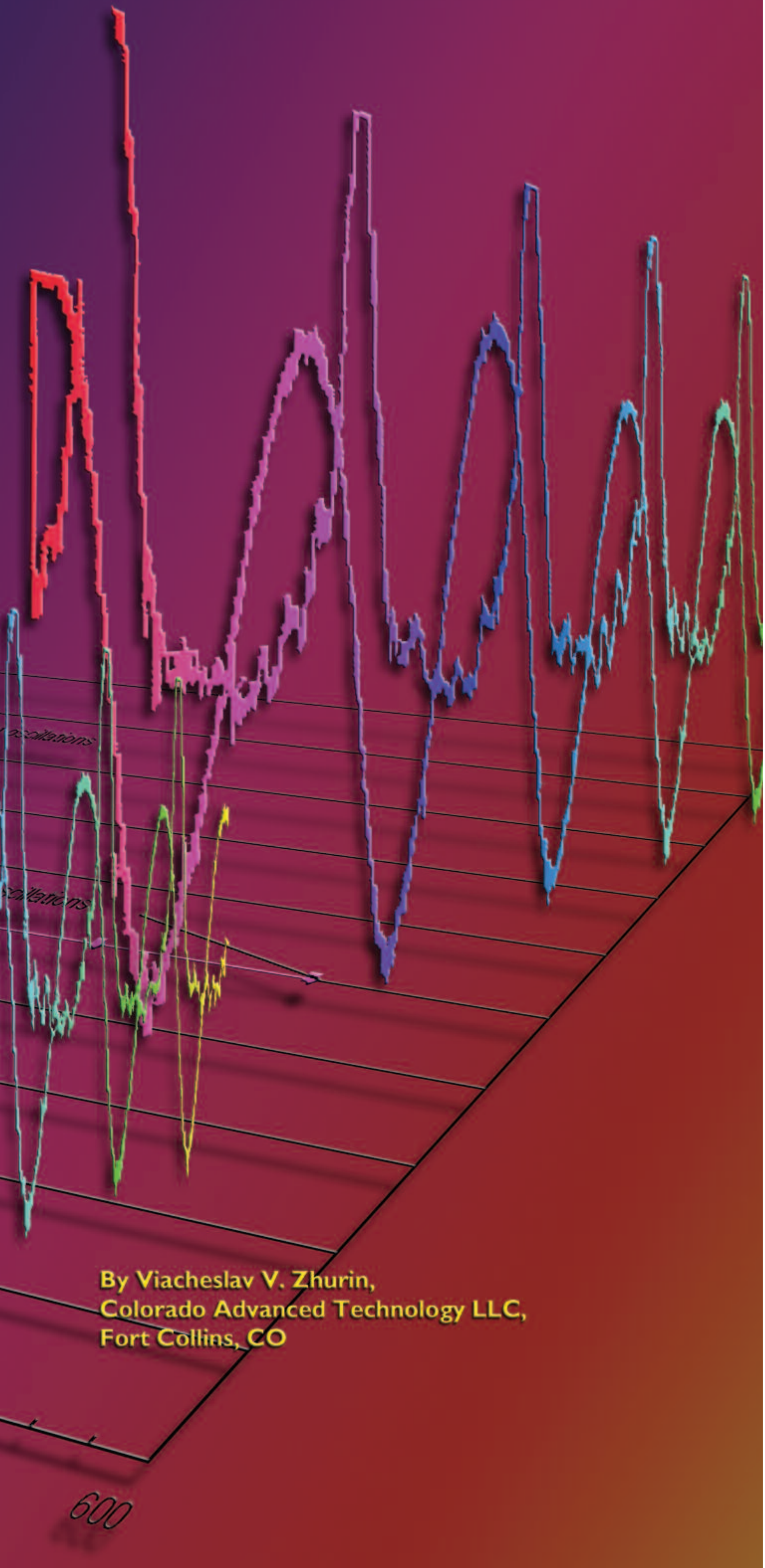
Oscillations and Instabilities in Hall-Current Ion Sources



