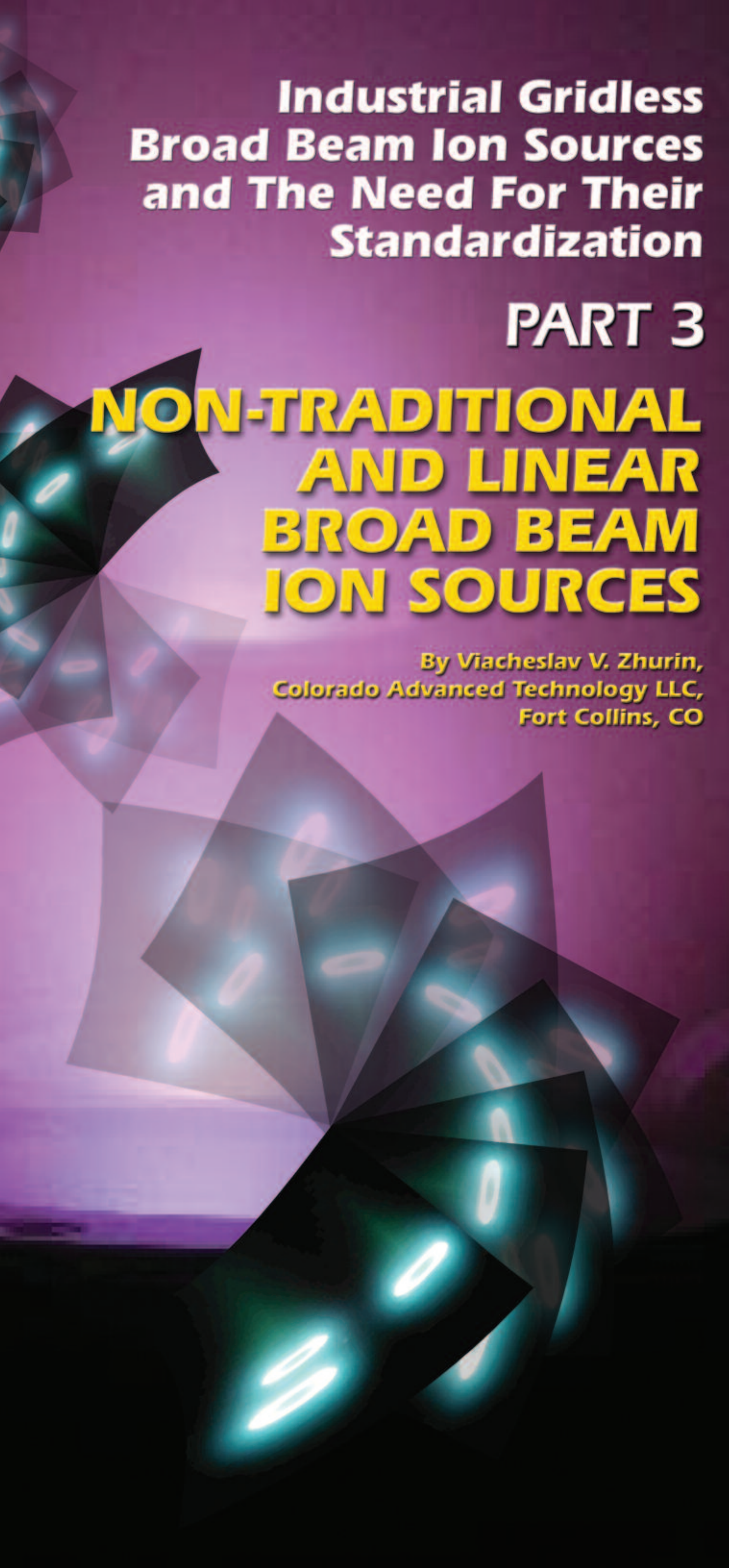

Industrial Gridless Broad Beam Ion Sources and The Need For Their Standardization

PART 3

NON-TRADITIONAL AND LINEAR BROAD BEAM ION SOURCES

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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 covers "Non-Traditional Ion Sources" and "Linear Ion Sources". And, Part 4 covers "Hall-Current Ion Sources Basic Operation Parameters Problems and Solutions" and "The Need for Standardization of Ion Sources".

Below there are presented several broad beam ion sources that have design different from the "classic" closed drift or end-Hall types described in Part 1 and Part 2 of this article. However, such sources produce ion beams that can be utilized in the thin film technology either for sputtering, or as ion assist devices, or for other purposes (stress control, designed or preferred crystal orientation and bonds, hardness, etc).

It seems that one of the first ion sources having certain similarities with the end-Hall type was developed in early 1970es and its description was published in [46].

In **Figure 14.** there is presented the schematic drawing of the Hall-current ion source for development of low energy ions, where: 1 is exit area for neutralized ion beam; 2 is a front flange; 3 is a discharge channel made of dielectric material; 4 is an anode connection with a Power Supply (PS); 5 is a back flange; 6 is cathode with a HF; 7 is a working gas; 8, 9, 10 is a system of electromagnetic coils for non-uniform axial-symmetric magnetic field distribution in a discharge channel.

Magnetic field in the discharge channel is sufficient for magnetization of electrons ($\omega_e\tau_e >> 1$). At the same time, ions are not magnetized ($\omega_i\tau_i < 1$), in the similar way like it takes place in Closed Drift thrusters-ion sources. The ion source was operated in stable conditions with several working gases, such as Hydrogen, Nitrogen and Argon, at discharge voltages $V_d = 150\text{-}600$ V and with discharge currents $I_d = 0.15\text{-}1.0$ 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.

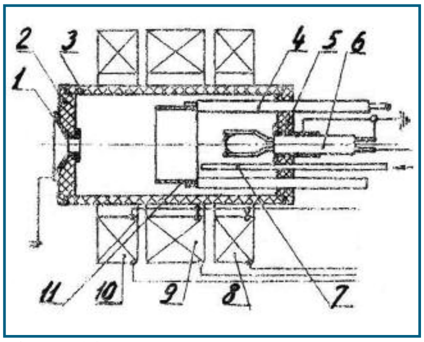

Figure 14. Stationary plasma source of low energy ions [46]

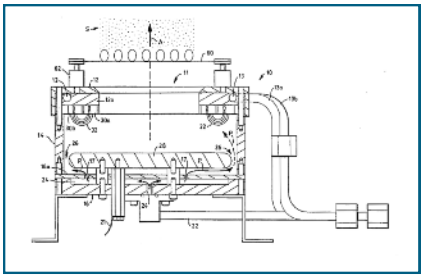

Figure 15a. Schematic drawing of DynaVac ion source [47] with peripheral magnetic field.

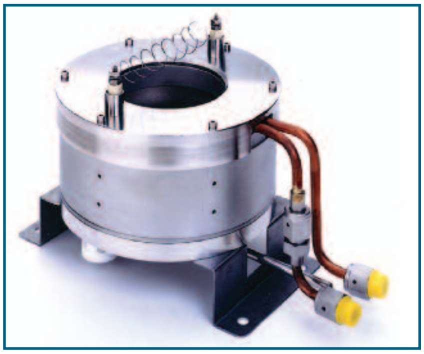

Figure 15b. DynaVac ion source assembled with a water-cooled magnetic system [48].

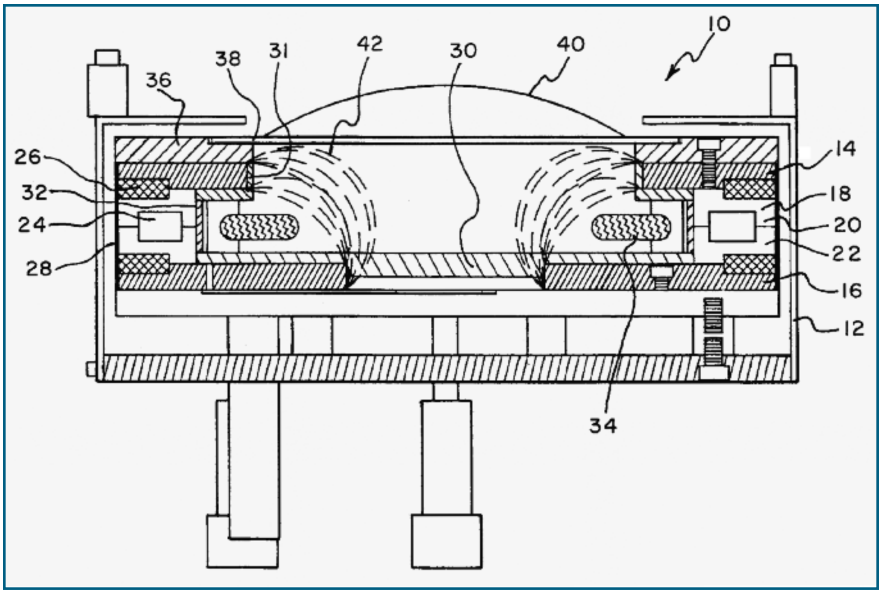

Figure 16. "Cold cathode" ion source of Denton Company [49]. Main parts: 16 – internal magnetic pole serving as a "cold" cathode; 14 – external magnetic pole; 26 – permanent magnets; 34 – anode; 40 – Hot Filament.

In **Figure 15a** there is shown the schematic drawing of the ion source produced by DynaVac Company [47]. A photographic picture of this ion source is shown in **Figure 15b**. The magnetic field is made by 40 button-like magnets 30a and 30 b with the diameter of about 12.7 mm and with a thickness of about 5 mm; the anode 28 is placed at the discharge chamber bottom; a working gas 26 is applied through the holes 17 from under anode, where in end-Halls usually is placed a gas distributor-reflector. Magnets 30a, 30b are water-cooled through the water line 13a, 13b.

