

## “Miniature Sputter-Ion Pump Design Considerations”

-- or --

“Why Do Ion Pumps Look the Way They Do; and What Can We Do About It?”

**S. L. Rutherford - Duniway Stockroom Corp.**

[www.duniway.com](http://www.duniway.com)

Abstract: An overview of sputter-ion pump weight versus pumping speed will initially be presented.

This will be followed by a review of the dependence of pumping speed on a variety of parameters, including: voltage, magnetic field strength, magnetic field uniformity, anode cell diameter, anode cell length, operating pressure, gas species, cathode material, cathode configuration and conductance.

Then, a discussion of the process of designing a small ion pump will be described. Starting with magnet configuration, materials, gap and stray field; choosing the combination of magnetic field and anode cell diameter for the target pressure range; using the magnetic gap efficiently for anode cell length, anode-cathode spacing, cathode thickness and envelope thickness; choosing the operating voltage and power supply characteristics; deciding on the cathode material and configuration for the gas species encountered; and determining the target lifetime of the pump for the application.

Illustrations of a number of miniature ion pumps will be included.

# “Miniature Sputter-Ion Pump Design Considerations”

S. L. Rutherford -- Duniway Stockroom Corp.

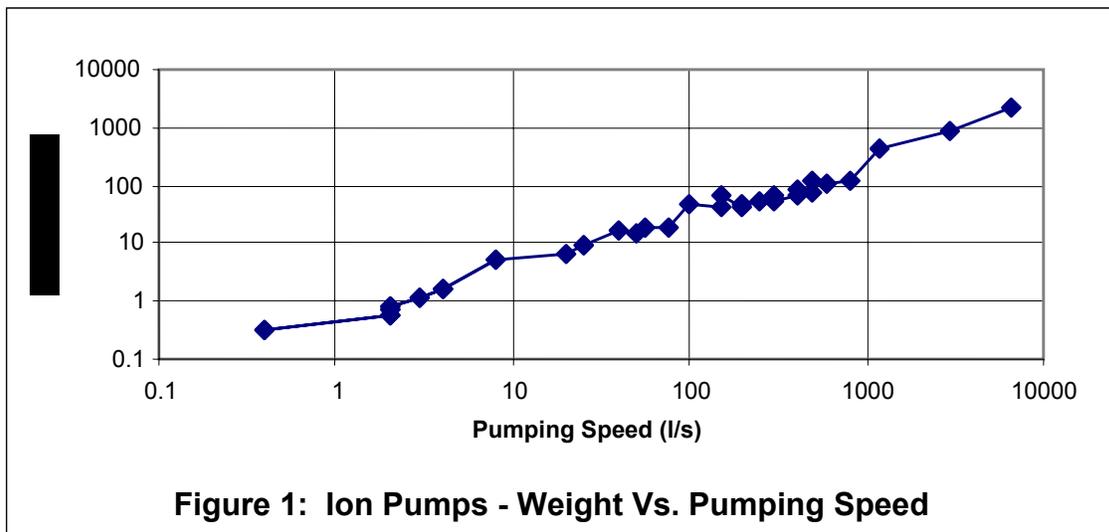
## I. Pump Weight versus Pumping Speed

### Introduction:

The sub-title of this presentation might be: “Why Do Ion Pumps Look the Way They Do; and What Can We Do About It?” Constraints of real life materials and physical laws all go together to make ion pumps look the way they do. This communication is intended to show examples of ion pump design parameters and specifically how they apply to miniature ion pumps. It is not intended as a recipe or a specification, but as a set of guidelines for creative mission problem solvers.

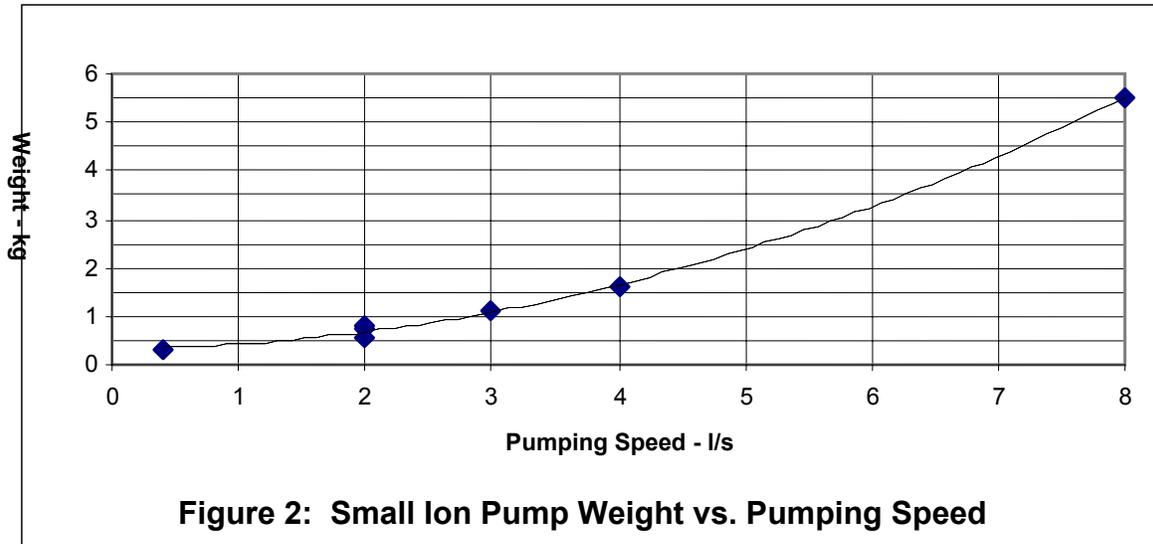
### Survey of a Wide Range of Commercial Pumps

In beginning to consider miniature ion pumps, it was interesting to look at what was commercially available, and whether a scaling factor could be determined from that information. Figure 1 shows a plot of ion pump weight versus pumping speed for a wide variety of ion pumps over a range of more than four orders of magnitude. (Pump weights include flanges.) Historically, this curve has moved down by about a factor of two, through more efficient magnet designs, but the general slope has remained the same.