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

There is another very important aspect about optimum and stable operation of ion sources in a wide range of discharge voltages and currents. It is the operation with small and large amplitude oscillations that can transform into instabilities. It is well-known fact that ion sources have different types of oscillations in various discharge voltage and current ranges. This is explained by experimentally registered and observed with regular and chaotic behavior of discharge plasma. After development of gridded ion sources and their utilization in thin film technology there were appeared new scientific-technical tasks that required low energies and higher ion beam currents. An example: for ion assisted deposition, one ion source is a main sputtering ion source, which can be either gridded, or gridless and directed to a target, and another one that is directed to a substrate for improvement of substrate properties; in this case, it is desirable to have ion assisting source with ion beam energy under a substrate's sputtering energy threshold. In 1980es there were invented new types of ion sources-gridless. They became so efficient for many thin film deposition tasks that after about year 2000 some companies producers of ion sources practically stopped making gridded ion sources and now produce varieties of gridless ion sources.

Development of oscillations and instabilities leads to direct increase of energy losses and corresponding decrease of ion source efficiency, ion beam current, broad smearing of ion beam energies, stability of operation. Because of that, it is necessary for ion sources developers and consumers to know the conditions, at which discharge plasma or an ion beam lose stability and to know the methods of plasma and ion beam stabilization and elimination of large amplitude oscillations leading to instabilities.

In the previous publication [*VT&C* "Optimum operation of Hall-current ion sources"] there was discussed the designs of two types of broad-beam gridless ion sources: the ion source with closed electron drift and the end-Hall ion source, both called sometime as Hall-current ion sources [1, 2, 3, 7, 8, 9].

First of all, it is necessary to indicate the fundamental difference between both types of ion sources. In closed drift ion sources magnetic field, which is mainly has a radial component, is at minimum in the anode area; and it gradually increases from anode to exit area, or a closed drift ion source can be called as an ion source with the positive gradient of magnetic field. The rate of the magnetic field increase is playing important role not only for the anode current value, but also for the stability of discharge process as instrument for reducing and suppressing current and voltage oscillations.

Closed drift ion sources/thrusters are very well-known for existing various oscillations and instabilities that can reduce the efficiency (ion beam current value and its divergence) or even disrupt (discharge extinction) operation of such ion sources/thrusters. Closed drift ion sources/thrusters oscillations were studied quite extensively for almost four decades, especially by Russian scientists [3, 6, 9, 10]. Quite contrary to that, there was practically no information about investigations of oscillations in end-Hall ion sources except of some recent publications [7, 8], though end-Hall ion sources also have various types of oscillations that produce significant impact on operation of such sources.

Those who worked with end-Hall ion sources know that major developers of end-Hall ion sources Veeco Instruments and K&R Inc. provide the operation range of such sources from about 50-60 V (for Argon) and about 80-90 V (for Oxygen and Nitrogen) to 300 V. Many consumers would like to have end-Halls with the discharge voltages up to 500-800 V for various etching and sputtering tasks. Also it is known that end-Halls operate in certain cases in quite unstable modes at discharge voltages between 200 V and 300 V, especially this problem exists with Oxygen as working gas.

Detailed analysis of plasma parameters in closed drift and end-Hall ion sources shows that physical processes in both types of ion sources are determined by various developed oscillations. The wide energy spectrum of end-Hall ion source shown in **Figure 3** and **Figure 7** of our previous article [*VT&C* "Optimum operation of Hall-current ion sources"] is caused not only by an extended region of ionization, but also by oscillations of electrical potential in a discharge channel.

The range of measured values of ions azimuthal velocity $v_{i\varphi}$ is happened to be in several times larger than calculated according to averaged parameters with account for quite a long length of ionization region. Also the value of longitudinal electron current I_{ez}, which is about 20-25% from a discharge current I_d exceeds by 2-3 orders of value if calculated by utilizing the Coulomb collisions. Detailed measurements of magnetic fields and currents propagating in discharge channels showed that the longitudinal electron current flows mainly in the whole volume, and the anomalous electrical conductivity of plasma is determined in general by oscillations.

