasons. The end-Hall ion source was suggested and patented [19] in 1989. The first end-Hall ion sources Mark-I and Mark-II were well designed and investigated for an ion beam current and an ion beam energy. They were comparatively simple in assembly-disassembly and in operation. They were robust, simpler and cheaper than the gridded sources. They were well qualified with discharge voltage and current as function of anode mass flow for main working gases: Oxygen, Argon and Nitrogen. They became very popular among many users especially for those working in optical depositions with special spectral properties. At the beginning of their utilization they could provide high ion beam currents (over 1 A) with various noble and reactive gases at quite low energies of about 50-150 eV. That something was practically impossible to do with the gridded ion sources especially at energies under 100 eV. And, despite their low ion beam current ratio to discharge current (about 0.2 at the beginning) they still had comparatively high ion beam current at low energies and found broad utilization. End-Hall ion sources at first were marketed and fabricated by a Commonwealth Scientific Corporation, and later by Veeco and K&R. New versions of end-Hall ion sources can provide the same low ion beam energies with ion beam currents up to about 3-4 A (Veeco's Mark-II$^+$ at $I_d = 15$ A).

In 1980s – 1990s there were no strong competitors makers of closed drift ions sources to a such simple convenient design like end-Halls Mark-I and Mark-II. At the same time, the closed drift concept was implemented very successfully as the highly efficient electric propulsion device-thruster for space applications.

After appearance of end-Hall ion source publications and on the market [19, 20] various companies began developing similar ion sources with changes in a discharge channel geometry, placement of magnets, ways for introduction of working gas into discharge channel, anode cooling, and other components.

Certain modifications of end-Hall ion sources improved their performance such as the higher ratio of an ion beam current to a discharge current, broader range of operating discharge voltages, reducing anode "poisoning", possibilities to reduce an ion beam divergence, etc.

However, some changes made by various end-Hall producers, such as placement of magnets and utilizing exotic magnets materials, gas distributing system, ion source dimensions were not justified and did not bring much of improvements.

In **Figure 6b** magnetic field lines are mostly axial in the area of a gas distributing plate – reflector, and magnetic field lines become more radial in the area of an ion source exit.

The anode usually is a hollow conical shape and made of various electrically conducting materials, such as stainless steel, copper, graphite.

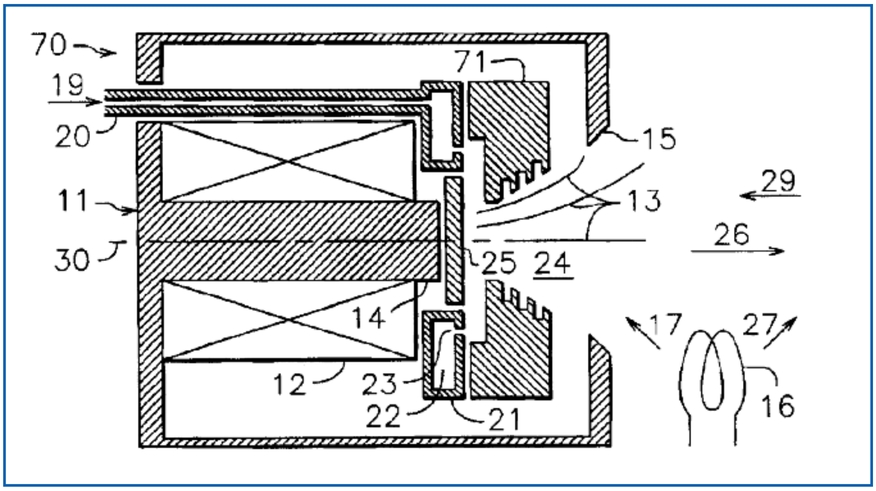


Figure 6c. Reduced "poison" End-Hall ion source [21]: 71 - grooved anode; 12 – magnet; 19 – gas flow; 16 – Hot Filament

There are known users making their own anodes of various materials: tantalum, tungsten, molybdenum that are quite expensive. Working gas is applied through a series of holes in a distributor-reflector. Anode and reflector are separated by a dielectric piece and the reflector is under a floating potential, meaning that it is separated from anode and ground potentials. Reflectors can be made besides the standard stainless steel for reactive gases and the graphite for noble gases of various low sputtering electrically conducting materials or materials such as Tantalum, Titanium that utilized for specific thin film tasks.

During operation the reflector becomes charged at a positive potential lower than anode's. Also, the reflector becomes damaged by an ion beam that is, due to a mainly longitudinal magnetic field in a reflector-anode area, directed not only to the exit, but to the reflector.

In **Figure 6c** there is shown an end-Hall ion source with a new form of anode [21] that operates with dielectric depositions for substantially longer time than the regular anode. This is a so-called grooved anode proved to be a good remedy against the "anode poisoning" caused by dielectric or insulating depositions that prevent normal operation. [*Detailed analysis and the means against dielectric depositions impact on regular ion source operation will be given in one of our following publications in *VT&C*.] The main feature of such anode is it grooved geometry with hidden anode surfaces that do not "see" particles returning back from a vacuum chamber, a target in to a source's discharge channel, and, in particular, to the anode surfaces that continue operation while the other surfaces with dielectric or insulating depositions stop continue electric conductive connection between anode and cathode. In this case, only the anode parts that have no depositions continue discharge.

In **Figure 7a** there is presented the picture of Veeco Instruments new version of end-Hall ion source Mark™+ Product Series [22] which has a modular anode subassembly indirectly cooled through a dielectric plate 222. The real advantage of such design is that, it is a very simple assembly with the anode sub-assembly now separated from water, or other cooling fluid. It can be assembled/disassembled in a matter of few minutes.