### Some Typical Miniature Pumps

More interesting for this presentation, however, is the low end of the scale. This is shown in Figure 2. At the small end, the scaling factor seems to be about 0.5 kg per liter per second. An improvement by a factor of two is possible by using exotic magnet materials and optimized pump design. These factors, among others are discussed in the material following.



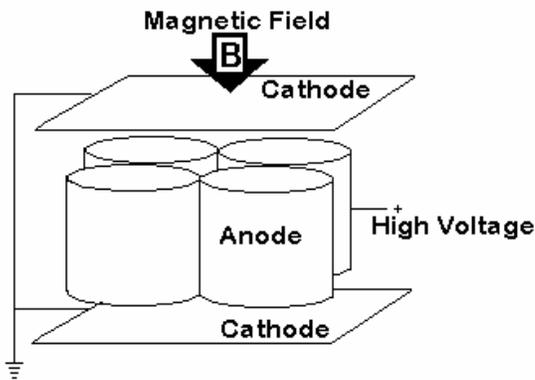
## II. Dependency of Pumping Speed on a Variety of Parameters

### The Penning Discharge Principles

The sputter-ion pump combines mechanical, electrical, magnetic and chemical principles to permanently capture residual gas molecules in vacuum systems. Figure 3 shows a typical structure; an array of circular anode cells at an electrical potential of several thousand volts is placed between chemically active cathode plates at ground potential and all immersed in an axial magnetic field of a few thousand gauss.

At pressures below about  $10^{-3}$  torr, an electrical discharge, called the Penning Discharge, is maintained within the anode cells and between the cathodes. The magnetic field forces electrons into a spiral path, which enhances their probability of ionizing residual gas molecules. Secondary electrons formed in this process contribute to the maintenance of the discharge intensity. An “avalanche” of electrons is produced as successively more ions are produced.

Ions formed in this process are accelerated to the cathodes, where they are a) buried and/or b) neutralized and/or c) cause sputtering of the cathode material and/or d) combine chemically with the freshly exposed cathode material. In addition, secondary electrons are released as the ions hit the cathode, and these electrons also contribute to the maintenance of the discharge.



**Figure 3 – Penning Discharge Configuration**

## Parametric Relationships

For several of the parameters involved in ion pump design, the plot of pumping speed versus the parameter in question follows the Ayer's Rock pattern:

Threshold value,  
Linear rise,  
Leveling off to a long plateau  
Saturation fall-off.

Practical considerations usually limit the operation to a restricted set of values. A selected set of information from the literature is presented below. As one can observe, there is a substantial interdependence of many of the parameters. However, this presentation is not meant to be an exhaustive description of the operation of the Penning discharge. A bibliography is provided to allow further study of this complex phenomenon.

## I/P and Pumping Speed

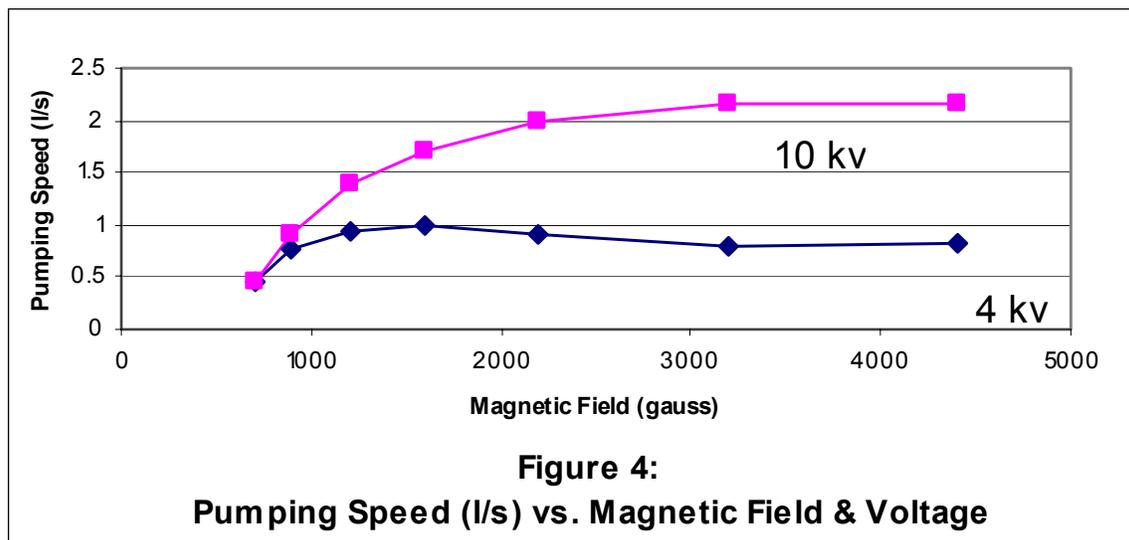
In much of the literature, and therefore this discussion, the ratio of ion current to pressure (I/P), is used as an indication of the pumping speed for ion pumps. At a particular pressure, more current flowing in the ion pump anode circuit represents more ions being formed and therefore more gas ions being pumped. The relationship is:

$$S = K * (I/P)$$

Where S is in liters per second, I is in amperes, P is in Torr. The value for K is between 0.05 and 0.2 for a large variety of configurations. So, for example, an 8 liter per second pump operating at 1200 gauss and 3000 volts would draw 1 milliamps at  $1 \times 10^{-5}$  torr, giving a K of 0.08 ( $8\text{l/s} = 0.08 \times 10^{-3} \text{ amps}/10^{-5} \text{ torr}$ ).

