Ion pump using cylindrically symmetric spindle magnetic field

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Abstract. For all accelerators and many research and industries, excellent vacuum conditions are required and the highest possible pumping rates are necessary. For most applications the standard ion sputtering pump (ISP) meets these requirements and is optimal for financial point of view also. The physical principle of the ISP is well known and many companies manufacture variety of ISP. Most of them use dipole magnetic field produced by permanent magnet and electric dipole field between the electrodes in which tenuous plasma is created because of interaction of between the relatively fast electrons slow residual gas atoms. Performance of an ISP depends basically on the electron cloud density in between the titanium electrodes but in the available present configurations no consideration has been given to electron confinement which needs a mirror magnetic field. If this is incorporated it will make a robust ISP surely; furthermore, the requirement of constant feeding of high voltage to electrodes for supplying sufficient number of electrons will be reduced too. A study has been performed to create sufficient rotationally symmetric spindle magnetic field (SMF) with inherent presence of magnetic mirror effect to electron motion to confine them for longer time for enhancing the density of electron cloud between the electrodes. It will lessen the electric power feeding the electrodes and lengthen their life-time. Construction of further compact and robust ISP is envisaged herein. The field simulation using the commercially available permanent magnet together with simulation of electron motion in such field will be presented and discussed in the paper.

1. Introduction
The first major use of vacuum technology in industry occurred in about 1900 in manufacturing of electric light bulbs. The advent of nuclear energy in the 1950’s provided impetus for development of vacuum equipment on a large scale. Increasing applications for vacuum processes were steadily discovered, as in space simulation and microelectronics. Any accelerator person cannot think about an accelerator, a beam-line, scattering or reaction chamber, and an ion or electron source without vacuum creation. The high energy beam accelerators like synchrotrons, storage rings and colliders need very good vacuum conditions because the beam of ions or electrons circulate a large number of times and unwanted collisions with residual gas atoms reduces the beam and its life-time. Vacuum is very important for transmission or scanning electron microscopes and they are needed to meet usual or unusual configurations economically. A focused ion beam system assist in achieving very small semiconductor structure and micron scale mechanical structures, which also need very clean vacuum environment. A wide variety of gases are used in such system and puts extra requirement of multiple level of vacuum at different positions. In many experiments, it is not only necessary to reach the pressures of of the order of 10⁻⁹ torr but to reduce the hydrocarbons in the residual gases to an absolute minimum. To achieve a vacuum of this order the vacuum vessel and the equipment inside...
must be cleared of residual gas (degassed) to the greatest extent possible, by means of a roughing
pump. To eliminate hydrocarbons, the unit is pumped down to about $10^{-3}$ torr using sorption pumps
and from there, ion sputtering pumps (ISP’s) and titanium sublimation pumps complete the task down
to $10^{-9}$ torr or below. Wide application of ISP is also attributed to its operation in any position and
without water or liquid nitrogen supplies. They have a long life and can provide very clean, ultrahigh
vacuum, free of organic contamination, moving part and vibration. Due to achieving clean vacuum,
bakeability, low power consumption and high pumping speed, an ISP is the ideal cost-effective
companion.

The working of an ISP was reported first by J. Plucker [1] and he found that with time the voltage
requirement to maintain a current in a gas discharge tube was more. Later, it was explained that the
current decreased because of pressure decrease in the tube and the relationship was found to be
directly proportional. This property was used by F. Penning [2] to measure the gas pressure inside the
tube and extended measurement in the range $10^{-5}$ to $10^{-3}$ torr in a vacuum vessel. Later some industries
exploited the invention in developing ISP’s and ion gauges for creating vacuum and measuring
pressure respectively. Apart from an ISP, various other types of pumps like diffusion pump, cryo
pump, turbo-molecular pump etc. are commercially available in the market for various applications.