Experiments with closed drift thrusters/ion sources showed that amplitude of oscillations at some regimes of operation could be quite high. In some cases the amplitude of electrical potential achieves 40-50% from the nominal operating discharge voltage V_d, the discharge current amplitudes also can reach over the nominal values by 50% and higher. Thus, at certain conditions and ranges of operation oscillations can be so high that they become instabilities leading to extinction of discharge in a discharge channel.

End-Hall ion sources in general have magnetic field values in discharge channel much higher than closed drift ion sources, but end-Halls magnetic field is high at the anode's bottom decreasing very fast to the exit flange. Closed drift thrusters/ion sources operate mainly with a radial magnetic field that increases from anode to exit flange (outer magnetic pole). The maximum magnetic fields are 200-300 G in regular size (exit diameter is from 50 to 100 mm, and in recent model is up to 200-220 mm) closed drift thrusters with extended acceleration region (this type, sometime called as magnetic layer, has a discharge channel made of dielectric material); the magnetic fields for anode layer thrusters (one of varieties of such thrusters/sources that have metal discharge channel) [3] are slightly higher, 300-400 G and at higher discharge voltages (500-800 V) the magnetic field is increased to about 400-500 G. Magnetic fields in end-Hall ion sources at the top of reflector-gas distributor that is located just under anode are usually from 500 G (for small exit diameter of about 30-40 mm) to about 1000-1300 G (for larger exit diameter of about 50-80 mm) and decrease to 40-70 G at the exit flange.

For better understanding of oscillations and instabilities taking place in ion sources, let us consider the Volt-Ampere characteristics of a typical closed electron drift and end-Hall ion source, which are quite similar to a certain degree. In this particular case, in **Figure 1** there are presented the Volt-Ampere characteristics of end-Hall ion source operating with Argon as a working gas with magnetic field at the reflector's top of about 1000 G with the discharge current of $I_d = 5$ A (lower curve),

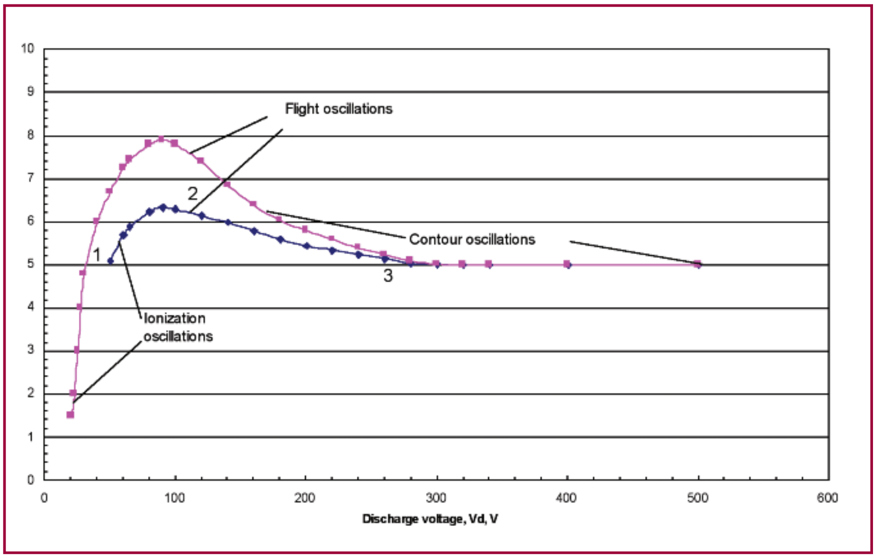


Figure 1. End-Hall ion source Volt-Ampere Characteristics for $I_d = 5$A and $I_{em} = 5$ and $I_{em} = 10$A, Argon.

with two emission currents $I_{em} = I_d = 5$ A, and $I_{em} = 10$ A (upper curve) and at discharge voltages V_d from about 20 V (for $I_{em} = 10$ A) and from 50 V (for $I_{em} = 5$ A) to about 500 V.