This Mark+ product design is available in two sizes: Mark I+ (~2 cm ID source opening for up to 300 W peak input discharge power) and Mark II+ (~5.7 cm ID source opening for between 900W and 3kW peak input discharge power). Both are available in radiation cooled versions with HF. The Mark II+ is available in a water-cooled high output "HO" (3 kW) version with HC providing discharge currents up to 15 A and discharge voltages up to 200 V with Argon and Oxygen [22, 23, 24]. Also, its gas utilization and ratio of ion beam current to discharge current (from about 0.3 to about 0.5) is increased substantially (by 10 to 70% depending on gas type and operating conditions) in compar-

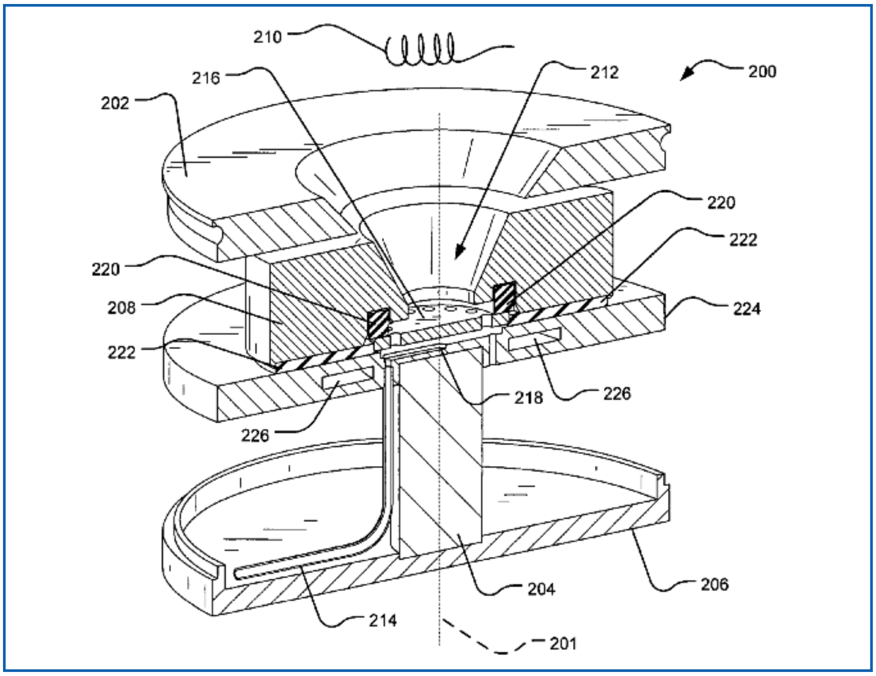


Figure 7a. Schematic picture of Veeco Instruments end-Hall ion source with new fluid cooled anode [21] through a dielectric plate 222, massive conical anode 208, front plate-pole 202, Hot Filament cathode 210, gas distributor-reflector 216 with holes, magnet 204 placed on source's axis 201, fluid cooling plate 224 with cavity for fluid 226.

ison with the traditional Mark II shown in **Figure 6**.

While the anode in the Mark II+ design is indirectly cooled and operates at a higher temperature than the Mark II, Veeco has done extensive laboratory and field tests to characterize its thermal performance, a factor of interest to processing of thermally sensitive substrates such as thermal plastics. Substrate temperatures were demonstrated to be effectively equivalent or lower with the water-cooled Mark II+ High Output with indirect anode cooling compared to Mark II with direct anode water-cooling when both were operated at the same discharge conditions [23]. The lower substrate temperature is notwithstanding the higher beam power output of the Mark II+ and was attributed to the fact that the gas distributor-reflector plate operates much cooler in the Mark II+ design. The lower operating temperature of the gas distributor-reflector plate can also result in lower erosion rates of this consumable component compared to the Mark II design. For applications using reactive gases, the higher anode temperatures have an added benefit against dielectric and insulating depositions that lead to anode "poisoning". With a higher temperature the indirectly cooled anode may operate longer with reactive gases than the direct water-cooled anode.

In **Figure 7b** there is shown a new Veeco Mark™+ Product Family including Mark™ I+ and Mark™ II+ ion sources and Mark™+ Controller

Beam ion energy distribution including the ratio of doubly-to-singly ionized species may be a consideration for some technological applications involving energy sensitive materials (see our publication in ***VT&C***, March 2009 "Ion Source and Vacuum Chamber, Influence of Various Effects on Ion Beam Parameters" [25]). Veeco may be unique among end-Hall ion source manufacturers for having made detailed measurements of the beam ion energy distribution including the double ion content of its Mark source designs [24]. In particular, Veeco has confirmed that the all of their new Mark+ Product Series have a double-to-single ion ratio in the range of 0.1 to 0.2 depending on power and operating discharge voltage and current, Vd, Id, a range that was very comparable with the original Mark II version when operated under the same conditions. However, users should be aware that, in some end-Hall source designs, depending on the geometry in the constricted parts of the discharge channel due to high energy concentration in small volume, it is possible to develop significant fractions of double ions. As pointed out above and in [25], these may produce detrimental impact on some technological processes and can also add confusion to the interpretation of measured beam current levels in characterizing process conditions or in switching from one ion source design to another in existing applications.

In **Figure 8** there is shown a new modular ion source of K&R Inc. with a detachable anode unit [27]. This version is with a radiation cooled anode, though a water-cooled anode version also exists. Working gas is applied in a similar way as it is shown in **Figure 6** of the first Mark-II version. The new modular K&R end-Hall

Figure 7b. Veeco Mark™+ Product Family including Mark™ I+ and Mark™ II+ ion sources and Mark™+ Controller. (Photos courtesy of Veeco Instruments, Inc.)

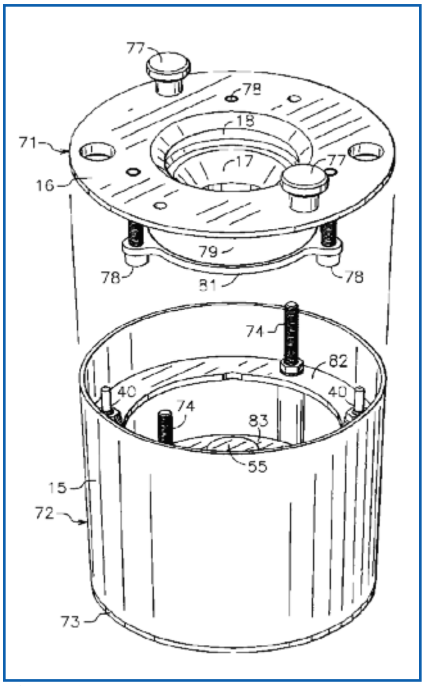


Figure 8. Schematic picture of K&R modular end-Hall ion source [27] with detachable anode module 71; main components: 72 - magnetic circuit, 17 – anode (shown in radiation cooling version), 55 – magnet, 82 - supporting ring, 40 – Hot Filament connections