The residual atoms/ molecules inside a vessel spread out in any direction through diffusion and
under pressure gradient to another vessel, if they are connected to provide gas conductance. Both
electric field and magnetic field are used in an ISP. The neutral atoms and molecules when enter the
pump chamber consisting of invisible fields, there is predominant ionization process due to presence
of energetic electrons. We know that electron is the best ionizing agent as an electron with sufficient
energy can impart maximum energy to the bound outer electrons in an atom. These electrons get
excited so much that they break away from the atom and mostly single charge ions are continuously
created. The charged particles get energy from the electrostatic field, which is created due to
application of appropriate voltage between the cathode and anode electrodes. As soon as ionization
starts, more and more electrons get sufficient energy for further ionization and a chain reaction is
established. Ions also get sufficient energy and strike the cathode made of titanium material, which is
highly reactive with hydrogen, oxygen, nitrogen, etc., while being lost on the cathode surface.
Furthermore, the titanium atoms are vaporized or sputtered from the cathode and they entrap (engrave)
those reactant atoms and product molecules on the cathode surface at the vicinity of the interior
surface of the pump chamber. The active gasses are pumped by chemical combination with the
sputtered titanium, the inert gasses by ionization and burial in the cathode and the light gasses by
diffusion into the cathode. Magnetic field is also present in the vacuum chamber. The most important
function of magnetic field is to increase the path length (mean free path) of the ionizing energetic
electrons in the vacuum chamber. Another effect of the magnetic field is to reflect most of the
electrons before being lost on the chamber surface. Thus, the average life time of the electrons
increases in the chamber causing more and more ionization. The created ions also gain energy and
always move in a curved path under the influence of the EM fields and ultimately get lost on the
cathode surface incessantly.

A typical ISP consists of two flat rectangular cathodes with a stainless steel anode between them
made up of many open-ended boxes. This assembly, mounted inside a narrow box attached to the
vacuum system, is surrounded by a permanent magnet (PM). The anode is operated at a potential of
about 7 kV, whereas the cathodes are at ground potential. They use PMs to generate sufficient field
(about 2 kG) with little mirror effect. But there is ample scope of improving the performance
significantly of an ISP by reconfiguring the magnetic field, which will reduce the electric load on
electrodes too. Here, we take advantage of the anti-solenoid field created by either a pair of coaxial
coil energized oppositely or a radially magnetized permanent magnet ring. It creates magnetic field
with convexity of field lines towards the centre of the chamber. The field has great inherent benefit of
confining the electrons inside the pump chamber for longer time to achieve maximum number of
ionization per energetic electron. Application of the field will enhance further its pumping speed and
reduce the electrical power consumption to make it more cost-effective.
2. Spindle magnetic field

First, we decide the geometry of the ISP as well as the magnet system with yoke. The geometry should be such that the pieces of the PM’s are arranged outside the chamber. The highly permeable iron yoke is enhances the field and reduces the volume of the PM material and it is properly placed around the PM ring and chamber ends. The yoke also protects the PM and keep them tightly bound around the curved surface of the cylindrical metal chamber. The geometry of the magnet and chamber is fixed after field optimization. The optimized geometry is shown in figure 1 below. It seems to be a big ISP to evacuate large vessel. Here, just an example of a big ISP is depicted for the purpose of following the procedure to design appropriate ISP’s suitable for applications.

Fig. 1. The pump is rotationally symmetric about the z-axis. The innermost shaded region is the cathode at the vicinity of the chamber surface. The anodes are cylindrically and radially gridded and several kV positive potential is applied. The rare-earth PM pieces are densely packed and are radially magnetized. The inner diameter of the PM ring is 22 cm. The outer shaded area levelled as ‘Y’ is the iron yoke of 1 cm thickness. The pump is connected to the vessel to be evacuated at C. Pumping speed will depend on the cathode surface area, applied potential, the produced magnetic field, ionization process and burial (capture) process of ions and atoms on the cathode surface.

2.1. Magnetic field computation

In the above geometry the rotationally symmetric magnetic field is generated due to the combination of the arranged PM’s and the highly permeable magnetic material (low carbon magnetic steel), which provide ruggedness and strength in structure of the pump. The magnetic lines of force (MLF) emanating radially from the PM surface, facing the chamber cylinder, are bent and meet the end yokes axially such that their convexity is towards the centre of the chamber. The field was calculated using the PANDIRA code [3]. The field configuration is shown in the following figure 2. The PM used for calculation has remnant field and coercive force 8.5 kG and 8.5 kOe respectively. The radial and axial
dimensions of the PM ring are 3 cm and 14 cm respectively. The yoke works as a shield also for external field and the pump will continue to work unaffected in an external magnetic field.