## Magnetic Field Strength

The threshold magnetic field for formation of the Penning discharge is usually several hundred gauss; for typical configurations the value is between 600 to 800 gauss. This value is determined by the point at which an electron path is curved enough by the magnetic field so that it produces enough ions and therefore, an electron avalanche, to allow the discharge to be self-sustaining. Figure 4 (from reference #1) shows some data for pumping speed for a single anode cell of 0.5" diameter at two different voltages and a range of magnetic fields.



Pumping speed rises more-or-less linearly with applied magnetic field from the threshold value up to a few thousand gauss. Increasingly curved electron paths give rise to more ionizing collisions, more electron avalanches and increases in current, therefore pumping speed.

A “Plateau” of pumping speed versus magnetic field is reached. This plateau is determined by the point at which the spiraling electron path is long enough so that it produces enough ions and therefore, electron avalanches, to produce a discharge in which the space-charge reaches a limit. Further increases in current and therefore pumping speed are limited.

At very high magnetic fields, well beyond the operating ranges of interest for small ion pumps, a fall-off in pumping speed has been observed. This is explained in the literature to be due to the fact that the maximum energy attained by an electron in its cyclical orbit falls below that necessary to produce ionization. At that point the current and therefore the pumping speed decreases rapidly. (See Reference #2).

Practical considerations with actual permanent magnet materials dictate that magnetic fields in the range of 1000 to 3000 gauss be used. Electro-magnets, especially superconducting magnets can produce much higher magnetic fields. Ion pumps for operation immersed in such fields have been designed and are operating in extremes of parameters not usually practical with permanent magnets.

## **Voltage**

The threshold voltage for formation of the Penning discharge is usually several hundred volts; for typical configurations the value is between 600 to 800 volts. This value is determined by the point at which an electron produces enough ions and therefore, an electron avalanche, to allow the discharge to be self-sustaining.

Pumping speed rises more-or-less linearly with applied voltage from the threshold value up to several thousand volts. Increasing electron energy allows more ionizing collisions/avalanches, therefore increasing current and pumping speed.

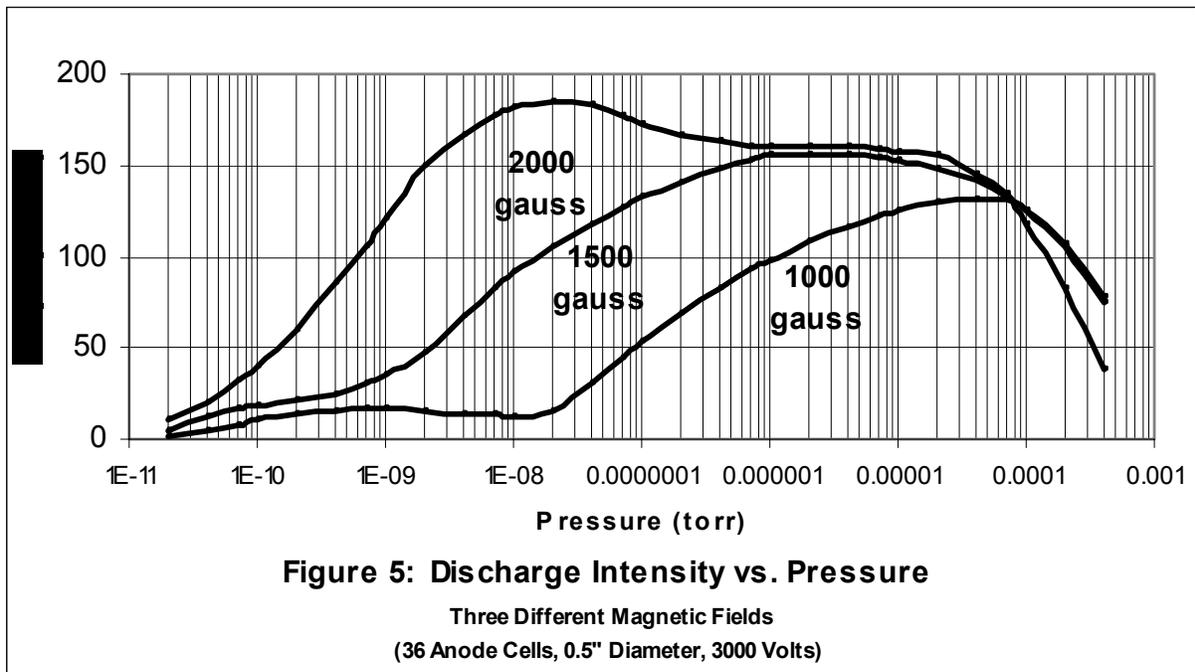
A “Plateau” of pumping speed versus voltage is reached. This is explained in the literature to be due to a build-up of space charge in the anode cell to some maximum value, at which point the current and therefore the pumping speed cannot increase further.