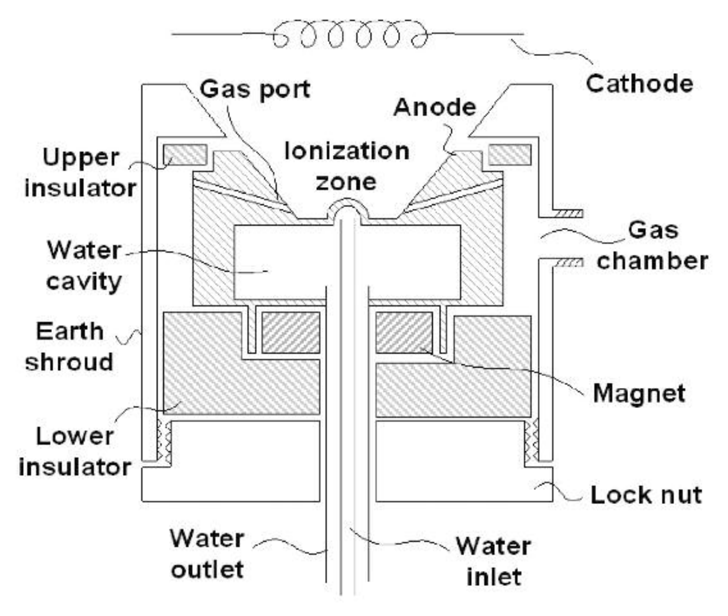


Figure 9. End-Hall ion source developed by W.Sainty

shown in **Figure 8** is called EH-1000 and its operational characteristics are quite close to Mark-II; its ion beam current to discharge current ratio instead of 0.2 is about 0.25. Also, in order to reduce the influence of plasma on a target and substrate, anode, heated front plate and Hot Filament on the targets-substrates the EH-1000 ion source can be made with a water-cooled anode and with a water-cooled front plate and with a Hollow Cathode [26]. Another improvement in EH-1000 and other new versions of this type is a possible utilization of the grooved anode [21] (**Figure 6c**) for reducing the impact of dielectric and insulating depositions on anode leading to an anode "poisoning".

About the area between the anode and reflector. In some new approaches, this area made larger in volume, so that there is more space for better working gas distribution, and, in some cases, for preliminary ionization. The holes in reflector should be placed in a way that working gas will be not going straight through to exit area (such a case is in **Figure 12a** shown for the hybrid ion source of closed drift with end-Hall), because, in such a case, some working gas can be "lost" for the ionization process. Working gas must also be well mixed.

In [28] working gas is applied at certain angle forming a vortex flow (pressure of applied working gas in immediate vicinity of a hole is 5-10 Torr, where a mean free path for neutral particles is short and a vortex flow can be developed) in an area that is substantially larger than in the original end-Hall of Mark series.

The range of discharge voltages of Veeco (Mark-I, I+, Mark-II, II+) and K&R (EH-200, 400, 1000, 2000 [*Numbers at EH indicate the maximum electric power that can be sustained by the source and the Alnico-5 and 8 magnet will be not overheated]) is from about 50 V to 300 V (noble gases, mainly Argon), and from about 80 V to 300 V (Oxygen, Nitrogen).

In **Figure 9** there is shown the schematic drawing of the end-Hall ion source developed by W.Sainty [29, 30]. The ion source, in general, reminds regular end-Halls of type Mark-I, II (Veeco) and EH series (K&R). It is simpler in design in comparison with first generation end-Halls. It has less number of parts and is very easy to assemble-disassemble. The differences are as follows. The reflector that usually is located at the ion source discharge channel's base now is connected with anode and, because of that, has an anode potential. Working gas in the Sainty's first versions was applied through the holes (called "showers") at the discharge channel's base; in the last version it is applied through the anode.

The magnet is of a rare-earth materials NdFeB that have high magnetic field, but sensitive to temperature changes, ranging from 0.10%/°C - 0.13%/°C [Magnetic Component Engineering Company].

The Sainty's ion sources have been used quite successfully for many thin film technology tasks, though the range of operation parameters is not as broad as Mark and EH series. But it is cheaper for some optical coatings and R&D problems; it may be a good ion source that is easy to assemble-disassemble.

The Sainty's company makes four types of end-Hall ion sources: ST3000 – (applied power is 2.5 kW; maximum discharge voltage is V_d = 300 V; maximum discharge current I_d = 12 A); ST55 – applied power is 1.3 kW ($V_{d,max}$ = 230 V, $I_{d,max}$ = 6 A); ST X-IAD - applied power is 800 W ($V_{d,max}$ = 200 V, $I_{d,max}$ = 4 A); ST-clean – applied power is 600 W ($V_{d,max}$ = 150 V, $I_{d,max}$ = 4 A). ST3000 and ST55 have two HFs.

In **Figure 10** there is shown the schematic drawing of the end-Hall ion source of Russian company "Luch" (Podolsk, near Moscow) [31] with magnets placed at the base of external shell (magnetic path) far from discharge chan-

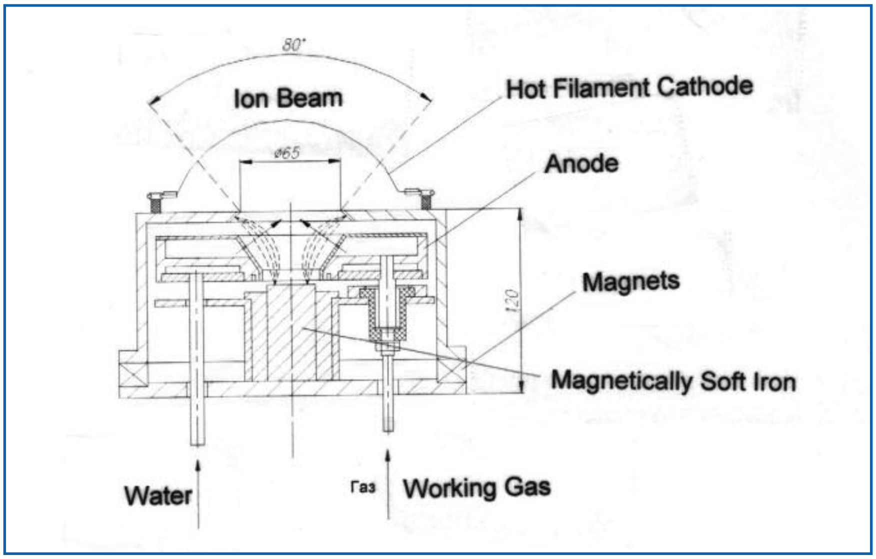


Figure 10. End-Hall of Russian company "Luch" [31]. The magnets are placed on periphery of the source' shell. Anode water cooled (shown); magnets also are water cooled (not shown).