The computed field has been plotted in figure 3 in 3D. In any r-z plane, field plot depicted in the figure is same. It is seen that the magnetic field at the vicinity of the centre characterised by r=z=0 is zero. And it rises from the centre in radial and axial direction both. This may be termed as zero-B field configuration. The magnetic field achieved at the chamber surface in z=0 radial plane and at r=0, end plate surfaces are almost same value ~1.86 kG. So, a symmetric spindle magnetic field (SMF) [4] is created to achieve regular magnetic mirror ratio for achieving good quality confinement of electrons for longer time. The legend of the shaded plot region is shown in the top region of the figure and the field values are in Gauss. The maximum field achieved, which is more than 3 kG, is near the ends at the highest radius, 9.5 cm. The maximum axial width of the vacuum chamber is 24 cm.

![Fig. 2. Plot of the MLF's due to the combined effect of the PM magnetization and induced magnetization of iron yoke. The vacuum chamber with electrodes is immersed in the created magnetic field. This clearly shows the configuration of the SMF. The maximum field inside the yoke is about 10.3 kG. These MLF's coerce the electrons to gyrate around them and follow their path. The electrons as well as ions have high probability of being lost at the cylindrical surface of cathode and on the cathodes at the ends.](image)

2.2. Motion of charged particles

Motion of the charged particle in the computed field has been achieved by TrapCAD code [5]. The SMF in the r-z plane is given as input. Here, simulation of motion of single charge oxygen ion has been performed. One after another, 11 ions were launched around the centre of the chamber with components of energy parallel and perpendicular to the MLF 1 keV and 2 keV respectively at different
launching positions. The LHS and RHS figures in figure 4 show the projections of the same plot in x-y and x-z plane respectively. It is clear that 7 ions are lost on the cylindrical surface and the rest on the end electrodes. The trajectory of an electron has been depicted in figure 5. The electron was projected at \( z=5 \) cm and \( r=4.0 \) cm with energy components 2 keV and 3.5 keV respectively in parallel and perpendicular direction with respect to the MLF at the launching position. The LHS and the RHS figures, in figure 5, are depicted in the tilted x-y-z coordinate system and the projection in the x-y plane respectively of the same trajectory. It is seen that the electron is reflected a large number of times. Number of reflection of the electrons depends on their energy components and total energy, launching position, magnetic field components and its gradient and curvature. Presence of electric field and scattering with other similar or different particles also affect their behaviour. When the charged particles pass through the zero field area at the centre, they experience Coulomb- like scattering and probability of losing it increases. So, their density at the centre decreases.

Fig. 3. The 3D plot of the computed magnetic field in the r-z plane.

Fig. 4. Trajectories of 11 oxygen ions in the chamber immersed in the computed SMF.
When one hundred electrons were launched distributed uniformly in the vacuum chamber several times with different total energy and its components, it was found that about 42 electrons were left on the average in the vacuum chamber after 200 ns. So, it proves that the average containment time of the electrons is more than 200 ns. Though electrons are almost tied with the MLF’s, they drift due to various reasons also. But the heavier particles are not so because of high momentum and they are bound to be lost on cathodes once they are ionized and reach its surface through curved path.

3. Conclusion
The described structure was taken as an example and shown that an ISP can be constructed using a SMF produced by a PM ring to suit the evacuation requirement. The magnetic mirror ratio on a curved MLF’s terminating on the electrode surface increases appreciably as one move towards the centre from the chamber surface. It causes more electron confinement because of multiple mirror reflections, so more ionization. Thus, a compact and more powerful ISP can be constructed due to rapid ion loss.

The most common parameter used to express the capability of a pump used for evacuation of a given vessel is pumping speed. The ionization rate, titanium sputtering process, gas burial and re-emission on the titanium anode, which are related to magnitude and structure of electric and magnetic field, determine the pumping speed of the ISP. Experiments only will corroborate the proposed idea.

References
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