The peripheral magnetic field of teeth like configuration can be described as a strong alternating magnetic field with the maximum value at the upper part of the discharge channel. The discharge in such a chamber can be considered as discharge with oscillating electrons and a relatively high anode area. According to the company's advertising information [48], the maximum applied power into a discharge channel is 1200 W with the discharge voltage range of 150-600 V and the discharge current from 0.5 to 7 A. The maximum gas mass flow is 50 sccm. Willey [50b] states that the source has been operated continuously at 1500 W and the discharge currents up to I_{db}= 10A. Normal operation is below V_d = 300 V and about $V_d \approx$ 90V has been achieved at the discharge current I_d= 3.5A.

In **Figure 16** there is shown the schematic drawing of the Denton company ion source having a circular anode 34 surrounded by magnets 26 [49]. This source is called a cold cathode ion source, but it has a HF Tungsten wire 40 for discharge ignition, working gas ionization and neutralization of ions with low energy electrons.

Typical cold cathode ion sources do not have any HFs or HCs and usually external flange, or conducting plates in the discharge channel used for development of electrons.

According to independent investigations [50a, 51] this ion source works quite well with inert and reactive gases and was used for certain thin film tasks with moderate discharge currents maximum up to 2-3 A and the discharge voltages up to 250-400 V.

This source has a mean ion energy [51] of E_i = (0.4-0.7)·eV_d depending on pressure. At low operating pressures from (1.5-2.0) · 10^{-4} Torr a mean ion energy is about E_i = (0.6-0.7)·eV_d; at higherpressures from about 4 · 10^{-4} Torr its mean ion beam energy is about E_i = 0.4eV_d. Also, the range of pressures for operation is from 1.5 to 5.5 · 10^{-4} Torr.

Despite that this ion source does not look as regular end-Hall ion source, it should be considered as the source with certain main features of the end-Halls. As one can see, the magnetic field lines are quite divergent, and the radial component H_r is at the ion source's exit part [*similar to end-Halls] and there is a magnetic strong longitudinal component H_z. This means that it can operate at low discharge voltages (energies) like the end-Hall. Also, in similarity with the end-Hall ion source and presence of a prominent longitudinal magnetic component that should direct generated in discharge channel ions not only into the exit area, but into the opposite side – into the bottom – the reflector's side, and that can lead to its substantial erosion, similar as it takes place in the end-Hall with the gas distributor-reflector.

In **Figure 17** there is shown the schematic drawing of a Hall-current ion source developed by a group of Chinese

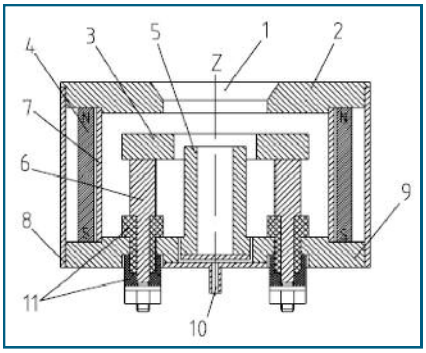

Figure 17. Hall-current-magnetron type ion source developed by University of Hong Kong group [52]: 1– discharge channel; 2 – cathode serving as magnetic pole; 3 – annular anode; 4 – SmCo permanent magnets; 5 – hollow cathode serving as inner magnetic pole; 6 – anode support post; 7–inner shield; 8 – outer shield; 9 – back shunt; 10 – working gas; 11 – insulator

scientists headed by P.K.Chu [52]. This ion source has an annular anode 3 and a cylindrical "cold" cathode 2 that also serves as an external magnetic pole.

An inner shield 7 and an outer shield 8 designed to make a mirror-like magnetic field profile in an upper part of a discharge channel. Because there is no heated cathode with electron emission the source operates more as a closed drift ion source of anode layer type. Its range of discharge currents is I_d = 0.5 - 4 A, the discharge voltages range is from V_d = 300 – 480 V; the mean ion energy $E_i \approx 0.5eV_d$ (in eV).

In **Figure 18** one can see the ion source of an ion magnetron type, in which an electron drift is closed around a magnetic field direction [*in regular closed drift ion sources an electron drift is closed around the direction of acceleration of ions]. Such type of ion source can be used for processing of cylindrical form targets, inside of targets. Also, such type of ion sources have been used in the Russian space program for removal of extra positive charges accumulated on surface of a space satellite.

In **Figure 19** there is shown the schematic picture of an ion source of anode layer type. In this ion source, there are no accelerating electrodes; because of this, it is possible easy to change discharge voltage and other parameters. Its principle is similar to the ion source with an electron drift around a magnetic field [53].

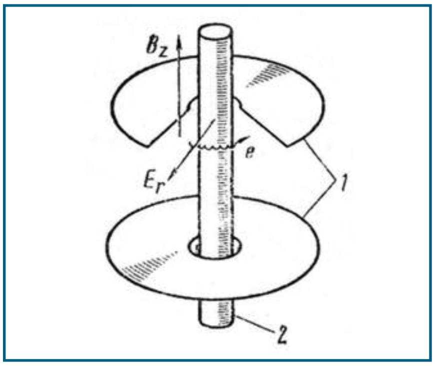

Figure 18. Ion Source with anode layer with ion beam propagating along azimuth: 1 – cathodes; 2 – anode [53]

The combined features of end-Hall and Anode Layer are in the ion source developed by Belarusian State University [54] is shown in **Figure 20**. This ion source in the end-Hall regime provides an ion beam current up to $I_i \approx 1.5$ A at a mean ion energy of 30-180 eV (V_d = 50-300 V) at pressures of $7.5 \cdot 10^{-5}$-$4 \cdot 10^{-4}$ Torr with noble and reactive gases; and in the Anode Layer "vacuum" regime it has an ion beam current up to 90 mA with mean ion energy of 300-2000 eV at pressures of $7.5 \cdot 10^{-5}$-$4 \cdot 10^{-4}$ Torr, and an ion beam current up to 1 A with mean ion energy of 100-250 eV at pressures of $7.5 \cdot 10^{-5}$-$1.5 \cdot 10^{-3}$ Torr.

Despite of the fact that the recent tendency in development of ion sources is a narrow range of operation parameters for certain thin film or other vacuum technology tasks, such combination of end-Hall and Anode Layer features can be quite useful for some universities laboratories looking for various ways in the synthesis of new materials

In **Figure 21** there is presented the schematic drawing of a Hall-current ion source that can be classified as a variety of end-Halls [55]. This ion source has a hollow anode and a cathode on the source's axis in a form of a HF. An electromagnetic coil provides magnetic field value in the acceleration region about 1500 G. Working gases are Hydrogen and noble gases with the mass flows up to about 60 sccm (Hydrogen). The maximum discharge voltage is V_d = 200-600 V; the discharge current range is I_d = 1-5 A. This particular design has a quite unusual part of the discharge channel that is so-called the reflector of electrons 3. As one can see in **Figure 21** this reflector is under a floating potential that is lower than the anode's 2. The electrode that is under a floating potential helps

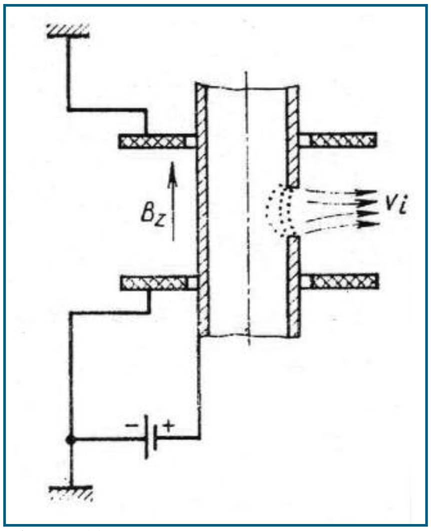

Figure 19. Ion source generating a wedge like ion beam [44]

to prevent a discharge current exit out of a discharge channel and to focus a plasma flow. [*Low-energy high-current ion sources, in particular MPD sources-thrusters are notorious for the electric current extension outside a discharge channel.

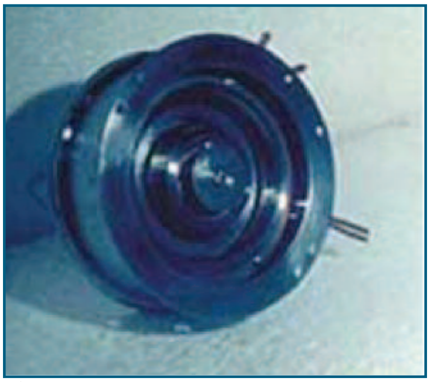

Figure 20. Ion source with combination of end-Hall and Anode Layer [54]

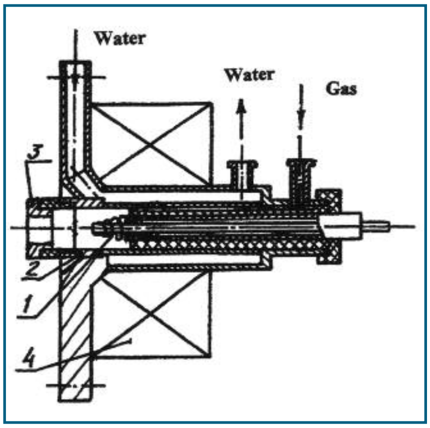

Figure 21. Hall-current ion source for technological tasks: 1–cathode;2–anode;3– reflector of electrons; 4 – electromagnetic coil [55]

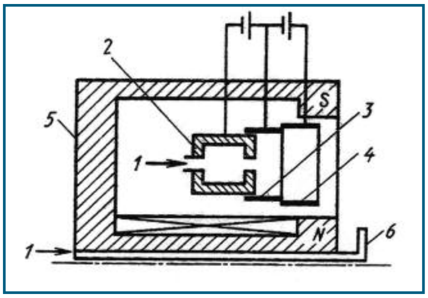

Figure 22. Two-stage ion source with extended acceleration region [56]

This type of ion source with external magnetic filed coils also experienced some discharge current moving outside the ion source's front flange.] It also helps to increase pressure in discharge channel and to reduce the ignition voltage. The HF lifetime was usually about 10 hours.