At very high voltages, well beyond the operating ranges of interest for small ion pumps, a fall-off has been hypothesized, but difficulties with measurements at high voltage have made confirmation of this prediction problematic.

Practical considerations in insulator design and materials for high voltage feedthroughs and stand-off insulators, limit ion pumps, especially miniature ion pumps, to the use of voltages in the range of 3000 to 6000 volts. At high operating voltages, leakage currents, especially field emission currents, interfere with using the ion pump current as an indicator of pressure. The exponential dependence of field emission leakage current versus operating voltage encourages the use of lower voltages, if current measurements are used. Most pump designs develop field emission leakage currents with extended use. The formation of flakes of sputtered material, which subsequently move around due to vibration, is the most likely source of sharp points. Design parameters to be avoided are: small spacings and sharp corners on parts where high voltage gradients exist.

## **Operating Pressure**

In Figure 5 (from Reference #4), we see a plot of discharge intensity (I/P) versus pressure for three different magnetic fields. A strong variation in discharge intensity (I/P) and therefore pumping speed versus pressure is shown. At high pressures, high voltage power supply current limitations cause a decrease in discharge intensity. Also, above about  $2 \times 10^{-4}$  torr, the discharge changes modes to a less confined form as the mean-free-path for charged particles and molecules decreases. This data is for a 36 cell array, cell diameter 0.5 inch operated at 3000 volts. The pumping speed of these arrays was in the range of 5-10 liters per second.

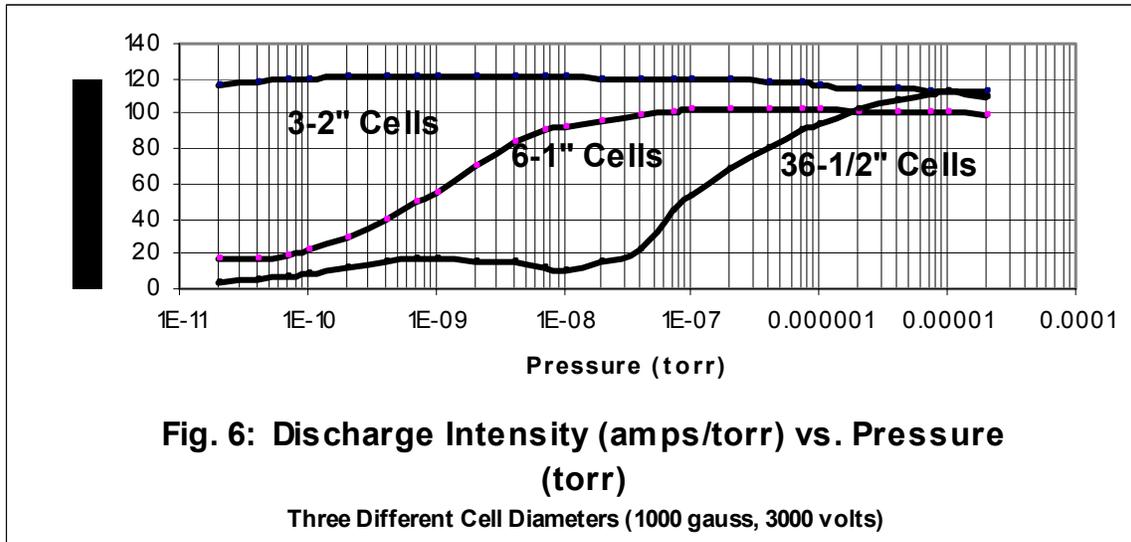


At pressures below  $10^{-4}$  torr, the discharge intensity has a broad plateau, and then a decline as pressure is further reduced. The onset of the decline is strongly influenced by the magnetic field strength. If one defines a “cut-off pressure”, as the point at which the discharge intensity is 50% of its peak value, then from Figure 5:

<u>Magnetic Field</u>	<u>Cut-off Pressure</u>
1000 gauss	$1.5 \times 10^{-7}$ torr
1500 gauss	$5.0 \times 10^{-9}$ torr
2000 gauss	$4.0 \times 10^{-10}$ torr

### Anode Cell Diameter

Figure 6 (from Reference #4) shows the dependency of discharge intensity over a wide pressure range for three different anode cell diameters. This shows the strong influence of anode cell diameter on “cut-off pressure”; larger anode cell diameters give better performance at low pressures. Magnetic field was 1000 gauss and voltage was 3000 volts.



<u>Cell Diameter</u>	<u>Cut-off Pressure</u>
0.5 inch	$1.5 \times 10^{-7}$ torr
1.0 inch	$8.0 \times 10^{-10}$ torr
2.0 inch	$< 10^{-11}$ torr

From the combination of the observations in Figure 5 and Figure 6, we see the importance of providing the highest product of magnetic field (B) and anode cell diameter (D) to maintain low pressure pumping speed.

### Anode Cell Length

It has been found that I/P and therefore pumping speed is proportional to anode cell length. Typical ion pumps have anode cells with lengths that are approximately 1.5 times their diameter. At more extreme lengths, the problem of maintaining the alignment of the anode cell with the magnetic field becomes difficult (see below). Also, conductance of gas molecules into the middle of the anode cells gets to be an issue for very long cells.