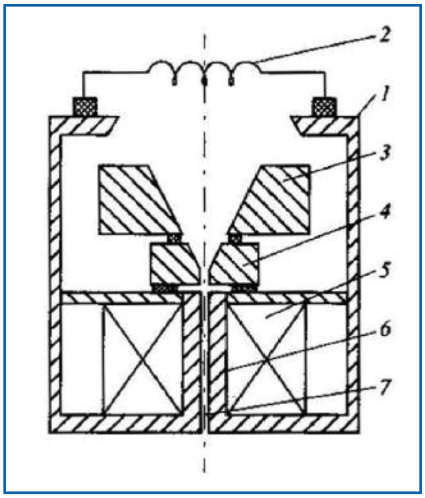


Figure 11a. End-Hall ion source developed by Belarusian scientists [32] called as the source with additional area of ions generation: 1 – source's shell; 2 – cathode HF; 3 – anode; 4 – conical insert; 5 – electromagnetic coil; 6 – core; 7 – working gas supply

nel's heat, and the magnets (not shown in this figure) and anode have separate water cooling systems. According to our information, the reflector shown in **Figure 10** has very low sputtering rate in comparision with regular Mark-I, II, EH end-Halls.The cathode is a HF with unusual placement of a Tungsten wire in the form of a semi-circle. The source operates at high discharge voltages from about 150 V to about 300 V and the discharge currents from 1 to 5 A with Argon, Xenon and Oxygen. However, the same company has the end-Halls with the central placement of the magnet and a HF is placed in the form of traditional Tungsten spiral with lower anode discharge voltages. The company makes quite sophisticated optical thin film coatings with the varieties of end-Hall ion sources.

In **Figure 11a** there is shown the schematic drawing of a end-Hall current ion source [32] with the additional area for generation of ions developed by Minsk Research Institute of Radio-Materials (Belorussia). This ion source is very much similar to the end-Hall ion sources made by major ion source producers with the exception that there is no typical reflector-gas distributor between anode and magnetic system. The conical insert 4 plays role of gas distributor where usually the plane reflector is placed at the bottom part of a conical hollow anode in the "typical" end-Halls (Mark and EH series). It is reported that the area is located between anode and the insert plays important role for additional generation of ions. Besides that, it seems that the ions directed in the opposite direction to the main ion flow toward to the conical insert do not produce much erosion. The magnetic field is provided by an electromagnetic coil 5. The measurements comparing this end-Hall ion source with the Mark-II type with the same discharge currents $I_d = 2.5$ A (working gas Argon) showed that the invented ion source produces an ion beam current higher by a factor 1.2-1.5 higher than the Mark-II type. Also, it is reported that the mean ion beam energy for this ion source is higher than in the end-Hall Mark-II type.

For comparison, end-Halls of Veeco and K&R have a mean energy of about $(0.6\text{-}0.7) \cdot V_d$ in the whole range of operating discharge voltages and the pressures from about $1 \cdot 10^{-4}$ to $2 \cdot 10^{-3}$ Torr.

In **Figure 11b.** there is presented the schematic drawing of the end-Hall ion source developed at the Ukrainian Scientific Center of Kharkov Physical-Technical Institute [33].

The working gas was Nitrogen and it was applied at the mass flows of $\dot{m}_a = 3\text{-}20$ sccm. The discharge voltage was $V_d = 100\text{-}600$ V; the discharge current was $I_d = 0.25\text{-}2.5$ A. The magnetic field generated by the

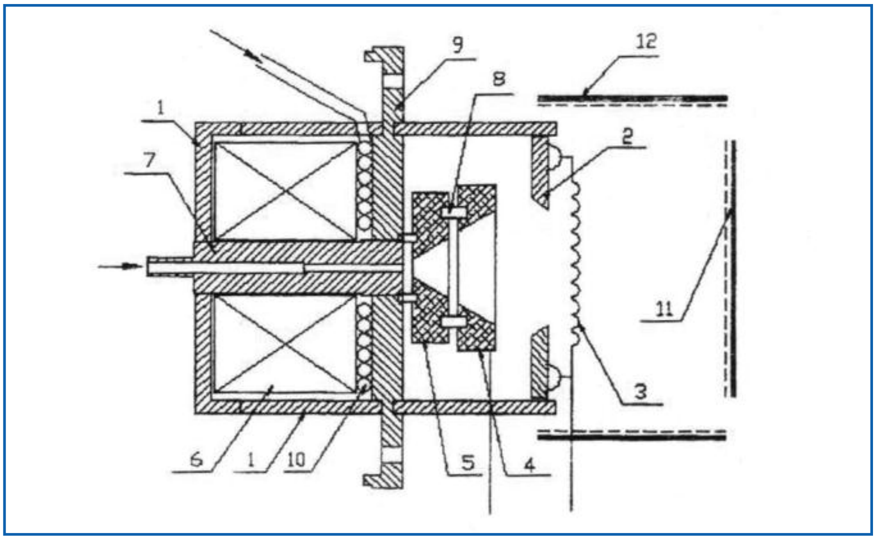


Figure 11b. End-Hall ion source of Ukrainian National Scientific Center [33]: 1 – body; 2 – exit flange; 3 – Hot Filament cathode; 4 – anode; 5 – gas-distributor; 6 – electromagnetic coil; 7 – core; 8 – ceramic ring; 9 – stainless steel flange; 10 – water cooling; 11, 12 – ion beam collectors

electromagnetic coil could be varied up to 600 G. Measurements of the ion beam current surprisingly showed that a radial ion current is at maximum up to about 1 A and the axial ion beam current was at about 30 mA. This is a quite unexpected result with the end-Hall type ion source. In the closed drift ion sources, when measurements were conducted at close distances from an ion source (5-10 cm), there were observed such type of ion beam distributions that were explained by the annular form of the discharge channel. At longer distances of 30-50 cm due to an ion beam expansion its distribution would gradually become with the maximum at the axis.