Volt-Ampere characteristics for both cases of electron emission have three important parts: 1 is the region of voltages (from about 20 V, or 50 V to about 90 V) with a positive inclination, in which a discharge current increases from it's low values under 5 A and then reaches the values over 5 A at about $V_d \approx 90$ V; 2 is the region with a negative inclination, where a discharge current decreases with voltage, from $V_d \approx 90$ V and to $V_d \approx 270$-300 V; and 3 is the region, where a discharge current practically does not depend of voltage, from $V_d \approx 270$-300 V and to $V_d = 500$-800 V.

All these and other regions of the high current intense discharge, its types of a non-self-sustained and a self-sustained and theirs modifications as distributed and concentrated discharges have been discussed and analyzed in detail in our previous publication in *VT&C* called "Optimization of Hall-Current Ion Sources".

It is well-known, from [3, 9, 10, 12] that certain regions of the Volt-Ampere characteristics can be associated with the certain types of discharge oscillations that discussed below (some of these regions are shown in **Figure 1**).

For example, the low part of Volt-Ampere characteristics, or region 1, is characterized by so-called azimuthal oscillations. The region with a negative inclination or region 2 is associated with so-called flight oscillations. The region 3 beside the varieties of high-frequency oscillations is associated with major strongest type that called contour oscillations.

Oscillations and Instabilities

First of all, it is necessary to clarify the difference between oscillations and instabilities. Oscillations of certain parameters take place in physical processes and even some parameters for normal operations can be, or must be in the form of oscillations. From the other hand, instabilities that take place usually as a consequence of oscillations can lead to unexpected undesirable interruption of a certain physical process. In some cases, normally existing oscillations can amplify amplitude and become instabilities and extinguish discharge. Before discharge will be interrupted ion beam and ion beam energies will be in a chaotic state and ion source operation will become unreliable.

That is why it is necessary to know what kind of physical processes can exist without or with oscillations, how to mitigate such oscillation, either to eliminate them, or to suppress, or just consider them as necessary part of the physical process. However, oscillations must not be in the state of transition into instabilities, and, in general, instabilities must be eliminated. As work with the closed drift thrusters/ion sources showed, for tasks as thrusters the closed drift thrusters/ion sources can operate with oscillations and quite successfully. However, for certain tasks in the thin film technology, when it is necessary to have well-distributed ion beam current over a tested surface, or an ion beam with a certain range of energies, an ion beam with oscillations can bring problems and it is desirable, if possible, to eliminate oscillations, or suppress them, or just to change operation conditions and move into the area that is free of oscillations.

Oscillations in end-Hall and closed drift ion sources can be classified for several types.

1. Large-scale azimuthal, sometime called ***ionization oscillations*** that exist in the range of frequencies from about 10 kHz to about 3 MHz. These oscillations are caused by a wave propagating along azimuth in the direction of drift of electrons from cathode to anode. The azimuthal wave (**Figure 2**) develops due to a non-uniform ionization of working gas in ion source and it exists in a certain range of discharge voltages corresponding to a low voltage Volt-Ampere characteristic, when ionization is on the rise (area 1 shown on **Figure 1**). These oscillations can transform into instabilities, but with further increase of discharge voltage (with higher ionization) they disappear. The pulsations can reach 15-20% of dicharge voltage.

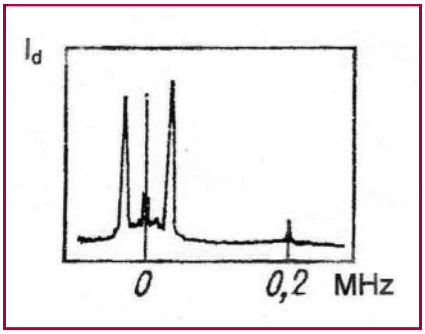


Figure 2. Ionization oscillations of discharge current caused by azimuthal wave; region 1 in **Figure 1** of Volt-Ampere characteristics