**Generalization:** From the data above, then, one can generalize that an ion pump with:

- A single anode cell,
- 0.5 inch diameter,
- 0.75 inch in length,
- operating in a magnetic field of 1500 gauss and,
- at 3000 volts;
- will have a pumping speed of approximately 0.5 liter per second,
- for nitrogen,
- with an I/P of about 3 amps per torr
- in the pressure range of  $1 \times 10^{-4}$  torr to  $1 \times 10^{-7}$  torr.

### Magnetic Field Uniformity

Non-uniform magnetic fields present problems for ion pumps. For example, bulging field lines near the edge of a magnet structure reduce the magnetic field in that region. Reduced magnetic field, as we have seen, means lower pumping speed and poor low pressure performance. Thus magnetic material should extend beyond the projected area of the anode cells in order to improve field uniformity.

Improper alignment of the axis of the anode cell with the magnetic field lines also reduces pumping effectiveness. If you imagine a view of a poorly aligned anode cell, looking in the direction of the magnetic field

line, only the part of the cell diameter that represents a clear view through is really effective. This means that the cell diameter is effectively reduced as increasing mis-alignment occurs. Especially at low pressures, this mis-alignment will reduce pumping speed.

## Gas Species

Chemically active gases, such as oxygen and nitrogen, are pumped by chemical combination with the metal cathode getter material. This pumping either occurs directly at the cathode, or more likely, at other surfaces of the pump structure where freshly sputtered cathode material has been deposited. The compounds formed are quite stable, these materials are permanently removed from the system. (See reference #3).

Hydrogen is buried into the cathode or gettered directly on freshly sputtered cathode material, where it forms a solution with the cathode material. This solution is temperature sensitive, with hydrogen being released at elevated temperatures.

Molecules, such as water vapor, carbon dioxide, carbon monoxide and light hydrocarbons are dissociated in the electrical discharge. The dissociated species are pumped by their normal mechanisms. There is substantial evidence that free carbon from these dissociated molecules sits around on the pump surfaces. Hydrogen diffusing out of the getter material can combine with this carbon to form methane. Thus, it is common to see methane as a residual gas in a pump that has been exposed to carbon-containing molecules.

Noble gases, such as argon, helium and neon, have a completely different pumping mechanism. Since they are chemically inert, their removal in an ion pump involves ionization in the discharge, acceleration to the cathode, neutralization at the cathode and burial at various locations on pump surfaces. When the neutralized noble gas atoms are buried in the cathode, they are subject to later release as additional sputtering takes place. The periodic pumping and re-emission can lead to pumping speed variation (and resultant pressure fluctuations). This re-emission can be solved by changing the configuration of the cathode plates to enhance the rate of net capture of noble gas atoms. Even though encountered only in low concentrations in the earth's atmosphere, noble gases, especially argon can cause problems with conventional diode ion pumps. See the sections below on cathode materials and geometry variations to address this issue.

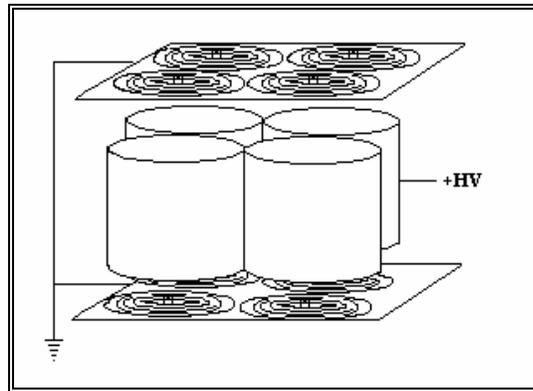
## Cathode Material

Traditionally, ion pump cathodes have been made of titanium. The high getter/chemical activity, low vapor pressure, ready availability and reasonable cost have made titanium the natural choice for general purpose pumping applications. For the pumping of noble gases, however, an ion pump with two titanium cathodes can lead to problems as noted above. By replacing one of the cathodes with a material of much higher atomic weight, such as tantalum, the balance of sputtering, ion neutralization and net burial can be shifted. This shift leads to higher and stable pumping speeds for noble gases. Pumps of this hybrid Ti-Ta cathode configuration are commercially called "Differential Ion" or "Noble Diode". Tantalum is substantially more expensive than titanium, leading to higher prices for such pumps. There is also about a 20% reduction in the active gas pumping speed available from a particular pump volume or structure. (See reference #5).

## Cathode Configuration

In addition to the hybrid Ti-Ta configurations mentioned above, other cathode geometry variations have been used to accomplish the same shift in the balance of sputtering, ion neutralization and net burial. Generally, this is accomplished by providing cathode areas where the gas ions strike the cathode at grazing incidence instead of normal incidence.

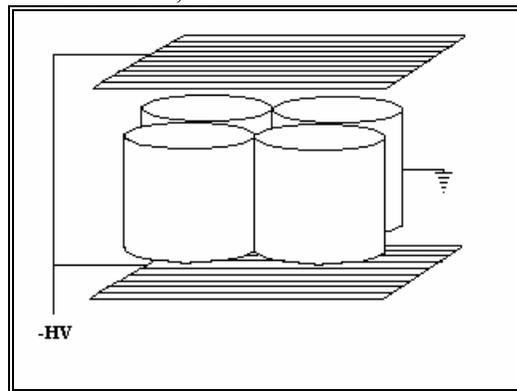
Diode cathode structures with slots and fins in the surface facing the discharge accomplish this function. A current version of this structure is called the "Galaxy<sup>™</sup>" design, providing spiral patterns cut through the cathode. (See Figures 7 and 14) These designs are simple and rugged, while providing stable noble gas pumping without the expense of tantalum cathode material. Also, there is no reduction in active gas pumping speed over normal diode pumps.