In **Figure 12a.** there is presented the schematic drawing of a hybrid ion source suggested in [34]. Similar concept of the hybrid thruster is described in [35]. However, magnetic shunts in [34] provide the positive gradient of magnetic field in discharge channel (**Figure 12b**).

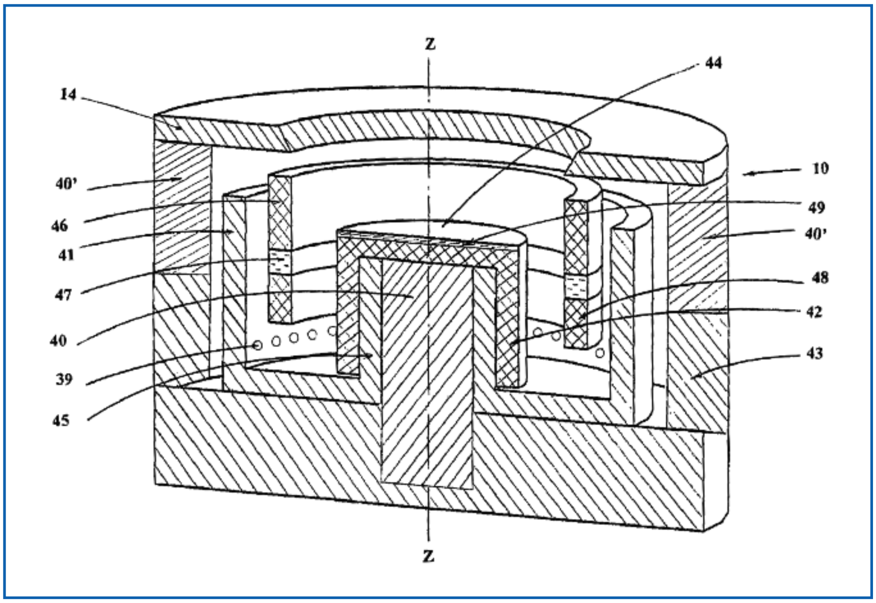


Figure 12a. Hybrid end-Hall and closed drift ion source [34] for obtaining wide range of operation parameters and with positive magnetic gradient. Some important parts: 14 – external magnetic pole; 39 – gas distributing holes; 40 – permanent magnet; 41 – magnet shunt; 47 - anode. Cathode is not shown.

This ion source has the features of both ion sources: the end-Hall and closed drift magnetic layer ion sources and allows to have various positive magnetic gradients in the discharge channel and to find the maximum ion beam current. The advantage of this source is a positive magnetic gradient in the discharge channel leading to reduced oscillations and higher efficiency of transformation of a discharge current into an ion beam current with $I_i \approx (0.8\text{-}0.9) \cdot I_d$.

Because most gridless ion sources have been invented and developed in USA and in former Soviet Union, for the specialists in gridless industrial ion sources and readers of *VT&C* it is certainly interesting to take a look at end-Hall, or Closed Drift ion sources produced by Chinese and South Korean companies, to learn how they look, operate, what their main features, what are the differences with existing established for over 20 years time ion sources produced by American and now Russian companies.

Unfortunately, for this article it was possible to obtain only a limited number of pictures of end-Hall and Closed Drift ion sources. In the Closed Drift type ion sources Chinese and South Korean companies make only linear Anode Layer Ion Sources without a cathode-neutralizer [*which will be discussed in Part 3 of this article]. All end-Hall ion sources utilize Hot Filaments as cathodes-neutralizers. Most end-Hall ion sources have two HFs, so when one HF will break, the second HF

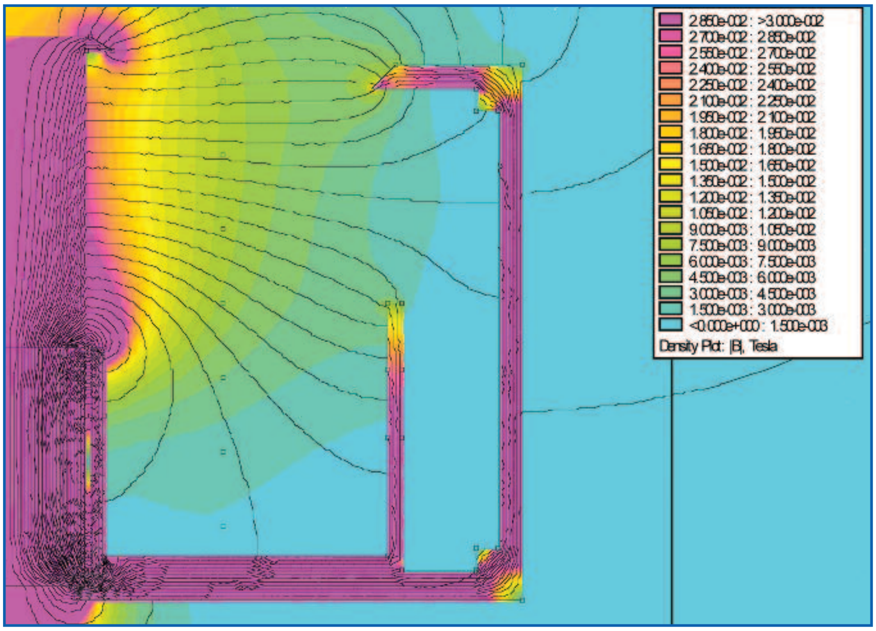


Figure 12b. Hybrid ion source. Computer simulation of one of the variants with magnetic shunts. Ion source's axis is on the left side of picture. [36]

automatically is turned on to continue the coating process.

Almost all Chinese and S. Korean producers of end-Hall ion sources have a water-cooled anode. It is certainly good to have a water-cooled parts of the discharge channel. They make possible to apply higher electric power. However, besides the designing difficulties a water-cooled anode, especially at low powers, testifies about insufficient optimization of the electric discharge, in particular, the magnetic system.

Another reason of water-cooled anodes in end-Hall ion sources is that some most Chinese and S. Korean producers do not utilize permanent magnets of Alnico type. Instead they have permanent magnets of rare-Earth materials and others that can provide high magnetic fields but they have very sensitive to high temperature magnets.