In certain cases, especially when it is necessary to have ion beams of light gases such as Hydrogen and at high energies over 1000 eV there are utilized two-stage modifications of anode layer ion sources. The distinctive feature of such ion sources is the utilization of two successive anode layers. The first one is for the development of ions, and the second one is for the ions acceleration.

In **Figure 22** there is shown the schematic design of a two-stage ion source [56], where: 1 is a working gas; 2 is an anode of the first stage; 3 is a cathode of the first stage [*serves as anode for the second stage]; 4 is a cathode of the second stage; 5 is a magnetic path; 6 is a cathode-neutralizer. Both stages are placed in the magnet's circular gap with the changeable pole's end-pieces. Cathodes and anodes of both stages are made usually of Molybdenum. The first stage anode also serves as a gas-distributor. The gas-distributor must provide a high azimuthal uniformity of applied working gas [*The importance of the azimuthal gas distribution uniformity will be specially analyzed in one of our further publications.]. This is achieved by correct selection of a gasdynamic resistance of gas flow applied in to the anode. The gasdynamic resistance must be significantly less than resistance of the holes, through which a working gas comes in to the discharge chamber. In the two-stage Anode Layer ion sources this is achieved by utilization of large number of holes (about 200) with small diameter of about 0.8 mm each.

The configuration of a circular gap and magnetic field are selected from different requirements. First of all, it is necessary to provide a magnetic field value corresponding to the theoretical estimations. Second, it is necessary to find the ion beam optimum magnetic focusing in order to minimize an ion bombardment of the discharge chamber. It is desirable to place the second stage behind a magnetic field maximum in order to have favorable conditions for discharge process, in particular, for acceleration of ions. [* The importance of a positive magnetic gradient for the Closed Drift thrusters-ion sources was discussed in our previous publication [2].] Third, it is necessary to reduce the dimensions of a flight area with an expanding magnetic field after the ion source's exit flange. Because in this area there can be developed the conditions for development of an ion beam electrostatic instability. [*This problem will be also discussed in one of our further publications.]

In **Figure 23** [56] there is shown the scheme of the multichannel ion source. The ion source has the common magnetic system, which is in comparison with an assembly of the cylindrical Anode Layer Thrusters-Ion Sources [59] [*Described in the next chapter of this article] makes possible to reduce substantially its mass for the same applied electric power. It was proved experimentally that all four channels practically do not influence on each other.

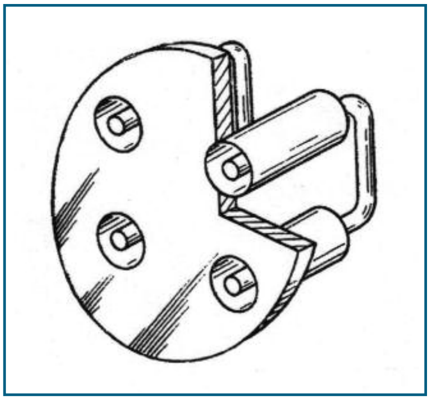

Figure 23. Scheme of a multichannel ion source [56]

Two-stage ion sources require, in general, two independent Power Supplies (PS). Stability of the system significantly increases when two PS with optimized external characteristics (with active ballast elements) are utilized [57].

The operation of a two-stage Anode Layer Ion Source at low discharge voltages $V_d < 500$ V was possible only at practically complete neutralization of an ion beam flow. Insufficient neutralization leads to the increase of an ion beam current to the magnetic system's poles [58]. Operation of ion source at low discharge voltages $V_d = 200 - 600$ V is also possible with certain limits on magnetic field and a working mass flow. In such a case, it is possible to have a very well focused ion beam with high stability of all basic parameters of an ion source.

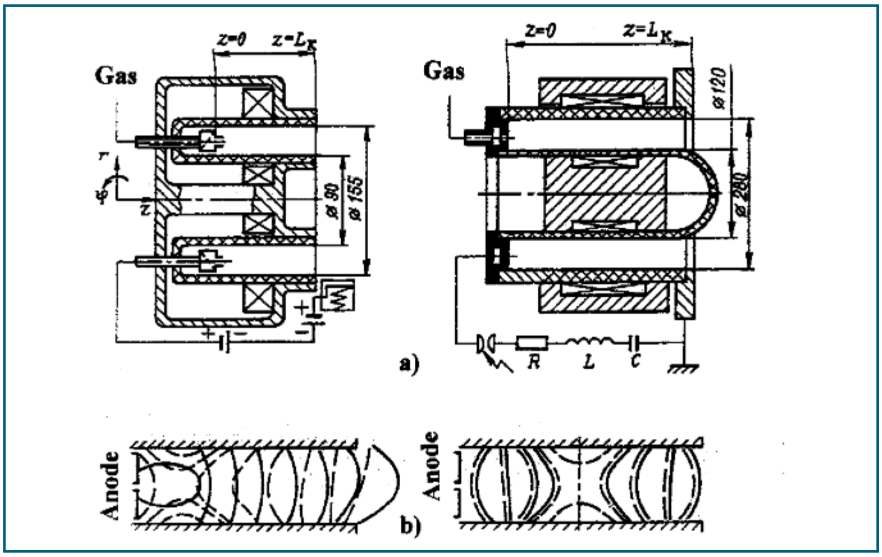

Figure 24. Single lens stationary (**a**) and two-lens quasi-stationary (**b**) Closed Drift ion sources for high ion beam energies and currents; design and magnetic field distributions along a discharge channel [59]

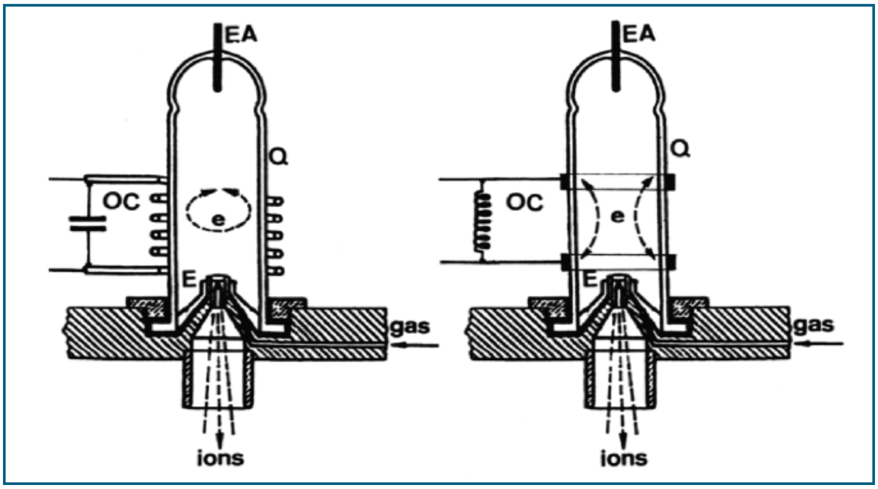

Figure 25. RF ion sources: inductive (left) and capacitive types [60]

There are some technological tasks that require significantly higher ion beam currents larger than 10-50 A. For such cases there was developed the special type of a Closed Drift ion source, so called a two-lens [*Magnetic configuration in the discharge channel sometime called as a lens, because its design is similar to a focusing of electrically charged particles by magnetic field] of a magnetic layer design [59] operating in the quasi-stationary regime of operation. This type of ion source is shown in **Figure 24.** It is operated in the quasi-stationary regime with the pulse duration of t_{pulse} = 5-10 ms, the discharge voltage range is up to $V_{d,max} = 4$ kV and the discharge current range is up to $I_{d,max} = 2$ kA. Magnetic field in the discharge channel is made with changing its polarity for compensation of the ions azimuthal moment at the exit from the ion source. The ion beam energy and current measurements showed that the mean ion beam energy $E_i \approx 0.7 \cdot eV_d$, and with this ion sources the ion beam currents $I_i \approx$ 300-1000 A with the mean ion beam energies $E_i \approx$ 1200-2000 eV have been obtained. The unexpected interesting feature of such a design is that a magnetic focusing in a two-lens model is more efficient than in the regular single-lens ion sources.

Such type of configuration can be utilized for certain R&D tasks in Universities and Governmental laboratories.

Another variety of ion sources is an RF-type ion source described in [60].

In general, there are two designs of RF ion sources: the Inductive and Capacitive types that are shown in **Figure 25.** Actually, gridless RF ion sources are quite rare, but they are frequently used with the certain design of gridded ion sources.

In the Inductive RF ion source the discharge chamber (usually made of a transparent dielectric material, like quartz, or a high-temperature resistant alumina, etc) is surrounded by an RF coil, or Oscillator Circuit (OC), in which electrons accelerated by the induced electric field.

In the Capacitive RF ion source the capacitors electrodes are placed inside the discharge chamber and electrons are accelerated by the oscillating electric field.

Usually gridless RF ion sources operate at pressures of order of 10^{-3} Torr with noble (Ar, Xe) and reactive gases (O_2, N_2).

RF ion sources are expected to have lower erosion rates of the discharge chamber. However, the practice shows that such ion sources at high discharge currents have their own problems, like deposition of a discharge channel internal part with conductive materials that gradually reduce energy transformation into the ionizing working gas. At this time, there is no any information about the practical gridless broad beam RF ion sources that could operate at high discharge currents reliably and for long time (hundreds of hours).

Conclusions about Non-Traditional Ion Sources

One of the purposes of this chapter is to present not only a review of existing non-traditional ion sources but to give a certain perspective to some users and developers of new and in some cases unusual approaches that also can work and produce the ion beams for varieties of thin film technology.