**Figure 7: Galaxy™ Diode Pump Configuration**

Another solution to pumping noble gases is the “triode” configuration. (See reference #6) An electrode of slotted titanium structure is placed between the anode cells and the pump wall. In this configuration, the anode is operated at ground potential and the slotted structures are operated at negative high voltage. The Penning discharge phenomenon operates in exactly the same way, but again, the balance of sputtering, ion neutralization and net burial is shifted to accomplish stable noble gas pumping. This structure is called “Triode” or StarCell<sup>®</sup> (see Figures 8 and 15) depending on the details of the slotted structure. It is somewhat more complex in structure than the diode pumps and the pumping speed for a particular volume is reduced by about a factor of approximately 20%

Galaxy™ is a trademark of Duniway Stockroom Corp.  
 StarCell<sup>®</sup> is a registered trademark of Varian, Inc.



**Figure 8: Triode Pump Configuration**

## Conductance

Regardless of the intrinsic pumping speed at the middle of an anode cell, an ion pump must provide sufficient gas access from the attached system in order to take advantage of that pumping speed. The conductance of the attachment tube between the pump and the system is obviously involved in this consideration, but it is also important to consider the conductance from the pump connection through the gap between the anode and cathode. The temptation to use all of the magnet gap for anode cell length, because of the gain in intrinsic pumping speed, can quickly limit the available speed due to lack of gas access to the ionizing zone of the anode cell.

The relationship of available pumping speed (  $S_a$  ) to conductance (  $C$  ) and intrinsic pumping speed (  $S_i$  ) is represented by the reciprocal formula:

$$1/S_a = 1/C + 1/S_i$$

A typical tubulation for a miniature pump might be 0.45 inches ID by 2 inches long, which gives a conductance of approximately 3 liters per second. If attached to a pump with intrinsic speed of 2 liters per second, the available pumping speed would be 1.2 liters per second, a 40% loss. Typical miniature pumps have even smaller tubes with resulting greater losses in speed.

If the gap between anode and cathode is 0.15 inches for an array of 4 anode cells of diameter 0.5 inch, the conductance from the inlet to the center of the array would be on the order of 1 liter per second per side. Adding the tube conductance above to the gap conductances gives a net conductance of 1.2 liters per second; calculating the resultant available pumping speed gives a value of 0.75 liters per second. This is a reduction of more than 60% from the intrinsic speed.

### **Other Considerations**

Discharge formation times come into consideration for low pressure operation. If the voltage is applied to an ion pump at low pressures, significant delays (minutes at  $10^{-10}$  torr) can occur before the Penning discharge 'starts'. The 'starting' of the discharge depends on an electron being available to initiate the avalanche formation. Formation times are shorter at high pressures and are reduced when multiple anode cells are in parallel.

For critical applications where starting delays can not be tolerated, a source of electrons, such as a filament or a mild radioactive source, supplies essentially instantaneous formation at any pressure or cell count.

## **III. Designing a Small Ion Pump**

The task of designing a miniature ion pump involves an iterative process of going through the combination of parameters discussed in Section II. The design process is fairly straight forward, albeit limited by the real materials and mission requirements. The degree of restrictions on the mission to be accomplished will determine whether a commercially available product or a custom design will be required.

### **Pumping Speed and Operating Pressure**

Designing a miniature ion pump starts with specifying the pumping speed required for the experimental gas load which will be encountered. Next, the operating pressure needs to be determined. From earlier discussions, these two design specifications will determine the range of cell diameters and magnetic field strengths which will fit the application. For example, operation in the  $10^{-7}$  torr range imposes only modest requirements on magnetic field and cell diameter; on the other hand, an operating pressure of  $10^{-9}$  or below requires larger cell diameters and/or magnetic fields in order to meet reasonable pumping speed values. These parameters in turn require larger volumes and heavier magnets.

### **Anode Cell Design**

From the above considerations and the data presented in Section II, above, choose a cell diameter, cell length, number of cells and operating magnetic field. This choice should be made to provide the specified pumping speed over the required pressure range.

### **Magnet Design**

In designing a miniature ion pump of a specific pumping speed, where size, weight and stray field are critical factors, magnet design becomes important.

If weight and stray field are not critical, a "U" shape or horse-shoe design using inexpensive materials can be used. See Figure 11 for an example of this style of design using Alnico V, which is normally a commercially available product.

If weight is critical, more expensive materials are required. See Figure 12 for a magnet design using samarium cobalt magnet materials. The two magnets shown are an Alnico 5 ‘horseshoe’ magnet which weighs 950 grams and a shielded samarium-cobalt magnet which weighs 750 grams.

If stray field needs to be minimized, a structure which completely encloses the magnet in low permeability shielding material is required. See Figure 10 for another example of a custom designed ion pump which embodies such a shielded design.

## Magnetic Materials

The choice of magnetic material for an application depends on considerations discussed above. Cost and magnetic energy available are the most common decision factors. The table below shows three commonly available materials used in ion pump magnet design. (The magnetic energy specification is designated: B-Hmax, which represents the point on the magnetization hysteresis curve where the product of applied field and resulting magnetization reaches a maximum. This represents the maximum magnetic energy that a unit volume of the magnet material can produce in an air gap). (See reference #7).