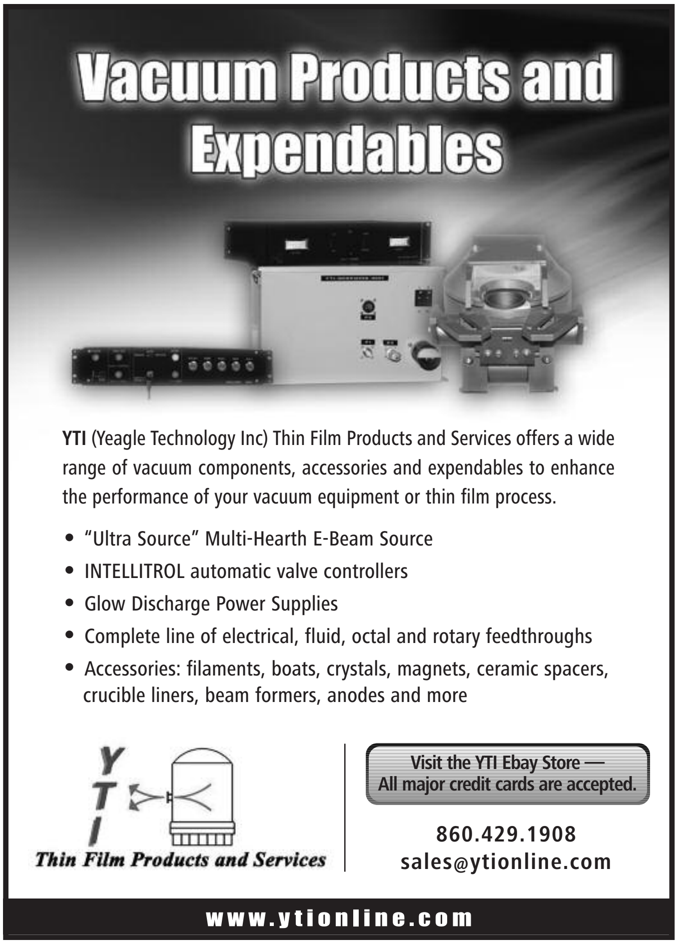
As it was mentioned earlier, the Closed Drift thrusters-ion sources due to well-optimized discharge can sustain much higher electric powers applied into the discharge channel than end-Hall ion sources with similar discharge area. That is why most Chinese and S. Korean producers have to utilize the anode water-cooled designs for most end-Halls. In other words, they need to work on discharge optimization that would make discharge separated from most area of the discharge channel.

One of disadvantages of water-cooled anodes is that they become more easily "poisoned" than "hot" anodes [*this problem will be discussed in Part 4 of this article].

There are no Hollow Cathodes, Plasma Bridge neutralizers, RF, or other type cathodes-neutralizers. It is quite difficult to find in Western scientific literature any articles from Chinese, or S. Korean developers of ion sources about improvements of Hall-current ion sources, or detailed analysis of utilization of ion sources for the thin film processes.

Below there are presented pictures of some end-Halls obtained by the author of this article either from internet sources, or from direct contact with the producers.

In **Figure 13a** there is shown picture of a Power Supply and end-Hall ion source of Chinese company Zhaoking Three Beam Coating Technology Development [37]. This Company makes two dimensions end-Halls SHI-800 and SHI-2000. One can assume that numbers correspond to applied power. Anodes are water cooled. The range of discharge voltages for both sources is V_d = 100-240 V. The SHI-800 ion source discharge current range is I_d =



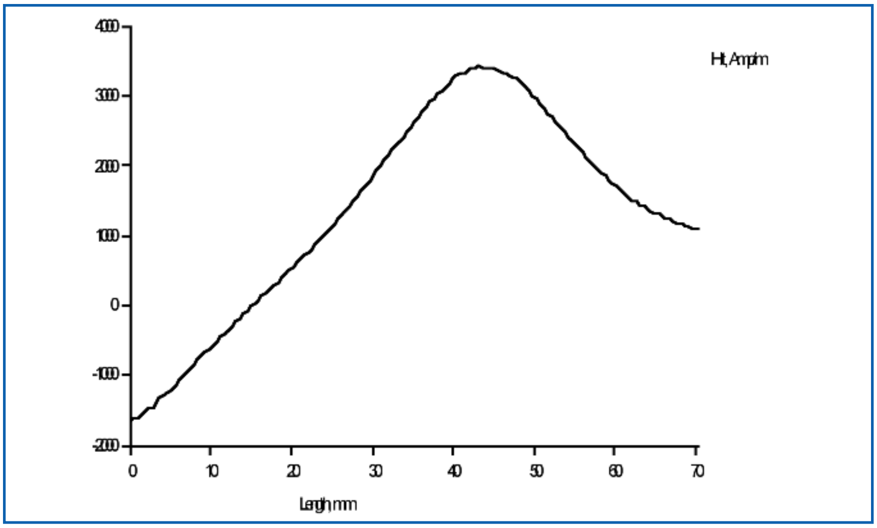


Figure 12c. Hybrid end-Hall and closed drift ion source with a positive gradient of magnetic field for one particular design with two magnetic shunts [36]

Figure 13a. PS and end-Hall ion source of Zhaoking Three Beam Coating Technology Development Co. Ltd [37]

Figure 13b. PS and end-Hall ion source of By Taika (Shanghai) Optoelectronics Technology Co., Ltd [38]

Figure 13c. End-Hall picture of Beijing Oriental An Taike High Tech Co [39]

0-4 A. The SHI-2000 ion source discharge current range is I_d = 0-10 A. It is reported that an ion beam current for SHI-800 is up to 1.6 A, or I_i/I_d = 0.4, and the SHI-2000 is up to 3.5 A, or I_i/I_d = 0.35. These numbers are too high for end-Halls in comparison with Veeco's and K&R's sources.

In **Figure 13b** there is shown a PS and end-Hall ion source of By Taika (Shanghai) Optoelectronics Technology Co., Ltd [38]. The operating parameters of the ion source are as follows: the discharge voltage is V_d = 50-250 V; discharge current range is I_d = 1-16 A; the maximum applied power is 4 kW, which is for discharge current I_d = 16 A can produce with the usual end-Hall's efficiency of discharge current transformation of about 0.2-0.25 can provide I_i = 3.2-4.0 A, that is quite good value for the ion beam current for most thin film tasks. Anode is a water-cooled.