The described various ion sources show that it is possible to look for the new ways in development of ion beams for different specific tasks. There is still a big room for inventions and implementations of new ideas in this field.

Despite that such ion sources are named here as non-traditional, the DynaVac and Denton companies ion sources have been utilized by many users in numerous thin film processes and quite successfully.

All gridless ion sources described in Part 1 (Closed Drift ion sources), Part 2 (End-Hall ion sources) and in Part 3 (Non-traditional ion sources and Linear ion sources) have a certain magnetic field from under 100 G and up to several kG, because magnetic field is necessary to provide prolongation of electrons lifetime in discharge channel and that electrons would ionize a working gas and neutralize created ions. Discharge without magnetic field, as a rule, goes straight from cathode to anode usually along a shortest path developing an uncontrollable arc. As it was above discussed, the magnetic field that magnetizes electrons provides sharp change of a plasma electric resistance and allows having high electric fields in plasma volume leading to high working gas ionization and development of positive ions.

For most non-traditional ion sources that utilized now in the thin film industry we would recommend to conduct the optimization of major operational parameters such as the ion beam current I_i and energy E_i, a ratio of the ion beam current to the discharge current, I_i/I_d, a ratio the ion beam mean energy to the discharge voltage, E_i/eV_d as function of magnetic field distribution applied in to the discharge channel, the Volt-Ampere characteristics, for example, $V_d = f(I_d)$ at certain working gas flows, or to test an ion source with slightly different condition, like $V_d = f(\dot{m}_a)$ for I_d = 1, 2, 3…5…10 A (if ion source is capable to sustain high discharge current and the permanent magnet will be not overheated).

5. LINEAR ION SOURCES

There are several types of linear broad beam ion sources: closed drift with magnetic layer, closed drift with anode

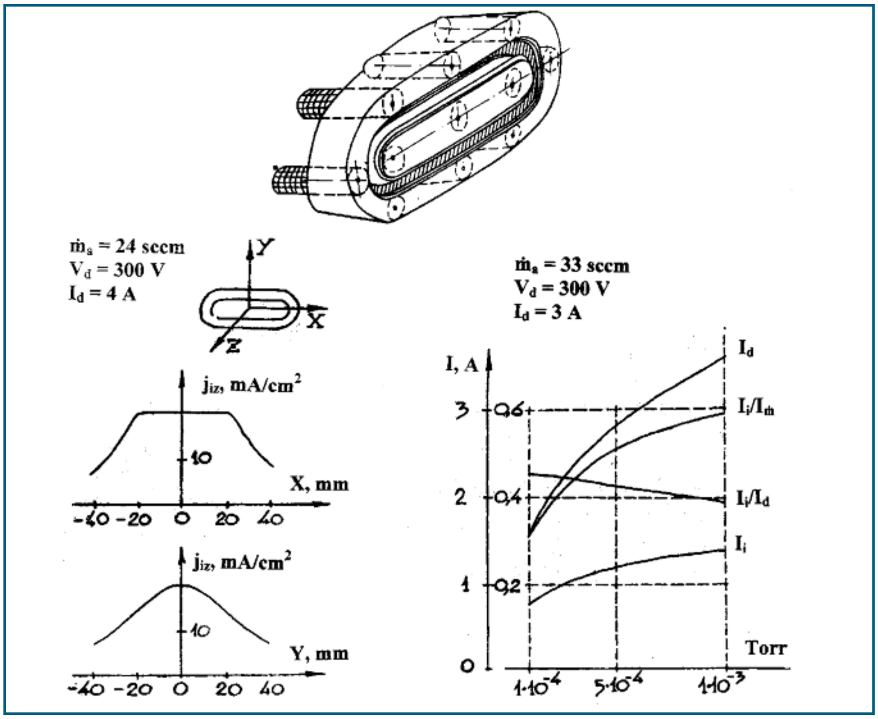

Figure 26. First Linear Closed Drift Magnetic Layer Ion Source "racetrack" [61]

layer, and end-Hall type. In some sense, that is almost exactly the situation exists with the round type ion sources. However, there are certain differences in the behavior of linear ion sources in comparison with the round sources.

The first linear ion source based on the principle of the closed drift electrons of the magnetic layer type was suggested and tested in 1982 [61]. This ion source is called a "race-track" source and was about 16 cm long and 4 cm wide. It operated in the following range of main parameters: the discharge voltages were from V_d = 200 to 500 V, the discharge currents were I_d = 1.0-4.0 A; the ion beam current is I_i = 0.8-1.8 A; the mean ion energy is E_i = 130-300 eV. The working gas mass flow (Ar, Xe) is from about $\dot{m}a$ = 20-60 sccm for Ar (for Xe is lower by about 3 times); pressures in vacuum chamber were $p_{ch} = 8\times10^{-5}$-1×10^{-3} Torr. The Hollow Cathode neutralizer is utilized as a source of electrons.

The second linear ion source based on the end-Hall ion source principles (magnetic field is at maximum in the gas-distributor area and decreasing to the source's exit) was introduced by K&R almost together with the cylindrical version and was made of three dimensions: 20 cm, 50 cm and 100 cm long. At present time these Linear end-Hall ion sources are produced by Veeco Instruments.

The 50 cm source [62a, 62b] shown in **Figure 27** and can sustain very high discharge currents I_d = 5 -20 A with Ar, N_2 and O_2 as working gases. The reasonably good linearity of an ion beam current is observed at the length of about 40 cm with the linear ion beam current density equal about ~20–200 mA/cm. The range of discharge voltages is from V_d = 55 to 150 V, and the mass flow at low discharge voltage is quite high, up to 200 sccm for I_d = 20 A. Also, two 50-cm linear sources placed close to each other can provide about 86 cm length of constant ion beam linear currents up to about 180 mA/ cm that is quite high value in comparison with frequently used now Anode Layer linear ion sources. These linear ion sources operate in a similar way as the regular end-Halls: they produce, in general, low-energy ion beams from about 30 to 90 eV.

For certain thin film tasks with low ion beam energies such sources are very good, but some users want higher ion beam energies (higher discharge voltages), some do not want to use a HC cathode-neutralizer and some vacuum chambers are not capable pumping very high working gas mass flows that are necessary for the end-Hall linear ion sources.

The third type of linear sources that most frequently used now is the Anode Layer type. There are several companies producers of Linear Anode Layer type ion sources. They are: Veeco; General Plasma Inc.; Belorussian State University of Informatics and Radio-Electronics; Applied Electronics, Tomsk, Russia; Bauman Technical University, Moscow, Russia; ULVAC, Japan; and several companies in China and S. Korea.

Like the cylindrical ion sources, the advantage of the Anode Layer type linear ion sources operating in the self-sustained discharge mode is in absence of source of electrons. However, as it was described in our previous publication [25], the operation of ion sources without a source of electrons leads to substantial increase of a plasma positive potential generated by an ion beam. This potential is delivered by non-neutralized ions on a target, or a substrate.

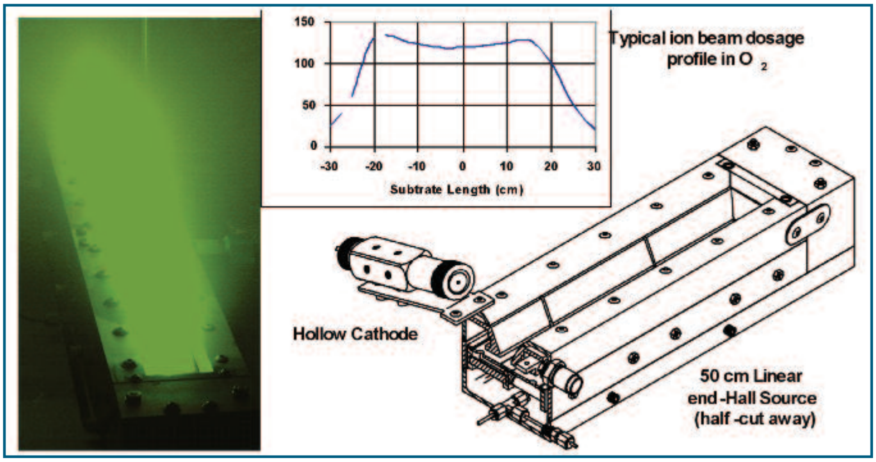

Figure 27. 50-cm linear end-Hall type ion source [62a, 62b]. Pictures, Photograph and images are courtesy of Veeco Instruments, Inc. Ion source shown with a Hollow Cathode and typical ion beam linear density profile in O_2 over a flat target at 15 cm from ion source.