<u>Material</u>	<u>B-Hmax</u>	<u>Cost</u>	<u>Application</u>
Ferrites	3-4 MG OE	Lowest	Most current ion pumps
Alnico 5	4-6 MG OE	Medium	Older ion pump designs
SmCo	15-20 MG-OE	High	Most light-weight magnet designs
NdFeB	30-50 MG-OE	High	Computer Disk Read-Write Heads

For lowest cost designs of modern commercial ion pumps, ferrite materials are chosen. However, for light weight, compact and highly shielded designs, samarium-cobalt materials are used, in spite of their higher cost.

In addition to the actual magnetic materials, high permeability pole pieces, such as mild steel are used to complete the magnetic circuit, directing the magnetic energy primarily to the air gap. Shielding structures to shunt stray fields, also require high permeability materials, such as mild steel or mu-metal.

**Note:** Magnetic circuit design is a discipline of its own. Knowledgeable resources should be used if substantial departures from existing designs are undertaken.

## Optimizing the Use of the Magnet Gap

Since the magnet gap is the commodity with the highest price, it must be used efficiently. The length of the anode cells uses up most of the gap, but additional requirements consume the gap also.

Anode-to-cathode spacing must be adequate to provide gas access and avoid electrical breakdown;  
 Cathode thickness must be adequate for the lifetime gas load anticipated;  
 Pump wall thickness must be adequate to support the ambient pressure differential of the mission.

## Voltage and Power

The power supply for the ion pump also involves optimization for the mission:

Operating voltage (usually kept relatively low, 3000 to 5000 volts) to avoid breakdown problems.  
 Maximum current required for highest encountered pressures.  
 Is electrical current measurement required for pressure indication?

## **Cathode Design**

Cathode design will be dictated primarily by the gas species which will be encountered on the mission. Also to be considered are the gases generated and/or to be avoided by the instruments which demand the vacuum environment.

For general outgassing loads from vacuum materials and instruments, the common diode with titanium cathode plates is a good solution.

If noble gases are encountered, one of the diode solutions will be required (Ti-Ta or Galaxy<sup>™</sup>). The Galaxy<sup>™</sup> solution will be lighter in weight, since no heavy tantalum is required. For miniature pumps, triode and StarCell<sup>®</sup> designs are to be avoided due to poor space utilization and more complex construction.

Lifetime gas load will determine how much material will be required. Normal ion pump designs, with cathode thicknesses between 0.060 and 0.090 inch have lifetimes on the order of 40,000 hours at  $1 \times 10^{-6}$  torr. For limited duration missions, thinner cathodes can be used. If large gas loads of hydrogen or noble gases will be encountered, more cathode material should be used.

## **Summary**

There are valid economic and physical reasons behind the designs of commercially available ion pumps. The main dependencies have been enumerated in this communication. Restrictions on magnetic materials, high voltage breakdown, gas access and physical ruggedness are the main limitations encountered in the design process. For particular applications, the equipment designer can optimize for the most important parameters to reach the goals of the mission.