Ionization oscillations besides a low discharge voltage curve also take place at high discharge voltages when these oscillations appear in a positive column of BE-discharge beginning with a certain critical value of the parameter k_i [10]

$$k_i = I_d B_r / \dot{m}_a. \qquad (1)$$

Here I_d is the discharge current value, B_r is the radial component of magnetic field, and since with the increase of discharge voltage V_d an anode mass flow $\dot{m}_a$ decreases the coefficient k_i increases and the amplitude of discharge voltage increases reaching 25-30% of nominal discharge voltage. However, when the discharge current begins exceeding mass flow current I_m the in equivalent units

$$I_d > e\dot{m}_a/M = I_m, \qquad (2)$$

where e is electron charge and M is molecular weight of working gas, discharge makes transition in the regime of complete ionization, in which the discharge current stops increasing with further increase of discharge voltage. At the Volt-Ampere characteristic with a discharge current saturation at $V_d = 90$-175 V, the oscillations in this region are quite low.

It is necessary to note that the value $I_m = e\dot{m}_a/M$ is frequently called as equivalent

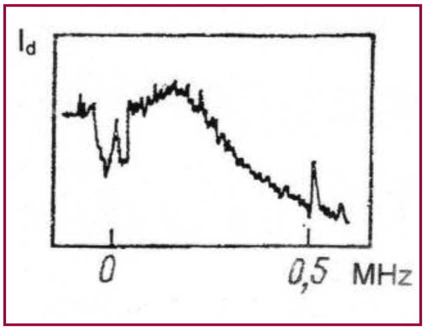


Figure 3. Flight oscillations of discharge current caused by an ion's flight time τ in discharge channel; region 2 in **Figure 1** of Volt-Ampere characteristics

mass flow current. Simple calculations for the equivalent mass current for $I_d = 1$ A give the mass equal to 13.9 sccm (standard cubic centimeters per minute) that holds for all working gases such as Ar, Xe, O_2, N_2. Here is conclusion for those who operate ion sources at high current and high voltage: as soon as mass flow decreases at high discharge voltages V_d usually over 250-300 V and the discharge current begins to increase, it means that the double-ionized particles developed and help increasing the discharge current. The double ionized particles in ion beam is a separate issue and will be discussed in some details in our next publication called "Ion Source and Vacuum Chamber, Influence of Various Effects on Ion Beam Parameters.

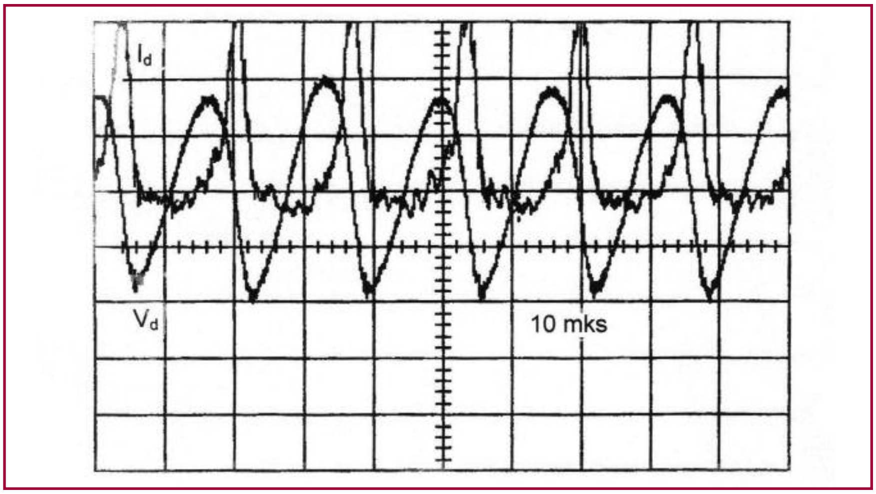


Figure 4. End-Hall type ion source operation with contour voltage and current oscillations at discharge voltage $V_d = 600$ V and discharge current $I_d = 5$ A.