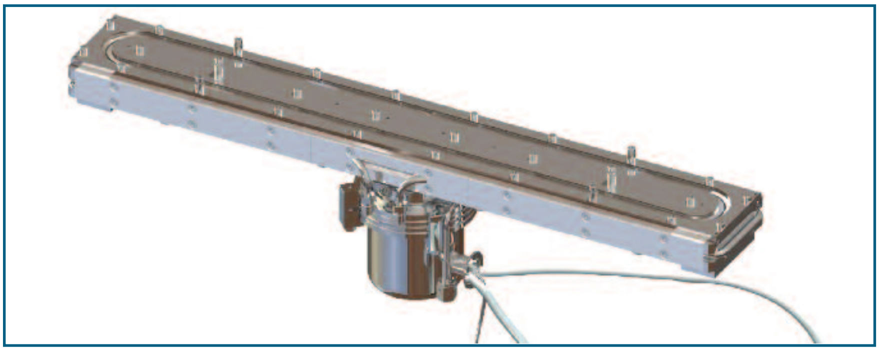

Figure 28a. Veeco's Anode Layer source ALS 650L [62b]

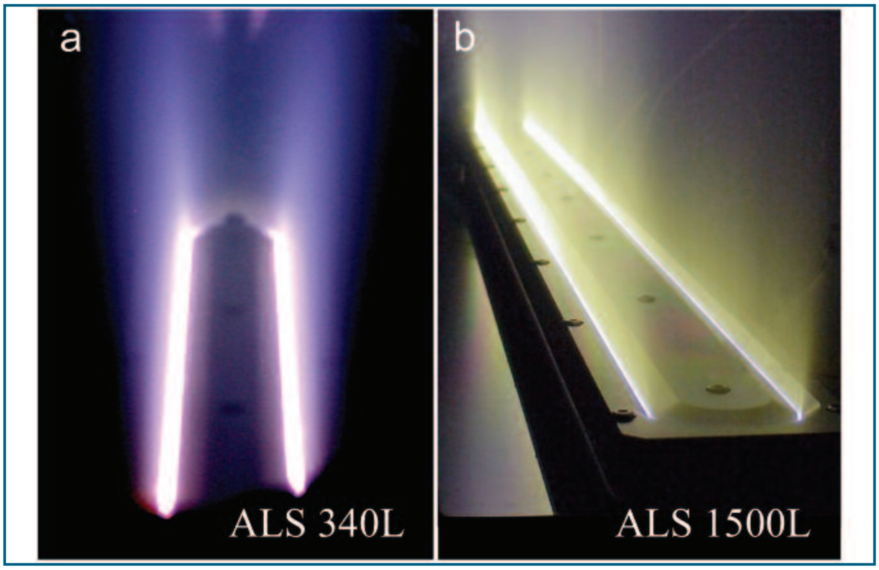

Figure 28b. Veeco's Anode Layer sources [62.b] in operation: (**a**) partial view of Veeco's ALS 340L with operation in Argon (**b**) Veeco's ALS 1500L with operation in Oxygen.

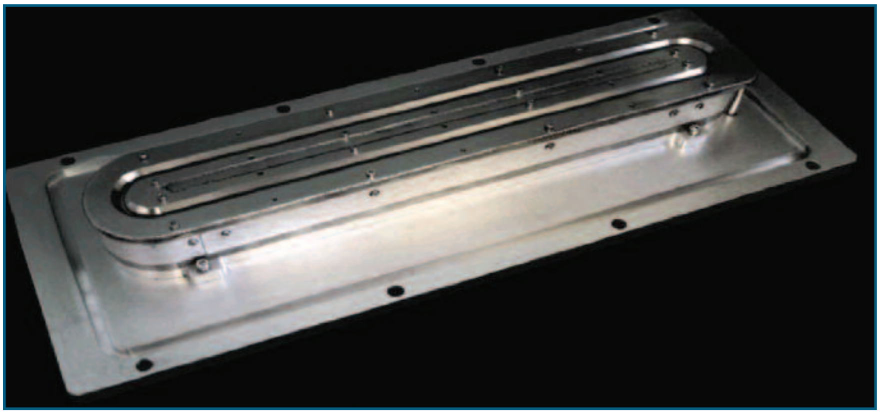

Figure 28c. Pointed Pole Anode Layer Linear Ion source produced by General Plasma Inc [63]

Ion beam positive potentials eventually become neutralized through sparks in vacuum chamber and on the target and substrate surfaces. Also, the underneutralized ion beam has a tendency for expansion.

Veeco's Anode Layer ion source (ALS 650L) shown in **Figure 28a** is designed for either internal or central flange mount installation. Veeco is focused on electrode optimization and other design features that substantially reduce (elemental iron and chrome) contamination levels on working substrates that originate from sputtering of the cathode at the discharge gap as occurs within most other Anode Layer source designs. In **Figure 28b** there are shown Veeco's Linear ALISs in action: 340L - Argon; 1500L - Oxygen.

In **Figure 28c** there is shown a so-called Pointed Pole Anode Layer Ion Source [63] by General Plasma Inc that makes nine varieties of such sources, from 34.5 cm and up to 338.8 cm of Anode Layer Linear ion sources, which require working gas mass flow from about 10 sccm and up to about 500 sccm. The discharge voltage is up to 4000 V with the mean ion beam energy of about 2000 eV. The linear ion beam current density is several mA/cm.

In **Figure 28d** there is shown a General Plasma Anode layer ion source operating on Oxygen.

In **Figure 28e** there is shown a 38 cm linear ion source produced by ULVAC [64] and in **Figure 28f** there is shown a schematic picture of ULVAC ALIS, a diagram of its main parts, and the method of the ion beam current measurements.

In **Figure 28g** ULVAC ALIS ion source is shown in action. One large permanent magnet of high Curie temperature and water-cooled is utilized. The range of discharge voltages is V_d = 500-3000 V, the range of discharge currents is I_d = 50-300 mA for the Lx-400 type. There are four different models with various lengths and applied powers, from about 32 cm to about 160 cm long, from about 450 W and up to 3000 W. Working gases are Argon, Oxygen and Nitrogen. It is reported [64, 65] that the ULVAC's ion sources can operate in a cumulative mode at quite high pressures above $7.5 \cdot 10^{-3}$ Torr.

As one can see, from outside the Linear Anode Layer ion sources made by Veeco, General Plasma Inc and by ULVAC look quite similar. However, according to the specifications, they operate quite differently. Unfortunately, there is not much of

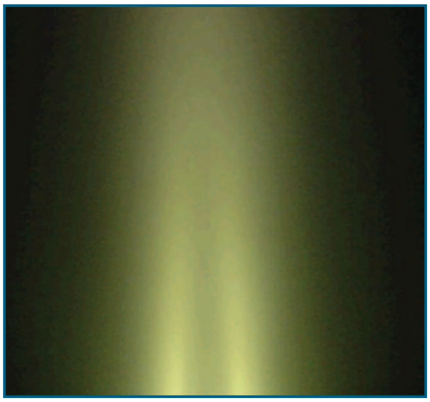

Figure 28d. General Plasma Anode Layer Linear Ion source in action operating with Oxygen. (Courtesy of General Plasma company)

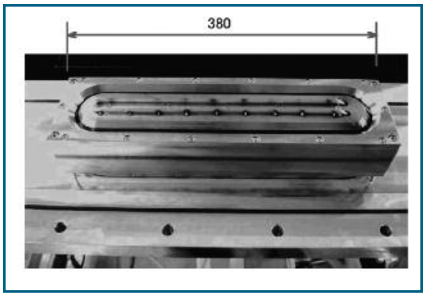

Figure 28e. Anode Layer Linear 38 cm ion source produced by ULVAC [64]

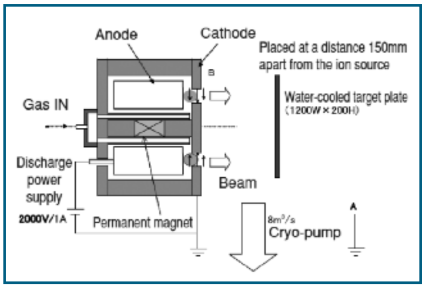

Figure 28f. Schematic picture of ULVAC ALIS; diagram of main parts, and measurement of ion beam current.

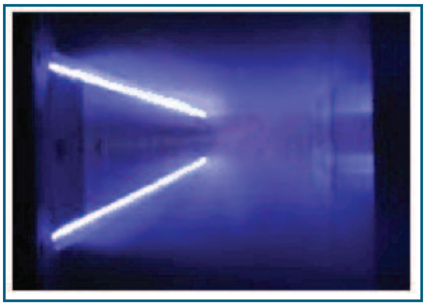

Figure 28g.. ULVAC Anode Layer Linear Ion source in action operating with Argon [65] (courtesy of ULVAC company)

scientific publications about physical processes and operations in such ion sources [*Except Russian publications that practically unknown in this country].

For those who make ALIS and who use them, it is necessary to remember that ALIS has two main regimes of operation. The first one is a high-voltage (1000-4000 V) "vacuum" regime with a collimated ion beam, and it exists at low pressures of working gas of $P_{ch} \leq 10^{-3}$ Torr; and the second one is a comparatively low-voltage (500-1000 V) regime with a highly spread ion beam at higher pressure of $P > 10^{-3}$ Torr. [*As it was above noted ULVAC reported [64, 65] that their Linear Ion Sources can operate in the accumulative mode at quite high pressures above $7.5 \cdot 10^{-3}$ Torr. In the regime with a collimated ion beam (most frequently used in practice) the discharge current increases with the discharge voltage. Increasing the working gas pressure leads to transition in the highly spread ion beam with the discharge current values that can be achieved much higher than with the collimated ion beam. The condition $n_e = n_i$ (there is no limit by the space charge for the ion current) begins to be performed at higher pressures in the discharge channel. However, there is no more control over the ion energy and beam collimation.

By increasing the working gas pressure there is observed an increase of a number of interactions of ions with neutral atoms leading to a charge exchange of high-energy ions and low-energy atoms according to the scheme:

$$A^{+}_{energetic} + B^{o}_{thermal} \rightarrow A^{o}_{energetic} + B^{+}_{thermal} + \Delta E.$$

During such interaction, an ion passing near atom takes away from a neutral particle its electron, preserving its velocity and direction of motion. In the exchange of charges a fast ion becomes a fast atom and a slow atom becomes a slow ion.

The developed low-energy ions, in general, are far from anode and can not be accelerated to the total anode potential. This process leads to expansion of ions energy distribution and an ion beam.

Some users are confused with difference between the charge-exchange and recombination processes between electrons and ions. In the pressure range of 10^{-5}-$5 \cdot 10^{-3}$ Torr the recombination process can be neglected.