In **Figure 13c** there is shown a picture of Beijing Oriental An Taike High Tech Co end-Hall ion source [39]. This company makes various end-Hall ion sources NH-1000, NH-1500, NH-1750 and NH-2000.

Figure 13d. End-Hall ion source of Shanghai Nanovac Company [40]

Figure 13e. End-Hall ion source of Beijing Vacuum Pre Matai Ke Technology Co [41]

Figure 13f. End-Hall ion sources of Teng Vacuum Technology Engineering Co [42]

Numbers at NH show the power in to ion sources that can be applied. The range of discharge voltages is V_d = 70-250 V; the discharge current range is I_d = 1-5 A.

Figure 13d there is shown a picture of End-Hall ion source of Shanghai Nanovac Company [40]. The range of discharge voltages is V_d = 80-200 V; discharge current range is I_d = 1-5 A; the ion beam exit diameter is 38 mm; working gases are Argon, Oxygen, Nitrogen. Two HFs are seen in the picture.

In **Figure 13e** there shown a picture of End-Hall ion source of Beijing Vacuum Pre Matai Ke Technology Co [41]. Two HFs are seen in the picture. No other details about this ion source are available.

In **Figure 13f** there is shown a picture of End-Hall ion sources of Teng Vacuum Technology Engineering Co [42]. Both ion sources have two HFs.

Based on pictures and some operational characteristics presented by some Chinese companies, their discharge voltages are under 250 V, or the ion beam energies under 150 eV. Also, some ion sources can not provide discharge voltages under 100 V. Only By Taika (Shanghai) Optoelectronics Technology Co., Ltd has the minimum V_d = 50 V. All these data testified about necessity for further development and optimization of the end-Hall discharge channel design and magnetic system.

In **Figure 13g** there is shown a picture of the end-Hall ion source of S. Korean Company VTC [43].

Anode has a water cooling system. The cathode is a HF. The ion sources operate with low and moderate ion beam energies with discharge voltages from about 50 V and up to 300 V (30-180 eV) with working gases such, as Argon and Oxygen. The company has two modifications of end-Halls VTC-2 operating from about V_d = 50-60 V up to 200 V (using another PS it can provide discharge voltages up to 300 V) with the discharge currents I_d = 1-5 A; and the larger source VTC-5 that can operate with V_d = 60 V and up to 300 V with the same range of discharge currents.

Figure 13g. End-Hall ion source of S. Korean Company VTC [43]

In **Figure 13h** there is shown a picture of End-Hall ion source of S. Korean Company INTEC Inc. The range of discharge voltages is V_d = 50-250 V; the discharge current range is I_d = 1-16 A; the total applied power can be up to 4 kW.

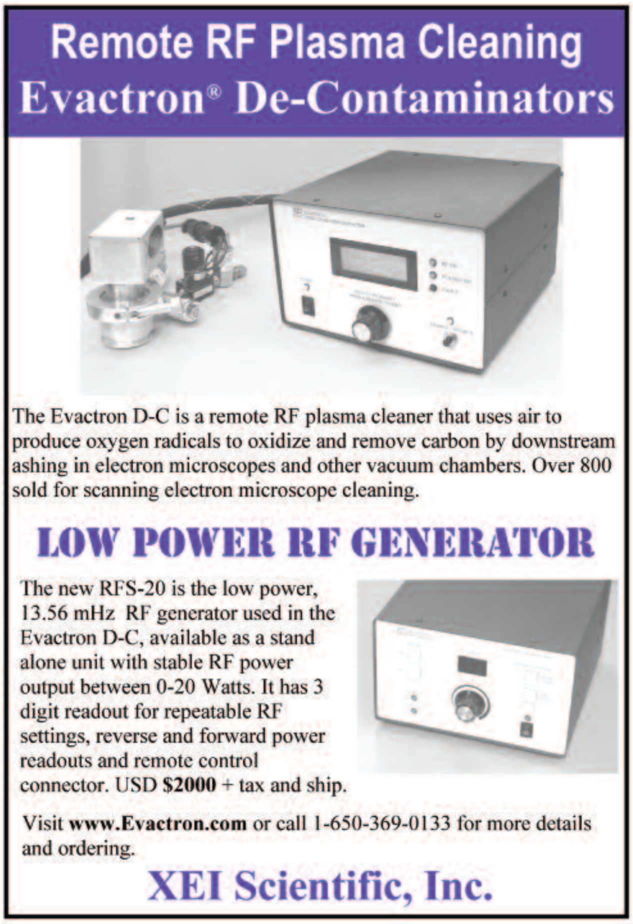


Figure 13h. End-Hall ion source of S. Korean Company INTEC Inc. [44]

Figure 13k. End-Hall ion source of S. Korean Company Hanil Vacuum Machine Co.

In **Figure 13k** there is presented end-Hall of S. Korean Company Hanil Vacuum Machine Co [45]. The range of discharge voltages is $V_{d,\ max} = 300$ V; the discharge current range is $I_d = 1\text{-}15$ A; the total power that can be applied is 4 kW; there are two HFs.

As it was above mentioned, it is very difficult to find any scientific articles about Chinese and S. Korean ion sources, how they operate, what kind of design they utilize. Also some companies make statements about high values of ion beam currents and mean ion beam energies. It is necessary to remember that end-Hall ion sources provide the ratio of the ion beam current to the discharge current $Ii/Id \approx 0.2$ (for not optimized designs) - 0.4 (for well optimized designs), and the mean ion beam energy of about $Ei \approx (0.6\text{-}0.7) \cdot Vd$. This information has to be presented by most end-Hall producers in China and S. Korea.