2. The other type of oscillations, sometime called as the ***flight oscillations*** (**Figure 3**), are characterized by a wide spectrum of frequencies (area shown on (**Figure 1**) typically from about 100 kHz and up to about 10 MHz. In these oscillations plasma potential and density of particles are changed synchronously all over the whole volume of accelerating channel, however, in the azimuthal direction these oscillations are asymmetrical and lead to development of alternating electric fields.

The main frequency responsible for flight oscillations correspond to an ion's flight time τ in discharge channel

$$\tau \approx L/v_i, \qquad (3)$$

where v_i is ion velocity and L is characteristic length of a discharge channel. The amplitude of flight oscillations can be 20-30% of average electric field in plasma

3. ***Contour oscillations*** have frequencies of discharge voltage and current of 1-30 kHz (**Figure 4**). The development of these oscillations is caused by instability of the ionization region in discharge channel. These oscillations are the most prominent and intensive in comparison with all other types of oscillations, especially with discharge voltages over about 200-250 V. In the regimes with developed oscillations of contour oscillations one can observe about 100% modulation of discharge voltage and current. The important feature of these oscillations is that they depend substantially on the discharge circuit and the "filter" parameters between ion source and power supply. Closed drift thrusters (**Figure 5**) have been tested with varieties of filtering devices [12, 13] and have achieved successful mitigation of contour oscillations. Our work [7] with end-Hall also showed that correctly selected filtering devices between a power supply and anode can reduce contour oscillations substantially and provide successful operation of ion sources over 300 V up to 800 V.

Contour oscillations, if there are no adequate filtering devices between anode and a Power Supply, usually transform into high amplitude instabilities that can extinguish discharge and stop an ion source operation.

Our work with ionization and contour oscillations showed the following results. At the condition $I_d = I_{em}$ the current oscillations were quite prominent at $V_d \approx 50$ V, the lowest discharge voltage we could get with high mass flow for Ar, and for $V_d \approx 80$ V for O_2. The current oscillations sharply decrease at $V_d = 80$ V for Ar and at $V_d = 100$ V for O_2. Then, after $V_d = 150$ V the current oscillations gradually increase and become quite high with amplitude exceeding the operating current value by almost 100%. Also, the current oscillations increase with the discharge current value, in other words, they are stronger for $I_d \geq 5$ A than for 1 and 3 A. For example, for Ar and $I_d = 1$ A and $V_d = 300$ V there are practically no oscillations.

Both working gases, Ar and O_2 produce different levels of current oscillations. We were interested, in general, in oscillations at high discharge voltages, $V_d \geq 250$ V. We found that Ar produces much less oscillations than O_2 at high voltages and practically do not extinguish discharge at such voltages. Also, the ion beam profiles for Ar were quite acceptable, not very curvy. All successful measurements have been performed with optimized applied magnetic field values (see our first publication in *VT&C* "Optimum Operation of Hall-Current Ion Sources").

Oxygen, however, at high discharge voltages produced high amplitude current oscillations leading to discharge extinguishing, and ion beam current density profiles in many cases were curvy and unreliable. So, our main efforts were applied to O_2 at high discharge voltages, $V_d \geq 250$ V.

In **Figure 6** there are shown oscillograms of discharge current of closed drift thruster/ion sources with various magnetic

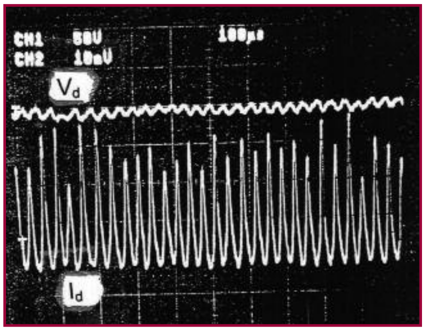


Figure 5. Closed drift thruster/ion sources with contour oscillations and filter between anode and Power Supply; $V_d = 300$ V, $I_d = 4.5$ A