A typical illustration of the ion beam current flux profile of anode layer sources across its short or minor beam is shown in **Figure 28h** for opertaion in the high voltage "vacuum" regime. The ion beam current density (mA/cm²) is peaked above each channel and scales with the anode discharge current settings. In typical applications, this beam current density is integrated along the minor beam axis to provide an ion current linear density (mA/cm). With special design and control of the anode cathode gap, it was possible to achieve the ion current density uniformity is held to within +/-5% over the active beam length as illustrated in **Figure 28i** (Veeco [62c]). As for most all Anode Layer on sources, the ion beam linear current density is peaked at the ends due to the radial turn of the closed-drift track.[62c].

Here are the considerations about measurements of an ion beam current by a large opened target. There are several sources of errors in such measurements from the real ion beam current. The first error is due to presence of the secondary electrons emitted by a target during collisions of ion beams with a target. The secondary electron emissions are determined by the ratio of a number of electrons leaving a target's surface to a number of incident electrons δ. This value should be utilized for the correction of the measured ion beam current I_{meas} that must be divided by the $1 + \delta$, or $I_i = I_{meas}/(1 + \delta)$. The value of δ varies substantially of energy and a sort of gas. For Argon it can be from 0.1 for energies under 1000 eV and significantly higher at higher energies.

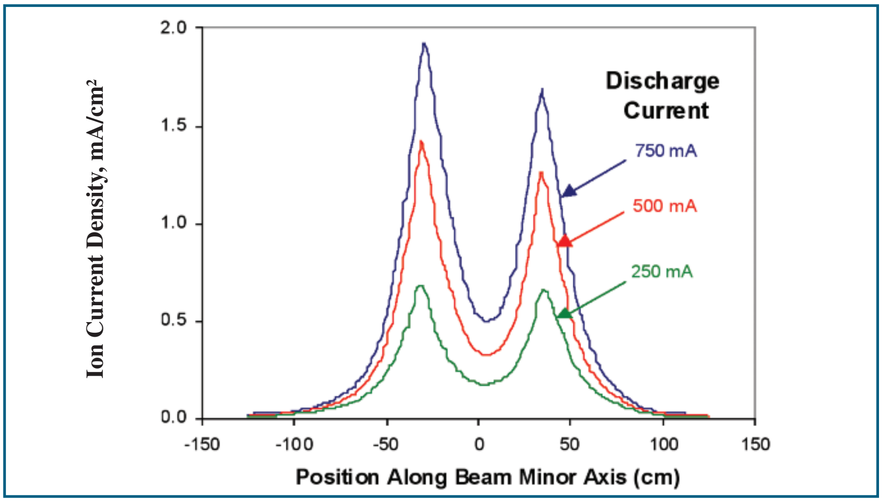

Figure 28h. Typical ion current density beam profiles across the short axis of Veeco's ALS 340L (340mm) for operation in Ar at V_{Anode} =3kV at various discharge currents at a probe distance of 10 cm [2]

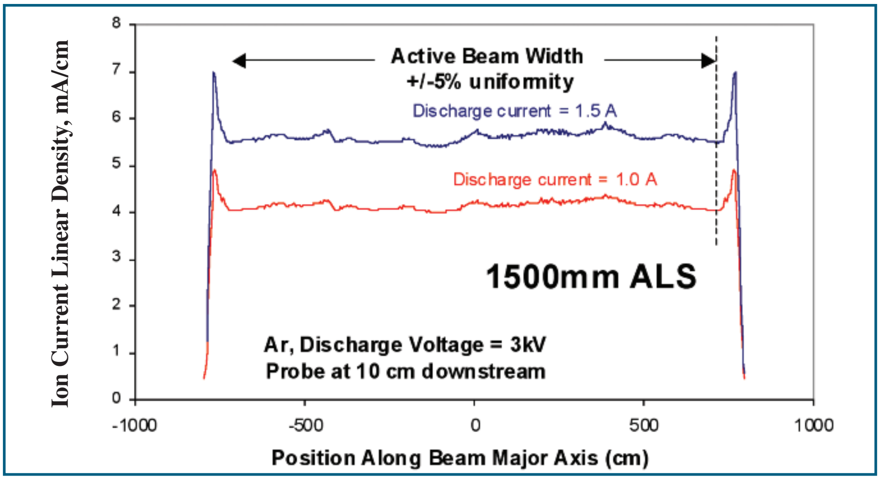

Figure 28i. Typical ion beam linear current density levels (integrated across source) along the major beam axis of [a] Veeco ALS 1500L (1500mm) for operation in Ar at V_{Anode} = 3kV at various discharge currents at a probe distance of 10 cm. [62.c]

A large size target measurements can produce another error due to existence of the charge-exchange ions [*Especially at pressures over 10^{-4} Torr; see our recent publication in *VT&C* about various factors influencing on the main ion source parameters, including the charge-exchange particles [25]]. The screened probe can be used for the correction of charge-exchange particles presence [66] [*In our following publications it is planned to present detailed analysis of operation of the probes for measurements of the current and energy of ion beams produced by the ion sources].

There is another factor. The underneutralized ion beam, as it was above mentioned, takes place with the Anode Layer high voltage linear ion sources, applies very high positive potential (over several hundred volts) to the measuring target causing high number of neutralizing small sparks that produce effect similar to development of secondary electrons. As it was above discussed in Part 1 of this article, in some cases, the sensitive targets receiving even much smaller positive potential as low as 6.4 V can cause damage by sparks leading to an ion beam neutralization [12].

Because Anode Layer Linear ion sources do not have external electron sources, some producers utilize an external flange surface under a ground potential as a "cold' cathode for partial neutralization of a positive ion beam flow. In such a case, an external flange becomes severely sputtered by an ion beam. Though, General Plasma Inc. developed the optimized magnetic field between the pointed magnetic poles(PPALS).

In **Figure 28j** there is shown the etch rate comparison between PPALS ion source and a conventional ALIS. The etch rate with PPALS was possible to reduce more than several times.

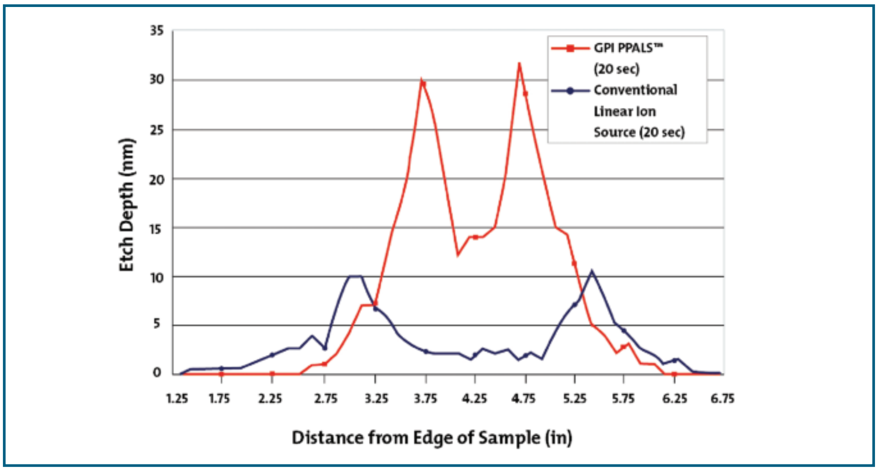

Figure 28j.

In **Figure 29a** one can see a picture of five operating small end-Halls of EH-200 [67] type that substitute one long linear ion source. The advantage of small ion sources is that they consume a low anode working mass flow and can operate with discharge voltage up to 200 V – 300 V (medium ion beam energy is about 140 eV – 210eV); a linear ion beam current density is about 40 mA/ cm on the axis; an ion beam completely neutralized with only one Hollow Cathode electron source.

As a further example, an end-Hall ion source array system was demonstrated using multiple Veeco Mark II+ ion sources **Figure 29b** with independent hollow cathodes used for each source in order to provide wide-area coverage [67b]. Veeco informed that such clustered arrays simulating linear ion source have been used in industrial applications for deposition of relatively thick tribological coatings and

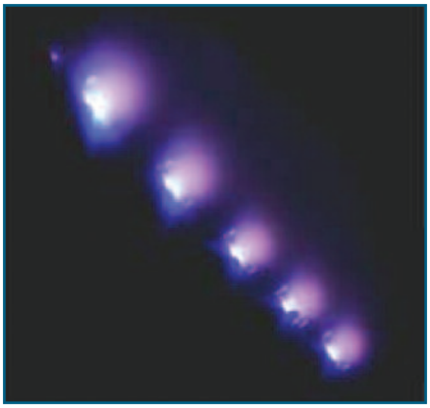

Figure 29a. Cylindrical small ion sources of EH-200 type [67a] placed as a linear array to substitute one long linear end-Hall source. All five ion sources utilize one Hollow Cathode for neutralization of ions.

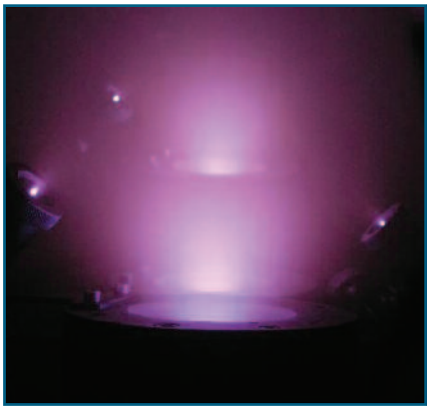

Figure 29b. Operation of multiple cylindrical end-Hall sources (three Veeco Mark II^{+}); working gas is Ar for wide area assist and etch applications [67b].