#### IV. Examples of Miniature Ion Pumps

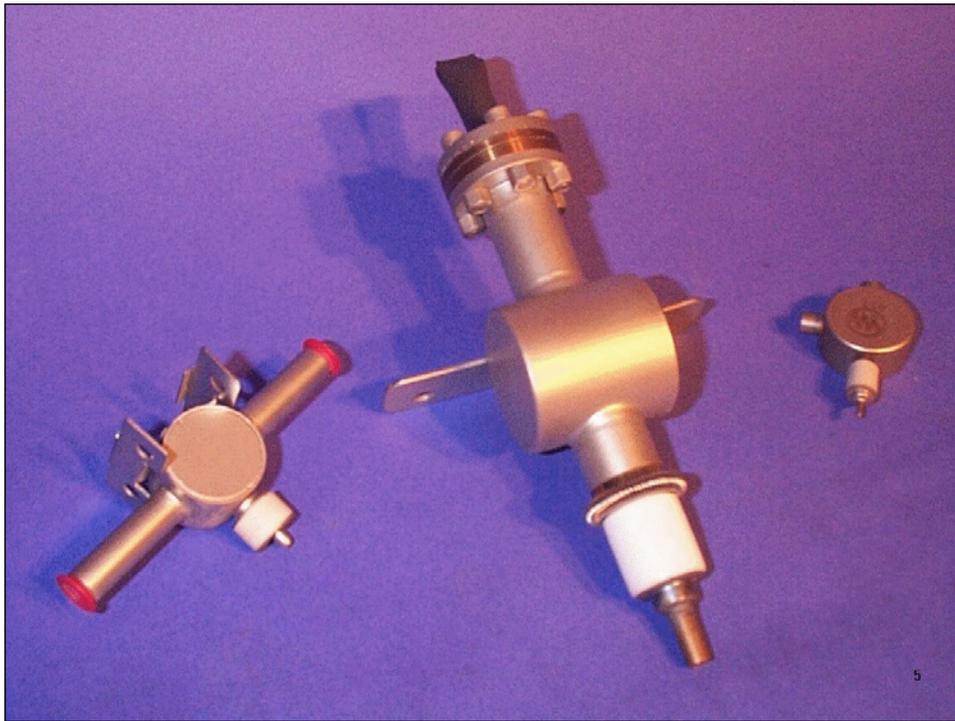


Figure 9: Varian-style “Mini”, “2 l/s” and “Micro” Ion Pumps



Figure 10: “Varian-style” Mini Ion Pumps – Various Forms with Magnet



Figure 11: Varian style 2 liter per second pump with SmCo and Alnico 5 Magnets

**Photographs of Ion Pump Cathode Designs**

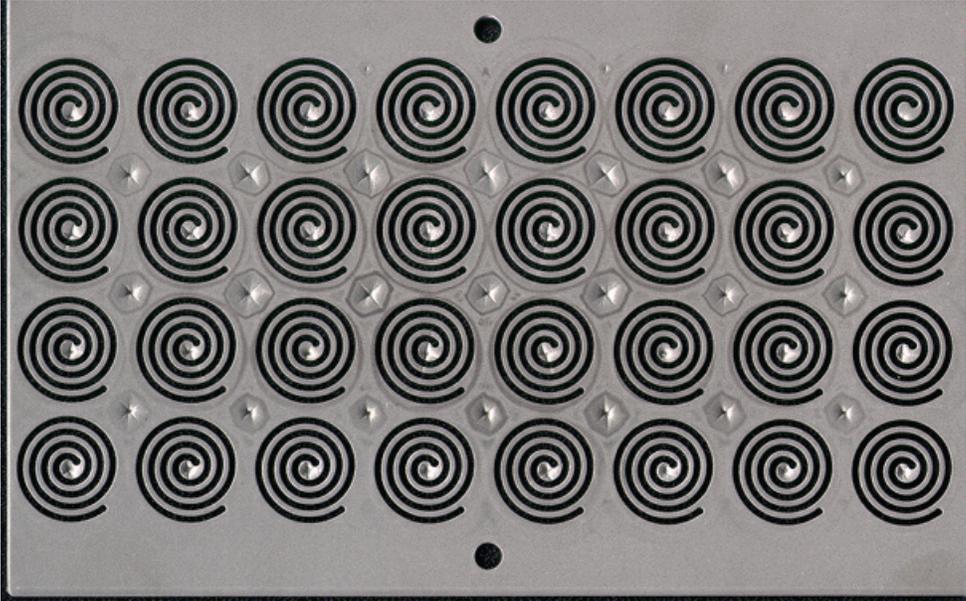
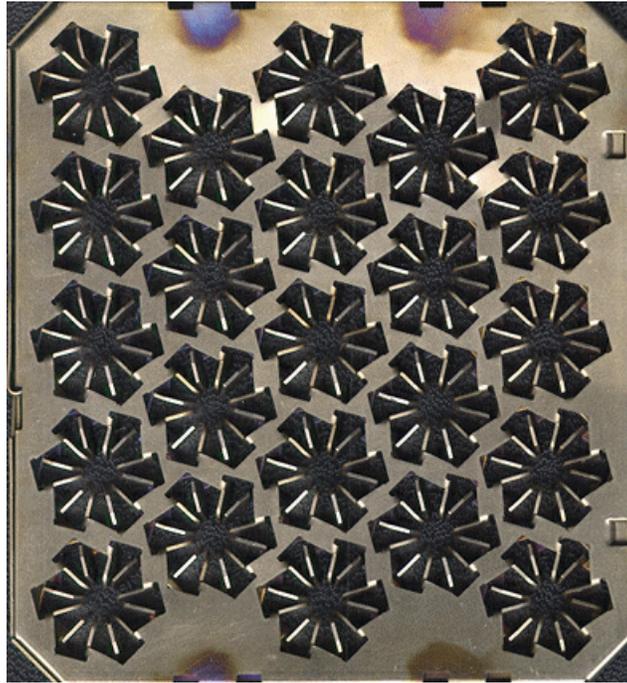


Figure 12: Example of Galaxy™ Cathode for Diode Ion Pump



**Figure 13: Example of StarCell<sup>®</sup> Cathode for “Triode” Ion Pump**

## **V. Bibliography**

1. R. L. Jepsen, “Important Characteristics of a New Type getter-Ion Pump”, *Le Vide*, Vol. 14, No. 80, pp. 80-94, (1959).
2. R.L Jepsen, “Magnetically Confined Cold-Cathode Discharges at Low Pressures”, *Journal of Applied Physics*, Vol. 32, No. 12, pp. 2619-2626, December, (1961).
3. S.L Rutherford, S. L. Mercer, and R. L. Jepsen, “On Pumping Mechanisms in Getter-Ion Pumps Employing Cold Cathode Gas Discharges”, *Transactions of the Seventh National Symposium on Vacuum Technology*, American Vacuum Society, pp. 380-382, (1961).
4. S.L. Rutherford, “Sputter-Ion Pumps for Low Pressure Operation”, *Transactions of the Tenth Annual National Vacuum Symposium*, American Vacuum Society, pp. 185-190, (1963).
5. T. Tom, and B. D. James, “Inert Gas Pumping Using differential Sputter Yield Cathodes”, *Journal of Vacuum Science and Technology*, Vol. 6, No. 2, pp. 304-307, (1968).
6. W. M. Brubaker, “A Method for Greatly Enhancing the Pumping Action of a Penning Discharge”, *Transactions of the Sixth Annual National Vacuum Symposium*, American Vacuum Society, pp. 302-306, (1959).
7. *Metals Handbook*, “Materials for Permanent Magnets”, American Society for Metals, p. 20-8, (1985).