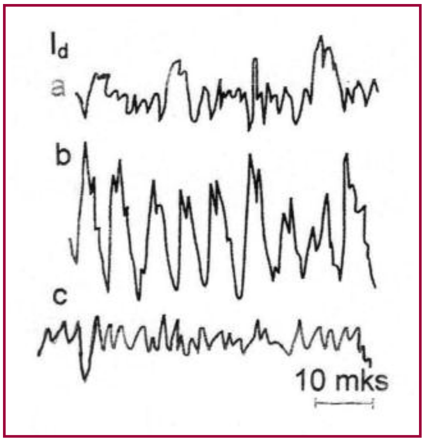


Figure 6. Closed drift thruster/ion sources with contour oscillations and various magnetic fields; $V_d = 300$ V, $I_d = 4.5$ A

fields as means for mitigation of contour oscillations

4. The hybrid azimuthal waves generating ***high-frequency oscillations*** with frequencies of 1-100 MHz. Such oscillations are developed in discharge channel with existence of the negative gradient of magnetic field. They are most prominent at discharge voltages over about 250 V.

5. **Oscillations caused by high pressure** in vacuum chamber. Usually, for end-Hall ion sources such pressures begin with 2-3 mTorr and up. In the case of utilization of a hollow cathode (HC), the ratio between a HC mass flow and pressure in vacuum chamber influences substantially on ion source performance leading to increase of potential gradients in the near cathode region. These gradients may lead to ionization instabilities in the near cathode region. These oscillations are possible to reduce by additional reactive elements in the system of power supply and ion source. Utilization of two hollow cathodes also helped decreasing oscillations in closed drift ion sources/thrusters [10]. Another method is utilization of excessive electron emission current helping to reduce such oscillations

6. ***Oscillations caused by under-neutralization*** of ion beam. When ion source operates without adequate cathode emission current, in plasma there takes place instability that under-neutralizes an ion beam that is developed in three stages: **1.** appearance of oscillation in ion source discharge; **2.** amplification of these oscillations in ion beam; **3.** further amplification of oscillations in plasma outside of ion source.

7. ***Oscillation caused by wrongful operation*** such as badly matched Power Supply and ion source, malfunction of gas flow controller, dielectric depositions on anode and discharge channel surface.

8. ***Oscillations caused by release of water vapors*** due to insufficient pumping time. Since most end-Hall ion sources are utilized in optical industry, very often those who operate vacuum systems with end-Halls do not provide adequate pumping limiting sometime just to 10-15 minutes. Water vapors accumulated during a vacuum chamber opening in discharge channel and in some cases in a gas distributing system can cause quite erratic behavior of discharge. After a vacuum chamber opening it is necessary to apply dry gas, such as argon, or nitrogen into a vacuum chamber, and especially into a discharge channel of an ion source. After closing a vacuum chamber it is advisable to increase a pumping time. Each vacuum chamber can be tested for the time that is necessary to eliminate an impact of water vapors on stable ion source operation.

Closed drift ion sources/thrusters in general work at discharge voltages from about 200 V to 500 V (300 V is the nominal operating discharge voltage for a closed drift thruster SPT-100). Also, closed drift ion sources/thrusters operate with well-developed oscillations and quite successfully. Closed drift ion sources/thrusters, as was above mentioned, mainly have a positive (increasing) magnetic field from anode to exit flange, and only in area at exit flange magnetic field becomes decreasing. A.I. Morozov [11] introduced a well-known criterion about importance of positive magnetic gradient in discharge channel for stable operation that states that unstable azimuthal wave in a decreasing magnetic field develops when the following condition takes place

$$\partial B_r/\partial z < 0. \qquad (4)$$

The Morozov's criterion was justified with over 100 modern closed drift thrusters-ion sources utilized on space satellites and is utilized for design such type of devices. In the closed drift thrusters of the first generation (SPT-50, SPT-60) the maximum of magnetic field distribution was in the center of discharge channel and at the exit it was decreasing, however, ***those first closed drift model with negative magnetic gradients have been working quite well.***

Our experiments with end-Hall ion sources excessive cathode emission, especially in the discharge voltage range between 200-800 V also helped to reduce ionization oscillations in end-Hall ion source in the wide range of discharge voltages and currents.