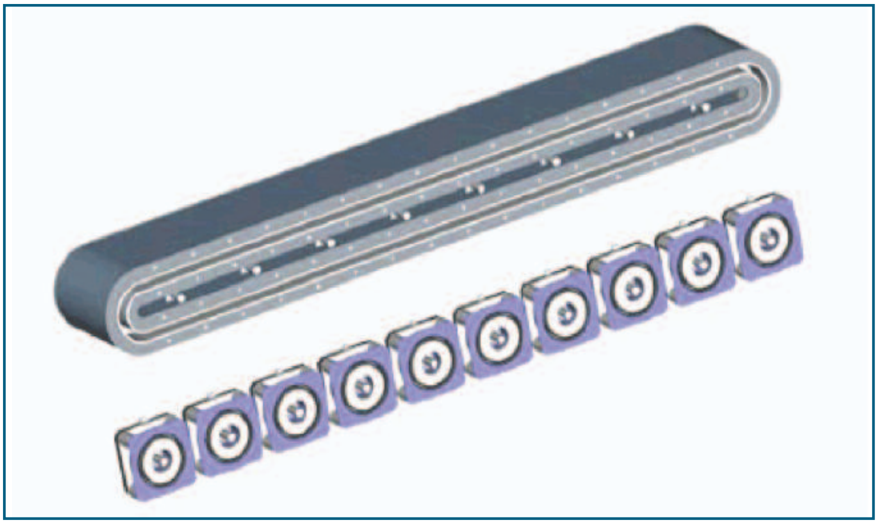

Figure 29c. Multisectional linear AL thruster-ion source and connected 10 small AL thrusters-ion sources with the effect of a linear device [68].

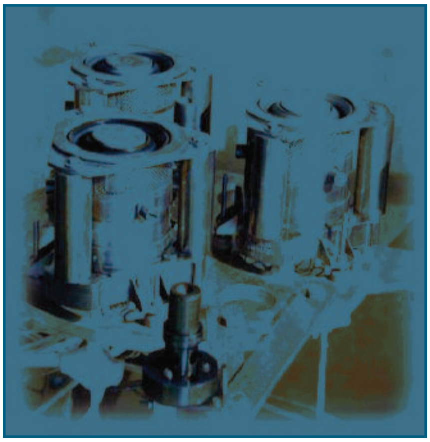

Figure 30a. Assembly of three Anode Layer Thrusters-Ion Sources [68]; one Hollow Cathode is utilized for all assembly.

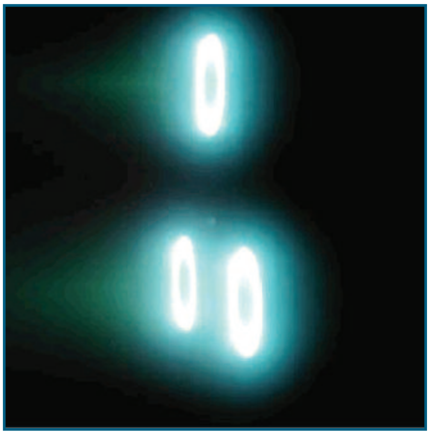

Figure 30b. Assembly of three Anode Layer Thrusters-Ion Sources in operation with one hollow cathode [68].

for ion beam assisted deposition of alumina-based films within data storage applications.

In **Figure 29c** there is shown another approach to the utilization of assembly of several small ion sources with a bunch of separate connected ion sources in a form of a linear ion source [68].

The cluster assembly of several large AL sources can also be used for obtaining broad beam area processed by the ion sources. One of such examples is shown in **Figure 30a** and in operation is in **Figure 30b.** The combined operation of a cluster assembly showed some unexpected results, like reduced level of the discharge voltage and current oscillations in comparison with just one thruster-ion source [68].

Because there are many companies making and utilizing the high-voltage linear ion sources without external source of electrons, it is necessary to give certain information about a proper way of utilization of such sources.

For those, who regularly use the high voltage Linear Anode Layer ion sources and want to know about the presence of single and double ionized particles (which carry double energy in comparison with the single ionized particles), it is the important to remind [*Also, see one of our previous publications [25]] that, as a rule, with the increase of the discharge voltage the portion of single ionized atoms falls and the flow of double ionized particles increases. General considerations indicate also that at small mass flows (5-20 sccm) these flows become equal at the discharge voltages of about 600-700 V for Xe [*Xe first ionization potential is 12.13 eV, and the second ionization potential is 21.21 eV] and for 800-1000 V for Ar [*Ar first ionization potential is 15.8 eV, and the second ionization potential is 27.6 eV]. At larger mass flows the equality of single and double ionized particles flows takes place at higher voltages [69].

Well optimized closed drift ion source permits the operation with quite high electric powers without having a water cooled anode. For example, the thruster-ion source SPT-100 that operates at $I_d = 4.5$ A and $V_d = 300$ V, with total applied power of 1350 W and can operate up to 1500 W as radiation cooled. Other types of ion sources, like end-Halls with such powers require a water-cooled anode, or anode can become overheated.

In work [69] there were conducted experiments with two different dimension cylindrical type closed-drift thrusters-ion sources. Special attention was given to operation at high discharge voltages. Volt-Ampere Characteristics (VAC) have been registered at discharge voltage range $V_d = 200\text{-}1000$ V with working gas Xenon. There was measured a presence of single and double ionized particles, the ion sources were optimized for a magnetic field [see **Part I Figure 4**] for a thrust (directly connected with an ion beam current). As experiments showed, with increase of the discharge voltage in the high voltage Closed Drift ion sources, it is necessary to increase the value of magnetic field at the source's exit plane. The number of single and double ionized particles was estimated theoretically according to [70] and experimentally confirmed in [69]. In [70] a plasma flow coming out of a thruster-ion source was considered as a completely ionized medium consisting of single and double ionized ions $\dot{m}_1$ and $\dot{m}_2$, and particles that were not accelerated $\dot{m}^*$. The portion of not accelerated particles can be due to various reasons: flow through discharge channel without ionization, loss of ions in discharge channel walls and their transformation into neutral particles.

In **Figure 31a** and **31b** one can see the mass flows of single, double and neutral particles in one of closed drift ion sources operating with working gas Xe at two different anode mass flows 40 and 15

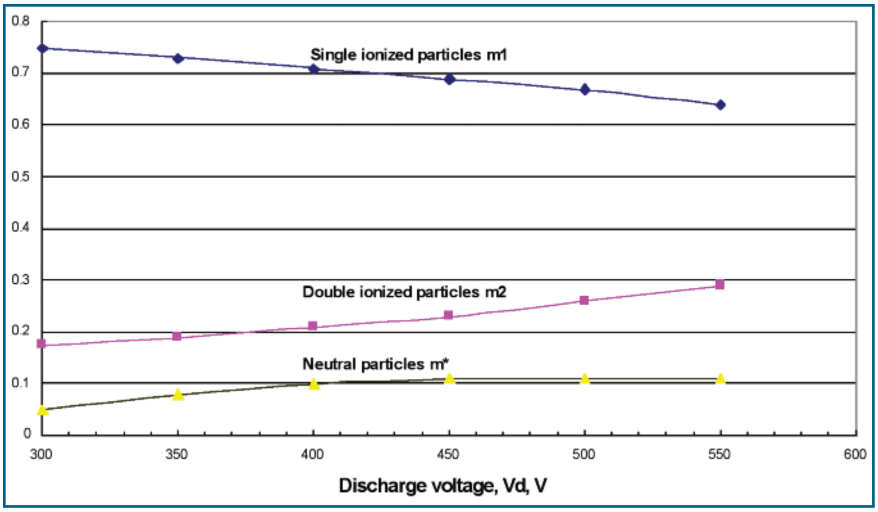

Figure 31a. Closed Drift Ion Source of Magnetic Layer type. Single, double and neutral particles in ion beam as function of discharge voltage V_d; working gas Xe; anode mass flow $\dot{m}_a = 40$ sccm [69].

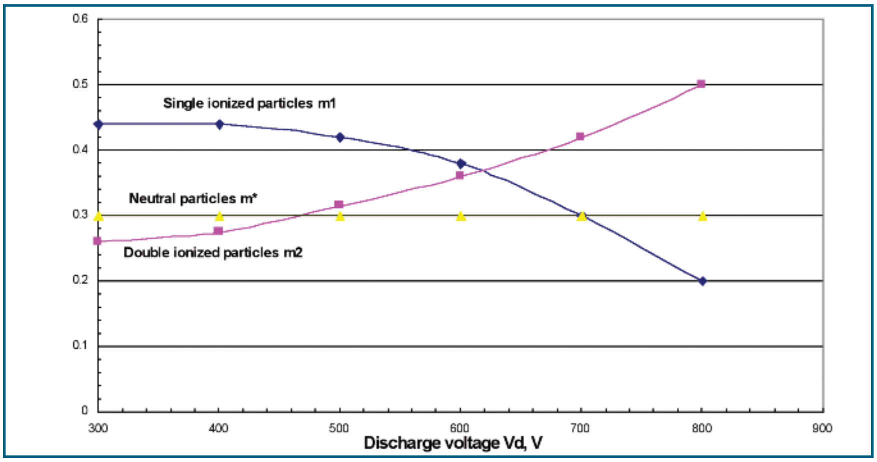

Figure 31b. Closed Drift Ion Source of Magnetic Layer type. Single, double and neutral particles in ion beam as function of discharge voltage V_d; working gas Xe; anode mass flow $\dot{m}_a = 15$ sccm [69].

sccm. As one can see, the number of single and double ionized particles for $\dot{m}_a = 15$ sccm becomes equal at about $V_d = 600$ V, and with further discharge voltage increase the majority of particles are becoming as double ionized particles. For the higher anode mass flow $\dot{m}_a = 40$ sccm such equalization will take place at about $V_d =$ 900-1000 V. Since these numbers are for working gas Xe, for Ar the double ionized particles will be shifted into the larger discharge voltages by about 200-300 V.

Conclusions About Linear Ion Sources

As one can see the Linear Ion Sources are also made with the different approaches in the generation of ion beams. There are several types of Linear Ion Sources based on the following principles of operation:

I. Closed Drift of Magnetic Layer type (magnetic field with a positive magnetic gradient; substantial distance between anode and exit flange-external pole) utilizing the cathode producing electrons, either a HC, or a HF; operates from low discharge voltages of about $V_d = 100$ V to higher voltages of about $V_d = 600$-800 V.