References

13. A.I.Morozov, "*Volumetric Electrostatic Fields in Plasma*", in book "Plasma Accelerators and Ion Injectors", edited by N.P. Kozlov, A.I.Morozov, 1984, Moscow, Nauka, p 82-106 (in Russian).
14. S.B.Lebedev, A.I.Morozov, "*Geometrical Optics of Plasma-Optical Systems*", Proceedings of I All-Union Conference on Plasma Accelerators, edited by L.A.Artsimovich, Moscow, Mashinostroenie, 1972, p 92-96 (in Russian).
15. A.I.Morozov, "*Introduction in Plasmadynamics*", Moscow, Fizmatlit, 2006, 571 pages (in Russian).
16. A.D.Grishkevich, A.M.Kapulkin, V.F.Prisniakov, "*Ion-Debye Regime of Accelerators with Closed Electron Drift*", in book "Ion Injectors and Plasma Accelerators", edited by A.I.Morozov, N.N.Semashko, 1990, Moscow, Energoatomizdat, p 68-77 (in Russian).
17. A.T.Antipov et al, "*Energy Characteristics of Two-Stage Accelerator with External Electric Field*", Proceedings of VII All-Union Conference on Plasma Accelerators and Ion Injectors, 1989, Kharkov, p 77-78 (in Russian).
18. S.P.Vakhnjuk, A.M.Kapulkin, V.F.Prisniakov, "*Stabilization of Plasma Instabilities in Accelerators with Closed Electron Drift by Boundary Feed-back System*", in book "Ion Injectors and Plasma Accelerators", edited by A.I.Morozov, N.N.Semashko, 1990, Moscow, Energoatomizdat, p 78-86 (in Russian).
19. H.R.Kaufman et al, "*End-Hall Ion Source*", US patent 4,862,032, Aug. 29, 1989.
20. H.R.Kaufman, R.S.Robinson, R.I.Seddon, "*End-Hall Ion Source*", J.Vac. Sci. Technol., A5 (4), 2081, 1987.
21. H.R.Kaufman, J.R.Kahn, R.S.Robinson, V.V.Zhurin, "*Hall-Current Ion Source*", US Patent No 6,750,600, June 15, 2004.
22. D.M.Burtner, S.A.Townsend, D.E. Siegfried, V.V. Zhurin, "*Fluid-Cooled Ion Source*", US Patent No 7,342,236, March 11, 2008.
23. L.Mahoney, D.Burtner, D.Siegfried, C. Dale, "A New End-Hall Ion Source with Improved Performance", American Vacuum Society 53rd Symposium, Nov. 14, 2006.
24. L.Mahoney, D.Burtner, D.Siegfried, "A New End-Hall Ion Source with Improved Performance", 49th Annual Technical Conference Proceedings of the Society of Vacuum Coaters, 2006.
25. V.V.Zhurin, "*Ion Source and Vacuum Chamber, Influence of Various Effects on Ion Beam Parameters*", Vacuum Technology & Coating, p 42-51, March 2009.
26. J.R.Kahn, H.R.Kaufman, V.V.Zhurin, "*Substrate Heating Using Several Configurations of an End-Hall Ion Source*", 46th Annual Technical Conference Proceedings, 2003, p 621-625.
27. H.R.Kaufman, "*Modular Gridless Ion Source*", US Patent No 6,608,431, Aug 19, 2003.
28. V.V.Zhurin, "*Hall-Current Ion Source for Ion beams of Low and High Energy for Technological Applications*", US Patent 7,312,579, Dec. 25, 2007.
29. D.Gardner, W.Sainty, "*Characterization of High Output Gridless Ion Source*", Society of Vacuum Coaters, 48th Annual Technical Conference Proceedings, 2005.
30. W.G.Sainty, "*Ion Source*", US Patent No 6,849,854, Feb 1, 2005.

31. G.I.Babaiants, V.G.Zhupanov, E.V.Kljuev, "*Calculation and Fabrication of Laser Windows with High Radiation Stability*", 9th Russian Conference "Vacuum Science and Technology", Moscow, 2002.

32. V.T.Svirin, A.I.Stogny, "*Formation of Equilibrium Density Beam in a Hall Ion Source with Opened End*", Russian Journal Pribory [Instrumentation] and Experimental Techniques, 1993, No 5, p 103.

33. S.V.Shary et al, "*Stationary Gaseous Plasma Source of Heavy Ions with Electron Drift*", Kharkov University Reports, series physics "Nuclear, particles, fields", issue 1/37- No 794, p 121-124, 2008 (in Russian).

34. V.V.Zhurin, "*High-Efficient Ion Source with Improved Magnetic Field*", US Patent 7,116,054, Oct. 3, 2006.

35. Y.Raitses et al, "*Cylindrical Geometry Hall Thruster*", US 6,448,721, Sept 10, 2002.

36. V.V.Zhurin, "*Magnetic Field Distribution in High-Efficient Ion Source with Improved Magnetic Field*", CATech Report, Sept 2005.

37. www.optochina.com/ion_sources.htm Zhaoking Three Beam Coating Technology Development Co. Ltd.

38. www.intecnet.cn By Taika (Shanghai) Optoelectronics Technology Co., Ltd.

39. www.optochina.com/ion_sources.htm Beijing Oriental An Taike High Tech Co.

40. www.nanovac.com.cn Shanghai Nanovac Company Ltd.

41. www.optochina.com/ion_sources.htm Beijing Vacuum Pre Matai Ke Technology Co.

42. www.optochina.com/ion_sources.htm Teng Vacuum Technology Engineering Co.

43. www.vac-tec.co.kr, S. Korean Company VAC-TEC.

44. www.intecinc.co.kr, S. Korean Company INTEC Inc.

45. www.vacuum-coater.com, S. Korean Company Hanil Vacuum Inc.

Viacheslav V. Zhurin, Ph.D. is President of Colorado Advanced Technology LLC (www.ion-plasma.com). Dr. Zhurin is an internationally-recognized specialist in Electric Propulsion. During 1970-1980's he presented Review Papers about Electric Propulsion achievements in Soviet Union and Russia. In early 1970's he worked at Department of Aeronautics, California Institute of Technology for two years. Before coming to USA in 1991 he was in several Academy of Science Research Institutes as a Head of Laboratories, Departments and Deputy Director. Since 1991 he is in USA and working on Electric Propulsion and Ion and Plasma Sources. He was at Kaufman & Robinson Inc. (1991-2004) and Veeco Instruments (2004-2005). He published over 100 scientific articles on fluid dynamics and shock waves, explosions, thrusters, ion sources, low-energy beams, thin film depositions; he is author of 14 US patents. Dr. V.Zhurin can be contacted at: slava@ion-plasma.com and slava_zhurin@msn.com