Conclusion and What To Do About Oscillations.

Regular users of ion sources in the cases of development of oscillations have to follow these procedures:

See if oscillations have large amplitude, with transition into instabilities, and can disrupt regular operation. Here are some examples, when oscillations develop producing certain unpleasant effects such as discharge flickering, ion beam current decrease, divergent ion beam, and ion beam energy value becomes quite uncertain (mean ion beam energy smears over a large range of energies):

1. Oscillations substantially increase, when the operating discharge voltages are close to the extreme low, or high voltages (development of oscillations with transition into instabilities is quite a normal phenomenon in these regions), for example, for end-Hall ion source V_d is under about 50 V for working gas Argon and under about 80 V for working gas Oxygen, or Nitrogen, or V_d is close to 300 V for Argon, or close to 250 V for Oxygen or Nitrogen. Remedy: if it is necessary to get into lower or higher voltages (read: low and high energies) the ion source needs to go through the optimization of magnetic field, or change discharge current (see our previous publication "Optimum Operation of Hall-current ion sources" in *VT&C*)

2. Oscillations developed and gradually increasing in the "well-operating region of discharge voltages; it may be due to several reasons, such as anode became covered with dielectric film from the process, especially, if an ion source works with working gases such as Oxygen, or Nitrogen that can develop dielectric films on anode surface. Remedy: clean dielectric film from anode surface, use grooved anode, or a baffle [15], if possible, place ion source and substrate so that there will be less reflected particles from substrate directed into end-Hall discharge channel.

3. Oscillations developed after opening and closing vacuum chamber, vacuum chamber absorbed water vapors and there was not enough time for pumping out these water vapors. Remedy. Pump longer a vacuum chamber, or take proper measures during opening vacuum chamber, like continue to supply a working gas (Argon) into anode area. It will be prudent during time of an opened vacuum chamber to apply Argon, or Nitrogen into a vacuum chamber.
4. Oscillations developed, and discharge interruptions are observed on a Power Supply, or through a vacuum chamber window, because there is a problem with working gas supply and it is applied into anode area with interruptions. Remedy. Check a mass flow meter, or bring a new filled with working gas bottle. Always use clean gas bottle not contaminated during wrongful opening.
5. Oscillations developed and do not disappear, and everything was done as advised in 1-4. Check the magnet (or magnets) for the magnetic field value for any particular model of ion source. As a rule, magnetic field of end-Halls is larger for big dimension ion sources; magnets with time, especially made of rare-Earth metals, lose magnetism and need to be remagnetized or substituted for the new ones.
6. In some cases, for those who are trying operation of end-Hall at high discharge voltages and with Oxygen and Nitrogen it is necessary to experiment with various filtering devices between anode and a power supply.

In all discussed above oscillations the most frequently observed and studied are the ***contour oscillations***. These oscillations have the following fundamental properties:

1. Contour oscillations are azimuthally symmetrical;
2. Contour oscillations do not produce major impact on the ion source integral characteristics, such as the ion beam current and the mean ion beam energy [14].
3. It is possible to have end-Hall ion sources operating with discharge voltages substantially higher than 300 V. Special care must be used with at such high voltages.
4. Power Supply must provide necessary power, and between the Power Supply and ion source anode there must be installed a special filtering device that can be specific for each end-Hall design and can mitigate large scale oscillation.
5. Together with the filter magnetic field should be optimized for the minimum voltage and current oscillations and the maximum ion beam current.

About high-frequency oscillations, which frequencies are in the range of from about 1 and up to about 100 MHz, there is opinion [14] that they probably do not play important role in the ion sources operation, and they were not well investigated. Finally, there are oscillations in the whole working range of discharge voltages – from 1 to 10 GHz. They are different in different discharge ranges, but, in general theirs role is low in operation process.

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