II. End-Hall type (magnetic field with a negative magnetic gradient utilizing a HC electron source); operates at low discharge voltages of about $V_d = 50$ V to about $V_d = 150$ V.

III. Closed Drift of Anode Layer type (magnetic field with a positive magnetic gradient; short distance between anode and exit flange-external pole); it does not utilize external source of electrons. These linear ion sources are most widely used with the high voltage (high energy) ion beams for cleaning of various objects before applying on them thin film depositions provided by the low energy ion beam. Linear Anode Layer ion sources operate in two main regimes: vacuum and regular.

1. Vacuum BE-discharge, in which the distribution of potential and electron concentration do not depend on the neutral atoms concentration, the discharge current is proportional to pressure in a wide range of pressures. In the vacuum regime BE-discharge operates at the magnetic fields of about $B \approx 2000$ G and up, at pressures $P \approx 7.5 \cdot 10^{-5} \cdot 7.5 \cdot 10^{-4}$ Torr [*Some companies claim that their ALIS can operate in the vacuum regime at higher pressures]. With the pressure increase over the critical value the BE-discharge makes transition in to the regular modification with $n_e \approx n_i$. The discharge structure in such a case is determined by the character of arrival of neutral atoms, by the processes of ions generation and various instabilities.

Also in the vacuum regime:

2. The energy of electrons is high; it is close to the applied potential difference (eV_d). The ion beam mean energy is much lower than in the ion sources that have electron sources for an ion beam neutralization. For the Linear and cylindrical ALIS $E_i \approx (0.1\text{-}0.5) \cdot eV_d$. Also, it is necessary to take into account that when a target becomes positively charged with about 100-500 eV (that takes place in reality with many ALIS operating with discharge voltages up to 3000 V), these values of 100-500 eV must be subtracted from the ion beam energy distribution. As it was above described, the most important problem for ALIS operating without external source of electrons is to find a proper way for adequate neutralization of positively charged ion beam coming out of ion source. Existing methods of utilization of grounded surfaces of discharge channel and external flange are not effective. They cause significant sputtering of such grounded surfaces. There is a good problem for solution to find simple, efficient, lasting long method of ion beam neutralization. The utilization of hot filaments can help neutralization, but hot filaments do not last long and they will be intensively sputtered and also can contaminate an ion beam. One of interesting solutions suggested in [71] is utilization of additional discharge over an ion source's front flange. Such discharge can provide neutralizing electrons and substantially change an ion beam energy distribution increasing its mean energy. [*In our previous publication [25] there was discussed impact of negative ions on contamination of ion source's discharge channel and was given suggestion [72] about utilization of additional discharge outside an ion source for prevention from negative ions moving into an ion source's discharge channel.]

3. The anode layer thickness is order of Larmour electron radius value.

4. The Hall current does not depend on heating of electrons.

In the vacuum regime an ion beam looks as well collminated and in the regular regime it is quite divergent. The main problem with the Linear ALIS is presence of highly positive ion beam that is not neutralized that can cause for certain types of processes sparks and oscillations. However, with the correct selection of technological processes, in which it is not necessary to have completely neutralized ion beam, the Linear ALIS is a very attractive device.

General conclusion about Anode Layer Ion Sources. Any ion sources that can operate in the self-sustained mode (discharge can be maintained without utilization of an external source of electrons) [1] still should use a source of electrons for adequate neutralization of a positive ion beam.

References

46. B.N.Titishov, S.V.Lebedev, *“Stationary Plasma Source of Low-Energy Ions”*, II All-Union Conference on Plasma Accelerators, Minsk, 2-5 October, 1973, p 101-102 (in Russian).

47. L.E.McCrary, R.R.Willey, *“Broad High Current Ion Source”*, US Patent No 5,576,600, Nov 19, 1996.

48. www.dynavac.com/VTA3/ion-source_new.html DynaVac *“IS1000 Ion Source”*.

49. D.Boyarsky, F.T.Zimone, *“Ion Source with Pole Rings Having Differing Inner Diameters”*, US Patent, March 30, 1999.

50a. R.R.Willey, *“Improvements in Gridless Ion Source Performance”*, 38th Annual Technical Conference Proceedings, Society of Vacuum Coaters, 1995, p 232-236.

50b. R.R.Willey, “*Practical Production of Optical Thin Films*”, Willey Optical, Consultants, 2008, p 172-174.

51. D. E. Morton and O. F. Farsakoglu, *“Characterization of a Plasma Ion Source and of Ion Assisted Deposited Optical Thin Films”*, Denton Vacuum Publications, 2008.

52. D. Tang, P. Chu et al, *“Characteristics of End Hall Ion Source with Magnetron Hollow Cathode Discharge”*, Nuclear Instruments and Methods in Physics Research, B 257, 2007, p 796-800.

53. S.D.Grishin, L.V.Leskov, N.P.Kozlov, *“Plasma Accelerators”*, Moscow, Mashinistroenie, p 76, 1983, (in Russian).

54. www.icm.by Films Research Laboratory, Belarusian State University of Informatics and Radioelectronics.

55. V.I.Baranov, S.N.Sabirov, *“End-Hall Accelerator for Technological Tasks”*, IV All-Union Conference on Plasma Accelerators and Ion Injectors, Proceedings, p 396-397, Moscow, 1978.

56. S.D.Grishin, L.Leskov, *“Electric Rocket Thrusters of Space Apparatuses”*, p 145, Moscow, Mashinistroenie, 1983, (in Russian).

57. S.S.Ivashenko, N.A.Mashtylev, V.A. Tkachenko, *“About Increasing of Parameters of Forming Stage of Accelerator with Anode Layer”*, IV All-Union Conference on Plasma Accelerators and Ion Injectors, Moscow, Nauka, 1978, p 21-22 (in Russian).

58. S.S.Ivashenko, A.S.Parshik,V.A. Tkachenko, Iu.V.Shipilov, *“Operation Specifics of Accelerator with Anode Layer at Low-Voltage Regimes”*, IV All-Union Conference on Plasma Accelerators and Ion Injectors, Moscow, Nauka, 1978, p 23-24 (in Russian).

59. Iu.V.Esipchuk, *“Investigation of Plasma Systems with Closed Electron Drift and Distributed Electric Field”*, “Plasma Accelerators” edited by L.A.Artsimovich et al, Moscow, p 75-84, Mashinostroenie, 1973 (in Russian)].

60. H. W. Loeb, *“Plasma Based Ion Beam Sources”*, 32nd EPS Conference on Plasma Physics combined with the 8th International Workshop on Fast Ignition of Fusion Targets, 2005, p 565-576.

61. E.E.Barkalov, A.N.Veselovzorov et al, *“Plasma Accelerators of Closed Drift Type with Plane Beam of Ions”*, V All-Union Conference on Plasma Accelerators and Ion Injectors, Moscow, Nauka, 1982, p 53-54 (in Russian).

62a. C.A.Wykoff, G.F.Hufnagel et al, *“50-cm Linear Gridless Source”*, Eight International Vacuum Web Coating Conference, Las Vegas, Nevada, Nov 6-8, 1994.

62b. www.veeco.com , Veeco Instruments – Anode Layer Ion Sources.

62c. D. Burtner, R. Blacker, J. Keem, D. Siegfried, and E. Wahlin, “Linear Anode-Layer Ion Sources with 340- and 1500-mm Beams,” 46th Annual Technical Conference Proceedings of the Society of Vacuum Coaters, 2003, p. 263-268.

63. www.generalplasma.com , General Plasma – *“Pointed Pole Anode Layer Ion Source”* (PPALS) Brochure

64. Narayasu Sasaki, Toshiju Kunibe et al, “Development of a Linear Ion Sources”, ULVAC Technical Journal, No63E, 2006

65. Toshiju Kunibe, “Operation Characteristics of ULVAC Anode Layer Ion Sources”, Private Communication, Feb 11, 2009.

66. P.A.Tsygankov, “New BaumVille Ion Probe Set”, Bauman Technical University, 2009.

67a. H.R. Kaufman, J.R. Kahn, and R.E. Nethery, *“Modular Linear Ion Source”*, Society of Vacuum Coaters, 47th Annual Technical Conference Proceedings, 2004.

67b. L. Mahoney, T. Alexander and D. Siegfried, “Characterization and Performance of Multiple Gridless Ion Sources for Wide-area Ion Beam Assisted Processes Applications”, 50th *Annual Technical Conference Proceedings of the Society of Vacuum Coaters*, 2007, pp. 239-245.

68. A.V.Semenkin, V.Kim, D.Manzela, V.Murashko, S.Tverdokhlebov, *“High-Power Hall Devices: Status and Current Challenges”*, TSNIIMASH, Korolev, Russia, June 25, 2004.

69. A.I.Bugrova, A.S.Lipatov, A.I.Morozov, S.B.Baranov, *“Influence of Ions with Different Ionization Ratio on Integral Parameters of Stationary Plasma Thruster (SPT) of ATON Type”,* Letters to Russian Journal of Technical Physics, 2005, V 31, issue 21, p 87-94.

70. A.I.Morozov, A.I.Bugrova et al, *“Stationary Plasma Accelerator Thruster ATON”* Russian Journal Physics of Plasma, 1997, V 23, No 7, p 635-645.

71. A.A.Goncharov et al, “*Plasma Accelerator with Anode Layer for Processing of Materials Surface*”, Plasma sbornik, Kharkov, 2003.

72. A.I.Morozov, A.I.Bugrova, “*Influence of Vacuum Conditions on Operation of SPT*”, Russian Journal Plasma Physics, 1996, V 22, p 701-706.